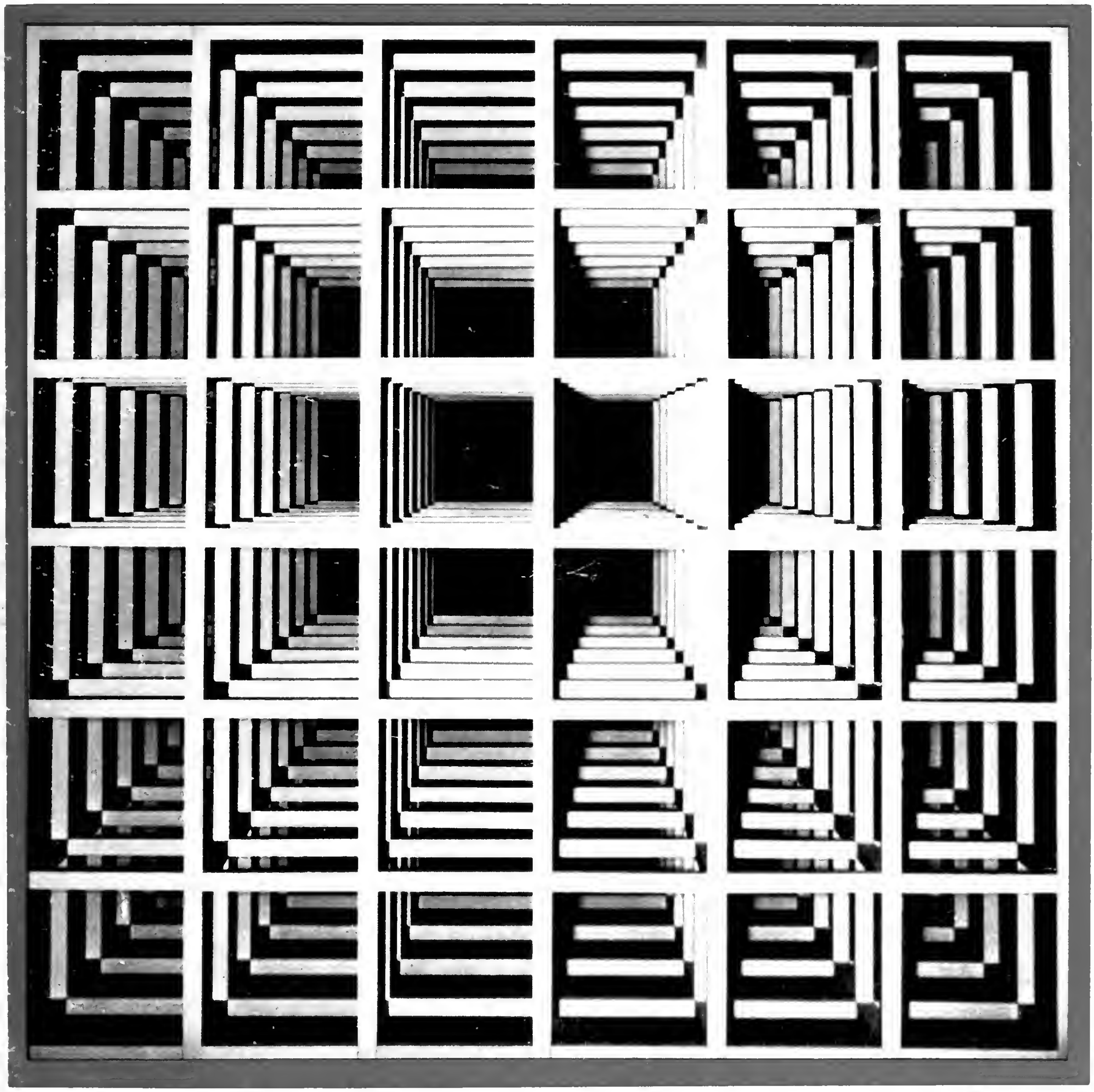
PROJECT PHYSICS READER

Readings in Classical and Modern Physics



PROJECT PHYSICS READER

Readings in Classical and Modern Physics

A Component of the
Project Physics Course

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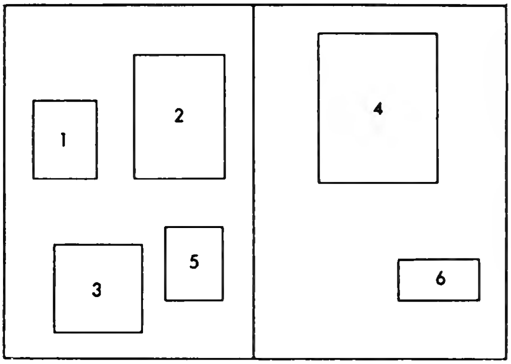

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This is not a physics textbook. Rather, it is a physics reader, a collection of some of the best articles and book passages on physics. A few are on historic events in science, others contain some particularly memorable description of what physicists do; still others deal with philosophy of science, or with the impact of scientific thought on the imagination of the artist.

There are old and new classics, and also some little-known publications; many have been suggested for inclusion because some teacher or physicist remembered an article with particular fondness. The majority of articles is not drawn from scientific papers of historic importance themselves, because material from many of these is readily available, either as quotations in the Project Physics text or in special collections.

This collection is meant for your browsing. If you follow your own reading interests, chances are good that you will find here many pages that convey the joy these authors have in their work and the excitement of their ideas. If you want to follow up on interesting excerpts, the source list at the end of the reader will guide you for further reading.

Readings in Classical and Modern Physics

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1

A Hole in the Sky

Walter Sullivan

An article from The New York Times Magazine, July 14, 1974

At 7:17 A.M. local time on June 30, 1908, something frightful occurred in the Tunguska area of central Siberia. As though a catastrophic mid-air explosion had taken place, virtually all trees within a radius of 20 miles were blown down. As recently as the nineteen-sixties, the charred tree trunks, many of them with the bark torn off, could still be seen from the air, forming a striking pattern of lines radiating from the explosion site.

Residents of the region who were alive at the time of the blast have reported that just beforehand they spotted a fireball crossing the sky that was so bright "it made even the light from the sun seem dark." From Kirensk, 250 miles away, a "pillar of fire" was seen, followed by three or four claps and a crashing sound.

Such was the force of the explosion that horses were thrown down in an area south of Kansk, more than 400 miles distant. Equally remarkable were the flash burns sustained by residents of this sparsely populated region. A farmer, S. B. Semenov, was sitting on the steps of his house, 40 miles away, when he saw the flash. He instinctively lowered his eyes, but the heat was searing. "My shirt was almost burned on my body," he told later visitors. When he raised his eyes again, the fireball had vanished. Moments later, the blast hurled him from the steps, leaving him briefly unconscious. When he recovered, a great thundering sound was audible. His neighbor, P. P. Kosolopov, was facing away from the fireball and the first he knew of it was when his ears burned painfully. He covered them with his hands and ran into the house.

A Tungus tribesman told scientists who reached the site long afterward that a herd of 500 reindeer had been wiped out: "The fire came by and destroyed the forest, the reindeer and all other animals." In one herdsman's storage hut, everything had been burned including his clothing, and his samovar as well as his silverware had melted.

Five widely divergent explanations for this event have been advanced:

- The first hypothesis was that a giant meteorite had fallen, exploding from the intense heat generated by its impact. Such a meteorite hit Arizona in prehistoric times, leaving a crater three-quarters of a mile wide. But when expeditions reached the remote Tunguska region, they could not find even a small impact crater.

- In the nineteen-fifties, it was suggested that a distant, highly advanced civilization may have somehow instigated a mid-air nuclear explosion. That the blast did, in fact, take place high in the air was shown by the dissection of tree branches that had been growing in 1908; the upper surfaces of the layer that had been exposed to the sky in that year had been scalded. In addition, recordings of fluctuations in the earth's magnetism at the time showed an effect strikingly like that produced by an atomic-bomb explosion in the atmosphere. And an expedition to the site in 1958 reported that unusually high levels of radioactivity had been detected there. However, a careful study of the area in 1961 showed that report to have been spurious.

- The explanation still favored by many scientists is that a comet head plunged into the atmosphere at such high velocity that it exploded in mid-air from heat generated by its entry into the atmosphere. Comet heads are widely believed to be huge "dirty snowballs," formed of frozen gases such as ammonia and water, with an admixture of dust, including particles of meteoritic iron. While such iron particles have been found in the soil of that region, they were not substantially more abundant than the accumulations of meteoric dust from the sky that are slowly deposited worldwide. Moreover, skeptical scientists have asked how a comet could have exploded without leaving even a trace of its own substance. And how could it have approached the earth without being seen?
- A more recent theory is that an "antirock" made of antimatter plunged into the atmosphere and was annihilated on contact with atoms of ordinary matter, producing a fireball of gamma rays and an explosion. This would account for the flash burns, the apparent absence of a mushroom cloud like those generated by ordinary chemical and atomic explosions, and the lack of any residual material.
- The latest proposal is that a tiny "black hole" hit Siberia, passing through the entire earth and emerging in the North Atlantic.

Nothing in the art of the medieval alchemist or the contemporary science-fiction writer is more bizarre than the concept of a black hole. Yet in the last year or two a number of physicists have come to believe that such "objects" represent a substantial – perhaps even the major – part of our universe. A black hole would be an assemblage of matter that has shrunk – more properly, collapsed – to a state so extremely dense that it has become invisible. Because of its density, it would generate gravity in its vicinity of such extraordinary strength that no light – or anything else – could escape from it; any light rays coming near it would be irretrievably drawn in.

Gravity is the weakest force in nature; for example, it takes the whole mass of the earth to make a feather fall. But if the earth were compressed to the size of a Ping-Pong ball, its gravity would become so concentrated that nothing could resist it – not even light. Visually, therefore, such a body would be a "black hole."

Because of the extreme conditions within such an object, the laws of nature with which we are familiar would be overwhelmed, and, many theorists believe "crazy" effects predicted by relativity theory (and to some extent already demonstrated) would prevail. Inside the black hole, time and space would be interchanged, so that, like Alice's experience in "Through the Looking-Glass," it would be no more possible to remain in one place than to stop the forward march of time in our world. Anyone who fell into a black hole would be stretched out like a string of spaghetti, then would disintegrate. Finally, even the atomic particles of the unfortunate person's body would lose their identity. Yet, theoretically, his or her image would linger, ghost-like, on the outer fringes of the hole, where light does not have quite enough energy to escape, preserving indefinitely the last glimpse available to an outside observer.

In contemplating such exotic explanations for the Tunguska event as antirocks or black holes, we realize how far our ideas about nature have gone beyond what we can see, hear and feel. The concept of antimatter arose as scientists learned more and more about the behavior of atomic particles. It was evident that there are striking symmetries in such behavior, and in 1928 the British theorist P.A.M. Dirac, whom many physicists rank with Einstein suggested that to complete the symmetries there must be a particle identical to the electron but with an electric charge that is positive instead of negative. Four years later, such a particle – the positron – was discovered in laboratory experiments, and it is now evident that for every particle of ordinary matter, there is an "equal-but-opposite" particle (the antiproton is another example). If such particles were assembled into atoms, and the atoms assembled into stones, people and worlds, they would constitute antimatter. Throughout our environment particles of antimatter are constantly formed by the impact on atmospheric atoms of high-energy particles (cosmic rays) raining on the earth from space. The antiparticles can be observed by sophisticated laboratory techniques, but they survive less than a millionth of a second. For as soon as they encounter an atom of ordinary matter – and there are plenty of those in our atmosphere – they are annihilated, leaving only a tiny but brilliant flash of light at the invisible but highly energetic wave lengths known as gamma rays.

While ordinary matter dominates our part of the universe, conceivably there are galaxies of antimatter with their own antiworlds and antipeople far out in space – antigalaxies, so to speak. Light generated by antimatter would be indistinguishable from our kind of light, so it would be impossible to identify an antigalaxy through a telescope. The physicist Harold P. Furth once wrote a ditty about Dr. Edward Teller, the "father of the hydrogen bomb," who had suggested that worlds may exist where antimatter predominates. In the poem, "Perils of Modern Living," Dr. Teller voyaged to a world where everything is opposite (for example, antimacassars became macassars):

Well up beyond the tropostrata
There is a region stark and stellar
Where, on a streak of antimatter,
Lived Dr. Edward AntiTeller.

Remote from Fusions's orgin,
He lived unguessed and unawares
With all his antikith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore three letters: A.E.C.
Out stepped a visitor from Earth.

Then, shouting gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
*Clasped, and the rest was gamma rays.**

The possibility that the Siberian explosion was caused by a meteorite of antimatter was examined by no less a physicist than Willard F. Libby, former member of the Atomic Energy Commission and winner of a Nobel Prize for his discovery of radioactive carbon dating. Libby and two other physicists observed in Nature, a British journal of worldwide repute, that since both antimatter and matter would be converted into energy if such a meteorite fell into the atmosphere (a far more efficient conversion than that of an atomic bomb), only a small amount of antimatter would be needed to produce a blast equal to that of 30 million tons of TNT – the estimated force of the Siberian explosion. They also pointed out that the disintegration of an antirock would briefly enrich the amount of carbon 14 in the air, which is normally manufactured at a fairly steady rate by the rain of cosmic rays from space. If there was more carbon 14 in the air than normal in 1908 and soon afterward, then wood formed in trees anywhere in the world during that period would be unusually rich in that form of carbon.

The amount of carbon 14 in successive rings of a 300-year-old Douglas fir from Arizona and a venerable oak from near Los Angeles were measured – and, indeed, the highest level in the wood was created in 1909, the year after the blast. Had the object been made entirely of antimatter, however, the effect would have been more marked. Thus the three scientists concluded that the evidence was inconclusive.

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—It was last September that two scientists then at the University of Texas, A. A. Jackson 4th and Michael P. Ryan Jr., suggested that the 1908 devastation was caused by a "mini" black hole. The "conventional" black hole is the residue of a giant star that has collapsed, leaving a superdense remnant with a mass comparable to that of the sun. In 1971, however, Stephen Hawking of Cambridge University had proposed that "mini" black holes might have been created during the initial "big-bang" phase of the universe's birth. Hawking pointed out that if the earliest period of the universal explosion were turbulent, there must have been areas of great compression, as well as regions where expansion was taking place. The compression would have squeezed material into mini black holes that would still permeate the universe. Writing in Nature, Jackson and Ryan proposed that the penetration of the atmosphere by such a mini black hole and its passage through the earth could account for all the reported effects.

The more conventional idea of a comet impact obviously makes scientists happier. But, in truth, no explanation satisfies everyone, and we are left with the real possibility of a recurrence. Should it take place without warning in a populated region and resemble a nuclear blast, could it trigger an atomic war? A better understanding of such phenomena could minimize the risks. In any case, the discussion of black holes as a possible cause demonstrates to what extent some scientists are rushing to explain various puzzles in astronomy and physics with this bewildering concept. Astronomical observations in the past year or two have made black holes seem a reality, although, as one physicist put it, they are "as pervasive in theory as they are evasive in observation."

The roots of the concept lie far back in the history of astronomy. In 1844, at the observatory in Königsberg, Prussia (now Kaliningrad in the U.S.S.R.), F. W. Bessel found that the path of Sirius, the sky's brightest star, was slightly irregular. To casual observers, it had always seemed to remain in the same spot, but being one of the nearest stars to the solar system its motion relative to distant objects in the universe could be traced through a telescope. Sirius, Bessel's data demonstrated, moves in a wavy line rather than a straight one.

This indicated to him that Sirius had an unseen companion, and that the two stars were circling each other as they flew through the void, "held in each other's arms" by their mutual gravity. Since the mass – that is, the weight – of Sirius could be estimated, it was possible, using the laws of gravitationally controlled motion spelled out by Newton, to estimate the weight of the seemingly invisible companion. It turned out to be about the same as that of our own sun. Why, then, was the companion star invisible?

It wasn't – not completely. Nineteen years after Bessel's observation, an American telescope maker named Alvan Clark spotted the companion while testing a new instrument. The star's intrinsic brightness proved to be one-four-hundredth that of the sun. The real surprise came, however, when light from the star was analyzed. By the early decades of this century it was recognized that the whiter the light from a typical star, the hotter, brighter and bigger it is. Small stars burn cooler, are dimmer and redder. But this faint star was as white as Sirius – which is whiter than the sun. If so white and hot, why was it so dim?

The only plausible explanation was that the star was very small and yet, to account for its matching the weight of the sun, extremely dense. As Sir Arthur Eddington wrote in 1927: "The message of the companion of Sirius when it was decoded ran: 'I am composed of material 3,000 times denser than anything you have come across; a ton of my material would be a little nugget that you could put into a matchbox.' What reply can one make to such a message? The reply which most of us made in 1914 was – 'Shut up. Don't talk nonsense.' "

Skeptics now similarly exhort the proponents of the black-hole theory to silence. But that is getting ahead of our story. Sirius's companion was a "white dwarf" not a black hole, and with only one such object on the register, it could be dismissed as a freak. In time, though, other white dwarfs were found. In fact, they proved to be fairly common, although so dim that only those close to earth could be detected.

The explanation became apparent in the late nineteen-twenties when scientists not only began to understand atomic structure but got their first inklings of what it is that makes stars shine – a major puzzle. The sun, it was evident, had been shining for billions of years. But no one knew what process could possibly account for such an enormous and continuous output of energy. Einstein had proposed, in theoretical terms, an equivalence between matter and energy. His formula suggested that conversion of even a small amount of matter would release vast amounts of energy. Although there was then no evidence that such conversions really take place, Eddington and others considered the possibility that the fusion of hydrogen nuclei to form helium nuclei might occur within stars. Since the helium nucleus would weigh 0.8 per cent less than the hydrogen nuclei from which it was formed, this small residue of matter would emerge as energy.

If fusion – such as the conversion of hydrogen into helium – were responsible for energy generation within stars, what would happen when the fuel for these nuclear fires burned out? Stars are made of gas, and as long as they are hot inside – as long as their "fires" burn – that gas tends to expand. Put another way, the energy generated in their cores fights its way out through the star in the form of radiation, exerting an outward pressure that counter-acts the massive weight of the star's own substance. But R. H. Fowler in Britain proposed in 1926 that when a star has burned up all its fuel, this resistance to the inward pressure of the star's own weight vanishes and the star collapses upon itself, forming an object of great density – like one gigantic, frigid molecule. This would be the superdense stuff of a white dwarf.

Was this applicable to all stars, no matter how large? In 1930 a young Indian, newly graduated from the University of Madras and on his way to do graduate work at Cambridge University in England, sought during the long passage to calculate what forces within an atom resist compression. On his arrival in England, Subrahamanyan Chandrasekhar, now known throughout the astronomical world as "Chandra," showed his calculations to Fowler, his doctoral supervisor. He had come to the startling conclusion that, for any star much larger than the sun, there was no known force that could halt the collapse. Contraction to a white dwarf was possible because of the hollow nature of atoms. According to the traditional (but schematic) description of an atom, it resembles the solar system, with a nucleus in place of the sun and electrons in place of planets. Like the solar system, it is largely formed of empty space. However, Chandra realized, when something is squeezed in a powerful press, there are forces within the atoms that resist. One arises from a basic law, the "exclusion principle," that had been enunciated by Wolfgang Pauli a few years earlier. The electrons occupy certain "slots" (not really comparable to planetary orbits) and only one is permitted in such a slot at any one time. Under high temperatures or great compression (as within a star) the electrons are forced out of their slots, forming a plasma of independently moving electrons and atomic nuclei. But the electrons still repel one another in the manner defined by Pauli and it is this effect that finally stops the collapse of a white dwarf.

Chandra, however, calculated that the weight of any star much larger than the sun would overcome this "electron pressure." There are giant stars 50 times more massive than the sun. They burn so intensely that their lifetimes are limited to 10 or 20 million years, and countless numbers of them must have burned out during the billions of years that have passed since, for example, the Milky Way was formed. What happens to them? "A star of large mass cannot pass into the white-dwarf stage," wrote the youthful Chandra, "and one is left speculating on other possibilities."

The leaders of the scientific establishment reacted with indignation to this suggestion that there is no limit to the collapse. Eddington pointed out that if a star kept on contracting, once it has shrunk to within a few miles' radius, its gravity would become "strong enough to hold the radiation" – that is, it would be a black hole. But Eddington refused to take the idea seriously. He turned Chandra's reasoning "almost *a reductio ad absurdum.*"

The first clue as to what actually happens when a large star collapses came from analysis of the most spectacular event that the heavens offer – a "supernova." In 1885 astronomers had observed an extraordinary flareup of a star in the great swirl of star clouds known as the Andromeda Nebula, which is the nearest galaxy resembling our Milky Way. For 25 days that single star shone more brightly than 10 million suns. Then it faded to such an extent that it was no longer visible through the most powerful telescopes.

Astronomers noted that in 1572 a similar flare-up, known as "Tycho Brahe's Nova," had occurred in our own Milky Way. (It was called a "nova" because it seemed to be a "new" star.) Two Mount Wilson Observatory astronomers, Walter Baade and Fritz Zwicky, pointed out that the star associated with the nova had seemingly vanished. It appeared that such a "supernova" occurs once in every few centuries within any one galaxy, generating radiation that probably would be fatal to any inhabited worlds nearby.

Baade and Zwicky theorized that a supernova marked the death of a very massive star whose collapse was so catastrophic that a large part of the star's substance was converted into energy, leaving something of considerably smaller mass. This residual star, they said, must have been compressed to such a degree by the explosion that it consisted almost entirely of tightly packed neutrons. Neutrons and protons are the two particles that form the atomic nucleus, but neutrons, being electrically neutral, could be packed together more tightly than protons, which, carrying a positive charge, repel one another. Also, since a neutron (when free of an atomic nucleus) eventually sheds an electron and turns into a proton, it seemed reasonably to suppose that, reversing the process, the compression of a sea of protons and electrons could produce neutrons.

Meanwhile, attention had been drawn to the most spectacular remnant of a supernova in the sky – the Crab Nebula, which today still looks like the high-speed photograph of an explosion. By comparing pictures of the nebula taken over a span of years, it was possible to trace the expansion of its luminous gas clouds. Running this "moving picture" backwards indicated that the original explosion must have occurred – that is, light from it must have reached the earth – in about 1054 A.D. That was a time when the Chinese were keeping careful astronomical records and in that year, according to chronicles of the Sung Dynasty, a star appeared so brilliant that for 23 days it could be seen in full daylight. If the Crab Nebula was a product of that explosion, Baade argued, perhaps it had left a neutron star at its center. Indeed, a faint and rather strange-looking star was observed in that region.

There was a strong suspicion, however, that the neutron star was a figment, an absurdity derived from theoretical manipulations. Whereas the concept of a white dwarf, a nugget of which would weigh a ton, had been considered pure nonsense, the idea of a neutron star, one cubic inch of which would weigh a billion tons, was preposterous. A white dwarf was formed from the material of a star as large as the sun compressed into the size of the earth, but a neutron star, formed from a star somewhat larger than the sun, would be a comparable amount of material crushed into a body with a five-mile radius.

Even greater skepticism greeted the proposals of a young physicist at the University of California in Berkeley named J. Robert Oppenheimer. Oppenheimer later became known for his leadership of the atomic-bomb project and for his professional martyrdom during the cold-war hysteria. However, his chief theoretical work was in the nineteen-thirties and led to the black-hole concept.

Taking off from the speculations of George Gamow, Edward Teller, the Russian Lev Landau and others, he and his students explored what would happen if the weight of the collapsing star was too great even for neutrons to resist. Put another way, what if the compression were sufficient to overcome the strongest force in nature – that exerted by such nuclear particles as neutrons upon one another at close range. The calculations of Oppenheimer and his group culminated in a 1939 paper that he wrote with Hartland Snyder "On Continued Gravitational Contraction." There was nothing, they said, in Einstein's theory of gravity – the so-called "general" theory of relativity – suggesting any reason why such a collapse should stop. As the contraction proceeded, the intensity of gravity in the heart of the star would increase, causing the collapse to run at an ever-increasing rate until finally the density would become so great that the gravity would be strong enough to prevent anything, including light, from escaping.

Because gravity, when very intense, slows time, the collapsing process, insofar as it could be followed from a distance, would seem to a distant observer to slow down as the gravity field increased in strength until, on the outer fringes of the black hole, the process would appear to have stopped altogether. The progression to total collapse could take as long as the lifetime of the universe. But to someone unfortunate enough to be falling into the stellar abyss, cut off from all contact with the outside, the collapse would seem to be running its course in about a day.

The ultimate destiny of such a black hole, derived from the Einstein equations, would be infinitely powerful gravity concentrated in an infinitely dense, infinitely small spot where time and space have lost their meaning – what is known as a "singularity." Whether "things" really go to that extreme in the heart of a black hole is one of the basic problems confronting theorists today. When proposed by Oppenheimer, however, the concept was, many thought, little more than an oddity with which to titillate physics students.

Then, in 1963, the discovery of quasars suddenly thrust the idea of gravitational collapse into the forefront, helping to bring Oppenheimer out of intellectual exile and reviving speculation about black holes. Quasars are bodies that seem far more distant than any other observable objects in the sky – so far away that it must have taken billions of years for their light to reach us, which means we see them as they were when the universe was relatively young. No ordinary process could make them shine so brightly. The nuclear reactions believed to occur inside a star seemed totally inadequate and so scientists inaugurated a series of annual meetings (initially in Texas) to explore how collapse processes involving enormous amounts of matter might be the answer.

Further evidence that matter sometimes collapses to extraordinary densities came from a new branch of science – radio astronomy. Until recently our knowledge of the heavens has depended almost entirely on looking through optical telescopes, that is, on observing visible wave lengths of light that penetrate the blanket of air covering our planet. But it has become possible with radio telescopes, space vehicles and other methods to view the heavens through other wave-length "windows" which are ordinarily invisible – radio waves, X-ray, gamma rays, ultraviolet and infrared emissions.

Surveying the heavens with radio antennas, astronomers at Cambridge University in England reported in 1968 that for several months they had been recording extremely rhythmic radio signals from four points in the sky. Each source generated pulses at a characteristic rate, all being in the range from one pulse per quarter-second to one every two seconds. Rhythmic phenomena were not new to astronomy, being typically associated with the spinning of stars, planets and moons, but nothing was known to spin as fast as once every second. "Our first thought," said Sir Martin Ryle, leader of the British group, "was that this was another intelligence trying to contact us." Then, however, the scientists began pondering what would happen if a star collapsed to a superdense state such as a white dwarf or – for those willing to entertain such a thought – a neutron star.

There is a basic law known as the conservation of angular momentum which is instinctively familiar to every figure skater or ballet dancer. In a pirouette, if the arms are extended, the spin rate slows. If they are held close to one's sides, the rate is fastest. Thus, if a star "pulls in its arms" by contracting, its spin rate will increase. Many stars spin roughly once a day, and it was calculated that if they collapsed to a superdense state, their spinning would accelerate enormously. If such a collapsed star had a magnetic field of great strength – as seemed likely – this field would cause emissions, including those at radio-wave lengths, to form directional beams that, with each rotation, would sweep the sky like an airport beacon, accounting for the pulses.

Many astronomers clung to white dwarfs as the explanation, avoiding so extreme a concept as the neutron star. But then came evidence that not all of the pulsing radio sources, or "pulsars," are beeping at sedate tempos. From the Crab Nebula, radio astronomers detected pulses at 30 times a second. Could Baade and Zwicky, then, have been right? Was it conceivable that the peculiar star in the heart of that supernova remnant was, in fact, a neutron star, spinning 30 times a second?

To test the possibility, special light-monitoring and stroboscopic television systems were aimed at the star. The astonishing discovery was made that it does, indeed, "switch itself off" 30 times a second – an optical as well as a radio pulsar.

It was hard to believe that even so compact an object as a white dwarf could spin that fast. Centrifugal force would tear it apart. The pulse rate of the Crab Nebula pulsar, moreover, was found to be slowing in a manner indicating that the original spin rate, right after the explosion seen in 1054, was at least 50 times a second. Assuming that it slowed more rapidly in the early years than recently, its initial spin could have been hundreds of revolutions per second. A neutron star seemed the only plausible explanation.

By now scores of pulsars have been detected, and, since we presumably can observe only those whose radio beams sweep in our direction, there must be many more in the Milky Way Galaxy. With such powerful evidence of neutron stars, the possibility of even more extreme forms of contraction – black holes – began to seem reasonable. A number of physicists, notably John W. Wheeler and Remo Ruffini at Princeton University, started thinking about how they could be detected despite their "blackness."

Mindful of the discovery of the first white dwarf through the effect of its gravity on an easily visible star, they proposed that a two-star system in which one member was a black hole might be found. Two-star systems are more common than single stars like our sun, and hundreds have been found in which one member cannot be seen. While light or matter cannot escape a black hole, its gravity should reach out an indefinite distance, making it possible for it to waltz through space with another star.

A further clue would be the detection of emissions from material falling into the hole. This material, being drawn in at extremely high velocity, would become so hot that it would "shine" at X-ray wave lengths. Whereas hot things glow red and very hot things become white-hot, this extreme heat would generate brilliant X-rays before the material vanished into the hole.

Where a black hole was circling with an ordinary star, robbing it of gas, the X-ray emission should be particularly intense. It has been calculated that this "sucking in" of gas by a black hole's gravity would be the most efficient of all processes that convert matter to energy (apart from the mutual annihilations of matter and antimatter). Energy radiated away, chiefly as X-rays, would equal the conversion into energy of 10 per cent of the mass of infalling material. This contrasts with the conversion of only 0.8 per cent in the fusion reactions of stars. It would therefore be many times more powerful a process than that of an atomic or hydrogen bomb.

As pointed out by Yakov B. Zeldovich and his collegues at the Institute of Applied Mathematics in Moscow, the gas in such a situation would not fall directly down the hole. Because the entire two-star system was in rotation, the gas would first swirl around the black hole, forming an "accretion disc." Because of the enormous speeds and pressures as the gas swirls down the hole, it would be heated until its X-ray emissions were 10,000 times as luminous as the sun.

The first hint that such X-rays were coming from certain points in the sky came in the nineteen-sixties. Seeking to glimpse the universe at wave lengths that cannot penetrate the atmosphere, scientists first sent balloons into the upper atmosphere, then fired rockets on short flights into space above the White Sands Proving Ground in New Mexico. Pinpointing the X-ray sources on these flights was difficult because ordinary optical systems could not be used; such rays, for example, tend to go through a mirror instead of being reflected. It was nevertheless evident that certain objects in the sky are extraordinarily brilliant at X-ray wave lengths. Four of the brightest were in Cygnus, the Swan, which decorates the evening sky in summer. They were given numerical designations, the most powerful being Cyg X-1.

Then, in 1970, a baby earth satellite built in the United States and launched from an Italian platform in equatorial waters off East Africa brought revolutionary discoveries. The satellite, named "Uhuru" (from the Swahili word for freedom), circled the equator sweeping both the northern and southern hemispheres of the sky with its X-ray detector. By the start of this year, it had located close to 100 sources of X-ray emission, but Cyg X-1 still ranks as the strongest. With Cyg X-1's precise location pinned down, C. T. Bolton of the University of Toronto pointed out that it coincides with a two-star pair – one of whose members is invisible. Such pairs can be identified, not only because of the wavy motion of the visible partner, but in many cases because the visible star seems (from the periodic alterations of the wave lengths of its light) to be moving more toward us and then away from us, as though circling something we cannot see. In the case of Cyg X-1, the visible star, a so-called supergiant known as HDE 226868, is circling something once every 5.6 days.

Just as it had been possible years earlier to deduce the mass of the invisible white dwarf circling with Sirius from its effects on Sirius, so Bolton and others have estimated that the unseen companion of HDE 226868 is eight times heavier than the sun – far too massive to be either a white dwarf or neutron star. Moreover, X-ray emissions from this spot in the sky seem to vary in tempo with the waltz of the two stars – in a cycle of 5.6 days. The brightness of the visible member varies at double that tempo. If the invisible companion, though very small, were drawing large amounts of luminous gas from the visible one, this would make the visible star appear elongated so that its brightness, as seen from earth, would reach a maximum twice during each rotation.

While some scientists now argue that many of the X-ray sources seen by Uhuru and more recent satellites are black holes, the erratic behavior of such sources remains to be fully explained. Cyg X-1 may vary fivefold in brightness within a few minutes. Other sources flare up to spectacular brightness within a day or two, then fade slowly away. Whether such eruptions could be associated with black holes is not clear.

Indeed, not all astronomers are convinced that the existence of black holes has been demonstrated. The evidence is, perforce, indirect. The proponents, on the other hand, are extremely eager to find such objects. As one of them puts it, "Either there are holes in the sky, or there are holes in the general theory of relativity."

All of the strange effects of black holes, such as the slowing of time, the tight curvature of space and the influence of gravity on light, were anticipated by Einstein's theory and have been confirmed by observation – but not on the scale that would occur in a black hole. As early as 1919, for example, Einstein's prediction that gravity would bend light was demonstrated when a star whose light had skirted the eclipsed sun appeared out of place. The powerful gravity of the sun at such close range had bent the light. Likewise, the effect of gravity on time has been demonstrated by carrying high-precision clocks in jet airlines at elevations where the earth's gravity is substantially weaker than at sea level. The chief reason for doubting that black holes exist, therefore, has not been uncertainty about relativity as much as the suspicion that, when one of the giant stars burns out, it blows off so much material in its death throes that the remainder is not massive enough for total collapse. There is still much uncertainty about what really happens in such a collapse.

Nevertheless, black holes have been heralded as a possible answer to two basic problems in cosmology: What is it that holds the universe together, and what binds the clusters of galaxies?

Einstein's theory predicted that there must be enough mass within the universe to keep it from flying apart indefinitely. In other words, although all of the galaxies (or clusters of galaxies) are flying apart, as though blown asunder by some primordial "big bang" it appears that they do not have sufficient velocity to escape one another's gravity. Their dispersal, like the flight of a ball thrown upward, seems to be slowing enough so that it must ultimately reverse itself, initiating a "falling back" that, many theorists believe, will plunge the entire universe into a single black hole. The trouble is that adding up all the material that can be seen or readily inferred accounts for only about 2 per cent of what would be needed to prevent eternal expansion. Black holes and the dark cinders of stars that remain after a white dwarf or neutron star has cooled off might make up for much, if not all, of this deficit.

The problem concerning clusters of galaxies is similar. Millions of galaxies like our own Milky Way can be seen through powerful telescopes. They are not randomly scattered through space but organized into clusters within which each galaxy is moving so fast with respect to its companions that the clusters should long ago have flown apart. Something is holding them together. Yet, again, not enough material can be observed to provide the necessary "glue" – the required amount of gravity. Black holes could be doing the job.

Cosmologists have seized upon the hypothesis in a variety of other ways. For example, if the universe was formed from a "big bang" and, confined by its own gravity, is destined to fall back together again, then we are living inside an incipient black hole from which, even now, no light can escape. As Kip Thorne, theorist at the California Institute of Technology, has put it, we are within a universe composed of space and time created by the explosion, "and we are trapped inside its gravitational radius. No light can escape from the universe."

It has been proposed that when the expansion gives way to contraction, the "arrow of time" will change direction. From the viewpoint of an observer outside the universe (although denied the ability to make such an observation) our lives would seem to begin with the grave and end in the womb. Yet to those inside the collapsing universe, time's arrow would appear normal. In that case we would have no way to know whether or not the collapse has already begun.

Also being discussed is the possibility that enormously massive black holes, comparable to millions or billions of suns, form the cores of some (or all) galaxies. Since such objects should be able to generate vast amounts of energy – for example by "swallowing" stars – it has been proposed that they could account for some of the breathtaking discoveries made by astronomers in recent years, such as the quasars, or the castastrophically explosive events that seem to occur in the cores of galaxies, sometimes blowing them apart.

A major dilemma is what happens within the black hole as it nears the ultimate – a "singularity." Some believe that just as Newton's laws break down under the extreme conditions where relativity becomes dominant, so relativity itself breaks down within the even more extreme conditions of a black hole, the laws that govern there being totally unknown.

It may also be, as noted by Roger Penrose of Birkbeck College at the University of London, that the black-hole contraction in some cases is sufficiently lopsided so that all sides are not closed off. This would permit one to peek into the forbidden sanctum – theorists call it a "naked singularity." What would we see there? Is it possible that such wild things happen to space and time that a singularity would constitute a window into some other universe, some other realm of space and time far removed from our own?

Several theorists, including Igor Novikov in the Soviet Union and Yuval Ne'eman in Israel, have proposed that a star which goes down the drain through a black hole may emerge in some other place and time as a quasar. Are the brilliant quasars, then, really "white holes" in which material (in energy form) is pouring into the here and now from "somewhere else" – perhaps even another universe?

That other universes may exist is certainly possible, in the view of John Wheeler at Princeton, who has probably pondered such questions as deeply as anyone of our time. Each universe would have its own dimensions, its own physical "constants" and laws. These universes would have their home in a "super-space" indefinite in space and time.

Efforts to understand black holes and related phenomena are drawing theorists over the horizon into new realms of speculation that may not be entirely esoteric. The effort to explain what made stars shine anticipated the discovery of nuclear energy. If we find out that black holes are the energy source in quasars and other superenergetic objects, it could be a revelation of comparable significance.

According to Chandra, the precocious graduate student of 1930 who, at the University of Chicago, is now a dominant figure in astrophysics: "The present situation is not unlike that in the twenties when the conversion of hydrogen into helium was contemplated as a source of stellar energy, with no sure knowledge that it could be accomplished; only years later were well-defined chains of nuclear reactions that could accomplish it formulated." To achieve an understanding of even more exotic phenomena, such as black holes, he believes, "we may similarly have to wait some years."

Chandra likes to cite an Indian parable, learned in his childhood, about dragonfly larvae at the bottom of a pond: "A constant source of mystery for these larvae was what happens to them when, on reaching the stage of chrysalis, they pass through the surface of the pond, never to return." Each larva, as it feels impelled to rise to the surface and depart, according to the parable, "promises to return and tell those that remain behind what really happens, and to confirm or deny a rumor attributed to a frog that when a larva emerges on the other side of their world it becomes a marvelous creature with a long slender body and iridescent wings. But on emerging from the surface of the pond as a fully formed dragonfly, it is unable to penetrate the surface no matter how much it tries and how long it hovers." As with someone who might fall into a black hole, communication is irrevocably cut off.

The parable ends with the endless and hopeless cry of the larvae:

> *... Will none of you in pity, To those you left behind, disclose the secret?*

Perhaps, in the long run, we will be more fortunate and will not have to fall into a black hole to guess what is there.

In this essay on the Industrial Revolution, Josiah Wedgewood, The Marriage of Figaro, Benjamin Franklin, The Lunar Society, and a zoetrope are featured, along with such key scientists and engineers as Joseph Priestly, James Watt, Sadi Carnot and James Prescott Joule.

2

The Drive for Power

J. Bronowski

A chapter from The Ascent of Man, 1973

Revolutions are not made by fate but by men. Sometimes they are solitary men of genius. But the great revolutions in the eighteenth century were made by many lesser men banded together. What drove them was the conviction that every man is master of his own salvation.

We take it for granted now that science has a social responsibility. That idea would not have occurred to Newton or to Galileo. They thought of science as an account of the world as it is, and the only responsibility that they acknowledged was to tell the truth. The idea that science is a social enterprise is modern, and it begins at the Industrial Revolution. We are surprised that we cannot trace a social sense further back, because we nurse the illusion that the Industrial Revolution ended a golden age.

The Industrial Revolution is a long train of changes starting about 1760. It is not alone: it forms one of a triad of revolutions, of which the other two were the American Revolution that started in 1775, and the French Revolution that started in 1789. It may seem strange to put into the same packet an industrial revolution and two political revolutions. But the fact is that they were all social revolutions. The Industrial Revolution is simply the English way of making those social changes. I think of it as the English Revolution.

What makes it especially English? Obviously, it began in England. England was already the leading manufacturing nation. But the manufacture was cottage industry, and the Industrial Revolution begins in the villages. The men who make it are craftsmen: the millwright, the watchmaker, the canal builder, the blacksmith. What makes the Industrial Revolution so peculiarily English is that it is rooted in the countryside.

During the first half of the eighteenth century, in the old age of Newton and the decline of the Royal Society, England basked in a last Indian summer of village industry and the overseas trade of merchant adventurers. The summer faded. Trade grew more competitive. By the end of the century the needs of industry were harsher and more pressing. The organisation of work in the cottage was no longer productive enough. Within two generations, roughly between 1760 and 1820, the customary way of running industry changed. Before 1760, it was standard to take work to villagers in their own homes. By 1820, it was standard to bring workers into a factory and have them overseen.

We dream that the country was idyllic in the eighteenth century, a lost paradise like *The Deserted Village* that Oliver Goldsmith described in 1770.

> Sweet Auburn, loveliest village of the plain,
> Where health and plenty cheered the labouring swain.
>
> How blest is he who crowns in shades like these,
> A youth of labour with an age of ease.

That is a fable, and George Crabbe, who was a country parson and knew the villager's life at first hand, was so enraged by it that he wrote an acid, realistic poem in reply.

> Yes, thus the Muses sing of happy Swains,
> Because the Muses never knew their pains.
>
> O'ercome by labour and bow'd down by time,
> Feel you the barren flattery of a rhyme?

The country was a place where men worked from dawn to dark, and the labourer lived not in the sun, but in poverty and darkness. What aids there were to lighten labour were immemorial, like the mill, which was already ancient in Chaucer's time. The Industrial Revolution began with such machines; the millwrights were the engineers of the coming age. James Brindley of Staffordshire started his self-made career in 1733 by working at mill wheels, at the age of seventeen, having been born poor in a village.

Brindley's improvements were practical: to sharpen and step up the performance of the water wheel as a machine. It was the first multi-purpose machine for the new industries. Brindley worked, for example, to improve the grinding of flints, which were used in the rising pottery industry.

Yet there was a bigger movement in the air by 1750. Water had become the engineers' element, and men like Brindley were possessed by it. Water was gushing and fanning out all over the countryside. It was not simply a source of power, it was a new wave of movement. James Brindley was a pioneer in the art of building canals or, as it was then called, 'navigation'. (It was because Brindley could not spell the word 'navigator' that workmen who dig trenches or canals are still called 'navvies'.)

Brindley had begun on his own account, out of interest, to survey the waterways that he travelled as he went about his engineering projects for mills and mines. The Duke of Bridgewater then got him to build a canal to carry coal from the Duke's pits at Worsley to the rising town of Manchester. It was a prodigious design, as a letter to the *Manchester Mercury* recorded in 1763.

> I have lately been viewing the artificial wonders of London and natural wonders of the Peak, but none of them gave me so much pleasure as the Duke of Bridgewater's navigation in this country. His projector, the ingenious Mr Brindley, has indeed made such improvements in this way as are truly astonishing. At Barton Bridge, he has erected a navigable canal in the air; for it is as high as the tree-tops. Whilst I was surveying it with a mixture of wonder and delight, four barges passed me in the space of about three minutes, two of them being chained together, and dragged by two horses, who went on the terrace of the canal, whereon I durst hardly venture . . . to walk, as I almost trembled to behold the large River Irwell underneath me. Where Cornebrooke comes athwart the Duke's navigation . . . about a mile from Manchester, the Duke's agents have made a wharf and are selling coals at three pence halfpenny per basket . . . Next summer they intend to land them in (Manchester).

Brindley went on to connect Manchester with Liverpool in an even bolder manner, and in all laid out almost four hundred miles of canals in a network all over England.

Two things are outstanding in the creation of the English system of canals, and they characterise all the Industrial Revolution. One is that the men who made the revolution were practical men. Like Brindley, they often had little education, and in fact school education as it then was could only dull an inventive mind. The grammar schools legally could only teach the classical subjects for which they had been founded. The universities also (there were only two, at Oxford and Cambridge) took little interest in modern or scientific studies; and they were closed to those who did not conform to the Church of England.

The other outstanding feature is that the new inventions were for everyday use. The canals were arteries of communication: they were not made to carry pleasure boats, but barges. And the

The Duke of Bridgewater.
A medallion by
Josiah Wedgwood.

barges were not made to carry luxuries, but pots and pans and bales of cloth, boxes of ribbon, and all the common things that people buy by the pennyworth. These things had been manufactured in villages which were growing into towns now, away from London; it was a country-wide trade.

Technology in England was for use, up and down the country, far from the capital. And that is exactly what technology was *not* in the dark confines of the courts of Europe. For example, the French and the Swiss were quite as clever as the English (and much more ingenious) in making scientific playthings. But they lavished that clockwork brilliance on making toys for rich or royal patrons. The automata on which they spent years are to this day the most exquisite in the flow of movement that have ever been made. The French were the inventors of automation: that is, of the idea of making each step in a sequence of movements control the next. Even the modern control of machines by punched cards had already been devised by Joseph Marie Jacquard about 1800 for the silk-weaving looms of Lyons, and languished in such luxury employment.

Fine skill of this kind could advance a man in France before the revolution. A watchmaker, Pierre Caron, who invented a new watch escapement and pleased Queen Marie Antoinette, prospered at court and became Count Beaumarchais. He had musical and literary talent, too, and he later wrote a play on which Mozart based his opera *The Marriage of Figaro*. Although a comedy seems an unlikely source book of social history, the intrigues in and about the play reveal how talent fared at the courts of Europe.

At first sight *The Marriage of Figaro* looks like a French puppet play, humming with secret machinations. But the fact is that it is an early storm signal of the revolution. Beaumarchais had a fine political nose for what was cooking, and supped with a long spoon. He was employed by the royal ministers in several double-edged deals, and on their behalf in fact was involved in a secret arms deal with the American revolutionaries to help them fight the English. The King might believe that he was playing at Machiavelli, and that he could keep such contrivances of policy for export only. But Beaumarchais was more sensitive and more astute, and could smell the revolution coming home. And the message he put into the character of Figaro, the servant, is revolutionary.

> Bravo, Signor Padrone -
> Now I'm beginning to understand all this mystery, and to appreciate your most generous intentions. The King appoints you Ambassador in London, I go as courier and my Susanna as confidential attachée. No, I'm hanged if she does –Figaro knows better.

Mozart's famous aria, 'Count, little Count, you may go dancing, but I'll play the tune' (*Se vuol ballare, Signor Contino . . .*) is a challenge. In Beaumarchais's words it runs:

> No, my lord Count, you shan't have her, you shan't. Because you are a great lord, you think you're a great genius. Nobility, wealth, honours, emoluments! They all make a man so proud! What have you done to earn so many advantages? You took the trouble to be born, nothing more. Apart from that, you're rather a common type.
>
> A public debate started on the nature of wealth, and since one needn't own something in order to argue about it, being in fact penniless, I wrote on the value of money and interest. Immediately, I found myself looking at . . . the drawbridge of a prison . . . Printed nonsense is dangerous only in countries where its free circulation is hampered; without the right to criticise, praise and approval are worthless.

That was what was going on under the courtly pattern of French society, as formal as the garden of the Château at Villandry.

It seems inconceivable now that the garden scene in *The Marriage of Figaro*, the aria in which Figaro dubs his master 'Signor Contino', little Count, should in their time have been thought revolutionary. But consider when they were written. Beaumarchais finished the play of *The Marriage of Figaro* about 1780. It took him four years of struggle against a host of censors, above all Louis XVI himself, to get a performance. When it was performed, it was a scandal over Europe. Mozart was able to show it in Vienna by turning it into an opera. Mozart was thirty then; that was in 1786. And three years later, in 1789 – the French Revolution.

Was Louis XVI toppled from his throne and beheaded because of *The Marriage of Figaro*? 'Of course not. Satire is not a social dynamite. But it is a social indicator: it shows that new men are knocking at the door. What made Napoleon call the last act of the play 'the revolution in action'? It was Beaumarchais himself, in the person of Figaro, pointing to the Count and saying, 'Because you are a great nobleman, you think you are a great genius. You have taken trouble with nothing, except to be born'.

Beaumarchais represented a different aristocracy, of working talent: the watchmakers in his age, the masons in the past, the printers. What excited Mozart about the play? The revolutionary ardour, which to him was represented by the movement of Freemasons to which he belonged, and which he glorified in *The Magic Flute.* (Freemasonry was then a rising and secret society whose undertone was anti-establishment and anti-clerical, and because Mozart was known to be a member it was difficult to get a priest to come to his deathbed in 1791.) Or think of the greatest Freemason of them all in that age, the printer Benjamin Franklin. He was American emissary in France at the Court of Louis XVI in 1784 when *The Marriage of Figaro* was first performed. And he more than anyone else represents those forward looking, forceful, confident, thrusting, marching men who made the new age.

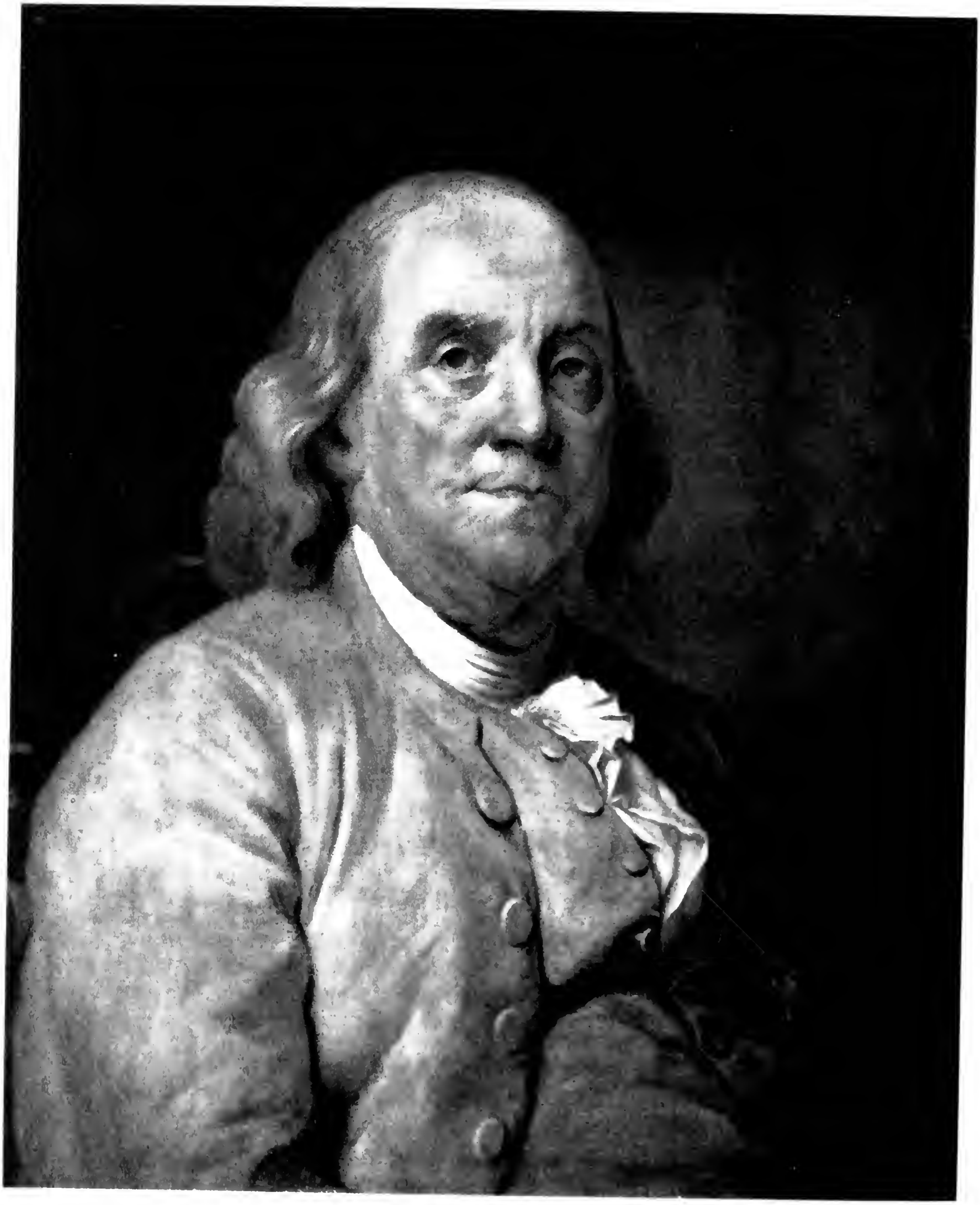
For one thing, Benjamin Franklin had such marvellous luck. When he went to present his credentials to the French Court in 1778, it turned out at the last moment that the wig and formal clothes were too small for him. So he boldly went in his own hair, and was instantly hailed as the child of nature from the backwoods.

All his actions have the stamp of a man who knows his mind, and knows the words to speak it. He published an annual, *Poor Richard's Almanack*, which is full of the raw material for future proverbs: 'Hunger never saw bad bread.' 'If you want to know the value of money, try to borrow some.' Franklin wrote of it:

> In 1732 I first published my Almanac . . . it was continued by me about 25 years . . . I endeavoured to make it both entertaining and useful, and it accordingly came to be in such demand that I reaped considerable profit from it; vending annually near ten thousand . . . scarce any neighbourhood in the province being without it. I considered it as a proper vehicle for conveying instruction among the common people, who bought scarcely any other books.

To those who doubted the use of new inventions (the occasion was the first hydrogen balloon ascent in Paris in 1783) Franklin replied, 'What is the use of a new-born baby?' His character is condensed in the answer, optimistic, down to earth, pithy, and memorable enough to be used again by Michael Faraday, a

Benjamin Franklin represents those forward-looking, forceful, confident, thrusting, marching men who made the new age.
Benjamin Franklin, by Joseph Duplessis. Painted in Paris, 1778.



greater scientist, in the next century. Franklin was alive to how things were said. He made the first pair of bifocal spectacles for himself by sawing his lenses in half, because he could not follow French at Court unless he could watch the speaker's expression.

Men like Franklin had a passion for rational knowledge. Looking at the mountain of neat achievements scattered through his life, the pamphlets, the cartoons, the printer's stamps, we are struck by the spread and richness of his inventive mind. The scientific entertainment of the day was electricity. Franklin loved fun (he was a rather improper man), yet he took electricity seriously; he recognised it as a force in nature. He proposed that lightning is electric, and in 1752 he proved it – how would a man like Franklin prove it? – by hanging a key from a kite in a thunderstorm. Being Franklin, his luck held; the experiment did not kill him, only those who copied it. Of course, he turned his experiment into a practical invention, the lightning conductor; and made it illuminate the theory of electricity too by arguing that all electricity is of one kind and not, as was then thought, two different fluids.

There is a footnote to the invention of the lightning conductor to remind us again that social history hides in unexpected places. Franklin reasoned, rightly, that the lightning conductor would work best with a sharp end. This was disputed by some scientists, who argued for a rounded end, and the Royal Society in England had to arbitrate. However, the argument was settled at a more primitive and elevated level: King George III, in a rage against the American revolution, fitted rounded ends to the lightning conductors on royal buildings. Political interference with science is usually tragic; it is happy to have a comic instance that rivals the war in *Gulliver's Travels* between 'the two great Empires of *Lilliput* and *Blefuscu*' that opened their breakfast egg at the sharp or the rounded end.

Franklin and his friends lived science; it was constantly in their thoughts and just as constantly in their hands. The understanding

A lightning conductor dating from Franklin's day.

of nature to them was an intensely practical pleasure. These were men in society: Franklin was a political man, whether he printed paper money or his endless racy pamphlets. And his politics were as downright as his experiments. He changed the florid opening of the Declaration of Independence to read with simple confidence, 'We hold these truths to be *self-evident*, that all men are created equal'. When war between England and the American revolutionaries broke out, he wrote openly to an English politician who had been his friend, in words charged with fire:

> You have begun to burn our towns. Look upon your hands! They are stained with the blood of your relations.

The red glow has become the picture of the new age in England – in the sermons of John Wesley, and in the furnace sky of the Industrial Revolution, such as the fiery landscape of Abbeydale in Yorkshire, an early centre for new processes in making iron and steel. The masters of industry were the ironmasters: powerful, more than life-size, demonic figures, whom governments suspected, rightly, of really believing that all men are created equal. The working men in the north and the west were no longer farm labourers, they were now an industrial community. They had to be paid in coin, not in kind. Governments in London were remote from all this. They refused to mint enough small change, so ironmasters like John Wilkinson minted their own wage tokens, with their own unroyal faces on them. Alarm in London: was this a Republican plot? No, it was not a plot. But it is true that radical inventions came out of radical brains. The first model of an iron bridge to be exhibited in London was proposed by Tom Paine, a firebrand in America and in England, protagonist of *The Rights of Man*.

Meanwhile, cast iron was already being used in revolutionary ways by the ironmasters like John Wilkinson. He built the first iron boat in 1787, and boasted that it would carry his coffin when he died. And he was buried in an iron coffin in 1808. Of course, the boat sailed under an iron bridge; Wilkinson had helped to build that in 1779 at a nearby Shropshire town that is still called Ironbridge.

Did the architecture of iron really rival the architecture of the cathedrals? It did. This was a heroic age. Thomas Telford felt that, spanning the landscape with iron. He was born a poor shepherd, then worked as a journeyman mason, and on his own initiative

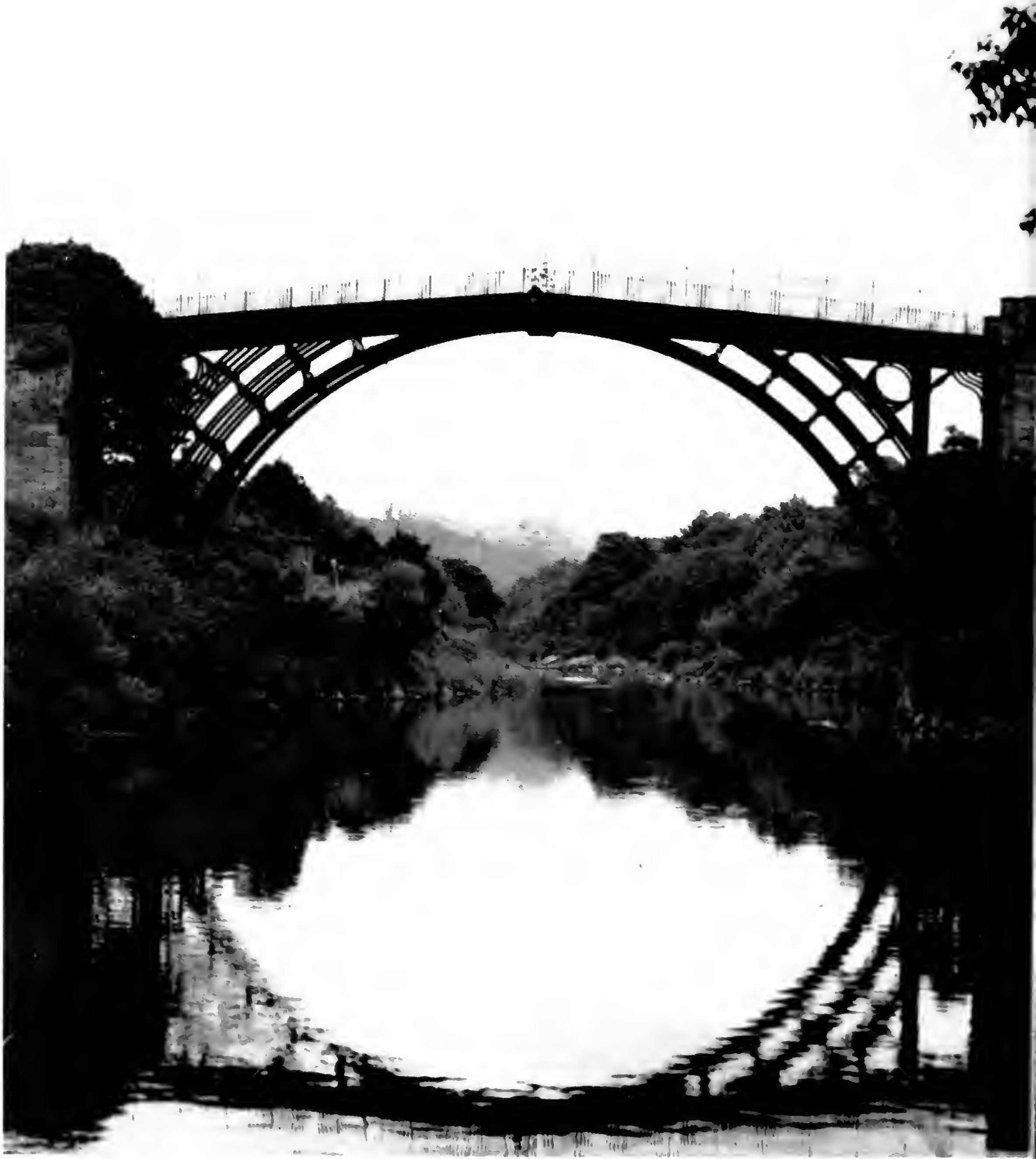
Ironmasters like John Wilkinson minted their own wage tokens, with their own unroyal faces on them.
A Wilkinson token, 1788.

became an engineer of roads and canals, and a friend of poets. His great aqueduct that carries the Llangollen canal over the river Dee shows him to have been a master of cast iron on the grand scale. The monuments of the Industrial Revolution have a Roman grandeur, the grandeur of Republican men.

The men who made the Industrial Revolution are usually pictured as hardfaced businessmen with no other motive than self-interest. That is certainly wrong. For one thing, many of them were inventors who had come into business that way. And for another, a majority of them were not members of the Church of England but belonged to a puritan tradition in the Unitarian and similar movements. John Wilkinson was much under the influence of his brother-in-law Joseph Priestley, later famous as a chemist, but who was a Unitarian minister and was probably the pioneer of the principle, 'the greatest happiness of the greatest number'.

The monuments of the Industrial Revolution have a Roman grandeur, the grandeur of Republican men.

The little bridge at Coalbrookdale, the first great iron span to be erected over the Severn between 1775 and 1779.



Josiah Wedgwood's pyrometer, for which he was elected a Fellow of the Royal Society of London.

Joseph Priestley, in turn, was scientific adviser to Josiah Wedgwood. Now Wedgwood we usually think of as a man who made marvellous tableware for aristocracy and royalty: and so he did, on rare occasions, when he got the commission. For example, in 1774 he made a service of nearly a thousand highly decorated pieces for Catherine the Great of Russia, which cost over £2000 – a great deal of money in the coin of that day. But the base of that tableware was his own pottery, creamware; and in fact all the thousand pieces, undecorated, cost less than £50, yet looked and handled like Catherine the Great's in every way except for the hand-painted idylls. The creamware which made Wedgwood famous and prosperous was not porcelain, but a white earthenware pottery for common use. That is what the man in the street could buy, at about a shilling a piece. And in time that is what transformed the kitchens of the working class in the Industrial Revolution.

Wedgwood was an extraordinary man: inventive, of course, in his own trade, and also in the scientific techniques that might make his trade more exact. He invented a way of measuring the high temperatures in the kiln by means of a sort of sliding scale of expansion in which a clay test-piece moved. Measuring high temperatures is an ancient and difficult problem in the manufacture of ceramics and metals, and it is fitting (as things went then) that Wedgwood was elected to the Royal Society.

Josiah Wedgwood was no exception; there were dozens of men like him. Indeed, he belonged to a group of about a dozen men, the Lunar Society of Birmingham (Birmingham was then still a scattered group of industrial villages), who gave themselves the name because they met near the full moon. This was so that people like Wedgwood, who came from a distance to Birmingham, should be able to travel safely over wretched roads that were dangerous on dark nights.

But Wedgwood was not the most important industrialist there: that was Matthew Boulton, who brought James Watt to Birmingham because there they could build the steam engine. Boulton was fond of talking about measurement; he said that nature had destined him to be an engineer by having him born in the year 1728, because that is the number of cubic inches in a cubic foot. Medicine was important in that group also, for there were new and important advances being made. Dr William Withering discovered the use of digitalis in Birmingham. One of the doctors who has remained famous, who belonged to the Lunar Society, was Erasmus Darwin, the grandfather of Charles Darwin. The other grandfather? Josiah Wedgwood.

Societies like the Lunar Society represent the sense of the makers of the Industrial Revolution (that very English sense) that they had a social responsibility. I call it an English sense, though in fact that is not quite fair; the Lunar Society was much influenced by Benjamin Franklin and by other Americans associated with it. What ran through it was a simple faith: the good life is *more* than material decency, but the good life must be *based* on material decency.

Wedgwood, by George Stubbs.

It took a hundred years before the ideals of the Lunar Society became reality in Victorian England. When it did come, the reality seemed commonplace, even comic, like a Victorian picture postcard. It is comic to think that cotton underwear and soap could work a transformation in the lives of the poor. Yet these simple things – coal in an iron range, glass in the windows, a choice of food – were a wonderful rise in the standard of life and health. By our standards, the industrial towns were slums, but to the people who had come from a cottage, a house in a terrace was a liberation from hunger, from dirt, and from disease; it offered a new wealth of choice. The bedroom with the text on the wall seems funny and pathetic to us, but for the working class wife it was the first experience of private decency. Probably the iron bedstead saved more women from childbed fever than the doctor's black bag, which was itself a medical innovation.

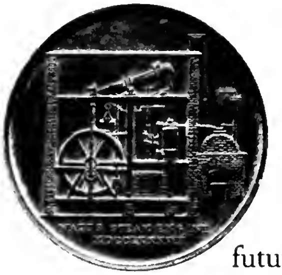
These benefits came from mass production in factories. And the factory system was ghastly; the schoolbooks are right about that. But it was ghastly in the old traditional way. Mines and workshops had been dank, crowded and tyrannical long before the Industrial Revolution. The factories simply carried on as village industry had always done, with a heartless contempt for those who worked in them.

Pollution from the factories was not new either. Again, it was the tradition of the mine and the workshop, which had always fouled their environment. We think of pollution as a modern blight, but it is not. It is another expression of the squalid indifference to health and decency that in past centuries had made the Plague a yearly visitation.

The new evil that made the factory ghastly was different: it was the domination of men by the pace of the machines. The workers for the first time were driven by an inhuman clockwork: the power first of water and then of steam. It seems insane to us (it *was* insane) that manufacturers should be intoxicated by the gush of power that spurted from the factory boiler without a stop. A new ethic was preached in which the cardinal sin was not cruelty or vice, but idleness. Even the Sunday schools warned children that

> *Satan* finds some Mischief still
> For idle Hands to do.

The change in the scale of time in the factories was ghastly and destructive. But the change in the scale of power opened the



A factory token stamped with Watt's Steam Engine, 1786.

future. Matthew Boulton of the Lunar Society, for example, built a factory which was a showplace, because Boulton's kind of metalwork depended on the skill of craftsmen. Here James Watt came to build the sun-god of all power, the steam engine, because only here was he able to find the standards of accuracy needed to make the engine steam-tight.

In 1776 Matthew Boulton was very excited about his new partnership with James Watt to build the steam engine. When James Boswell, the biographer, came to see Boulton that year, he said to him grandly, 'I sell here, sir, what all the world desires to have – power'. It is a lovely phrase. But it is also true.

Power is a new preoccupation, in a sense a new idea, in science. The Industrial Revolution, the English revolution, turned out to be the great discoverer of power. Sources of energy were sought in nature: wind, sun, water, steam, coal. And a question suddenly became concrete: Why are they all one? What relation exists between them? That had never been asked before. Until then science had been entirely concerned with exploring nature as she is. But now the modern conception of transforming nature in order to obtain power from her, and of changing one form of power into another, had come up to the leading edge of science. In particular, it grew clear that heat is a form of energy, and is converted into other forms at a fixed rate of exchange. In 1824 Sadi Carnot, a French engineer, looking at steam engines, wrote a treatise on what he called 'la puissance motrice du feu', in which he founded, in essence, the science of thermodynamics – the dynamics of heat. Energy had become a central concept in science; and the main concern in science now was the unity of nature, of which energy is the core.

And it was a main concern not only in science. You see it equally in the arts, and the surprise is there. While this is going on, what is going on in literature? The uprush of romantic poetry round about the year 1800. How could the romantic poets be interested in industry? Very simply: the new concept of nature as the carrier of energy took them by storm. They loved the word 'storm' as a synonym for energy, in phrases like *Sturm und Drang*, 'storm and thrust'. The climax of Samuel Taylor Coleridge's

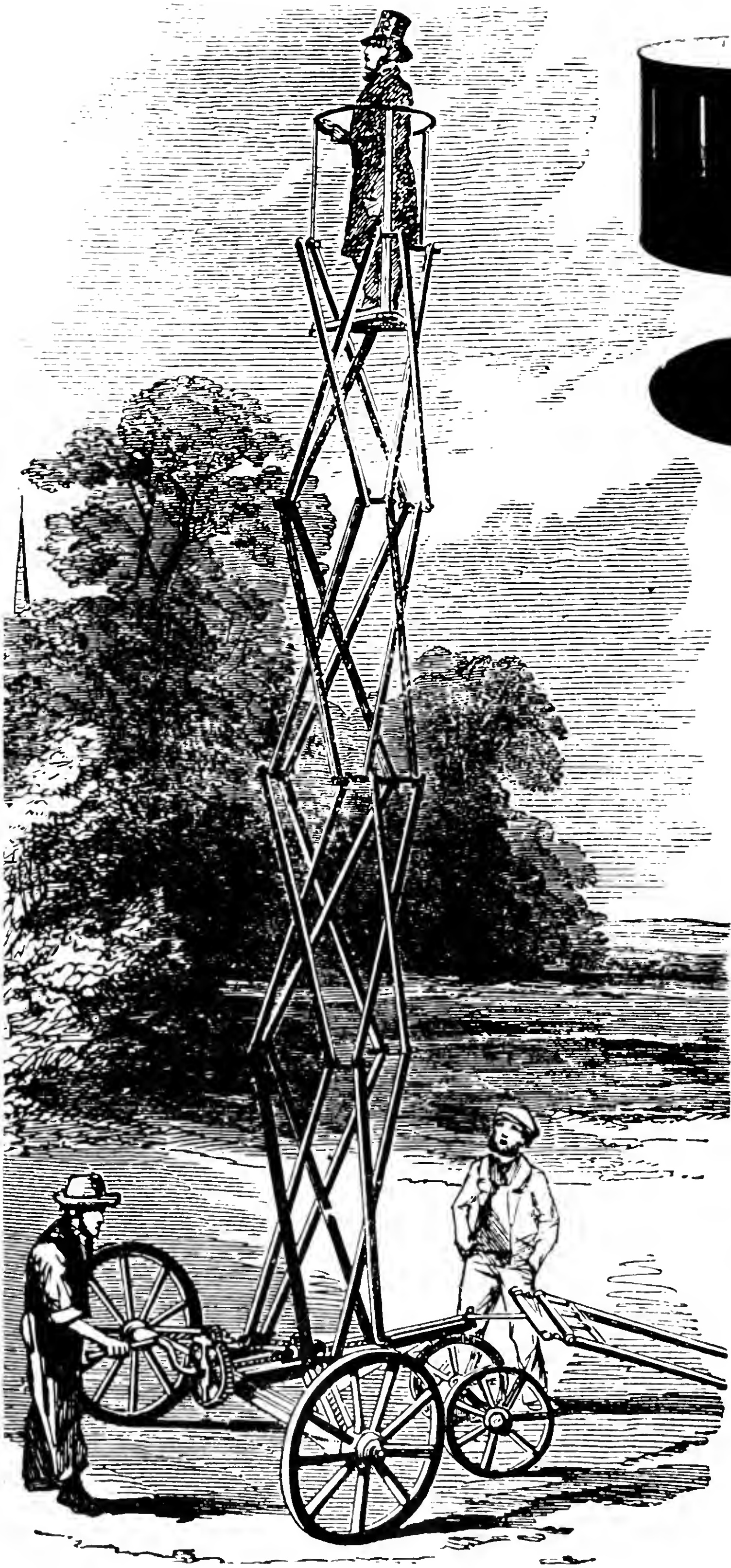
Rime of the Ancient Mariner is introduced by a storm that breaks the deadly calm and releases life again.

> The upper air burst into life!
> And a hundred fire-flags sheen,
> To and fro they were hurried about!
> And to and fro, and in and out,
> The wan stars danced between.
>
> The loud wind never reached the ship,
> Yet now the ship moved on!
> Beneath the lightning and the Moon
> The dead men gave a groan.

A young German philosopher, Friedrich von Schelling, just at this time in 1799, started a new form of philosophy which has remained powerful in Germany, *Naturphilosophie* – philosophy of nature. From him Coleridge brought it to England. The Lake Poets had it from Coleridge, and the Wedgwoods, who were friends of Coleridge's and indeed supported him with an annuity. Poets and painters were suddenly captured by the idea that nature is the fountain of power, whose different forms are all expressions of the same central force, namely energy.

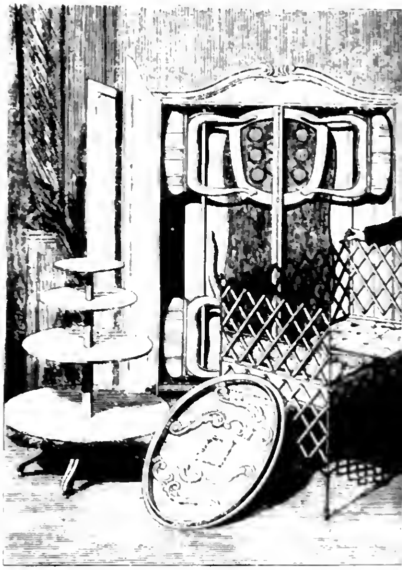
And not only nature. Romantic poetry says in the plainest way that man himself is the carrier of a divine, at least a natural, energy. The Industrial Revolution created freedom (in practice) for men who wanted to fulfil what they had in them – a concept inconceivable a hundred years earlier. But hand in hand, romantic thought inspired those men to make of their freedom a new sense of personality in nature. It was said best of all by the greatest of the romantic poets, William Blake, very simply: 'Energy is Eternal Delight'.

The key word is 'delight', the key concept is 'liberation' – a sense of fun as a human right. Naturally, the marching men of the age expressed the impulse in invention. So they produced a bottomless horn of plenty of eccentric ideas to delight the Saturday evenings of the working family. (To this day, most of the applications that lumber the patent offices are slightly mad, like the inventors themselves.) We could build an avenue from here to the moon lined with these lunacies, and it would be just about as pointless and yet as high-spirited as getting to the moon. Consider, for example, the idea of the zoetrope, a circular machine for animating a Victorian comic strip by flashing the pictures



So they produced a bottomless horn of plenty of eccentric ideas to delight the Saturday evenings of the working family.

The Zoetrope; a patent elevator-platform; and patent Viennese Folding Bedroom Furniture.



past the eye one after another. It is quite as exciting as an evening at the cinema, and comes to the point rather quicker. Or the automatic orchestra, which has the advantage of a very small repertoire. All of it is packed with homespun vigour which has not heard of good taste, and is absolutely self-made. Every pointless invention for the household, like the mechanical vegetable chopper, is matched by another superb one, like the telephone. And finally, at the end of the avenue of pleasure, we should certainly put the machine that is the essence of machineness: it does nothing at all!

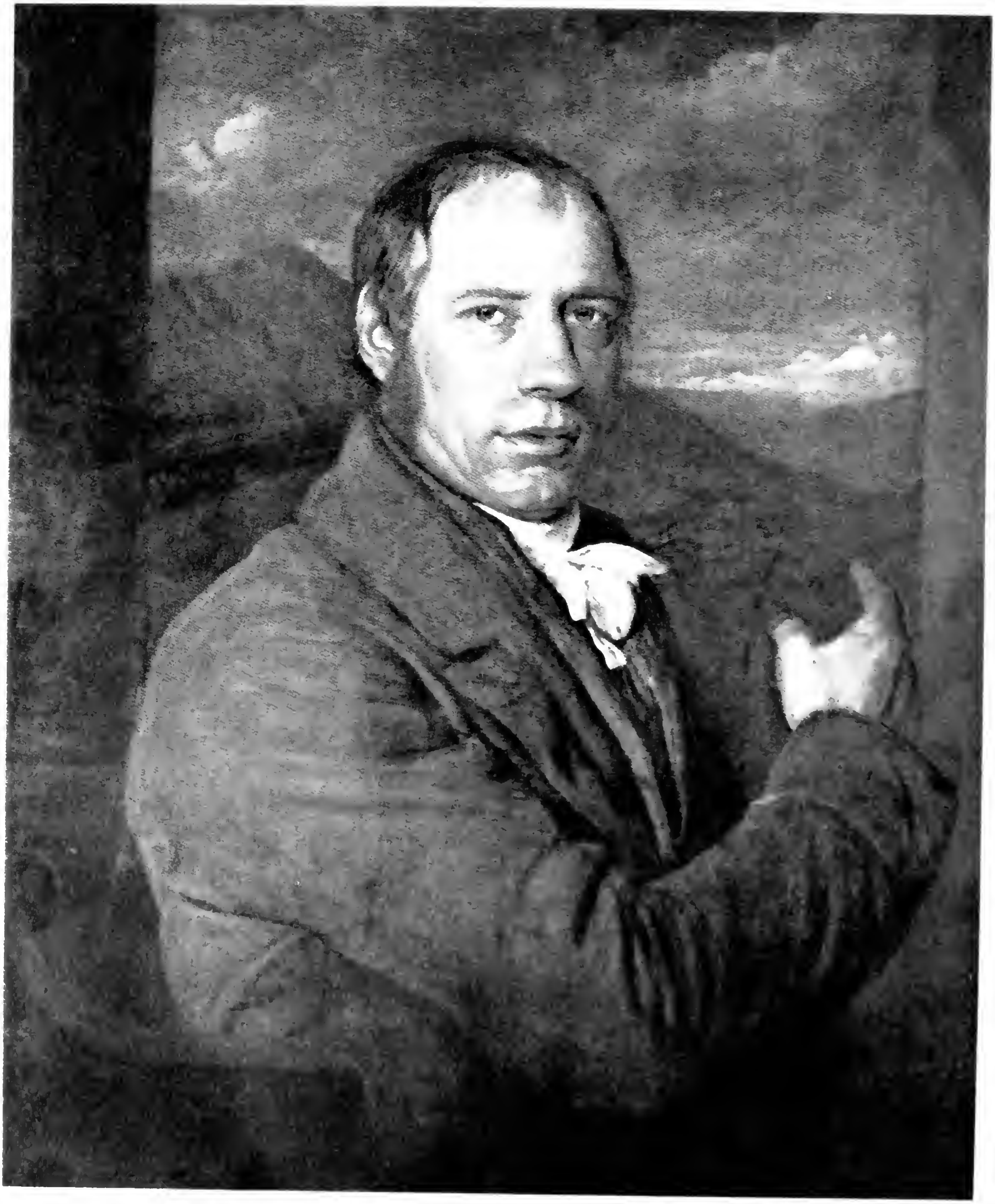
The men who made the wild inventions and the grand ones came from the same mould. Think of the invention that rounded out the Industrial Revolution as the canals had begun it: the railways. They were made possible by Richard Trevithick, who was a Cornish blacksmith and a wrestler and a strong man. He turned the steam engine into a mobile power pack by changing Watt's beam engine into a high-pressure engine. It was a life-giving act, which opened a blood-stream of communication for the world, and made England the heart of it.

We are still in the middle of the Industrial Revolution; we had better be, for we have many things to put right in it. But it has made our world richer, smaller, and for the first time ours. And I mean that literally: our world, everybody's world.

From its earliest beginnings, when it was still dependent on water power, the Industrial Revolution was terribly cruel to those whose lives and livelihood it overturned. Revolutions are – it is their nature, because by definition revolutions move too fast for those whom they strike. Yet it became in time a social revolution and established that social equality, the equality of rights, above all intellectual equality, on which we depend. Where would a man like me be, where would you be, if we had been born before 1800? We still live in the middle of the Industrial Revolution and find it hard to see its implications, but the future will say of it that in the ascent of man it is a step, a stride, as powerful as the Renaissance. The Renaissance established the dignity of man. The Industrial Revolution established the unity of nature.

That was done by scientists and romantic poets who saw that the wind and the sea and the stream and the steam and the coal are all created by the heat of the sun, and that heat itself is a form of energy. A good many men thought of that, but it was establi-

Richard Trevithick
turned the steam engine
into a mobile power pack.



shed above all by one man, James Prescott Joule of Manchester. He was born in 1818, and from the age of twenty spent his life in the delicate detail of experiments to determine the mechanical equivalent of heat – that is, to establish the exact rate of exchange at which mechanical energy is turned into heat. And since that sounds a very solemn and boring undertaking, I must tell a funny story about him.

In the summer of 1847, the young William Thomson (later to be the great Lord Kelvin, the panjandrum of British science) was walking – where does a British gentleman walk in the Alps? – from Chamonix to Mont Blanc. And there he met – whom does a British gentleman meet in the Alps? – a British eccentric: James Joule, carrying an enormous thermometer and accompanied at a little distance by his wife in a carriage. All his life, Joule had wanted to demonstrate that water, when it falls through 778 feet, rises one degree Fahrenheit in temperature. Now on his honeymoon he could decently visit Chamonix (rather as American couples go to Niagara Falls) and let nature run the experiment for him. The waterfall here is ideal. It is not all of 778 feet, but he would get about half a degree Fahrenheit. As a footnote, I should say that he did not – of course – actually succeed; alas, the waterfall is too broken by spray for the experiment to work.

The story of the British gentlemen at their scientific eccentricities is not irrelevant. It was such men who made nature romantic; the Romantic Movement in poetry came step by step with them. We see it in poets like Goethe (who was also a scientist) and in musicians like Beethoven. We see it first of all in Wordsworth: the sight of nature as a new quickening of the spirit because the unity in it was immediate to the heart and mind. Wordsworth had come through the Alps in 1790 when he had been drawn to the Continent by the French Revolution. And in 1798 he said, in *Tintern Abbey*, what could not be said better.

For nature then . . .
To me was all in all – I cannot paint
What then I was. The sounding cataract
Haunted me like a passion.

'Nature then to me was all in all.' Joule never said it as well as that. But he did say, 'The grand agents of nature are indestructible', and he meant the same things.

Models are not themselves the same thing as the real world objects or ideas they represent, but nevertheless they do help scientists and engineers learn about the real world. This article shows how.

3 Modeling

The Engineering Concepts Curriculum Project

A selection from Man and His Technology, 1973

I | THE NATURE OF MODELS

According to an old story, six blind men who had never seen an elephant tried to decide what it was.* The first man, feeling the elephant's flat, vertical side, concluded that the beast was similar to a wall. The second man touched a round, smooth, sharp tusk and decided that an elephant is similar to a spear. Grasping the squirming trunk, the third blind man said that the animal resembled a snake. The fourth man, who touched a knee, observed that elephants resembled trees. From an exploration of the ear of the elephant, the fifth man was convinced that the animal had the shape of a fan, while an examination of the tail convinced the sixth blind man that an elephant was similar to a rope.

* The Blind Men and the Elephant (J. G. Saxe, 1816–1887). The poem is given in Question 15 at the end of the chapter.

Each, of course, was partially correct, but insofar as a complete representation of the elephant was concerned, all were wrong. Each man, after observing the "real world," formulated a description, or *model*. But since the observations were incomplete, the models were incorrect.

Every time we describe an object, we are really making a model. We use our senses to find information about the real world. From this information, we decide what the object is. Then we pick out the *important* features. These make up the model.

The model is an efficient way of viewing things. A good model includes only those parts which are useful. But, by restricting our thoughts to a few features, we are able to understand the object or system. We can anticipate the effects of actions we might take. On this basis, we can select the best action. Thus, man's ability to control his environment and to build useful systems depends directly on his capacity to find models.

Models Are Usually Quantitative

Models begin as conceptions; they are ideas about the structure and nature of something. Before we can go very far with the model, we usually have to develop a *quantitative model*, one which tells how much, where, and when in terms of numbers. In other words, we use the language of mathematics to describe our situation.

The importance of a quantitative model can be illustrated by the task of the man who is in charge of scheduling elevators in a twenty-story office building from 8:45 to 9 A.M. every weekday morning as people arrive for work. There are six elevators, each able to stop at every floor.

When the building is first opened, the elevator supervisor simply loads each elevator in turn. As soon as it is loaded, it departs. Our supervisor notices that service is extremely slow. Occasionally, an elevator is loaded with one passenger for each of 15 different floors. The poor passenger who works on the highest floor has a ten-minute ride. (Especially since the passengers at the back of the elevator as it starts up always seem to be the ones who want to get off first.)

As the complaints about service become more and more bitter, our supervisor wonders if service might be improved by using a better plan. He might, for example, use two elevators for floors 2-8 only, two others for floors 9-15, and the other two for 16-20. He might stop only at even-numbered floors and force employees to walk down one flight of stairs to reach the odd-numbered floors. Obviously, there are many possible strategies which could be tried to improve service.

The choice of a desirable strategy depends on the way employees arrive in the morning for each of the floors. For example, the fifteenth floor holds the executive suite for the top officers of the company. If any of them should arrive during this busy period, they must be delivered as rapidly as possible. This priority for Floor 15 means that at least one elevator should go directly to this floor. Similarly, certain floors may have many employees and should be given preference. In other words, to derive a sensible plan or strategy our supervisor needs at least a rough quantitative picture of the flow of people. This is the model.

The model may be very approximate and rough, guessing only that the number of employees is the same for each floor. Or it may be very detailed with the number for each floor, their probable arrival times, and their relative importance to the company. If the model is very simple, the supervisor may be able to decide intuitively on a strategy; if the model is very detailed, a computer may be required to evaluate and compare the possible strategies.

The important feature of this example is that no intelligent decision is possible unless a model is used, whether or not the supervisor calls his picture a model.

2 | THE GRAPH AS A DESCRIPTIVE MODEL

To form a model, we need to collect data about some aspect of the real world. We might wish to determine whether a simple relationship exists between the heights and the weights of twenty-

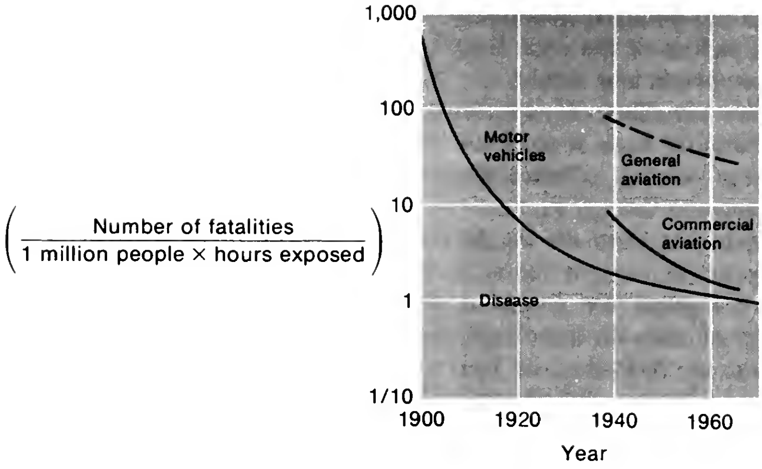


Fig. 4–2. *A different model which shows the willingness of people to accept risk. The vertical axis is a measure of the risk involved in different activities (the number of deaths in the U.S. divided by the total number of hours a million people are exposed to the risk). For example, 10 means that there are ten deaths every hour a million people engage in this activity.*

The interesting part of this model is that just living (with possible disease) has about the same risk as driving a car or flying a commercial airplane. (Only about 5% of the people ever fly; 85% ride in a car.) People seem willing to accept this risk of 1. Cigarette smoking has a risk of 3, skiing about 1, and normal railroad travel 1/10. This model gives us some idea how safe we must make new forms of transportation (moving sidewalks or 300-mph trains).

The model is discouraging if we are interested in cutting down traffic accidents. It suggests that the average person may be willing to accept today's death rate. (Chauncey Starr, "Social benefit versus technological risk," UCLA report, 1969.)

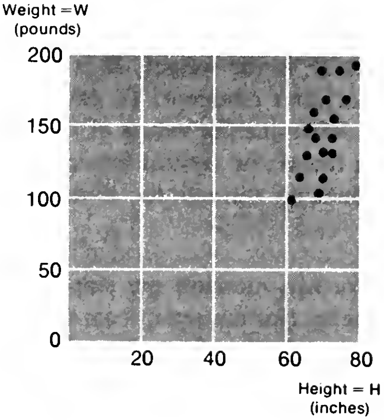


Fig. 4–3. Height-weight data for 20-year-old men.

year-old men. After making several experimental measurements, we may secure a set of related numbers such as 5′6″, 130 lb; 6′1″, 180 lb; 5′7″, 155 lb. But it is difficult to discover any systematic relationship in this way. Even though we may have a reasonable expectation that as height increases, weight will increase, this verbal model is vague and imprecise.

In order to present the data in a way which we can interpret more easily, we make a graphical plot, as in Fig. 4–3. Each point represents the height-weight data for one man. We notice now that the points are not scattered, but seem to be closely grouped. What can we say about the relationship between height and weight?

A straight line can be drawn through the points to represent averages for these data (Fig. 4–4). This picture of the data is a *graphical model* of the relationship between height and weight.

This graphical model presents a clear but simplified description of the real world. It can be used as the basis for some reasonable predictions. From the straight-line average we can estimate the probable weight of a twenty-year-old man even though we know only his height. Let us suppose that we wish to estimate the weight of someone who is 73″ tall. The corresponding weight for this height can be immediately obtained from our graph. The graphical model permits us to estimate the weight of such an individual, even if our original data did not include any individual of this height. Thus, we may predict from our graphical model that an individual who is 73″ tall probably weighs about 180 pounds.

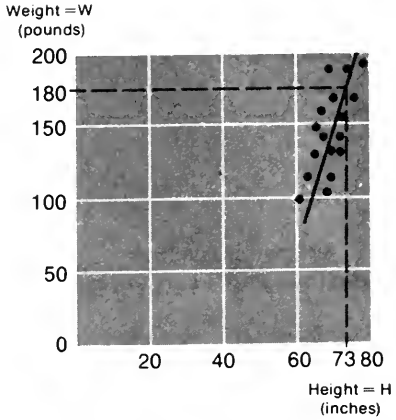


Fig. 4–4. Weight expected from a man 73″ tall.

An Equation As a Model

While the graph of Fig. 4–4 is an appropriate model for our weight-height relationship, it is also often convenient to have a mathematical equation. The straight-line graph is exactly equivalent to an equation, which in this case happens to be

$$W = 8H - 407$$

(We derive this in the next paragraph.) Even though the graph and the equation say exactly the same thing, it is often a nuisance to have to redraw the graph every time we want to tell someone what the model is. Furthermore, it is frequently easier to work with the equation. For example, what is the height expected for a 150-pound man? From the equation,

$$150 = 8H - 407 \text{ or } H = 70''$$

Since our graph is a straight line, we know from algebra that the equation has the general form $y = mx + b$, or in this case,

$$W = mH + b$$

where W is the weight, H is the height, m is the slope, b is the vertical axis intercept. To complete the equation, we must therefore determine the values of the constants m and b. Since b represents the W, or vertical intercept of the line, Fig. 4–5 reveals that the line cuts through the W-axis at a value of -407. Hence,

$$W = mH - 407$$

We can measure the slope m directly. When H increases by 10 inches (for example, from 60 to 70), W increases by 80 pounds. The slope is thus $\frac{80}{10}$ or 8, and the equation is

$$W = 8H - 407$$

Once the equation is determined, the weight W can be found for any given height, or the height for any given weight.

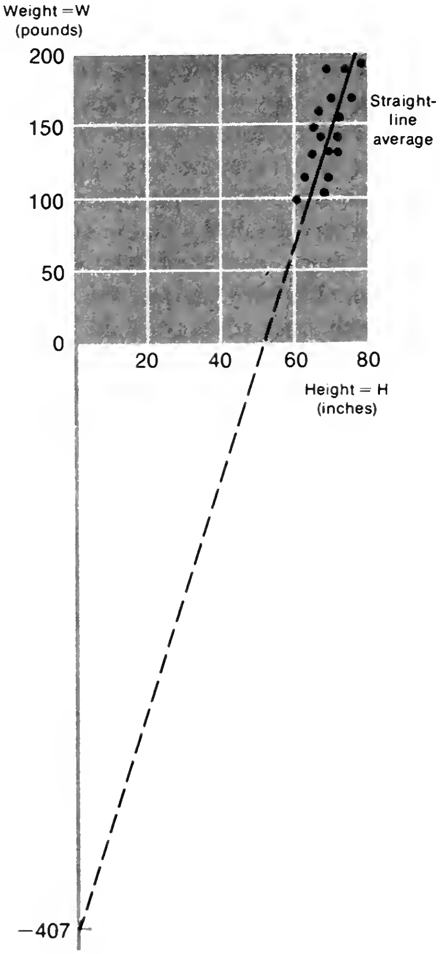


Fig. 4–5. Straight line extended until it hits the W axis.

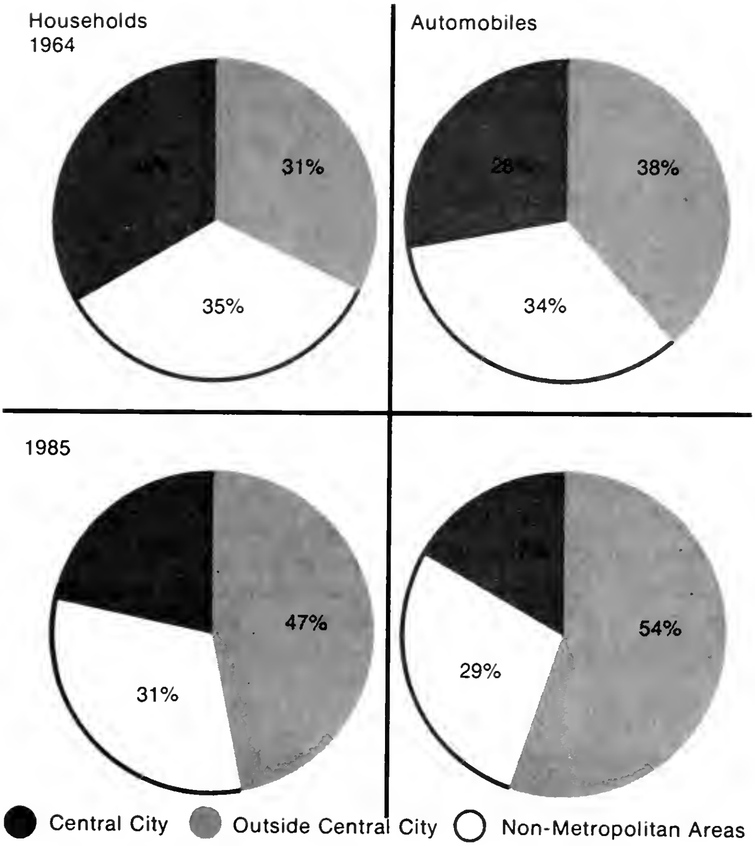


Fig. 4–6. A completely different form of graphical model. In this case, we are interested in showing the changes expected from 1964 to 1985. The "pie" charts show how the suburbs will grow, primarily as the central city becomes less important (if present trends continue). Thus, a model can be portrayed in many different forms. (Technology Review *of M.I.T.*)

We can use this model to predict points which were not originally in our data sample. But these predictions must be carefully examined. For instance, the line we have drawn tells us that an individual who is 54″ tall will weigh about 25 lb; worse yet, a 24″ person can be expected to tip the scale at an impressive *negative* 215 lb! Surely these are curious figures for twenty-year-old men. What is wrong with our model?

The straight-line average that we drew was extended so that the W intercept (−407) could be found. But we are not entitled to say that all points on the entire line must represent real situations. Actually, the only use we can make of this model is to predict within our data field. We know that anywhere inside of the cluster of measured points we are in the neighborhood of a real-world possibility. However, *we run into the danger of unrealistic prediction if we apply the model beyond the region that has been measured.* This danger applies to either the graph or the equation.

Our model, therefore, has its limitations. It must not be used to predict beyond the region of results experimentally obtained unless there are very good reasons to believe that real-world laws are not being violated. To test this model requires that we obtain a fresh sample of twenty-year-old men, either the data from the same school for other years or from other schools or from the army. Then we either enter them on the plot or compare them with predictions made from the algebraic model.

The equation is a mathematical model which says exactly the same things as the graphical model. Both of these models are more useful than the verbal model with which we started.

One of the most interesting aspects of this model is that it turns out to be so simple. This is quite unexpected. If we think of the people we meet while walking down a busy city street, we know that all sizes and weights are combined. It is true that the sample studied was passed through two strainers (age and sex) to make it more manageable.

We should give one final word of caution. We must remember where our original data came from. If we had measured the heights and weights of the members of the Kansas City Chiefs professional football team, we probably could not expect to use the model to predict the weight of a six-foot, 25-year-old starving artist. At least, we should be suspicious of the prediction. The model is only useful as long as we stay with the part of the world from which the model was derived.

3 | A DESCRIPTIVE MODEL OF TRAFFIC FLOW

A key urban problem is the question of how to handle motor traffic in the streets. Some cities have gone so far as to ban all automobiles from a few streets. This does not so much solve the problem as eliminate it—at least from those streets. Furthermore, it sometimes substitutes other problems, for example for the elderly and infirm, or for the shopkeeper trying to attract customers. It also increases the cost of goods since delivery expenses rise.

If a traffic engineer is to improve present conditions he must be able to predict the results of changes. To do this he must construct a model of the traffic flow in and around the city. Since such a model is too complicated, we use a study of the simpler circumstances within a school; even this we limit to what goes on at a single corridor intersection, such as that shown in Fig. 4–8. The limited model we derive for a single intersection could be extended to a whole building. The resulting larger model can be of practical use to school administrators, schedule-makers, and architects.

In order to construct our model, we must determine what affects the behavior of the system. We are primarily interested in the rate at which people (including teachers and custodians) pass from one corridor to another, in other words, in the density of traffic as measured in people per minute. The measurement will be made by *sensors*, devices which respond in some way whenever a person passes. An example would be the device often called an electric eye, but for short-term service a much more practical sensor is a person stationed at the proper spot

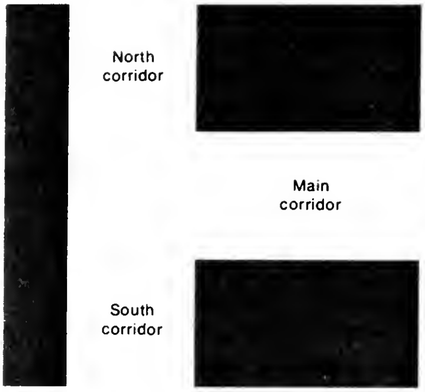


Fig. 4–8. A school corridor intersection.

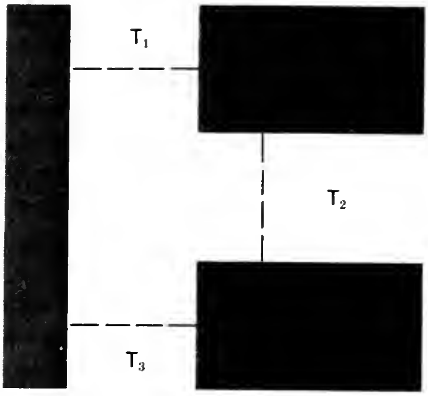


Fig. 4–9. Where traffic density is measured.

Figure 4–9 shows the intersection with measurement points identified. Traffic problems usually arise at intersections rather than in the main corridors.* What we need for the present is a count, minute by minute during the time when classes are being changed, and for a minute (or more) before and after.

Table 4–1 shows a possible result of such a set of measurements. The actual number of people who go through the intersection during the counting period is about half that shown because each person was counted twice, once when he entered and once when he left (if we forget people like Joe and Susan).

Table 4–1. Detailed traffic count at one intersection, end of first period.

Minute number	Counting station T_1	T_2	T_3	Total counts
1	26 counts	50 counts	30 counts	106
2	42	63	47	152
3	61	102	55	218
4	112	184	73	369
5	38	42	28	108
6	22	17	9	48
			Total for period	1001

The data can be shown more effectively if we present them in a plot, rather than a column of numbers. One form of plot which is often used in displaying a count of events is called a histogram. It has the form shown in Fig. 4–10 for the total number of individuals passing through this intersection.

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* As Joe passes position T_2 going east, he sees that Susan is going south past T_1. He reverses his field and meets her in the middle of the intersection. Therefore, they both hold up traffic and he is counted three times at T_2; he might even stroll a few yards down the south corridor with Sue and add two more tallies to his total.

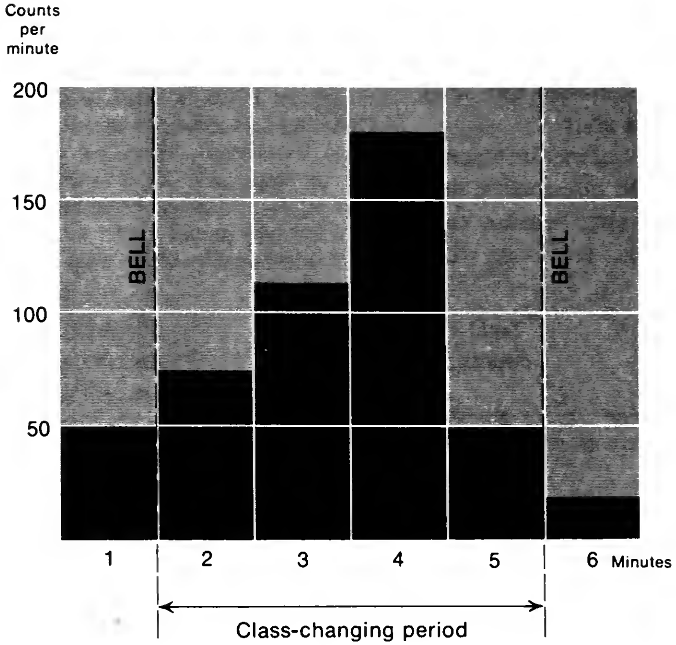

Fig. 4–10.
Bar graph of traffic at one intersection at the end of the first period.

The height of each vertical column is proportional to half the total count for the minute indicated below it, half the total for the reason just explained. It is evident that most of the traffic, but not all, occurred during the interval between classes. The school administrator confronted with such a bar graph might well be suspicious of the large traffic during the minute before the bell rang for class changing: Are some teachers dismissing their classes early? He might also be disturbed by evidence of a good deal of tardiness.

Further information, useful to the scheduling officer, can be obtained if another bar graph is made, this time of total counts at the end of each period during the day (Fig. 4–11). Here the peaks shown for traffic at the ends of the first and fourth periods might suggest altering the room assignments in such a way as to lessen the traffic through this intersection at these times. For example, more students might be scheduled for successive classrooms in the same corridor to avoid the intersection.

A full study of a school's traffic pattern requires that data be obtained at every intersection for every class-changing period throughout the day or even the entire week. If there are ten important intersections, the total data can be portrayed in fifty histograms similar to Fig. 4–11 (ten for each of five days) or similar curves on a minute-by-minute basis. Inspection of these data then reveals the times and locations of major congestion.

In processing data of this type, it is common practice to indicate those particular data points which are either unusually large or notably small. We might show in red all parts of the histograms which are larger than a predetermined amount (corresponding to troublesome congestion). We may choose to make up a small

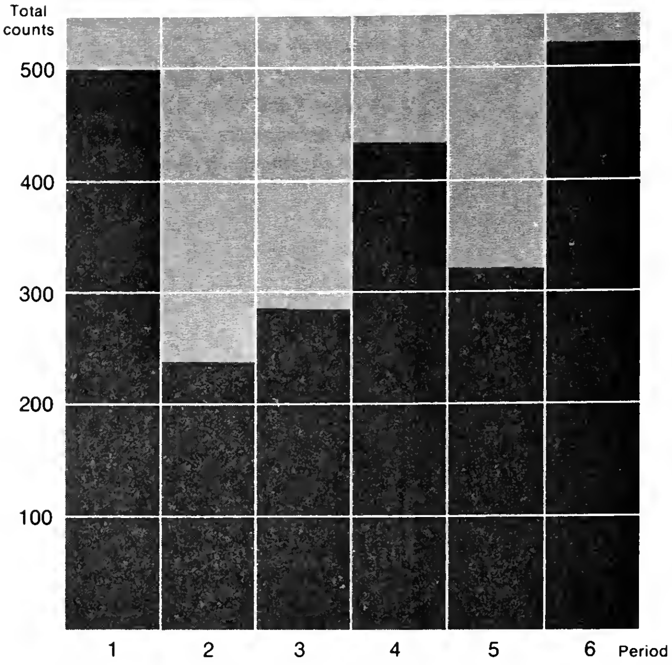

Fig. 4–11. Bar graph of total daily traffic at one intersection.

separate list showing critical data only. Such selective presentation of critical data is called "flagging"; we flag data which are especially important.

This type of traffic-flow study is closely related to the queueing problem described in Chapter 3. Queues occur when traffic density increases. In the city traffic problem, the results are obvious. Excessively long travel time ruins emergency services (ambulances, fire trucks, and police cars), lowers the income of taxi drivers, raises the cost of goods, and causes lost time for workers. One of the reasons some small businesses are moving out of the cities to the suburbs is the consistent tardiness of workers because of transportation problems. In one recent study, a manufacturing business employing 700 workers measured tardiness in the morning, lost time at the lunch hour, and early departures in the afternoon. The model showed that if the company moved to the suburbs, production would increase 12% with the same size labor force. Even if all employees were given free lunches, profits would increase 4% just from the greater production.

Studies based on such models reveal the importance of adequate transportation in the life of any town or city. They also are a commentary on the way business is carried out in a city. When commuting trains, buses, and subways so often bring the businessmen to work an hour late, one has to wonder whether most organizations don't employ more men than they really need.

4 | MODELS FOR RESOURCE MANAGEMENT

Management of resources is a fertile area for the use of models and decision making. In this section, we illustrate this by looking at the history of the buffalo in the western United States. Then we show how this resource could have been managed with some simple models and logical decisions.

The ideas which we present are currently being used in many different ways. In the northwestern United States, the salmon population is being modeled in detail in order to determine how to regulate salmon fishing and changes in water to ensure that the salmon supply will continue in the future. France has several programs for sea "gardening," growing fish and shellfish for food. The invasion of the Great Lakes by lampreys (eels) and the resulting changes have been under study for more than two decades, with a variety of decisions made to restore the fishing industry and sport.

The buffalo provide an interesting example of what is apt to happen with no national policy for resource management—no model, no logical decision.

A Model for 1830

In 1830, there were 40 million buffalo roaming the western United States. In terms of weight (at 1000 pounds each), there were 40 billion pounds of buffalo compared to only 24 billion pounds of human beings today in the entire United States. The buffalo dominated the western plains to an extent unknown for any other animal in history, including human beings.

In 1830, the railroad arrived and the rapid westward expansion of the United States began. By 1887, there were only 200 buffalo left. In this slaughter, animals were often killed for only the tongues and hides. An average of only 20 pounds of meat (of a possible 500) per buffalo was eaten. The peak was reached in 1872 when national heroes like "Buffalo Bill" Cody led the killing of more than seven million.

In less than sixty years, the lack of any sort of policy led to the destruction of what could have been a major source of meat for today's population of this country. A single buffalo could provide the entire meat supply for at least five people for a year.

Had the nation been aware of the potential problem in 1830, a model could have been constructed. In order to decide how many buffalo can be killed each year, we first must know how the population rises or falls from natural causes. Recent studies of buffalo have indicated the following facts:

1. Buffalo reach maturity at age 2.
2. 90% of the females age 2 or older have one calf a year.
3. 53% of the calves are male, 47% female.

4. 30% of the calves live for two years, or to maturity (infant mortality is high for most animals).
5. 10% of the mature beasts die each year (from tuberculosis, drowning, predation, and so on).

From these observations, we can construct a model in mathematical form to show the number of mature females alive at the beginning of each year.* For example, let's look first at year seven. How many females are there at the beginning of year seven? Of course, this can be any year picked at random.

First, the answer depends on the number there were at the beginning of year six. Ten percent of those have died. Some other fraction have been *harvested* (killed for meat and hides). Let us call this fraction k. Then, of those who started year six, $(0.9 - k)$ as many start year seven.

This is not quite the whole story. During year six, some female buffalo have reached maturity (two years old). For every 100 mature females at the beginning of year five, 90 calves are born; 47% of these, or 42.3, are female; 30% of these, or 12.69, live to be two years old. Thus, 0.1269 of the female population at the start of year five become mature females at the start of year seven.

Therefore, the number at year seven is $(0.9 - k)$ times the number at year six plus 0.1269 times the number at year five. If we call F_7 the number of females at the start of year seven, we can summarize this model very simply by an equation

$$F_7 = (0.9 - k)\,F_6 + 0.1269\,F_5$$

We can change the 7, 6, 5 to any three consecutive years. All this equation says is that the mature population depends on the size a year earlier and also two years earlier. The first term arises from the total death rate, the second term from the births two years ago.

Fig. 4–15.
Seal of the U.S. Department of the Interior. It is ironic that the animal we slaughtered so enthusiastically is the symbol of a government department and even appears on our coins.

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* The same general sort of model is used for males. The total population is, of course, the sum. To simplify the discussion, we consider only the females. (The male calves born depend on the number of females, so it is easiest to find the number of females first.)

A Decision Policy

Once the model is known, we can choose k to control the population. We might want the population to increase, stay constant, or decrease.

As an example, if the decision in 1830 had been to keep the population constant at 20 million mature females, how should k be chosen? Now in the preceding equation, we want F_7, F_6, and F_5 to be the same (20 million). Then we can cancel these F's or divide each term by F. This leaves an equation

$$1 = (0.9 - k) + 0.1269$$

which states that k should be 0.0269. This means we can harvest 2.69% of the mature females each year. The population will not change. Since 0.0269 times 20 million is 538,000, we can harvest for food and hides 538,000 mature females each year. (Even more males can be harvested, since more males are born.)

If both males and females are counted, we could have provided enough meat for 6 million people a year since 1830 and still had a buffalo population of 40 million. All that was missing was an intelligent decision policy.

If we were actually managing the buffalo population, we would have to measure the death and birth rates each year. If there were an epidemic, we might want to decrease the harvest until things were back to normal.

We could also construct a more detailed model. Birth rates depend on the age of the mature females, the weather, and other factors. Infant mortality varies with location (the number of predators, the food supply, and so forth).

The interesting feature of the example is the obvious benefit from a very simple model. Even if the numbers in the model are slightly in error, the decision (or policy) ensures that the population changes will be slow. If after several years we find the population is decreasing, we can reduce the harvest slightly. Over a period of years, we can reach a policy which gives a stable population. We can continually improve our model and our policy with experience.

5 | A POPULATION MODEL

While we worry about saving the buffalo or the falcon from extinction, there is much greater concern today about trends in the population of human beings. A model of the world's population is interesting because it represents a dynamic situation (one in which events change with time). Furthermore, the derivation of the model illustrates how we often need to refine or improve our model after it is initially determined.

It has been estimated that since the appearance of man on the earth, a total of 15 billion human beings have existed. With a world population of nearly 3 billion today, 20% of all the people who have ever lived are alive today. Our population is growing at an explosive rate.

Demography, or the study of population, is of increasing concern to economists, ecologists, sociologists, political scientists, engineers, and many others who must understand the present and plan for the future. Models of population change are exceedingly important to such study. They make possible analysis and prediction which can lead to more effective planning for the many goods and services that people need.

We wish to obtain a simple model which would let us estimate the world population at some future date. The present average rate of population increase for the entire world is estimated to be close to 2% per year, and we assume in this section that this rate of increase does not change. At the start of 1960, population was approximately 3 billion (that is, 3 followed by nine zeros, or 3×10^9).

If the rate of increase is 2% per year, by the start of 1961 the increase is 0.02(3,000,000,000), or 60,000,000 people, to make a total of 3,060,000,000. We can then calculate the increase for the next year and for all succeeding years. The results are shown in Table 4–2.

Year	Population at start of year	Increase	Population at end of year
1960	3,000,000,000	60,000,000	3,060,000,000
1961	3,060,000,000	61,200,000	3,121,200,000
1962	3,121,200,000	62,424,000	3,183,624,000
1963	3,183,624,000	63,672,480	3,247,296,480
1964	3,247,296,480	64,945,930	3,312,242,410
1965	3,312,242,410	66,244,848	3,378,487,258
1966	3,378,487,258	67,569,745	3,446,057,003
1967	3,446,057,003	68,921,140	3,514,978,143
1968	3,514,978,143	70,299,562	3,585,277,705
1969	3,585,277,705	71,705,554	3,656,983,259

Table 4–2. Estimated world population, 1960 to 1969. These data can be compared with more recent estimates: In July 1967, the Population Reference Bureau used United Nations and other statistics to estimate that, in the summer of 1966, world population was 3.34 billion, an increase in one year of 65 million.

The table shows that the increase is *greater* each year. The growth is always 2% of the population at the beginning of the year. As the population rises, the growth also increases. In fact, if we continued Table 4–2, we would find a population of 6 billion by 1995. That is, the population will double in about 35 years.

Carrying the calculation further, we would notice that this doubling occurs *every* 35 years. This would be true for any population number we start with, as long as the rate of increase is 2%

per year. If the rate of increase were 3%, the doubling would occur in 23.5 years.*

Are these numbers in our table really accurate? From the entry in Table 4–2 for the population at the beginning of 1966, the model predicts exactly 3,378,487,258 people, a precise value. We have, however, ignored the fact that the numerical values with which we started were only approximations: The 3 billion initial population was a rounded number, and the 2% was an estimated average growth rate. If the initial population was *exactly* 3,000,000,000 and the rate of increase was exactly 2.000,000,000%, then we should obtain ten meaningful digits in our answer. But since precision was lacking in our measurement of both the starting population and the rate of increase, the results can have only a limited number of significant figures. We must, therefore, be content to use rounded numbers. The extent of precision when two numbers are multiplied is restricted by the number with the smaller precision. If in this case it is the 2% figure, and we assume that we are certain of its value to three significant figures (2.00%), then the rounded number having acceptable accuracy is not 3.378487258 billion, but 3.38 billion.

If we continue our example with a 2% rate of increase, we find that in the year 2060, just one hundred years from our starting date, the population will be nearly 22 billion. By the year 2160, it will reach an enormous 157 billion! With a doubling of population in 35 years, the growth after two centuries results in a population which is more than fifty times the original population.

Plots of Population Growth

We have already seen that a plot or graph is much easier to understand than a table of numbers. We now construct such a plot. For this, we use the predicted population at the beginning of each decade from 1961 to 2060 (Table 4–3).

Decade	Population (in billions)
1961–1970	3.06
1971–1980	3.72
1981–1990	4.55
1991–2000	5.55
2001–2010	6.77
2011–2020	8.20
2021–2030	10.06
2031–2040	12.2
2041–2050	15.0
2051–2060	18.3

Table 4–3. Estimated world population at start of each decade, 1961–2060.

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* This is the same growth as compound interest gives. A rough rule is that the time to double is 72 divided by the rate of increase or interest in %. Thus, 5% interest doubles the money in $\frac{72}{5}$ or a little over 14 years.

As a matter of convenience, we have used the population for the first year of the decade, although the actual number continually grows. In the United States, where a census is made every tenth year, the count obtained is often considered to be the legal population until the next census is completed, even though the Census Bureau issues an annual estimate of the current number of our people. These values are plotted as a bar graph in Fig. 4–16. The height of each vertical column is proportional to the population at the start of that decade as given by the table. Not only do the heights of the bars go up in each ten-year period, but the steps become increasingly larger.

The bar graph is one way of plotting the population growth. At the beginning of each decade (the start of 1961, 1971, and so forth), the figure is an accurate estimate or prediction. Then for the next ten years (Fig. 4–16), we show the population as constant until the start of the next decade. Actually, we know that the population tends to increase fairly smoothly year by year, month by month, and day by day.

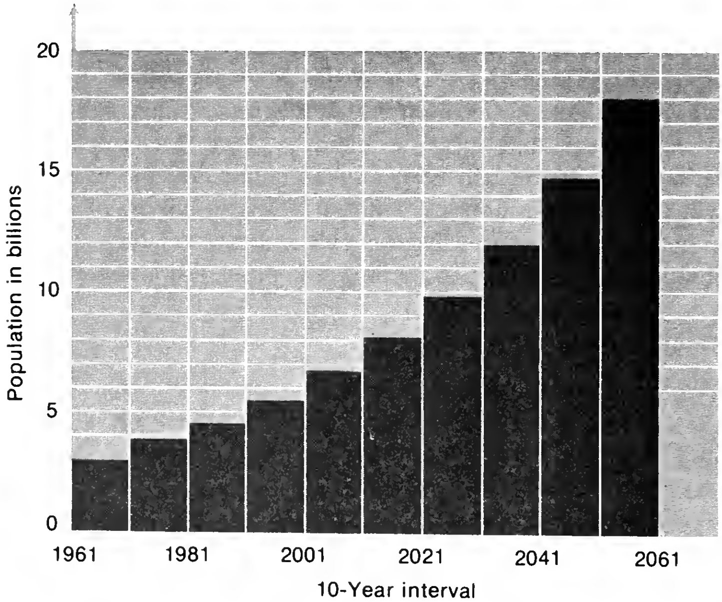

Fig. 4–16. Estimated growth of world population.

This steady growth in population can be portrayed if we

1. Plot the points corresponding to the start of each decade (the points shown in Fig. 4–17).
2. Draw a smooth curve through these points, as shown in the figure. This smooth curve gives only an approximate model of the real situation, since the population growth does fluctuate from year to year due to famine, epidemics,

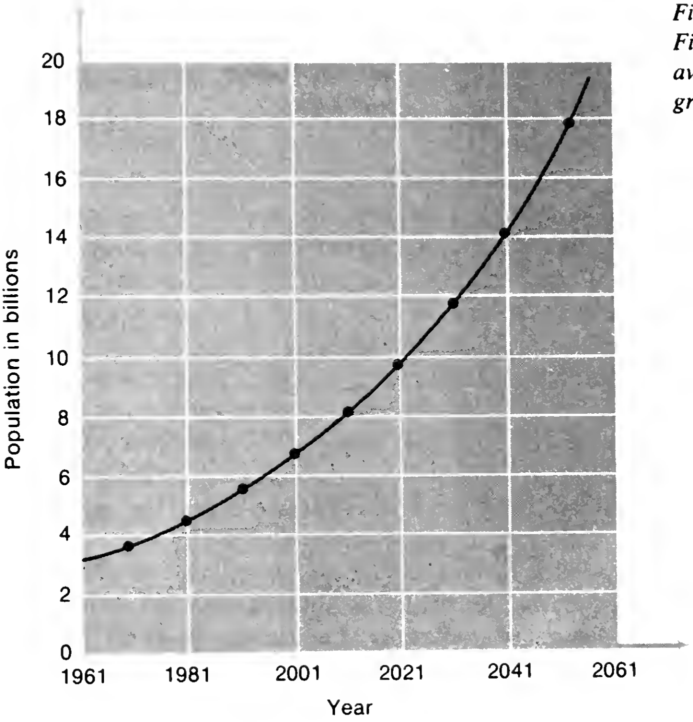

Fig. 4–17.
Fitting a smooth average line to the population growth graph.

wars, and so forth. The curve does represent a prediction of world population if we assume:

a starting figure of 3,060,000,000 in 1961 (or 3.06 billion at the start of 1961) and

a growth of 2% per year.

Now the extremely fast growth of population is clear. Even though the percentage increase remains constant at 2% per year, the larger increases each year produce a curve which becomes steeper and steeper. This curve is different from those we found in our previous models. The previous plots were linear. The population curve of Fig. 4–17, however, is not a straight line.

Furthermore, this is a particular kind of curve. Each new value of the variable is obtained by adding a constant percentage of the previous value to that value. We have a growth that is proportional to the accumulated size: “the bigger it gets, the faster it grows.” A snowballing relationship of this type is called *exponential.* The curve of Fig. 4–17 is known as an exponential curve. This very important curve represents a model which is encountered frequently, and we find other examples later in this chapter.

Population Plots Over Longer Time Scales

We now consider another plot of population increase, from 1700 to 2165. This is shown in Fig. 4–18. The eye tends to follow the curve upward to the right; but it is also important to note that the graph drops as we look to the left, or as we go backward in time. In fact, prior to 1800 the height of the curve on the scale of this graph is so small that it is difficult to measure its value. This reflects the fact that a "population explosion" has occurred: The population of the earth in the past was extremely small compared to the present population. The curve makes more reasonable the earlier statement that approximately 20% of all the people who have ever lived are alive today. From a larger scale copy of the curve we could find the even more striking fact that the population *increase* from 1940 to 1963 (just 23 years) was greater than the total population of the world in 1800!

Since we have extended our look backward in time, it is appropriate also to look further into the future. We might attempt to look ahead to the year 2700, a period only slightly more than 700 years from now. This represents about the same time difference as that between the present and the time of Marco Polo. The graphical results of the computations are shown in Fig. 4–19.

Can this really be expected? The curve shoots up at a fantastic rate. The vertical scale on the left is much larger than in the preceding figure—so much so that the steeply rising curve to the year 2165 (Fig. 4–18) cannot even be seen. Our new exponential curve has reached such proportions by the year 2700 that, if we tried to

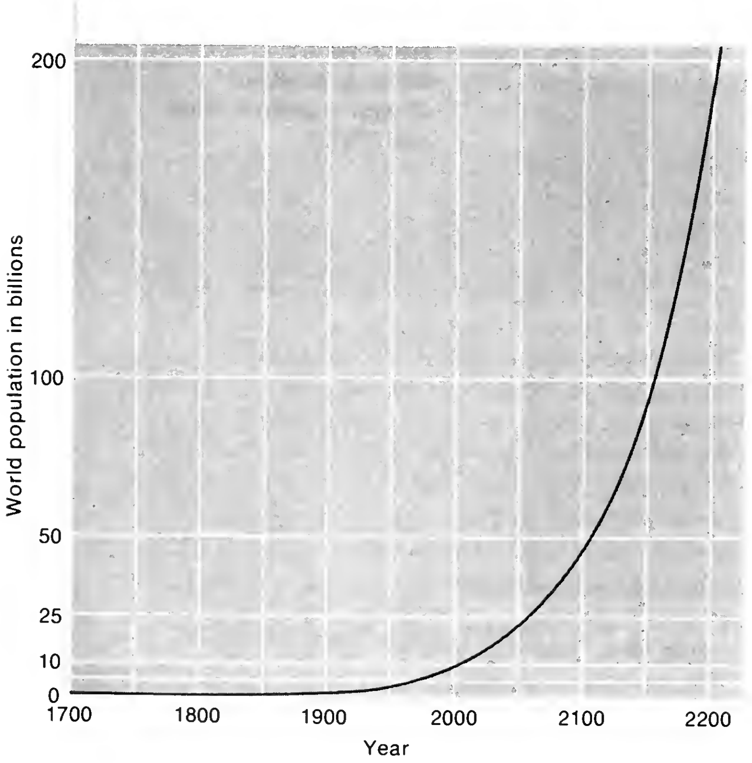

Fig. 4–18. The growth of world population from 1700 to 2165. Prior to the present time the curve is based on historical fact. Later values are predicted from a model.

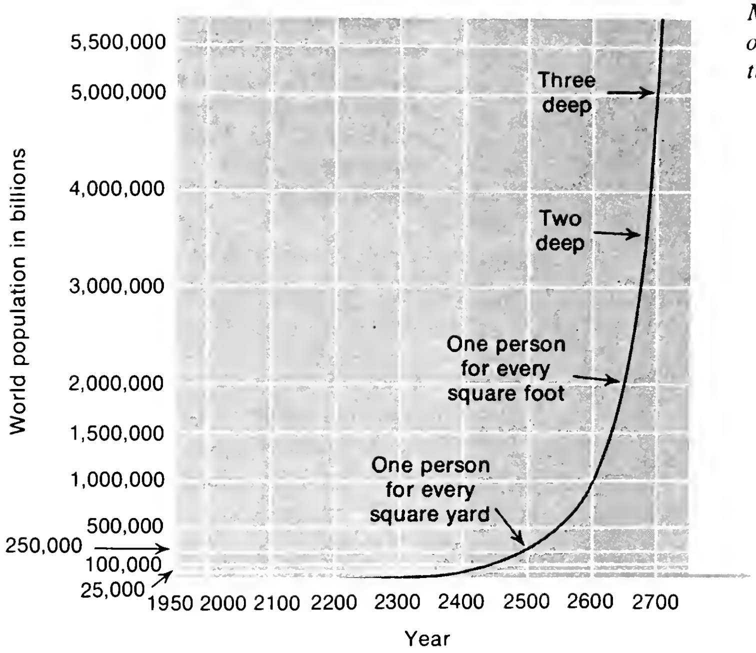

Fig. 4–19. Modeling prediction of world population to the year 2700.

plot it on the scale of Fig. 4–18, we would need a sheet of paper 27 thousand times as high, or 11 thousand feet (more than two miles) high instead of five inches.

What does this curve of Fig. 4–19 tell us? By the year 2510 we should expect to have a world population of nearly 200,000 billion people, by 2635 about 1,800,000 billion people. Thirty-five years after that it will have doubled to approximately 3,600,000 billion. In the year 2692, the model predicts a 5,450,000 billion population.

How large is 5,450,000 billion? We can express it in many ways. The number when written completely would appear as:

5,450,000,000,000,000

It may be written as 5.45×10^{15}, but this form does not give one a good "feeling" for the enormous size.

Here is one picture that helps to visualize the magnitude of the number. There are roughly 31 million seconds in each year. If we counted one thousand persons per *second*, it would take us 176,000 years to complete the census.

There is yet another way to grasp the significance of this estimate of 5,450,000 billion population. Let us ask where these people will be: How much room will they have? The surface of the earth contains approximately 1,860,000 billion square feet. About 80% of this area is covered by water, but let us suppose that all of the surface were land. We can calculate that in the year 2510 when the population is 200,000 billion, there will be 9.3 square feet per person, or about one person per square yard *all over the earth.* Worse yet, in 2635 each person will only have one square foot on which to stand, and in 2670 if they insist on retaining that much real estate, they will be standing on each other's shoulders *two deep.* And only 22 years later they will be *three deep.* Now, if we do not assume that these people can tread water but instead must occupy the land area only ($\frac{1}{5}$ of the total area), in 2692 we should expect to see totem poles 15 persons high on every square foot!

6 | EXPONENTIAL GROWTH

The model of the last section obviously is not useful for predicting population too far into the future. The model is based on a 2% increase every year. Once the land becomes too crowded, this growth rate certainly will fall. The population will level off. In the next section, we will consider how to change our model to include this fact.

The model is useful, however, to predict what will happen in the next thirty years. If the present growth rate is 2% per year, we can guess that this will not change very much in the near future. Regardless of the international efforts to control births, any real change requires educating masses of people. Even if reasonable laws were passed to limit the number of children a family could have, years would pass before the laws could be enforced effectively.

Furthermore, there is a time lag involved in any program of population control. This is a factor in the model which is often overlooked when people write or speak about the population problem. To reduce the number of babies born each year, we need to reduce the number of women of child-bearing age. But the number of women 20 to 40 years old depends on the number of babies born more than twenty years ago.

Consequently, even if the number of babies born this year were reduced, it would be more than twenty years before the effects were really noticeable. In other words, the population growth rate is fairly well determined already for the period from now until the year 2000. The real effects of any population-control program would not show up until about the year 2000.

Such a time lag is found in problems where we are trying to control the environment. For example, even if all new cars built from today on were made to have no lead compounds in the exhaust gases, it would be several years before there was a noticeable change in the lead in the air simply because of all the cars already on the road. Ten years would pass before almost all of the cars on the road were "clean."

Because of this time lag, the model based on 2% growth per year gives a reasonable prediction of population for the next thirty years. (We assume there will be no world war, great epidemic, or

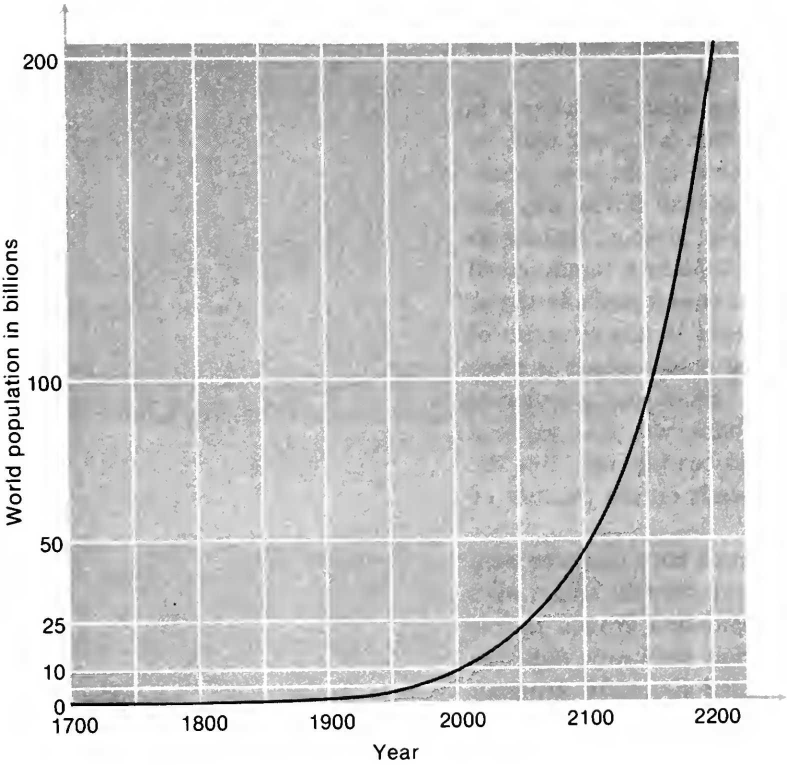

Fig. 4–20. The growth of world population from 1700 to 2165.

mass starvation.) In this section, we want to look in more detail at models which have such a constant growth rate.

A Plot with Constant Growth Rate

A signal (or a quantity such as population) with a constant growth rate is called an *exponential.* This simply means that the *percentage change* in each year (or hour or second) is the same. Each year the population increases by 2%.

When we try to plot population, we run into the problem shown in Fig. 4–20. A plot which shows what is beginning around the year 2000 is useless before 1800 (where the curve is almost zero on our vertical scale). Also, the curve starts to rise so rapidly after 2100 that it quickly goes off the paper. The trouble is clear. Our vertical scale only allows us to plot values from perhaps 2 billion to 200 billion. Over the years of interest, the population varies over a much wider range than this.

When we have a constant growth rate, we can simplify the plotting if we use a different vertical scale. The population is 3 billion in 1960 and we are interested in the years from 1760 to 2160. How do we plot?

We first take a sheet of paper and mark the years off in the regular way. 1960 is in the middle, and every 50 years are shown from 1760 to 2160. We know the population in 1960 is 3 billion, so the middle of the vertical axis is set at 3.

In the last section we saw that the population doubled every 35 years (with a 2% increase per year). Hence, we have the points

Year	*Population*
1995	6
2030	12
2065	24
2100	48
2135	96

Along the vertical scale, we show a doubling every equal space (Fig. 4–22). In other words, the distance from 3 to 6 is the same as

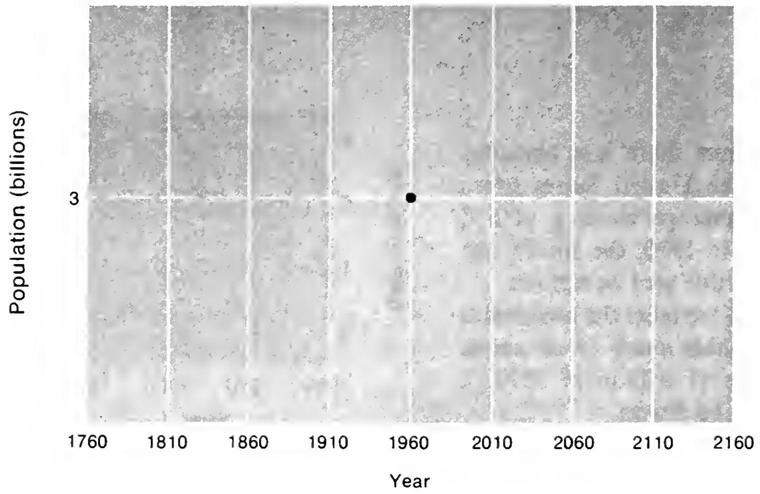

Fig. 4–21. Years marked off for the population plot.

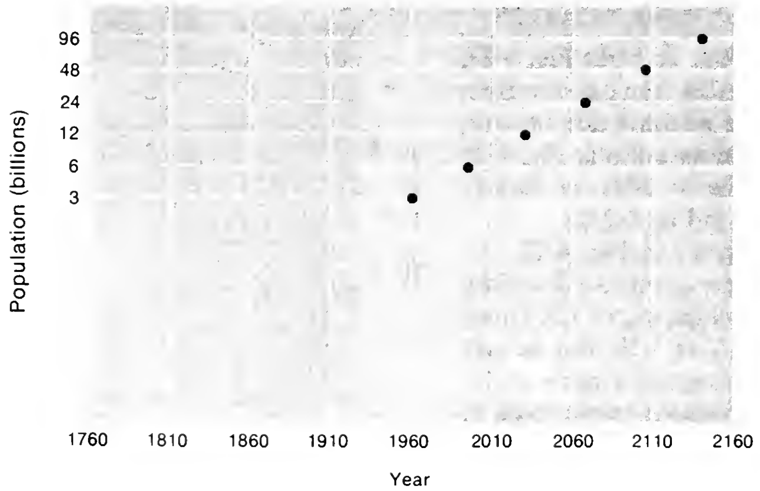

Fig. 4–22. Points into the future shown with an unusual vertical scale.

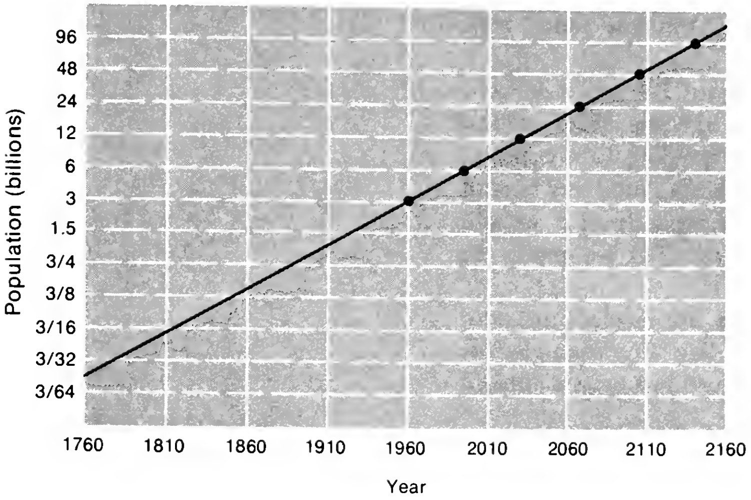

Fig. 4–23. Plot of population growth from 1760 to 2160 with increase of 2% each year.

from 6 to 12. Once the vertical axis is labeled in this "odd" way, we can mark the above points.

The usefulness of this plot is now obvious. *The points are on a straight line.* The population doubles every 35 years. If the vertical axis is marked to show a doubling corresponding to a constant distance up, the curve moves up this same amount every time it moves across by 35 years. This is just the property of a straight line. If we draw the rest of the curve back to 1760, we obtain the complete graph of Fig. 4–23.

Once the horizontal and vertical scales are labeled, we need only two points to determine the straight line. For example, the 1960 population is 3, and the 1995 is 6. We can just draw a straight line through these two points.

An Economic Model

The plot of Fig. 4–23 is useful whenever there is a constant rate of growth. The economic plots of the United States gross national product, for instance, show an average increase of 5% each year. If the total is 1 trillion dollars in 1970, the future can be predicted from Fig. 4–24. We construct this plot as follows.

The years of interest are 1960 to 1990, so we label the horizontal axis. The 5% rise each year means we double every $\frac{7.2}{5}$ or about every 14 years. We now have two points (1 trillion in 1970, 2 trillion in 1984). The straight line can then be drawn.

The graph shows that in 1990 the gross national product will be almost 3 trillion dollars. Since the United States population in 1990 is expected to be about 300 million, the average per person income should be 3 trillion 300 million or $10,000. (In 1970 it was about $5,000.)

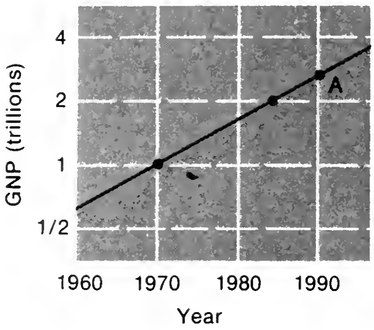

Fig. 4–24. Expected gross national product of the United States.

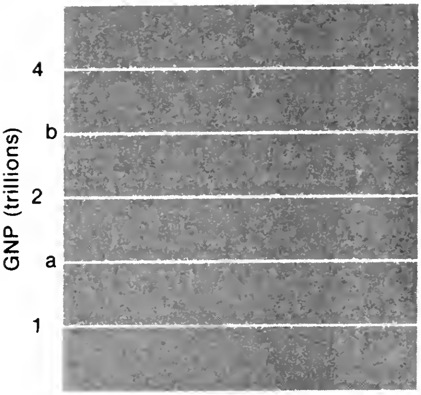

Fig. 4–25. Vertical scale for an exponential plot (a *is 1.4*, b *is 2.8*).

One word of caution should be given here. To make Fig. 4–24, we have used an odd vertical scale (Fig. 4–25). The distance from 1 to 2 is the same as from 2 to 4. Each time we move this distance, the quantity being measured doubles. When we asked in Fig. 4–24 what the gross national product would be in 1990, we had to estimate a value between 2 and 4 (point A in Fig. 4–24).

To make this estimate, we must recognize in Fig. 4–25 that if *a* is halfway from 1 to 2, *a* does not correspond to 1.5 trillion.

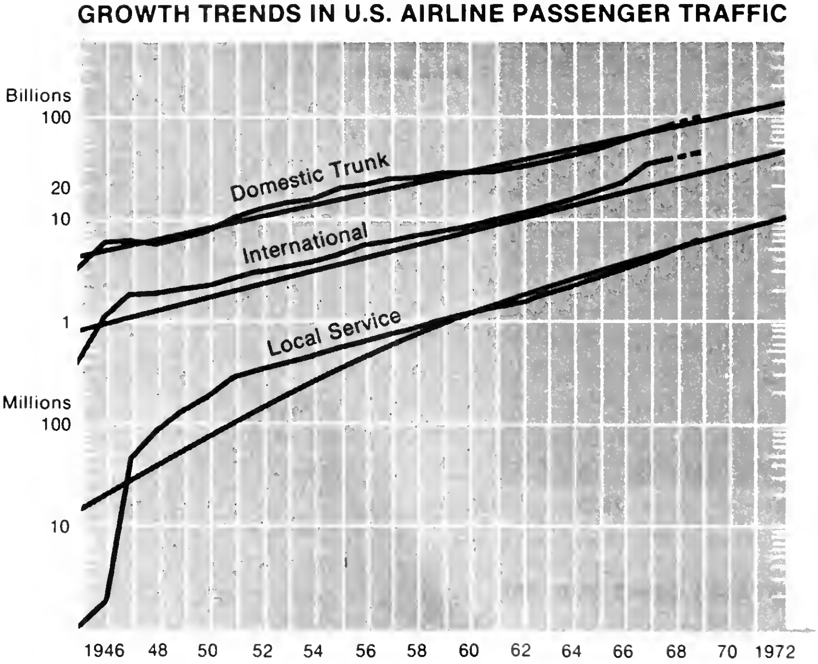

Fig. 4–26. Another example of a plot of exponential growth. The way in which the actual data follow the straight lines promises that the changes in the next few years can be predicted with reasonable confidence.

These particular curves are used by airport planners, airlines, travel agencies government agencies, and companies building equipment for the air-travel industry.

The straight line for international travel shows that the travel doubles every 5 years (1962 to 1967). Thus, the annual increase is 72/5 or 14%. (Aviation Week and Space Technology)

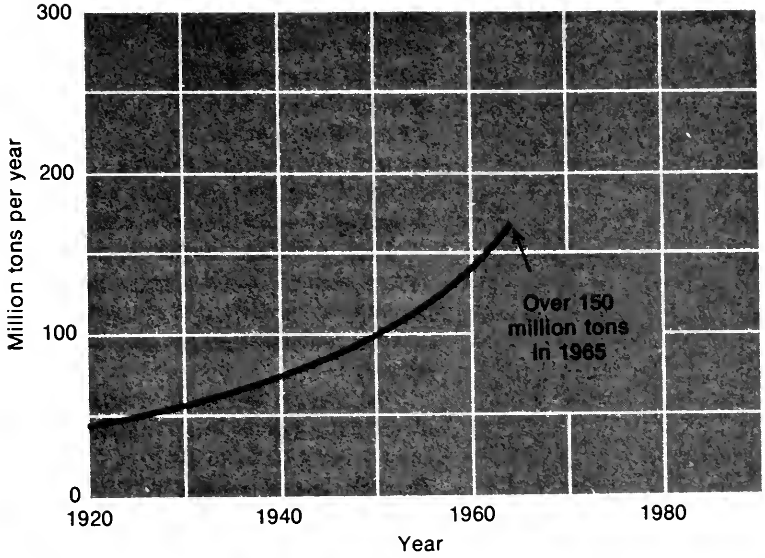

Fig. 4-27. United States solid waste.

If it did, going from 1 to a would mean multiplying by 1.5. Going from a to 2 would mean multiplying by $\frac{2}{1.5}$ or 1.33. But we said equal distances on the vertical scale correspond to equal multiplying factors. If this is to be true, the point a corresponds to $\sqrt{2}$ trillions, or 1.4 trillions; b midway between 2 and 4 is $2\sqrt{2}$ trillions or 2.8 (not 3).

The Solid-Waste Problem

If the United States is considered as one vast system (containing as elements the manufacturing plants, the transportation vehicles, the people, and the natural and man-made devices), one of the important signals which can be measured is the solid waste. Such solid-waste material includes all the material which we throw away: the 6 million cars which are scrapped every year, the appliances discarded, the refuse from construction and demolition of buildings, and the garbage. Our highly advanced technology and the associated high standard of living lead to a national problem of increasingly serious magnitude. How can we dispose of this solid waste economically and without dangerously fouling the environment? If we take a longer range viewpoint, how can we recycle this trash? In other words, how can we conserve our natural resources by using again the materials we are throwing away?

The magnitude of the problem is vividly portrayed in Fig. 4-27,* which shows the quantity of solid waste produced per year

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* Figures 4-27 and 4-28 are taken from the report, "A Strategy for a Livable Environment," published for the U.S. Department of Health, Education, and Welfare, June, 1967.

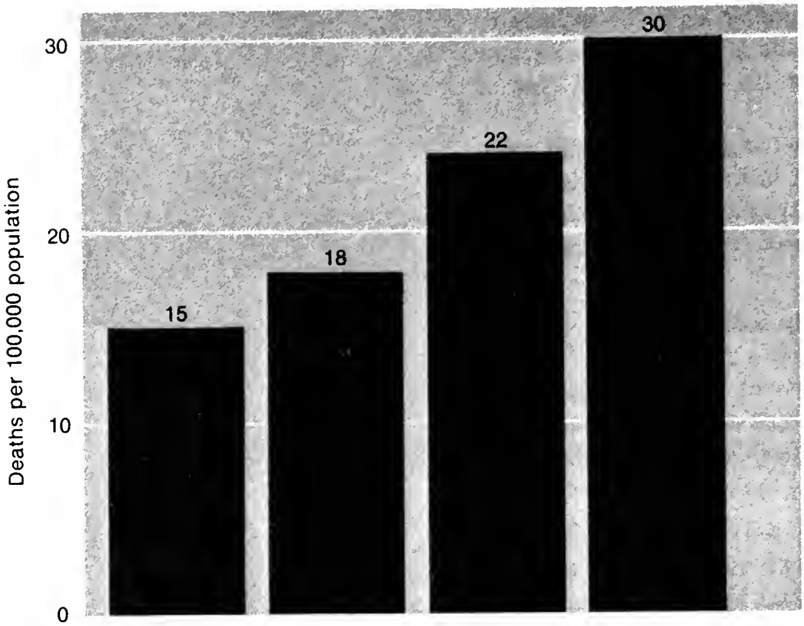


Fig. 4–28.
Annual deaths from lung cancer per 100,000 population as a function of the size of the community in which the people live.

in the United States since 1920. The significance of this particular signal is perhaps clearer if we note that in 1965 nearly five pounds were produced each day for each person in the country. Furthermore, the rate of increase is appreciably greater than the rate of population increase. (Indeed, the United States is by far the most efficient producer of rubbish in the history of civilization. With less than 10% of the world's population, we generate well over half of its rubbish.)

The importance and urgency of the problem derive from two principal factors:

1. In most cities, available land for dumps is being rapidly exhausted. At the same time, the nature of the solid waste is changing. A few decades ago, the rubbish was primarily garbage and ashes. Today it includes vast quantities of metals, plastics (e.g., non-returnable containers), and other new products, many of which cannot be economically burned without contributing to air pollution.
2. We know very little about the effects of environmental pollution on our physical and mental health. To what extent are polluted air or mounds of junked automobiles responsible for the increases observed in mental illness, in urban unrest, and in such physical illnesses as lung cancer? Even data such as shown in Fig. 4–28 are not easily interpreted. Individuals living in the city may smoke more heavily, may lead lives under greater nervous tension, and so forth. The problem of evaluating the importance of

> environmental pollution is further complicated by the realization that major effects on the balances of nature and the characteristics of man are unlikely to become evident for a generation or more, when it may well be too late to reverse the established trends. (The problem of the time lag enters again.)

Whether we are worried about a single city or a whole region, the intelligent planning of new methods for disposing of waste requires that we predict how much waste will be produced in the future. For example, if we decide to build a new incinerator to burn the rubbish, six years may be required until the incinerator is operating. Thus, if a decision is made in 1970, the incinerator which is built should be designed for the quantity and type of rubbish which will appear after 1976.

In this discussion, we consider only the quantity of solid waste produced. Figure 4–27 shows the past history of the system over the years 1920 to 1965. We wish to use the data to predict the signal at least a few years in advance. This need for prediction arises for two reasons:

1. Data are usually available only some time after they are valid (in problems of this broad a nature, a year or two may be required). Thus, the curve of Fig. 4–27 runs only to 1965, even though it was published nearly two years later.
2. Design and construction of the facility require several years, so that the system is truly being built for the future.

Before we try to use the data of Fig. 4–27 to predict solid waste in the future, we notice that the quantity is increasing at a constant rate. Every 12 years, the amount increases by 50%. This is exactly the property of an exponential. Consequently, we can change the plot of Fig. 4–27 to the exponential form.

In 1950, there are 100 million tons generated. In 1962, the figure is 150 million tons. We label the time axis from 1920 to 2000. The vertical axis includes 100, and then successive lines 1.5 times as much (Fig. 4–30).

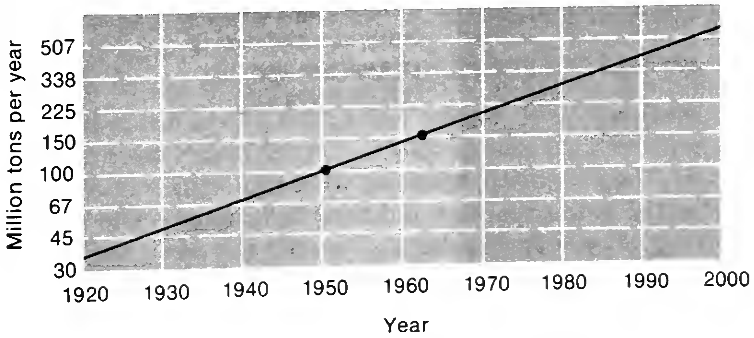


Fig. 4–30. Solid waste generated with vertical scale chosen to show 50% every 12 years.

Once the straight line is drawn, we can predict the quantity probably generated at any future date. For example, by the year 2000 we can expect almost 500 million tons per year. With 300 million people, this is about 1.6 tons or 3200 pounds per person per year. (Almost 10 pounds a day!)

One proposal has been to build an artificial mountain of rubbish from New Jersey to California. When it is completed, it could be covered with grass and landscaped so it would provide a recreation area for future generations. The proposal does not suggest how to compensate the people who happen to live nearby and have to watch it grow.

More attractive proposals are to raise the cost of goods so that the manufacturer has to reclaim them. Automobiles are a prime target. In 1969, more than 50,000 cars were simply abandoned on the streets of New York City. Any person driving through the United States soon encounters automobile junk yards steadily growing in size and ugliness.

The Exponential As a Planning Device

In this section, we have seen that exponentials can be plotted as straight lines if the vertical scale is marked as follows. Each unit distance up corresponds to multiplying the quantity by the same factor.

Because exponentials occur so often, this form of plot is particularly important. In using such plots for prediction of the future, it is important to recognize that we usually do not need great accuracy. Whether the solid waste generated in the United States in the year 2000 is 500 million tons or 450 million tons is not very important. Regardless of what the number will actually be, we need to start planning immediately if we are not to be swamped by rubbish. Either we have to stop its growth or we must find better ways to recycle it or dispose of it.

This type of prediction is called *extrapolation*. We extrapolate (or extend) what has happened in the past into the future. We assume that the growth rate will not change. We should recognize that such extrapolation is not necessarily valid. New changes may occur in our way of living which may increase or decrease the rate of population growth or solid-waste generation. (See Box 4–1.)

7 | AN IMPROVED POPULATION MODEL

Obviously the population model with 2% growth is incorrect, at least after some time in the future. Quite clearly there are some limiting factors which prevent such a population increase. Actually our model is too simple because we did not take into account several important factors that tend to limit our predictions.

To learn more about these factors, it is helpful to examine functional models of the world population. Such models are easy

Box 4–1

EQUATIONS FOR EXPONENTIALS

For those who like to live by mathematics, we can write an equation for an exponential growth curve. The solid-waste generation data are used as an example.

The general equation for an exponential is

$$y = A\, r^{t/T}$$

Here y is the quantity we are measuring (the solid waste generated per year in millions of tons). r is the factor by which y is multiplied in T years. In our case, r is 1.5 and T is 12 years. t is the time (in years) measured from any reference point. If we select the 100 value in 1950 as the reference, t is measured from 1950. (Thus, a t of 7 represents 1957, a t of -21 represents 1929.) Finally, A is the quantity at the time t is zero. (In our case, A is 100 since that is the solid waste in 1950.)

Thus, the equation for United States solid-waste generation is

$$y = 100\,(1.5)^{t/12}$$

where t is measured from 1950. In 1998, t is 48 and

$$y = 100\,(1.5)^4 = 506$$

The equation predicts 506 million tons generated in 1998.

The equation gives exactly the same information as our straight-line graph.

to find in a biology laboratory. Any small organism that reproduces rapidly will do. Fruit flies, yeast, and bacteria are commonly used examples. Here we describe a population model using yeast. First the experimenter must prepare a food supply, a "nutrient medium." For many yeast species, this may be simply a weak sugar syrup slightly modified by addition of other substances. Then there is need for a jar in which to keep the yeast as they gorge themselves, and for Adam and Eve, so to speak: the syrup must be inoculated with a few yeast cells to start with. The temperature should be kept constant, and the medium should be gently but constantly stirred.

It is hardly possible to take a census of yeast cells as one does of people. Instead, a sampling technique is used. Knowing the starting volume of his experiment, the investigator can withdraw a definite, very small percentage of it and count the yeast cells in that. Since the solution of food has been stirred, he can safely assume that his sample is typical, and that he can simply multiply by the proper factor to learn the total population. Such models as this one are particularly convenient because they take up very little

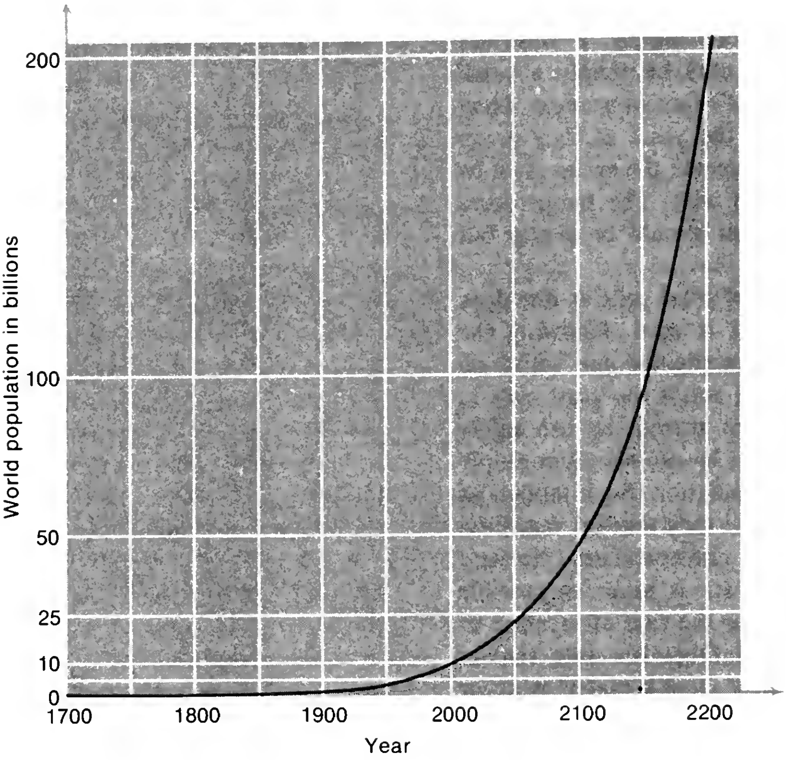


Fig. 4–32. Exponential growth curve.

space; moreover, it is easy to try different circumstances ("to vary the parameters" as the professional puts it). It becomes possible to answer such questions as these: What is the rate of increase of population when the experiment begins? Does this rate remain constant as the population becomes larger? Does it matter whether the available space for the organisms remains constant or is made to increase as the population grows? Yeast cells produce an alcohol (there are many kinds of alcohol) from the sugar they consume; what is the effect of leaving the alcohol to accumulate in the nutrient medium? Of removing all but a constant fraction? Of removing all of it as it forms? (Removal can be rather easily accomplished by continually pumping fresh nutrient medium in and at the same time allowing the used medium to trickle out through a filter.)

Which of these possible experiments cast light on our graphical model of world population? First, we know that the entire land surface of the earth is not inhabited but that it is not unlimited. (There is room for population to increase but the space will be used up someday.) This is modeled in the yeast case by using bigger jars (and more medium) up to a certain point, but then no more. Second, we know that food production can be increased for human beings but not without limit. We can supply more sugar to the yeast on a schedule that we think is comparable to the future history of the world; even better, we can try many schedules. In short, we can test our model and thus refine it, by comparing it with what we already know about the course of development of the human population.

Now it turns out that such experiments as those described are practically always alike in one feature. Growth is roughly exponential at first; the *rate* of increase is not necessarily constant, but the population curve is closely similar to that of Fig. 4–32. If the experiment lasts long enough, however, the rate of growth sooner or later begins to decrease and in time reaches zero. The curve stops its exponential growth and tends to level out, as suggested in Fig. 4–33. Because this curve has a kind of S-shape, it is known as a *sigmoid* (from the Greek word *sigma* for the letter S).

The basic reason for the change of shape shown is overcrowding. Without unlimited space in which to grow and unlimited food to support life, the individual yeast cell has neither room nor food to allow it to reach normal size. No doubt there are other reasons, but they are less important.

In the case of small animals and insects tested in a laboratory or carefully controlled environment, the same leveling off of population has been observed. The rate of growth tends to decrease as the animals become badly overcrowded because of both physical and mental deterioration resulting from inadequate supplies of food, air, and water, excessive nervous tension associated with inability to move freely, and so forth. In actual experiments with rats, once severe overcrowding occurs, mothers reject their young, adults kill females, and reproduction falls rapidly. Whether such experiments have any meaning for human beings is not at all clear.

Certainly nature ultimately limits population growth, although typically with a serious deterioration of the species as suggested in the preceding paragraph. One would assume that man will limit his population growth significantly before serious damage has been done to his general physical and mental condition. Indeed, the

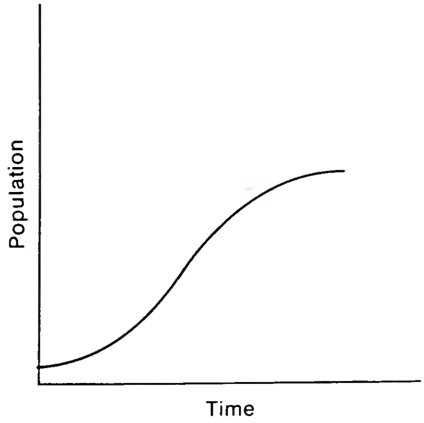


Fig. 4–33. Population growth in laboratory studies.

focus of the recent worldwide emphasis on population control is to limit the population to levels at which adequate food resources and land are available to ensure happy and healthy individuals.

Perhaps the first man to recognize the sigmoid character of population growth (although he did not express it in this way) was Thomas Robert Malthus (1766–1834). He was an Englishman who wrote a gloomy essay pointing out that a time must come when population will outrun food. Then the growth of population would be stopped, he believed, by widespread epidemics, or starvation, or war, or some combination of these. Instead of a truly sigmoid curve, however, his curve would probably actually turn downward. He predicted that the end of the growth period would come during the nineteenth century. That it did not was the result of the discovery of chemical fertilizers. With these an acre of ground brings forth several times as much food as was possible in Malthus' day. We can see, however, that some limit, at some time, must be reached in the number of pounds of food that can be won from an acre of ground or of sea. The supplies of potash and phosphate easily recovered must someday disappear, so the cost of fertilizers must rise. The third major fertilizer element, nitrogen, is available without foreseeable limit from the air. The current research in development of food from the sea promises to provide the possibility of feeding adequately a great number of people, but not an unlimited number.

A Model with Decreasing Growth

Even if we agree that the population model of the preceding section (with 2% annual growth rate) is impossible, we can still use this exponential growth curve to predict moderately into the future. The sigmoid characteristic of Fig. 4–33 does behave as an exponential in the early portion. Recent population data indicate that we are indeed still in this part of the curve.

If we desire to peer further into the future, we need a model which shows the eventual slowing of growth. To obtain such a model, we need to assume that the growth rate will eventually decrease as the population increases.

In the population model, we worked with a growth rate of 2% a year. The population in any year is 1.02 times the population a year earlier. In a stable situation, with the population constant, the value in any year is just 1.00 times the value the preceding year.

Thus, to obtain a sigmoid curve, we need to reduce the 1.02 to 1.00 as the population increases. Exactly how do we put in this change? When does the factor change from 1.02 to 1.01, for example? Then when from 1.01 to 1.00? Where will the population start to level off?

Obviously, we can only guess. Today we are still in the region of exponential increase. This growth will eventually be slowed, but we do not know what factors will cause the leveling off.

Box 4–2

MATHEMATICS OF A SIGMOID MODEL

The man who relishes mathematical language can derive a model for the sigmoid characteristic as follows.

Exponential growth In the exponential case, the population in any year is a constant (1.02 in our case) times the value a year earlier. If P_{n+1} is the population in the year $(n + 1)$, P_n in the year (n), then

$$P_{n+1} = r\ P_n$$

Thus, if P_{1960} is 3 billion and r is 1.02,

$$P_{1961} = 1.02 \times 3 = 3.06 \text{ billion}$$

Sigmoid behavior To obtain the leveling off, the factor r must decrease as population increases. This change occurs if we choose

$$r = r_0 - c\ P_n$$

r_0 is 1.02. This value is reduced by $c\ P_n$ where c is a constant. As the population P_n increases, the r decreases. Then

$$P_{n+1} = (r_0 - c\ P_n)P_n$$

Example If r_0 is 1.029 and c is 0.003, and we measure population in billions, we obtain

$$r_0 - c\ P_n = 1.029 - 0.003 \times 3 = 1.02$$

when the population is 3 billion. That is, in 1960 the growth rate is 2%.

As P_n increases, the factor $(r_0 - c\ P_n)$ decreases steadily. This factor becomes one when

$$1.029 - 0.003 \times P_n = 1$$

or

$$P_n = 9.7 \text{ billion}$$

According to this model the population levels off at 9.7 billion. This value depends critically on what we choose for the constant c, which represents the rate at which the growth decreases. Since we do not know what factors will limit population, we really can only guess at c.

The particular population model of this section is not especially important; indeed, major political or social changes may make our predictions of future world population look ridiculous to the historians of the year 2000. Our purpose in this section, however, is to introduce the idea of model refinement. We discovered that our 2% model is ridiculous if we try to predict hundreds of years into the future. On the basis of our rather superficial understanding of population growth, we then found an alternative model which at best has the property of leading to a limited ultimate population. (See Box 4–2.) Since we know we cannot predict population accurately too far into the future, our simple models are probably as good as much more complicated ones.

8 | USES OF MODELS

Predictive population models are often used with great success in governmental planning at all levels—town, state, and federal. For example, the design of a transportation system for a region requires that we have reasonably reliable predictions of population distribution in order to assess future transportation needs (for transporting people and the materials which people require).

In such a problem, the complete system model includes population models for hundreds or thousands of separate towns. The complete model is often a mathematical model composed of many equations. Some of these are similar to the equations we have used and some are more complicated. Not only must birth and death rates (net growth) be considered, but the relationships among other factors must be included. There are also influences which make the populations of towns interdependent. If one town becomes unduly crowded, there is a strong tendency for neighboring towns to grow more rapidly. Immigration and emigration rates thus are important considerations for the development of an accurate dynamic model: a model in which the interrelationship of factors changes with time.

Many Models for One System

It is possible for one system to be represented by a number of different models. As in the case of the blind men and the elephant, no one model describes the real thing completely, but separate models of sub-systems are often necessary and useful.

An air-conditioner provides an example of this characteristic. One model can be developed which is based on heat flow: how heat is extracted from a room, how the fluid in the unit changes its temperature as it absorbs heat, and how this heat is then transferred outside of the room. This model must include such factors as expected temperature ranges, characteristics of the refrigeration unit and blower, and intake and outlet duct air flows.

Another model to describe the same system might be a control model which includes the thermostat, the various relays and contacts, and the electrical network which links the electrical parts of the system.

Yet another model of an air-conditioner could be developed for a study of its mechanical behavior. For example, we may wish to know how much noise and vibration the equipment will produce and how to design the air-conditioner to minimize the noise and vibration. For this objective the model would include a number of

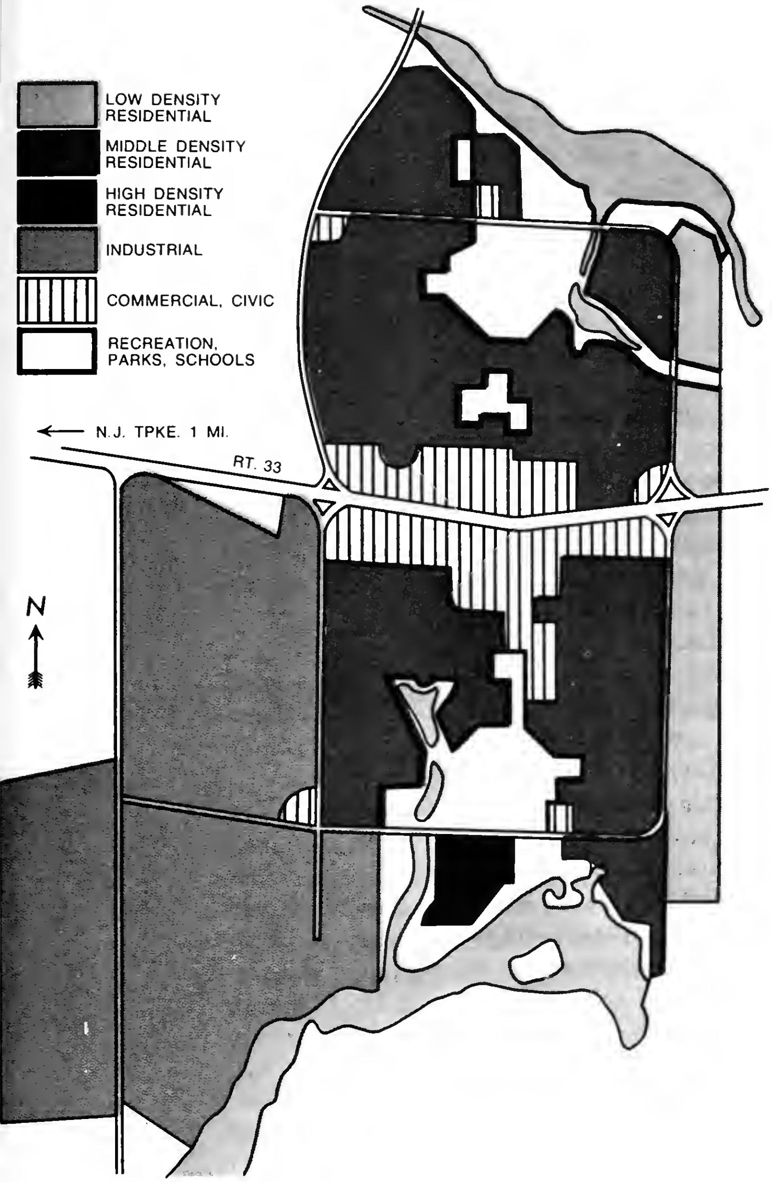


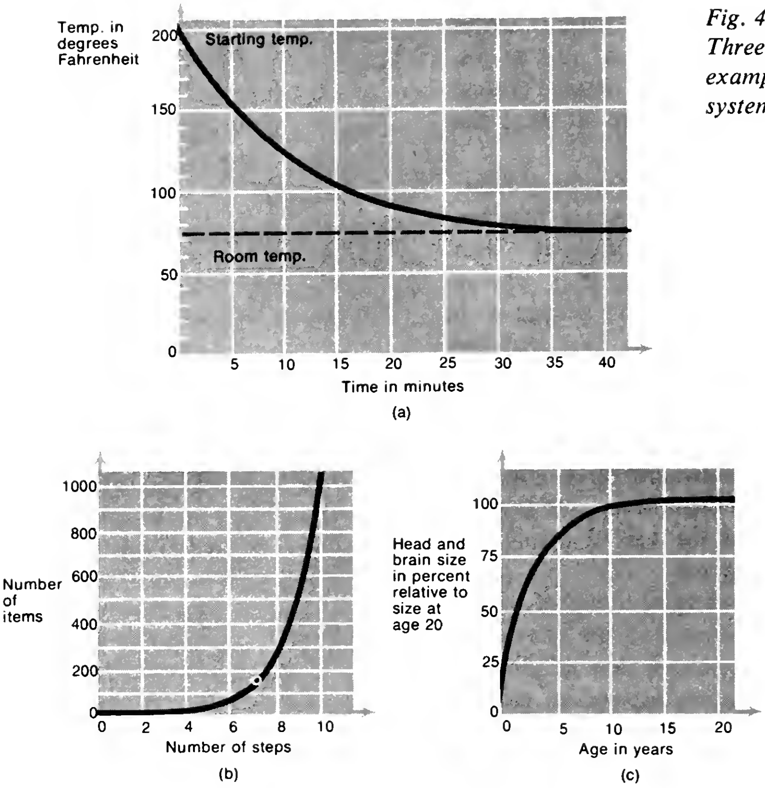
Fig. 4–34.
An initial model for the planning of a new town—in this case Twin Rivers, New Jersey, with a planned population of 10,000.

This first model shows the general planning to include the land uses and the highways and lakes. (The two irregular areas are lakes.) Once this overall model is adopted, each section can be planned in detail. When the town is designed in this way, schools, parks, and shopping areas can be located within walking distances of most residential areas. Streets can be planned to avoid too many pedestrian crossings. The goal is to create a town which avoids many of the annoyances and difficulties of existing towns which have grown without overall planning. (© 1970 by The New York Times Company. Reprinted by Permission)

factors such as the characteristics of the moving parts, their mountings, the location of shock absorbers, and the geometrical arrangements of the openings, the absorbent surfaces, and the baffles.

One Model for Many Systems

What is there in common among the way in which a cup of coffee cools, the way in which the numbers of chain letters increase, and the way in which a human head grows? Just as it is possible



(a)

(b)

(c)

Fig. 4–35. Three examples of exponential systems.

for one system to be described by several different models, so one model frequently is applicable to many kinds of systems. In Fig. 4–35 there are models of three different processes which one would not ordinarily think of as being similar. In (a) is shown how the temperature of a cup of coffee drops as the coffee cools to room temperature. The initial temperature is just below the boiling point. It drops rapidly at the start, then more and more slowly. After a half hour, the temperature of the coffee has dropped to within a few degrees of room temperature.

The illustration in (b) describes a system in which the production of an item doubles at each step. During the early part of the curve the values are not readily observed because of the scale of the graph axis, but as the number of steps goes from 1 to 2 to 3 to 4, the number of items increases from 2 to 4 to 8 to 16. The increases become larger with each step; for instance in going from 9 to 10 steps the number of items doubles from 512 to 1024. This is a model for the chain-letter process, where an individual writes to two people, each of these writes to two others, and so on. After 20 steps in such a process the number of letters (items) being written is more than one million, and after 30 steps the number becomes greater than one billion.

This rapid growth of an exponential is the basis for the familiar story of the golf game between Mike and Dick. On the first tee, Mike suggested they play for a penny on the first hole and then double the bet each hole. By the eighteenth hole, Dick was so nervous he missed his drive completely, while Mike played with total relaxation. It was only after the match was over that the mathematically slow Mike realized that the bet on the last hole was more than $1300.

Figure 4–35c shows how the size of a human head grows from birth to age twenty. At birth it is a little less than $\frac{1}{4}$ its full size, and it is growing very rapidly. At the age of five the growth begins to slow down appreciably, and at the age of fifteen the head is within a few percent of its ultimate size.

We can see what is common to the cooling of a cup of coffee, the rate of increase in a chain-letter situation, and the growth of the human head. Each displays an exponential rate of change. In each of the processes, as in the population expansion, growth either increases or decreases exponentially.

Our exponential curve thus fits many systems. Such things as the rate at which an automobile coasts to a stop, the growth of plants, and the accumulation of bank interest can also be represented approximately by an exponential curve. All these examples show that one model may represent many different systems.

Another remarkable aspect of modeling is how often we can find mathematical relationships among important quantities. As a final example, violent storms are of four general types: tornadoes, thunderstorms, hurricanes, and cyclones. There is a relationship between the size of the storm and its duration: the larger the storm, the longer it lasts. Indeed, if we call D the diameter of the storm in miles and T the duration in hours, the model is given by the equation:

$$D^3 = 216\ T^2$$

Once we have found such a model from observation of many storms, we can answer such questions as:

> How long does a cyclone with a diameter of 600 miles last?
> How large is a thunderstorm which lasts one hour?
> If a hurricane has a diameter of 100 miles, what would be the anticipated duration in days?
> A tornado lasts 11.5 minutes; what is the expected size?

The answers are 1000 hours, 6 miles, 2.8 days, and 2 miles.

Such a model is only approximate. Any given storm may deviate from our equation just as any particular seventeen-year-old boy may be 5 feet 2 inches tall and weigh 300 pounds. In spite of such occasional deviations, however, the model yields a picture of typical average relationships among physical quantities.

Determination of Models

Once an idea of the structure and nature of a thing is conceived, it may be expressed in many different ways. We may have different models. Some, as we have seen, are verbal models. A map is a model, a graphical model. Other models are mathematical in which quantitative expressions are used to describe relationships in a precise way. Some models are developed using computers.

An aircraft represents so complicated an aerodynamic problem that a complete mathematical description may be impossible. Therefore, it is usually modeled by constructing a small-scale version of metal or wood for testing in a wind tunnel.

Models are used, not only to describe a set of ideas, but also to evaluate and to predict the behavior of systems before they are built. This procedure can save enormous amounts of time and money. It can avoid expensive failures and permit the best design to be found without the need for construction of many versions of the real thing. Models evolve, and it is customary to go through a process of making successive refinements to find a more suitable model.

For example, in the development of a model for a nerve cell, there is need for successive refinement. A preliminary model is designed, it is tested against the real nerve cell, then the model is modified so that it becomes more realistic in its behavior. In the process of model construction it is essential to alternate back and forth between the real world and the model.

The essential parts of the model-making process are shown in Fig. 4–36. Measurements or observations of the real world are used to develop a model. After a preliminary model is made, measurements made using the model are compared to the behavior of the real world. In most cases these tests show that the model is not completely satisfactory, so that it must be refined. This process is repeated until the model is acceptable.

In the modeling of a nerve cell, or the modeling of the growth of a population of people, the real-world measurements are made on a system which already exists. In this case our model-making process is intended to produce a model which accurately matches

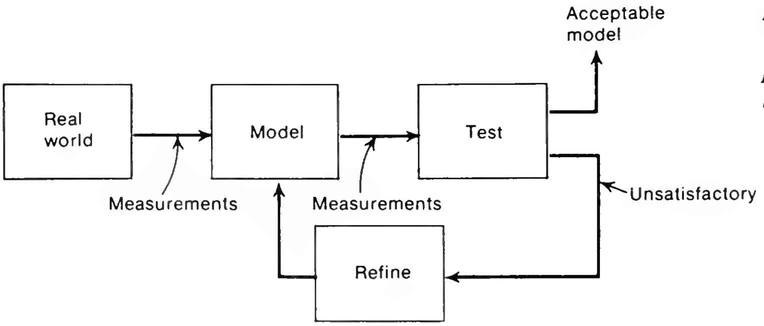


Fig. 4–36.
The model-making process, shown as a block diagram.

the real world. In the case where scale-model airplanes or spacecraft are modeled, the real-world object may not yet exist, and the box marked "Real World" in Fig. 4-36 theoretically contains the real object which we imagine and wish to achieve, as well as all pertinent facts about the real world (such as the properties of air, characteristics of flight systems which have already been built, and the characteristics of various materials and fuels). The model-building procedures are no different from those already discussed.

Models can be *descriptive*, as in verbal, graphical, or mathematical representations. They can also be *functional* (they "really work"), as in scaled-down airplanes for use in wind tunnels or working replicas of nerve cells. The model includes only those parts of the system which are important for our purposes. The model guides our thinking and suggests how we can improve the system.

Questions for Study and Discussion

1. "No model is ever complete." Would it be helpful if one could in fact construct a complete model? Explain briefly.
2. Discuss the differences between
   a) functional and descriptive models.
   b) dynamic and static models.
   Give an example of each.
3. Suggest two reasons why a mathematical model may be desirable.
4. When a model is first designed, what is the next step which should be taken with it?
5. Figure 4-3 shows the height-weight data for twenty-year-old men as a somewhat scattered cloud of points. Explain why it is reasonable and useful to draw a *particular* straight line through these points.
6. The greatest height shown by the graph line of Fig. 4-4 is about 6′5″. Would you be justified in using the graph line to predict the weight of a candidate for center on the basketball team if he is 6′10″ tall? Why, or why not?
7. From the equation for the relationship between weight and height of twenty-year-old men, find the expected height of a young man who weighs 145 lbs.
8. A forester might use a method similar to that of Section 2 to study the relationship between the height of a tree and the diameter of its trunk. It was pointed out that the height-weight data had been "passed through two strainers (age and sex)." What "strainers" would the forester have to use?
9. How do highway engineers take a traffic count?
10. To use an electric eye as a sensor in a corridor, a beam of light is arranged to shine from one wall (where the light source is) to the other wall (where the electric eye is). Whenever the light beam is interrupted by a person passing, the circuit of the electric eye operates a counter. Why would such a device give an incorrect count in the situation shown in Fig. 4-8? Can you think of a way to make it count correctly?
11. The text discussion on the uncontrolled harvesting of buffalo is but one example of how man has willfully brought a species of animal to the point of extinction. Describe five other examples of how man has either willfully or unwittingly produced this effect.
12. The movements of the elk pictured in Fig. 4-14 are monitored from a satellite. Describe how this is done and explain what elements of the life habits of an animal can be learned in this way.

13. In the text, several factors which affect the growth rate of a town are listed: birth rate, death rate, nearness of other crowded towns, transportation system. Suggest five other factors which might influence the growth rate of a town. In each case, explain briefly why the factor would be likely to increase or to decrease the growth rate.

14. We have seen that it is possible for one system to have a number of different models which apply to it. Many times an engineer finds it necessary to have models of sub-systems. Suggest three models which could be used to describe a submarine.

15. The poem on the blind men is:

THE BLIND MEN AND THE ELEPHANT

It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.

The First approached the Elephant,
And happening to fall
Against his broad and sturdy side,
At once began to bawl:
"God bless me! but the Elephant
Is very like a wall!"

The Second, feeling of the tusk,
Cried, "Ho! what have we here
So very round and smooth and sharp?
To me 'tis mighty clear
This wonder of an Elephant
Is very like a spear!"

The Third approached the animal,
And happening to take
The squirming trunk within his hands,
Thus boldly up and spake:
"I see," quoth he, "the Elephant
Is very like a snake!"

The Fourth reached out an eager hand,
And felt about the knee.
"What most this wondrous beast is like
Is mighty plain," quoth he;
" 'Tis clear enough the Elephant
Is very like a tree!"

The Fifth who chanced to touch the ear,
Said: "E'en the blindest man
Can tell what this resembles most;
Deny the fact who can,
This marvel of an Elephant
Is very like a fan!"

The Sixth no sooner had begun
About the beast to grope,
Than, seizing on the swinging tail
That fell within his scope,
"I see," quoth he, "the Elephant
Is very like a rope!"

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong.
Though each was partly in the right
And all were in the wrong!

John Godfrey Saxe
American Poet 1816–1887

A modern version of the six blind men and the elephant is suggested by the following problem. A printed capital letter of the English alphabet is scanned photoelectrically and the resultant signal is read into a digital computer. Seven subroutines in the digital computer inspect it. The first states that the letter is like a U because it has at least one pocket to hold rain coming from above; the second shows that it is like a K because it has at least one pocket to hold rain from below; the third and fourth find that it is like an A because it has no pockets on right or left; the fifth shows that it is like a V because it has two ends; the sixth shows that it is like an S because it has no junctions; the seventh shows that it is like a D because it has two corners. Combining these models of the letter, determine what it is.

The idea of exponential growth and decay can help you understand many natural events — the expansion of human and animal populations, compound interest, and geological dating are some of the examples treated in this article.

4

Exponential Process in Nature

Donald F. Holcomb and Philip Morrison

A chapter from My Father's Watch: Aspects of the Physical World, 1974

FIGURE 4.1 SHOWS SKETCHES of the population of a rabbit colony at successive times. The time interval between each frame and the next is the same, 6 mo. We are immediately struck by the several features of the population growth of the rabbit colony. The first feature is the legendary ability of the bunny to reproduce himself in copious numbers. The second feature thrusts itself upon us with nearly the same force.

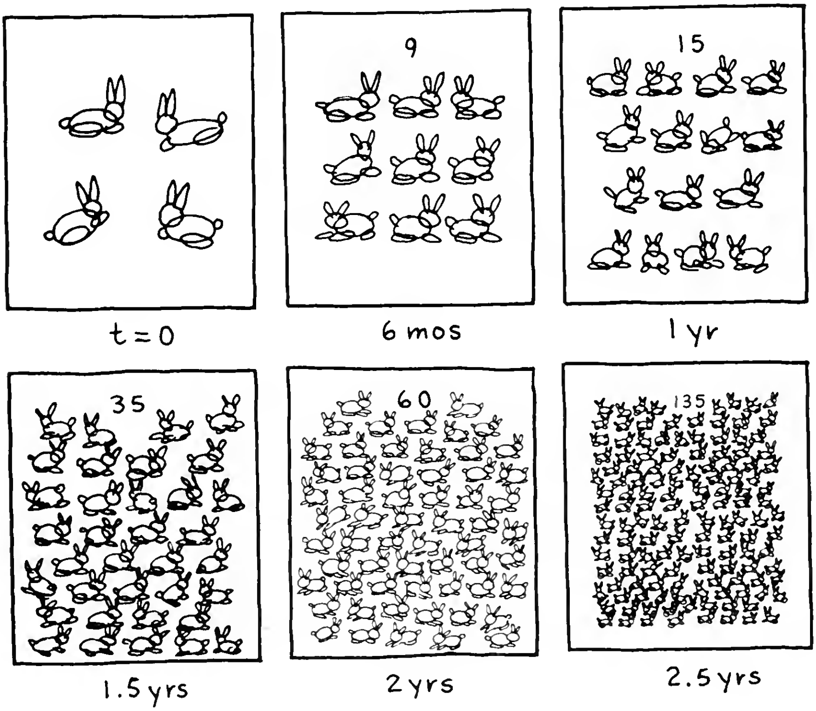


Figure 4.1

Sketches of the inhabitants of an imagined rabbit colony, at the successive times indicated.

It is the related fact that the total number of rabbits seems to be rapidly getting out of control at the later times. Suppose we plot the number of rabbits as a function of time. Figure 4.2 displays such a plot. We see that the number of rabbits is certainly not a linear function of time.

Let us now try to isolate the key feature of the growth of the number of rabbits that tends to produce the "runaway" numbers. Each pair of rabbits will produce some number of offspring. Let us assume that the rabbits are all indistinguishable from one another, so that each pair will produce about the same number of offspring in a given period of time. Suppose that this reproduction rate results in the rabbit population doubling in a time period of 190 days. Since reproduction is a pairwise phenomenon, we shall expect that doubled number of rabbits to double itself again in a second time period of 190 days. Here is the key! We are dealing with a fundamentally multiplicative process rather than an additive process. That is, if the population changes from N to $2N$ in a certain interval of time, we expect it to change to $4N$ in the next equal interval of time, and to $8N$ in the next succeeding interval. If the basic process were additive, the population would change only to $3N$ in that second interval, and to $4N$ in the subsequent one.

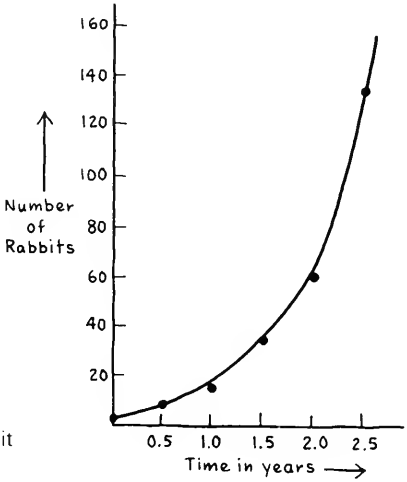


Figure 4.2

A graph of the growth of the rabbit population shown in Fig. 4.1.

A MATHEMATICAL MODEL FOR POPULATION GROWTH

We can now produce a mathematical model that encompasses our analysis of the rabbit problem. What we have said about rabbits in the previous paragraph leads us to realize that the increase of population in a certain time interval is directly proportional to the total population which existed at the beginning of that interval. For the population at the beginning of the interval we use the symbol N. The time interval is labeled Δt, and the population increase in that interval is called ΔN. Then the mathematical statement of our proposition is given by the relation

$$\frac{\Delta N}{\Delta t} \propto N. \tag{4.1}$$

If we choose to write an equation rather than a proportionality, the equation becomes

$$\frac{\Delta N}{\Delta t} = kN \tag{4.2}$$

where k is some proportionality constant.

With our unprepossessing rabbits, we have described an example of what we can call an exponential growth process. An exponential growth process is defined as one which is described by an equation of the type represented by Eq. (4.2). The reason for the choice of the word "exponential" will appear later on, after we follow through a variety of examples and analyses of similar population problems.

Q. Because of concern for exhaustion of the earth's resources, there are those who urge the earth's peoples to plan for ZPG—"zero population growth." If N is the population of the earth, what value of k in Eq. (4.2) will yield ZPG?

Graphing with Logarithmic Scales

But before going to other examples, we want to use the rabbit colony to develop a graphical technique that turns out to be particularly powerful in analyzing these exponential processes. Let us take the data shown in Fig. 4.2 and make another graph. For the vertical axis in our new graph, we shall take the *logarithm* (using base 10) of the number of rabbits rather than the number itself—retaining the time axis unchanged. Figure 4.3 includes the small table of logarithms that we need. These were extracted from numerical tables. The numbers are followed by a graph of these data. We see a remarkable mathematical feature of the rabbit population. Although Fig. 4.2 shows us that the total number of rabbits certainly does not grow linearly with time, Fig. 4.3 shows us

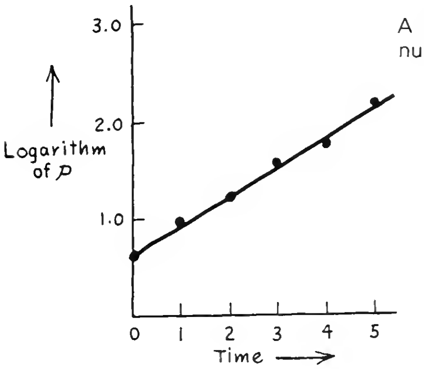


Figure 4.3

A graph of the logarithms of the rabbit numbers of Fig. 4.1, as a function of time.

Population Number	Logarithm
4	0.602
9	0.954
15	1.176
35	1.544
60	1.778
135	2.130

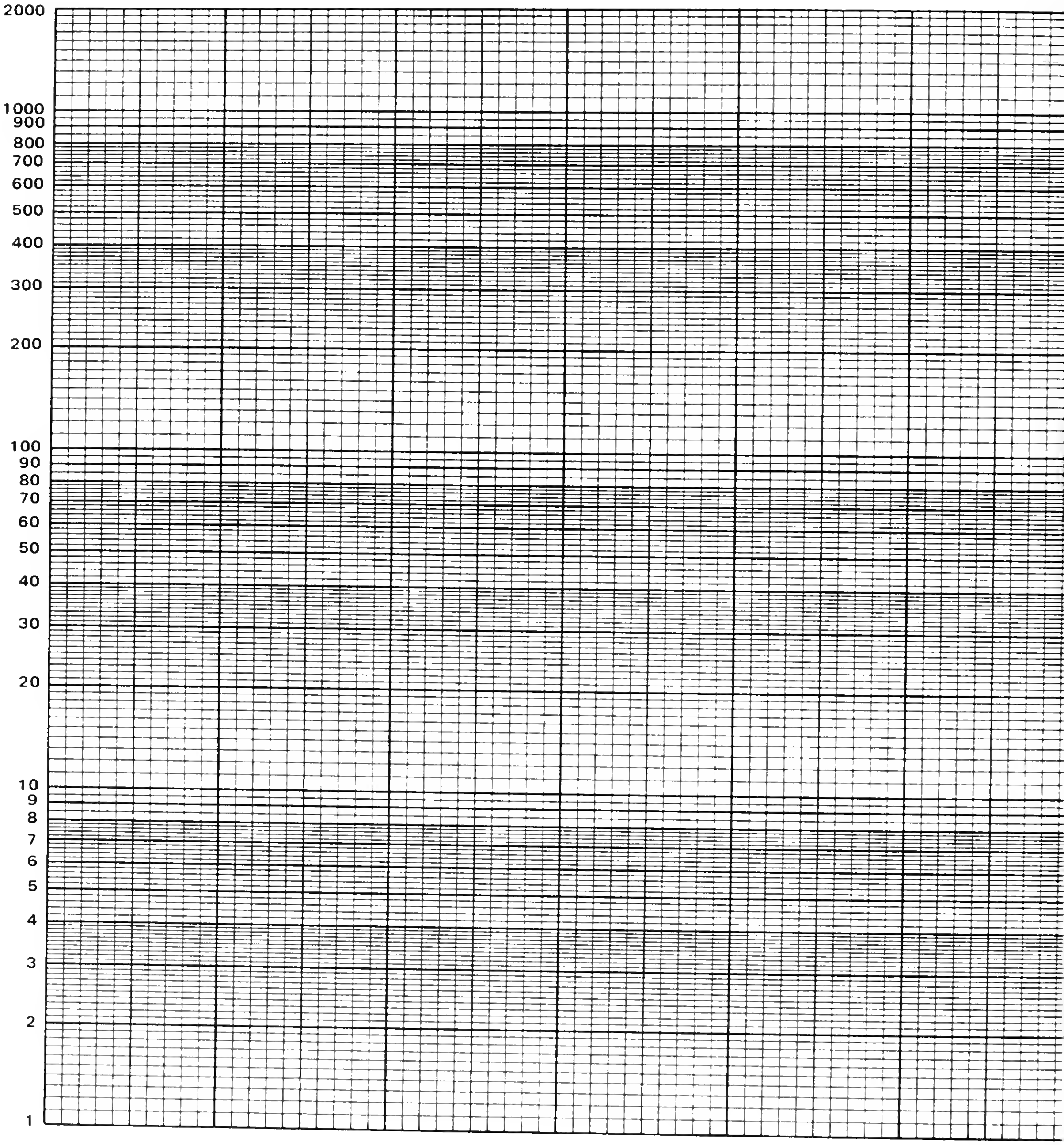


Figure 4.4

A reproduction of a sheet of semi-logarithmic graph paper.

that the *logarithm* of this total number does follow a straight line quite closely. If we think a bit about the character of logarithms, we may not be surprised at the situation. As a number changes from 1 to 10, its logarithm (base 10) changes from 0 to 1. As the number goes on to 100, its logarithm increases to a value of 2. We see that the logarithms of the numbers turn out to be the natural representation of the fundamental property of the rabbit population. The population grows by a fixed *multiplicative* factor in each interval of time so that the logarithm of the population number will grow by a fixed additive factor.

In the box, we write the central feature of the rabbit problem. It is the key organizational principle, which we shall use in the remainder of this chapter.

KEY TO EXPONENTIAL PROCESSES: If the growth or decay of a population over some fixed interval of time or distance is proportional to the population that existed at the beginning of the interval, then the population will follow the exponential growth or decay curve, and the logarithm of the population will increase or decrease linearly with the independent variable, be it time or distance.

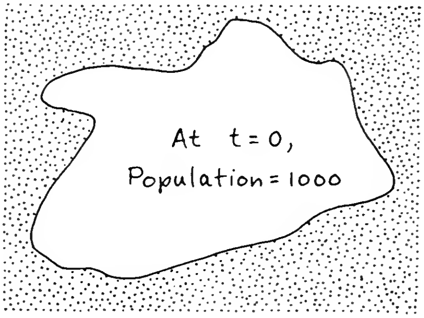
For cases such as the rabbit population, Eq. (4.2) is a compact mathematical statement of the words in the box.

A graph of the sort that we made in Fig. 4.3 is often called a "semilogarithmic plot," so called because one axis of the graph remains a linear plot whereas the other axis uses a logarithmic scale. Use of these plots is sufficiently common that graph paper manufacturers have found it profitable to produce a special paper in which the vertical scale is marked according to the logarithms of the numbers rather than the numbers themselves. Figure 4.4 shows a section of such paper. The key feature of the logarithmic scale is that equal divisions on the scale correspond to multiplication by a certain factor. For the linear scale, we reflect that equal divisions correspond to *addition* of a certain number. Thus, in Fig. 4.4, the horizontal axis uses a linear scale and the vertical axis uses a multiplicative scale. Appendix 4A explores in more depth how the graph paper designer figures out how to place the numbers on the logarithmic scale in Fig. 4.4.

Applications of the Exponential Model to Description of Social and Physical Phenomena

Population

Example 1: Suppose we maroon 1,000 people on an unhealthy desert island. It turns out that there is subsequently a net decrease (births minus deaths is negative) in the population of about 20% each year—i.e., if we start observation at any date, we will find the population decreased by $\frac{1}{5}$ over the next 12 mo from the value it had *at the beginning of that 12-mo period.* Thus, the population data might look like the table shown in Fig. 4.5. Let us graph these data in two ways. In the first plot in Fig. 4.5a, we make a simple graph of population as a function of time, using a linear scale on both axes. In the second plot, Fig. 4.5b, we use a logarithmic scale for the population axis. As we found with the growing rabbit population, a straight line graph results from the use of the logarithmic scale.



Example 2: Suppose the climate on our island becomes suddenly salubrious at year 10, and the population starts to grow at 5% per year. Now the yearly multiple shifts to 1.05, and the curve turns around. Figure 4.5c shows what happens. (Note that the time scale is compressed in comparison to that of Fig. 4.5a and 4.5b.)

In the preceding examples, the key feature that leads to the exponential decay or growth is present. That is, the change in the population in any interval of time is proportional to the value of the population number at the beginning of the interval, and we expect Eq. (4.2) to

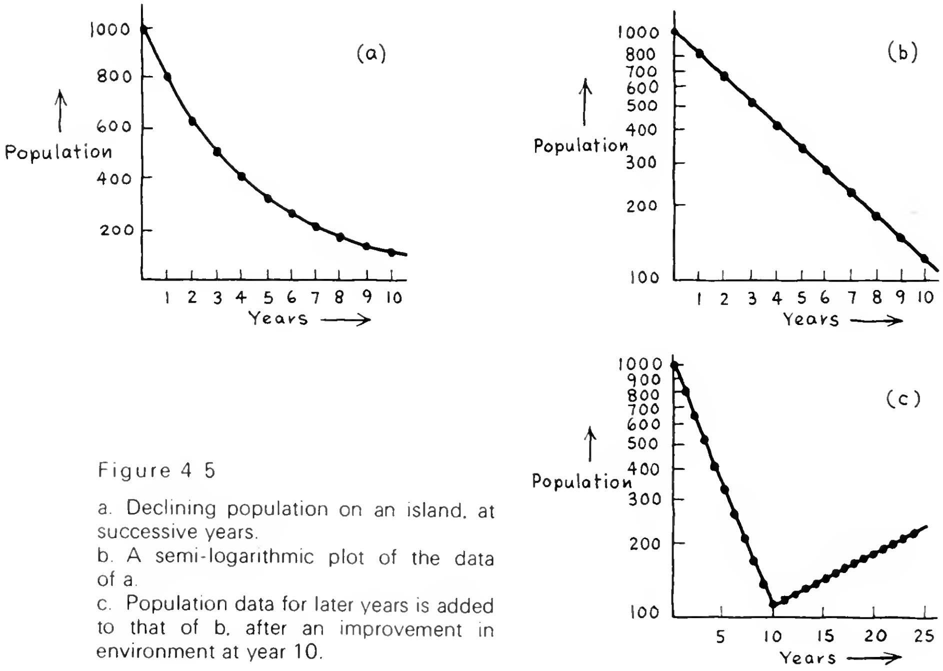


Figure 4 5

a. Declining population on an island, at successive years.
b. A semi-logarithmic plot of the data of a.
c. Population data for later years is added to that of b, after an improvement in environment at year 10.

describe the problem. Specifically, for the first 10 years on the island, if we choose the value of Δt to be one year, then $k = -0.20$/year.

Q. For Example 2, for times greater than 10 years, what is the value of k if we again choose the interval Δt to be 1 yr?

If you are interested in demography, you may already have been saying to yourself, "But the exponentially *growing* population cannot really follow the exponential model forever, growing without limit." Quite right. Eventually, in any real physical, biological, or social system, the exponentially growing population will run into some limiting factor that causes the growth curve to flatten out. In our example of the maroonees on the desert island, after the change from shrinking to growing population, the population would probably eventually be limited by food supply. The world population is presently growing exponentially, which is a reason for great concern. When populations or other exponentially growing functions begin to bump into some natural ceiling, such as food supply, great strains may develop in the system in the process of accommodating itself to the new conditions.

Compound Interest

Another familiar example of an exponentially growing quantity is a sum of money invested at compound interest. We see the inexorable power of the pure exponential if we imagine Queen Elizabeth I investing the English equivalent of 1,000 dollars at compound interest of 5% in 1576 AD. Her accumulation, if that rather modest exponential growth factor continued unchanged, would be about 10^{12} dollars in 1990, the approximate present value of the U.S. gross national product.

Air Pressure at Various Altitudes

Population problems in various forms provide the majority of the ready examples of exponential processes. In these problems, it is generally equal intervals of time which are to be associated with multiplication of the interesting population number by a constant factor. However, in certain physical and biological phenomena, there is one other common situation. In it, intervals of *distance* are associated with multiplication of the quantity of interest by equal factors. We look at one example of such a process—the air pressure in our atmosphere as a function of altitude.

The table shows data obtained with pressure gauges carried in a rocket fired from White Sands, New Mexico.

In Fig. 4.6a, we plot the data on a linear scale. If we suspect that an exponential model might describe the situation, we then plot the pressure on a logarithmic scale, as in Fig. 4.6b. The exponential model seems to work. We shall not attempt to explore the physics of why this should be so, but we have already made the first step to testing any physical description. We know that, since the exponential model seems to describe the data correctly, the decrease in pressure for each unit

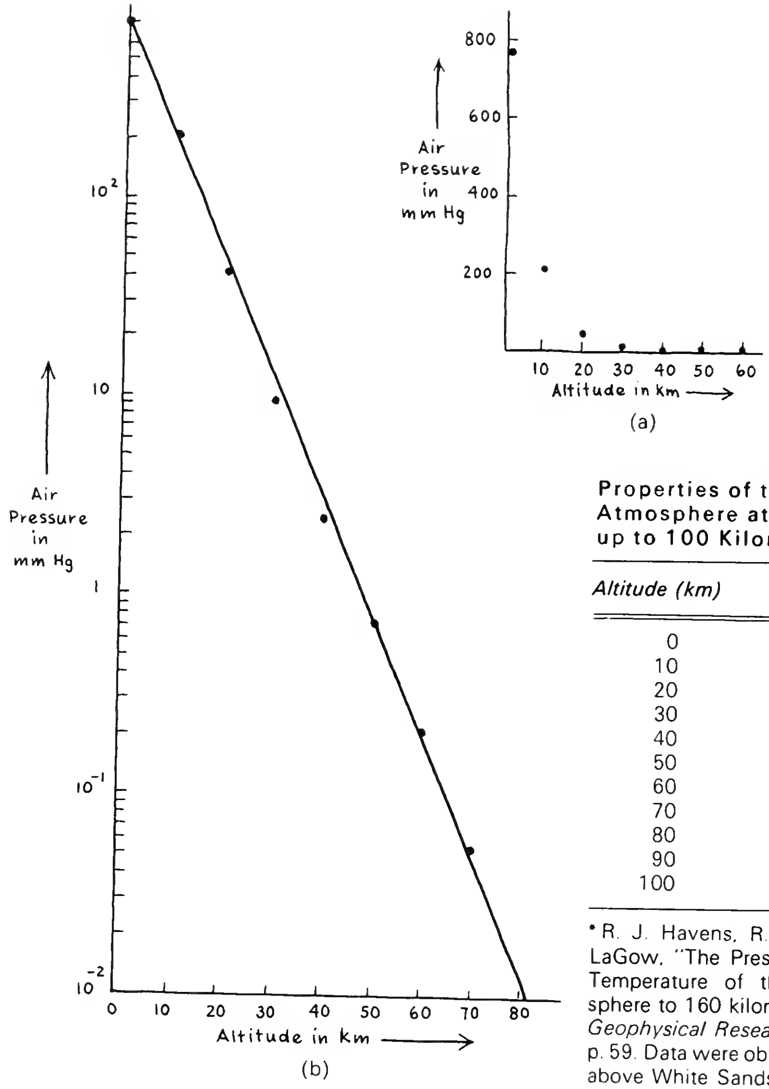


Figure 4.6

Rocket data of air pressure as a function of altitude. The inset shows a linear graph, the larger graph a semi-logarithmic plot.

Properties of the Earth's Atmosphere at Elevations up to 100 Kilometers*

Altitude (km)	*Pressure (mm Hg)*
0	760
10	210
20	42
30	9.5
40	2.4
50	7.5×10^{-1}
60	2.1×10^{-1}
70	5.4×10^{-2}
80	1.0×10^{-2}
90	1.9×10^{-3}
100	4.2×10^{-4}

* R. J. Havens, R. T. Koll, and H. E LaGow, "The Pressure, Density, and Temperature of the Earth's Atmosphere to 160 kilometers," *Journal of Geophysical Research*, March, 1952, p. 59. Data were obtained with rockets above White Sands, New Mexico.

increase in height is proportional to the pressure existing at the given original height. (We are simply rephrasing the boxed statement given on p. 91 in words appropriate to this example.) Any *physical* model we propose must be consistent with the observed fact that the exponential *mathematical* model correctly describes the situation.

Q. The height of Mt. Everest is 8.9 km. Assuming the exponential model holds, what is the air pressure at the top of Mt. Everest, according to Fig. 4.6b, expressed in the units of the graph, mm Hg?

RADIOACTIVE DECAY AS A NATURAL CLOCK

We now return to a very particular kind of population phenomenon, which was introduced in Chapter 2, and explore it in some detail. We investigate the population of radioactive atoms that are decaying through radiation and, thus, changing to a different kind of atom. (Review the material of pp. 50–51.)

Radioactive decay processes of various nuclei have been put to an enormous variety of uses in modern applied science. About 42 different naturally occurring nuclei, and a much larger number of artificially produced radioactive nuclei, undergo the decay process. Some of the uses depend upon the fact that the "radiation" sent out during the decay process itself can serve as an identification signal. In this chapter, we shall explore a use more directly coupled to our topic of interest. By following the population of a radioactive nuclear species, one can tell something about the chronology of the material in which the nuclei are imbedded. This scheme is called "radioactive dating."

The basic idea of radioactive dating is simple. Suppose a population of radioactive atoms was encapsulated in some fashion at a reasonably well-defined time in the past. Then, the fraction of those which remain undecayed at any given time will measure the time interval since the encapsulation, provided one knows the characteristic decay rate.

Half-Life

The characteristic decay rate of a population is often stated in terms of the "half-life," the time for the population to drop to one-half from some chosen initial value. In mathematical language, if we use the symbol $T_{1/2}$ for the half-life, and start with a population N_0 at time $t = 0$, then the population N, at subsequent times t, will be given by the equation

$$N = N_0 \cdot 2^{-t/T_{1/2}}. \tag{4.3}$$

Q. (1) By letting $t = T_{1/2}$, verify that Eq. (4.3) coincides with the word definition of $T_{1/2}$ given previously.

Q. (2) From the graph of Fig. 4.4a or 4.4b, determine the half-life of the population of island inmates.

We can now understand the source of the term "exponential process." It is any process in which the quantity of interest (such as our population, N) is proportional to some base number, such as 2, raised to a power which is itself a linear function of some running variable of interest, such as the time, t. The general form is

$$Q = Q_0 \cdot 2^{ay},$$

where a is a constant, either positive or negative, y is some variable such as time or distance, and Q is the quantity of interest. Its value at $y = 0$ is Q_0.

Experiment shows us that each nuclear species has a particular half-life, determined by the degree of internal stability of the nucleus. Fortunately, for the purposes of applications, these half-lives span an enormous range of times. We shall here discuss only two particular species used in dating. Even within the area of dating measurements, there is a wide range of different species used, depending on the particular application.

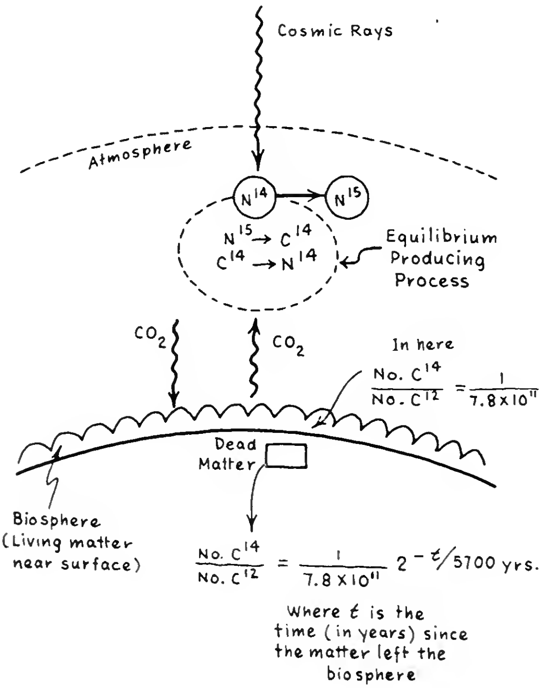
Radiocarbon Dating of Materials Removed from the Biosphere

One dating scheme with some quite spectacular archaeological implications depends on measurement of the decay of a particular variety of carbon nuclei, labeled C^{14}. The half-life of this nuclear species is 5,700 yr. When a C^{14} atom decays, it becomes a nitrogen atom, N^{14}.

The C^{14} species is itself produced in the Earth's atmosphere as the corpse of another radioactive decay process, which is stimulated by cosmic ray bombardment from outerspace. The parent of the C^{14} atoms is a nitrogen species, labeled N^{15}. The amount of C^{14} in the atmosphere, and hence the ratio of the C^{14} to the common carbon species C^{12}, is maintained at a stable value by the balance between C^{14} production and C^{14} decay suggested in the diagram of Fig. 4.7. We find that

Figure 4.7

Production of C^{14} nuclei in the atmosphere and subsequent passage through the biosphere to interment.



the carbon nuclei, C^{12} or C^{14}, are carried about primarily as ingredients of carbon dioxide molecules. Since all living matter undergoes a continual carbon exchange process through inspiration or respiration of carbon dioxide, all living matter has the same ratio C^{14}/C^{12} as the equilibrium value maintained in the atmosphere by the cosmic ray bombardment.

Now comes the "encapsulation process." When living matter dies—a tree is cut down or the flax for linen is harvested—the carbon exchange process stops. Then the C^{14}/C^{12} ratio gradually decreases as the C^{14} decays. If we take an ancient block of wood or piece of linen and measure this C^{14}/C^{12} ratio, we shall then know what fraction of the C^{14} remains undecayed. We then have a time measure in terms of the known half-life of C^{14}.

But, you immediately ask, how do you know what the C^{14}/C^{12} ratio in the atmosphere was in the dim past, when the material of interest left the biosphere? The answer is: we don't *know*. Everything else we know suggests that the value should have been about the same as it is now for an indeterminate time into the past. Hence, a measure of the present atmospheric C^{14}/C^{12} ratio gives us a working value for that equilibrium ratio. (Actually, the ratio is now changing somewhat. Burning of fossil fuel that is poor in C^{14} tends to decrease the ratio, and C^{14} produced in nuclear weapons tests tends to increase it: one more example of how man's tinkering alters his environment.)

We note that, with a half-life of 5,700 yr, an initial C^{14} population will decay to $\frac{1}{16}$ of its original value in 22,800 yr. This fact suggests that

Table of Some Archaeological Objects Dated with C^{14}

Place	*Sample*	*Age in Years*
Tikal, Guatemala	wood lintel from Mayan temple	481 ± 120 AD*
N. Newfoundland†	charcoal associated with iron and slag at the site of a great hall at L'Anse aux Meadows	1,060 ± 70 AD*
	linen wrappings from Dead Sea Scrolls Book of Isaiah	1,917 ± 200
Gt. Britain	charcoal sample from Stonehenge (first phase)	3,798 ± 275
Egypt	wheat and barley grain from site at Fayum	6,391 ± 180
Near Clovis, N.M., U.S.A.	charcoal from campfire hearth connected with elephant hunters	11,260 ± 360
France	charcoal from Lascaux Cave (site of famous cave paintings)	15,516 ± 900
Iraq	charcoal ash sample from cave at Sulimaniyah	$\gg$25,000

* Actual date given here, rather than age.

† *Scientific American*, May, 1967, p. 78. Other References are from W. F. Libby, *Radio Carbon Dating*, Chicago: University of Chicago Press, 1952

this method might run out of accuracy as the remnants of C^{14} become difficult to observe. Such is the case—20,000 yr is about as far back as this method will take us.

Geological Dating

For measurement of long times into the past, and in particular for the purpose of establishing the time scale of the Earth's geological history, the use of radioactive elements incorporated into the Earth's crust when it formed has been invaluable. Several different elements have turned out to be useful. Perhaps the most popular have been uranium, potassium, and strontium. We shall discuss the scheme for using radioactive potassium atoms in enough detail so that the methodology is at least outlined.

In 1935, A. O. C. Nier showed that the common chemical element potassium (symbol, K) contains a very small concentration of a particular variety of potassium which is radioactive. This radioactive species of atom, labeled K^{40}, is rather rare, there being only one K^{40} atom to each 8,400 nonradioactive potassium atoms. However, instruments for detection of the radioactive decay process are extremely sensitive, and this small fraction of "tracer" atoms turns out to be sufficient for the purpose. A sample of K^{40} atoms, as it decays with a half-life of 1.3×10^9 years, produces atoms of argon gas, labeled A^{40}, as a decay product. It turns out that the K^{40} atoms may also change into a different chemical species, Ca^{40}. In fact, only 12% of the decaying atoms form argon, and the other 88% form calcium. However, that ratio, $\frac{12}{88}$, is determined by the inner structure of the potassium nucleus and is, hence, always the same. Thus, for every 12 argon atoms produced, we know that, on the average, 100 potassium atoms have decayed, 88 of them producing calcium. Despite the fact that calcium atoms are more numerous, we are most interested in the argon atoms. The great advantage of the argon atoms over calcium atoms is that they form a chemically inert gas, which is trapped in interstices of the material containing the original potassium. A sample of the material may then be broken down, and the argon is released without further ado. Calcium, on the other hand, readily enters into formation of chemical compounds, which must then be chemically broken down before analysis. Figure 4.8 sketches the sequence of reasoning steps and experiments used to find the formation date of a piece of potassium-containing material in the earth's crust.

Example[1]*:* Suppose a sample of mass 1 g is found, upon analysis, to contain 4.21% potassium by weight, and 13.6×10^{15} A^{40} atoms.

At what time in the past was the material formed?

1. First, we determine the number of K^{40} atoms remaining in the sample at the present time. It is known, using the ideas of

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[1] Taken from Patrick M. Hurley, *How Old is the Earth?* New York: Doubleday Science Study Series, 1959.

chemistry, that each gram of potassium contains a total number of potassium atoms given by the relation

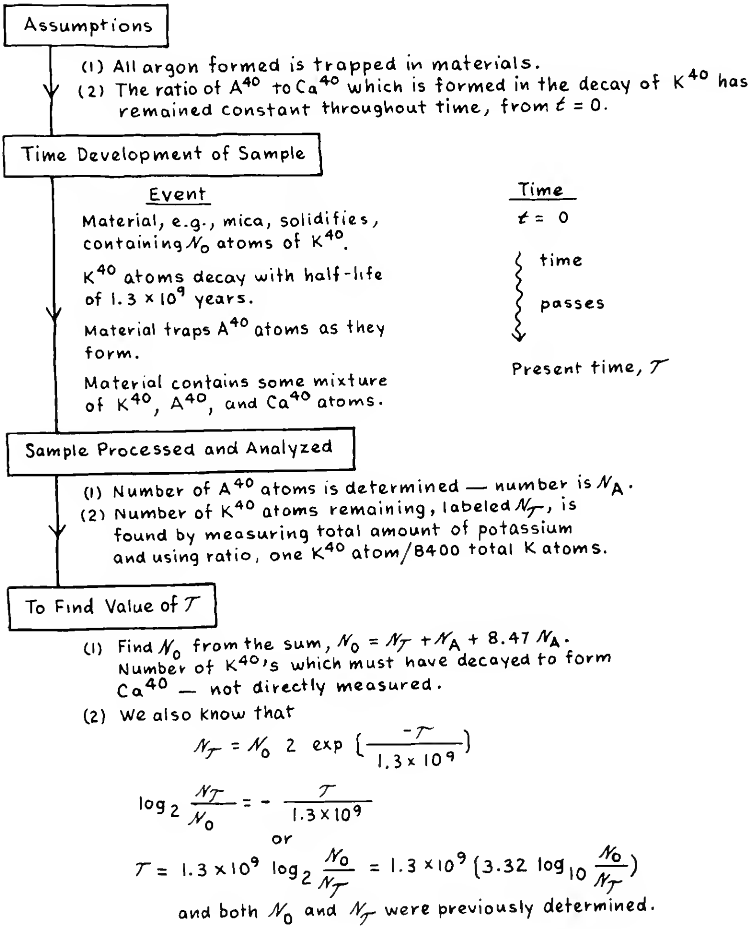
$$\frac{\text{Avogadro's number}}{\text{atomic weight}} = \frac{6.02 \times 10^{23}\text{ atoms}}{39.1\text{ g}}$$
$$= 1.54 \times 10^{22}\text{ atoms/g}.$$

Therefore, the number of potassium atoms in *our* sample is

$$0.0421\text{ g} \times 1.54 \times 10^{22}\text{ atoms/g} = 6.49 \times 10^{20}\text{ atoms}.$$

But only $\frac{1}{8400}$ of these are the tracer K^{40} atoms. Thus,

$$\text{no. } K^{40}\text{ atoms} = \frac{6.49 \times 10^{20}\text{ atoms}}{8400} = 77.1 \times 10^{15}\text{ atoms}.$$



Assumptions

(1) All argon formed is trapped in materials.
(2) The ratio of A^{40} to Ca^{40} which is formed in the decay of K^{40} has remained constant throughout time, from $t = 0$.

Time Development of Sample

Event	Time
Material, e.g., mica, solidifies, containing N_0 atoms of K^{40}.	$t = 0$
K^{40} atoms decay with half-life of 1.3×10^9 years.	time
Material traps A^{40} atoms as they form.	passes
Material contains some mixture of K^{40}, A^{40}, and Ca^{40} atoms.	Present time, $\mathcal{T}$

Sample Processed and Analyzed

(1) Number of A^{40} atoms is determined — number is N_A.
(2) Number of K^{40} atoms remaining, labeled $N_{\mathcal{T}}$, is found by measuring total amount of potassium and using ratio, one K^{40} atom/8400 total K atoms.

To Find Value of $\mathcal{T}$

(1) Find N_0 from the sum, $N_0 = N_{\mathcal{T}} + N_A + 8.47\, N_A$. Number of K^{40}'s which must have decayed to form Ca^{40} — not directly measured.
(2) We also know that

$$N_{\mathcal{T}} = N_0\ 2\ \exp\left(\frac{-\mathcal{T}}{1.3 \times 10^9}\right)$$

$$\log_2 \frac{N_{\mathcal{T}}}{N_0} = -\frac{\mathcal{T}}{1.3 \times 10^9}$$

or

$$\mathcal{T} = 1.3 \times 10^9 \log_2 \frac{N_0}{N_{\mathcal{T}}} = 1.3 \times 10^9 \left(3.32 \log_{10} \frac{N_0}{N_{\mathcal{T}}}\right)$$

and both N_0 and $N_{\mathcal{T}}$ were previously determined.

Figure 4.8

Flow diagram for K^{40} dating scheme.

2. Now we can compute the total *original* number of K^{40} atoms to have been

$$\underbrace{77.1 \times 10^{15}}_{\substack{\text{remaining}\\ K^{40}\\ \text{atoms}}} + \underbrace{13.6 \times 10^{15}}_{\substack{\text{no. } A^{40} \text{ atoms}\\ \text{created since}\\ \text{material}\\ \text{formed}}} + \underbrace{(8.47 \times 13.6 \times 10^{15})}_{\substack{\text{no. } K^{40}\text{'s which must}\\ \text{have decayed to } Ca^{40},\\ \text{which we do not}\\ \text{measure}}} = 205.6 \times 10^{15}$$

3. Therefore, our basic exponential decay law becomes, inserting the known numbers,

$$77.1 \times 10^{15} \text{ atoms} = (205.6 \times 10^{15}) \text{ atoms} \times 2 \exp\left(\frac{-t}{1.3 \times 10^9 \text{ yr}}\right).$$

Solving for t, we have

$$\begin{aligned} t &= 1.3 \times 10^9 \text{ yr} \log_2 \frac{205.6 \times 10^{15} \text{ atoms}}{77.1 \times 10^{15} \text{ atoms}} \\ &= 1.3 \times 10^9 \text{ yr} (3.32 \log_{10} 2.67) = 1.3 \times 10^9 \times 1.42 \\ &= 1.8 \times 10^9 \text{ yr}. \end{aligned}$$

The material was laid down into solid form 1.8×10^9 years ago.

Q. This K^{40} method does not depend on any assumptions about what fraction of potassium atoms were K^{40} atoms at the time the material was laid down. Explain what features of this scheme differentiate it from the carbon dating scheme described previously, which *does* depend on an assumption about C^{14}/C^{12} ratio at the time the material in question left the biosphere (see Fig. 4.7).

In our discussion of C^{14} dating of objects removed from the biosphere, we noted that the value of the half-life of the particular radioactive species chosen tends to set the scale of times which can be accurately measured. After several half-lives, it is difficult to determine precisely the amount of the mother species remaining. The half-lives of K^{40} and several other species used for geological dating are of order of magnitude 10^9 yr, which turns out to be the natural time unit for treating the whole history of the earth (and, for that matter, of the solar system). Actually, this apparent coincidence of the half-lives of several prevalent radioactive species and the geological time scale is not really a coincidence at all. The nuclear species were themselves apparently formed not too long before the birth of the solar system, and the radioactive species that remain in substantial amounts are those whose half-lives roughly match the present age of the solar system. (In case the reader has substantial interest in the interlocked questions of the age of the Earth, our solar system, and. indeed, our universe, he is referred to the introductory discussion for Special Topic B, Geological History of the Earth p. 363.)

In conclusion, we note that the basic justification for our radioactive dating schemes depends upon our deeply held belief that the intrinsic properties of the atoms have been unchanged since the dawn of time. For the exponential decay depends upon the steady work of the law of equal fractional change in equal time, and only if the probability of any given atom decaying in the next year remains always fixed does that law hold over all of the time scale. Appendix 4B, which discusses various aspects of radioactive decay processes that we have bypassed so far, examines that belief.

CONCLUSION

The main purpose of this chapter has been to show how a mathematical model of the exponential processes can be exploited as an organizing principle for a wide variety of natural phenomena. There remains one important feature that we should call to your attention, if you have not already wondered about it.

The mathematical model, embodied either in Eq. (4.2), which gives the primary condition for validity of the exponential model, or in Eq. (4.3), which gives the population as a function of time for a decaying population, would predict population numbers that *exactly* fit a straight line on a semilogarithmic plot of the sort given in Figs. 4.3 and 4.5. In fact, the natural systems all have small deviations from the exact fit. Does such a situation invalidate the model? Of course not. We simply have another case of the abstraction process described in our Prologue. We abstract the essential element of a set of natural phenomena, find that a mathematical model is an excellent description of those abstracted systems, and so we use it fully. In the back of our minds we always remember that, for a variety of reasons which vary for different systems of interest, the true population numbers will fit the predictions of the mathematical model only in a statistical sense, not in an exact numerical sense.

EXERCISES

1. Suppose a particular human population is described by Eq. (4.2), with a certain value of the constant k. If a birth-control campaign is instituted, is k likely to become larger or smaller?
2. Consider the accompanying rounded-off figures for the population of the U.S., 1790–1870. Do these numbers show a roughly exponential growth of population? State briefly the reasoning behind your answer.

Date	*Population*
1790	3.93×10^6
1800	5.31×10^6
1810	7.24×10^6
1820	9.64×10^6
1830	12.87×10^6
1840	17.07×10^6
1850	23.19×10^6
1860	31.44×10^6
1870	38.56×10^6

3. The accompanying table gives the U.S. gross national product at 10-year intervals from 1869 to 1969. The units are 1929 dollars; that is, the raw figures are corrected for changes in value of the dollar, so they presumably represent some real measure of goods and services produced. Do the numbers show a roughly exponential growth in GNP? If there are fluctuations, can you correlate these with any other significant happenings in the society?

Year	GNP *in 1929 Dollars*
1869	9.0×10^9
1879	16.1
1889	24.0
1899	37.1
1909	55.0
1919	74.2
1929	104.
1939	111.
1949	171.
1959	230 (est.)
1969	380 (est.)

4. During the Summer Olympics at Mexico City, 1968, there was considerable agitation about the effect of the altitude (7,350 ft = 2.24 km) on runners unaccustomed to thin air. If the oxygen content of one breath is directly proportional to the air pressure, find, using Fig. 4.6, by how much the oxygen intake per breath was reduced for these runners. Does the effect appear significant to you?

5. The atoms most used for geological dating, along with their half-lives, are listed. Suppose we started with equal numbers of these three species at $t = 0$.
After a time equal to 5.0×10^{10} years, what would be the ratios of remaining populations of the three species?

Species	*Half-Life*
Potassium^{40}	1.3×10
Rubidium^{87}	5.0×10
Uranium^{238}	4.5×10

6. It is believed that formation of the Earth's crust took place about 2.8×10^9 years ago. If we assume that the potassium in the crust was all deposited at about this time, and we know that there is, at present, one radioactive K^{40} atom to 8,400 inert K^{39} atoms, what was the approximate value of the ratio of number of K^{40} atoms to number of K^{39} atoms at the time the crust formed?

The following two problems extend the material in the text, rather than just exercising your knowledge of it.

7. In the case of money gathering compound interest, Eq. (4.3) would have the form

$$\$ = \$_0 2^{t/T_{1/2}},$$

where $T_{1/2}$ is now the doubling time rather than the half-life, since we are dealing with growth rather than decay. The doubling time, $T_{1/2}$, if expressed in years, is simply related to the compound interest rate, R, expressed in percent, by the following equation:

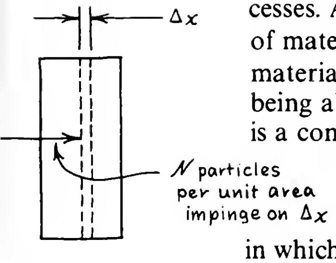
$$T_{1/2} = \frac{69.3}{R}.$$

Note that if, for example, the interest rate is 5%, the doubling time is 13.9 yr. At a simple interest of 5%, the doubling time would be 20 yr. Explain to your own satisfaction why the doubling time is so much shorter than the 20-yr figure.

8. (An extension of the previous problem.) The population of the U.S. grew from 180,000,000 in 1960 to 203,000,000 in 1970. If this growth rate were to continue at a constant value, in approximately what year would the U.S. population double its 1960 value?

9. (This problem introduces another example of a very common exponential process. The first part of the problem describes the

physical situation and how it can be connected to the exponential model. A question about a specific experiment is asked in the last paragraph.)



Consider the following common situation in natural processes. A stream of some kind of particles impinges upon a layer of material that absorbs or deflects some of the particles. If the material is uniform, so that the probability of any given particle being absorbed or deflected in a given thickness of material, Δx, is a constant, then we have the following relation,

$$\frac{\Delta N}{\Delta x} \propto N,$$

in which N is the number of particles per unit cross-sectional area impinging on a layer of thickness Δx, and ΔN is the number of these that are knocked out of the stream in thickness Δx by absorption or deflection. We see that we have just the condition for an exponential decay of the particle density in the stream. In this case, it is equal intervals of distance which lead to decrease by equal multiplicative factors, similar to the air pressure problem discussed on p. 94.

If a stream of high-energy electrons has its particle density cut in half by passing through a piece of aluminum 1 cm thick, what density would be necessary to insure that its density would be less than $\frac{1}{1000}$ of the original value? (This is a common practical problem in shielding against high energy radiation of one sort or another.)

10. (A difficult problem, combining scaling ideas with the exponential problem.) Consider the situation in which the weight of a raindrop increases as it falls through fog. Assume that the weight of fog that is added to the drop in each unit of time is proportional to the surface area of the drop. Under these circumstances, will the weight of the drop increase with time as an exponential curve?

SUPPLEMENTARY READINGS

Brown, Harrison, Age of the Solar System. *Scientific American*, April, 1957.

Cipolla, Carlos M., *The Economic History of World Population*. Harmondsworth, England: Penguin Books, Ltd., 1965, 117 pp. Cipolla discusses particularly clearly some of the important perturbations (e.g., agricultural and industrial revolutions) that have caused large departures from exponential growth of the world's population.

Hurley, Patrick M., *How Old is the Earth?* New York: Doubleday Science Study Series, 1959.

Price, Derek J. DeSolla, *Little Science, Big Science*. New York: Columbia University Press, 1963. This short book, based on a lecture series, analyzes many aspects of the growth of modern science, since the time of Newton, in terms of exponential models. In particular, Chapter 1, A Science of Science, is a very useful example of how one develops an application of the exponential model to natural population problems. Among other things, Price discusses some examples of possible behavior of a natural system that has been growing exponentially but then approaches some natural limit to its size.

The modern sciences are becoming more and more interwoven. Here we see some of the ways in which the methods and concepts of physics contribute to the advancement of biology.

5 Physics in Biology

Physics Survey Committee NRC-NAS

An excerpt from Physics in Perspective, 1973

> Biology has become a mature science as it has become precise and quantifiable. The biologist is no less dependent upon his apparatus than the physicist. Yet the biologist does not use distinctively biological tools—he is always grateful to the physicists, chemists, and engineers who have provided the tools he has adapted to his trade.
>
> Until the laws of physics and chemistry had been elucidated it was not possible even to formulate the important penetrating questions concerning the nature of life.
>
> PHILIP HANDLER
>
> *Biology and the Future of Man* (1970) (Chapter I, pages 3 and 6)

PHYSICS IN BIOLOGY

Nature of the Interface

An especially active scientific interface, and one that is attracting an increasing number of physicists, is that between physics and biology. The problems posed relate to fundamental questions of life and hold the promise of substantial contributions to the alleviation of human ills and misery. This interface combines fundamental science and both immediate and long-range social goals in a close and balanced relationship. Growing application of the methods, devices, and concepts of physics to some of the central biological problems should result in increasingly rapid progress. The scientific returns from such applications are already impressive.

The title of this section, "Physics in Biology," rather than the more usual biophysics, is indicative of the Committee's approach to the interface. Rather than a survey of all biophysics, this report focuses on the role of physics and physicists in attacking some of the major problems of modern biology. The implications of such a role for physics education and the overall physics enterprise also receive attention.

To describe the interaction of physics with biology requires study of the flow of manpower, ideas, and procedures through the interface. The title, "Physics in Biology," implies a flow from left to right. It is convenient to divide the subject into three parts: (a) the flow of physicists into biology; (b) the flow of physics into biology, which includes the flow of ideas, techniques, and equipment, often through the intermediaries of engineering and chemistry; and (c) the interface called biophysics, in which the powers of physics are merging with the problems of biology in new ways that require nonstandard combinations of skills from both disciplines.

The goal of biophysics is to be biologically useful. When it is successful, it merges with other branches of biology, such as biochemistry and molecular biology, a major goal of which is to understand, in molecular terms, how genetic information is transmitted. The following example illustrates the contributions of biophysics to molecular biology. In 1944, it was shown that DNA, rather than proteins, contained the genetic information with which molecular biology is principally concerned. In 1953, J. Watson and F. Crick, working in the Cavendish Laboratory, developed from the accumulated chemical studies of DNA and a consideration of its biological function an interpretation of the x-ray studies of M. Wilkins in terms of the now famous double helix. Since then, molecular biology has developed rapidly, and biological function is now so interwoven with the structure of DNA that the term "structure and function" has become a platitude.

At the same time, and in the same laboratory in Cambridge, the crystal structures of the proteins were first being determined by x-ray crystallography, with a parallel influence on enzymology and biochemistry. In all these cases the isolation of the molecules and the definition of their biological functions were accomplished after roughly a century of chemical research. The physicists who determined the crystal structures were attacking a biologically important problem. Their boldest and most original step was their starting assumption that these large biological molecules had unique structures that could be determined by x-ray crystallography. Physicists are accustomed to this kind of simplicity in science; assuming such simplicity is a reflection of their previous training and research style. The revolutionary nature of their findings depended on the originality of their assumptions. However, given their background as physicists, trained in x-ray crystallography under Bragg, and their interest in biology, their directions of attack were almost predetermined. Thus, in these illustrative and illustrious cases, physicists and physics created an exciting field of research in biophysics, which has now been merged with biochemistry and molecular biology.

Determination of the structure of large biological molecules will continue to be an active field of research. In addition to x-ray crystallography, other physical techniques such as nuclear magnetic resonance, electron spin resonance, Mössbauer studies, and optical studies are being used more and more. These techniques, when used for structural studies, often complement x-ray data by giving information on a finer scale. This research is directed toward structural determinations of larger molecular aggregates, that is to say, membranes and membrane-mediated enzyme systems; ribosomes, which are the site of protein synthesis, composed of nucleic acids and protein, with a molecular weight of $\sim 10^6$; mitochondria, the membrane-bound volume in which the chemical energy of nutrients is converted to more usable forms by electron transfer reactions; and the photosynthetic unit in which photons are converted to chemical energy. In all of these systems, scientists are trying to understand biochemical functions in terms of the structure of the molecules and the physical interactions among them. Beyond the structures of isolated biological molecules lie the complicated questions of intermolecular interactions, which should challenge physical methods for many years. The collision techniques, which are only now beginning to be applied to the elucidation of elementary chemical reaction kinetics of simple inorganic molecular complexes, were developed in atomic and nuclear physics. Application of these approaches to molecular systems of biological interest is an exceedingly difficult but highly promising field.

When structure is examined at finer levels than the molecular, it is quite clear that quantum-mechanical understanding of the electronic structure of certain parts of biological molecules will become increasingly important. The advances made through electronic understanding of the molecules of interest to chemists and condensed-matter physicists show the promise of this approach. Recently, as experimental molecular physicists have studied biological molecules with the goal of understanding their electronic properties, the amount of systematic data has approached the point needed for theoretical synthesis and advances. This synthesis could lead in the future to a larger role for theoretical studies. Previously, the theorist's contribution to molecular biophysics has been very small, because, unlike the best experimenters, he generally has not learned enough biology to be able to ask good questions.

An exception occurs in the case of the theoretical models that are playing an increasingly important role in biology. This trend reflects the physicist's typically different viewpoint on biological problems. One of these differences is the physicist's desire for a simple, comprehensive model, capable of providing a first-order explanation of a wide variety of observations. It is often baffling to a physicist when biologists insist on the complexity of nature and the uniqueness of each result. It is, of course, equally unappealing to a biologist, struggling with complexities of DNA replication, to be informed by a physicist that the Ising model, or enough molecular quantum mechanics, would solve his problem. However, in the middle ground between these two extremes of oversimplification lies the productive application of physical models, based as always on experimental observations. For example, the concept of a genetic code proposed by physicists and theoretical chemists such as Crick, Orgel, Gamow, and Griffith appealed to a mind trained in physics. Various theoretical models were examined. One question that was proposed and answered was how much information had to be stored. The answer was that there were 20 amino acids that had to be coded by the DNA. Because DNA has only four possible bases as coding units, a minimum of three bases is required. Was the code overlapping? This question was answered negatively by considering the known mutations that had been observed.

Another useful model was that of Monod, Wyman, and Changeux, on allosteric proteins, whose function with respect to one small molecule can be affected by other small molecules. They proposed a generalized molecular basis for feedback in biological molecules and thus stimulated many experiments and analyses to determine the crucial facts.

Activity

Perhaps the most active research area at the interface between physics and biology is that involving the study and determination of the molecular bases for biophysical processes. This work has engaged some of the best people in the subfield and uses a variety of physical techniques and probes, from x-ray crystallography through nuclear magnetic resonance and Mössbauer techniques (see Figure 4.93) to nanosecond fluorimetry.

An older research area, but one that retains excitement and interest, is neural physiology. In part, this interest reflects the hope that such research can lead eventually to the understanding of the mysterious processes of human thought and memory, one of the remaining frontiers of man's understanding. In part, it reflects the physicist's assumption that when information is transmitted and processed by essentially electrical mechanisms, the problem should be amenable to physical analysis.

A striking example of physical reasoning in elucidating a particular property of a biological cell is the analysis of the electrical state underlying excitability in the giant axon of the squid. Its virtually unique diameter

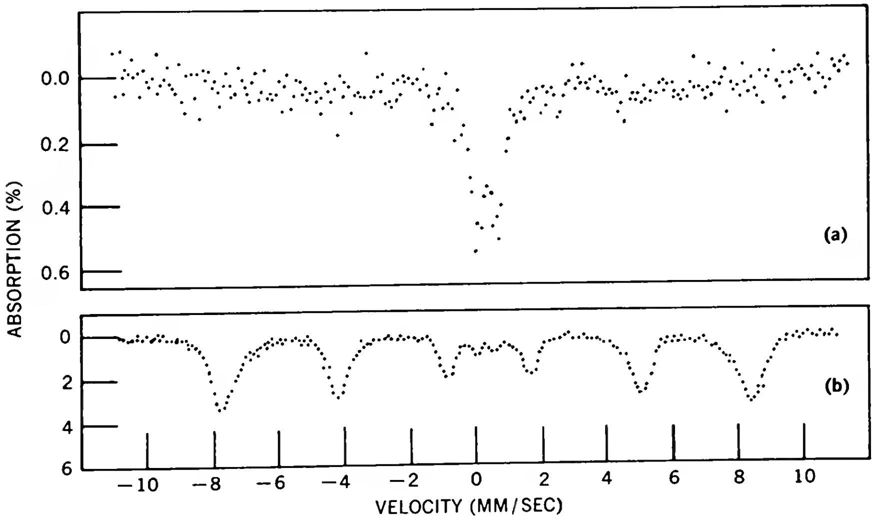


FIGURE 4.93 Human lung material from healthy lung (a) and from lung of hemosiderosis victim (b). Mössbauer spectrum of diseased lung indicates an abnormally large amount of iron (note the difference in absorption scales in the spectra), which appears to be in the form of a finely divided, low-molecular-weight compound. [Source: C. E. Johnson, "Mössbauer Spectroscopy and Biophysics," Physics Today *24,* 40 (Feb. 1971).]

(500–100 μm) enabled Hodgkin and Huxley, in 1949, to conduct a series of fundamental electrical measurements that, in turn, made it possible to establish for the first time an adequate quantitative description of the electrical state associated with the nerve impulse. Both the design and execution of the experiments required a thorough knowledge of electronic circuits, in which feedback plays a crucial role, and of the theory of ionic electric currents. Moreover, the interpretation of the data demanded an ingenious mathematical analysis. This achievement was in large measure a product of Hodgkin's and Huxley's training in physics.

One of the basic findings of their analysis was that the ionic currents in the axonal membrane display strikingly nonlinear behavior in that the conductances are voltage-dependent and time-variant. The property of nonlinearity implies that, in a single neuron and chains of neurons (neural circuits), the elaborate calculations required to treat the excitable state can be carried out in general only with modern computers. And the statistical physics underlying the conductance changes in the cell membrane and at the junction between two cells (the synapse) presents a problem requiring highly sophisticated analysis.

The study of neural physiology is typical of the advanced research conducted on macromolecular aggregates in modern biophysics. It involves the design and development of new measurement techniques, computer simulation of neural behavior, and the study of signal-transmission characteristics of biological media. It continues to provide important surprises. Recent work on the brains of primitive animals, in which the brain contains at most only a few hundred cells, has shown that, even here, a remarkable symmetry of structure and function has developed.

Neural physiology stimulated some of the earliest physicists to move into biophysics; probably it will continue to attract them. Progress in neurobiology will demand advances in the biochemistry and ultrastructure of the neuron; but, in any event, the elucidation of physical mechanisms, for example, the analysis of excitability in the giant axon of the squid, will continue to play a crucial role.

A third major activity at the interface involves the interaction of radiation with high- and low-level biological systems. The types of radiation employed range from ultraviolet light to very-high-energy, heavy nuclear particles and mesons. The transfer of the techniques of nuclear physics—radioactive tracers, accelerator radiations, and nuclear instrumentation—has brought about a revolution in biophysics and in both clinical and research medicine.

Radioactive isotopes have contributed enormously to the general improvement in diagnosis, and a large number of radioisotopes are now in routine use. Isotopes commonly used include: ^{131}I, ^{125}I, ^{59}Fe, ^{113m}In, ^{99m}Tc, ^{51}Cr, ^{57}Co, ^{60}Co, ^{75}Se, ^{85}Sr, ^{197}Hg, ^{32}P, and ^{198}Au. These are used for visualization of the thyroid, brain, liver, lung, kidney, pancreas, spleen, heart, bone, and placenta and for a variety of physiological tests in which the rate of disappearance or rate of uptake of a particular labeled substance reflects the function of a given organ system (see Figures 4.94 and 4.95). In 1968, there were some four million administrations of labeled com-

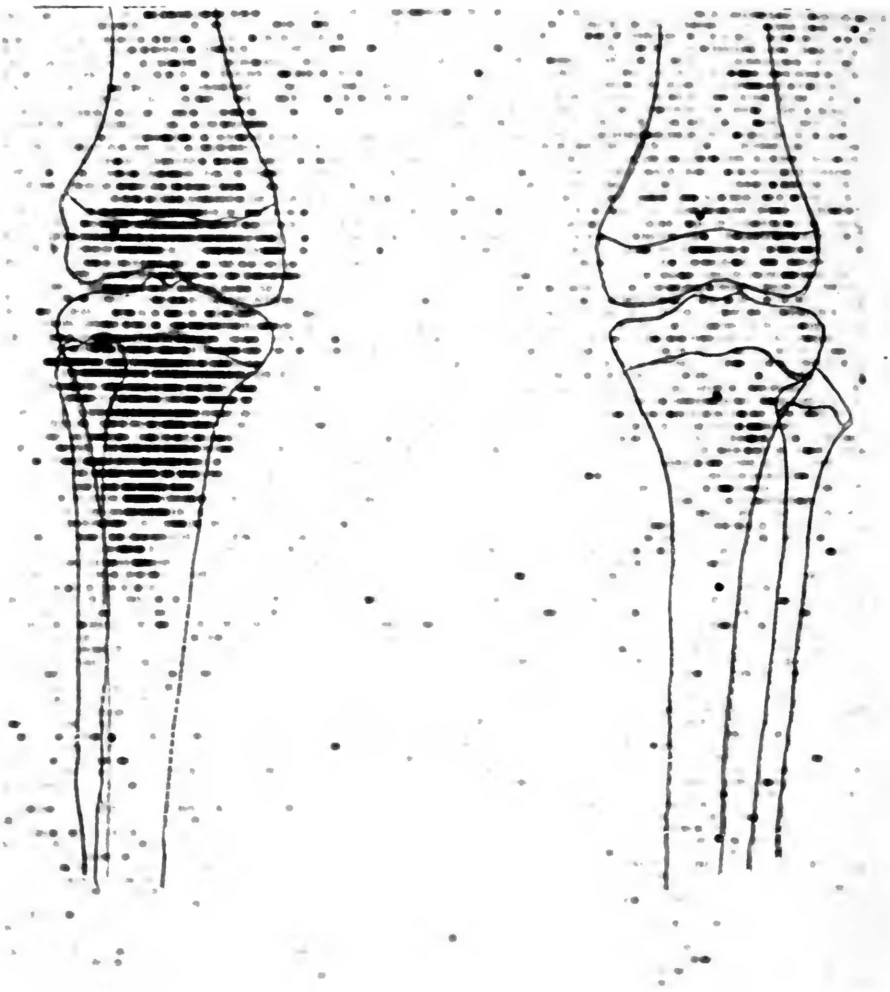


FIGURE 4.94 This is a bone scan made with short-lived strontium-87*m* (half-life 2.8 h). The patient was a 13-year-old girl with a bone sarcoma of the right tibia. The greater strontium uptake in the right leg indicates the presence of the lesion. [Source: J. H. Lawrence, B. Manowitz, B. S. Loeb, *Radioisotopes and Radiation* (Dover, New York, 1969).]

pounds to patients, and the rate of use has been growing rapidly. These isotopes are employed routinely in practically every hospital in the United States.

Increasing attention is being given to the use of very-short-lived isotopes, particularly ^{11}C, which should be especially useful because of the enormous potential for incorporation into a wide variety of biological compounds, with consequent extension of the range of diagnostic procedures. The short half-life, some 20 min, markedly limits the time for synthesis of the isotope into the desired compound and the time available for use. Thus the source

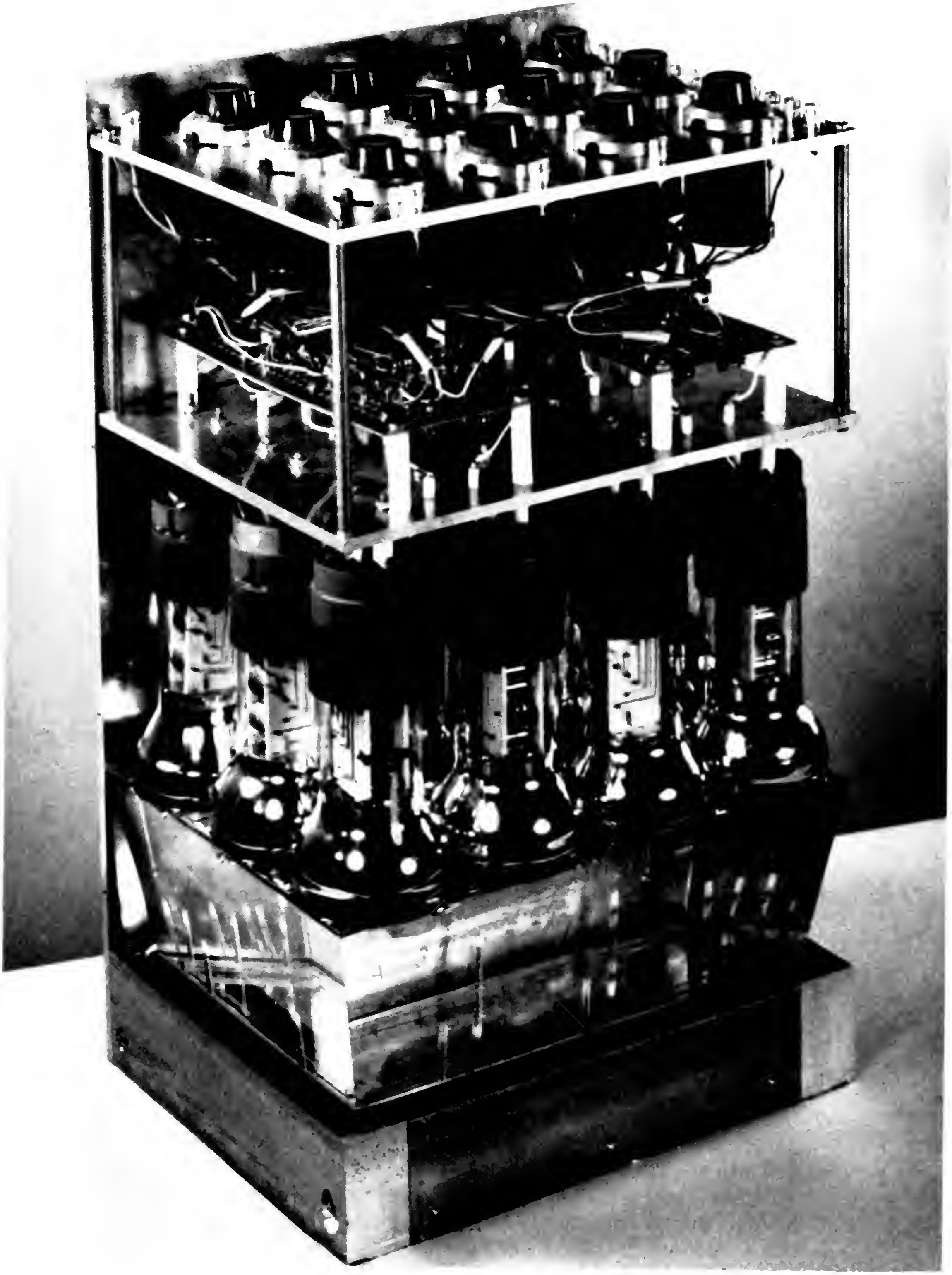
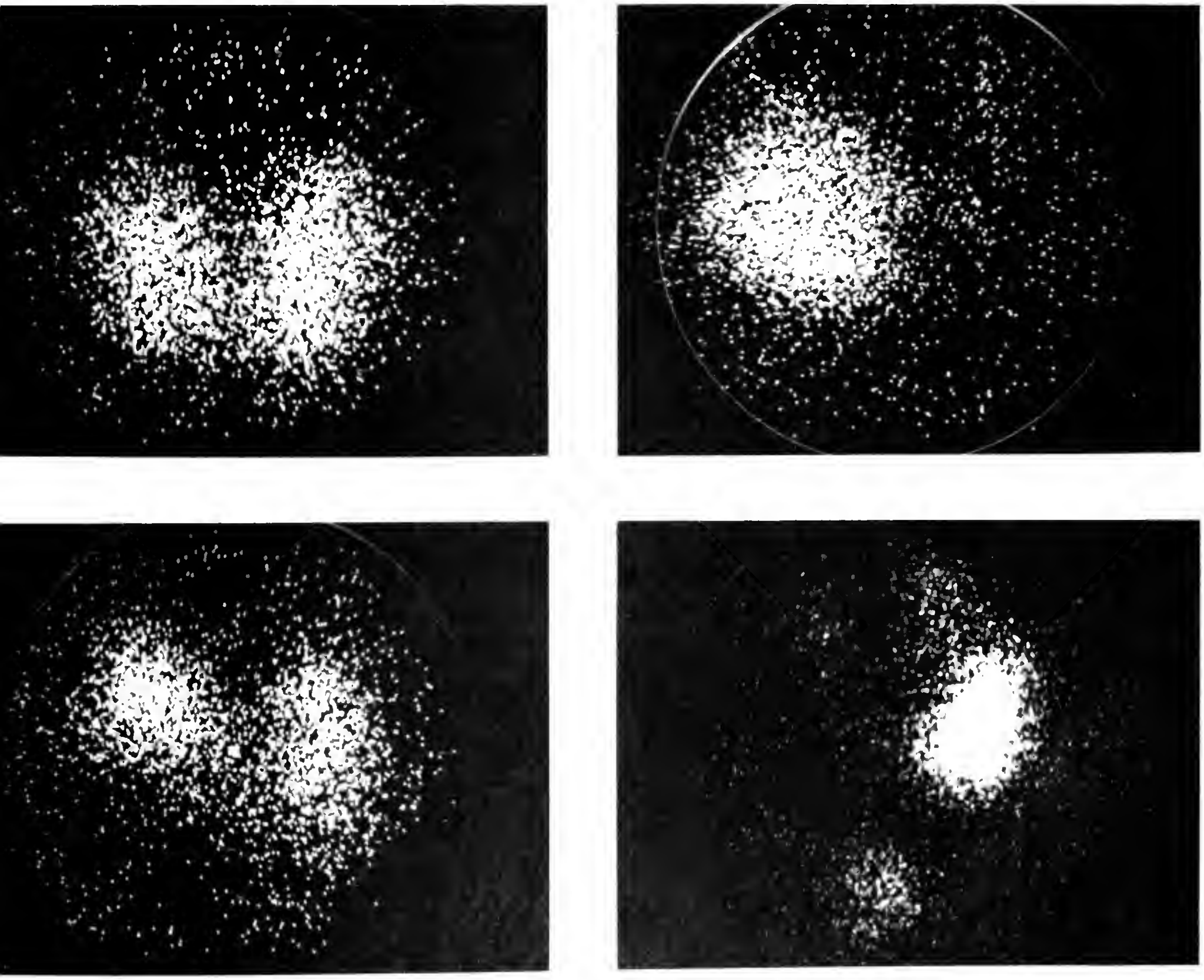


FIGURE 4.95 *Left:* The autofluoroscope detector shown with its 2-in. lead shield removed. A bank of 293 sodium iodide crystals is in the lead-encased enclosure at bottom. This bank is separated from the 12 photomultiplier tubes by a 4-in. Lucite light pipe. The data are transferred electronically and recorded on Polaroid film.

Below: Four neck scintiphotos of different individuals made with the gamma-ray scintillation camera 24 h after administration of 25 to 50 μCi of iodine-131. *Upper left:* Normal, butterfly-shaped, thyroid gland. *Upper right:* Solitary toxic nodule in right lobe. This "hot" nodule takes up the iodine-131 to a greater extent than the normal thyroid tissue. *Lower left:* Degenerating cyst seen as a dark area in lower left of picture. This "cold" nodule is nonfunctioning, hence does not take up the radioisotope. *Lower right:* This patient had undergone a "total" thyroidectomy 2 years previously. The photo shows regrowth of functioning tissue, right, and also a metastasis, lower center.

[Source: J. H. Lawrence, B. Manowitz, and B. S. Loeb, *Radioisotopes and Radiation* (Dover, New York, 1969).]



of the isotope (an accelerator), facilities for rapid synthesis, and clinical facilities must be in close juxtaposition. A closely cooperating team of physicists, chemists, and clinicians is required for effective application. Use of this isotope, although still in its relatively early stages, is increasing rapidly and has great promise.

Another rapidly developing diagnostic procedure involves the determination of the entire amount of a given element, for example, calcium, in the body by means of activation analysis. The entire body is exposed to a beam of fast neutrons, which thermalize in tissue and are captured by the element in question. The patient is then placed in a whole-body counter and the total amount of the given element deduced from the total induced activity. The entire procedure can be accomplished with the delivery of only a small fraction of 1 rad to the patient.

Isotopes are now used widely in radiotherapy in a variety of ways. High-intensity external sources, such as cobalt-60 and cesium-137, have in many instances replaced x-ray machines for routine radiotherapy. The depth–dose characteristics of radiations from these sources are more favorable than those of most x-ray beams, and the units have the advantage of ease of operation and maintenance. As a specific example, the cure rate in cases of mammary cancer increased dramatically when cobalt-60 therapy replaced that with 100-kV x rays. The reason was that the higher energy ^{60}Co radiations were able to penetrate the sternum to a lymph node behind it, whereas the x rays could not. In addition, beta emitters such as strontium-90 are beginning to be used more frequently for the therapy of some superficial external lesions.

Physiological localization of radioactive isotopes is used in some forms of therapy, for example, iodine for treatment of hyperthymism and thýroid tumors and ^{32}P for treatment of some diseases of the bone marrow. These procedures represent optimal therapy only in a relatively few situations.

Accelerators have contributed greatly to the improvement of radiotherapy. Early accelerators allowed transition from the use of relatively low-energy x rays for radiotherapy to the use of supervoltage x rays, permitting the delivery of a relatively large dose to the tumor in depth, with a minimal dose to the intervening normal tissues. Electron accelerators such as the betatron have permitted an additional distinct improvement in the therapeutic ratio, or dose-to-tumor, dose-to-normal-tissue ratio.

Somewhat in the future is the therapeutic use of beams of negative pions, which currently are produced only in elementary-particle and very-high-energy nuclear-physics facilities. These have the enormous advantage of delivering not only their ionization energy but also their entire rest mass energy to their final destination in matter. Thus, while traveling to the therapy site, they do relatively little damage to surrounding tissues; their capture then releases some 200 MeV of energy at the treatment site.

Currently, there is much interest in the use of accelerators to produce beams of fast neutrons for radiotherapy. The rationale is that all tumors quickly develop small foci of poorly oxygenated or hypoxic cells. These hypoxic cells are markedly resistant to damage by x or gamma radiation but are much more susceptible to damage by neutrons or other densely ionizing radiations. Although a variety of reactions and neutron spectra might be used, the approximately 14-MeV neutrons from the D–T reaction are optimal in terms of penetrating characteristic and density of ionization. The procedure is experimental, and several years will be required to evaluate its efficacy. Man-made transuranium isotopic sources of neutrons, such as ^{252}Cf, have just recently become available and are also being used, with the same rationale.

Not only are radiations in the high-energy or nuclear realm used in such studies and applications but also ultraviolet and infrared radiation (see Figure 4.96). For example, Setlow and his collaborators at Oak Ridge

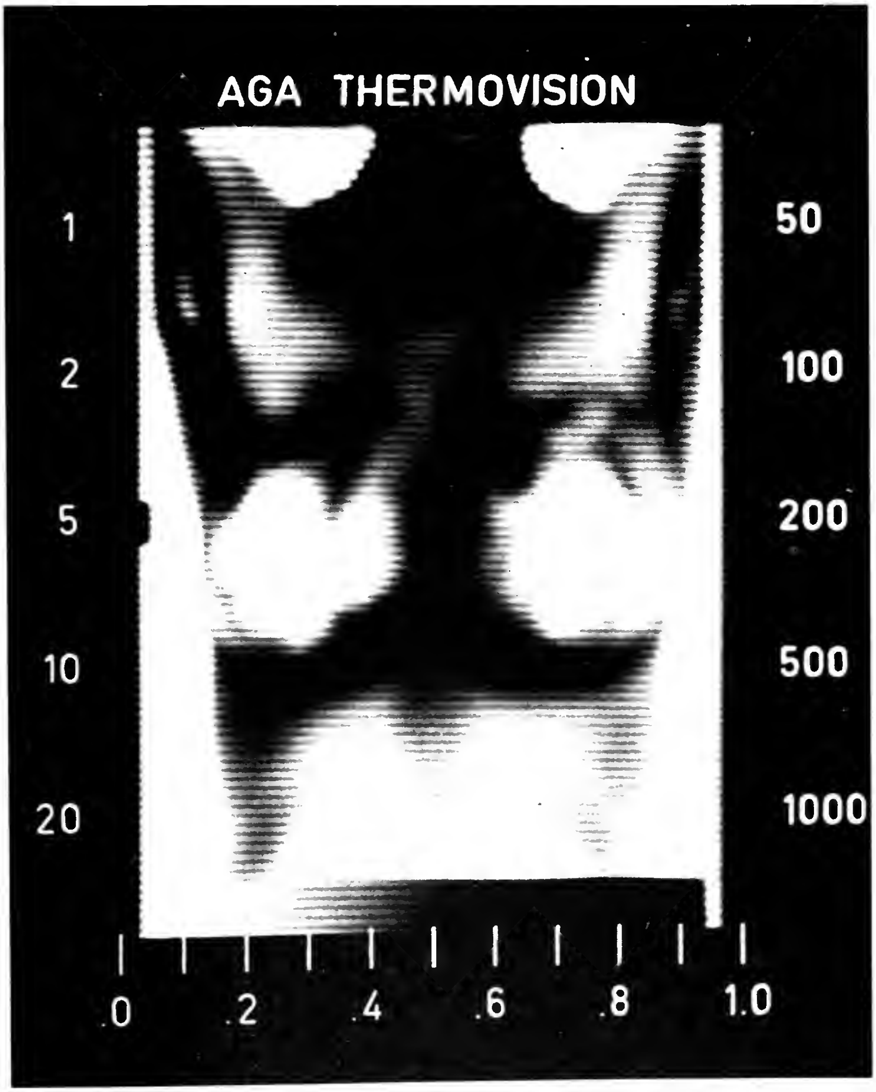


FIGURE 4.96 Detection of breast cancer by infrared thermography. [Photograph courtesy of the Lovelace Foundation for Medical Education and Research.]

very recently discovered that a particular species of skin cancer can be traced not only to a specific damage site in the human cell DNA induced by ultraviolet radiation but also to the lack, in susceptible individuals, of a rather rare enzyme the function of which is to repair such damage. Already a test has been developed that can detect the total lack of this enzyme *in utero* and make possible therapeutic termination of the pregnancy; otherwise, with total lack of the enzyme, the normal life-span of a child would be brief. It is hoped that further research will result in a technique for the detection of, and compensation for, the partial lack of this enzyme in the population.

The use of infrared photography as a diagnostic tool is now rather well developed. Reflecting the increasing metabolism of cancer cells is a local temperature elevation that shows clearly in an infrared photograph; this technique is extremely simple, over 90 percent effective, and widely employed.

The long-term effects of very-low-level radiation on a population is, of course, a matter of continuing concern and controversy. The controversy arises largely because, at the levels now under consideration, even granting the validity of the mouse–man extrapolation, it has been estimated that an 8-billion-mouse colony would be required to yield statistically significant results. This situation shows the importance of understanding mechanisms not just doing statistical experiments. It is an example of a situation that Weinberg has defined as "trans-science," * a problem in which it appears superficially that in principle science should be able to give concrete answers but, when examined in greater detail, exceeds the scope of any economically feasible scientific study.

Although now of somewhat less importance than in past decades, the overall questions of thermodynamic energy balance and stability in biological systems continue to occupy the attention of a small group of physicists in biology. Although the broad outlines of the physics involved in the intricate energy-transfer mechanisms have been established, major questions remain unanswered.

In fluid physics and rheology there also are problems. The dynamics of human body fluids are still inadequately understood and can pose significant problems in vascular surgery and repair and in the more ambitious organ-replacement projects now in developmental phases. In rheology, a wide range of open questions in regard to bone growth, muscle attachment, and the like need answers.

Biomedical engineering has become a specialty in its own right, stimulated by the pressures for improved man–machine interface designs in supersonic aircraft, space vehicles, and precision industrial production lines, as well as by more prosaic needs such as improved kitchen appliances. The design of artificial organs, prosthetic devices, and the like is another part of this field. Progress in the development of long-lived portable power

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* *Science*, *174*, 546–547 (Nov. 5, 1971).

sources and parallel progress in ultraminiaturization of semiconductor electronic components should lead to a greatly increased capability to mitigate human infirmities. Much of this work represents applied physics at its best.

One of the most difficult tasks in the biomedical engineering areas of bacterial colony analysis, brain scintigram analysis, blood-cell identification, chromosome analysis, and heart image extraction from a cardioangiogram is the extraction of relevant objects from an irrelevant background. The principal reason is that the pictures in these fields are often complicated by unwanted background, and object images are poorly defined. In recent years, computer processing of radiographic images has emerged as a highly promising technique.

Three aspects of biophysical instrumentation merit attention. The first involves instrumentation for clinical application in both diagnosis and treatment. Major progress is under way in clinical instrumentation; a modern hospital's intensive-care wing illustrates the vital role that physics research plays here. A second aspect of instrumentation involves biological and biochemical laboratories in which new techniques, devices, and approaches permit massive increases in both the speed and quality of measurement, thus making possible the extension of the most modern diagnostic aids to a much larger segment of the population. The techniques also facilitate ongoing research in biology, biochemistry, and biophysics. Third, advances in instrumentation open entirely new areas of biophysical research. Examples of devices that have led to major breakthroughs are the scanning electron microscope, the ultracentrifuge, and nuclear magnetic resonance.

There is more to a cup of coffee than you thought.

6 Observations of an Early Morning Cup of Coffee

Vincent J. Schaefer

An article from the American Scientist, 1971

If a cup of very hot black coffee is illuminated with a strong beam of light parallel to the surface, a number of extremely interesting chemical, physical, and optical phenomena can be observed. I first noticed these effects ten years ago along the edge of boiling hot pools at Yellowstone Park in the wintertime (*1*). A few years later I encountered them again while having coffee with my wife shortly after sunrise at the Research Center of the Museum of Northern Arizona, near Flagstaff.

At Yellowstone, the effects were often hard to see because moisture from the hot water condensing in the air obscured the surface of the pool much of the time. At Flagstaff, on the other hand, the clean air of the early morning and the brilliance of the rising sun provided ideal conditions for viewing the multiple effects which I will now describe.

When a cup is filled to the brim with black coffee (instant or otherwise) which is close to boiling and is viewed with good illumination, the first thing noticed is that the surface of the steaming coffee displays an irregular cellular pattern. The cells, in polygonal array, show cross sections of approximately 1 to 3 cm and appear to consist of dusty white areas outlined by narrow dark lines. These visible cells mark areas of rising columns of hot water, and the dark lines mark the region where the spreading, slightly cooled liquid is descending into the body of the coffee to form what are called Bēnard cells.

These convection cells are present in all liquids and gases that are unstable because they are hotter at the bottom than at the top. It doesn't matter whether the air or liquid is heated at the bottom or cooled at the top, so long as the temperature decreases toward the top. Related phenomena range in size from the microscopic dimensions first observed by the Frenchman Henri Bēnard in 1900 under his microscope to certain cloud patterns of the earth, water patterns in the sea, and even the granular structures of the sun.

On the surface of the hot coffee, the Bēnard cells are observable because of the phenomenon called Stefan flow. In fact, this is one of the most elegant ways to see the elusive phenomenon named after Joseph Stefan (1835-1893). The intense flux of water vapor molecules rising from the hot surface of the coffee exerts a positive upward force on the cooler atmosphere immediately above the surface of the liquid. Most of the water droplets that condense in the saturated air tend either to fall back into the liquid or to drift away into the air above and evaporate.

However, there is a certain size of droplet that is too large to escape from the microenvironment but too small for gravity to overcome the positive force of the upward thrust of vapor molecules arising from the surface of the hot liquid. These condensed particles are thus balanced between the field of gravity fall and the upward molecular thrust in such a way

Holt, Rinehart and Winston Photo by Russell Dian

that they are literally balanced or levitated above the surface of the hot coffee. At the boundaries of the cells, however, there is a negative vapor flux that prevents the balance of droplets and thus reveals the black surface of the coffee.

If observed under a low-powered binocular microscope, the dust-like patches of tiny water droplets over the rising current of hot coffee will be seen to consist of arrays of highly uniform, densely packed water droplets. Their size and height above the hot liquid is controlled by the combination of upward force, the number of effective nuclei in the region, and gravity fall.

That they are highly charged and thus stabilized can be shown by moving a charged object, such as a hard rubber comb, above the surface. Under these conditions all the suspended droplets suddenly disappear.

That their size and number are controlled by the presence of ambient condensation nuclei is shown by generating a larger number of nuclei by holding a lighted match below the edge of the coffee cup. When this is done, the concentration of particles suddenly increases, but they are noticeably smaller and are suspended closer to the surface of the hot liquid.

If, instead of a charged comb, a radioactive source is brought near the particles, they will also disappear as they coalesce and fall back into the liquid. However, the effect is much less dramatic than with the charged comb.

When illuminated with a strong beam of parallel light, such as the rising sun, a slide projector, or a strong flashlight, beautiful colors will be observed over the surface of the dark liquid when viewed in the direction of the illumination and close to the axis of the light beam. This phenomenon (*2*), called the High Order Tyndall Spectra, also produces the color in the corona surrounding the sun or moon when seen through a cloud composed of nearly uniform droplets and the so-called mother-of-pearl clouds occasionally seen when lenticular and other wave clouds, made up of small, uniform droplet size that appear red, blue, and green, are viewed in the direction of the sun.

Close observation of the surface of the hot, black coffee showing a nice array of Bénard cells will often disclose another phenomenon. With the cells delineated by the dark lines that mark the descending current of liquid, a dark line will suddenly cut across the grayish zones of levitated droplets. This is caused by a tiny whirlwind that develops in the rising hot, moist air, which locally possesses a superadiabatic lapse rate. The transient vortex is generally of very short duration, having a lifetime of milliseconds.

A very special and quite fascinating electrical phenomenon can be seen by the careful and adept experimenter. With a stable zone of balanced particles in equilibrium with the hot liquid and its surroundings, a charged object such as an electrified hard rubber comb, if not too highly charged, will produce a very dense stream of droplets that originate in an electric wind generated by the proximity of the charged object. Depending on the geometry of the charged object, this strange effect may consist of one or more streams of small droplets condensing on ions coming from the charged object. When I first observed this effect, it was generated by several teeth of a charged hard rubber comb.

While a cup of hot, black coffee is an ideal arrangement to see some or all of these phenomena, the effect dies away as the coffee cools. In order to study the effects for extended periods of time, I arranged the following set-up. An empty sardine can was cleaned, filled with water blackened with ink, and heated on a hot surface. A discarded but usable electric iron, held upside down with a clamp, was used as a hot plate. This arrangement permitted me to conduct experiments for as long as desired. A lantern slide projector served as an excellent light source, and a binocular microscope made it possible for me to see the packing size and other features of the floating droplets. Subsequently, I found that hot glycerine provided an improved substance for extended studies. The higher refractive index and very low vapor pressure permit experiments not easily carried out with water.

When the liquid becomes sufficiently heated so that droplets appear above the surface of the liquid, they may be removed by lifting them off in a vortex induced by holding a flat, stiff card or thin sheet of metal in a vertical position near the surface of the hot liquid. A very slight drift of air curling around the vertical edge of the thin sheet will start a vortex that will continue in the highly unstable air above the hot liquid.

If the surface of the liquid becomes contaminated, it sometimes will fail to show the phenomena. The surface may be cleaned by dropping a small piece of newsprint or other paper onto the surface of the liquid and immediately removing it. The contaminating monolayer, dust or other substance, will plate out onto the paper surface and adhere to it upon removal. Several successive applications of fresh paper may be necessary to clean the hot liquid surface. While the paper plating method is a very simple and effective method for cleaning films from liquid surfaces, a small Langmuir trough (*3, 4*) is more efficient for extended research studies.

It is, of course, quite easy to contaminate intentionally the coffee or other hot liquid surface in order to explore the effect of molecular coatings on the phenomena described. One might anticipate that a monolayer of hexadecanol (*5*), which is so effective in reducing the evaporation of water from water reservoirs, would prevent the formation of the floating droplets, but such a monolayer has no apparent effect on the evaporation of hot water. This apparently is due to the liquidity of the film. Since the melting point of hexadecanol is 49.3°C, hexadecanol in excess of a monolayer appears as a liquid lens rather than the small "islands" of powder which exude a very effective evaporation-reducing film when placed on cold water.

A visible film of indicator oil, however, which conversely is quite ineffective in reducing the evaporation of water from a water reservoir, is immediately effective in cutting off the Stefan flow effect.

One word of warning! It may be desirable to use glycerine or ink-colored water from the start. A number of my friends have accused me of conspiring to prevent them from enjoying their hot cup of coffee; they tell me that the effects are not only intriguing but they last until their coffee has lost that hot tang that tastes so good early in the morning!

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As a young man, Werner Heisenberg, later to become a famous physicist, was advised to choose music as a career. He explains here why he turned to science instead.

7

The Decision to Study Physics

Werner Heisenberg

A selection from Physics and Beyond: Encounters and Conversations, 1971

From school I did not go straight on to the university; there was a sharp break in my life. After my matriculation, I went on a walking tour through Franconia with the same group of friends, and then I fell seriously ill and had to stay in bed for many weeks. During my long recuperation, too, I was locked away with my books. In these critical months I came across a work that I found extremely fascinating, though I was unable to understand it fully. The author was the famous mathematician, Hermann Weyl, and the book was entitled *Space, Time and Matter.* It was meant to provide a mathematical account of Einstein's relativity theory. The difficult mathematical arguments and the abstract thought underlying that theory both excited and disturbed me, and, in addition, confirmed me in my earlier decision to study mathematics at the University of Munich.

During the first days of my studies, however, a strange and, to me, most surprising event took place, which I should like to report in brief. My father, who taught Middle and Modern Greek at the University of Munich, had arranged an interview with Ferdinand von Lindemann, the professor of mathematics, famous for his solution of the ancient problem of squaring the circle. I intended to ask permission to attend his seminars, for which I imagined my spare-time studies of mathematics had fully prepared me; but when I called on the great man, in his gloomy first-floor office furnished in rather formal, old-fashioned style, I felt an almost immediate sense of oppression. Before I could utter a word of greeting to the professor, who rose from his chair very slowly, I noticed a little black dog cowering on the desk, and was forcefully reminded of the poodle in Faust's study. The little beast looked at me with undisguised animosity; I was an unwelcome intruder about to disturb his master's peace of mind. I was so taken aback that I began to stammer, and even as I spoke it dawned on me that my request was excessively immodest. Lindemann, a tired-looking old gentleman with a white beard, obviously felt the same way about it, and his slight irritation may have been the reason why the small dog now set up a horrible barking. His master tried to calm him down, but the little beast only grew more hysterical, so that we could barely hear each other speak. Lindemann asked me what books I had recently been reading, and I mentioned Weyl's *Space, Time and Matter.* As the tiny monster kept up his yapping, Lindemann closed the conversation with "In that case you are completely lost to mathematics." And that was that.

Clearly mathematics was not for me. A somewhat wearing consultation with my father ended with the advice that I ought to try my hand at theoretical physics. Accordingly, he made an appointment with his old friend Arnold Sommerfeld, then head of the Faculty of Theoretical Physics at the University of Munich and generally considered one of the most brilliant teachers there. Sommerfeld received me in a bright study with windows overlooking a courtyard where I could see a crowd of students on benches beneath a large acacia. The small squat man with his martial dark mustache looked rather austere to me. But his very first sentences revealed his benevolence, his genuine concern for young people, and in particular for the boy who had come to ask his guidance and advice. Once again the conversation turned to the mathematical studies I had pursued as a hobby while still at school, and to Weyl's *Space, Time and Matter.* Sommerfeld's reaction was completely different from Lindemann's.

"You are much too demanding," he said. "You can't possibly start with the most difficult part and hope that the rest will automatically fall into your lap. I gather that you are fascinated by relativity theory and atomic problems. But remember that this is not the only field in which modern physics challenges basic philosophical attitudes, in which extremely exciting ideas are being forged. To reach them is much more difficult than you seem to imagine. You must start with a modest but painstaking study of traditional physics. And if you want to study science at all, you must first make up your mind whether you want to concentrate on experimental or theoretical research. From what you have told me, I take it that you are much keener on theory. But didn't you do experiments and dabble with instruments at school?"

I said that I used to like building small engines, motors and induction coils. But, all in all, I had never been really at home in the world of instruments, and the care needed in making relatively unimportant measurements had struck me as being sheer drudgery.

"Still, even if you study theory, you will have to pay particular attention to what may appear trivial little tasks. Even those who deal with the larger issues, issues with profound philosophical implications—for instance, with Einstein's relativity theory or with Planck's quantum theory—have to tackle a great many petty problems. Only by solving these can they hope to get an over-all picture of the new realms they have opened up."

"Even so, I am much more interested in the underlying philosophical ideas than in the rest," I said rather bashfully.

But Sommerfeld would have none of this. "You must remember what Schiller said about Kant and his interpreters: 'When kings go a-building, wagoners have more work.' At first, none of us are anything but wagoners. But you will see that you, too, will get pleasure from performing minor tasks carefully and conscientiously and, let's hope, from achieving decent results."

Sommerfeld then gave me a few more hints about my preliminary studies, and said that he might well come up with a little problem connected with recent developments in atomic theory on which I could try my mettle. And it was decided that I would join his classes for the next few years.

This, my first conversation with a scholar who really knew his way about in modern physics, who had personally made important discoveries in a field impinging on both relativity and quantum theory, had a lasting effect upon me. Though his call for care in small details struck me as eminently reasonable—I had heard it often enough from my own father—I felt dejected at the thought that I was still such a long way from the field that really interested me. No wonder that this interview became the subject of many discussions with my friends. I remember one of these particularly well: it bore on modern physics and the culture of our time.

That autumn, I saw a great deal of the boy who had played Bach's Chaconne so magnificently in Prunn Castle. We would meet in the house of our mutual friend, Walter, himself a fine cellist, and practice for a private recital of Schubert's B Major Trio. Walter's father had died at an early age, and his mother had been left to care for her two sons in a large and very elegantly furnished house in Elisabeth Strasse, just a few minutes' walk from my parents' house in Hohenzollern Strasse. The magnificent Bechstein grand in the living room was an added reason for our frequent visits. After we had finished playing, we would often talk deep into the night, and it was on one such occasion that the conversation came round to my proposed studies. Walter's mother wondered why I had not decided to make music my career.

"From the way you play and speak about music, I get the impression that you are much more at home with art than with science and technology, that you prefer the muses to scientific instruments, formulae and machinery. If I am right, why ever have you chosen natural science? After all, the future of the world will be decided by you young people. If youth chooses beauty, then there will be more beauty; if it chooses utility, then there will be more useful things. The decision of each individual is of importance not only to himself but to the whole of mankind."

"I can't really believe that we are faced with that sort of choice," I said rather defensively. "Quite apart from the fact that I probably wouldn't make a very good musician, the question remains in which field one can contribute most. Now I have the clear impression that in recent years music has lost much of its earlier force. In the seventeenth century music was still deeply steeped in the religious way of life; in the eighteenth century came the conquest of the world of individual emotions; in the nineteenth century romantic music plumbed the innermost depths of the human soul. But in the last few years music seems to have quite deliberately entered a strange, disturbed and rather feeble stage of experimentation, in which theoretical notions take precedence over the desire for progress along established paths. In science, and particularly in physics, things are quite different. Here the pursuit of clear objectives along fixed paths—the same paths that led to the understanding of certain electromagnetic phenomena twenty years ago—has quite automatically thrown up problems that challenge the whole philosophical basis of science, the structure of space and time, and even the validity of causal laws. Here we are on *terra incognita,* and it will probably take several generations of physicists to discover the final answers. And I frankly confess that I am highly tempted to play some part in all this."

My friend Rolf, the violinist, demurred. "As far as I can see, your remarks about modern physics apply equally well to modern music. Here, too, the path seems to be clearly mapped. The old tonal barriers are collapsing and we find ourselves on promising virgin soil, with almost complete freedom to choose what sounds and rhythms we like. Hence the musician has every chance of discovering as many riches as the scientist."

Walter now raised several objections of his own. "I don't really know whether 'freedom of expression' and 'promising virgin soil' are necessarily the same thing. At first sight it admittedly looks as if greater freedom must necessarily mean enrichment, wider possibilities; but this I know to be untrue in art, with which I am more familiar than with science. I would think that progress in art takes place in the following way: First a slow historical process transforms the life of men in spite of themselves, and thereby throws up fresh ideas. A few talented artists then try to give these ideas a visible or audible form by wresting new possibilities of expression from the material with which they work—from colors or musical instruments. This interplay or, if you like, this struggle between the expressive content and the limitations of the expressive medium is, I think, a *sine qua non* of the emergence of real art. If the limitations of the expressive medium were taken away—if in music, for instance, we could produce any sounds we liked—then the struggle would be over, and the artist's effort would reach into a void. For that reason I am skeptical about too much freedom.

"In science," Walter continued, "a continuous flow of new experiments is made possible by new techniques; there are new experiences and as a result new contents may be produced. Here the means of expression are the concepts by which the new ideas are grasped and made explicit. For instance, I have read that Einstein's relativity theory, which interests you so much, was born from the failure of certain experiments designed to demonstrate the motion of the earth through space by means of the interference of light rays. When this demonstration misfired, it became clear that the new results, or, what amounts to the same thing, the new ideas, called for an extension of the means of expression, i.e., of the conceptual system proper to physics. Quite likely, no one anticipated that this would demand radical changes in such fundamental concepts as space and time. It was Einstein's great achievement to appreciate before anyone else that the ideas of space and time were not only susceptible to change but, in fact, had to be changed.

"What you have said about recent developments in physics could reasonably be compared with developments in music in the middle of the eighteenth century. At that time, a gradual historical process had led to a growing awareness of the emotional world of the individual—as all of us know from Rousseau and later from Goethe's *Werther*—and it was then that the great classicists—Haydn, Mozart, Beethoven and Schubert—succeeded in extending the means of expression and so discovered the musical language needed for depicting this emotional world. In modern music, on the other hand, the new contents appear to be highly obscure and implausible, and the plethora of possible expressions fills me with deep forebodings. The path of modern music seems to be determined by a purely negative postulate: the old tonality has to be discarded because we believe that its powers have been exhausted, and not because there are new and more forceful ideas which it is incapable of expressing. Musicians are entirely in the dark about the next step; at best they grope their way forward. In modern science the questions are clearly posed, and the task is to find the right answers. In modern art, however, even the questions are uncertain. But perhaps you had best tell us a bit more about the new fields you intend to explore in the world of physics."

I tried to convey what little bits of knowledge I had gleaned during my illness, mainly from popular books on atomic physics.

"In relativity theory," I told Walter, "the experiments you have mentioned, together with other experiments, caused Einstein to discard the prevailing concept of simultaneity. That in itself was exciting enough. Every one of us thinks that he knows precisely what the word 'simultaneous' means, even if it refers to events that take place at great distances. But we are mistaken. For if we ask how one determines whether two such events are, in fact, simultaneous and then evaluates the various means of verification by their results, nature herself informs us that the answers are not at all clear-cut but depend on the observer's state of motion. Space and time are therefore not independent of each other, as we previously believed. Einstein was able to express the 'new' structure of space and time by means of a simple and coherent mathematical formula. While I was ill, I tried to probe into this mathematical world, which, as I have since learned from Sommerfeld, has already been opened up fairly extensively and has therefore ceased to be unexplored territory.

"The most interesting problems now lie in a different field, in atomic physics. Here we come face to face with the fundamental question why the material world manifests ever-recurring forms and qualities—why, for example, water with all its characteristic properties is invariably reproduced during the melting of ice, the condensation of steam or the combustion of hydrogen. This has been taken for granted in physics, but has never been fully explained. Let us suppose that material bodies—in our case, water—are composed of atoms. Chemistry has long made successful use of this idea. Now, the Newtonian laws we were taught at school cannot tell us why the motions of the particles involved should be as stable as they, in fact, are. Only quite different natural laws can help us to explain why atoms should invariably rearrange themselves and move in such a way as to produce the same substances with the same stable properties. We first caught a glimpse of these laws twenty years ago, in Planck's quantum theory. Since then, the Danish physicist, Niels Bohr, has combined Planck's theory with Lord Rutherford's atomic model. In so doing, he was the first to throw light on the curious stability of atoms which I have just mentioned. But Sommerfeld believes that in this sphere we are still a long way from a clear understanding of the ways of nature. Here we have a vast unexplored field, in which new relationships may be discovered for decades to come. By the appropriate reformulation of natural laws and with correct new concepts we might, for instance, be able to reduce the whole of chemistry to atomic physics. In short, I firmly believe that in atomic physics we are on the track of far more important relations, far more important structures, than in music. But I freely admit that 150 years ago things were the other way round."

"In other words," Walter asked, "you believe that anyone concerned with cultural progress must necessarily make use of the historical possibilities of the age in which he lives? That, if Mozart had been born in our day, he, too, would be writing atonal and experimental music?"

"Yes, I suspect just that. If Einstein had lived in the twelfth century, he would not have been able to make important scientific discoveries."

"Perhaps it is wrong to keep bringing up such great men as Mozart and Einstein," Walter's mother said. "Few individuals get the chance to play such decisive roles. Most of us must content ourselves with working quietly in a small circle, and ought to ask simply whether playing Schubert's B Major Trio is not more satisfactory than building instruments or writing mathematical formulae."

I agreed that I myself had quite a few qualms and mentioned Sommerfeld's quotation from Schiller: "When kings go a-building, wagoners have more work."

"We all feel the same way about it," Rolf declared. "Those of us who want to become musicians have to take infinite pains to master their instruments, and even then can only hope to play pieces that hundreds of better musicians have played much more proficiently. And you yourself will have to spend long hours with instruments that others have built much more competently, or retrace the mathematical thoughts of the masters. True, when all this has been done, the musical wagoners among us are left with no small sense of achievement: constant intercourse with glorious music and the occasional delight of a particularly successful interpretation. Likewise, you scientists will occasionally manage to interpret a relationship just that little bit better than anyone before you, or determine a particular process more accurately than your predecessors. But none of us ought to count on the fact that he will be doing trail-blazing work, that he will make decisive discoveries. Not even when he works in a field where a great deal of territory has still to be opened up."

Walter's mother, who had been listening attentively, now said something, more to herself than to us, as if she were trying to formulate her thoughts as she spoke:

"The parable of the kings and the wagoners may have quite a different import. Of course, superficially it looks as if the glory is entirely the kings', as if the wagoners' work were purely subsidiary and unimportant. But perhaps the very opposite is true. Perhaps the kings' glory rests on the work of the wagoners, on the fact that the wagoners have put in many years of laborious effort, reaping joy and success. Perhaps men like Bach or Mozart are kings of music only because, for two long centuries, they have offered so many lesser musicians the chance of reinterpreting their thoughts with love and conscientious attention to detail. And even the audience participates in this careful work as it hears the message of the great musicians.

"If you look at historical developments—in the arts no less than in the sciences—you will find that every discipline has long periods of quiescence or of slow growth. Even during these periods, however, the important thing is careful work, attention to detail. Everything that is not done with utter devotion falls into oblivion and, in fact, does not deserve to be remembered. And then, quite suddenly, this slow process, in which general historical developments introduce changes in the contents of a particular discipline, opens up new possibilities, quite unexpected contents. Talented men feel an almost magical attraction for the process of growth they can sense at work here, and so it happens that, within a few decades, a relatively small region of the world will produce major works of art or scientific discoveries of the greatest importance. In the late eighteenth century, for instance, classical music poured forth from Vienna; in the fifteenth and sixteenth centuries painting had its heyday in the Netherlands. True, great men are needed to express the new spiritual contents, to create the forms in which further developments can be molded, but they do not actually produce these new contents.

"Of course, it is quite possible that we are on the threshold of an exceptionally fruitful scientific epoch, in which case it would be wrong to dissuade any young man from participating in it. It seems unlikely that important developments will take place in more than one branch of art or science at one time; we ought to be grateful enough if it happens in any one area, if we can share in its glory either as bystanders or as active participants. It would be foolish to expect more. That is precisely why I find popular attacks on modern art—be it painting or music—so unjust. Once music and the plastic arts had solved the great problems posed to them in the eighteenth and nineteenth centuries, there just had to be a more restful period, in which much of the old could be preserved and new things were tested by trial and error. To compare modern compositions with the finest achievements of the great epoch of classical music seems utterly unfair. Perhaps we ought to finish the evening with the slow movement of Schubert's B Major Trio. Let's see how well you can play it."

We did as we were asked, and from the way in which Rolf played the somewhat melancholic C major figures in the second part of the movement, I could sense how sad he was at the thought that the great epoch of European music might be gone forever.

A few days later, when I walked into the hall where Sommerfeld usually gave his lectures, I spotted a dark-haired student with a somewhat secretive face in the third row. Sommerfeld had introduced us during my first visit and had then told me that he considered this boy to be one of his most talented students, one from whom I could learn a great deal. His name was Wolfgang Pauli, and for the rest of his life he was to be a good friend, though often a very severe critic. I sat down beside him and asked him if, after the lecture, I might consult him about my preparatory studies. Sommerfeld now entered the hall, and as soon as he started to address us Wolfgang whispered in my ear: "Doesn't he look the typical old Hussar officer?" After the lecture, we went back to the Institute of Theoretical Physics, where I asked Wolfgang two questions. I wanted to know how much experimental work had to be done by someone interested chiefly in theory, and what he thought of the respective importance of relativity and atomic theory.

"I know," Wolfgang told me in reply to my first question, "that Sommerfeld lays great stress on experimental studies, but I myself am not cut out for them; I hate the whole business of handling instruments. I quite agree that physics is based on experimental results, but once these results have been obtained, physics, at least modern physics, becomes much too difficult a subject for most experimental physicists. This is probably so because the sophisticated instruments of modern physics take us into realms of nature that cannot be adequately described with everyday concepts. We are forced to employ an abstract kind of mathematical language and one that presupposes a considerable amount of training in modern mathematics. It is a sad fact but true that we all have to specialize. I find abstract mathematical language quite easy, and hope to put it to good use in my work. Needless to say, I realize that some knowledge of the experimental side is absolutely essential. The pure mathematician, however good, understands nothing at all about physics."

I then repeated my conversation with old Lindemann, and told Wolfgang about his black lap dog and his reaction to my reading Weyl's *Space, Time and Matter.* My report obviously caused Wolfgang the greatest amusement.

"That's just what I would have expected," he said. "Weyl really does know a lot about relativity theory, and for Lindemann such knowledge is enough to disqualify anyone from bearing the title of serious mathematician."

As to the respective importance of relativity and atomic theory, Wolfgang had this to say: "The so-called special theory of relativity is now a closed chapter; you simply have to learn it and use it like any other theory in physics. Nor is it of particular interest to anyone anxious to make new discoveries. However, the general theory of relativity, or, what comes to much the same thing, Einstein's theory of gravitation, is still wide-open. But it is rather unsatisfying in that, for each experiment, it will give you a hundred pages of theory with the most complicated mathematical derivations. No one can really say whether the whole thing is correct. Nevertheless it opens up new possibilities of thought, and for that reason must be taken seriously. I have recently written a fairly lengthy article on the general theory of relativity; perhaps that is one of the reasons why I find atomic theory so much more interesting.

"In atomic physics we still have a wealth of uninterpreted experimental results: nature's evidence in one place seems to contradict that in another, and so far it has not been possible to draw an even halfway coherent picture of the relationship involved. True, Niels Bohr has succeeded in associating the strange stability of atoms with Planck's quantum hypothesis—which has not yet been properly interpreted either—and more recently Bohr is said to have given a qualitative explanation of the periodic system of the elements and of their chemical properties. But I can't for the life of me see how he could have done so, seeing that he, too, is unable to get rid of the contradictions I have mentioned. In other words, everyone is still groping about in a thick mist, and it will probably be quite a few years before it lifts. Sommerfeld hopes that experiments will help us to find some of the new laws. He believes in numerical links, almost in a kind of number mysticism of the kind the Pythagoreans applied to the harmony of vibrating strings. That's why many of us have called this side of his science 'atomysticism,' though, as far as I can tell, no one has been able to suggest anything better. Perhaps it's much easier to find one's way if one isn't too familiar with the magnificent unity of classical physics. You have a decided advantage there," Wolfgang added with a malicious grin, "but then lack of knowledge is no guarantee of success."

Despite this little broadside, Wolfgang had confirmed everything I myself had been thinking before I decided to make physics my career. I was very glad not to have tried my hand at pure mathematics, and I looked back on Lindemann's little dog as "part of that power which still produceth good, whilst ever scheming ill."

Some artistic responses to science and technology — Expressionism, Futurism, and the Bauhaus.

8 Science and Modern Art

Dietrich Schroeer

A chapter from Physics and Its Fifth Dimension: Society, 1972

Blue is the masculine principle, robust and spiritual. Yellow is the feminine principle, gentle, serene, sensual. Red is matter, brutal and heavy.

Franz Marc

The suffering of a man is of the same interest to us as the suffering of an electric lamp, which, with spasmodic starts shrieks out the most heartrending expression of color.

Umberto Boccioni

Yellow light has a wavelength of 0.000052 centimeters.

Textbook on optics

This chapter contains an examination of the response of painters and allied artists to science and technology in the early 20th century. The German Expressionists exemplify a retreat to an organic nature, while the Italian Futurists represent an exploration of the feelings induced by modern technology. The Bauhaus is presented as an example of a successful fusion of art and technology.

INTRODUCTION

This chapter will explore the impact of science and technology on painters and architects during the first third of this century. Needless to say, it is not very easy to establish any direct connection between these very different human activities. In addition, the approach and interpretation will necessarily be quite personal and subjective. Since there is then the possibility that I may be trying too hard to make the facts fit a preconceived conclusion, this whole discussion must not be taken too seriously. The overall objective will be to try to outline possible artistic responses to science and technology and, in the process, to convey the atmosphere in which the modern scientific revolution was taking place.

TECHNOLOGY AND ART: 1900–1933

The paintings I like best date from the period 1900-1933. My two favorite paintings were painted in 1914; *Three Riders*, by Wassily Kandinsky, and *Tyrol*, by Franz Marc. I have at times wondered why my preference should lie there. One guess is that this is so because this period contains many varied responses to the ever-increasing pervasiveness of science and technology.

Science has always had some interaction with painting; Goethe with his *Theory of Colors* is a prime example of this. There was, of course, a great change in painting in the later part of the 19th century due in part to the introduction of photography, which eliminated the need for painting as a faithful record of the visible (see, e.g., Ref. 15.4). Painting then became more and more a subjective and ultimately nonrepresentational picture of what the artist felt rather than a picture of the objects which he saw. The Impressionists were in some ways the forerunners of this subjectivity. Georges Seurat, for example, studied the separation of white light into its component colors and found that color mixing could be done by the eye as well as directly on the canvas; thus his pointillism consisted of putting small spots of pure color on the painting and letting the observer's eye and brain carry out the fusion. Analysis of the observer's role in the visual process was carried even further by Van Gogh, particularly in his last pure-color pictures of 1888-90. The subjective trend then went through the French Fauvists (wild beasts), like André Derain, to the German Expressionists like Marc, Kandinsky, and Ernst L. Kirchner, and the Italian Futurists like Umberto Boccioni and Gino Severini. It has continued with the Cubists like Pablo Picasso, Georges Braque, and Fernand Leger and on to Bauhaus painters like Klee and Feininger. Contemporary with the latter painters is the art-artisan movement of the Bauhaus following the First World War, and the architecture of Le Corbusier, Mies van der Rohe, and Frank Lloyd Wright. All these movements put more and more of the painter's subjective

impressions into the paintings, in particular his reaction to the increasingly more technological surroundings. And the three movements of the Expressionists, the Futurists, and the Bauhaus are particularly interesting because they reveal the three alternate reactions of retreat, absorption, and integration.

EXPRESSIONISM

In Germany the Expressionistic movement after 1900, such as the Blaue Reiter in Munich, reacted to science and technology by retreating to an organic nature, by painting landscapes and animals with background of fantasy.

The attitude in 1912 of the Russian-born painter Kandinsky (Fig. 15.1) may be characterized by his concern with the human soul:

> On the basis of a deeply felt criticism of the materialistic structure of the contemporary world, he strove to ferret out and combat every form of materialism in art. The modern sciences had transmuted the material substance of things into symbols of energy; in painting Matisse had liberated colour from its function of signifying objects and giving it a spiritual significance. Picasso had done the same for form. For Kandinsky these were 'great signs, pointing to a great goal.' From all this he drew his own conclusion: 'The harmony of colours and forms can be based on only one thing: a purposive contact with the human soul.' The expressive resonance of pure coloured forms provided the painter with a means of making visible the inner resonance of things, their vibration in the human soul. The vibrations of the soul can be raised to the surface and made visible by pure pictorial harmonies uncluttered by objective or metaphoric images, just as they are made audible by the pure sounds of music. . . . These were the ideas that moved Kandinsky's friends to cast off their ties with the images of the visible world and to discern the reflections of a higher world in the responsive stirrings of their psyche. For these ideas did not revolve exclusively round 'art,'

◄ **Fig. 15.1** *Lyrisches* by Wassily Kandinsky (1911). (Photo courtesy of Museum Boymans-van Beuningen, Rotterdam.)

> but were embedded in a religious intimation of an encompassing Being, at the centre of which, between the earthly things of nature and the transcendent realities above them, stood man, endowed with antennae that enabled him to enter into communication with the whole. (Ref. 15.5, p. 117)

So Kandinsky retained a sense of fairy-tale fantasy, combined it with the resonances of colors in the soul, and by 1914 was able to break away completely from any representational content in his paintings.

Marc was even more strongly motivated by a dread of the technological world, by a fear of losing any bonds with the reality of nature. So to him the key symbols were animals; he felt that animals were embedded in the great rhythms of nature (Fig. 15.2). The colors of his animals, as in the *Tiger* or the *Blue Horses*, always represented the spiritual essence of their nature. As his paintings became more abstract, nature and world were not excluded, but rather transposed into the wider dimension of the whole modern spirit. Along with Marc at Verdun in 1916, the whole Expressionist movement in painting died in World War I. But its spirit continued in many other fields, particularly in architecture, as will be pointed out later.

FUTURISM

The Italian parallel to Expressionism was Futurism, lasting from about 1908 to 1914. "The Futurists were not only the first artists to take cognizance of the dynamism of a technological society, but they also produced works of art of extraordinary emotional impact. They translated the kinetic rhythms and the confused, intense sensations of modern life into potent visual form." (Ref. 15.1, p. 7.) Fillippo Tommaso Marinetti in Milan in 1909 wrote the founding manifesto, which cried in part "burn the museum," "drain the canals of Venice," as a protest against the older styles of painting. Beyond this protest was a new ideal in art. The modern world was to be typified by the automobile with its violently pulsing, noisy life; the staggering speed of this mechanical achievement was to replace the classical characterizations of the mythical horse Pegasus. As Marinetti put it:

> We declare that the world's splendour has been enriched by a new beauty; the beauty of speed. A racing motor car, its frame adorned

Fig. 15.2 Jumping Ponies by Franz Marc (1913). (Photo courtesy of Bernard S. Myers.) The New York Public Library, Astor, Lenox and Tilden Foundations

> with great pipes, like snakes with explosive breath . . . a roaring motor-car, which looks as though running on shrapnel, is more beautiful than the *Victory of Samothrace*. . . . We shall sing of the great crowds in the excitement of labour, pleasure and rebellion . . . of bridges leaping like gymnasts over the diabolical cutlery of sunbathed rivers . . . (From the Sackville exhibition catalog, London, March 1912, as quoted in Ref. 15.1, p. 124.)

The painter Severini said:

> We choose to concentrate our attention on things in motion, because our modern sensibility is particularly qualified to grasp the idea of speed. Heavy powerful motor cars rushing through the streets of our cities, dancers reflected in the fairy ambiance of light and color, airplanes flying above the heads of the excited throng. . . . These sources of emotion satisfy our sense of a lyric and dramatic universe, better than do two pears and an apple. (From the Marlborough Gallery catalogue, London, April 1913, as quoted in Ref. 15.1, p. 11.)

And Boccioni:

> We cannot forget that the tick-tock and the moving hands of a clock, the in-and-out of a piston in a cylinder, the opening and closing of two cogwheels with the continual appearance and disappearance of their square steel cogs, the fury of a flywheel or the turbine of a propeller, are all plastic and pictorial elements of which a Futurist work in sculpture must take account. The opening and closing of a valve creates a rhythm just as beautiful but infinitely newer than the blinking of an animal eyelid. (Translated by R. Chase, as quoted in Ref. 15.1, pp. 131–132.)

The Italian Futurists were fighting estrangement from the world—the lonely isolation of the individual that was not only the inheritance of the artist but a common threat to modern man. They wanted their art to restore to man a sense of daring, an assertive will rather than submissive acceptance. "We want to re-enter life,"

Fig. 15.3 *Study for Dynamic Force of a Cyclist II* by Umberto Boccioni ▶ (1913). (Photo courtesy of Yale University Art Gallery, gift of Collection Société Anonyme.)

Fig. 15.4 *Street Light* by Giacomo Balla (1909), oil on canvas, 68-3/4 × 45-1/4″. (Photo courtesy of the Collection of the Museum of Modern Art, New York, Hillman Periodicals Fund.)

they said, and to them life meant action. "Dynamism" was the magic word to them. The Futurists wanted to put the spectator in the center of the picture. "We Futurists," said Carlo Carra, "strive with the force of intuition to insert ourselves into the midst of things in such a fashion that our 'self' forms a single complex with their identities." This is like the Expressionists, but with more emphasis on the mechanical innovations rather than on an escape into the animal world. And their works bear such titles as *Cyclist*, by Boccioni (Fig. 15.3), *Abstract Speed—Wake of Speeding Automobile*, by Giacomo Balla, *Expansion of Lights*, by Severini, and *The Street Light—Study of Light* (Fig. 15.4), by Balla. Dynamic action is indicated by multiple images, by rays of light interrupted by action, and by the conflict of separated colors. Balla, who was interested in all scientific matters, was so fascinated by astronomy that the vision of the planet Mercury passing before the sun as it might be seen through a telescope served in 1914 as inspiration for one of his happiest series of paintings. "The form/force," said Boccioni, "is, with its centrifugal direction, the potentiality of real form"; obviously the language of the Futurists itself owes debts to the sciences. The confrontation with technology is direct; man clearly must bend technology to his own will.

This attempt by the Futurists to absorb technology into art also came to an end with World War I. To them in 1914 the war promised to be the ultimate awakening and unifying force. Several of them signed up in the bicycle messenger corps; and some died in the war, terminating the movement, a movement which in any case could by its very nature probably not have survived the postwar period.

THE POSTWAR BAUHAUS MOVEMENT

After the war, there was a great confrontation of society with cruel reality; in Germany, for example, by 1924 it took a wheelbarrow full of billion-mark bills to buy a loaf of bread. In this atmosphere there could no longer be a complete retreat from technology. And an institution developed in 1919—the Bauhaus, or House of Building—which attempted to unite the arts and industry/technology. The Bauhaus was founded by Walter Gropius in Weimar, the residence long before of Goethe, and the place where the constitution of the new German Republic was drawn up after the war. Although the Bauhaus movement included many artists, such as Kandinsky and Klee, who had been involved in the Expressionist movement before the war, it was started by Gropius to become a consulting art center for industry and the trades. In every subject the students were to be trained by two teachers, an artist and a master craftsman. And these students, once familiar with science and economics, quickly began to unite creative imagination with a practical knowledge of craftsmanship, and thus to develop a new sense of functional design.

Not that the Bauhaus was the first to try the combination of art and design. There were, for example, in the middle of the 19th century attempts in Great Britain to provide this kind of synthesis. But those were failures because the products were not mass-producible. Somehow the genius of Gropius avoided this problem at the Bauhaus. The artistic instruction included the theory of form and color, mathematics, and physics; rigorous analyses of lines and planes and space were attempted by Klee, Kandinsky, and Laszlo Moholy-Nagy. The technical skills were produced both by workshops and by industrial experience. The students were not just idealists, but included many veterans of the war who were searching for a meaning of life. It is this contact with reality, through industrial work, for example, which made the Bauhaus so successful.

The fate of the Bauhaus was symbolic of its time. In 1925, when the political climate in Germany was particularly bad, the Bauhaus left conservative Weimar and moved to Dessau. In 1928 Walter Gropius left; in 1933 overnight the Nazi regime locked the doors. The impact of the Bauhaus—of the fusion of art with science/technology—is, however, still with us. Our modern tubular metal chairs are frequently based on Bauhaus designs, as are many of our advertisements, fabrics, and much of our architecture.

OTHER EXAMPLES OF SCIENCE AND ART

There are many other interesting traces of the sciences in art and architecture during the postwar period. Worthy of special note are three:

1. There is the Expressionistic architect Erich Mendelsohn, who in the period 1917–1920 constructed the Einstein tower near Potsdam as an observatory to run tests on the general theory of

relativity, fusing Expressionism with the grandeur of the Einsteinian concept (see Fig. 16.1.).

2. There is the architect Rudolf Steiner, who in his younger years edited Goethe's works and whose views were hence strongly colored by Goethe's views on science. These viewpoints are incorporated into Steiner's Expressionistic buildings Goethenaum I and II.

And, finally,

3. Le Corbusier took mathematical proportions along the lines of Pythagoras, and the idea of modularity from crystallography, to form his concept of a modulator—a series of proportional sizes based on man to build up all dimensions of buildings. While he used technological products, Le Corbusier's architecture was very much man-oriented.

Note the parallel in the interest of Goethe as a poet-scientist and in Einstein as a philosopher-scientist.

We could also speak of Cubism in painting, with its attempts to modularize the areas of paintings, which then led to the work Mondrian and his squares and rectangles. As a final example there is the painter Leger. Before the First World War he tried many styles of painting, none of which seemed satisfactory. Then came his wartime service in an engineering unit, where he came in close contact with men who felt at home with technology. Their optimism about the machine world inspired him:

> He felt that as an artist his task was to discover forms of expression appropriate to modern life. The shining, precise, abstract beauty of the machine provided a visual point of departure. He understood that the mechanical thing possessed a representative value as the truest creation of modern civilisation and that the images derived from it could become evocative emblems of the modern industrial world. (Ref. 15.5, p. 253)

After the war he integrated industrial objects into his art as motifs to evoke modern esthetics. The gleaming machine, the concreteness of wheels, and the dynamism of repeated motion—all these are reflected in Leger's works (Fig. 15.5).

Fig. 15.5 Three Women by Fernand Léger (1921), oil on canvas, 72-1/4 × 99″. (Photo courtesy of the Collection of the Museum of Modern Art, New York, Mrs. Simon Guggenheim Fund.)

SUMMARY

We might sum up this chapter as follows. Adding to the whole atmosphere of the period 1900 to 1933 was a confrontation between the individual artistic intellect and science/technology. This confrontation profoundly influenced the arts of the period. Some artists, like the German Expressionists, rebelled against technology by retreating to a more organic view of nature, by making something fairy-tale-like of the technology; for example, in Expressionist pictures, railroads always look like toys. Other artists, like the Italian Futurists, tried to absorb technology rather than confronting or avoiding it; for example, the Futurist's railroads look like dynamic machines. Neither of these cases necessarily involved a deep understanding of the basic scientific trends. Nonetheless, these were profound cultural reactions to the new science-based industrial age. The third, and most successful approach, was the attempt by the Bauhaus to totally integrate the arts and industry. The resultant impact is still enormously visible in all of industrial designing. Nonviolent confrontations of the two cultures can indeed be quite productive.

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Interesting reading

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QUESTIONS FOR DISCUSSION

1. It has been suggested that the impression we have of people's faces is actually a time average, and that this is the reason why paintings are better portraits than photographs (which record one instant). Is this indeed the difference?
2. Painters use such words as "resonance" and "vibration." Do they know the scientific meaning of what they are saying? Does it matter whether they understand these words?
3. What is Op art? Does contemporary art include a response to science?
4. Is the artist's response primarily to science or to technology?
5. Should we make artists study physics?
6. Why do artists continually refer to the science of Goethe rather than to that of Newton? Why do artists such as Dali make portraits particularly of Einstein?

What is symmetrical, what is not, and how you can tell is discussed in this article. The concept of symmetry turns out to be of surprising importance and continuing interest in physics.

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9 Symmetry

Donald F. Holcomb and Philip Morrison

A chapter from My Father's Watch: Aspects of the Physical World, 1974

A. SYMMETRY* "Symmetry" is a word with pleasant and orderly connotations to the civilized mind. But symmetry provides, as well, an organizing principle of considerable power in collecting certain knowledge about the behavior of the physical world. The purpose of this nearly self-contained special topic is to explore that knowledge.

The Balance and Symmetry

We begin with a dicussion of one of the simplest of all measuring instruments, the balance, and view it as seen by Archimedes. Archimedes (287–212 BC) was a resourceful scientist, but he was practically innocent of any knowledge of forces, weights, lever arms, and the like. He approached the "why" of the behavior of the simple, equal-arm balance on the basis of arguments about symmetry and the principle of insufficient reason.

Consider the equal-arm balance shown in Fig. A.1 with identical weights on the two sides. Archimedes took the position that since the physical system is initially completely symmetrical—i.e., the two sides are mirror images of one another—there is no reason why it should turn one way or the other. Hence, it remains balanced. (This is the meaning of the term "principle of insufficient reason"—there is insufficient reason for the system to go one way or the other.)

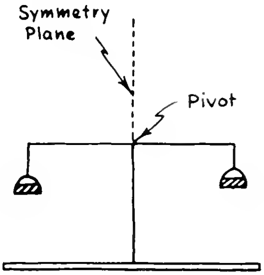

Figure A.1

The equal-arm balance shows symmetry on the two sides of a plane which passes through the pivot point.

Q. We know very well that it is possible to have such a system balanced with weights that are *not* identical, at least in appearance. For example, one weight could be made of lead, the other of aluminum. Does this possibility destroy Archimedes' argument?

In passing, we note that the reflection symmetry (i.e., one-half the system is a mirror image of the other half) which we tacitly recognize in the case of the balance is everywhere around us. Most animals have approximate reflection symmetry about a central plane. We shall shortly discuss carefully the precise method of characterizing the reflection symmetry. For the moment, we ask, are animals *really* symmetrical? Is the reflection symmetry perfect? The answer is, of course, "No—there are many small asymmetries, as we note for the human animal if we look at ourselves in a double mirror." But we recognize the overwhelming validity of the approximation of symmetry, despite small deviations.

Experiment: In the quiet of your room, try to arrange a set of mirrors so that you can see your face and its mirror image side-by-side. How true is your own reflection symmetry?

Figure A.2 shows a sketch of one of the few animals that deviates significantly from reflection symmetry—the flounder. This fellow's mouth and eyes seem to us to be misplaced, so accustomed are we to the symmetrical appearance of animals.

Recognizing that in this argument about symmetry Archimedes was dealing with the special case of reflection symmetry, we now return to further consideration of the balance, to develop his arguments a bit further.[1]

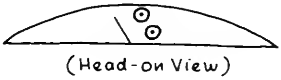

Figure A.2

A sketch of the flounder, a rare example of an animal that lacks reflection symmetry.

Consider the arrangement of a balance beam and four identical weights sketched in Fig. A.3a. Should this arrangement balance, on the basis of Mr. A's appeal to symmetry? It is clearly not an arrangement with exact reflection symmetry. But now we introduce an additional argument: "Symmetrical motion of two identical weights about the center line of the two maintains the balance condition." That is, by

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[1] Ernst Mach's famous book, *The Science of Mechanics*, London: Open Court Publishing Co., 1942, pp. 13–20, gives a careful discussion of the strengths and weaknesses of Archimedes' approach to the problem.

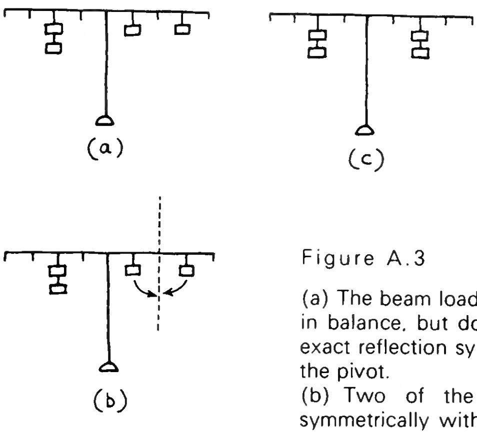


Figure A.3

(a) The beam loaded with four weights is in balance, but does not appear to have exact reflection symmetry with respect to the pivot.
(b) Two of the weights are moved symmetrically with respect to the dotted line.
(c) The movement of the two weights maintains balance, and also produces reflection symmetry.

means of the operation suggested by Fig. A.3b, moving one weight one direction and an equal weight the other direction by the same distance, bringing us to the configuration of Fig. A.3c, we assert that we shall not change the balance condition. Since we have reduced the situation to one of obvious reflection symmetry, it must also follow that the configuration of Fig. A.3a was also in balance. Archimedes apparently used an argument of this sort in an attempt to reduce any situation to one of self-evident symmetry by means of what he considered a "reasonable" procedure.

Q. Consider the initial situations shown in Fig. A.4a and A.4b. Apply the scheme outlined in the discussion of Fig. A.3 to move weights in each of the configurations of Fig. A.4 in order to reduce these configurations to ones with clear reflection symmetry. That is, move 2 weights at a time symmetrically about their midpoint, toward one another or apart, in an operation similar to that of Fig. A.3b. Sketch the final configuration in each case.

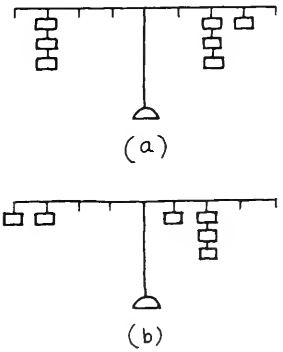


Figure A.4

The sketches labeled (a) and (b) show two examples of a beam which is balanced but has an apparently asymmetric arrangement of weights. Suitably symmetric movement of the weights, two at a time, can maintain balance and also move toward a symmetrical arrangement of weights for either example.

Symmetry of Appearance vs. Symmetry of Physical Effects

More extensive investigation of physical systems quickly shows us that we must be careful not to infer that visual reflection symmetry automatically guarantees reflection symmetry of all physical effects connected with the system. By implication, we have ascribed such a position to Archimedes.

Suppose one has a wire that is to carry an electric current, as shown in Fig. A.5a. The light arrows indicate the direction the electric current will take when we turn it on. (One need know nothing about the nature of electric current to follow this example, only to accept the fact that the current consists of something which flows, and thus has a flow *direction* associated with it. In practice, one might produce the current by connecting two ends of the wire to a battery; then the current could be reversed simply by reversing the connections to the two terminals of the battery.) Above the wire is placed a compass needle, which we align parallel to the wire before switching on the electric current. We could achieve this arrangement on the Earth's surface by aligning the wire in the direction in which the compass needle naturally points—i.e., toward magnetic north. This configuration, Fig. A.5a, appears to have reflection symmetry about the dotted plane shown; as with the balance, there is nothing to distinguish right from left. However, when the current is passed through the wire, we find that the compass needle takes up a position something like that shown in Fig. A.5b. If the current is reversed, the configuration in Fig. A.5c results. Neither configuration A.5b nor A.5c possesses the reflection symmetry of the original arrangement, and we appear to have a breakdown of the principle of insufficient reason.

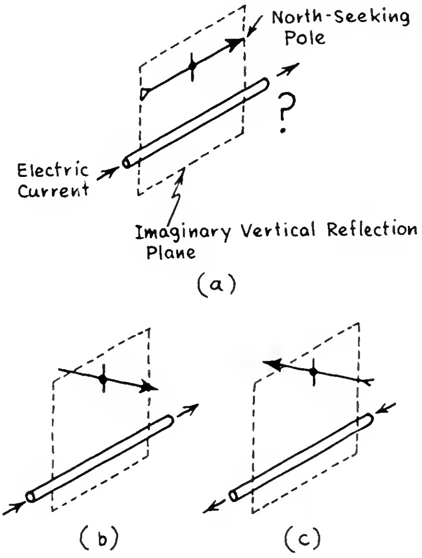


Figure A.5

(a) A compass needle and current-carrying wire are arranged so as to lie in a single vertical plane.
(b) As the current is turned on, the compass needle swings in such a fashion that the initial reflection symmetry is destroyed.
(c) Reversing the current reverses the direction of the compass needle.

What do the results of this imagined experiment show? Two possibilities are obvious.

1. The principle of insufficient reason is itself fundamentally flawed.
2. Some aspect of the system, not immediately apparent to the human eye, destroys the reflection symmetry that Fig. A.5a suggests.

Possibility (2) turns out to be the correct one. We shall eventually return to discuss in some detail the property of the compass needle that is not immediately apparent. First, however, we discuss the common types of geometrical symmetry and their use in describing properties of natural systems.

Geometrical Symmetry

We now want to explore systematically the use of symmetry as a useful concept for organizing observations. Before doing so, we must engage in the very characteristic scientific activity of describing carefully the meaning of the term in question. Rather than attempt to produce a definition of symmetry in the Websterian sense, we shall define the term by answering the following question: "How can one describe unambiguously the symmetry properties of an object?" The answer gives our definition.

The symmetry properties of an object are described by cataloging all the operations one can perform on the object which leave it indistinguishable from its original form.

Some examples of operations one might perform on an object to test its symmetry properties are as follows:

1. Movement through space without reorientation.
2. Reorientation about some axis in space.
3. Imaging in a mirror.
4. Inversion (to be defined later—this term has a specific meaning that is difficult to render in everyday language).

More formally, if one performed one of these operations and found the object's appearance to be indistinguishable from its appearance before the operation was performed, he would say, "The object does not change under the operation of

1. translation, or
2. rotation, or
3. reflection, or
4. inversion."

(The numbers in the two lists correspond.) We shall investigate these four symmetry operations in varying degrees of detail. Our chief aim will be to understand the interplay between the ideas of symmetry gained from dealing with abstract geometrical forms and the application of those ideas to the real physical world around us.

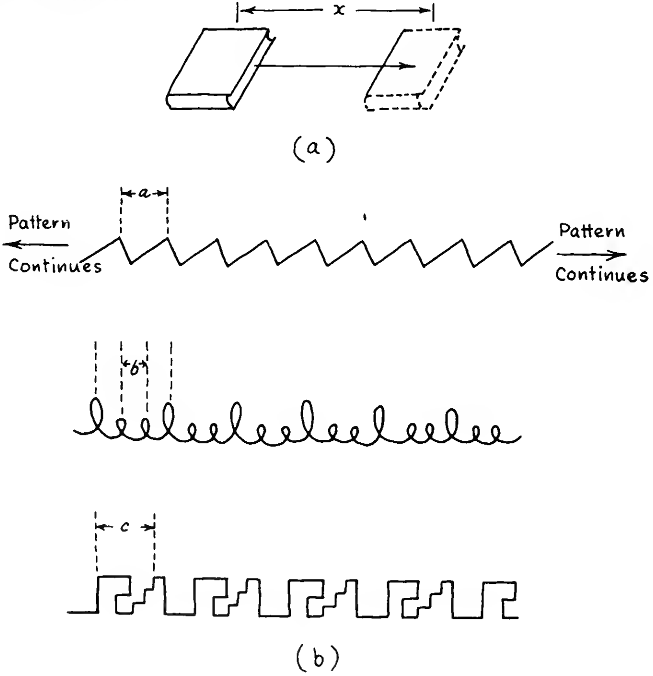
Translation

The operation of "translation" is perhaps the simplest of all—we move the object of interest through space without reorienting it. Suppose we perform a translation of a book by a distance X. Figure A.6a sketches the operation. Are the book's properties distinguishable from those it had before the operation? Yes and no. The book is obviously in a different position with respect to its background. However, various physical experiments would find the book to behave identically. The equivalence of one point in space to any other point, so far as the laws of physics are concerned, is at once a trivially obvious and deeply fundamental fact.

Rather than pursue that one, however, we turn to a rather different, but practically more important example. Consider the three patterns shown in Fig. A.6b. We assume that these repeating patterns extend indefinitely far out of the figure to both left and right. Consider the first pattern, for example. A translation of the whole pattern by some dis-

Figure A.6

(a) A book is translated by distance X. No other change takes place.
(b) Three repetitive patterns are sketched. We say that each of these patterns has symmetry under translation by some characteristic distance.



tance to right or left will, in general, produce a pattern visibility distinct, since the zigs and zags would be in different places. However, if we displace the pattern by a distance *a*, or any multiple thereof, it will appear not to have been changed, since all zigs and zags will appear in the same positions. Therefore, the first pattern of Fig. A.6b has translation symmetry under displacement by distance *a*.

Q. By what distances could you displace the second and third patterns in Fig. A.6b and still leave each of them indistinguishable from its original form?

Although they are interesting primarily to the artist and artistic analyst, we cannot resist the temptation to call attention to the many interesting examples of the use of translational symmetry to produce aesthetic effects in various forms of decoration. Figure A.7 shows two of these.[2] Figure A.7a shows a photograph of the Doge's Palace in

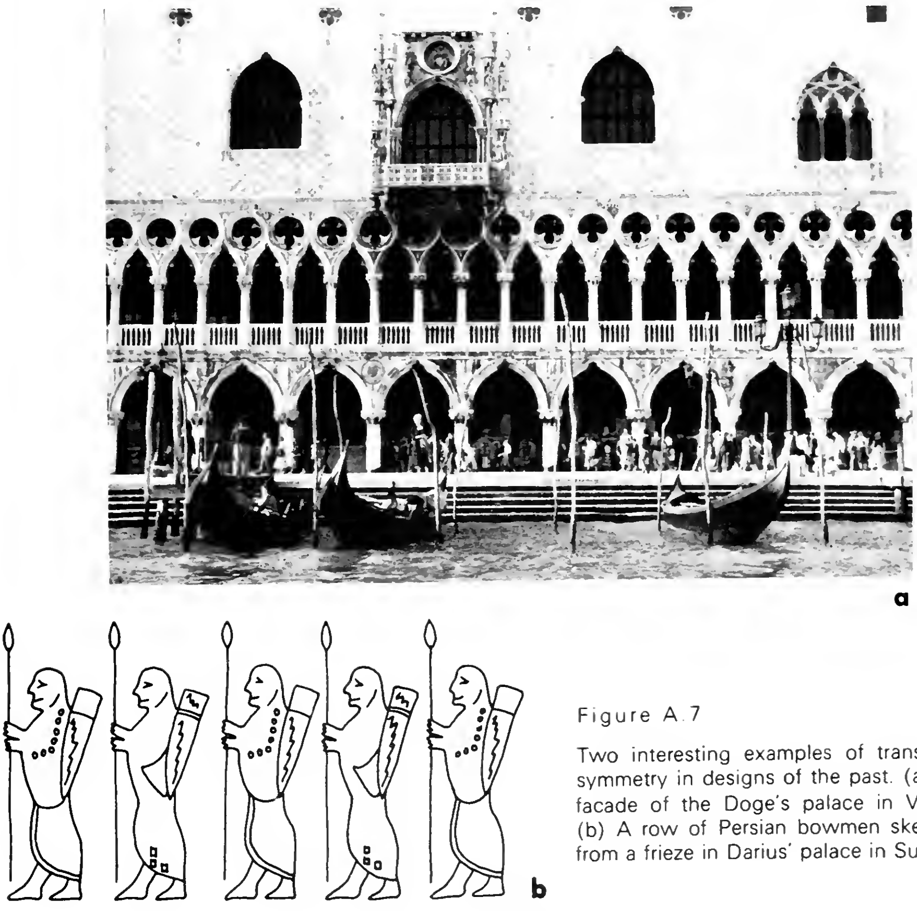


Figure A.7

Two interesting examples of translation symmetry in designs of the past. (a) The facade of the Doge's palace in Venice. (b) A row of Persian bowmen sketched from a frieze in Darius' palace in Susa.

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[2] These examples are noted in Herman Weyl, *Symmetry*, Princeton: Princeton University Press, 1952, pp. 49, 50

Venice; Fig. A.7b is a sketch of a pattern in a frieze of Persian Bowmen from Darius' palace in Susa.

Q. What is the repetition distance in the Bowmen pattern of Fig. A.7b?

In physical science, perhaps the most useful application of the ideas of translation symmetry comes in the field of crystallography, which is the analysis and description of the forms taken by natural crystalline materials. These crystalline materials are made up of three-dimensional arrays of fundamental building blocks, and the specification of the translational repetition distances is an indispensable scheme for describing the characteristics of a particular crystal. Figure A.8 shows models of sections of three different crystals, each of which is made up of one or two kinds of atoms. As with the one-dimensional examples in Fig. A.6, we assume that the models extend indefinitely in all directions.

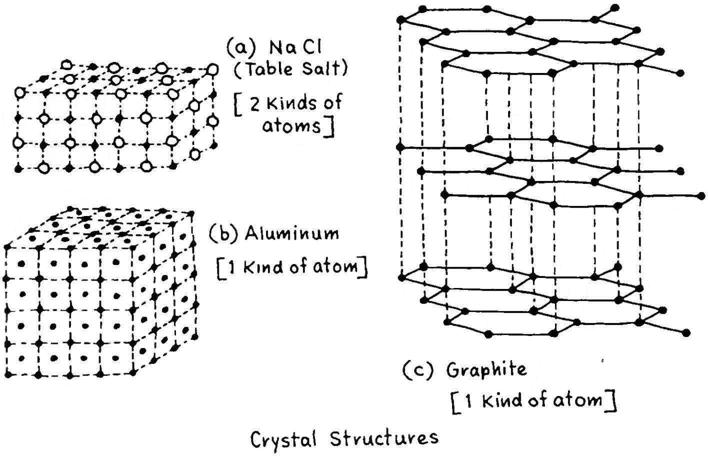


Figure A.8

Crystal structures show repeating patterns, and thus have translational symmetry under certain movements. (a) Model of sodium chloride crystal structure. (b) Aluminum has a different but still simple structure. (c) The graphite structure is more complicated.

Q. Can you describe the translational symmetry properties of the atomic lattices of sodium chloride and aluminum shown in Fig. A.8? That is, what translation distances, in what directions, will cause the structure to overlay precisely its original configuration?

Rotation About an Axis

Another operation we can perform on an object is rotation about some chosen axis. Figure A.9 shows two plane figures, a square and an equilateral triangle. If we rotate the square about an axis through its center, which is perpendicular to the plane of the square, we find that the figure is indistinguishable from its original form whenever the rotation angle is some multiple of 90°. Thus, in one full revolution there are four indistinguishable positions. We describe this property by saying, "The square has a four-fold rotation symmetry about an axis through the center and perpendicular to the plane of the square." In the case of the equilateral triangle, the repetition period is 120° rather than 90°. We say, "The equilateral triangle has a three-fold axis through its center."

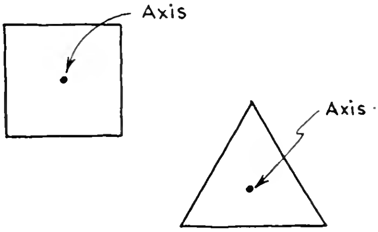


Figure A.9

We imagine rotating these simple figures about a vertical line passing through the axis spot.

Q. 1. Do all triangles have this three-fold axis? If not, can one say anything in general about the rotational symmetry of triangles?

2. Sketch a two-dimensional figure with a two-fold axis, and one with a six-fold axis.

Note carefully that one must always specify the axis about which the rotation takes place. The axis is often so obvious in the case of highly symmetrical figures that one tends to forget its importance. But consider Fig. A.10. We have chosen an axis through one corner of

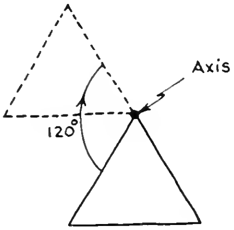
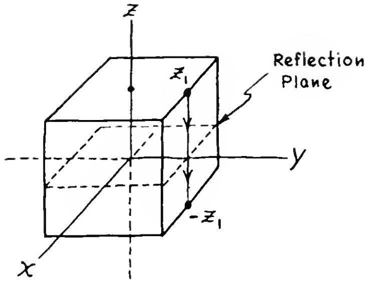


Figure A.10

An equilateral triangle rotated about an axis through one corner does not exhibit three-fold symmetry.

Figure A.11

The operation of reflection with respect to the x–y plane is carried out by changing the sign of the z-coordinate for each point of the object. The cubical frame shown would be reflected by a series of movements such as that shown.



the equilateral triangle and then have rotated by 120° about this axis—the threefold symmetry simply does not exist about this axis. The dotted triangle is obviously different from the original one, since it is in a different place.

Reflection with Respect to a Plane

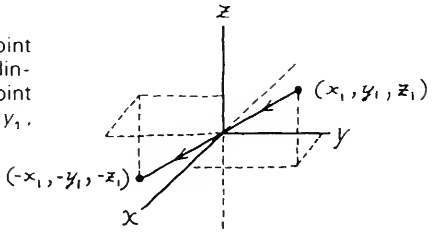
A third familiar operation is that of reflection in some plane. This operation is particularly familiar because the reflection operation is precisely what a mirror does if placed in the chosen plane. Figure A.11 shows a cube and one of its reflection symmetry planes. Mathematically speaking, if we set up a coordinate system as shown in the figure with the reflection plane chosen to be the x-y plane, the reflection operation consists of taking a point at some z coordinate—say, z_1—and taking it to $-z_1$. This reversal of z coordinate is done for all points of the figure, and the mirror image is thus produced. Note particularly that one must always specify the plane with respect to which the reflection operation is performed, just as he must specify the axis for the case of rotation.

Inversion with Respect to a Point

Suppose we establish a coordinate system as shown in Fig. A.12, with x, y, and z axes. If we now take *each* point of an object, with coordinates x_1, y_1, and z_1, and move the point to coordinates $-x_1$, $-y_1$, and $-z_1$, we have performed the operation of inversion on the object, about the point O, the origin of coordinates. If this operation leaves the object indistinguishable from its original state, then we say the object has inversion symmetry with respect to the point that is the origin of the xyz axes. For an easily visualized example, consider a two-dimensional example in Fig. A.13, the letter A. In two dimensions, inversion with respect to the point O takes all points at coordinates x, y to coordinates

Figure A.12

In the operation of inversion, each point has the sign of all three cartesian coordinates reversed. In this figure, the point (x_1, y_1, z_1) goes to the point $(-x_1, -y_1, -z_1)$ shown.



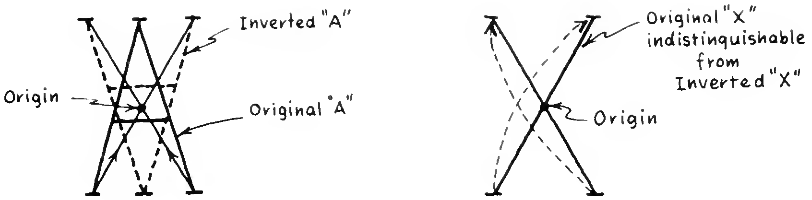


Figure A.13

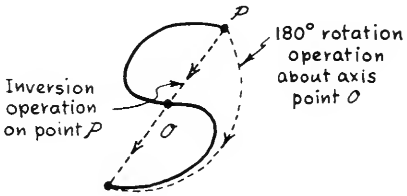
The letter A does not have inversion symmetry about a central point, but letter X does have this property.

$-x$, $-y$. The figure sketches the inversion process for the letters A and X. We see that X has inversion symmetry about the given point. The inverted letter A is clearly different from the original. Hence, A does not have inversion symmetry about the chosen point—in fact, there is *no* point with respect to which A has inversion symmetry. For such a situation, we usually say, simply, "A does not have inversion symmetry."

Two nominally different symmetry operations may sometimes be equivalent, in certain special circumstances. For example, consider a two-dimensional object such as the letter S in Fig. A.14. In two dimensions, rotation of 180° about the axis through point O is identical with the inversion process taken with respect to point O. This coincidence of rotation through 180° and inversion about O cannot occur with three-dimensional figures, however.

Figure A.14

In two dimensions, inversion with respect to any point such as O is always equivalent to a rotation of 180° about an axis through that point.



Q. **1.** **Consider the two letters A and H. Classify each according to the classes of symmetry operations—rotation, reflection, and inversion—under which they remain unchanged. In figuring out the symmetry classes, consider the letters as constrained to remain in a plane—i.e., the letters cannot be rotated out of the plane of the paper.**

2. **Describe the symmetry properties of a featureless sphere, using the language we have developed in this chapter.**

3. **Is there anything symmetrical about a glove? What about a pair of gloves?**

4. **Describe the symmetry properties of a helix with ends, such as an automobile coil spring. Assume the two points of the helix to be exactly diagonally opposite one another.**

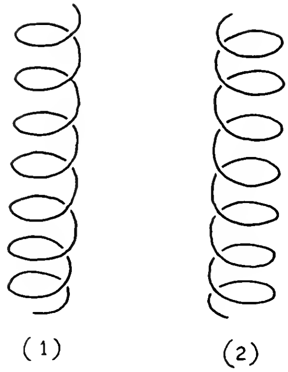


Figure A.15

A right-handed helix (1) is the mirror image of a left-handed helix (2).

Right and Left Symmetry

In the last question at the end of the previous section, we inquired about the symmetry properties of a helix. We now want to focus on one particular property of the helix that is profoundly significant in determining certain properties of biological systems, and which leads us to deeper thoughts about the basic symmetry properties of nature.

Figure A.15 shows two helices; they are mirror images of one another. Perhaps, after your thinking about the previous question about helices, you can see that no conceivable rotation performed on No. 1 will make it look like No. 2. By convention, No. 1 is called a right-hand helix, and No. 2 a left-hand helix. [The convention is the same as that used in labeling a right-hand screw thread (the usual kind) and a left-hand screw thread (which probably appears most commonly on the bolts used by certain manufacturers to fasten automobile wheels to hubs on one side of the car).]

As a result of a long series of biological experiments, beginning with the work of Pasteur in 1848 on the forms of tartaric acid molecules and continuing through the elucidation of the structure of the DNA molecule by Watson and Krick in 1953, it is known that many large chemical molecules of biological interest possess a full or partially developed helicity. This statement means that the molecule has a mirror image which is geometrically distinct. Much more importantly, the mirror image molecule turns out to be chemically and biochemically different. This effect has the profound result that only one of the two mirror forms of certain types of molecules is employed by living matter. Figure A.16 illustrates the two mirror forms of a simple compound of biological interest, alanine. These two molecular forms, called *l*-alanine and *d*-alanine, are made up of precisely the same atomic constituents—3 carbon atoms, 7 hydrogen atoms, 1 nitrogen atom, and 2 oxygen atoms—formed with exactly the same internal relationships *except* that one form is the mirror image of the other. But on this subtle difference hangs a weighty matter. Alanine is a fundamental processing chemical present in the biological machinery of man. If you were to replace his normal supply of *l*-alanine with *d*-alanine, he would die. His body cannot use *d*-alanine. Feynman has put the matter pungently.

> So far as we know, in principle, we could build a frog, for example, in which every molecule is reversed, everything is like the "left-hand" mirror

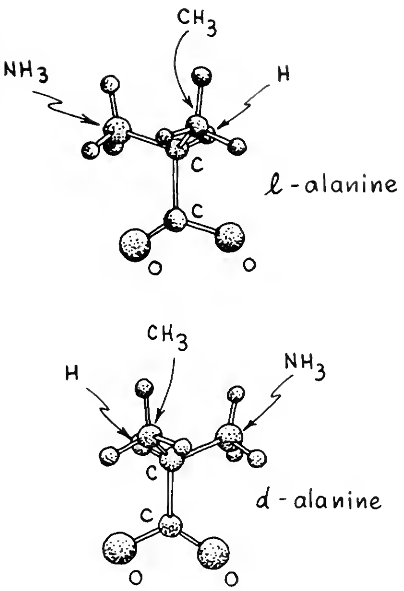


Figure A.16

A right-handed molecule, *d*-alanine, and its left-handed counterpart, *l*-alanine, are analogous to the pair of helices in Fig. A.15. Look upwards along the vertical line between two C atoms and imagine taking this line as a rotation axis. You can see that a left-handed tour around the upper part of the molecule for *l*-alanine will find the sequence: CH_3 group, NH_3 group, H atom, whereas one must do a right-handed tour for *d*-alanine in order to generate the same sequence.

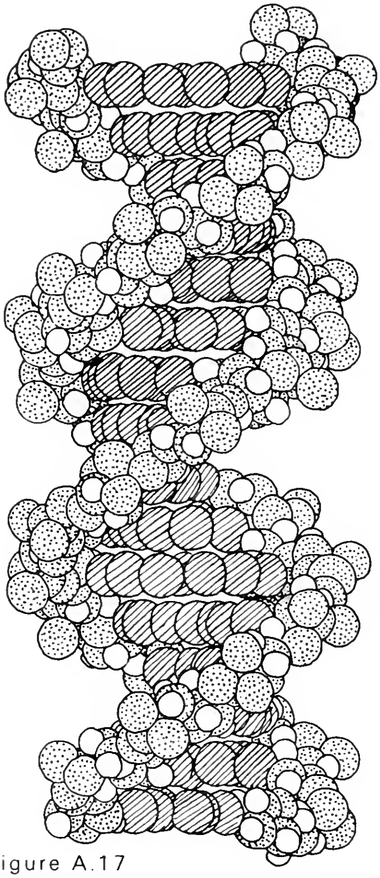


Figure A.17

The huge DNA molecule, of genetic importance, is in the form of a double helix. The sketch shows only a portion of a DNA molecule, which is made up of three kinds of molecular building blocks. The small white circles are hydrogen atoms which serve as links between the "backbone" of sugar-phosphate groups and the nitrogen-based groups of the outer, double helix.

image of a real frog; we have a left-hand frog. This left-hand frog would go on all right for a while, but he would find nothing to eat, because if he swallows a fly, his enzymes are not built to digest it—unless we give him a left-hand fly.[3]

Figure A.17 shows a sketch of a model[4] of the DNA molecule, which carries the genetic code in animals. Only the form with the right-

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[3] R. P. Feynman, *Lectures on Physics*, Reading, Mass.: Addison-Wesley Publishing Co., Inc., 1963, pp. 52–56.

[4] Reproduced from Hugh Grayson-Smith, *The Changing Concepts of Science*, Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1967, by permission of the publishers.

hand helicity shown is found in nature despite the fact that its mirror image is equally stable chemically.

Now comes the deeper question of the natural philosopher. What caused the choice in nature? Why do we not have left-helix people who use all of the left-helical molecules and build up a complete left-oriented (no political overtones, please) organism? The true reason for the fact that all known systems in nature use chemical molecules of the same helicity is lost in the misty beginnings of evolution. There is no evidence that there is any fundamental scientific reason for this choice, and one is led to believe that our present situation is the result of pure chance—at some stage early in the process, a chance fluctuation momentarily favored the population of molecules of one helicity, and a dominance was established that soon pervaded all the primitive biochemical forms and was sustained as they moved toward more complicated biological structures.

Parity

One implication of the previous discussion is that if we *did* succeed in building a left-handed biological world, it would function precisely according to the same natural laws as the world we have. In fact, for a very long time scientists believed that there was an immutable symmetry property of nature at work here—namely, that any natural system has a conceivable mirror image whose properties would unfold in time so that the two would always be mirror images of one another. We quote Feynman again:

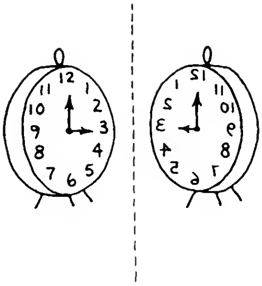

Figure A.18

In a parity-conserving world, a clock and its mirror image will run so as always to remain mirror images.

> Suppose we build a piece of equipment, let us say a clock, with lots of wheels and hands and numbers; it ticks, it works, and it has things wound up inside. We look at the clock in the mirror. How it *looks* in the mirror is not the question. But let us actually *build* another clock which is exactly the same as the first clock looks in the mirror—every time there is a screw with a right-hand thread in one, we use a screw with a left-hand thread in the corresponding place of the other; where one is marked "2" on the face, we mark a "Ƨ" on the face of the other; each coiled spring is twisted one way in one clock and the other way in the mirror-image clock; when we are all finished, we have two clocks, both physical, which bear to each other the relation of an object and its mirror image, although they are both actual, material objects, we emphasize. [Figure A.18 shows Feynman's Clocks.] Now the question is: If the two clocks are started in the same condition, the springs wound to corresponding tightnesses, will the two clocks tick and go around, forever after, as exact mirror images? (This is a physical question, not a philosophical question.) Our intuition about the laws of physics would suggest that they *would.*[5]

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[5] R. P. Feynman, *Lectures on Physics*, Reading, Mass.: Addison-Wesley Publishing Co., Inc., 1963, pp. 52–54.

The faith of scientists in this so-called parity conservation principle (that the two clocks or their equivalents would evolve so as always to remain mirror images) was so strong that the demonstration of its failure in a remote realm of nature through an experiment by Wu, Ambler, Hayward, Hoppes, and Hudson in 1956 led to a Nobel Prize for T. D. Lee and C. N. Yang, who had suggested the experiment and postulated the failure.[6]

So far as we presently know, this failure of the parity conservation principle is restricted to a particular class of subatomic phenomena that are almost completely isolated from interaction with the matter world as we know it. We do not have space to pursue the details of the Wu, Ambler, Hayward, Hoppes, and Hudson experiment and many subsequent investigations that have delimited the particular class of phenomena for which systems exhibit an innate and immutable handedness. An annotated list of references is given at the end of this section. But we should emphasize the distinction between this situation and the biochemical one. In the biochemical case, the predominance of one kind of molecule is believed to be a chance situation, and an otherwise identical chemical molecule of opposite helicity always exists. For the subatomic particles involved in the *breakdown* of the parity principle, the right or left helicity is an integral part of the makeup of the particle, and if the helicity is changed, the particle no longer evolves according to the same set of natural laws. In other words, the true mirror image of one of these particles does not exist in nature.

We now return briefly to the question of the wire and compass needle (see Fig. A.5 and accompanying text). Can we identify the hidden property of the system shown in Fig. A.5a that causes the breakdown of the apparent reflection symmetry? Yes, we can. The physical effect of the current through the wire is to generate magnetic effects which intrinsically possess a helicity. Figure A.19 is a modification of Fig. A.5a, which includes imaginary magnetic lines of force drawn to represent the helicity. The arrangement has lost its mirror symmetry about the dotted plane as a result of addition of the magnetic lines of force, and we have no reason to apply the principle of insufficient reason. Figures A.5b and A.5c become Figs. A.18b and A.18c. We now see that the configuration of Fig. A.18c is simply that of A.18b rotated through 180° about the dotted axis AA', and there are no longer any surprises remaining.

Not only Geometry!

Our examples of the uses of symmetry have been drawn mostly from geometry alone. Left-right symmetry, symmetry of motion along a wire, symmetry of position along a line are typical. But physical objects have properties which cannot be described by geometry, of

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[6] A description of this experiment is given in the article entitled The Overthrow of Parity, by P. Morrison, *Scientific American*, April, 1957.

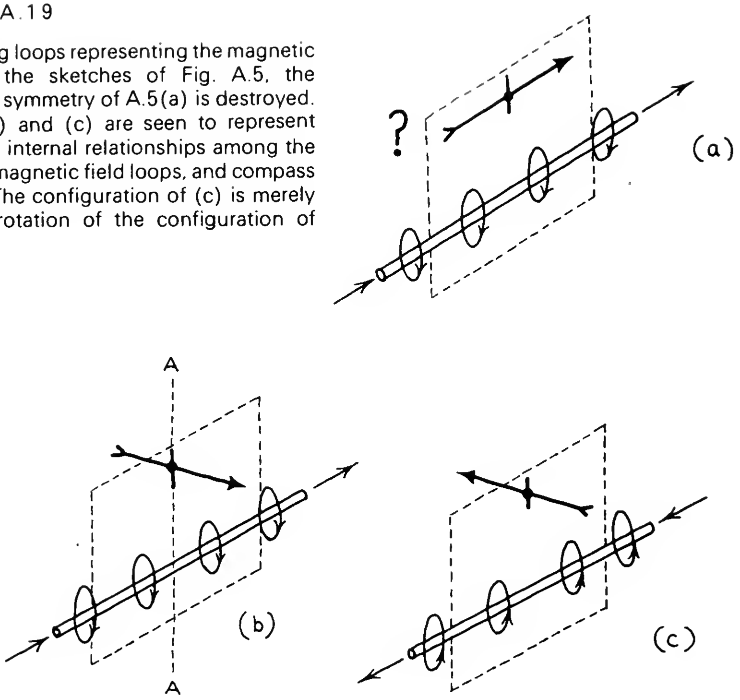


Figure A.19

By adding loops representing the magnetic field to the sketches of Fig. A.5, the apparent symmetry of A.5(a) is destroyed. Now, (b) and (c) are seen to represent the same internal relationships among the current, magnetic field loops, and compass needle. The configuration of (c) is merely a 180° rotation of the configuration of (b).

course, and sometimes symmetry goes with these. For example, electric charge is a property of many physical objects. Perhaps you recall the catch words, "like charges repel, unlike charges attract." That phrase correctly described the behavior of electric charge. Describing the forces between electric charges in this way implies a kind of symmetry. It doesn't matter how we choose to assign the names positive and negative to the two kinds of charge—plus works on plus just like minus on minus, and the force of plus on minus is indistinguishable from that of minus on plus. This feature means that you can exchange all plus charges for minus charges in a system, and vice versa, and nothing in simple electrical phenomena will change. Thus, charge exchange is a symmetry operation, and evidently an important one.

When the twentieth century came around, physicists learned that the positive charges in ordinary matter are always carried by protons, and the negative charges always by electrons. The protons and electrons could be found combined in various ways. But protons are not at all like electrons. For example, they weigh about two thousand times more. So the symmetry between electrical charge types seemed to be lost, once you imagined exchanging the particles which really carry the charges.

Then came some remarkable discoveries. In the early thirties, it was found both by experiments and in theory that there are particles called positrons which share all the properties of electrons *except* that they have positive charge, not negative. By 1960 we had also found particles which share all the properties of protons save that they have *negative* charge. Thus, the symmetry of charge was restored, but in modified form. It was now clear that if you changed the charge, substituting positrons for electrons and negative protons for protons, both together, the whole system should behave as before. The symmetry is shown to be more elaborate than we guessed. Charge must go with mass in just the right way. The new particles are called anti-particles, and their world is the anti-world. We do not really know if the anti-particles occur anywhere in large numbers. If they do, the anti-matter they make there must behave just the same as the matter we know and are made of, at least in all electromagnetic ways.

The restoration of that simple symmetry of charge in such a full fashion has given physicists even greater respect for the power of the idea. Symmetry still rules the domain of fundamental physics. But just as with the charge symmetry, the further symmetries which we now seek are more subtle and complex than those which appear easily in drawings. But all can be described by our basic test—if we specify some operation upon a physical system and find it unchanged in some fundamental way as a result of that operation, then the operation in question is a symmetry operation, and we have catalogued yet another symmetry property of nature.

EXERCISES

1. Consider all the letters of the alphabet (excepting A and H, which you have already worried about), and arrange them in groups according to the classes of symmetry operations—rotation, reflection, and inversion—under which they remain unchanged. In figuring out the symmetry classes, consider the letters as constrained to remain in a plane—i.e., the letters cannot be rotated out of the plane of the paper.
2. Consider a tennis ball or baseball, complete with seams, and describe its symmetry properties. Assume that the interior is homogeneous. (*Suggestion:* The real thing is a big help here, rather than trying to visualize from a two-dimensional picture or sketch.)
3. Describe the symmetry properties of a card table, including the leg-folding mechanism. (Again, direct observation will help.)
4. Trace the sketch of the crystal structure of graphite given in Fig. A.8c. Imagine yourself located at the position of one atom. Find and show with arrows on your tracing the three possible translational movements of the lattice structure that will bring another carbon atom to your position with its surrounding atoms in an identical configuration to that seen from your position before the move. (These movements are the elements of translational symmetry of that lattice, since they generate configurations indistinguishable from the original one.) We emphasize again that the sketch shows only a fragment of a structure assumed to extend indefinitely far in all directions.
5. Given the fact that the Earth is a sphere, can you argue rigorously on symmetry grounds that "gravity" should pull objects toward the center of the Earth (as it does) rather than pulling them parallel to the surface?

SUPPLEMENTARY READINGS

FEYNMAN, RICHARD P., ROBERT B. LEIGHTON, and MATTHEW SANDS, Symmetry in Physical Laws, *The Feynman Lectures on Physics.* Reading, Mass.: Addison-Wesley Publishing Co., Inc., 1963, Chap. 52. Feynman provides a lively discussion of the meaning of the phrase "symmetrical behavior of physical laws" in contrast to pure geometrical symmetry. The author concentrates on mirror symmetry, concluding with a discussion of conservation of parity. With hard thinking by students and a bit of embroidery in the form of detailed facts furnished by an instructor, this chapter is largely accessible to nonscience students.

STAPP, PHILIP, with JUDITH BREGMAN, R. DAVISSON, and ALAN HOLDEN; *Symmetry*, a film (1967). Available from Contemporary Films, Inc., 267 W. 25th St., New York, N. Y. 10001. This film, which grew as an experimental project, uses visual and sound channels in an imaginative way to communicate the nature of geometrical symmetries. Its content will be perceived very differently by students with different frames of reference and may communicate better than the linear, printed, or spoken word channel to some students. It deals entirely with two-dimensional figures.

WEYL, HERMANN, *Symmetry*. Princeton: Princeton University Press, 1952. (A large portion of the book is reprinted in James R. Newman, ed., *The World of Mathematics*, vol. 1, New York: Simon and Schuster, Inc., 1962.) In this 145-page book, Weyl gives a beautiful overview of the role that symmetry, in both its aesthetic and mathematical senses, plays in art, biological systems, and crystals. Most of the book is roughly at the mathematical level of this section, and is quite accessible to the general student.

WOOD, E. A., *Crystals and Light*. Princeton: D. Van Nostrand Co., Inc., Momentum Paperback, 1964. Chapter 1, Symmetry, provides a clear exposition of the scheme for classifying geometrical symmetries. If one wishes to make an excursion into crystallography, the field that employs ideas of geometrical symmetries most extensively, Chapter 2, Symmetry in Crystals, 18 pages long, provides a sensible introduction.

Only one person in several thousand is a physicist. Should it matter to the others what he or she does, or that he or she is there at all?

10 The Nature of Physics

Physics Survey Committee NRC-NAS

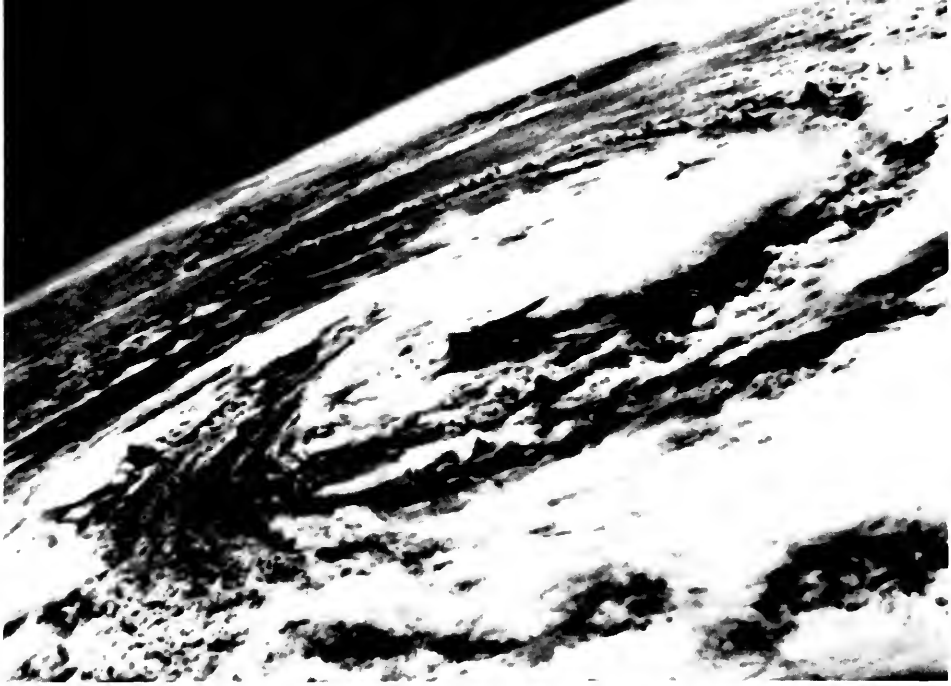
An excerpt from Physics in Perspective, 1973

> *scire*—to know
> *scientia*—knowledge
>
> *Nam et ipsa scientia potestas est*
>
> FRANCIS BACON (1561–1626)
> *Of Heresies*

INTRODUCTION

Science is knowing. What man knows about inanimate nature is physics, or, rather, the most lasting and universal things that he knows make up physics. Some aspects of nature are neither universal nor permanent—the shape of Cape Cod or even a spiral arm of a galaxy. But the forces that created both Cape Cod and the spiral arm of stars and dust obey universal laws. Discovering that has enabled man to understand more of what goes on in his universe. As he gains more knowledge, what would have appeared complicated or capricious can be seen as essentially simple and in a deep sense orderly. The explorations of physical science have brought this insight and are extending it—not only insight but power. For, to understand how things work is to see how, within environmental constraints and the limitations of wisdom, better to accommodate nature to man and man to nature.

These are familiar and obvious generalities, but we have to begin there if we want to discuss the value of physics in today's and tomorrow's world. Going beyond generalities evokes sharp questions from several sides. Will the knowledge physicists are now striving to acquire have intrinsic value to man, whether it has practical application or not? Is it possible to promise that material benefits will eventually accrue, at least indirectly, from most of the discoveries in physics? How does technology depend on further advances in physics (and vice versa)? How does physics influence other sciences? Is vigorous pursuit of new knowledge in physics still beneficial, as it demonstrably was in the past, to chemistry, astronomy, and the other sciences for which physics provided the base? Is physics perhaps approaching the end of its mission, without very much more to discover? Has the physicist himself an intrinsic value to human society? Must he justify his



(*Above*) Hurricane Gladys was stalled west of Naples, Florida, when photographed from Apollo 7 on October 17, 1968. Its spiraling cumuliform-cloud bands sprawled over hundreds of square miles. A vigorous updraft hid the eye of the storm by flattening the cloudtops against the cold, stable air of the tropopause (then at 54,000 feet) and forming a pancake of cirrostratus 10 to 12 miles wide. Maximum winds near the center were then 65 knots. [From National Aeronautics and Space Administration, *This Island Earth*, O. W. Nicks, ed., NASA SP-250 (U.S. Government Printing Office, Washington, D.C., 1970).]

(*Below*) NGC 3031, spiral nebula in Ursa Major photographed with the 200-inch reflector of the Palomar Observatory. [Courtesy Hale Observatories] work by relating it to pressing social problems? Only one person in several thousand is a physicist; will it matter to the others what he does, or that he is there at all? Or is that the right test to apply, no matter how it comes out?

We speak briefly to such questions in this and the following chapter. The entire Report, including the reports of the various subfield panels, provides in copious detail answers to some of these questions or facts from which a reader can form his own judgment, for these are not questions that even all physicists would answer in just the same way.

FUNDAMENTAL KNOWLEDGE IN PHYSICS

Mathematics deals with questions that can be answered by thought and only by thought. A mathematical discovery has a permanent and universal validity; the worst fate that can overtake it is to be rendered uninteresting or trivial by enclosure within a more comprehensive structure. Mathematicians make up, or one could say discover, their own questions in the timeless universe of logical connection. In a science such as geology, on the other hand, the questions arise from local, more or less accidental features of nature. How was this mountain range formed? Where was Antarctica two billion years ago? To answer such questions one has to sift physical evidence. The answers are not universal truths. Geology, as its name attests, differs from planet to planet.

Physics, like geology, is concerned with questions that cannot be decided by thought alone. Answers have to be sought and ideas tested by experiment. In fact, the questions are often generated by experimental discovery. But there is every reason to believe that the answers, once found, have a permanent and universal validity. All the evidence indicates that physics is essentially the same everywhere in the visible universe. A physicist who asks, "Does the neutron have an electric dipole moment?" and turns to experiment to find out, could as well perform the experiment on any planet in any galaxy—it is just more convenient here at home. The question itself concerns a fact as general as (and perhaps even more basic than) the size of the universe. Physics is the only science that puts such fundamental questions to nature.

Take the question: Do all electromagnetic waves, including radio waves and light waves, travel through empty space at the same speed? Present theories assume so, but the contrary is at least conceivable. Perhaps there is a difference so slight that it has not been noticed. To decide, the physicist must turn to experiment and observation. In fact, this particular question has recently received renewed attention. As not infrequently happens, the most sensitive test was applied by asking what sounds like a different question but can be shown to be logically equivalent. Indeed, the experimental evidence shows that the speed of long and short electromagnetic waves is the same to extraordinarily high precision. The result implies that the light quantum, the photon, cannot have an intrinsic mass as great as 10^{-20} *

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* Physicists commonly use powers of 10 as a convenient shorthand for expressing large numbers. Thus, for example, 1000 becomes 10^3 and 1,000,000 becomes 10^6. The numeral 1 followed by zeros equal in number to the value of the exponent is the rule of thumb. This notation is used throughout the Report.

of the mass of an electron. No one was astonished by the result. Most physicists have always assumed the photon rest mass to be exactly zero and can only be relieved that such peculiarly perfect simplicity has survived closer scrutiny. Those who examined the evidence may have been a little disappointed—but their time was not wasted.

This quite unsensational episode is characteristic of fundamental inquiries in several ways. Fundamental experiments in physics often—indeed usually—yield no surprises. However, had the result been otherwise, it would not have demolished electromagnetic theory. A generalization or enlargement of the theory would have been necessary. Finally, the test, sensitive as it was, could not settle the question once and for all, for no real experiment achieves infinite precision. So the question will doubtless be raised again, in one form or another, should a new experimental technique or a bright idea create the opportunity for a significantly more stringent test. An equally fundamental assumption, the proportionality of inertial and gravitational mass, was tested in experiments of successively higher precision by Newton (1686), Bessel (1823), Eötvös (1922), and Dicke (1964) —in the last case to an accuracy of 10^{-11}.

Thanks to such relentless probing of its foundations, even where they appear comfortably secure, physics has acquired a base far more solid than is popularly appreciated. When a physicist states that a proton carries a charge equal to that of the electron, he can point to an experiment that proved any inequality to be less than one part in 10^{20}. When he expresses confidence in the special theory of relativity, he can refer to a multitude of experiments under ultrarelativistic conditions in which even a slight failure of the theory would have been conspicuous. Electromagnetic interactions are today more completely accounted for—that is to say, better understood—than any other phenomena in physics. Quantum electrodynamics, the modern formulation of electromagnetic theory, has now been tested experimentally over a range of distance from 10^{9} cm down to 10^{-14} cm, a range of 10^{23}. This theory was itself developed in response to experiments that revealed small discrepancies in the predictions of the much less complete theory that preceded it. No one will be much surprised if quantum electrodynamics in its present form fails to work for phenomena involving still smaller distances; that will not diminish its glory or its validity within the vast range over which it has been tested. Nor did the extension of electromagnetic theory into quantum electrodynamics deny the essential truth of Maxwell's equations for the electromagnetic field. Knowledge thus won is about as permanent an asset as mankind can acquire.

The most fundamental aspects of the physical universe are manifest in symmetries. In the history of modern physics, the concept of symmetry has steadily become more prominent. The beautiful geometrical symmetry of natural crystals was the first evidence of the orderliness of their internal structure. Exploration of the arrangement of atoms in crystals by x-ray diffraction, begun 60 years ago, has mapped the structure of thousands of substances and is now revealing in detail the architecture of the giant molecules involved in life. Meanwhile, physicists became concerned with more than just geometrical symmetry. Symmetry, in the broadest sense, involves perfect indifference. For example, if two particles are distinguishably different in some ways but show absolutely the same behavior with respect to some other property, a physicist speaks of symmetry. The notion of identity of particles is intimately related. All these ideas acquire their real importance in quantum physics, where an object, a molecule for instance, is completely characterized by a finite number of attributes.

In probing questions of symmetry in the domain of elementary particles, the physicist is again, like the first crystallographers, seeking a pattern of all-pervading order. A sobering lesson learned from modern particle physics, a lesson the Greek atomistic philosophers would have found unpalatable, is that man is not wise enough to deduce the underlying symmetries in nature from general principles. He has to discover them by experiment and be prepared for surprises. No one guessed before 1956 that left and right made a difference in the interaction of elementary particles. After it was found that the true and perfect indifference in the weak interactions is not left/right but left-electron/right-positron, it was again disconcerting to find even this rule of symmetry violated in certain other interactions. But it has by no means been all surprises. Symmetry rules guessed from scattered clues often have been amply corroborated by later experiments; and in particle physics, thinking about symmetries has been enormously fruitful. A grand pattern is emerging, largely describable in terms of symmetries, that makes satisfying sense.

The primary goal of research in fundamental physics is to understand the interactions of the very simplest things in nature. That is a basis, obviously necessary, for understanding larger and more complicated organizations of matter anywhere in the universe. The shape of a particular galaxy is not, from this rather narrow point of view, a fundamental aspect of nature, but the motion of an electron in a magnetic field is fundamental and has implications for many things, including life on earth and the shapes of galaxies.

However, physics has to be concerned with more than the elementary few-body interactions of particles and fields. It can be a gigantic step from an understanding of the parts to an understanding of the whole. To appreciate the total task of physics, a broader view of what is fundamental is necessary. Consider, for example, man's practically complete ignorance of the evolution of the flat, patchily spiral distribution of gas and stars that he calls his own (Milky Way) galaxy. (Only very recently some plausible theories have been developing; it is too early to say how much they can explain.) The interaction of molecules, atoms, ions, and fields is now well enough known for this problem, and Newtonian gravitation, on this scale, is unquestionably reliable. With these simple ingredients, why doesn't the problem reduce to a mere mathematical exercise? One good reason—perhaps not the only reason—is that a complete and general theory of turbulence is lacking. It is not just a lack of efficient methods of calculation. There is a gap in man's understanding of physical processes, which remains unclosed, even after the work of many mathematical physicists of great power. This gap is blocking progress on several fronts. When a general theory of turbulence is finally completed, which probably will depend on the work of many physicists and mathematicians, a significant permanent increase in man's understanding will have been achieved. That will be fundamental physics, using both fundamental and physics in a broad sense, as, to take an example from the recent past, was the explanation of the mystery of superconductivity by Bardeen, Cooper, and Schrieffer. Although pedantically classifiable as an application of well-known laws of quantum mechanics, it was truly a step up to a new level of understanding.

These two examples, turbulence and superconductivity, stand near opposite boundaries of a wide class of physical phenomena in which the behavior of a system of many parts, although unquestionably determined by the interaction of the elementary pieces, is not readily deducible from them. Physicists know how to deal with total chaos—disorganized complexity. Statistical mechanics can predict anything one might want to know about a cubic centimeter of hydrogen gas with its 10^{19} molecular parts. As for the hydrogen molecule itself, it presents the essence of ordered simplicity. Its structure is completely understood, its properties calculable by quantum mechanics to any desired precision. What gives physicists trouble, to continue the classification suggested by Warren Weaver, is organized complexity, which is already present in a mild form in so familiar a phenomenon as the freezing of a liquid—a change from a largely disordered to a highly ordered state. Here a general feature is that what one molecule prefers to do depends on what its neighbors are already doing. How drastically that feedback changes the problem is suggested by the lack of a theory that can predict accurately the freezing point of a simple liquid. In the physics of condensed matter, many such problems involving cooperative phenomena remain to challenge future physicists. A turbulent fluid, on the other hand, confronts the physicist with a system in which order and disorder are somehow blended. Complex it certainly is, but not wholly disorderly, admitting no clean division between the random flight of a molecule of the fluid and the organized motion of a row of eddies.

The solution of these major problems of organized (or partly organized) complexity is absolutely necessary for a full understanding of physical phenomena. Extraordinary insight and originality will surely be needed, as indeed they always have been. The intellectual challenge is as formidable as that faced by Boltzmann and Gibbs in the development of statistical mechanics. The consequences for science of eventual success could be as far-reaching.

Broadly speaking then, the unfinished search for fundamental knowledge in physics concerns questions of two kinds. There are the primary relations at the bottom of the whole structure. How many remain to be discovered and how small the number to which they can ultimately be reduced are not yet known. Then there is the knowledge needed to understand all the behavior of the aggregations of particles that make up matter in bulk. Here the mysteries are perhaps not so deep, although the remaining unsolved problems are of formidable and subtle difficulty. It is easier to imagine how this part of the development of fundamental physics could be concluded, if the even more difficult problem of organized complexity in living organisms is left for the physiologist, assisted by the biochemist and biophysicist, to solve.

What has been learned in physics stays learned. People talk about scientific revolutions. The social and political connotations of revolution evoke a picture of a body of doctrine being rejected, to be replaced by another equally vulnerable to refutation. It is not like that at all. The history of physics has seen profound changes indeed in the way that physicists have thought about fundamental questions. But each change was a widening of vision, an accession of insight and understanding. The introduction, one might say the recognition, by man (led by Einstein) of relativity in the first decade of this century and the formulation of quantum mechanics in the third decade are such landmarks. The only intellectual casualty attending the discovery of quantum mechanics was the unmourned demise of the patchwork quantum theory with which certain experimental facts had been stubbornly refusing to agree. As a scientist, or as any thinking person with curiosity about the basic workings of nature, the reaction to quantum mechanics would have to be: "Ah! So that's the way it really is!" There is no good analogy to the advent of quantum mechanics, but if a political–social analogy is to be made, it is not a revolution but the discovery of the New World.

THE QUESTION OF VALUE

Most people will concede that fundamental scientific knowledge is worth its cost if it contributes to human welfare by, even indirectly, promoting the advance of technology or medicine. It is easy to support a claim for much of physics. But now that some frontiers of fundamental research have been pushed well beyond the domain of even nuclear engineering, that justification is not always plain to see. A connection between many-body theory and the latest semiconductor device is not much more difficult to trace than the connection between thermodynamics and a jet engine. But it is not easy to foresee practical applications of the fundamental knowledge gained from very-high-energy experiments or, say, tests of general relativity.

Two responses can be made, each of which has some validity. First, inability to foresee a specific practical application does not prove that there will be none. On the contrary, that there almost certainly will be one has become a tenet of conventional wisdom, bolstered by familiar examples such as Rutherford's denial of the possibility of using the energy of the nucleus. Applying this principle to strange-particle interactions will probably raise fewer doubts among laymen than among physicists. Even here the conventional wisdom may be sound after all. High-energy physics is uncovering a whole new class of phenomena, a "fourth spectroscopy" as it is termed elsewhere in this Report. In the present state of ignorance, it would be as presumptuous to dismiss the possibility of useful application as it would be irresponsible to guarantee it.

A secondary benefit that can be expected, as a return for supporting such research, is the innovation and improvement in scientific instrumentation that such advanced experiments stimulate. (This point is discussed in a subsequent section of this chapter on the contributions of physics to technology.) Other sciences also benefit from the development of experimental techniques in physics.

But these responses do not squarely face the question: What is fundamental knowledge itself worth to society? Elementary-particle physics provides an example. A permanent addition to physicists' knowledge of nature was the recognition, several years ago, that there are two kinds of neutrino. This fact, although compatible with then existing theory, was not predictable *a priori,* nor is the reason understood. The question was put to nature in a fairly elaborate high-energy experiment, at a total monetary cost that reasonable accounting might put at $400,000 (not including beam time on the Alternating Gradient Synchrotron Accelerator). The answer was unequivocal: The electron neutrino and the muon neutrino are not identical particles.

For physics this was a discovery of profound significance. Neutrinos are the massless neutral members of the light-particle or lepton family, of which the familiar electron and its heavier relative, the muon, are the only other known members. Just how these particles are related—even why there is a muon—is one of the central puzzles of fundamental physics, a puzzle that is as yet far from solution. Obviously, it was not about to be solved while physics remained ignorant of the fact that there are two kinds of neutrino, not just one.

Still, how does this bit of knowledge benefit the general public, interesting as it may be to the tiny fraction of scientists who know what "two kinds" means in this connection? The answer must be that the discovery was a step—a necessary step—toward making nature comprehensible to man. If man is going to understand nature, he has to find out how it really is. There is only one way to find out: Experiment and observe. If man does not fully understand the leptons, he cannot claim to understand nature.

On the other hand, the neutrino is a rather esoteric creature. It would be absurd to expect wide and instant appreciation of this fundamental discovery. Even of fundamental knowledge there is too much for most people to absorb. Many a physicist who could calculate on the back of an envelope the neutrino flux from the sun remains complacently ignorant of the location and function of the pituitary gland in his body. The point is that the value of new fundamental knowledge must not be measured by the number of people prepared to comprehend it. To say that man understands this or that aspect of nature usually means that some people do, and that they understand it sufficiently well to teach it to any who care to learn and to maintain a reliable base from which they or others can explore still further. The great thing about fundamental scientific knowledge is that it is an indestructible public resource, understandable and usable by anyone who makes the effort. When so used in its own domain, it is a thing of beauty and power.

The great American physicist Henry Rowland once replied to a student who had the temerity to ask him whether he understood the workings of the complicated electrostatic machine he had been using in a demonstration lecture: "No, but I could if I wanted to." Knowledge of fundamental scientific laws makes for economy of human thought. It is the great simplifier in a universe of otherwise bewildering complexity. It is not necessary to analyze every cogwheel in an alleged perpetual motion machine to know that it will not work or to keep tracking all the planets to be sure that they are not about to collide. The revelation that the electron and muon neutrinos are different, although it might appear to have complicated matters, was in fact a step toward ultimate simplicity, because it brought closer the essential truth about leptons.

Some of the fundamental ideas of physics have slowly become part of the mental furnishings of most educated people. The following statements probably would elicit general assent: All substances are composed of atoms and molecules; nothing travels faster than light; the universe is much larger than the solar system and much older than human life; energy cannot be obtained from nothing, but mass can be turned into energy; motions of planets and satellites obey laws of mechanics and gravity and can be predicted precisely. That is surely a rather meager assortment, but, even so, what an immense difference there is between knowing these few things and not knowing them—a difference in the relation of a person to his world. A child asks his father "What is a star?" or "How old is the world?" In this century he can be answered, thanks to hard-won fundamental knowledge. What is that worth? The answers can hardly contribute to anyone's material well-being, present or future. But they do enlarge the territory of the human mind.

Much of what modern physics has learned has not yet become common knowledge. Here is an example. Not only physicists but everyone who has studied quantum mechanics knows that all known particles, without exception, fall into one or the other of just two classes, called fermions and bosons, which differ from one another profoundly on a certain question of symmetry. The difference is as fundamental as any difference could be. Although usually expressed somewhat abstractly, the distinction is less recondite than some theological distinctions over which men have quarreled fiercely. Its concrete manifestations are vast, among them the astonishing properties of superfluid helium (a boson liquid), the electrical properties of metals, and, indeed, through the Pauli exclusion principle, the very existence of atoms and molecules, hence of life. Now it would seem that this profound, essentially simple truth about the physical universe ought to be known to most fairly well-educated persons, to as many, perhaps, as understand the difference between rational and irrational numbers. Yet, it is probably safe to say that a majority of college graduates have never heard of fermions and bosons, and that an even larger majority is not equipped to understand what the distinction means. Probably far less than 10 percent of current college graduates have had a course in physics or chemistry in which the exclusion principle was mentioned. Perhaps 10 percent will learn enough mathematics so that, if they are interested, they could be made to understand a statement such as "the wavefunction changes sign on exchange of particles."

But can anyone except physical scientists be interested in such a question? History suggests that it is possible. Long before the atomic bomb made mc^2 a catchword, the theory of relativity (both special and general) engaged the public interest more intensely than anything else in twentieth century physics. The fascination lay not only in the enigmatic figure of Einstein and the notion of a theory that, as the newspapers were fond of claiming (quite erroneously), only 12 men could understand. There was at the same time a sustained, genuine intellectual interest, at all levels of understanding commencing with zero, in the puzzling implications of new ideas about space and time. To this day, nothing beats the twin paradox for stirring up spirited argument in an elementary physics class. People who have any interest at all in ideas seem to be more interested, on the whole, in fundamental questions than in practical questions. It is usually easier to interest an intelligent layman in the uncertainty principle than in how the mass spectrograph works. Of course, that is true only if he or she can be given some idea, not wholly superficial, of the meaning of the uncertainty principle. This can be done; it has been accomplished many times, in different styles, by imaginative teachers and writers. Nor is it hard to convey to a thoughtful person the essential notion of antimatter, or the question of left- and right-handedness in nature, both ideas that intrigue many nonscientists. It may even turn out that nonphysicists of the next generation, many of whom were brought up with the new math and are on speaking terms with computers, will find the abstract rules of particle physics a more satisfying statement about nature than would an old-fashioned physicist.

Admittedly, there are difficulties in engaging the active interest of nonscientists in some of the most fundamental ideas of physics. They are illustrated in the example of the fermion–boson distinction. Unlike relativity, this subject makes no connection with familiar concepts such as time, space, and speed. No paradox or controversy stirs the imagination in first acquaintance. The intelligent layman can only listen to the explanation of fermions and bosons as if he were hearing a story about another world. There is nothing to argue about. It may serve as brief intellectual entertainment; most likely it will not impinge on or disturb the ideas he already has. He may not be eager to tell someone else about it. In that case it can hardly be claimed that the person has gained something of permanent value to him. And yet, when followed to a slightly deeper level, this idea has a direct bearing on a question that has engaged human throught for 2000 years—the ultimate nature of substance. It gives a most extraordinary answer to philosophical questions about identity of elementary particles, questions that were already implicit in the cosmology of Democritus but were never faced before quantum mechanics. Here, too, is a key to the wave–particle duality with which the quantum world confounded man's mechanistic preconceptions. The philosophical implications of the fermion–boson dichotomy are still, after 40 years, poorly understood by philosophers.

So the problem is one of teaching. Very many people who are not scientists are interested or can be interested in the basic questions that have always attracted human curiosity. The discoveries of physics, even those presently described in abstruse language, bear directly on some of these questions—so directly that when understood they can transform a person's conception of the atomic world or the cosmos. To promote that understanding is a task for the scientist as teacher, in the broadest sense of teacher. In the short run, drawing a potential audience from college graduates of the past 20 or 30 years, and perhaps the next 10, the physicist must apply his imagination and ingenuity to convey interesting and meaningful, and essentially true, accounts of some of the fundamental developments in physics. It is to be hoped that some day the educated layman he addresses will have had enough physical sciences and mathematics in his general education to turn a discussion of the symmetries of elementary particles into some sort of dialogue.

The audience need not be of a size that would impress a national advertiser but only a few million people—a few hundred, say, for every physicist. Of course, the distribution of potential interest and comprehension is a many-dimensional continuum. Everyone ought to be, and can be, given some glimpse of what fundamental physics is about. However, it is impossible to compare the value of a brief exposure of 10^8 people to news of a discovery in physics with the value of sustained and active interest on the part of 10^6 people. Both are valuable now, and both will help, in the long run, to make the fundamental knowledge that physics is securing meaningful and useful to all people.

The value of new fundamental scientific knowledge is not, after all, contingent on its appreciation by contemporary society. It really does not matter now whether Clerk Maxwell's ideas were widely appreciated in Victorian England. Their reception is interesting to the historian of science, but mainly as a reflection of the attitudes and structure of the society in which Maxwell worked. The full value of a scientific discovery is concealed in its future. But even as the future unfolds, the value that one may set on an isolated piece of fundamental knowledge often becomes uncertain because of the interconnection in the growing structure. In the end, one is forced to recognize that there is just one structure; understanding of the physical universe is all of one piece.

PHYSICS AND OTHER SCIENCES

Physics is in many ways the parent of the other physical sciences, but the relation is a continually changing one. Modern chemistry is permeated with ideas that came from physics, so thoroughly permeated, in fact, that the sudden demise of all physicists—with the exception of an important class calling themselves chemical physicists—would not immediately slow down the application of physical theory to chemical problems. The last great theoretical contribution of physics to chemistry was quantum mechanics. For another such contribution there is no room, almost by the definition of chemistry. From the point of view of the physicist, chemistry is the study of complex systems dominated by electrical forces. Strong interactions, weak interactions, gravitation—these are of no direct interest to the chemist. There is no reason to doubt, and voluminous evidence to show, that quantum mechanics and electromagnetic theory as now formulated provide a complete theoretical foundation for the understanding of the interactions between atoms and molecules.

An immense task remains for the theoretical chemist, a task that is in some part shared by the physicist interested in the same problems. One area of common interest is statistical mechanics, especially the theory of "cooperative" phenomena such as condensation and crystallization, where, although the forces that act between adjacent molecules are known, the behavior of the whole assembly presents a theoretical problem of singular subtlety. Other problems that attract both chemists and physicists include phenomena on surfaces, properties of polymers, and the fine details of the structure and spectra of simple molecules. A subject of very intense research in which physics and chemistry are thoroughly blended is the study, both experimental and theoretical, of reactions in rarefied partially ionized gases. This study has direct applications in plasma physics, the development of high-power lasers, the physics of the upper atmosphere, and astrophysics.

There is really no definable boundary between physics and chemistry. There never has been. Approximately 5000 American scientists, on a rough estimate, are engaged in research that would not be out of place in either a physics or a chemistry department. Some call themselves physicists and their specialty chemical physics or just physics. Others are physical chemists. The label generally reflects the individual's graduate training and correlates with some differences of interest and style. These chemical physicists have illustrious predecessors, including Michael Faraday and Willard Gibbs. And those who, like them, have made a permanent mark on both sciences are likely to be thought of as physicists by physicists and chemists by chemists.

Physics serves chemistry in quite another way. It is the source of most of the sophisticated instruments that the modern chemist uses. This dependence on physics has been, if anything, increasing. Perhaps the infrared spectrograph and the x-ray diffraction apparatus should be credited to the physics of an earlier era; their present highly refined form is largely the result of commercial development stimulated by users. But mass spectrographs, magnetic resonance equipment, and microwave spectrometers, all of which originated in physics laboratories in relatively recent times, are found in profusion as well as are the more general electronic components for detecting photons and atoms—electron multipliers, low-noise amplifiers, frequency standards, and high-vacuum instrumentation. One might follow a research chemist around all day, from spectrograph to computer to electronic shop to vacuum chamber, without deducing from external evidence that he was not a physicist, unless, as might still happen today, the smell of his environment gave it away.

Radiochemistry is in a class by itself. The radiochemist and the nuclear physicist have been partners indispensable to one another since before either specialty had a name. The dependence of experimental nuclear physics on radiochemical operations is perhaps less conspicuous, seen against the whole enterprise of nuclear physics, than it was 10 or 20 years ago. On the other hand, advances in the use of labeled elements and compounds in chemical, biochemical, and medical research continue to be paced by improvements in detection methods. These came directly from physics. A spectacular recent example is the solid-state particle detector, with parentage in nuclear physics and solid-state physics.

Instead of viewing physics and chemistry as different though related sciences, it might make more sense to consider a science of substances, with its base in quantum physics and objects of study ranging from the crystalline semiconductor (now assigned to the solid-state physicist) to the alloys of the metallurgist, to the molecular chain of high-polymer physics and chemistry, to the elaborate molecular structures of the organic chemist. Through this whole range of inquiry one can discern a remarkable convergence in theoretical treatment, and also in experimental methods. The first comes about as fundamental understanding replaces phenomenology. When the properties of the complex system, be it a boron whisker or a protein molecule, can be systematically deduced from the arrangement of its elementary parts, which are nothing but atoms governed by quantum mechanics, a universal theory of ordinary substances will be at hand. Such a theory has not yet been achieved, but as theoretical methods become more powerful, they become, as a rule, more general, and there is steady progress in that direction. Already the language of theory in organic chemistry is much closer than it used to be to the language of theory in solid-state physics.

The convergence in experimental methods, which of course should never become complete, also reflects the tendency of more powerful analytic methods to be more general. The scanning electron microscope is equally precious to the biochemist and the metallurgist. The infrared spectrograph is almost as ubiquitous as the analytic balance. Radioactive labeling is practiced in nearly all the physical sciences.

Notwithstanding the staggering accumulation of detailed information in the materials sciences, a drastic simplification of scientific knowledge is occurring in these fields. As the facts multiply, the basic principles needed to understand them all are being consolidated. To be sure, the need for specialization by individuals is not declining; the quantity of information vastly exceeds what one mind can assimilate. But the specialist is no longer the custodian of esoteric doctrine and techniques peculiar to his class of substances. Quantum physics is replacing the cookbook, and the mass spectrograph is replacing the nose. The future organic chemist acquires a rough working knowledge of quantum mechanics very early—often earlier, the physicist must concede with chagrin, than his roommate who is majoring in physics. Soon, if it is not already so, any single section of this enormously rich and varied picture will be understood at a fundamental level by anyone equipped with a certain common set of intellectual tools.

Well under way here is nothing less than the unification of the physical sciences. This unification is surely one of the great scientific achievements of our time, seldom recognized or celebrated, perhaps, because, having progressed so gradually, it cannot be seen as an event. Nor can it be credited to one science alone. The influence of quantum physics on chemistry was clearly a central development, and, if one wishes to symbolize that development by one of its landmarks, there is Linus Pauling's *The Nature of the Chemical Bond.* In physics there are many landmarks in the theory of condensed matter, from the first application of quantum theory to crystals by Einstein and Debye to the solution of the riddle of superconductivity, among them the quantum theory of metals, the understanding of ferromagnetism, and the discovery of the significance of lattice imperfections in crystals. But the basic contribution of physics is the secure foundation on which all this knowledge is built—on understanding, confirmed by the most stringent experimental tests, of the interactions between elementary particles and the ways in which they determine the structure of atoms and molecules. The fruits of this immense achievement are only beginning to appear.

Biology obviously derives part of its nourishment from physics by way of chemistry. Biochemistry and molecular biology are equally dependent on physical instrumentation. X-ray diffraction, electron microscopy, and isotopic labeling are indispensable tools. Modern electronics is important in physiology, most conspicuously in neurophysiology, where spectacular progress has been made by observing events in single neurons, made accessible by microelectrodes and sophisticated amplifiers. Other examples are described in the Report of the Panel on Physics in Biology.

These are products of past physics. One might wonder whether future physics is likely to prove as fruitful a source of new experimental techniques for biology and medical science. There are two reasons for thinking that it will. First, there is no apparent slackening of the pace of innovation in experimental physics. In almost every observational dimension, short time, small distance, weak signal, and the like, the limits are being pushed beyond what might have been reasonably anticipated. If there is one thing experience teaches here, it is that quite unforeseen applications eventually develop from any major advance in experimental power. Through the Mössbauer effect, preposterous as it seems, motions as slow as that of the hand of a watch can be measured by the Doppler shift of nuclear gamma radiation. Even after this discovery, when Mössbauer experiments were going on in dozens of nuclear-physics laboratories, a physiological application would have seemed rather fanciful. In fact, the Mössbauer effect is being used today to study, in the living animal, the motion of the basilar membrane in the cochlea of the inner ear, perhaps the central problem in the physiology of hearing.

There is another reason to look forward to contributions to the life sciences from inventions not yet made. It is the existence of some obvious and rather general needs, the satisfaction of which would not violate fundamental physical laws, for example, an x-ray microscope with which material could be examined *in vivo* with a resolution of, say, 10 Å or a better way of seeing inside the body than the dim shadowgraphs, remarkably little better than the first efforts of Roentgen, that medical science has had to be content with for half a century. But the breakthroughs probably will again come in unexpected ways; one cannot guess what will play the role of Roentgen's Crookes tube. The physicist can only feel rather confident that an active, inventive period in experimental physics eventually will have important effects on the way research is done in the biological sciences.

The intellectual relations between physics and biology are changing, perhaps more because of what is happening in biology than what is happening in physics. Most physicists who have any acquaintance with biology, if only through semipopular accounts of the latest discoveries, find the ideas of current biology, especially molecular biology, intriguing and stimulating. No physicist could fail to be stirred by the elucidation of the genetic code or by the other glimpses into primary mechanisms of life. This wonderful apparatus works by physics and chemistry after all! But it is far more ingenious and subtle than any contrivance of wires, pulleys, and batteries. From the intricate engine of muscle fiber to the marvelous information processer in the eye, plainly there are hundreds of mechanisms in which physics, chemistry, and biological function are inextricably involved. Also, the evident universality of basic processes in the cell appeals strongly to a mind trained in the physicist's approach to structure and function. There is no doubt that biology is going to attract some students who would have made good physicists, which cannot be deplored. It is to be hoped that there soon will be a growing number of biologists who are not only well grounded in physics but who share, and possibly derive some encouragement from, the physicist's conviction that the behavior of matter can be understood in terms of the interactions of its elements; this behavior and these interactions are the goals of experimental study.

At the other end of the scale is astronomy. Physics began with astronomy, but after the foundations of Newtonian mechanics were secured, astronomical observations (not counting as such the observations of cosmic rays) did not directly generate new fundamental physics. However, astronomy did provide a rich field for the application of physics. Great advances in astronomy such as the elucidation of the structure and evolution of stars depended on an understanding of the structure of atoms. That came from the physics laboratory and from quantum theory as it developed. Then it was nuclear physics that supplied the keys to the generation of energy in the stars and to the production of the elements. These questions were highly interesting to physicists and inspired both theoretical and experimental work. But, broadly speaking, this work was merely physics applied to astronomical problems.

At a different level, though, astronomy has always had a powerful intellectual influence on physics. The heavens confronted man with tantalizing mysteries. His conceptions of what he saw there strongly influenced philosophical attitudes toward nature. Astronomy has given the physicist confidence that the universe at large is governed by beautifully simple laws of physics, discoverable from earth by man. That belief gives the explorations of physics a wider purpose and significance. It attracts the physicist's attention to cosmological questions, to the physics of gravitation, and to phenomena occurring under conditions utterly unattainable in a terrestrial laboratory.

Today the interaction of physics and astronomy is more vigorous than at any time since Newton. Astronomy has entered an astonishingly rich period of significant discovery. This is due, in part, to observing over a greatly widened spectrum, from the long waves of radio astronomy, which have in 25 years greatly increased the knowledge of the large-scale universe, to x rays and gamma rays, which are just beginning to produce interesting information. In part, too, it reflects the increased power and scope of astrophysical theory, working from a more complete base in atomic and nuclear physics. Also, nature has provided some incredibly marvelous, totally unexpected features for telescopes to discover, displaying on a grand scale phenomena that involve most of physics. Less than ten years after the maser was invented in a physics laboratory, the maser process was found to occur in clouds of interstellar gas. It is typical of the present intensive involvement of physicists in astronomy that this discovery was made by some of the same physicists, now turned radio astronomers, who had participated in the microwave spectroscopy that led to the invention of the maser.

Nuclear physicists and astrophysicists have been engaged for more than 20 years in a collaboration from which has come not only an understanding of the source of energy in stars but of the production of the chemical elements found in the universe. This knowledge bears directly on the history of the universe, providing much of the solid evidence against which cosmological theories can be tested. More surprising is the emerging importance to astronomy of elementary-particle physics. The opacity of matter to neutrinos turns out to be relevant not only to the reconstruction of a primordial big bang but to what is going on now at the centers of galaxies. Inside pulsars there is almost certainly "hyperonic" matter, composed of particles more massive than protons, known only in the laboratory as evanescent products of high-energy collisions. Perhaps a not negligible fraction of the matter in the universe is compressed into this state, a form of matter hardly speculated about before pulsars were discovered five years ago. It may be difficult to forecast commercial applications on planet Earth for high-energy physics, but its importance in the universe as a whole may have been greatly underestimated.

Of course, cosmic rays have been studied by physicists, not astronomers, for 50 years; and these particles, still the most energetic a physicist can hope to see, have been transcendentally important in the development of modern physics. It is hard to imagine how elementary-particle physics would have progressed if the earth had been shielded from cosmic rays. Although the source of cosmic rays was obviously astronomical, it is only rather recently that the importance of cosmic radiation as a constituent of the interstellar medium has been appreciated. Something like a merger of cosmic-ray and related high-energy physics with astrophysics has taken place; the new Division of Cosmic Physics in the American Physical Society is one indication. Magnetohydrodynamics and plasma physics are very lively subjects of common interest to members of both groups. Beyond these obvious cases of interest, even solid-state physicists have been drawn into astrophysics by the discovery of neutron stars.

In the same period, a resurgence of interest in gravitation has occurred among both astronomers and physicists—among astronomers because of the discovery of systems close to the theoretical conditions for gravitational collapse and among physicists because of experimental developments that bring some predictions of gravitational theory within the range of significant laboratory test.

All these developments are bringing again to physics and astronomy a wonderful unity of interest. Never before have so many parts of physics directly concerned astrophysicists; seldom before have astronomical phenomena so stirred the imagination of physicists.

The cosmos is still the place where man must look for answers to some of the deepest questions of physics. Were the fundamental ratios that characterize the structure of matter as found here and now truly precisely constant for all time? Observations of distant galaxies offer a view backward in time to an earlier stage of the universe. Is Einstein's general relativity an exact and complete description of gravitation? Is the visible universe a mixture of matter and antimatter in equal parts, or is what is called matter overwhelmingly more abundant throughout? Already astronomers have observations that bear on these questions. The conclusions are only tentative now, but it seems quite certain that the questions will be answered.

As for the earth sciences, a gap no longer exists between astronomy and geology. A look at the relation of physics to the earth sciences shows a network of interconnected problems, stretching from the center of the earth to the center of the galaxy. The earth's magnetic field provides a good example. How it is generated has always been a puzzle. Now it appears, although the explanation is not complete, that magnetohydrodynamic theory is about to produce a convincing picture of the electric dynamo that must be at work within the earth's fluid core. Furthermore, the same ideas may explain the generation of magnetic fields of stars and even, when applied on a very different scale, the magnetic fields that pervade the whole galaxy. These developments are the work of both geophysicists and astrophysicists, many of them people whose breadth of interest would justify both titles. In addition, the interplanetary magnetic fields in the solar system, which are dominated by the solar wind, are of interest to both the planetary physicist and the solar physicist.

The theoretical base for these interrelationships is the dynamics of highly conducting fluids, including ionized gases, which is also the base for such potentially important engineering developments as the magnetohydrodynamic generator. Not new fundamental physics but ingenious and insightful analysis and the development of more powerful theoretical tools are needed.

From the point of view of physics, the other sciences might be grouped into four very broad divisions: a science of substances, including chemistry and also a part of physics; life sciences; earth sciences plus astronomy (for which a good name that will comprehend the range from meteorology to cosmology is lacking); and engineering science. These divisions are, of course, multiply overlapping, with a topology that would defy a two-dimensional diagram. A category of current interest, environmental science, would overlap all four.

Engineering science is suggested as a fourth division, although it is not as extensive or as well recognized as the others, to emphasize a distinction between the products of technology and the growing body of knowledge—scientific knowledge—that constitutes the intellectual capital of engineering. To this knowledge both engineers and physicists contribute continually, with a mutual stimulation of ideas. To call different portions of this body of knowledge mere applied mathematics does not do justice to the imaginative work that goes on or to the potential influence on the other sciences of the ideas generated. A previously mentioned example is the important subject of fluid dynamics, with its ubiquitous problem of turbulence, in which engineering science naturally has a big stake. Consider, as another example, communication theory, developed in its many aspects by people calling themselves variously engineers, mathematicians, and physicists. Sophisticated treatments of fluctuation phenomena, including quantum effects, the relation of information to entropy, and the rich ramifications—including holography—of Fourier duality are just a few of the ideas it encompasses. Or consider the theory of automatic control with feedback, which was developed mainly within engineering science but is now an indispensable aid in most experimental sciences, including physics. The point is that between physics and engineering science there are strong intellectual, one might even say cultural, links. That is only one aspect of the relation of physics to technology, a topic explored more fully in the following section.

No one would question the importance of physics in the development of these fields of science. However, because chemistry needed physics does not necessarily imply that chemistry now needs help from physicists. Physicists have made fairly direct contributions to chemistry, even recently; and physics, at least as a source of new experimental tools and techniques for other sciences, may be as fruitful a source in the immediate future as it has been in the past. But can essential contributions from physics to the other sciences in the form of new and basic ideas be expected? Do the chemists or the earth scientists, who have fairly well assimilated the apparently relevant parts of physics, need the physicist for any service except to teach physics to their students? What is their interest in his hunt for quarks or gravity waves?

There are two ways to answer such questions from the physicist's point of view. One can meet example with example, explaining, for instance (as will be done in Chapter 4 when this question is addressed with specific reference to high-energy physics), how the isolation of the quark could have immense practical consequences. Or one can make a more general reply along the following lines. The increasing unity of the physical sciences at the basic level and the proliferation of interconnections among the fields, and especially with physics, make intellectual vigor widely contagious. New ideas tend to stimulate other new ideas. As long as physics has great questions to work on, its discoveries can hardly fail to excite resonances in neighboring fields.

TECHNOLOGY AND PHYSICS: THEIR MUTUAL DEPENDENCE

Everyone knows that today the main sources of new technology are research laboratories of physics and chemistry and not the legendary ingenious mechanic or Edisonian wizard. Actually, the relation of technology, that is, applied science, to basic science has been close for more than a century. Think of Faraday, Kelvin, Pasteur. It is true that Morse and Bell were amateurs in electricity, while Maxwell, it is said, found the newly invented telephone not interesting enough to serve as a subject of a scientific lecture. But the sweeping exploitation of electromagnetism that began in the latter half of the nineteenth century was based directly on the fundamental understanding achieved by Maxwell. No one would suggest that today's semiconductor technology could have been created solely by engineers ignorant of the relevant fundamental physics. Research in physics provided the base from which present technology is developing.

But physics research did, and is doing, more than that. Research is a powerful stimulator of fresh ideas. One reason is that in research, and especially in the most fundamental research, the scientist is often trying to break new ground. He may need to measure something at higher energy (remember Van de Graaff and the electrostatic generator) or closer to absolute zero (Kamerlingh Onnes discovering superconductivity) or in a previously inaccessible band of the spectrum. Years before World War II the magnetron was first exploited for the generation of 1-cm waves by the physicists Cleeton and Williams at the University of Michigan. They used it to make the first observation of the inversion resonance of the ammonia molecule.

Also, and this applies to both experimental and theoretical research, to be challenged by a puzzling phenomenon stimulates the imagination. One is likely to try looking at things from a new angle, questioning assumptions that had been taken for granted. P. W. Bridgman once described the scientific method as "the use of the mind with no holds barred." The uninhibited approach of the research scientist to a strange problem has even generated a whole discipline—operations research. Prominent among its creators were scientists like P. M. S. Blackett and E. G. Williams, who came from fundamental physics research, both experimental and theoretical, of the purest strain.

The research laboratory, including the theoretical physicist's blackboard or lunch table, provides the kind of freewheeling environment in which an idea can be followed for a time to see where it leads. Most new ideas are not good. In a lively research group these are quickly exposed and discarded, often having stimulated a fresh idea that may be more productive.

In such a setting, physicists are not generally intellectually constrained by the distinction between fundamental science and technology. For one thing, experimental physics heavily depends on some very advanced technology. The research physicist is not only at home with it, he has often helped to develop it, adapt it, and debug it. He is part engineer by necessity—and often by taste as well. An experimental physicist who is totally unmoved by a piece of excellent engineering has probably chosen the wrong career. One cannot make such a sweeping statement about theoretical physicists, but even they, as was spectacularly demonstrated long ago in the Manhattan Project, frequently can apply themselves both effectively and zestfully to technological problems. Currently, in fields such as plasma physics and thermonuclear research, there are many theoretical physicists, with a broad range of interest and expertise, some with a background in elementary-particle physics, intimately concerned with engineering questions.

Ongoing basic research is necessary for the translation of scientific discovery into useful technology, even after the discovery has been made. As a rule, the eventual value to technology of a discovery is seldom clearly evident at the time. It often emerges only after a considerable evolution within the context of fundamental research, sometimes as an unexpected by-product. Nuclear magnetic resonance (NMR) is now widely used in the chemical industry for molecular structure identification. This possibility was totally unforeseeable in the early years of NMR research. It came to light only after a major improvement in resolution had been achieved by physicists studying NMR for quite different purposes. However, a backlog of unapplied basic physics is not all that it takes to generate new technology; it may not even be the main ingredient.

Some of the most startling technological advances in our time are closely associated with basic research. As compared with 25 years ago, the highest vacuum readily achievable has improved more than a thousandfold; materials can be manufactured that are 100 times purer; the submicroscopic world can be seen at 10 times higher magnification; the detection of trace impurities is hundreds of times more sensitive; the identification of molecular species (as in various forms of chromatography) is immeasurably advanced. These examples are only a small sample. All these developments have occurred since the introduction of the automatic transmission in automotive engineering!

On the other hand, fundamental research in physics is crucially dependent on advanced technology, and is becoming more so. Historical examples are overwhelmingly numerous. The postwar resurgence in low-temperature physics depended on the commercial production of the Collins liquefier, a technological achievement that also helped to launch an era of cryogenic engineering. And today, superconducting magnets for a giant bubble chamber are available only because of the strenuous industrial effort that followed the discovery of hard superconductors. In experimental nuclear physics, high-energy physics, and astronomy—in fact, wherever photons are counted, which includes much of fundamental physics—photomultiplier technology has often paced experimental progress. The multidirectional impact of semiconductor technology on experimental physics is obvious. In several branches of fundamental physics it extends from the particle detector through nanosecond circuitry to the computer output of analyzed data. Most critical experiments planned today, if they had to be constrained within the technology of even ten years ago, would be seriously compromised.

The symbiotic relation of physics and technology involves much more than the exchange of goods in the shape of advanced instruments traded for basic ideas. They share an atmosphere the invigorating quality of which depends on the liveliness of both. The mutual stimulation is most obvious in the large industrial laboratory in which new technology and new physics often come from the same building and, sometimes, from the same heads. In fact, physics and the most advanced technology are so closely coupled, as observed, for example, on a five- to ten-year time scale, that the sustained productivity of one is critically dependent on the vigor of the other.

EXPERIMENTAL PHYSICS

An experimental physicist is usually doing something that has not been done before or is preparing to do it, which may take longer than the actual doing. That is not to say that every worthwhile experiment is a risky venture into the unknown. Many fairly straightforward measurements have to be made. But only *fairly* straightforward! The easy and obvious, whether in basic or applied physics, has usually been done. The research physicist is continually being challenged by experimental problems to which no handbook provides a guide. Very often he is trying to extend the range of observation and measurement beyond previous experience.

A most spectacular example is the steady increase in energy of accelerated particles from the 200-keV protons, with which Cockcroft and Walton produced the first artificial nuclear disintegrations in 1930, to the 200-GeV protons of the National Accelerator Laboratory—in 40 years a factor of a million! This stupendous advance was achieved not in many small steps but in many large steps, each made possible by remarkable inventions and bold engineering innovations produced by physicists. Although numerical factors of increase do not have the same implications in different technologies, few branches of engineering have come close to that record. A possible exception is communication engineering. Transmission by modulated visible light, now feasible, represents an increase in carrier frequency of roughly a million over the highest radio frequency usable 40 years ago. What is really more significant, the information bandwidth achievable has increased by a comparable factor. This great advance was, of course, made possible by development in basic physics and at many stages was directly stimulated by the basic research of physicists. Even accelerator physics contributed at one stage by stimulating the development of klystrons. The accelerator physicists have a remarkable record of practical success as engineers. From the time of the early cyclotrons to the present, no major accelerator in this country, however novel, has failed to work; most of them exceeded their promised performance.

In other branches of experimental physics, too, people are doing things that would have appeared ridiculously impractical only 10 to 20 years ago. For example, a discovery in the physics of superconductivity (the Josephson effect) made it possible to measure precisely electric voltages and magnetic fields a thousand times weaker than could be measured previously. Electrons, also positive ions, can be electrically caged, almost at rest in space, for hours. By another technique, neutral atoms can be stored in an evacuated box for minutes without disturbing a natural internal oscillator that completes, in that time, about 10^{12} cycles of oscillation. One by-product is an atomic clock that is accurate to about a second in a million years. By recent laser techniques, light pulses of only 10^{-12} seconds' duration have been generated and observed. The local intensity of light that can be created with lasers is many million times greater than anything known in the laboratory ten years ago. Effects can be readily observed that in the past could be only the subjects of theoretical speculation, thus opening to investigation as entire field of basic research—nonlinear optics. Within the same decade, the highest magnetic-field strengths easily available in the laboratory, which had hardly changed in a century, were roughly quadrupled by superconducting magnets. In the same period, low-temperature physicists extended downward by a factor of 10 the temperature range usable for general experimentation.

These developments and others mentioned subsequently in this Report show that experimental physics is not running out of ideas or becoming a routine matter of data-gathering. In fact, experimental physics could be entering a new period, distinguishable (by criteria other than austerity of budgets!) from two preceding periods of conspicuous experimental advance in modern physics: the decade before World War II, which, in terms of tools and techniques, could be called the "cyclotron and vacuum tube" period, and the immediate postwar period, in which microwave electronics and nuclear technology, largely the fruits of wartime physics, made possible an enormous advance in experimental range. Within the past 10 to 15 years, several postwar developments have come of age that, considered as a group, promise a comparable advance in experimental capability. These include cryogenics in all its ramifications, semiconductor technology, laser–maser techniques, and the massive exploitation of computers. One trouble with any such historical formula, and the glory of physics as an adventure, is the existence of the important and unclassifiable exceptions. For example, the continuously spectacular progress in high-energy accelerators fits only very loosely into the scheme just outlined. A more modest exception is the simple proportional counter, one of the most elegant and sensitive devices of physics since the torsion pendulum, which has survived through all three periods, earning in each a new lease on life.

Whether it signifies a new era or not, the enormous advance in observational power that is occurring now will in all likelihood open still more fields of research in physics. It will certainly lead to applications yet unforeseen in other sciences and technology.

PHYSICS—A CONTINUING CHALLENGE

It is possible to think of fundamental physics as eventually becoming complete. There is only one universe to investigate, and physics, unlike mathematics, cannot be indefinitely spun out purely by inventions of the mind. The logical relation of physics to chemistry and the other sciences it underlies is such that physics should be the first chapter to be completed. No one can say exactly what completed should mean in that context, which may be sufficient evidence that the end is at least not imminent. But some sequence such as the following might be vaguely imagined: The nature of the elementary particles becomes known in self-evident totality, turning out by its very structure to preclude the existence of hidden features. Meanwhile, gravitation becomes well understood and its relation to the stronger forces elucidated. No mysteries remain in the hierarchy of forces, which stands revealed as the different aspects of one logically consistent pattern. In that imagined ideal state of knowledge, no conceivable experiment could give a surprising result. At least no experiment could that tested only fundamental physical laws. Some unsolved problems might remain in the domain earlier characterized as organized complexity, but these would become the responsibility of the biophysicist or the astrophysicist. Basic physics would be complete; not only that, it would be manifestly complete, rather like the present state of Euclidean geometry. Such an outcome might not be logically possible.

One might be more seriously concerned with the prospect of reaching a stage short of that, in which all the basic physics has been learned that is needed to predict the behavior of matter under all the conditions scientists find in the universe or have any reason to create. From chemistry to cosmology, let us suppose, all situations are covered, but one cannot predict with certainty the scattering cross section for e-neutrinos on μ-neutrinos at 10^{30} V. Suppose further that the experiments required to explore fully all the physics at 10^{30} V are inordinately costly and offer no prospect of significantly improving physics below 10^{20} V, which is already known to be sufficiently reliable. If some such state were reached, one might reasonably expect that research in fundamental physics would be at least brought to an indefinite halt if not closed out entirely as being in the state of perfection previously postulated. It would be said that all the physics that mattered had been learned.

Some physicists are supposed to have made this statement about physics at about the end of the nineteenth century. That they were wrong, spectacularly wrong, is a reminder that human vision is limited; it proves nothing more. For the state of knowledge of physics today is essentially different from that in 1890, just before the curtain was pulled back, so to speak, from the atomic world. Where the problems lie is evident. As far as the behavior of ordinary matter is concerned, it is hardly conceivable that the detailed picture of atomic structure, the product of quantum theory and exhaustive experimentation, should turn out to be misleading or that the main problem in nuclear physics should suddenly be revealed as one hitherto ignored. There are mysteries, but they lie deeper. If it were possible to fence off a particular range of application, for example, chemistry at temperatures below 10^{5} deg, then a state in which all the relevant fundamental physics is essentially complete could be reasonably anticipated. Indeed, for a sufficiently restricted application, the day might already have arrived.

The trouble is that the range of interests continues to widen, and in unexpected ways. Because of pulsars, the structure of atoms exposed to a magnetic field of 10^{12} G (ten million times the strongest fields in laboratory magnets) becomes a question of some practical concern, as does the shear strength of iron squeezed to a billion times its ordinary density. Just now astronomy seems to be making the most new demands on fundamental physics; there the end is not in sight.

Even if the physicist could reliably and accurately describe any elementary interaction in which a chemist or an astronomer might be interested, the task of physics would not be finished. Man's curiosity would not be satisfied. Some of the most profound questions physics has faced would remain to be answered, if understanding of the pattern of order found in the universe is ever to be achieved. The extent of present ignorance still is great.

It is far from certain that in the presently recognized elementary particles the ultimate universal building blocks of matter have been identified. The laws that govern the behavior of the known particles under all circumstances are not known. It is even conceivable that the study of particle interactions at ever higher energy leads into an open domain of never-decreasing complexity. Probably most physicists would doubt that. Cosmic rays afford an occasional glimpse of matter interacting at energies very much greater than particle accelerators provide, and no bizarre consequences have yet been observed. It seems rather that physicists now face not mere complexity but subtlety, a strangeness of relationship among the identified particles that might render the question of which of them is truly elementary essentially meaningless.

Even if physicists could be sure that they had identified all the particles that can exist, some obviously fundamental questions would remain. Why, for instance, does a certain universal ratio in atomic physics have the particular value 137.036 and not some other value? This is an experimental result; the precision of the experiments extends today to these six figures. Among other things, this number relates the extent or size of the electron to the size of the atom, and that in turn to the wavelength of light emitted. From astronomical observation it is known that this fundamental ratio has the same numerical value for atoms a billion years away in space and time. As yet there is no reason to doubt that other fundamental ratios, such as the ratio of the mass of the proton to that of the electron, are as uniform throughout the universe as is the geometrical ratio $\pi = 3.14159$. Could it be that such physical ratios are really, like π, mathematical aspects of some underlying logical structure? If so, physicists are not much better off than people who must resort to wrapping a string around a cylinder to determine the value of π! For theoretical physics thus far sheds hardly a glimmer of light on this question.

The question was posed in even sharper form 40 years ago by Eddington, who argued that the structure perceived in nature can be nothing but a reflection of the methods of observation and description that must be employed. That view would reduce fundamental physics to metaphysics. But Eddington's own conception of the structure did not survive. Such evidence as he had adduced was soon washed away in a flood of discovery. The whole history of physics since then gives no sign that physics is about to become an exercise in deduction. Every attempt to close the theoretical structure to all changes except refinements has been confounded by an experimental discovery. This has happened so often that there has been some accession of intellectual humility along with the vast increase in knowledge of the underlying structure of matter. Surely the end of the story is yet far off.

The fundamental question survives, if not the attempts to answer it: Is there an irreducible base, or design, from which all physics logically follows? The history of modern physics warns that the answer to such a question will not be attained just by thinking about it. To be sure, brilliant theoretical ideas, probably many, will be needed, and some future Bohr or Einstein may become renowned for the flash of insight that eventually reveals a key to the puzzle (or the absence of a puzzle!). But without experimental exploration and discovery, new ideas are not generated. Physics will remain an experimental science at least until very much more is known about the fundamental nature of matter.

Some of the fundamental differences between science and politics are highlighted in this reexamination of what may have been the most momentous decision of World War II.

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11 The Decision to Drop the Atomic Bomb

Dietrich Schroeer

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> *. . . the physicists felt a particularly intimate responsibility for suggesting . . . and . . . for achieving the realization of atomic weapons. . . . In some sort of crude sense, which no vulgarity, no humor, no overstatement can quite extinguish, the physicists have known sin; and this is a knowledge which they cannot lose.*
>
> J. Robert Oppenheimer in *The Open Mind*, p. 80

Some of the military, political, and emotional background to the decision to use the atomic bomb is presented. The interaction of the views of the nuclear physicists with those of the military and the President is discussed.

INTRODUCTION

In 1941 the nuclear scientists proposed the atomic bomb, in 1945 some of them were opposed to its use, and now there are those who consider the use of the bomb to be the event wherein scientists for the first time tasted sin. In this chapter we will examine the scientific, emotional, and military-political background behind the decision of the United States to actually use the atomic bomb as a weapon in the Second World War.

This was a particularly interesting decision for at least two reasons. First, in the United States the atomic bomb was proposed by scientists primarily because of fear of German militarism. Yet it was finally used against an enemy who would have been easily defeated without it. Secondly, the bomb was proposed and built by scientists who were trained to think in terms of a consensus. Yet because of the secrecy of the Manhattan Project, only a very select group of persons was in a position to influence the final decision concerning use of the bomb—a group which did not even include the members of Congress.

We shall begin by considering the basis for the fear of a German atomic bomb. Then the attitudes of the scientists toward the use of the bomb on Japan will be outlined. Finally, the military and political situation which led to its use will be compared with the consequences of its use. Hopefully this review will make clear the resulting ambivalence in the attitude of the scientific community toward this mixture of great scientific, technological, and organizational achievement combined with the horror of its wartime usage.

THE FEAR OF THE SCIENTISTS

The original motivation of the scientists in the United States for proposing the atomic bomb as a weapon was fear. The immigrant scientists had tasted Hitler's Germany firsthand; they knew the oppression which an Axis victory would bring. Even Einstein, though basically a pacifist, knew there would be circumstances intolerable enough to negate his pacifism; and he knew that a war against Nazism was one of these.

But beyond this general fear, the immigrant nuclear scientists had the more direct fear that Germany would be the first to build an atomic bomb and use it to win the war. This fear was the reason Einstein wrote his letter to President Roosevelt; his primary purpose was to get the President to convince the Belgians not to let Hitler capture their stock of uranium, and to thereby delay the Germans as long as possible in building the bomb. This fear led to the overriding concern of the scientists that the Allies should be the first to possess the bomb; until the German surrender this was the specter haunting the Manhattan Project. There was, in fact, so much fear at the end of 1942 that some scientists convinced themselves that Hitler would attack Chicago with the radioactivity from a reactor (on Christmas day, of course); they so convinced themselves that they sent their families to the country.

THE GERMAN ATOMIC BOMB

It is interesting to examine this specter a little closer in order to see how substantial it may have been. When the curtain of wartime secrecy shut off contact between the two scientific camps, the Germans were rapidly moving toward building the atomic bomb. Not only had fission first been observed in Berlin by Hahn, but in April of 1939 a first meeting concerning an atomic bomb had already been held under the official auspices of the Reich Ministry of Education. There had also been a bomb proposal to the War Office; even the Postal Ministry began to perform nuclear research with such a bomb in mind. By September 1939, more than a fortnight before Sachs could obtain an interview with Roosevelt to transmit Einstein's letter, nine German nuclear physicists had met in the Army Weapons Office and drawn up a detailed program of research. The Uranium Club was then formed, with Heisenberg (the discoverer of the Uncertainty Principle) as head; and the Kaiser Wilhelm Institute for Physics in Berlin was made the club's Scientific Center. Negotiations were begun for all the uranium and radium from the Joachimsthal mines in Czechoslovakia; a 3500-ton supply of uranium was captured when Germany overran Belgium; and when Norway was taken over by Germany, the Germans captured the world's only large-scale plant for manufacturing the heavy water which would make a nuclear reactor an easy thing to build. As far as the Americans and the British could see, the Germans had then a two-year headstart toward an atomic bomb, had all the natural advantages, and were clearly moving rapidly in the right direction. This was a self-feeding fear. The lack of any nuclear-progress spy reports after 1939 surely meant simply that supersecrecy was instituted to hide tremendous German achievements. And when the V-2 rocket construction started, the worry arose that, since the V-2 was too small to have much effect with ordinary explosives, it must be intended to deliver nuclear warheads.

The fear of the German atomic bomb evoked three different responses. First the British and later the American atomic-bomb programs were pushed with great vigor. Secondly, the Norwegian heavy-water plant was bombed and sabotaged. The plant was promptly rebuilt; this indicated to the Allies that the German atomic-bomb program must have very high priorities. The third part of the response was the "Alsos" mission. ("Alsos" is Greek for "grove;" the mission was presumably named in honor of General Groves.) Alsos was an intelligence group which included physicists whose assignment was to pick up German scientific secrets as Axis laboratories and universities were captured by the Allies. The scientific chief of this operation was Dr. Samuel Goudsmit (now editor of the *Physical Review Letters*, perhaps the most prestigeous physics journal in the West). This group went along with the Allied armies (sometimes even ahead of them) and examined the files at the universities and laboratories for hints about the nuclear operations. As the story uncovered, it became clear that not only was there no German atomic bomb, there wasn't even an operational nuclear reactor.

There were many factors contributing to the German failure to build an atomic bomb. The first was the competition among the scientists participating in the program. Although Berlin had been set up as the center for the Uranium Club, most of the physicists preferred to do their work in their own institutes. There was constant competition between the three agencies supporting the groups working on the bomb—between the Educational Ministry, the War Office, and the Post Office. When the Postal minister informed Hitler about his bomb project, Hitler joked, "Look here gentlemen, while you experts are worrying about how to win the war, here it is our Postal Minister who brings us the solution." In the United States a similar problem was finally terminated by Oppenheimer when he set up the centralized laboratory at Los Alamos. In Germany, however, the competition continued, and its results were manifold. There were constant fights as to who was to be allowed to use the limited amounts of pure uranium and heavy water; even in the last days of the war these materials were still being shuttled from one laboratory to another, with no group ever having enough to run a conclusive reactor experiment. Splits between those groups came out also in discussions of separation processes, and as a result the priorities for programs were usually determined by the pecking order; in part as a consequence of this, no separation process had made any significant progress by the end of the war.

One of the more powerful brakes on the program was a purely technical mistake. Very early in the war a measurement was carried out which indicated that carbon in the form of graphite could *not* be used as a moderator in a fission reactor using natural uranium. Presumably the carbon used in this measurement had impurities in it; after all, Fermi in the United States successfully built a graphite reactor in 1942. As a consequence of this error, the German physicists thought they needed heavy water for a reactor, and hence made themselves totally dependent on that captured Norwegian heavy-water plant. The Allied sabotage and bombings of this plant then completely upset the program.

Another significant reason for the lack of progress toward the bomb was the very nature of the German Nazi state and ideology. As indicated in Chapter 16, by 1937 nearly 40% of the German university professors had been dismissed, and many more had fled. Between 1932 and 1937 the number of university students in mathematics and the sciences had dropped to 36% of its former level. It was only in 1942, when it became clear that the end of the war was not imminent, that the government began to recognize this problem. Then Goering said:

> What the Führer abhors is any strict regimentation of science, with results like this: "This invention may indeed be vital—extremely vital to us, and would bring things a long way for us; but we can't touch it because the fellow's got a Jewish wife, or because he's half-Jewish himself. . . ."
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> I have discussed this with the Führer himself now; we have been able to use one Jew two years longer in Vienna, and another in photographic research, because they have certain things which we need and which can be of the utmost benefit to us at the present. It would be utter madness for us to say now: "He'll have to go. He was a magnificent researcher, a fantastic brain, but his wife is Jewish, and he can't be allowed to stay at the University, etc." The Führer had made similar exceptions in the arts all the way down to operetta level; he is all the more likely to make exceptions where really great projects or researchers are concerned. (As quoted in Ref. 18.3, p. 126.)

And, as was pointed out in Chapter 16, political meetings had to be called to decide what physics was consistent with the party philosophy. This not only was discouraging to any real scientists; it further was very encouraging to all scientific quacks who were party members.

But the final and perhaps most decisive reason for the failure of the German atomic-bomb program was the attitude of the German scientists. They felt no fear; they were not worried about an American atomic bomb; after all, German science was superior. The prompt rebuilding of the Norwegian hydro plant after the sabotage and bombing and the prompt production of pure uranium made it clear that German industry and the war offices were prepared to support an atomic-bomb program. But the scientists never learned to ask for money; from either a lack of confidence or of desire, they never pushed the program very forcefully. When the scientists had a talk with the sympathetic Armaments Minister Speer, they asked for so little money that he was embarrassed. The German scientists themselves claim that they never really wanted to build an atomic bomb (e.g., Refs. 18.1 and 18.5). To them the program was an opportunity to preserve some German science for the postwar period; by doing defense work they were able to keep away from the front and to maintain a semblance of university teaching and research. Doubts have been expressed as to the correctness of this after-the-fact explanation (e.g., Ref. 18.3), but in any case, fission research was not pursued in Germany with enough energy to lead to significant progress.

THE ATOMIC BOMB AND JAPAN

The Alsos mission and the surrender of Germany in May of 1945 ended any fear of a German atomic weapon on the part of American scientists in the Manhattan Project. And Japan clearly had not the facilities, the resources, or the scientific establishment necessary to build such a weapon. Once the fear motive was removed, American nuclear scientists could then think about the longer-term implications of the bomb and specifically about its possible application to the war with Japan. Should it be used, and if so, how? And what would happen to nuclear research and nuclear information once the war was over? To the military, including the man in charge, General Groves, there was no question that the weapon would be used if built; the only worry was that it might not be finished in time. So any change of plans had to occur at the very top; only the President could decide the ultimate use of the bomb.

There were attempts to influence Roosevelt on this issue. Alexander Sachs, who had passed the Einstein letter to him, debated the question with him in December of 1944 and later claimed that Roosevelt at that time agreed to a rehearsal demonstration of the atomic bomb before international and neutral witnesses prior to any wartime use. But this agreement, if it indeed existed, was never mentioned to Secretary of War Stimson, who on March 15, 1945, had his last talk on the subject with Roosevelt:

> I went over with him the two schools of thought that exist in respect to the future control after the war of this project, in case it is successful, one of them being the secret close-in attempted control of the project by those who control it now, and the other being international control based upon freedom of science. I told him that those things must be settled before the projectile is used and that he must be ready with a statement to come out to the people on it just as soon as that is done. He agreed to that. (Quoted for example in Ref. 18.1, p. 175.)

A report by Szilard on the scientists' feelings about the bomb was lying on Roosevelt's desk when he died. After Roosevelt's death, any changes in the decision about the use of the bomb required convincing the new President, Harry S. Truman, who had never heard of the weapon while he was Vice President.

THE SCIENTISTS' VIEWPOINT

The most general and wide-ranging discussions about the use of the bomb took place among the nuclear scientists in Chicago, where toward the end of the war there was not so much pressure since the production processes had already passed on to industry; this stood in contrast with Los Alamos where everyone continued to work at fever pitch until the very end to meet the bomb-construction and testing deadlines. It was in Chicago that the Jeffries Report, *Prospectus on Nucleonics*, was prepared—a report which contained discussions of a possible future armaments race as well as of the future applications of nuclear fission. Early in 1945 several of the Chicago scientists became convinced that international control of nuclear knowledge would be the best way to ensure open dissemination of this new information. As James Franck put it in April of 1945:

> We read and hear about all the efforts which the best statesmen devote to peace planning in Dumbarton Oaks, San Francisco, etc., and we hear about plans to control industries, etc. in the agressor states, but we know in our hearts that all these plans are obsolete, because the future war has an entirely different and a thousand times more sinister aspect than the war which is fought now. How is it possible that the statesmen are not informed that the aspect of the world and its future is entirely changed by the knowledge that atomic energy can be tapped, and how is it possible that the men who know these facts are prevented from informing the statesmen about the situation? One of the grave political decisions which will soon have to be made is how and when to inform the public, since in a democratic country effective political steps cannot be taken without enlightened public opinion. (As quoted in Ref. 18.2, pp. 294–295.)

A "Committee on the Social and Political Implications of Atomic Energy" was formed under Franck. It completed the Franck Report in early June of 1945, a report which was promptly classified. A quotation from the preamble to this report is appropriate here because it shows that the scientists were aware that they could speak about the implications only as well-informed citizens, not as experts:

> The scientists on this Project do not presume to speak authoritatively on problems of national and international policy. However, we found ourselves, by the force of events, during the last five years, in the position of a small group of citizens cognizant of a grave danger for the safety of this country as well as for the future of all the other nations, of which the rest of mankind is unaware. We therefore feel it our duty to urge that the political problems, arising from the mastering of nuclear power, be recognized in all their gravity, and that appropriate steps be taken for their study and the preparation of necessary decisions. We hope that the creation of the Committee by the Secretary of War to deal with all aspects of nucleonics, indicates that these implications have been recognized by the government. We believe that our acquaintance with the scientific elements of the situation and prolonged preoccupation with its world-wide political implications, impose on us the obligation to offer to the Committee some suggestions as to the possible solution of these grave problems. (As quoted in Ref. 18.2, p. 302.)

The objections raised in the report to the use of the atomic bomb were that it would be likely to induce an armaments race and thus reduce the possibility of an international control agreement. While the report was signed by all seven members of the committee, there were other scientists who felt that an all-out attack on Japan by the atomic bomb would significantly shorten the war. There were petitions and counterpetitions. A poll was carried out July 12, 1945, among 150 out of the 250 nuclear scientists at the Chicago Metallurgical Lab. The following alternatives were presented:

> Which of the following five procedures comes closest to your choice as to the way in which any new weapons that we may develop should be used in the Japanese war:
>
> 1. Use them in the manner that is from the military point of view most effective in bringing about prompt Japanese surrender at minimum human cost to our armed forces.
>
> 2. Give a military demonstration in Japan to be followed by renewed opportunity for surrender before full use of the weapon is employed.
>
> 3. Give an experimental demonstration in this country, with

> representatives of Japan present; followed by a new opportunity for surrender before full use of the weapon is employed.
>
> 4. Withhold military use of the weapons, but make public experimental demonstration of their effectiveness.
>
> 5. Maintain as secret as possible all developments of our new weapons and refrain from using them in this war.

The results were as follows:

Procedure indicated above	1	2	3	4	5
Number voting	23	69	39	16	3
Percent of votes	15	46	26	11	2

(As quoted in Ref. 18.2, p. 304.)

Clearly there was concern among the scientists, but there was no unanimity; some scientists wanted the weapon to be first demonstrated before being used in combat in Japan, but this view was not universal; there was concern about the moral and political aspects of being the first nation to use this weapon, but it was the concern of private individuals.

The new President, Truman, did ask for advice about the way to use the bomb; near the end of April 1945 he appointed the so-called Interim Committee. It included Stimson, Secretary of War; George L. Harrison, Stimson's assistant; James F. Byrnes, future Secretary of State; Ralph A. Bard, Undersecretary of the Navy; William L. Clayton, Assistant Secretary of State; Dr. Bush; Dr. Karl T. Compton, president of M.I.T; and Dr. Conant. A panel of four scientists was appointed to advise the committee: A. H. Compton, Fermi, Lawrence, and Oppenheimer. According to Stimson, after discussions with the scientific panel, the committee unanimously adopted the following recommendations:

> 1. The bomb should be used against Japan as soon as possible.
>
> 2. It should be used on a dual target—that is, a military installation or war plant surrounded by or adjacent to houses and other buildings most susceptible to damage, and
>
> 3. It should be used without prior warning [of the nature of the weapon]. One member of the committee, Mr. Bard, later changed his view and dissented from recommendation.
>
> In reaching these conclusions the Interim Committee carefully considered such alternatives as a detailed advance warning or a demonstration in some uninhabited area. Both of these suggestions were discarded as impractical. . . . (As quoted in Ref. 18.2, pp. 296–297.)

Since President Truman ultimately followed the advice of this committee, a critical point is whether indeed all possible alternatives had been considered or whether the agreement was not just an act of rubber-stamping. Apparently many different alternatives were considered, such as a nighttime airflash several miles above Tokyo, the demonstration bombing of a forest area in the vicinity of Tokyo, or at least a detailed advance warning. But all the alternative uses of the bomb were rejected because they would not be impressive enough or their results could be hidden through military secrecy or they could be negated by moving prisoners of war into the area. The consensus in the committee was not quite as total as implied by Stimson. The scientific panel, for example, only advised; it did not vote on the recommendations. And Mr. Bard had never heard of the Manhattan Project prior to this meeting; consequently, his agreement was so forced that he subsequently withdrew his consent to the recommendations and a month later resigned his naval post to emphasize his opposition to the bombing (feeling that the Navy was quite able to bottle up Japan and that the Army just wanted to share in the glory of the final victory). There is, however, no question that Truman received the recommendation from this high-level committee (with a large representation from science and technology) that only a bombing of a live target would be convincing to the Japanese. The scientists certainly were not unanimously against the usage of the bomb.

THE MILITARY SITUATION IN JAPAN

In the meantime, the war situation was as follows. Okinawa had been invaded in a very bloody battle with suicidal kamikazi plane missions taking place on a large scale. On March 9, 1945, 325 B-29's bombed Tokyo with 2000 tons of incendiaries. The resulting fire storm killed approximately 100,000 people, flattened 16 square miles, and destroyed 250,000 buildings. In five months of bombing, the 21st Bomber Command had paralyzed 66 metropolitan centers and had made eight million Japanese homeless. Hunger was a constant torture; rice rations were down to one-fourth of the prewar level. And overriding all this was fear; as the B-29's and the planes from the carriers dominated the people's very movement, the civilian population of Japan was on the edge of desperation.

Attempts to negotiate concerning a surrender began as early as May, 1945—through Switzerland, over radio propaganda broadcasts, and even through Russian intermediaries (since Russia still had not declared war on Japan). But the Japanese military was not prepared to surrender. The plans for the defense of the homeland were to kill as many invaders as possible and thus to shatter American morale enough to lead to a negotiated peace in place of the demanded unconditional surrender. And the American military plans still called for an invasion of Japan; casualty estimates were hundreds of thousands of Americans, plus many more Japanese.

The Potsdam Conference was going on at this time, and on July 24 Truman "casually" told Stalin that the U.S. had a new weapon of unusual destructive force. The Russian premier showed no special interest in this weapon. He only said that he was glad to hear it and hoped the U.S. would make "good use of it against the Japanese." He never asked a question about it. In the Potsdam Declaration of July 26 there was an ultimatum threatening complete destruction of Japan. For the Japanese the biggest stumbling block in the way of surrender was Point 6 of this declaration. This point said: "There must be eliminated for all time the authority and influence of those who have deceived and misled the people of Japan into embarking on world conquest." They interpreted this as requiring the abdication of the Emperor, which was an unacceptable condition. In his radio response to the Potsdam Declaration, Premier Suzuki tried to say that the government would "withhold comment," but he accidentally used the words meaning to "take no notice of, treat with silent contempt, ignore." Truman could only interpret this as a refusal to surrender, so he authorized the use of the atomic bomb. On August 6 the B-29 named "Enola Gay" took off. The weather was good, so at 8:15 a.m. local time, the "Little Boy" was dropped on Hiroshima. (The city of Kyoto had been struck from the original target list since it had been the ancient capital of Japan and was a shrine of Japanese art and culture.) Truman made a public statement: "It is an atomic bomb." Three days later, one day after Russia entered the war, a plutonium bomb was dropped on Nagasaki. As part of this flight, a letter was dropped by parachute, addressed by Professors L. Alvarez, R. Serber, and P. Morrison to their former colleague at Berkeley, Professor R. Sagane at the Imperial University of Tokyo:

> We are sending this as a personal message to urge that you use your influence as a reputable nuclear physicist, to convince the Japanese General Staff of the terrible consequences which will be suffered by your people if you continue in this war.
>
> You have known for several years that an atomic bomb could be built if a nation were willing to pay the enormous cost of preparing the necessary material. Now that you have seen that we have constructed the production plants, there can be no doubt in your mind that all the output of these factories, working 24 hours a day, will be exploded on your homeland.
>
> Within the space of three weeks, we have proof-fired one bomb in the American desert, exploded one in Hiroshima, and fired the third this morning. We implore you to confirm these facts to your leaders, and to do your utmost to stop the destruction and waste of life which can only result in the total annihilation of all your cities if continued. As scientists, we deplore the use to which a beautiful discovery has been put, but we can assure you that unless Japan surrenders at once, this rain of atomic bombs will increase manyfold in fury. (See, for example, the facsimile in Ref. 17.7, p. 258.)

The number of dead due to these two atomic bombs is not very accurately known, but is on the order of 150,000. Official Japanese statistics placed the number of dead at Hiroshima (out of a population of 400,000) at 70,000 up to September 1, 1945, and the number of wounded at 130,000 with 43,500 severely wounded. The supreme Allied Headquarters announced in February of 1946 that the casualties in Hiroshima were:

dead — 78,150;
missing — 13,983;
seriously wounded — 9,428;
slightly injured — 29,997.

The horror of those days has been often described (as in Refs. 18.12 through 18.15); the survivors still bear psychological scars (Ref. 18.15).

Fig. 18.1 Remains of the Nagasaki Medical College after the A-bomb drop on August 9, 1945. (Photo courtesy of the United States Atomic Energy Commission.)

Even after the atomic bomb was used, the Japanese cabinet was still split on whether to surrender or not; one man who was basically committed to the policy of trying to get better surrender terms by bleeding the Americans on the beaches was the War Minister Anami, spokesman for the Army and the most powerful man in Japan. But finally Emperor Hirohito saved face for everyone by taking the onus of surrender on himself: "... the time has come when we must bear the unbearable." On the 10th August, Japan offered to surrender. Members of the Army briefly tried to rebel and to destroy the Emperor's recording of the planned surrender radio broadcast; but Anami vacillated and the uprising failed. Included in the brief 300-word announcement of August 15 (nine days after the first atomic bomb) were the following statements:

> ... the war situation has developed not necessarily to Japan's advantage.... Moreover, the enemy has begun to employ a new and most cruel bomb, the power of which to do damage is indeed incalculable, taking the toll of many innocent lives. Should we continue to fight, it would not only result in an ultimate collapse and obliteration of the Japanese nation, but would also lead to the total destruction of human civilization. (Quoted for example in Ref. 18.7, p. 182.)

SUMMARY

In fear of a German atomic bomb, the U.S. scientists proposed such a weapon and built it. But then they lost control of it, as it inexonerably was used in defeating Japan. President Truman had to make the final decision concerning its use, and it is questionable whether he ever had any major doubts in his mind about the correctness of his ultimate choice. The bomb may or may not have significantly shortened the war, but now the world must live with that memory.

For the scientists there is much irony in the course of events related to the atomic bomb. First, the fear of Germany was groundless insofar as the bomb ultimately was not necessary for the winning of the war. Secondly, the designing of the bomb was a technological feat, but it was not science since it was product-oriented. In fact, this wartime contact with secrecy and its consequent hampering of scientific activities impressed the participating scientists tremendously, and colored all their future political attempts at arranging the course of science. And finally, the instincts of the scientists were right when they tried to get the broadest possible audience for the discussions on the bomb's use—when they asked for a more general public consensus. Perhaps it would have been the very best possible thing if the discussion could have been made totally public; only in that way could the most socially responsible decision have been reached. But this was impossible under wartime secrecy, a secrecy which perhaps was not necessary but which did exist. The decision to drop the bomb could, therefore, in no sense be called a scientific decision. This whole exercise brought home to the nuclear scientists the difference between science and politics, a difference which they have had to continually relearn. They discovered that no consensus was possible in the latter field.

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QUESTIONS FOR DISCUSSION

1. Was it right for the German nuclear physicists to want to preserve some German physics (as opposed to some physics for Germany)?
2. Do the reasons given seem to adequately explain the failure of the German atomic bomb as compared to the success of the American program?
3. Can we say with hindsight that the decision to use the bomb was wrong? Is it not good that the world saw a demonstration of the effects of such a weapon?
4. To whom belongs the glory of this magnificent achievement? To whom belongs whatever guilt may be associated with it?

Because of their traditional sense of coexistence with nature, the Japanese did not come until recently to look upon nature as something to be investigated or exploited.

12 The Conception of Nature in Japanese Culture

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Man's Harmony with Nature

Some ten years ago, when I had the privilege of teaching at the University of Missouri, I read an old Japanese story to my class one day and asked each of the students to write a short comment on it. It was a story related by Lafcadio Hearn,[1] a European-American journalist and writer who came to Japan in 1890 and decided to stay here permanently because he was fascinated by Japanese life and culture.[2] From the comments of my American students on this story, I learned that one point which most impressed them was that, in order to welcome his adopted brother home from a long journey, a Japanese warrior filled the vases in his guest room with chrysanthemum flowers. They observed that this was quite different from American custom and perhaps was unique to Japan.

As the students had noticed, this small incident pointed to something characteristic of Japan: a love of nature which has existed from very early days. This love of nature has resulted in a refined appreciation of the beauty of nature in, for example, landscapes, miniature gardens (*hakoniwa*), miniature trees (*bonsai*), flower arrangement (*ikebana*), the tea ceremony (*chanoyu*), short poems called haiku, and even the art of cookery.

Nature for the Japanese has not traditionally been an object of man's investigation or exploitation for human benefit as it has been for Westerners. For the Japanese and for other Oriental peoples, man was considered a part of nature, and the art of living in harmony with nature was their wisdom of life.

I recall a story an American missionary to China once told me. Three men went to see Niagara Falls. One was an Indian from India, one a Chinese, and one an American. On seeing the falls, the Indian, as a matter of course, thought of his god, manifested in this grandeur of nature. The Chinese simply wished to have a little hut beside the falls, where he might invite a friend or two, serve tea, and enjoy conversation. The American, however, immediately asked himself what could be done to make the most of such an enormous amount of energy. Of course, the roar of Niagara Falls might have been too much for the Chinese, but the story illustrates the different attitudes of different peoples.

To a Chinese or a Japanese, drinking tea and eating food are not merely matters of nourishment or meaningful companionship, but are also considered occasions for artistic appreciation of nature. Therefore, the landscape you look at while eating, the room in which you serve your meal, as well as the tableware you use and the food itself, must suit your attitude. This appreciative attitude toward nature has been a central theme of Japanese culture.

During my first visit to America twenty years ago, one of my American friends saw the powdered tea leaves which I had brought from home, and he thought it was instant green tea.

In fact, it was for use in the tea ceremony, during which one sits formally on the floor for at least half an hour while the tea is being prepared. The Japanese people now have instant tea, but without Western influence would never have thought of making it in an instant form, as the tea ceremony is an inheritance from the medieval Japanese people, embodying their intuitive recognition of the beauty of nature and life.

Flower Arrangement and Western Cosmology

A similar theme is expressed in the art of flower arrangement, which was developed primarily in the 15th century. The underlying principles of flower arrangement are indicated by three main stems or branches that symbolize Heaven, Man, and Earth. The "primary stem" is symbolic of Heaven and forms the central line of the whole arrangement. Therefore, the arranger selects for it the strongest stem available. Next to the primary stem is the "secondary stem," which is symbolic of Man. It is placed in such a manner as to give the effect of growing sideways and forward from the center line. It should be approximately three-quarters of the height of the primary stem and inclined toward it. The "tertiary stem," symbolic of Earth, is the shortest and is placed to the front or slightly to the opposite side of the roots of the first two. All are fastened securely in a holder to give the effect of growing from one stem. Additional flowers may be added to fill out each arrangement, but it is the correct arrangement of the three principal stems which is of paramount importance.

Although the idea of a structured universe was alien to the Japanese mind in the 15th century, the composition of the flower arrangement may be compared with Western cosmology to illustrate differing views of man and nature.

Traditional Western cosmology originated in the Middle Ages. It was a creation of Christian theology, given form by the adoption and modification of the Aristotelian-Ptolemaic theory of world structure. Not only did it represent the physical setting of the visible world, but it was also symbolic of spiritual truth.

As exemplified by Dante in his *Divine Comedy*, man was seen as the crucial intermediary in a world comprising a hierarchical chain of substance that stretched from the inert clay of the center to the pure Spirit of the Empyrean. As described in Genesis, man was made of earth, and medieval scholars held that he therefore

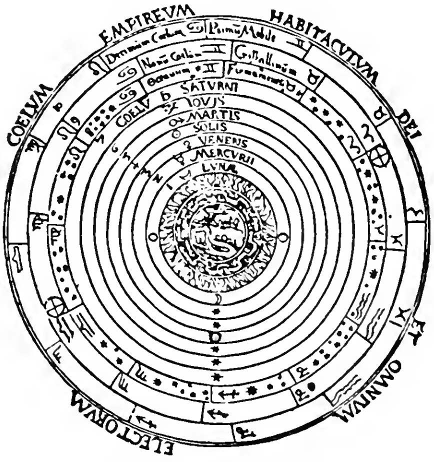


Fig. 1 (left). Japanese flower arrangement, an illustration from an old textbook by Ibuki Sanjin Seiko, *Sunabachi Ikebana Den* (1775). Fig. 2 (right). Medieval European cosmology. [From Apianus, *Cosmographia* (Antwerp, 1539)]

Fig. 3. "Fisherman and Woodcutter" by Sesshu Toyo (1420–1506).

gravitated naturally toward the center of the world, the locus of Hell. However, it was also written in Genesis that man was the only terrestrial creature inspired by the Spirit of God. Therefore, he constantly aspired to ascend to the realm of God, the highest of the Heavens. The entire setting of medieval cosmology thus mirrored man's hope and fate. Although this physical structure was later altered by the so-called Copernican revolution, the basic idea of man which it portrayed remained little changed and continued to play an important role in the history of Western thought.

Because the Japanese people did not adopt the sort of cosmology that can be expressed in terms of a geometrical structure, the form of the flower arrangement could be considered most comparable to the structure of Western cosmology. A comparison of the two reveals that they represent very different ideas of man and the world. It is true that, in either case, man's place was intermediate between heaven and earth. In the Western system, however, heaven and earth were, by definition, diametrically opposite, forming a dichotomous world in which man's place was absolutely crucial. On the other hand, there was no such dichotomy in the traditional Japanese ideas. There, nature was a unity, and man lived in it as a part of this unity.

The Rise of Modern Science

In the Western conception, man was not an ordinary part of nature. He was a specially privileged creature, and nature was subordinate to him and even to his sin. He was the master of the natural world, which was at his disposal to analyze, examine, and make use of. The rise of modern science in the West was premised on this sort of religious and philosophical view of nature.

At the very moment when John Milton was preparing his long epic "Of Man's first disobedience, and the fruit/Of that forbidden tree" which brought about the "loss of Eden,"[3] in the same England, Robert Hooke the scientist started the Preface of his *Micrographia* (1665) with the following words:

> It is the great prerogative of Mankind above other Creatures, that we are not only able to behold the works of Nature, or barely to sustein [sic] our lives by them, but we have also the power of considering, comparing, altering, assisting, and improving them to various uses. . . .
>
> . . . And as at first, mankind fell by tasting of the forbidden Tree of Knowledge, so we, their Posterity, may be in part restor'd by the same way, not only by beholding and contemplating, but by tasting too those fruits of Natural knowledge, that were never yet forbidden.[4]

This also illustrates how deeply and positively modern scientific investigation of nature was rooted in Western thought and culture.

Moreover, since the natural world and the whole universe were manifestations of God's creation, the study of it was not only a useful but also a highly esteemed endeavor. Cotton Mather, an American colonial divine and scientist, stated that knowledge of "The Book of Creatures" was indispensable for an understanding of "The Book of Scriptures"[5]—an idea shared by many scientists of the 17th and 18th centuries. Both the study of science and the utilization of science for the comfort of mankind were important items among Calvinistic "good works." Indeed, such an outlook provided some of the important religious motivation which fostered the development of modern science in the Western world.

Nature for the Japanese was different. It was an object not of his mastery, but of his appreciation, and was even his best companion. An illustration is a famous haiku, a verse of seventeen syllables, composed by a young female Japanese poet of the 18th century, Kaga no Chiyo. Early one summer morning, when she went out as usual to draw water from her well, she found to her surprise that the pole of her well-bucket was entwined by the tendrils of a morning glory with fresh, dewy flowers. Instead of removing the plant from her pole, she went to a neighbor for water. Later, with brush in hand, she described the scene and her sentiments in haiku form.

The well-pole taken by a morning glory,
I went to a neighbor for water.

Another illustration from Japanese literature may be drawn from "An account of my hut," an essay by Kamo no Chomei written in the early 13th century.[6] The author presented a pessimistic view of the world by enumerating recent natural disasters, such as fires, typhoons, famines, and earthquakes, and he deplored the hardship and impermanence of life. His only escape was to "abandon the world" and retire to a lonely but quiet life in a small hut in the

Fig. 4. Section from *Choju Jinbutsu Giga* (scrolls of frolicking animals and people), attributed to Toba Sojo (Heian period, 12th century).
The scrolls are owned by the Kozanji Temple, Kyoto, Japan.

countryside. He wrote that "my only desire for this life is to see the beauties of the seasons" and "It is better to have as friends musical strings and bamboo and flowers and the moon." (A somewhat similar hermit tradition has existed in the West also.)

In the Japanese view, there existed varieties of beings and seasons, but there was no absolute division of heaven and earth, nor an absolute "onceness" of time in the Western sense. Everything came and went in cycles. Even though the violence of nature, together with the pessimistic teaching of the Buddhism of his time, made a man like Chomei so pessimistic, he still found his rest in nature. As pointed out by a contemporary Japanese critic,[7] similar attitudes of the Japanese people were revealed in their reactions to the great earthquake and consequent fire of 1923, which almost completely destroyed Tokyo and Yokohama.

Although the Japanese people have been frequently visited by earthquakes, they did not initiate the scientific study of earthquakes. Even though they were knocked down by typhoons, floods, or earthquakes, they were happy as soon as they realized in themselves that they were nestled in the bosom of nature. In this way, they were relieved and recovered without going on further to an objective clarification of these calamities. It was only after Japan was opened to the Western world in the late 19th century, and Western visitors were exposed to earthquakes here, that seismology was initiated. Without this beginning, Japan would not have become one of the leading countries in the study of seismology,despite its high frequency of earthquakes.

Unique Japanese Contributions to Science

If the view of nature in Japan has traditionally been as I have outlined, is there any possibility that traditional elements can make a positive and unique contribution to the science of today and of the future, rather than simply being presented as relics in arts and literature? This is an important but difficult question. When it was put to a group of Japanese people staying in America, one of them gave a figurative answer. Making a comparison with the construction of a modern Western-style building, he suggested that for structure and materials we Japanese have to rely mainly upon Western methods, but in interior decoration we may contribute elements of our own. This was about as far as I too could see, until I met a more promising sign in an article by John Frisch.[8]

Frisch, who studied anthropology at the University of Chicago and now teaches at Sophia University in Tokyo, evaluated Japan's contribution to modern anthropology in the article. According to him, a group of Japanese scholars have gained worldwide recognition by their unique contributions to studies of the social behavior of animals. From their many years of observation of the life of wild monkeys around feeding stations, these Japanese fieldworkers were able to discover much concerning the social structure of the groups of monkeys, the variability of behavior between different groups, and the "inventive behavior" of the monkeys.

The results of their investigation have been regarded as important in that they show that nonhuman primates can adapt to change conditions by spontaneously modifying their habits. In other words, they are able not only to modify or enlarge already existing behavioral patterns but also to create new ones. These discoveries, anthropologists consider, make a positive contribution to one of the key issues of modern anthropology, namely, the understanding of the origins of human culture and society.

Even more interesting, however, is the fact that the approach used by the Japanese fieldworkers contains something original which is not often found in similar studies by Westerners. It may well reflect the traditional Japanese way of looking at nature, that is to say, an affinity and sympathy with all living things. To most observers, all monkeys look very much alike, and it is difficult to identify individuals in a group. Therefore, most Western fieldworkers catch the animals and mark them with numbers. The Japanese, however, became acquainted with the faces, general appearance, and personalities of the monkeys, and succeeded in identifying individuals not by numbers but by giving them names of popular and traditional figures from Japanese history. "This seems hard to imagine for Western scientists," wrote Frisch.

Thus, the Japanese observers were able to produce abundant and valuable data concerning the life and behavior of the animals. Such an approach might not have developed so naturally in the Western cultural zone, where the distinction between man and other living things has been observed more strictly. In other words, to quote Frisch, "while the Western scientist tends to regard the animals as objects situated in front of him, somewhat as bacteria under the microscope, his Japanese colleague tends to think in terms of a personal relationship with individuals who have names and whose life stories are often familiar to him."[9]

Frisch maintained that the intellectual and spiritual tradition of Japan constitutes a most favorable environment for the science of nonhuman primate behavior, and that "we may see in this particular example an indication of the nature of the contribution which Japan can be expected to make, not only to anthropology, but to our wider understanding of nature in its relation to man."[10]

Environmental Problems

In his Nobel lecture entitled "Japan the Beautiful and Myself" (1968), Yasunari Kawabata first quoted a poem of the Zen priest Myōe (1173–1232):

> Winter moon, coming from the clouds to keep
> me company,
> Is the wind piercing, the snow cold?[11]

Then he commented on it, saying:

> Winter moon, going behind the clouds and coming forth again, making bright my footsteps as I go to the meditation hall and descend again, making me unafraid of the wolf: does not the wind sink into you, does not the snow, are you not cold? I choose it as a poem of warm, deep, delicate compassion, a poem that has in it the deep quiet of the Japanese spirit.[12]

Thus, things in nature are intimate companions for the Japanese people.

Since the nation itself has been highly industrialized, the attitude of the people may be changing greatly. Basically, however, much of this attitude remains unaltered. A verse in one of the contemporary popular songs in Japan asks:

> Chimneys are so high that, you moon,
> Don't your eyes smart from the smoke?

After a day's work, Japanese workers are happy drinking sake, singing this song, and addressing it to the moon. They are merged with nature, forgetting themselves and even forgetting the dreadful destruction constantly inflicted upon nature and themselves by the smoke from the chimneys. Such optimism seems, though, to have favored the too rapid growth of the gross national product.

Now, the underlying idea of Lynn White's article, "The historical roots of our ecologic crisis,"[13] is closely related to my view outlined above. In discussing the environmental crisis today, he asserts that "both modern technology and modern science are distinctively *Occidental*," that "Human ecology is deeply conditioned by beliefs about our nature and destiny—that is, by religion," and that "Our science and technology have grown out of Christian attitudes toward man's relation to nature. . . ." In the counterculture groups he discerns "a sound instinct in their affinity for Zen Buddhism," but he is doubtful of the viability of these faiths among Western people, an opinion with which I agree. White ends his article by proposing as "a patron saint for ecologists" St. Francis of Assisi, who "tried to depose man from his monarchy over creation and set up a democracy of all God's creatures."

I do not know whether White would include Buddhist priests in a catalog of patron saints for ecologists. But let me cite two instances of Buddhist practice. When going out for the daily mendicancy, it was customary for Southeast Asian monks to wait until there was sufficient light to see the lines on the palms of their hands, lest they should tread on little worms and insects while walking. A second example comes from the life of Ryokan (1757–1831), a Japanese Zen priest and poet who had a particular following among farmers and children. He is said to have used a mosquito net in summer, not to protect himself from being bitten by mosquitoes, but to prevent his unconsciously slapping them while sleeping. He left one of his legs outside the net so that mosquitoes might live on him.

Obviously, this kind of sentiment has been rapidly fading in Japan. Contemporary Japanese, while extensively utilizing modern science and technology, are not fully aware, however, that a view of nature considerably different from their own underlies these activities. In their hearts they are still immersed in nature, and their attitude is still one of relying upon nature. The urgent task before the Japanese people is, therefore, that they fully realize man's responsibility for nature, unite this realization with their traditional closeness to nature, and endeavor to overcome the current environmental crisis.

Notes

[1] "Of a Promise Kept," in Lafcadio Hearn, *A Japanese Miscellany,* Rutland, Vt. & Tokyo, 1954, pp. 11–19.

[2] Lafcadio Hearn (1850–1904) thus came to contribute a great deal to the introduction of Japanese culture to the Western world.

[3] John Milton, *Paradise Lost,* I, lines 1 & 4, in *The English Poems of John Milton (World's Classics),* Charles William, ed., London, 1971, p. 114.

[4] Robert Hooke, *Micrographia* (1665), New York, 1938, Preface.

[5] Cotton Mather, *The Christian Philosopher,* London, 1721, p. 8.

[6] Kamo no Chomei, in *Anthology of Japanese Literature from the Earliest Era to the Mid-Nineteenth Century,* Donald Keene, ed., New York, 1955, p. 221.

[7] Ikutarō Shimizu, in *Kindai Nihon Shisōshi Kōza,* Vol. 3, Tokyo, 1960, pp. 9–62.

[8] John Frisch, "Japan's Contribution to Modern Anthropology," in *Studies in Japanese Culture,* Tokyo, 1963, pp. 225–244.

[9] Ibid , p. 240.

[10] Ibid., p. 243.

[11] Yasunari Kawabata, "Japan the Beautiful and Myself," translated by Edward G. Seidensticker.

[12] Ibid.

[13] Lynn White, Jr., *Science,* Vol. 155, March 10, 1967, pp. 1203–1207.

13

Facts on Household Appliance Energy Use

Electric Energy Association

How much energy do your appliances use?

While all major appliances (excluding heating and water heating) consume only about 5% of our nation's total annual energy supply, it is, nevertheless, still important that we use these appliances in the most efficient manner possible.

To help you achieve this, we have reprinted here a listing* of the more common electric appliances and their estimated yearly kilowatt hour consumption. These listings are based on normal use and may vary somewhat depending on the size and location of your house, the efficiency of your equipment and the number and living habits of the people in your home.

*Source: annual energy requirements of electric household appliances, (1973), Electric Energy Association, New York, N.Y.

	Average wattage	Est. kwh* consumed annually
Food preparation		
Blender	386	15
Broiler	1,436	100
Carving Knife	92	8
Coffee Maker	894	106
Deep Fryer	1,448	83
Dishwasher	1,201	363
Egg Cooker	516	14
Frying Pan	1,196	186
Hot Plate	1,257	90
Mixer	127	13
Oven, microwave (only)	1,450	190
Range		
with oven	12,200	1,175
with self-cleaning oven	12,200	1,205
Roaster	1,333	205
Sandwich Grill	1,161	33
Toaster	1,146	39
Trash Compactor	400	50
Waffle Iron	1,116	22
Waste Disposer	445	30
Food preservation		
Freezer (15 cu ft)	341	1,195
Freezer (Frostless 15 cu ft)	440	1,761
Refrigerator (12 cu ft)	241	728
Refrigerator (Frostless 12 cu ft)	321	1,217
Refrigerator/Freezer (14 cu ft)	326	1,137
(Frostless 14 cu ft)	615	1,829

	Average wattage	Est. kwh* consumed annually
Laundry		
Clothes Dryer	4,856	993
Iron (hand)	1,008	144
Washing Machine (automatic)	512	103
Washing Machine (non-automatic)	286	76
Water Heater	2,475	4,219
(quick recovery)	4,474	4,811
Comfort conditioning		
Air Cleaner	50	216
Air Conditioner (room)	860	860**
Bed Covering	177	147
Dehumidifier	257	377
Fan (attic)	370	291
Fan (circulating)	88	43
Fan (rollaway)	171	138
Fan (window)	200	170
Heater (portable)	1,322	176
Heating Pad	65	10
Humidifier	177	163
Health & beauty		
Germicidal Lamp	20	141
Hair Dryer	381	14
Heat Lamp (infrared)	250	13
Shaver	14	1.8
Sun Lamp	279	16
Tooth Brush	7	0.5
Vibrator	40	2
Home entertainment		
Radio	71	86
Radio/Record Player	109	109
Television		
black & white		
tube type	160	350
solid state	55	120
color		
tube type	300	660
solid state	200	440
Housewares		
Clock	2	17
Floor Polisher	305	15
Sewing Machine	75	11
Vacuum Cleaner	630	46

*KWH is the abbreviation for kilowatt hour. A kilowatt hour is equal to 1000 watts of electricity working for one hour. For example: a 100-watt light bulb left on for 10 hours uses one KWH of electricity.

**Based on 1000 hours of operation per year. This figure will vary widely depending on area and specific size of unit.

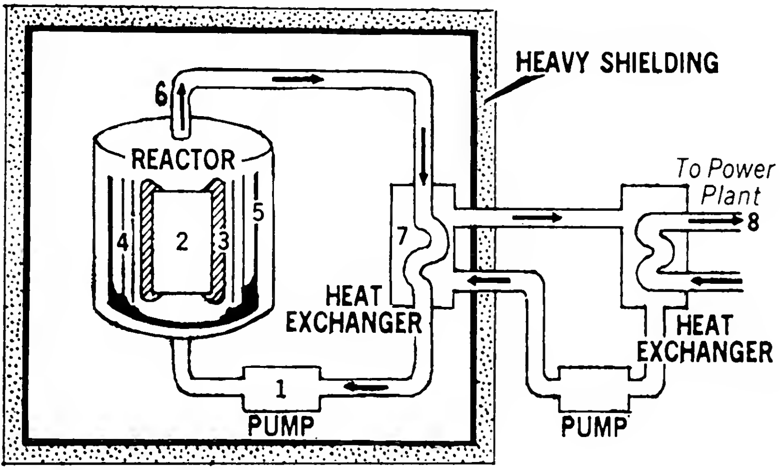
Here described is an unusual device that generates useful energy and in the same process produces more fuel than it uses.

14

Breeder Reactors

Walter Sullivan

How the Breeder Reactor Works



The breeder reactor is a unique source of energy: In the process of generating power to produce electricity, it makes more fuel than it consumes. It uses U-235 atoms (in short supply) or plutonium for its fuel. Neutrons produced by the fission of these elements react with U-238, which is in abundant supply but is nonfissionable and therefore useless. The reaction, however, converts the U-238 into plutonium, which is fissionable and thus can be used as a fuel. This is how the breeder works:

A pump (1) drives liquid sodium into reactor vessel. Neutron radiation from reactor core (2) generates heat, raising the temperature of the sodium. The neutrons bombard U-238 in the breeder blanket (3) and convert the U-238 into plutonium. Reflectors (4) divert neutrons back into reactor. The neutron shield (5) prevents any escape of radiation. The heated sodium is transferred (6) to a second circulation system (7) which is filled with sodium that is not radioactive. This sodium is then used to generate steam for the power plant (8). The original sodium is recycled back through the reactor. Thus sodium that has passed through the radiation environment of the reactor never leaves the heavily shielded inner plant.

An article from The New York Times, July 22, 1973

Barbara Clark

In 1951 the world's first breeder reactor—a small, experimental device—went into operation at the reactor testing station near Idaho Falls, Idaho. In succeeding years American atomic energy specialists became increasingly convinced that such reactors—which, in producing energy, manufacture more fuel than they consume—offer the best hope of avoiding a serious shortage of nuclear fuel, or of energy, until new power sources are developed.

Today, however, 23 years later, the United States still has not begun construction of a full-scale breeder plant, but other countries have. Last week the Soviet Union announced that its big breeder plant at Shevchenko, on the west shore of the Caspian Sea, had gone into commercial operation.

Next month, the French hope to warm up their Phoenix reactor, the first of a number of projected European breeder reactors. At Kalkar on the Rhine another is being built, with West Germany footing 70 per cent of the bill and Belgium and the Netherlands sharing the remainder.

And at Dounreay, on the bleak north coast of Scotland, the British version is almost complete. Operating personnel have begun taking over some units of the complex, whose final cost is expected to be $1-billion. It is hoped that power generation can start late this year or early in 1974.

More than 99 per cent of natural uranium is U-238, whose atoms cannot be split in a reactor. That is, they are useless as reactor fuel. The attraction of a breeder reactor is that, while "burning" fissionable uranium (U-235) or some other nuclear fuel, it converts the U-238 present into plutonium, and plutonium is useful as reactor fuel. In this way the reactor can produce more fuel than it consumes, as illustrated in the diagram.

The reasons for the European progress, and American tardiness, are several. The United States, because of its huge atomic weapons program, has had ample facilities for extracting the tiny fraction of U-235 in uranium as it occurs in nature. This provided the American nuclear energy program with ample fuel and thus there was no early pressure to build breeders to convert U-238.

The Europeans, with meager facilities for extracting U-235, were early motivated to develop breeders. But now, in view of the world's limited uranium reserves, the United States Atomic Energy Commission has been pressing for a full-scale prototype breeder plant. However, the project has been stalled by legal maneuvers of those who believe such reactors could be hazardous.

The projected prototype plant would be situated near Oak Ridge, Tenn., the site of various nuclear installations, but the construction has been blocked by the court action of the Scientists' Institute for Public Information.

A major concern of those with misgivings about this type of reactor is the large amount of plutonium involved. The Dounreay reactor is impressively large, although less than a quarter the size of those that, it is expected, must be built to be economical. And yet this plant will contain a ton of plutonium.

The breeders foreseen for the future will produce many tons of this material each year. If even small amounts escaped into the air or water of a region, they could wreak havoc, for the substance can be lethal and retains its radioactivity for many years. Elaborate measures are taken in the breeder plants to avert any such escapes, but opponents of the program fear they are not foolproof.

Another concern is the possibility that, with so much of the stuff in atomic plants around the world, some of it might be smuggled off to make atomic bombs. Only a small amount is needed for such a weapon.

While those who have designed the breeders believe they have made adequate provision against any "credible" mishap, the technology is complex. It requires, for example, liquid metal at a temperature as high as 1000 degrees Fahrenheit flowing at extreme speed to keep the reactor from overheating. The flow rate in the Dounreay reactor will be 3.5 tons a second. The coolant used is liquid sodium because it does not boil at the high temperatures that give breeder reactors their superior efficiency. However sodium reacts almost explosively on contact with water, so the plumbing must be foolproof.

In those countries where the breeders are in operation or nearing completion—Britain, France and the Soviet Union—the public seems largely to have been persuaded that the precautions are adequate. It is, however, these same three countries that have pressed forward with supersonic transport development, whereas in the United States the SST program has been suspended because of environmental concerns. The parallel, so far as breeder reactors are concerned, is striking.

A lively response to current characterization of the scientist as a Doctor Frankenstein, a Mandarin, or an Adding Machine.

15

Reflections of a Working Scientist

Steven Weinberg

An article from Daedalus, 1974

I ONCE HEARD the period from 1900 to the present described as "this slum of a century." Certainly the case could be made that the twentieth century fails to come up to the nineteenth in the grand arts—in music, in literature, or in painting. Yet the twentieth century does stand among the heroic periods of human civilization in one aspect of its cultural life—in science. We have radically revised our perceptions of space, time, and causation; we have learned the basic principles which govern the behavior of matter on all scales from the atomic to the galactic; we now understand pretty well how continents form and how the genetic mechanism works; we may be on the verge of finding out the over-all space-time geometry of the universe; and with any luck we will learn by the end of the century how the brain is able to think. It seems strange to me that of all the enterprises of our century, it should be science that has come under attack, and indeed from just those who seem most in tune with our times, with contemporary arts and ways of life.

I take it that my role in this issue is not so much to defend science—if science turns you off, then a scientist defending science must absolutely disconnect you—but rather to serve as an exhibit of the "genuine article," the unreformed working scientist. I will therefore simply list three of what I take to be the common current challenges to science, and react to each in turn.

These reflections arise from my own experiences as a theoretical physicist specializing in the theory of elementary particles, and I am not really certain how far they would apply to other areas of science. I intend most of my remarks to apply to the whole range of natural nonbehavioral pure sciences, but some of them may have a more limited validity. On the other hand, I explicitly do not intend my remarks to apply to the social or psychological sciences, which seem to me to face challenges of a special and different sort.

The Scientist as Dr. Frankenstein

I suppose that public attitudes toward science, favorable or unfavorable, are shaped far more by the expectation of good or evil technological developments, than by approval or disapproval of the scientific enterprise itself. This is much too big a problem to cover here in any but the most fragmentary way, and it can be logically separated from a judgment of science *qua* science, but it is a matter of such overriding public concern that it cannot be altogether passed over. I will discuss it briefly under the headings of five criticisms of the part that "pure" scientists have played in the creation of new technology.

1. *Scientists pursue their research, without taking due account of the harm that may be done by practical application of their work.*

This is in some degree true. There are even some scientists, though I think not many, who argue that it is their business to pursue knowledge wherever it leads them, leaving the question of practical application to businessmen, statesmen, and generals whose responsibility it is to worry about such matters. For example, many critics point to the nuclear weapon as the ugliest product of "pure" research. But this charge overestimates the degree to which the scientist can look into the future. The nuclear physicists who discovered fission at the end of the 1930's were not so much indifferent to the danger of nuclear weapons as they were unaware of it. (Meitner, Strassmann, and Hahn, for example, published their work in the open literature in 1938–1939.[1]) Later, of course, nuclear weapons were developed in the United States and elsewhere by scientists who knew perfectly well what they were doing, but this was no longer for the sake of pure research, but in the hope of helping to win World War II.

I do not see how my present work on elementary particles and cosmology could possibly have any applications, good or evil, for at least twenty years. But how can I be sure? One can think of many dangers that might arise from present pure research, especially research on genetics and the human mind, and I hope that the researchers will be able to hold back the most dangerous lines of research, but they will not have an easy time of it. For a scientist unilaterally to cut off progress along certain lines because he calculates that more harm than good will come out of it requires a faith in the accuracy of his calculations more often found among businessmen, statesmen, and generals than among natural scientists. And do the critics of science really want the scientist and not the public to make these decisions?

2. *In order to gain material support for their "pure" research or for themselves, scientists prostitute themselves to industry or government by working directly on harmful technological developments.*

Again, scientists being human, this charge is, in some measure, true. One has only to think of Leonardo's letter to the Duke of Milan offering his services in the construction of ingenious instruments of war. It seems strange to me, however, to single out scientists to bear the burden of this charge. Returning to the unavoidable example of nuclear weapons, Oppenheimer, Fermi, and the others who developed the nuclear fission bomb in World War II did so because it seemed to them that otherwise Germany would develop the bomb first and would use it to enslave the world. Since World War II a large fraction of the physicists whom I know personally have washed their hands of any involvement, part-time or full-time, in military research and development. I know of no other group, certainly not workers or businessmen, who have shown a similar moral discrimination. And what of those scientists who have not washed their hands? Admittedly; there are some who work on defense problems for money, power, or fun. There are a few others who are convinced on political grounds that any weapon that adds to military strength should be developed. However, most of the "pure" scientists in the U.S. who have been involved in military work have tried to draw a line at one point or another, and to work only on a limited class of problems where, rightly or wrongly, they felt that more good than harm could be done. My own experience has been mostly through work in the JASON group of the Institute for Defense Analyses, and more recently for the U.S. Arms Control and Disarmament Agency. Many of the members of JASON, myself among them, simply declined to do work in support of the U.S. effort in Vietnam. Others worked on the so-called "electronic battlefield," because they believed (as it happened, wrongly) that by laying an impassible barrier between North and South Vietnam, they would induce the U.S. to stop bombing North Vietnam. In recent years many of us have tried to switch our work over entirely to problems of strategic arms control, but it is not easy; the Nixon administration has recently fired or canceled the consultant contracts of many of those in the Arms Control Agency (including me) who had worked on SALT.

I would like to be able to argue that academic scientists have had a humane and restraining influence on military policy, but looking back, it is hard to find evidence that I, or even those much more active and influential than myself, have had any influence at all. However, I am convinced at least that the world would not be better off if we had kept our hands out.

3. *Scientific research of all types is oppressive, because it increases the power of the developed nations relative to the underdeveloped, and increases the power of the ruling classes relative to the ruled.*

This charge rests on such far-ranging political and historical assumptions that I cannot begin to do it justice. I am not convinced that new technology tends to support old power structures more than it tends to shake them up and put power in new hands. I am also not convinced that one should always support underdeveloped nations in conflict with more modern ones; for instance, it is the Arab states that threaten the existence of Israel, not the other way around. Furthermore, this argument for stopping scientific research logically requires a permanent general strike by everyone whose work helps to keep modern industrialized society going, not just by scientists. Perhaps some do reach this conclusion, but they must have more faith in their ability to look into the future than I have in mine. I would agree, however, that certain special kinds of technology are particularly liable to be used in an oppressive way, especially the modern computer with its capacity for keeping track of enormous quantities of detailed information. I would be in favor of cutting off specific kinds of research where specific dangers clearly present themselves, but decisions in this realm are always very hard to make. Usually, as in the case of computer technology, it is not possible, by closing off lines of research, to ward off the dangers of technology without at the same time giving up its opportunities.

4. *Scientific research tends to produce technological changes which destroy human culture and the natural order of life.*

I am more sympathetic to this charge than to most of the others. Even apart from what has been done with new weapons of war, a terrible ugliness seems to have been brought into the world since the industrial revolution through the practical applications of science. As an American, I naturally think of what I see from my car window: the great superhighways cutting cross the countryside, the suburban strips with their motels and gas stations, and the glittering lifelessness of Park Avenue.

I am not sure why this should have happened. Earlier new technology, such as the pointed arch and the windmill, created more beauty than ugliness. Perhaps it is a question of scale; so many people now have cars and electric appliances that the impact of highways, factories, and power stations is too great to be absorbed into the natural background—unlike an occasional windmill or cathedral.

If this diagnosis is correct, then a cure will be extraordinarily difficult. When industrialization offered cars and electric appliances to the general public, it offered a mobility and ease previously enjoyed only by the few who could keep carriages and servants, and people accepted with alacrity. Are we now going to ask them to go back to the status quo ante? I suppose that the only answer here, as before, is to make judgments as well as we can in favor of the civilizing technology and against the brutalizing. And there *are* examples of civilizing technology, like the bicycle, the LP record, and the railroad. As W. G. Hoskins, himself a bitter enemy of the superhighway and the jet airport, says in his wonderful book, *The Making of the English Landscape:*[2]

> Indeed, the railways created as much beauty as they inadvertently destroyed, but of a totally different kind. The great gashes they inflicted on the landscape in their cuttings and embankments healed over, and wild flowers grew abundantly once more. Going down to the south-west in spring, the cuttings through Somerset and Devon sparkle with primroses. Even in Clare's own country, the railway has been absorbed into the landscape, and one can enjoy the consequent pleasure of trundling through Rutland in a stopping-train on a fine summer morning; the barley fields shaking in the wind, the slow sedgy streams with their willows shading meditative cattle, the early Victorian stations built of the sheep-grey Ketton stone and still unaltered. . . .

The problem of identifying the civilizing technology and of regulating society so as to suppress the rest is far too complicated to go into here. In any case, it is not a problem on which scientists' opinions are worth more than anyone else's.

5. *While serious human needs go unfulfilled, scientists spend large sums on accelerators, telescopes, etc., which serve no purpose other than the gratification of their own curiosity.*

There is no doubt that a great deal of scientific work is carried out without any expectation of practical benefit, and indeed would be carried out even if it were certain that no practical benefit would result. It is also true that some of this work is very expensive, for the simple reason that in any given field the experiments that can be done with string and sealing wax tend to have been done already.

I suppose that if one takes the strictly utilitarian view that the only standard of value is integrated public happiness, then scientists ought to be blamed for doing any research not motivated by calculations of how much it would contribute to public welfare. By the same reasoning, no one ought to support the ballet, write honest history, or protect the blue whale, unless it can be shown that this will maximize public happiness. However, anyone who believes that knowledge of the universe is, like beauty or honesty, a good thing in itself, will not condemn the scientist for seeking the support he needs to carry out his work.

This does not mean that the support must be granted; the public has to weigh the practical benefits that will be "spun off"—the teaching that most pure scientists do to earn their salaries and the general strengthening of technological capabilities that seems to accompany pure research. These are hard to calculate. As Julian Schwinger points outs,[3]

> And one should not overlook how fateful a decision to curtail the continued development of an essential element of the society may be. By the Fifteenth Century, the Chinese had developed a mastery of ocean voyaging far beyond anything existing in Europe. Then, in an abrupt change of intellectual climate, the insular party at court took control. The great ships were burnt and the crews disbanded. It was in those years that small Portuguese ships rounded the Cape of Good Hope.

I do not want to argue here about whether the public gets its money's worth. My point is that, in seeking support for scientific research, scientists need not agree with the public as to why the work should be done.

The Scientist as Mandarin

There is a widespread suspicion that science operates as a closed shop, closed to unorthodox ideas or uncomfortable data, especially if these originate outside a small circle of established leaders. One recalls countless movies in which elderly scientists in white coats wag their grey goatees at the young hero and expostulate, "But what you propose is quite impossible, because. . . ." If the public is receptive to Sunday supplement stories about unidentified flying objects or quack cures for arthritis. it is in part because they do not believe the scientific establishment gives the possibility of such things a fair hearing. In short, not everyone is convinced that the scientists are as open-minded as they ought to be.

This is not one of the most important or profound challenges to science; nevertheless, I want to present some answers to it here, because this will give me a chance to explain some of my enthusiasm for the *process* of scientific research. Also, this is an easy challenge to meet, because it arises not so much from political or philosophical differences, as from simple misapprehensions of fact. For convenience I will discuss separately the questions of the receptivity of scientists to ideas from young or unestablished scientists; to ideas from outside the scientific profession; to unorthodox ideas from whatever source; and to uncomfortable data.

1. *How open is science to new ideas from the young, unestablished scientist?*

Of course, there is a scientific *cursus honorum*, and those who are just starting are less influential than their seniors. The fact is, however, the system of communication in science, probably more than that in any other area of our society, allows the newcomer a chance at influencing his field.[4]

In physics, my own field, the preëminent journal is the *Physical Review*. Almost all physicists at least scan the abstracts of the articles in their own specialties in each issue. The *Physical Review* has a panel of over a thousand reviewers who referee submitted papers, but in fact about 80 percent of all papers are accepted, and of the others a good proportion are rejected only because they are unoriginal. The *Physical Review* is an expensive operation, supported by subscriptions and page charges paid by the authors' institutions, but if an author cannot arrange to have the page charge paid, the paper is published anyway (though admittedly with a few months' delay).

There is also a more exclusive journal, *Physical Review Letters*, which publishes only short papers judged to contain material of special importance. As might be expected, there is a crush of authors trying to get their papers published in *Physical Review Letters*, and every year sees several editorials in which the editor wrings his hands over the difficulty of making selections. Nevertheless, *Physical Review Letters* does a good job of judging the paper rather than the author. (In 1959, when I was an unknown research associate, I had several papers accepted by *Physical Review Letters;* in 1971, as a reasonably well-known professor at M.I.T., I had one rejected.)

In addition to the *Physical Review* and *Physical Review Letters*, there are a great number of other physics journals in which it is even easier to publish. So well does this system work that it has become quite common for a physics department chairman who needs advice on the work of a young physicist in his own department to solicit comments from senior physicists in other universities who have never even met the young physicist, on the assumption that they will of course be familiar with his or her published work.

Of course, the humanities and social sciences also have widely circulated journals, but I have the impression that they do not provide anywhere near so effective a channel of communication for the young or unestablished scholar as do the natural science journals. The reason is that the natural sciences have more objective (though not necessarily more reliable) standards for judging the value of a piece of work. A young physicist who succeeds in calculating the fine-structure constant from first principles, or in solving any one of dozens of other outstanding problems, is sure of a hearing. For instance, my own subfield of theoretical physics was shaken up in 1971 by work of a previously unknown graduate student at Utrecht,[5] and then again in 1973 by a previously unknown graduate student at Harvard.[6] I suspect that a graduate student in history who has revolutionary ideas about the fall of the Roman Empire might have a harder time getting a hearing.

The less academic professions such as law, medicine, business, the military, and the church, are even less open. In these, a young person's work is, I believe, directed to a small circle of superiors rather than to an international community, and it is natural for their judgment of his ideas to be colored by subjective factors, such as the degree to which he accommodates himself to their preconceptions. Only a few, after getting over these hurdles, reach a level from which they can communicate to their whole profession.

None of this reflects any moral superiority in the scientists themselves. It is a natural outgrowth of the fact that they work in specialities small enough that a beginner has a chance to communicate with the whole international community of specialists, and with standards objective enough that they all can recognize the value of a piece of important research. However, it does seem peculiarly inappropriate to charge the sciences with being closed to new ideas from the young and unestablished.

For the sake of fairness, I should add here that these observations are strongly colored by my own experience as a theoretical physicist who works alone at his desk or at a blackboard with one or two colleagues. I concede that the scientific enterprise may look very different to experimental scientists, and most especially to those experimentalists in high energy nuclear physics who work in large research teams.

For instance, a recent paper[7] reporting the discovery of an important new class of neutrino interaction had no less than fifty-five authors from seven different institutions. I do not know to what extent a junior member of such a team can really get a hearing for an idea of his own.

2. *How open is science to new ideas from outside?*

My remarks so far only indicate the openness of the scientific community to ideas which are at least expressed in a language that is familiar to established scientists and deal with problems that they recognize as important. Otherwise, the work is unlikely to be published in a scientific journal or, if published, to be read. Then what about the prophet in the wilderness, the truly original genius outside the scientific community whose ideas cannot be understood by the pedants in university science departments?

I submit that there is no such person. I do not know of any piece of work in physics in this century which was originally generally regarded as crack-pot—as opposed to merely wrong—which subsequently turned out to be of value. It is true that Einstein was only a patent clerk when he invented special relativity, but his work was on a recognized problem, was duly published in the *Annalen der Physik*, and was received with respect, though not with instant acceptance by the physics community.

In reaching a judgment on the closed-mindedness of scientists to ideas from outside their ranks, it should be kept in mind that the system of scientific communication has evolved, not merely to transmit ideas and data, but to do so in a way that leaves the scientist time to get some of his own work done. If we had to struggle through every paper, even when the author did not accept the conventions of scientific language, we would literally have no time to do anything else. It may be that we miss a pearl of wisdom every century or so, but the price has to be paid.

3. *How open is science to truly revolutionary ideas?*

Even granting that the scientific communication system works as well as it ought to, are not scientists' minds closed to ideas, from whatever source, which challenge orthodox scientific dogma? (As Gershwin tells us, "They all laughed at Wilbur and his brother, when they said that man could fly.") Many laymen and some scientists seem to believe that any number of scientific revolutions would immediately become possible if only scientists would give up some of their preconceptions.

I believe that this is a mistake, and arises from a misconception as to the nature of scientific advance. The scientific principles which at any given moment are accepted as fundamental are like structural timbers which support a great superstructure of successful predictions. It is easy to imagine knocking down any of these timbers, but very hard to imagine what would then keep the roof from falling on our heads.

For a major scientific advance to occur, it must become clear not only that fundamental changes are necessary, but also how the successes of the previous theory can be saved. For example in 1957 T. D. Lee and C. N. Yang brought about a revolution in physics through their proposal that parity is not conserved—that is, that there is an absolute distinction in nature between left and right.[8] (It can be shown mathematically that if right and left are equivalent, then every physical state can be classified as having odd or even parity, according to how it seems to change when viewed in a mirror. It can also be shown that the parity is conserved—that is, it does not change with time.) It was quite easy to imagine that parity is not conserved; what was hard to see was that parity conservation had to be violated, and that it could be violated without losing the spectroscopic selection rules and other consequences which had given rise in the first place to the idea of parity conservation. As it happened, Lee and Yang were led to their proposal by a puzzle in meson physics. Two different kinds of meson were identified as having positive and negative parity respectively, through their decay into states of positive and negative parity, and yet the masses and lifetimes of the two mesons were observed to be identical. Many solutions were tried, including fundamental changes in the principles of quantum mechanics. Finally, rejecting any such radical solution, Lee and Yang proposed that the two different mesons were really only one, that the meson had seemed like two because it could decay both into states of the same and of different parity. This proposal would have gotten nowhere if they had not pointed out at the same time that parity could be changed in these decays because they were "weak" (that is, they have rates only of order 10^{10}/sec per particle), thereby leaving unchallenged the successful predictions of parity conservation in the much faster (say, 10^{20} to 10^{24}/sec) "strong" and electromagnetic processes.

Even the greatest scientific revolutions show a similar conservatism. Einstein changed our understanding of space and time, but he did so in a way which was specifically designed to leave our understanding of electricity and magnetism intact. What the scientist needs is not a wide open mind, but a mind that is open just enough, and in just the right direction.

4. *How open is science to uncomfortable new data?*

One often reads in popular histories of science that "So and so's data showed clearly that this and that were false, but no one at the time was willing to believe him." Again, this impression that scientists wantonly reject uncomfortable data is based on a misapprehension as to the way scientific research is carried on.

The fact is that a scientist in any active field of research is continually bombarded with new data, much of which eventually turns out to be either misleading or just plain wrong. (I speak here on the basis of my experience in elementary particle physics and astrophysics, but I presume that the same is true in other fields as well.) When a new datum appears which contradicts our expectations, the likelihood of its being correct and relevant must be measured against the total mass of previously successful theory which might have to be abandoned if it were accepted.

During the latter half of the nineteenth century, for instance, there were known anomalies in the motions of the moon, Encke's comet, Halley's comet, and the planet Mercury, all of which seemed to contradict Newton's theory of gravitation. These anomalies might have caused a tremendous amount of effort to be wasted looking for alternative theories of gravitation, but most physicists either ignored the data or assumed that some less radical explanation would turn up.[9] As it happened, they were 75 percent correct; simple explanations (such as an improvement in the treatment of tidal forces) were later found for the anomalies in the motions of the moon and the comets. The anomaly in the motion of Mercury did, in 1916, turn out to be of fundamental importance when Einstein showed how it arose from relativisitic corrections to Newtonian mechanics. But even this is an exception that proves the rule. If physicists had taken the anomaly in the motion of Mercury seriously from the beginning, presumably they would also have taken the anomalies in lunar and cometary motions seriously, and would thereby have been led away from rather than toward the discovery of general relativity.

Here is a simpler and more recent example. At a high energy physics conference in 1962, data were reported to the effect that neutral K mesons and their antiparticles can both decay into a positive pi-meson, an electron, and a neutrino. If true, this would have overturned a theory of weak interactions, the "current-current model," which had served as the basis of a great number of successes in other contexts. I remember Murray Gell-Mann rising and suggesting to the meeting that since the experiments didn't agree with the theory, the experiments were probably wrong. The next generation of experiments showed that this was indeed the case.

I realize that it may seem to the reader that the theorists in these examples were merely closed-minded and lucky. However, no scientist is clever enough to follow up hundreds of clues that lead in hundreds of different directions away from existing theories. (This is especially true of data of dubious provenance which would revolutionize scientific knowledge, such as evidence on unidentified flying objects, psychokinesis, and copper health bracelets.) What a scientist must do is to be open to just that piece of new data which can be integrated into a comprehensive new theory, and to file the rest.

Above all, in judging the openness of science, one should remember its unique capacity for discovering its own mistakes. Most natural scientists have the experience several times in their lives of being forced by new data or mathematical demonstrations to recognize that they have been seriously wrong about some important issue. (For instance, I was sure that Lee and Yang were wrong when they first proposed that parity is not conserved, and became convinced only by subsequent experiments.) On a larger scale, the physics community has many times been forced by new data to scrap large bodies of existing theory. If this takes away from our reputation for infallibility, it should also take away the impression that our minds are closed.

The Scientist as Adding Machine

The most profound challenge to science is presented by those, such as Laing and Roszak, who reject its coldness, its objectivity, its nonhumanity, in favor of other modes of knowledge that are more human, more direct, more rapturous.[10] I have tried to understand these critics by looking through some of their writings, and have found a good deal that is pertinent, and even moving. I especially share their distrust of those, from David Ricardo to the Club of Rome, who too confidently apply the methods of the natural sciences to human affairs. But in the end I am puzzled. What is it that they want *me* to do? Do they merely want the natural scientist to respect and participate in other modes of knowledge as well as the scientific? Or do they want science to change in some fundamental way to incorporate these other modes? Or do they want science simply to be abandoned? These three possible demands run together confusingly in the writings of the critics of science, with arguments for one demand often being made for another, or for all three. In accordance with my role here as a specimen of the unregenerate working scientist, I will try in what follows to keep the issues raised by these three demands logically distinct, and to analyze each in turn.

1. *We should recognize the validity of other modes of knowledge, more human and direct than scientific knowledge.*

Roszak expresses this view in terms of a metaphor he attributes to Stephen Toulmin:[11]

> When we insist on making scientific expertise the arbiter of all knowledge, it is exactly like believing that cartographers know more about the terrain than the natives who live there, or the artists who have come to paint its beauties, or the priests who tend its holy places.

This does not seem to me to be an issue which raises any problems for science. Scientists, like other folk, are perfectly willing to respect and participate in various kinds of mental activity—aesthetic, moral, even religious. Perhaps the hang-up is with the word "know." For my part, since I view all epistemological arguments with perplexity anyway, I am willing to describe the perceptions of the Lake of Nemi experienced by Turner or the priests of Diana as "knowledge." For certain practical decisions, such as where to have a picnic, I would even be guided by this "knowledge" rather than by a contour map of the lake. Continuing Toulmin's metaphor, the real problem is whether maps should all be redesigned to incorporate aesthetic and moral information, or, if this is impossible, whether maps have any value at all? This is the problem I address below.

2. *Science should change so as to incorporate other modes of knowledge.*

To quote Roszak again,[12]

> What should come of this ideally is not some form of separate-but-equal coexistence, but a new cultural synthesis.

And again,[13]

> It is a matter of changing the fundamental sensibility of scientific thought—and doing so even if we must drastically revise the professional character of science and its place in our culture. There is no doubt in my mind that such a revision would follow. Rhapsodic intellect would slacken the pace and scale of research to a degree that would be intolerable by current professional standards. It would subordinate much research to those contemplative encounters with nature that deepen, but do not increase knowledge. And it would surely end some lines of research entirely out of repugnance for their reductionism, insensitivity, and risk.

My answer is that science cannot change in this way without destroying itself, because however much human values are involved in the scientific process or are affected by the results of scientific research, there is an essential element in science that is cold, objective, and nonhuman.

At the center of the scientific method is a free commitment to a standard of truth. The scientist may let his imagination range freely over all conceivable world systems, orderly or chaotic, cold or rhapsodic, moral or value-free. However, he commits himself to work out the consequences of his system and to test them against experiment, and he agrees in advance to discard whatever does not agree with observation. In return for accepting this discipline, he enters into a relationship with nature, as a pupil with a teacher, and gradually learns its underlying laws. At the same time, he learns the boundaries of science, marking the class of phenomena which must be approached scientifically, not morally, aesthetically, or religiously.

One of the lessons we have been taught in this way is that the laws of nature are as impersonal and free of human values as the rules of arithmetic. We didn't want it to come out this way, but it did. When we look at the night sky we see a pattern of stars to which the poetic imagination gives meaning as beasts, fishes, heroes, and virgins. Occasionally there is drama—a meteor moves briefly across the sky. If a correlation were discovered between the positions of constellations and human personalities, or between the fall of a meteor and the death of kings, we would not have turned our backs on this discovery, we would have gone on to a view of nature which integrated all knowledge—moral, aesthetic, and scientific.

But there are no such correlations. Instead, when we turn our telescopes on the stars and carefully measure their parallaxes and proper motions, we learn that they are at different distances, and that their grouping into constellations is illusory, only a few constellations like the Hyades and Pleiades representing true associations of stars. With more powerful instruments, the whole system of visible stars stands revealed as only a small part of the spiral arm of one of a huge number of galaxies, extending away from us in all directions. Nowhere do we see human value or human meaning.

But there are compensations. Precisely at the most abstract level, furthest removed from human experience, we find harmony and order. The enormous firmament of galaxies is in a state of uniform expansion. Calculations reveal that the rate of this expansion is not very different from the "escape velocity" which would just barely allow the expansion to continue forever. Furthermore, there seems to be a frame of reference in which the expansion is spherically symmetric, and we find that this cosmic frame is rotating at less than one second of arc per century.

The order we find in astronomy on the largest scale is only a small part of a much grander intellectual picture, in which all the systematic features of nature revealed by experiment flow deductively from a few simple general laws. The search for these laws forces us to turn away from the ordinary world of human perception, and this may seem to the outsider to be a needless specialization and dehumanization of experience, but it is nature that dictates the direction of our search.

When Galileo measured the frequencies of pendulums of varying lengths, Simplicio might have objected that this was a purely artificial phenomenon invented by Galileo himself, less worthy of attention than the natural bodies falling freely through the open air that had been discussed by Aristotle. However, Galileo perceived the existence of laws of motion which could more easily be approached through the nearly frictionless motion of a pendulum than through the study of bodies subject to the resistance of the air. Indeed, Galileo's great contribution to mechanics was precisely this perception, rather than the discovery of any particular law of motion.

In the same way, when we spend millions today to study the behavior of particles that exist nowhere in the universe except in our accelerators, we do so not out of a perverse desire to escape ordinary life, but because this is the best way we know right now to approach the underlying laws of nature. It is fashionable these days to emphasize the social and political influences upon scientific research, but my reading of history and my own experience in physics convince me that society provides only the *opportunity* for scientific research, and that the *direction* of this research is what it is to an overwhelming degree because the universe is the way it is.

We have, of course, a long way to go in understanding the laws of nature.[14] However, as far as we can now see, these laws are utterly cold, impersonal, and value free. By this, I don't at all mean that they are without beauty, or that there are no consolations in science. What I mean is that there does not seem to be anything in the laws of nature which expresses any concern for human affairs, of the sort which we, in our warm-blooded furry mammalian way, have happily learned to feel for one another.

Having committed ourselves to the scientific standard of truth, we have thus been forced, not by our own choosing, away from the rhapsodic sensibility. We can follow Roszak's lead only by abandoning our commitment. To do so would be to lose all of science, and break off our search for its ultimate laws.

3. *If science cannot be reformed, it should be abandoned.*

One must doubt that the world would be happier if we could forget all about the laws of nature. The prescientific mind peopled the world not only with nymphs and dryads, but also with monsters and devils; at least in one historian's view, it was only the triumph of science that put an end to the burning of witches.[15] But suppose for the sake of argument that the case could be made that we would be happier if science were driven into some obscure utilitarian corner of our consciousness. Should we let this happen?

In the end, the choice is a moral, or even a religious, one. Having once committed ourselves to look at nature on its own terms, it is something like a point of honor not to flinch at what we see. For me, and perhaps for others, the helplessness of man in the face of pain and death also gives a certain bitter satisfaction to the attempt to master the objective world, if only in the mind. Roszak and Laing point out what they see as the moral dangers of objectivity, fearing that it is likely to leave the scientist himself as cold and value free as an adding machine. I do not see this happening to my colleagues in science. But, in gurus and flower-children, I do see the danger of subjectivity, that the rejection of an external standard of truth can leave a person as solipsistic and self-satisfied as a baby.

Finally, I must emphasize again that the "coldness" I have referred to above only characterizes the discovered *content* of science, and has nothing to do with the wonderfully satisfying *process* of scientific research. In the last section I tried to show how scientists are joined together in a world society, fairer and more open than most. On an individual level, although we accept a discipline in testing our ideas against experiment, the generation of scientific premises is left to the scientist's imagination, guided but not governed by his previous experience. As Gerald Holton recently reminded us in citing Einstein's letter to Solovine, the method of scientific discovery often involves a logically discontinous leap upward from the plane of experience to premises.[16] For some scientists, in our time notably Einstein and Dirac, the aesthetic appeal of the mathematical formalism itself often suggested the direction for this leap. And even though scientific research may not fill us with the rapture suggested by a Van Gogh, the mood of science has its own beauty—clear, austere, and reflective, like the art of Vermeer. Or to use a different simile: if you accept the cliché that hearing a Bach fugue is like working out a mathematical theorem, then you ought also to realize that working out a mathematical theorem is like hearing a Bach fugue.

In the Science Museum in Kensington there is an old picture of the Octagon Room of the Greenwich Observatory, which seems to me beautifully to express the mood of science at its best: the room laid out in a cool, uncluttered, early eighteenth-century style, the few scientific instruments standing ready for use, clocks of various sorts ticking on the walls, and, from the many windows, filling the room, the clear light of day.

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This chapter from a biography of Albert A. Michelson, the first American to win the Nobel Prize, recounts some interesting events from his life as a young man.

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16 Strzelno to the Golden West

Dorothy Michelson Livingston

A chapter from The Master of Light, 1973

SUNLIGHT filled the village square of Strzelno, Poland, dressed in garlands and bunting for a celebration, and shone upon the faces of the men and women standing near the town hall and on the many children lined up in orderly rows. They had gathered on that July day in 1963 to hear the speeches of the Mayor, the local Commissar, and the Dean of Science of Copernicus University in Torun at the dedication of a plaque to the memory of a man born in their village on December 19, 1852, who had won the Nobel Prize.

"Strzelno is proud of her son," said the Mayor, "And although his life was spent far away from us, we will remember that his genius came into being here among our people. It is a great moment in Polish science. He has put us into history."

The leader of a small band of musicians had made a special effort to procure the music for the United States national anthem, not readily available in Iron Curtain countries. As the band struck up the unfamiliar strains of "The Star Spangled Banner," the Mayor unveiled a tablet marking the birthplace of Albert Abraham Michelson. When the speeches were over, a procession formed and moved down the road to Ulica Michelsona (Michelson Street), followed by the band and all the children.

Albert's mother was born Rosalie Przylubska, the second of three daughters of Abraham Przylubski, a Polish businessman from Inowroclaw near Strzelno. The family name and a picture of her mother suggest that she came from typical Polish peasant stock. Her older sister Auguste married a doctor, and perhaps it was at their wedding that Rosalie first met Samuel Michelson, a young merchant of Jewish descent, who had come to live in Inowroclaw. He had little in the way of financial security to recommend him as a husband; he had no store of his own and probably sold his wares from a pushcart. Since Rosalie certainly did not marry him for money or position, he must have had a generous amount of personal charm. He was twenty-five and Rosalie just a year younger when they married and moved to Strzelno, and there Samuel opened a shop of his own. No doubt he had some help and plenty of advice from his father-in-law, the distance between the villages being 30 kilometers, less than a day's ride on horseback.

Albert was their first baby, born on December 19, 1852. He was a healthy boy and much loved. Two little girls, Pauline and Johanna, followed shortly. Pauline lived to a ripe old age, but poor Johanna seems to have been ill-starred from the beginning. Her birth was registered under the wrong name and Samuel had to have the entry in the register corrected several months later. After that, there is no further mention of her. Probably she died in infancy. Her brother never spoke of her.

The Michelson family seems to have left Strzelno late in 1855. (The last date related to their affairs in the local register is August 21, of that year.) Their decision to emigrate was probably influenced by the political situation in the Prussian-dominated section of Poland. The abortive "revolution of 1848" had left conditions very unsettled. Anti-Semitism was rife, and purges of Jews were frequent in the towns and villages around Strzelno. Curfews were enforced and the ghettos became intolerable.

After working their way across northern Europe, Samuel and Rosalie and their children embarked on a steamer sailing between a Baltic seaport, probably Hamburg, and New York. For emigrants, the crossing in steerage was a mixture of joy and terror. There was triumph in having extricated themselves from a hopeless past, regret at leaving their relatives and the familiar way of life, and fear of the vast ocean tossing their ship on its waves. Rosalie, pregnant again, had need of all her courage to withstand the discomfort of the crowded vessel and to gather her forces against the unknown life ahead.

The crossing took almost three weeks. Upon landing in New York, the Michelsons went to the house of Rosalie's relatives, the Friedenburgs, on the lower East Side, where they stayed to refresh themselves from the long sea voyage. Here they heard talk of the wild adventures and the sudden fortunes made overnight in the growing rush for California gold. Among the "forty-niners" were Samuel's sister Belle and her husband, Oscar Meyer, who had made a quick success at Murphy's Camp in Calaveras County. This news spurred the Michelsons to follow.

There were three routes by which they might continue their journey to San Francisco, all dangerous and expensive: by covered wagon across the continent; by ship around Cape Horn; or by a combination of ship and mule wagon to Panama, across the Isthmus, and up the West Coast. The last was the route they finally chose.

Samuel booked passage on a small ship to Porto Bello, on the Isthmus, where a vessel might be warped beside the pier. The alternative was to risk disembarking in the shark-infested waters of a shallower harbor such as Chagres. Porto Bello hardly lived up to its name. It was a tropical slum known as the "grave of Europeans." Many inhabitants, black, white, and Indian, lived there in squalor; many were ill with "brain fever," malaria, or smallpox. Apathy lay upon the town like a shroud. Money was useless even to those who had it to spend. Thieves and robbers looted the dead, the sick, and the unarmed passengers. There were no police.

The Michelsons escaped the perils of Porto Bello and set forth on their journey across the Isthmus, traveling in canoes paddled by natives, through swamps and lakes. Gaudy parrots sitting in the mango trees protested the intrusion, while flocks of herons and cranes rose from the river bank as they progressed. Changing to muleback on the higher land, they passed Indian villages perched on the crests of low, rounded mountains.

The next stage of their journey was probably made on the pioneer railroad completed in 1855 between Aspinwall (now Colon) and Panama City, a distance of less than fifty miles. Here fresh discomforts awaited them. Drinking water was available only at exorbitant prices, because it had to be carted several miles in barrels. Raw sewage flowed down steep and narrow streets lined with saloons, gambling halls, and brothels. Violence was common and sensible people armed themselves to the teeth, looking like brigands to avoid being taken by them.

In this tropical hell, Samuel and his family waited for passage to San Francisco. Although Albert was not yet four years old, the horrors of this trip across the Isthmus, often retold by his parents, remained in his memory as long as he lived. Several weeks passed before cabin space was obtained on a ship of the Aspinwall Line. After sixty days at sea, the Michelsons reached the Golden Gate.

Clipper ships lying at anchor crowded San Francisco harbor. Many of these stately square-rigged vessels were deserted; their crews had gone to the "diggings" seeking gold. Samuel, however, did not have the prospecting fever. He felt safer in his own familiar trade and so bought supplies that would be needed by the miners. As soon as he was able to get accommodations, he and his family climbed into a stagecoach for the last lap of their journey to Murphy's Camp in the foothills of the Sierra Nevada, some 150 miles east of San Francisco.

Murphy's Camp, or Murphy's Diggings as it was first known, had been founded in 1848 as a trading post with the Indians. John Murphy and his brother Daniel were among the first to begin panning for gold in the stream. They hired some Indians for this work, and in one year, it is said, they took out two million dollars in gold, simultaneously creating a land boom in the area of Calaveras.

By 1856, when the Michelsons arrived, Murphy's had grown into a flourishing mining town, fairly well settled. Here they were greeted by Samuel's sister and her husband. Oscar Meyer was engaged in a mining operation. With his help, Samuel set up a little store, stocked with picks and shovels, pans for gold-panning, pot-bellied stoves, heavy boots and jackets, blankets, bedding, and canvas tents.

The rough life of the camp and town made a vivid impression on Albert. He acquired here some of the tenacity and toughness of mind that he brought to his mature life as a scientist. The atmosphere was exciting. For a few lucky ones money was rolling in—the claims at Murphy's were the richest of any in Calaveras County. Five million dollars was taken from just one four-acre placer area. An ounce of gold dust to the pan was rather common, four or five ounces was not unusual, and many claims paid sixteen ounces to the pan. In a period of ten years, during the 1850s and 1860s Wells, Fargo and Company shipped fifteen million dollars' worth of gold dust from Murphy's. Individual claims were restricted to 80 square feet. Arguments were usually settled with fists, knives, or bullets, and the women and children were safer behind locked doors after sundown because the men of the town then became gun-happy from gambling and whisky.

During Albert's second year in Murphy's, work began on a great suspension flume, an aqueduct across the canyon at the lower end of the valley. It connected with a supply of water brought from the Stanislaus River some fifteen miles higher up in the mountains. The water was brought to the Central Hill Mine, on a ridge a mile south of Murphy's, to wash out the miners' gravel. The construction of this flume, completed in three months' time, was one of the great engineering feats of the early miners. The watertight boxes, suspended on wires, zigzagged overhead amid a network of struts and stays, carrying the main force of the stream across the valley.

Narrow wooden houses with two-story balconies lined both sides of Murphy's unpaved street. No one had time to paint them. Bret Harte describes a hotel, modeled after the one in Murphy's, in "The Luck of Roaring Camp":

> It was designed with an eye to artistic dreariness. It was so much too large for the settlement that it appeared to be a very slight improvement on outdoors. It was unpleasantly new. There was the forest flavor of dampness about it, and a slight spicing of pine. Nature, outraged, but not entirely subdued, sometimes broke out afresh in little round resinous tears on the doors and windows.’

Harte's character, Perthonia, whom he describes as "dirty, drabbled and forlorn," told how she had given up little by little what she imagined to be the weaknesses of her early education. Now, transplanted to a backwoods society, she was hated by the women and called "proud" and "fine." Such epithets may well have been thrown at Rosalie Michelson when she insisted that her son begin his schooling, mind his manners, and even start lessons on the violin at a time when he was hardly able to reach out far enough to hold the fiddle or stretch his fingers on the strings. Rosalie set a high standard for her children. To be sure, there was no lack of gaiety or fun, but it was always after the work was done. No child of Rosalie's failed to absorb an enormous respect for literature and a love of beauty in one form or another. The effect on Albert of his mother's values is clear. Her training made him able to resist the lure of easy money all his life.

Across the street from the Michelsons lived the blacksmith, Dave Baratini, and a few houses farther away the apothecary, Dr. William Jones, who did everything from probing for bullets, to dispensing pills and arnica to the miners. A young girl, Bee Matteson, operated the first telegraph office in Murphy's. Her father, T. J. Matteson, was the surveyor who had laid out the route of the canal from the Stanislaus River. He also operated the pioneer stagecoach line daily from Murphy's to Angels, a nearby town.

The stagecoach usually came into town dreadfully overloaded, with fifteen or more people clinging to the top-heavy vehicle. When time came for departure, Matteson's drivers often had trouble in preventing more men from climbing aboard the coach than it could safely hold.

Murphy's provided more sinister forms of excitement. Public hangings took place frequently, in the hope of intimidating outlaws. One of the outlaws, a "handsome, fancy dresser," was a Spaniard named Joaquin Murieta, the three-fingered bandit whose raids of revenge upon the men who had flogged him kept the whole town in terror during the early 1850s.

On Sundays, the villagers enjoyed a quieter diversion. They could board a coach in front of the Sperry and Perry Hotel (next door to the Michelson house) and ride twelve miles to the Big Trees in Calaveras Grove. These were the first *Sequoia gigantea* to be discovered, and they attracted people from all over the world. Among them were Ulysses S. Grant and Mark Twain.

Albert attended the first public school built in Murphy's. It was furnished with handmade desks, built by the local carpenter. In 1857, there were fifty-five children enrolled under a Mr. Jaquith, the principal, and his assistant, Isaac Ayers. Albert's first-grade teacher was Mary Anne Conway, an Irish girl of only fourteen who had come around the Horn to California in 1847 on the *Susan Drew*, one of the first ocean-going steamships built in the United States. Mary Anne had been educated in Spanish at the Convent of Monterey and had almost forgotten her English.

On a Sunday afternoon three years after the Michelsons had arrived in Murphy's, the great fire of 1859 demolished the town. In forty minutes everything was in ashes except Peter Travers' General Store and the sagging walls of the Murphy Hotel. Since the residents of Murphy's had no title to their property except pre-emption or "squatters' rights," the fire caused a good many arguments over boundaries. Albert's family luckily escaped personal injury. Along with the others, the Michelsons soon began to rebuild, and out of the ashes a new town was born, marking a new and more opulent era. The crowning feature of the new Murphy's was Putney's Opera House, on the site of the old Smith's Saloon and the office of Judge Putney, Justice of the Peace.

Albert was eight when the Civil War broke out. It took some months for the news to reach Murphy's, but when they heard it, the miners sided unanimously with the Union. Money poured out of their coffers and almost every man who had two legs to walk—and some who did not—joined the Calaveras Light Guard, as they called themselves. They drilled up and down the street, preparing for the conflict.

Excitement ran riot in the town when a captain with a company of 300 men passed through Murphy's in 1862 on his way over Ebbett's Pass to the battlefields of the East. Many of the miners left their claims to join the Union Army. When news finally came that Lee had surrendered and the war was over, the whole population became frantic. Bells tolled, guns roared, and for days no one, not even Samuel Michelson, was sober. But Murphy's was a town of extremes. The residents' exuberance in victory was equaled by their despair in mourning Lincoln's assassination. Out of love for the late President, the Michelsons gave Albert the middle name of Abraham.

During these lively years, the Michelson family expanded. Julie, Benjamin, Bessie, and Miriam were born in Murphy's while the gold rush rose to its peak.

When Albert reached the age of twelve, his parents felt that he had exhausted the slender opportunities for education at Murphy's. It was time, they thought, to send him to a "proper" school in San Francisco. The decision was made easier by the departure for that city of Belle and Oscar Meyer, with their sons Mark and young Oscar, in 1864. Albert was sent along with his cousins and spent the next two years living with the Meyers and attending Lincoln Grammar School.

In September of 1866, Albert transferred to the San Francisco Boys' High School (now called Lowell High School). The principal, Theodore Bradley, was so much impressed with him that he took him into his own home and gave him the job of setting up experiments for the science class and helping with the chores. In the evening, when Albert's studying was finished, Bradley encouraged him to practice the violin.

It was Bradley also who taught Albert the "manly art of self-defense," instilling in him the knowledge that he need never tolerate insults or be afraid to fight with his fists. The boy took to boxing with pleasure; his quick coordination compensated for his slight build. Albert was fortunate in his teacher. Bradley believed in developing his promising student into a well-rounded man rather than a prodigy.

After his first year of high school in San Francisco, Albert went home to spend the summer of 1867 with his parents at Murphy's. The town was in complete decline; empty shacks and abandoned mine shafts were everywhere, and it was impossible to earn a living. The center of prospecting had shifted to Virginia City, over the mountains in Nevada, where, in 1859, silver had been found in the Comstock Lode. Though still sparsely populated, the former Nevada Territory had been declared a state by President Lincoln in October of 1864.

The difficulty of supporting his large family caused Samuel to follow the miners to Nevada. He and Rosalie piled their belongings and their six children into a mule wagon and joined the procession of wagons and freight teams winding their way past Lake Tahoe and Carson City toward their new home in the silver-mining town, Virginia, as the city was often called. Samuel, profiting from his ten years of experience in supplying miners' needs, sank all his resources into a vast stock to be shipped once he had settled himself in a suitable spot.

Virginia, an overcrowded town of 30,000 people, sprawled over the side of Mount Davidson. Gold Hill and Silver City, originally separate villages, had been absorbed by the expanding town. On the outskirts grazed a herd of Bactrian camels, remnants of an experiment of 1861 to introduce the two-humped beasts from China to carry salt over the mountains. Although more useful than mules on desert ground, the animals were unsteady on precarious mountain trails where the rocks cut into their soft feet. Travelers were terrified when they first came upon the camels, and horses often broke into a stampede at the mere smell of them. Consequently, the poor creatures were penned up in the daytime and allowed to graze only after dark.

At the foot of Mount Davidson lay the Chinese section of

Virginia, the result of another unpopular experiment in transplantation. The miners both envied and disliked the Chinese laborers who toiled sixteen hours a day, successfully reworking the discarded mine dumps. The pungent odor of burning opium hovered over the entire quarter.

Higher up, clinging to the steeper slopes, were the squalid shacks of the Piute and Washoe Indian tribes, now thoroughly subdued. Livery stables and feed stores lined the road along the outskirts of Virginia, but in the town itself brick and stone houses had replaced the wooden shacks of yesterday's pioneers. At night the streets were lighted by gas, and at crossroads every corner boasted a thriving saloon. In one year a million dollars' worth of liquor was consumed in Virginia City, and that year was said to have been rather a dry season; in bonanza periods three times as much "tangle leg," "sheepherder's delight," or "tarantula juice" went down the miners' throats. Men were said to fall asleep in the road crossing from one saloon to another.

The Michelsons settled in a new house at 24 South C Street, where Samuel kept his store on the first floor. Somewhat intimidated by the struggle for survival in this gilded jungle, Rosalie watched over her family closely, barring the shutters at night against burglars or stray bullets. The children's enjoyment of their life in the mountains was later expressed by Albert's sister Miriam, when she became a successful novelist.

> They all came, mothers or mothers-to-be of those boys born to the town trade, to the miner's lot; and of those girls who graced the firemen's engines in the Fourth of July procession, bare-armed, bare-necked with crimped tresses flying, glowing goddesses of red, white and blue liberty. . . .
>
> But if nothing ever came to Virginia City in that season, but spring itself, 'twould be enough . . . there would be air fit for the hierarchy of heaven to breathe, honey-strained through infinite planes of crystal clear sky. Air, and a rare, ineffable odor breathing over the sunned-through purity, exhilarating, intoxicating, of white sage perhaps, of Heaven knows what!
>
> No wonder we believed in the season's intangible, incredible, maddening promise. No wonder we lost hold

> of prosaic possibilities and, betting on the radiant future, gambled with life itself."

Below the road, the track of the Virginia and Truckee Railroad, the richest, most picturesque line in the history of the American West, was being laid from Carson City up the steep grade to Virginia. The ascent was over 1,600 feet in 13½ miles, spanning ravines and tunneling through the mountains. Day after day the Michelson children, along with most of the child and adult population of Virginia, watched the giant construction winding up the valley. When it was finally completed in 1870, the railroad became a symbol of the spirit of Western adventure.

While the silver mines roared with activity, the Michelson family flourished. Albert's brothers and sisters were swept into the drama of Western life. They reveled in the exciting gossip about fortunes won or lost, the uninhibited feelings displayed, and the joyous abandon of everyday life in this boom town. Some of this raucous spirit and much of the vitality were to be imbibed by Charlie Michelson, born in 1869 in Virginia City.

But Albert, who graduated from high school the year of Charlie's birth, had acquired a different set of values. He could see no prospect of continuing his studies, as he wanted to do. A paper he wrote on optics had drawn favorable comment from Bradley and he hoped to explore the subject further. A possibility opened when Samuel Michelson spotted in the *Territorial Enterprise* of April 10, 1869, a letter from the Honorable Thomas Fitch, Nevada Representative in Congress, stating that he proposed to appoint a candidate to the Naval Academy from the State of Nevada. The appointment, open to all Nevada boys from fourteen to eighteen years of age, would be subject to the results of an examination judged by a board of examiners. If he could win it, Samuel told his son, his family would be proud of him. Bradley also encouraged Albert, pointing out that he would have splendid instruction in the natural sciences, including physics and chemistry. Albert agreed to take the examination. He brought with him a letter of recommendation from his teacher:

> To whom it may concern:
>
> This certifies that the bearer, Albert Michelson, has been a member of the San Francisco Boys' High School

during the last three years; that he has graduated with honor from the same; that in character as well as scholarship he is worthy of great commendation; and that he exhibits great aptitude for scientific pursuits.

Very Resp'y,

Theodore Bradley
Principal

San Francisco
June 1869

The examination took place on June 10. Albert was one of three who tied for first place. His rivals were James Wilson Blakely and William Gifford Cutler. The examining committee passed on this information to Congressman Fitch and left it to him to decide which of the boys would get the appointment. Fitch selected Blakely for three reasons: his parents could not afford to give him a good education, he was the son of a man who had lost his right arm (some said in the Civil War) and "with whom fortune has not always dealt kindly," and his appointment was strongly recommended by the Honorable D. R. Ashley, Fitch's predecessor in Congress.

"I hope the numerous friends of the other candidates will be satisfied with my settlement of this vexed question, and will receive this as a reply to the one hundred and thirteen letters and telegrams on this subject I have had the honor to receive during the last four days. I return my thanks to the committee for what they did and forgive them for what they left undone," Fitch wrote to a local paper.

After this announcement, Fitch no doubt received another inundation of mail protesting the injustice of his choice. If he followed Blakely's record at the Naval Academy, he would have been forced to recognize that his candidate proved to be very poor material indeed. His first academic tests show him listed well below passing, he was unable to retrieve his standing in the following year, and on November 16, 1871, he was dropped from the Academy.

Whether from the pricking of his conscience or, more likely, because of the threats of a powerful section of his constituency, Fitch did not abandon Albert. He was prevailed upon to write to the recently elected President, Ulysses S.

Grant, stating the reasons he hoped young Michelson could be given another chance.

Hamilton, White Pine County, Nevada
June 17th, 1869

Sir

I respectfully solicit your personal perusal of, and attention to, the communication I now have the honor to address you.

Having been notified by the Secretary of the Navy of the [*sic*] a vacancy in the Naval Academy from this State, I determined to submit the appointment to competition, and did so by public advertisement—a copy of which I have annexed hereto. A number of boys competed for the prize, and after an examination of unusual length and severity, the committee reported three of the candidates as equal in scholastic attainments—I annex a copy of the committee report. I also annex a copy of the reasons I have given for selecting the lad who has received the nomination for Midshipman.

The object of this communication is to solicit from you the appointment of Midshipman for one of the three who received the Committee's endorsement—Master A A Michelson.

Had I felt at liberty to be governed by considerations of political expediency, I should have selected him. His father is a prominent and influential merchant of Virginia City, and a member of the Israelite persuasion, who by his example and influence has largely contributed to the success of our cause, and induced many of his co-religionists to do the same. These people are a powerful element in our politics, the boy who is uncommonly bright and studious is a pet among them, and I do most steadfastly believe that his appointment at *your* hands, would do more to fasten these people to the Republican cause, than anything else that could be done.

I am sure that young Michelson could pass even a severer examination than that made at the Naval Academy, and that he would be an ornament to the service, and a credit to his nominator, and if you can give him the place you will never regret it.

> The Union people of Nevada are proud and grateful for the recognition they have received at your hands in the manner of appointments and will demonstrate to you hereafter, that the "strong box" of the nation will be the stronghold of your administration on this coast. I know you can greatly please them and strengthen us by making this appointment, and I take the liberty of expressing my deep solicitude that it may be made.
>
> Very Respy. Yours
>
> Thomas Fitch
>
> To the President

Michelson never saw this letter or knew of its existence, because it was mailed to the White House. At the same time, he was dispatched to Washington with another letter of introduction, full of praise but minus the political implications.

He set off alone across the continent, riding one of the first trains of the transcontinental railway. Only a month before his departure, the Central Pacific had raced the Union Pacific to a rendezvous midway, each trying to see which could build the farthest and fastest, for a prize of vast government land grants and bonds, allotted on a mileage basis. The attention of the nation was focused on this meeting at which the last rail was laid on a tie of California laurel, fastened with a "golden spike," while the two locomotives faced each other on a single track.

Albert saw the breadth of the country for the first time. Crossing the Continental Divide, the train descended from the Rocky Mountains, scattering great herds of buffalo as it crossed the broad plains. Armed guards were posted on every car because of the danger of an Indian attack or a holdup by bandits.

When Albert announced himself at the White House, President Grant, slumped in his chair, received him and listened with kindness and interest to his story. Drinking had coarsened Grant's face and rounded his belly so that he no longer looked like the pictures Albert had seen of him as a general charging into battle. But his voice was gentle as he broke the news to Albert that he could not help him, having already filled the ten appointments-at-large that were allotted the President.

Albert concealed his disappointment with difficulty. He thanked the President politely, bowed, and left his office with one of Grant's naval aides. This officer, admiring the boy's determination, advised him to go to Annapolis on the chance that a vacancy might occur if one of the President's ten appointees failed to pass his examination.

On his arrival at Annapolis in late June, 1869, Michelson went straight to the office of the Commandant of Midshipmen, Captain Napoleon B. Harrison. He waited three days before he finally was granted an interview, was examined, and then told there was no vacancy. Embittered and discouraged, his money almost gone, he returned to Washington and boarded a train for San Francisco. Just as the train was about to leave, a messenger from the White House came aboard, calling out his name. For the second time, Michelson was taken to see the President, who had been persuaded by Vice Admiral David D. Porter, Superintendent of the Academy, and one of Michelson's examiners, to make an exception in his case. Brushing regulations aside, Grant gave him the nomination for an eleventh appointment-at-large, which he received on June 28.

Michelson, telling this story in later years, chuckled over beginning his naval career by what he thought was "Grant's illegal act." But having once exceeded his quota, Grant went on to appoint two more midshipmen-at-large, a total of thirteen, in 1869.

Energy is in the news and may well remain there prominently for the rest of this century. This article surveys the key scientific, technological, and social issues related to our use of energy.

17

Energy and the Environment

John Fowler

An article from The Science Teacher, December, 1972

I

ENERGY: WHERE IT COMES FROM AND WHERE IT GOES

THE WORLD runs on energy, both literally and figuratively. It spins on its axis and travels in its orbit about the sun; the winds blow, waves crash on the beaches, volcanoes and earthquakes rock their surroundings. Without energy it would be a dead world. Energy was needed to catalyze the beginning of life; energy is needed to sustain it.

For most of life, animal and plant, energy means food; and most of life turns to the sun as ultimate source. The linked-life patterns—the ecosystems—which have been established between plants and animals are very complex; the paths of energy wind and twist and double back, but ultimately they all begin at that star that holds us in our endless circle.

When man crossed that threshold of consciousness which separated him from animals, his uses of energy began to diversify. He, too, needed food, but poorly furred as he was, he also needed warmth. With the discovery of fire he was able to warm himself. He also found that fire could make his food digestible and thus increase its efficiency as an energy source. After a while he began also to use fire to make the implements through which he slowly started to dominate nature.

Man's use of energy grew very slowly. In the beginning he required only the 2,000 or so Calories [1] per day for food; the convenience of warmth

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[1] We will consistently deal with Calories (kilocalories), the amount of heat energy needed to raise the temperature of one kilogram of water one degree Celsius.

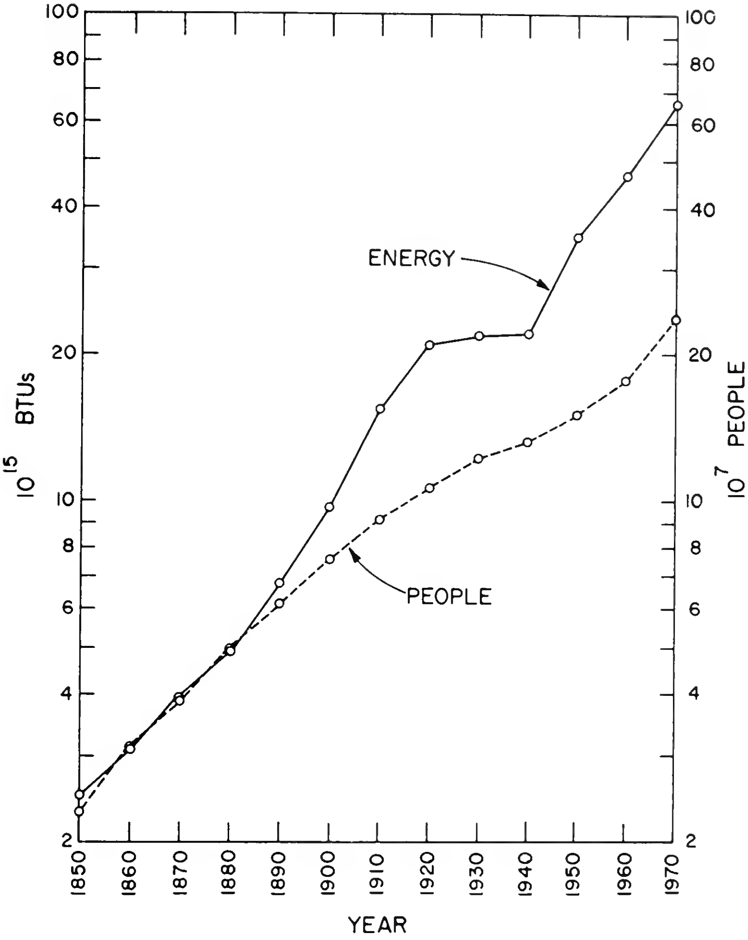


Figure 1. Comparison of energy and population growth, United States, 1850-1960.

added a few thousand more Calories from easily obtainable wood. The first big jump in energy use came about four or five thousand years BC when man domesticated several animals and —at the cost of a little food, much of which he gathered himself—was able to triple the amount of energy at his service.

The waterwheel appeared in the first century BC and again multiplied the amount of energy available to man. Its introduction was perhaps even more significant because it was a source of inanimate energy. For a long time the waterwheel was the most important source of energy for the nascent industry. It was not until the twelfth century, more or less, that the analogy between flowing air and flowing water led to the use of windmills.

The beginning of the modern era of industry coincided with the development of the steam engine. Since that time the world's use of energy, which until then had been very nearly proportional to the number of people, began to grow in the industrial countries more rapidly than the population increased. This growth, shown in Figure 1 for the United States, continues.

The second historical trend which, together with the increasing per capita use, has brought us to the present state, is the constant change in the energy mix. Wood was the dominant fuel in the 1850s but had lost all but 20 percent of the market to coal by 1900. Coal in turn lost out after 75 years to petroleum products, which now account for 75 percent of the energy, but they in turn will be (and *must* be as we shall see) replaced by other sources. Nuclear energy is the best present candidate.[2]

Energy as a Commodity

In the early stages of man's history, energy was food, something to be found and consumed. But as life became more complex, and early barter systems were followed by a money-based economy, energy had to be bought. At first it was purchased indirectly as food or fuel. With the introduction of electricity, energy could be piped directly into the house or factory.

Energy is a commodity; it can be measured, bought, and sold. But its price depends on the form in which it is purchased—as food or fuel or electricity. Table 1 is an "energy shopping list." It is clear that we pay for the good taste of energy in the form of steak.

Energy values for some fuels and foods (retail prices).

Source	Energy (*Cal/kg*)	Energy (*kWh/lb*)	Cost (*per 1000 kWh*)
Coal (stove coal)	7,200	3.86	$ 5.20
Fuel oil	10,800	5.72	4.30
Natural gas	11,000	5.86	5.46
Alcohol (denatured)	6,460	3.42	10.25
Alcohol (Scotch, 80 proof)	2,580	1.37	2,920.00
Bread	2,660	1.42	220.00
Butter	7,950	4.20	200.00
Sugar	4,100	2.16	68.00
Beef steak (sirloin)	1,840	.97	1,640.00
Electricity	—	—	20.00

Where It Goes

The energy crisis is not a crisis caused by the "using up" or the disappearance of energy. The First Law of Thermodynamics assures us of that. Energy is conserved, at least in the closed system of the universe. The crisis must then be found in the pathways of energy conversion.

[2] See Cook, E. "The Flow of Energy in an Industrial Society," *Scientific American* 224: 134-144; September 1971.

We use energy in its kinetic form, as mechanical energy, heat, or radiant energy. The form in which it is stored is potential energy. We know from physics that the potential energy of a system is increased by ΔE when we operate against a force over a distance ΔX, i.e.,

$$\Delta E = \vec{F} \cdot \Delta\vec{X}$$

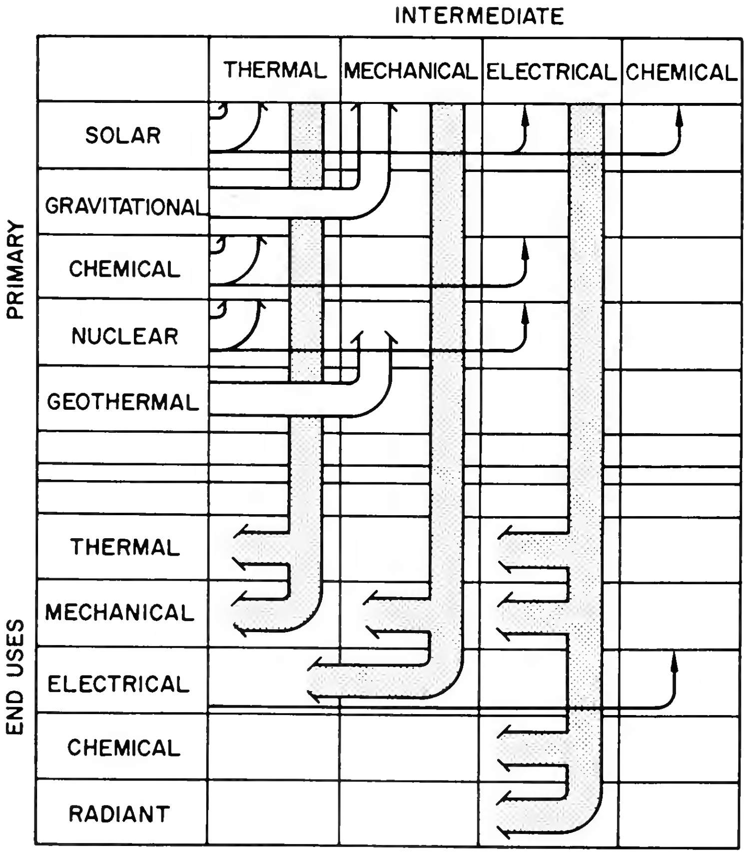
In the infinite variety of the universe we have, so far, discovered only three types of forces: gravitational, electrical, and nuclear (there seem to be two nuclear forces corresponding to the weak and the strong nuclear interaction). It follows, therefore, that there are three primary sources of energy: gravitational, electrical (chemical), and nuclear. On the scale of the universe these are the most important, and the weak force, gravitational, and the strong one, nuclear, give us the most visible effects.

At earth's scale we choose other primary sources of energy. Solar energy, radiated from the thermonuclear processes in the sun, is the most important of these. It gives us the kinetic energy of water power and wind power, warms us, is stored as chemical energy in growing things, and was preserved in the fossil fuels.

We store the gravitational energy of lifted water in reservoirs, but the only true primary source of gravitational energy of which we make commercial use (in a small way, admittedly) is that of the tides. Here we draw on the gravitational energy stored in the earth-moon system.

We show these and the other important primary sources of energy in Figure 2. The chemical energy of fossil fuels is at present far and away the most important of these, but there are two non-solar sources, geothermal energy from the earth's heated interior (originally heated by gravitational contraction and kept warm by radioactivity) and the new entrant onto the scene, nuclear energy.

Figure 2. Paths of energy conversion.



Excepting solar energy, the other primary sources are of little direct use to us; they must be converted to the intermediate forms and often converted again to the end uses which are also shown schematically in Figure 2.

The major sources of energy in this country are the chemical energy of the fossil fuels. From them we get 95.9 percent of the inanimate energy we use. They are fuels; their chemical energy is released by burning. Thus the major conversion pathway is from primary chemical energy to intermediate thermal energy. In fact, most of the conversion pathways go through the thermal intermediate form.

We will look later in detail at the distribution of energy among the various end uses. We know in advance, however, that the major end uses are thermal (space heating, for example) and mechanical. Mechanical energy is also a major intermediate form and is also converted to that most important intermediate form, electrical energy. The convenience of electrical energy shows up in its ready conversion to all the important end uses.

Conversion Efficiency

The most important conversion pathway is thus chemical → thermal → mechanical; and here we enter into the domain of the Second Law of Thermodynamics. It is this "thermal bottleneck" through which most of our energy flows that contributes mightily to the various facets of the energy crisis. We burn to convert, and this causes pollution. We are doomed to low efficiencies by the Second Law, and the wasted heat causes "thermal pollution." Let us consider the efficiency problem first.

Efficiency, the ratio of output work to input energy, varies greatly from

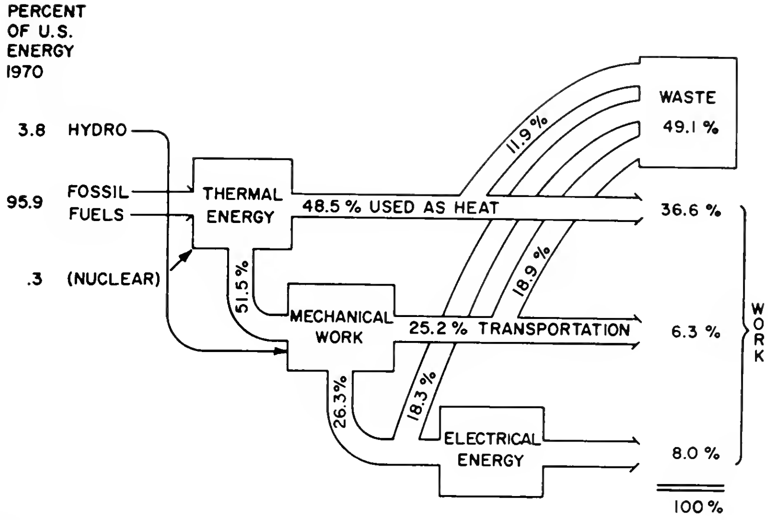


Figure 3. The flow of energy in the United States.

conversion to conversion. Generally speaking, we can convert back and forth from electrical energy to other forms with high efficiency, but when we convert other forms of energy to heat and then try to convert heat to mechanical energy we enter the one-way street of the Second Law.[3]

The efficiency of a "heat engine" (a device for converting heat energy to mechanical energy) is governed by the equation:

$$\text{Eff.} = \left(1 - \frac{T_{\text{out}}}{T_{\text{in}}}\right) 100$$

where T_{in} and T_{out} are the temperatures of intake and exhaust. This equation sets an upper limit of efficiency (it is for a "perfect" Carnot cycle). Since we are forbidden $T_{\text{out}} = 0°\text{K}$ or $T_{\text{in}} = \infty$, we are doomed to the intermediate range of modest efficiencies. For example, most modern power plants use steam at 1,000°F (811°K) and exhaust at about 212°F (373°K) with a resulting upper limit of efficiency of 63 percent. The actual efficiency is closer to 40 percent. Nuclear reactors presently operate at a T_{in} of about 600°F (623°K) and T_{out} of 212°F (373°K) for an upper limit of 40 percent. They actually operate at about 30 percent. In an automobile the input temperature of 5,400°F (3,255°K) and output of 2,100°F (1,433°K) would allow an efficiency of 56 percent. The actual efficiency is about 25 percent.

So far we have talked about the efficiency of the major conversion process, heat to mechanical work. What is more important to an understanding of the entire energy picture, however, is the system efficiency; for example, the overall efficiency with which we use the energy stored in the petroleum underground to move us down a road in an automobile. Table 2 shows the system efficiency for transportation by automobile and the production of electric power. One can see that overall there are large leaks in the system and that most of the available energy is lost along the way.

"Lost" does not, of course, describe precisely what happens to energy. We know what happens; it is converted to heat. The inexorable Second Law describes the one-way street of entropy. All energy conversion processes are irreversible; even in the highly efficient electrical generator some of the mechanical work goes into unwanted heat. The conversion of other forms of energy to heat is a highly efficient process—ultimately 100 percent. It is a downhill run. But the reverse is all uphill; heat energy can never be completely converted to mechanical work. The potential energy available to us, whether it be chemical, nuclear, or gravitational in form, is slowly being converted to the random motion of molecules. We cannot reverse this process, we can only slow it down.

Patterns of Consumption

Ever since President Johnson turned off the lights in the White House there has been a small (too small) but growing effort to save energy. It seems reasonable that this country and perhaps all countries will, at least for a while, have to make a real effort in this direction. To produce measurable effects, however, these efforts will have to be aimed at important sections of consumption.

A gross flow chart of energy in our economy is shown in Figure 3. One sees the thermal bottleneck. Heat is the desired end product from about half of our energy. We do use that amount of energy efficiently. Of the half that goes to provide mechanical work, however, large amounts are lost in the production of electrical energy and transportation. The net result is that overall (and one must remember here that we are dealing with refined fuels delivered to the converters) our system is about 50 percent efficient.

Table 2. Energy system efficiencies.

	Efficiency of Each Step	Efficiency Including All Preceding Steps
	Percent	*Percent*
Automobile		
Production of crude petroleum	96	96
Refining of petroleum	87	83.5
Transportation of gasoline	97	81
Thermal efficiency of engine	29	23.5
Mechanical efficiency of engine	71	16.7
Rolling efficiency	30	5
Electric Power Generation		
Production of coal	96	96
Chemical energy of fuel → boiler heat	88	84.5
Boiler heat → mechanical energy	50	42.3
Mechanical energy → electrical energy	99	42
Transmission efficiency	80	33.5

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[3] See Summers, Claude M. "The Conversion of Energy." *Scientific American* 224: 149-160; September 1971.

II

ENVIRONMENTAL EFFECTS OF ENERGY USE

Patterns of Consumption

The intimate connections between energy, our way of life, and the natural environment occur at many places. The most important points are, of course, in the production of energy—in the mines and wells, refineries and generating plants—and at the points of consumption. Figure 3 gave a crude picture of consumption; we need to look at it in more detail.

Figure 4 gives both a crude breakdown and details of the 60,526 trillion BTUs* of energy in each category. One sees that industry and transportation use the lion's share. The importance of space and water heating also shows up strongly. Predictions are that transportation and commercial use will be the fastest growing sectors.[4]

Electrical Energy— The People's Choice

What doesn't show up in this presentation is the special case of electrical energy. It is there, contributing heavily to all categories except transportation, and it shares with transportation most of the blame for energy's role in environmental degradation.

The growth rate of electrical energy consumption, shown in Figure 5, is the highest of all the various forms of energy. In discussing growth a most useful concept is "doubling time." The energy curve of Figure 1 shows several different periods of growth and, therefore, several different doubling times. In the late 1800s the doubling time was about 30 years; by the early 1900s this had been cut in half to about 16 years. The doubling time during the growth period from 1950 to 1960 was 25 years, and for the period 1960 to 1970 dropped to 18 years.

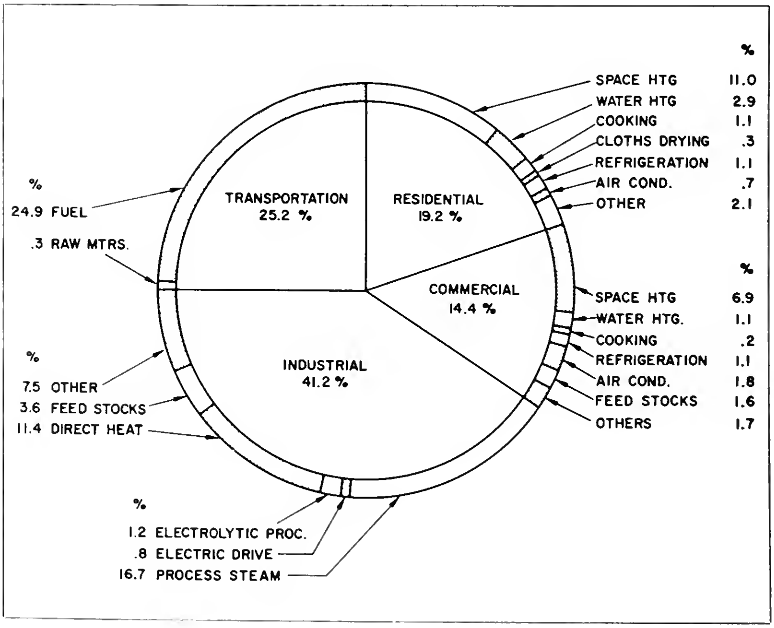
Electrical energy can be said to have arrived commercially with the start-up of the Pearl Street Station by Thomas Edison in 1882. (The energy curve in Figure 1 breaks away from the "people" curve by about 1890.) The doubling time for per capita electrical energy consumption of Figure 5 was only 7½ years during the start-up period of 1910 to 1920, was about 14 years in the 1950s and 60s and has decreased to about 10 years now. This means that in the period 1970 to 1980 the per capita use of electrical energy will be expected to double.

The impact of electrical energy can be better understood from the plot of total electrical energy consumption also shown in Figure 5. This curve has been doubling every 10 years since 1950. This means that in each of those 10-year periods the United States used as much electrical energy as in its entire previous history.

The reasons for the rapid increase in demand for electrical energy are several. It is in many ways the most convenient of the forms of energy. It can be transported by wire to the point of consumption and then turned into mechanical work, heat, radiant energy, or other forms.

It cannot be very effectively stored, and this has also contributed to its increasing use. Generating facilities have to be designed for peak use. In the late 50s and early 60s this peak

Figure 4. U.S. energy consumption 1968 (total 60.5 x 10^{15} BTUs).



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* In 1973 the U.S. Consumption was 75,561 trillion BTU's.

[4] Landsberg, H. H., and S. H. Schurr. *Energy in the United States: Sources, Uses and Policy Issues.* Random House, New York. 1960. P. 76.

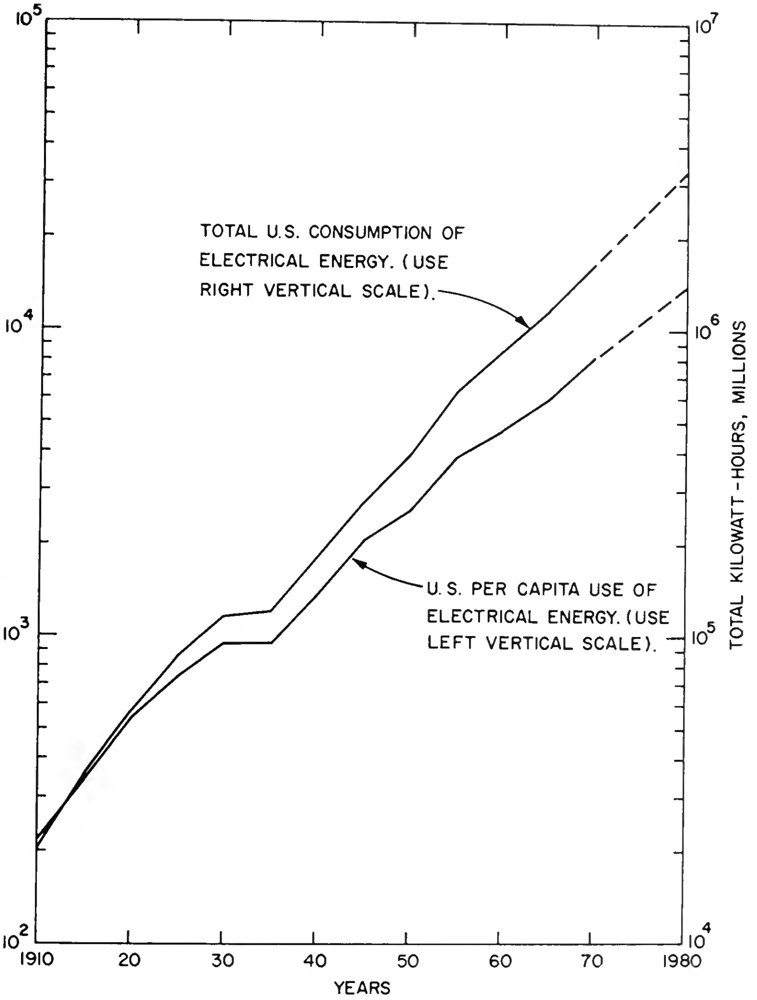
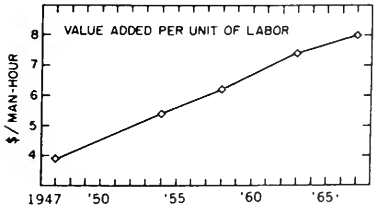


Figure 5. Growth of electrical energy consumption in the United States since 1910.

came in the winter, when nights were longer and more lighting and heating were needed. It was economically sound to heavily promote off-peak use, such as summer use of air conditioners.

Figure 6. Labor productivity in the period 1947-1968.



This promotion was so effective that the summer is now the peak time, and the sales effort seems to be going into selling all-electric heating for off-peak winter use.

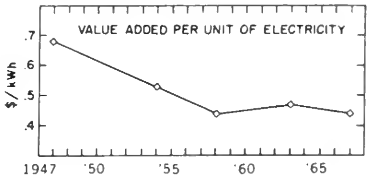
The rate structure has also contributed to increasing use of electrical energy. Rate reductions are offered to attract bulk consumers. Hindsight suggests that there has been an imbalance between research and promotion. The figures bear this out. Senator Lee Metcalf has reported that the utilities in 1969 spent $323.8 million on sales and advertising and $41 million for research and development.

Perhaps the most important clue to the great increase in the use of electrical energy was suggested by Barry Commoner in an address to the American Association for the Advancement of Science.[5] Commoner looked at the important economic parameter "productivity," which is defined as the ratio of value added to a product/man-hours to produce it. The strength of the economy is built on increasing productivity. The data Commoner presents, for the period 1947 to 1968 (Figure 6) show that labor productivity has been steadily increasing. He and his colleagues then looked at the history of electric power productivity. These two quantities, man-hours and kilowatt-hours, do play similar roles in industry—electricity amplifies the existing muscle power in many cases. This analysis of electric power productivity showed the very different results of Figure 7. The ratio of value added to kilowatt-hours/electric power productivity, declined sharply from 1947 to 1958 and has flattened out since then. This suggests the important conclusion (which merits much more careful study) that the increase in labor productivity has been bought, at least partially, at the expense of a decrease in power productivity. Since labor is more expensive than electric power, the effects on the economy have been beneficial. But what about effects on the environment?

Environmental Effects: Air Pollution

There are two major areas of pollution, air and thermal, which are almost completely attributable to energy consumption. Air pollution is unhappily well known to all of us through smog—

Figure 7. Electric power productivity in the period 1947-1968.



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[5] Commoner, Barry. "Power Consumption and Human Welfare." Paper prepared for delivery at the annual meeting of the American Association for the Advancement of Science, December 29, 1971.

that collection of irritating hydrocarbons and oxides of sulfur and nitrogen which is becoming a fixture of urban living. Table 3 gives a breakdown of the contributions to pollution of the various categories of polluters. One sees that the generation of electric power is the major source of sulfur oxides, while the automobile leads for three other pollutants.

It is of course not possible to deduce the importance of these pollutants from their gross weight because they have very different effects. Some, like carbon monoxide, affect health in even minute concentrations, others, like the particulates, largely add to cleaning bills. This article is not the place for a detailed discussion of the effects of air pollution.[6] We will simply summarize the costs, which come from effects on the health, damage to crops and exposed materials, and property values, by quoting the Second Annual Report of the Council on Environmental Quality, August 1971.

> The annual toll of air pollution on health, vegetation and property values has been estimated by EPA at more than 16 billion dollars annually—over $80 for each person in the United States.[7]

The dependence of our society on the automobile for transportation presents us with a complex mix of problems; in addition to polluting the air, it uses one quarter of our energy total in a very inefficient way, leads to the covering of our countryside with concrete, contributes to many aspects of the problems of our cities, and takes a high toll of human life. The discussion of these problems and suggestions for solutions are fascinating and important, but cannot be undertaken here.

The generation of electric power at present depends almost entirely on the burning of the fossil fuels. The sulfur oxides come from the sulfur impurities in these fuels. The burning of these fuels also converts large amounts of carbon to carbon dioxide. This familiar gas is not a pollutant in the ordinary sense, but its steady increase in the atmosphere is a cause for concern. Carbon dioxide is largely transparent to the incoming short-wave solar radiation, but reflects the longer-wave radiation by which the earth's heat is radiated outward, producing the so-called "greenhouse effect." Presently about six billion tons of CO_2 are being added to the earth's atmosphere per year, increasing its CO_2 content by 0.5 percent/year. By the year 2000 the increase could be as much as 25 percent. Our understanding of the atmosphere is not sufficient to predict the eventual effects on climate which might be produced by this increase and by a related increase in water vapor and dust, but small changes in the average temperature could have catastrophic effects.

Nuclear Reactors—Clean Power?

There are strong forces in this country pushing the nuclear reactor as an answer to our need for clean power sources. The reactor gains its energy from the fission of U^{235} or Pu^{239}. The energetic by-products of this fissioning are stopped in the fuel rods, heating them, and this heat is transferred by some heat exchanger to a conventional steam-powered electric generator.

The fission products are radioactive, dangerously so. They have many different half-lives, but the whole mess averages a half-life of perhaps 100 to 150 years. The switch to nuclear energy for the generation of electricity will be accompanied by a growing problem of disposal for this radioactive waste. Snow[8] has estimated that the 16 tons of radioactive fission products from reactors accumulated in 1970 will have grown to 388 tons by 1980 and will be more than 5,000 tons by the year 2000.

Nuclear reactors are carefully designed against the release of these products which are collected and stored for safety. But the storage problem itself is a far from negligible one, with no generally agreed-on solution in sight. It has been proposed that the most dangerous wastes be dried and stored in salt mines in Kansas. There are now indications that above-ground storage will be the approved means.

So far the radioactivity associated with nuclear reactors seems to have been handled with exemplary safety. Any exposure to the general population from this source is in the range of present exposure from past nuclear testing. It is in all likelihood causing damage, but so do all the other forms of power generation.[9] What really must concern us when we consider substituting the fissioning of uranium for the burning of fuel is the possibility of accident.

When discussing accidents, we are not talking about a real nuclear explo-

Table 3. Estimated emissions of air pollutants by weight nationwide, 1969; total 281.2 million tons[a] (in millions of tons/year).

	CARBON MONOXIDE		PARTICULATES		SULFUR OXIDES		HYDROCARBONS		NITROGEN OXIDES		TOTAL
Source	Amount	Percent	Amount	Percent	Amount	Percent	Amount	Percent	Amount	Percent	Amount
Automobile	111.5	74	0.8	2	1.1	3	19.8	53	11.2	46	**144.4**
Power plants	1.8	1	7.2	21	24.4	73	.9	2	10.0	42	**44.3**
Industrial	12.0	8	14.4	41	7.5	22	5.5	15	.2	1	**39.6**
Refuse burning	7.9	5	1.4	4	.2	1	2.0	5	.4	2	**11.9**
Miscellaneous	18.2	12	11.4	32	.2	1	9.2	25	2.0	9	**41.0**
Total	151.4	—	35.2	—	33.4	—	37.4	—	23.8	—	**281.2**

[a] Council on Environmental Quality. *Environmental Quality*. P. 212. (See also footnote 7.)

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[6] *Air Pollution*, a Scientists' Institute for Public Information Workbook. SIPI, 30 East 68th Street, New York.

[7] *Environmental Quality*, the second annual report of the Council on Environmental Quality, August 1971. U.S. Government Printing Office, Washington, DC. P. 107.

[8] Snow, J. "Radioactive Waste from Reactors: The Problem that Won't Go Away." *Science and Citizen* (Environment Magazine) 9: 89-95; May 1967.

[9] This is treated more fully in *The Environmental Cost of Electric Power Production*. A SIPI Workbook. SIPI, 30 East 68th St., New York.

sion in which a "critical mass" of fissionable material accumulates and goes off. The low enrichment densities preclude that. But since the reactor core is a witches' caldron of radioactive waste products, any accident which opens that up and spreads it over the countryside is catastrophic. The accident that designers fear is cooling system failure. If the cooling-water were somehow denied the fuel rods, in only a matter of seconds they would begin to melt, leaving the reactor core an uncontrollable blob of melting metal, heated internally so that it continues to melt. The resulting steam pressure explosions then could release the radioactivity to the environment. It is this small but troublesome chance of accident that keeps reactors away from the cities where their products, electricity and heat, are needed.

Heat as a Pollutant

As we have earlier stressed, energy conversion is largely a one-way street: All work eventually produces heat. The "heat engines," because of their inefficiency, however, are particularly troublesome. A steam power plant, which is only 30 percent efficient, dumps two units of heat energy for every one it converts to electricity. As our appetite for electricity grows in its apparently unbounded way, so also grows the problem of heat discharged to the environment.

In the steam power plant the waste heat problem is associated with the necessity to lower the temperature of the exhaust steam (so that the piston will not have to work against an appreciable back pressure). The most inexpensive and convenient way to accomplish this is to divert water from a stream or river. Nuclear reactors, since their working parts are steam engines, have the same problems. In fact, the nuclear reactor, because of its lower efficiency, presents a more serious cooling problem. Because of the difference in power plant efficiencies (30 percent versus 40 percent) and in fuel efficiency, and because the fossil-fuel plant discharges about 10 percent to the atmosphere through its stack, the reactor dumps about twice as much heat per kilowatt hour of energy produced as does the fossil-fuel plant.

We do not need to look ahead very far to see that this heating up of the environment cannot go on. There are two different sorts of projections that make this point.

The first of these concerns the cooling-water needs. If the growth of Figure 5 continues, we will need one-sixth of the total fresh-water run-off of this country to cool our generating plants by 1990 and one-third by the year 2000.[10] Long before we reach that point we will have to make some hard decisions about stream and river use and plant siting if we are to preserve inland aquatic life.

The second projection is even more indicative of the problem. If we express our consumption of electricity in terms of energy released per square foot of U.S. land area, we obtain for 1970, .017 watts/ft^2. At our present doubling time of 10 years for electric power consumption, in 100 years we will have gone through 10 doubling periods, and the energy release will be 17 watts/ft^2—almost the same as the 18 or 19 watts/ft^2 of incoming solar energy (averaged over 24 hours). Long before we reach such a level, something will have to be changed.

These two projections only serve to emphasize what should by now be obvious: Energy use, particularly electric power, cannot be allowed to continue to grow as it has. There are other data that reinforce this conclusion. Electricity means power plants and transmission lines; doubling consumption means doubling these. There are now about 300,000 miles of H.V. transmission lines occupying four million acres of countryside in the United States. By 1990 this is projected to be 500,000 miles of lines occupying seven million acres.[11]

All this serves to make the point that exponential growth cannot continue. But we could have learned that from nature. Exponential growth is unnatural; it occurs only for temporary periods when there is an uncoupling from the constraints of supply and of control. For instance, it will be demonstrated for a while by the growth of a bacterial population with plenty of food, but will eventually be turned over either by exhaustion of the food supply or by control from environmental processes which resist the population growth. We have examined some of the areas of environmental damage which may cause us to resist continued growth of energy production and consumption. What about our energy sources; are they likely to be the controlling factor?

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[10] Federal Power Commission Staff Study. "Selected Materials on Environmental Effects of Producing Electric Power." Joint Committee on Atomic Energy, August 1969. P. 323.

[11] Energy Policy Staff. "Electric Power and the Environment." Office of Science and Technology, August 1970. U.S. Government Printing Office, Washington, DC.

III

RESOURCES AND NEW SOURCES

Before we ask for a statement of the lavish deposits nature has made to our energy account, we must shed our parochial view and briefly look at energy consumption as the world problem it is.

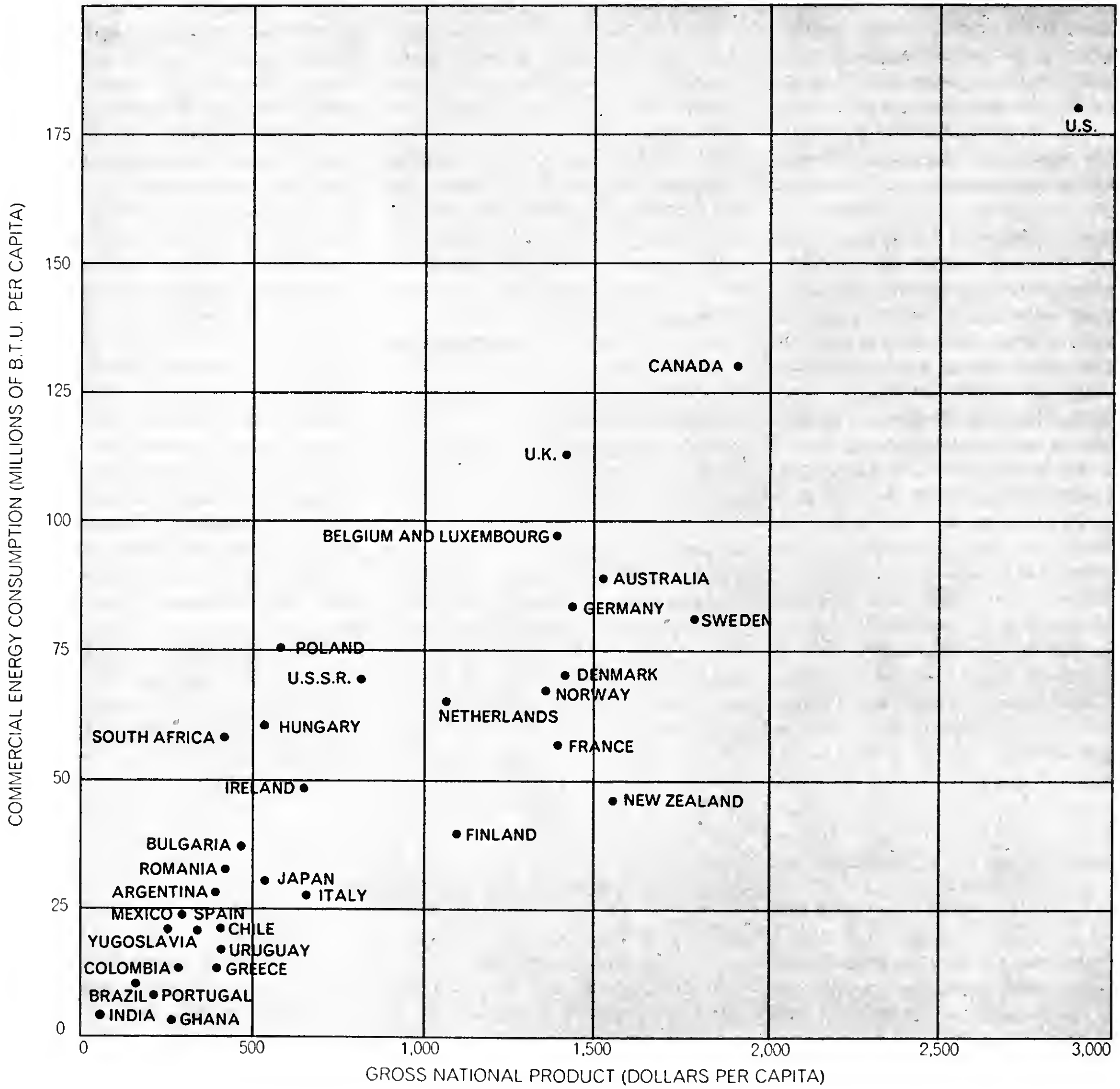
Energy and the GNP

It can and will be argued that man can live happily and productively at rather low levels of energy consumption. The fact remains, however, that today per capita energy consumption is an indicator of national wealth and influence—of the relative state of civilization as we have defined it. That this is so is seen most clearly by plotting that talisman of success, the (per capita) gross national product (GNP) against the (per capita) energy consumption shown in Figure 8. There appears a rough proportionality between per capita GNP and per capita energy consumption with the United States at the top, and countries like Portugal and India near the bottom. To the right of the "band of proportionality" lie the countries which manage a relatively large GNP with a relatively small energy expenditure. Perhaps they are worthy of study.

There are two lines of interest which lead out from this kind of data and bear on future uses of energy. One is to look at the time dependence of GNP/energy data. Data for the United States show two interesting effects.

We find a long period, 1920 to 1965, during which the country was progressively more efficient in its energy use or at least managed to increase its per capita GNP more rapidly than its per capita energy expenditure. This was apparently largely due to increased efficiency of conversion and end-use techniques. This trend reversed, however, around 1965, and we now are in a period during which this ratio is rising steadily. Reasons for this seem

Figure 8. Per capita consumption of energy and gross national product for some countries of the world. From Cook, Earl. "The Flow of Energy in an Industrial Society." Scientific American 224:142; September 1971.



to be in part at least due to a rise in non-GNP connected energy uses, such as heating and air conditioning. Since these uses are on the increase and since we are near ultimate efficiency in most of our major conversion and end-use techniques, this rise in energy consumed per dollar of GNP is expected to continue for a while and must be built into energy use projections.

The second line of inquiry concerns ultimate world use. The United States, with 6 percent of the world's population, uses 35 percent of the world's energy. If we look at comparative rates of growth, we see that the U.S. per capita energy consumption is much larger (a factor of about 30) than that of India, for instance, and is growing more rapidly. The world figure is some five times smaller but is growing a bit more rapidly than is the U.S. figure.

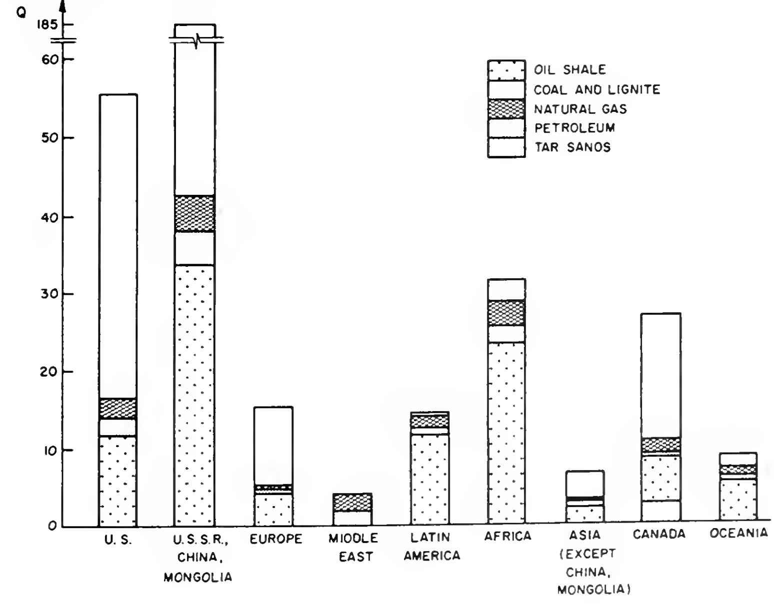
Even if the United States were to stabilize at the present per capita figure of 250 kWh/day, it would take about 120 years for the world per capita average to equal it and hundreds of years for India at its present rate of growth to catch up.[12] If some sort of equalization of world energy use is what we are aiming at, with the present U.S. figure as target, then we are talking about increasing world consumption by a factor of about 100. And this brings us to energy resources.

How Long Will They Last?

As someone said, "Prophecy is very difficult, especially when it deals with the future." Predicting the lifetime of energy resources is doubly difficult. Energy use curves must be projected and then unknown resource potentials guessed at. It is difficult to hope for much accuracy in either of these processes.

The estimation of resources is based on general knowledge of the kind of geological conditions associated with the resource and on detailed knowledge of the distribution and extent of a resource within a favorable geological area. Coal is the easiest to work with, for it seems almost always to appear where it is predicted. Oil and natural gas on the other hand are erratic in distribution within favorable areas and are found only by exploration. In addition to coal, oil, and natural gas, there are two other sources of organic carbon compounds which are potential fuel sources, the so-called tar sands and oil shale. In the tar sands, which so far have been found in appreciable amounts only in Canada, a heavy petroleum compound (tar) binds the sands together. A Canadian refinery is currently producing oil products from this material. Oil shale is shale rock containing considerable amounts of a solid organic carbon compound (kerogan). Oil can be extracted by heating the rocks, but this process has not yet been demonstrated to have commercial viability.

Figure 9. Remaining recoverable energy resources by region. From Williams, R. H. and K. Fenton. "World Energy Resources: Distribution, Utilization, and Long-Term Availability." (See footnote 13.)



In Figure 9 we show the estimates of world fossil fuel resources of various types and the global distribution of these resources.[13] The unit used to measure these resources is the Q, 10^{18} BTUs. As a crude reference to the size of a Q, it would take about that much energy to boil Lake Michigan. Perhaps more useful is the fact that U.S. total energy consumption in 1970 was about 0.07 Q, and world consumption about 0.2 Q.

One sees from these data that most of the remaining fossil-fuel resources, for the United States and for the world, are in the form of coal.

Presenting data on resources does not by itself answer the question "How long will they last?" To answer that question one has to look at data on the rate at which the resources are being used. A simplified but very graphic way of displaying this has been adopted by M. King Hubbert of the U.S. Geological Survey.[14] Since supplies of fossil fuels are finite, the curve which traces their production rate will be pulse-like, that is, it will rise exponentially in the beginning, turn over when the resources come into short supply, and then decay exponentially as the resources become harder and harder to find. Such data for U.S. oil and U.S. coal are displayed in Figures 10 and 11.

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[12] These points are discussed in more detail in Starr, C. "Energy and Power," and Cook, E. "The Flow of Energy in an Industrial Society." *Scientific American* 224: 37-49 and 134-144, respectively; September 1971.

[13] Williams, R. H., and K. Fenton. "World Energy Resources: Distribution, Utilization, and Long-Term Availability." Paper delivered at the annual meeting of the American Association for the Advancement of Science, December 29, 1971.

[14] Hubbert, M. K. Chapter 8. "Energy Resources," in *Resources and Man*. W. H. Freeman, San Francisco, CA. 1969.

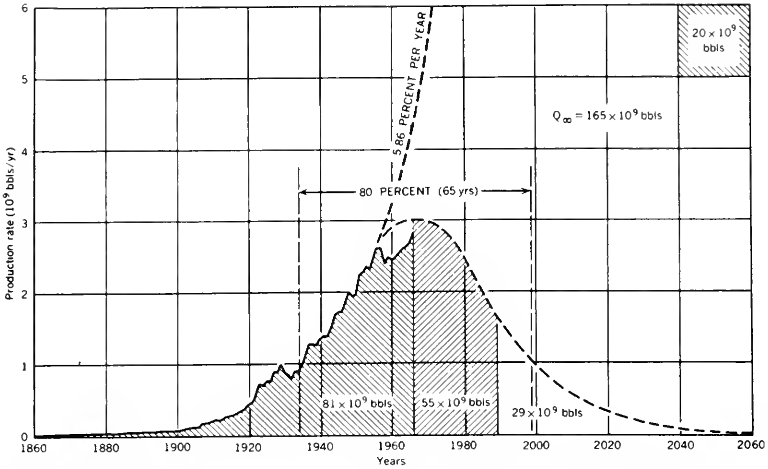


Figure 10. Use rate for U.S. oil resources. From Hubbert, M. K. Resources and Man. *P. 183. (See footnote 14.)*

The curve for U.S. oil is of particular interest. It shows that the actual rate of production from 1880 to the present does have roughly the predicted shape. If Hubbert's choice of total resources, 165×10^9 billion barrels, is correct, it also shows that the United States is probably now past the peak of oil production. The most important feature of a curve like this is its width, for that tells us how long a resource might be expected to last. We see that for oil, these data suggest that the total amount of oil to be produced by the United States is 165×10^9 billion barrels and that 80 percent of that will be produced in the 65-year period from 1934 to 1999. Thus, within our lifetime we can expect to see a radical change in the fuel mix, with petroleum losing its dominant position. The effects of this on automobile transportation will be of major importance in our automobile-centered economy.

Figure 10 for coal is consistent with the previous Figure 9. We have a great amount of coal and are just started up the slope to the peak in production. The time scale is much larger, the time to produce 80 percent of the U.S. coal is on the order of 300 to 400 years.

In combination, Figures 9, 10, and 11 give a representative view of the state of U.S. and world fossil-fuel resources. They give a qualified answer to, "How long will they last?" The answer: "Not very long," if we are talking about crude oil and natural gas; "long enough for us to find other sources," if we are talking about coal.

The answer might also have been: "Long enough for us to wreck our environment." Without much improvement in the protection we give our environment about two more doubling periods of energy consumption may be all it can take. Each doubling not only reduces the resources but, for instance, doubles the generating capacity (more plants), doubles (almost) the amount of transmission lines, doubles the coal-mining activity, doubles (unless rigid controls are implemented) the sulfur oxides and fly ash in the atmosphere, and so on.

Are There Clean Continuous Energy Sources?

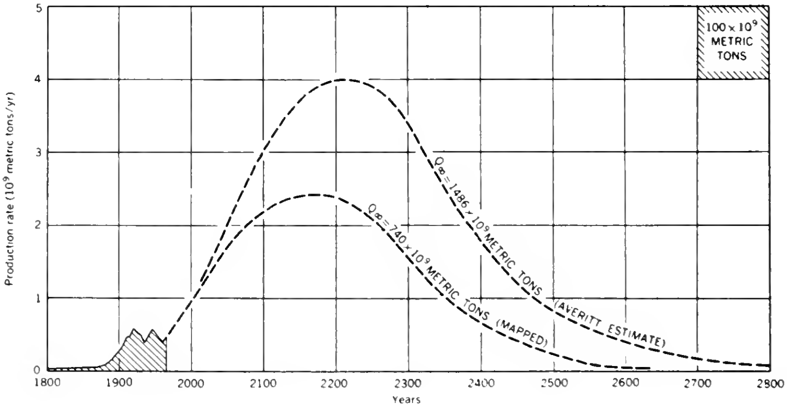
While coal may provide for our energy needs for 300 to 400 years, it won't last forever; on the scale we hope is still appropriate to mankind, the period of fossil-fuel dependency will be a short blip on the sweep of time. If we are to see a world in which all people have "energy slaves" in numbers which approach the U.S. standard, we must find some source of energy which can last for at least a few tens of thousands of years.

In Part I we cataloged the primary energy sources. Let's look at them again. The primary sources with their important components are shown in Table 4.

From Table 4 it is easy to see the necessary shape of our long-range future. Of the continuous sources only solar energy can provide energy at the level of expectation. And for solar energy, the three converters we now use—photosynthesis, hydro power, and wind power—even at maximum utilization, could just barely suffice.

If we look to the depletable sources and spend no more time discussing the fossil fuels, we see some interesting things. In the first place, we are struck by the fact that the ordinary nuclear reactor is not a long-term answer. If we successfully convert to the controversial breeder reactor, we see our first big number, and we increase our potential by a factor of 100. Finally, looking somewhat further into the future,

Figure 11. Use rate for U.S. coal resources. From Hubbert, M. K. Resources and Man. *P. 200. (See footnote 14.)*



determinedly rosy-hued, successful application of the D-D reaction in a fusion reactor could, due to the vast amounts of deuterium in the ocean, give us an essentially infinite source.

Let us now take off the rose-colored glasses and look somewhat more sceptically at the most important of these estimates. We refer the interested reader to the suggested general reading for more detailed reviews of these various topics.

Table 4. Primary energy sources with maximum power available.[a]

CONTINUOUS SOURCES	MAXIMUM POWER—WORLD *(Units 10^{12} watts)*
Solar	28,000
Photosynthesis fuel	13
Hydro power	3
Wind power	0.1
Gravitational (tidal)	1.0
Geothermal	0.06
World cumulative demand 1960–2000	~ 500
World annual demand by year 2000	~ 15
Depletable sources	
Chemical (fossil fuels)	~ 1000
Nuclear	
Fission ordinary reactor	~ 3000
breeder reactor	~ 300,000
Fusion	$> 5 \times 10^9$

[a] Adopted from Starr, C. "Energy and Power," *Scientific American* 224: 43; September 1971.

Solar Energy

Even at the great distance of earth from sun, our share of the solar output is impressive. Solar energy, which fuels life, pours onto the earth in prodigal amount. But to harness it for the massive needs of industry is something else. Solar energy has several disadvantages. It is dilute: approximately ~18 watts/ft^2 averaged over 24 hours. It is erratic: not only is there a familiar cycle of light and darkness but less regular cloud obscuration. This latter is a serious problem since neither heat nor electricity—the most likely forms to which solar energy will be converted—can be readily stored.

There are ambitious schemes being proposed to capture and convert significant amounts of solar energy, and the budget for solar energy research is climbing from the present "hobby" level of about $50,000/year to several million. We are beginning to make a real effort to use this clean free energy more massively, but it will take decades to see results.[15]

Nuclear Energy—Fission

We have discussed in Part II some of the dangers of the ordinary nuclear reactor. This country has embarked on a program to develop the fast-breeder reactor, which uses some of the neutrons from the fissioning fuel to convert U^{238} to the reactor fuel Pu^{239}.[16] The energy arguments for this are easily seen from Table 4. What is not seen are the problems this will bring. The breeder reactor poses several. It is a new and difficult technology, running at higher temperatures (more efficient but more susceptible to cooling-water accidents), it will probably use a liquid metal heat exchanger. Most serious, however, are the dangers associated with plutonium. Creating this material in large quantities means that the half-life of waste (in which there will be some plutonium) will go from about 150 years to > 20,000 years. Can we guarantee safe storage for that long? It also means that the material for "atomic bombs" will now be created in ton lots and shipped across country and maybe across oceans. The political implications are obvious.

Nuclear Energy—Fusion

We have dreamed for 20 years of tapping the essentially unlimited resources of deuterium to fuel a D-D fusion reaction. But so far it is largely a dream. Scientifically we understand the theory, but to create a plasma of fusionable material at the 100,000,000°F we need and to hold it together for long enough to get appreciable power out, is presently beyond our means. Research in this area is being accelerated, and the optimists predict scientific feasibility by 1980 and pilot demonstration by 2000. The pessimists laugh.[17]

Fusion, if it can be tapped, offers much; not only essentially unlimited fuel, but at least hundredfold reduction in the radioactive waste problem. It will also be, we expect, free from threat of accident. There will still be heat to worry about, but the combination of cleanliness and safety may allow siting to take advantage of this heat.

Conclusion

Mankind is in the midst of a crisis of energy. It has several dimensions. On a short time scale, we are faced with a serious shortage of natural gas and, in certain places where demand has exceeded present capacity, with a shortage of electric power.

On an intermediate time scale, 30 to 60 years, we are faced with the necessity of finding a substitute for the petroleum products which now dominate the energy mix.

Finally, on a larger scale, 300 to 400 years, we are faced with the exhaustion of fossil fuels.

What can we do? Some of the answers are obvious. We can plan more carefully and further ahead. We can try to reduce energy expenditures and increase research and development support. As citizens we must demand this. We must also demand a role in the decision-making process and decide, for instance, whether we lean heavily on the breeder reactor with its dangers or rely on coal and coal products (gases and liquids).

The science teachers of this country have a vital role to play in the next few years. These decisions must be based on information, and it is the science teacher who must make sure that developing citizens have access to the necessary information devoid of bias and distortion. It is my hope that this summary, brief and sketchy as it is, can serve as a part of the foundation of that necessary effort. ☐

Suggested General Reading

1. *Scientific American* 224; September 1971. The issue is devoted entirely to energy.
2. "The Energy Crisis." *Bulletin of the Atamic Scientists* 27; September and October 1971. Two issues on energy.
3. *The Science Teacher* 39; March 1972. Five articles on energy.
4. Romer, R. H. "Energy-Resources, Production and Environmental Effects." A Resource Letter of the American Association of Physics Teachers. *American Journal of Physics* 40: 805; June 1972.
5. "Energy and the Environment." J. M. Fowler, McGraw-Hill Book Co., N.Y., 1974.

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[15] For further details see Glaser, P. E. "Solar Energy—Prospects for Its Large-Scale Use." *The Science Teacher* 39: 36-39; March 1972.

[16] Seaborg, G. T., and J. L. Bloom. "Fast Breeder Reactors." *Scientific American* 223: 13; November 1970.

[17] For a review of progress toward fusion see: Auer, P. L., and R. N. Sudan. "Progress in Controlled Fusion Research." *The Science Teacher* 39: 44-50; March 1972.

The human eye versus the camera lens as an optical instrument in this interesting article.

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18 The Lens, a Most Imperfect Eye

Norman Goldberg

An article from Popular Photography, 1970

Hermann Von Helmholtz, the 19th century's foremost authority on the eye and the nature of vision, is credited with observing that whoever made the human eye had not properly learned his craft. In the hundred years since he reached this conclusion, other workers in the field have passed similar judgments, based mainly upon their direct comparison between the eye and a lens.

Researchers have removed the eye from freshly slaughtered animals and examined the image it formed. Almost every account of these experiments reaches conclusions that seem to prove that Helmholtz's remark was true. The bulk of these observations were made prior to the breakthrough in optical design brought about by the development of the modern high-speed computer.

Just think how much further today's lenses would have tipped the scales had they been available when comparisons between the eye and a camera lens were first being made.

Why such comparisons were made (and are still being made) at all is probably the result of attempts to explain the workings of one by referring it to the other. Most of you have seen primary-level books on how cameras function. In most of these, there's at least one drawing showing the parallel between the eye and the camera. The eyelid is compared to the shutter, the iris to the diaphragm, the lens of the eye to the camera's lens, and the retina to the image-recording film.

If we were to limit ourselves to discussing the eye within this framework, we could come up with some figures that might be useful in seeing how true past comparisons were when they judged the eye to be an inferior optical instrument. If an average of values from a variety of sources can be used as at least the *basis* of a "normal" eye lens, its specifications would be:

Focal length (modified zoom)—a 22.7-mm average; *speed*—*f*/2.8; *minimum aperture* (without benefit of morphine)—*f*/11; *angle of view*—vertical: 130 degrees, horizontal: 200 degrees; *resolving power*—on axis: 70 L/mm, one degree off-axis: 56 L/mm, five degrees off-axis: 24 L/mm, 20 degrees off-axis: 7 L/mm, 50 degrees off-axis: 1.8 L/mm; *closest working distance*—av.: 250-mm (varies with age).

Care and maintenance—self-cleaning, shutter fatigues after about 16 hours of use; *stability*—varies from hour to hour; *standard accessories*—built-in UV absorption filter, automatic diaphragm, automatic focus control, automatic target-seeking control with instant lock-on once target is within axial spot, optional over-ride on command.

Now tell me—can you find a lens that would justify those old cats' putting the eye down? And before you pore through your lens collection, let me sneak one more thought into the argument. Most of us have two eyes, so let's add a few things to our list in view of this:

Stereoscopic, with 130-degree field; *fully automatic* convergence and divergence linked to target distance and relative position. Manual override possible; *shutters* may be independently operated for special effects such as providing a homing signal to other units similarly equipped, but with certain basic constructional differences.

But no one can really be serious about the comparison between eye and lens. I wouldn't trade my eyes for any lens or lenses made anywhere, anytime—and neither would you! The eye *can't* be talked about in lens-alone terms, because it's so much more than simply a lens. Romantic aspects aside, the eye is part of an image *system* that employs memory, experience, and lots more.

About the closest man-made contrivance would be a twin-lens, stereo TV camera system, with full color response, auto-exposure control, auto-focus, auto-timing, and all the other features listed above for the lowly (according to Helmholtz) eye.

What *is* curious is the way lens designers have learned to imitate the eye in some details. They've found it necessary to use several elements, each with a different refractive index to overcome certain aberrations. The eye's crystalline lens employs this same feature, but more gracefully.

The eye is not made up of a big chunk of stuff having one refractive index, followed by another with a different index, followed by more of the same. Instead, the eye's lens is made up of layers of fibers, each so thin that the more than two thousand layers (encased in a clear, elastic membrane) take up no more room than a small lima bean.

Successive layers have slightly different refractive indexes, so that a ray-trace through the whole bean-sized lens would curve gradually, instead of displaying the abrupt changes in direction encountered in a ray going through a man-made lens. And there's considerably more.

To focus the eye between its far and near points of distinct vision requires an involuntary act on the part of the owner called "accommodation." This involves the contraction or relaxation of some tiny muscles that cause the crystalline lens to change its shape from a thin lens with relatively flat faces, to a fat, squat, bulging lens.

The thin shape occurs when the eye is relaxed and looking at distant objects, while the more bulging shape occurs when the muscles tighten around it for close-up work. The whole process of focusing from far to near involves a change in lens thickness of only 1/2-mm (about 1/50 in.). Take a camera lens of the same focal length, change its focus from infinity to 10 in., and you'll have to move the whole assembly 2.3-mm. (about 1/10 in.).

Because of the short focal length, the figures involved are small, but notice that the camera lens has to be moved about *five times as much* as the eye. And the eye doesn't even move (in relation to the body)—its lens merely bulges a bit at the center. It's almost as though it were taking a deep breath, but it costs the owner not even that small effort.

The cornea, which is the outermost (and most highly refractive) element of the eye is the one that *can* be compared rather closely to a man-made lens. It can be likened to a meniscus lens whose center is thicker than its edges—that is, a positive meniscus. By itself, it has a focal length of about 25-mm, so you can see that in the compound structure that is the eye, the cornea contributes most of the light-bending power.

In fact, the main function of the eye's lens is to change the focus by altering its shape, thereby changing its focal length. So, now you know

Many animals are thought to see in monochrome rather than in color, as we do.

why we can call the eye a zoom (or variable focal-length) system.

Sooner or later I'll have to defend my listing of the eye's resolving power, so let's have at it now. It is true that the eye possesses the characteristic of having a central spot (called the fovea) measuring about 0.3-mm in diameter, that, alone among all other regions of the eye, is capable of distinguishing fine detail. The remaining regions (away from the foveal area) become less and less able to discern the information-filled fine detail.

This is the kind of situation that, if noted in a camera lens, would spell "no-sale." But in the eye it makes perfectly good sense. Because of the tiny region in which fine details can be distinguished, our minds aren't cluttered with stimuli from all over the 130-degree field we see (in stereo). We concentrate on the region of acute vision provided by the fovea.

To see how this works, try to look intently at both dots in the brackets (:). You'll soon discover that only one dot at a time can really be scrutinized. Because the eye is continuously scanning objects, we're unaware that our region of acute vision is so tightly restricted.

What about all the rest of the eye's field of view? The image on the retina other than the tiny fovea is not going to waste. The outlying areas of the retina are richly supplied with photo sensors called "rods" (which are highly sensitive to dim light), while the fovea is richly supplied with "cones," which are responsible for this region's great acuity of vision.

It is in the outer regions that the "automatic target-seeking control" information is gathered. City dwellers who survive traffic while crossing streets instinctively learn not to fix their gaze on any one small detail.

They're better off staring at nothing in particular so that their peripheral vision is free to warn them of some idiot bearing down on them with 300 horsepower. This kind of vision requires only that gross form and motion can be detected. High resolving power isn't necessary.

When making a close examination of something with fine detail, we need all available resolving power. How about the figure of 70 L/mm for the on-axis portion of the eye: is it at all comparable to a fine lens? Let's define our terms first. When I give the figure of 70 L/mm as the resolving power for the eye, I'm treating the eye as if it were a lens looking at a bar-target chart and forming the image on the retina.

How good is 70 L / mm?

The 70 L/mm is what I could theoretically see (with proper magnification) on the surface of the retina. This translates to the eye's ability to clearly distinguish a one-millimeter space sliced into 14 pieces and placed *at normal reading distance*.

If we have a 35-mm camera and want to be able to enlarge the negative it makes to 8x10 in., and on this print be able to fully exploit our eye's best ability to distinguish fine detail, the finished print will have to contain details of about 7 L/mm (remember that in lens-resolving-power jargon, as applied to photos, a "line" is taken to mean a line-and-a-space). This boils down to the negative's having detail of at least 56 lines/mm on it.

NASA studies reveal that with average photo-sensitive materials, a lens's resolving power is cut in half. So, if we apply this factor in our example, the lens under consideration will have to be capable of rendering over 100 L/mm at a usable contrast level. This is a rather tall order.

While many lenses have this capability, only the very best ones can deliver this kind of performance over any sizeable portion of their field. As a final crusher to anyone comparing eye and camera to the disadvantage of the eye, consider what optical instrument we use when judging the camera lens's final product.

We use our eye's marvelous ability to detect tonal quality, and rendition of fine detail. And, most important, (something that only the combination of eye, brain, and emotions can do) we decide if we *like* the picture. ✪

If you are interested in exploring some of the connections between science and humanity's other creative activities, look through this bibliography.

19

Science, Technology, and the Arts: A Reference Bibliography for Students

William Davenport

I. INTRODUCTION

■ The following annotated bibliography is an abridged and condensed rearrangement of items from "Resource Letter TLA-1 on Technology, Literature, and Art since World War II" (American Journal of Physics *38,* No. 4, April 1970) and "Resource Letter TLA-2 on Technology, Literature, and the Arts, Contemporary" (American Journal of Physics, forthcoming). Selected primarily for students, it concentrates on journals and books most likely to be generally available to them. (Other relevant resource letters include "Science and Literature," by Marjorie Nicolson in American Journal of Physics *33,* 175, 1965; and "Collateral Reading for Physics Courses" by Bork and Arons, American Journal of Physics *35,* 171, 1967.)

■ The items below are suggestions, not prescriptions, meant to widen perceptions and tempt readers to go further on their own. Such exploration might include the annual bibliographies in the journals *Technology and Culture* or *Isis,* and collections like *Science for Society: A Bibliography,* compiled by John A. Moore.

■ The rationale for providing this list involves the following presumptions: Our century has already seen the stereotype of the isolated "pure" scientist fade, in many instances, before a new image of a human being whose work is often, if not now inevitably, related to social or political issues. We are now also beginning to see that a complete overview of contemporary science and technology brings in the interplay between them and the arts, involving matters of values and choices: Is "Switched-On Bach" musically sound and defensible? Is the sculptor vanishing in a mass of electronic gadgets and laser beams? To what extent have the Machine and the Bomb affected modern literature?

■ This is not to say that specialists and specialization are outdated, or that all students must be Renaissance men and women. But just as it has become apparent that the first mark of a professional, as Lynn White tells us, is knowledge of the history of his or her craft, so is it fast becoming clear that the *complete* physicist, chemist, mathematician, or engineer will be a better person *and* professional for realizing, as John Donne said, that "no man is an island," that some small corner of educational progress must include such topics as physics and musical tone; the humanistic implications of biochemistry; the aesthetics of mathematics; and the social responsibility of the engineer.

■ Students who examine some of the following materials will surely find exciting possibilities for projects and papers, inspiration for creative work, stimulus for personal intellectual activity, and enjoyable reading in the bargain.

II. BIBLIOGRAPHY

1. "Art and the Corporation," David Antin. *Art News 70,* No. 5, 22 (September, 1971). The author, with a book on art and technology forthcoming, makes the point that the

artist views science as trying to understand reality and technology as trying to manipulate it. The need for technological art was seen by such architects as Charles Ashbee, who stated, "Modern civilization rests on machinery, and no system for the endowment, or the encouragement, or the teaching of art, can be sound that does not recognize this."

2. *Poetics of Space.* Gaston Bachelard. (Orion Press, New York, 1964). A physicist-philosopher justifies poetry as an answer to technology and formulas. In a provocative discussion of the "spaceness" of cellars, attics, and closets and of their relative effects on us, of which we are generally unaware, the author makes us see the familiar in a new light. He offers stimulating contrasts with common notions of space in physics and in the public mind, as influenced by Apollo missions.

3. *Science and Technology in Art Today.* Jonathan Benthall. (Praeger, N. Y., 1972). In this modestly priced, well illustrated paperback, Benthall traces the ups and downs of the science-technology-art relationship in modern times; his book is a primer of sorts. Pointing out that virtually all art uses some form of technology, the author feels that those who remain aloof simply prefer technologies already "absorbed into traditional art"; not many using the new media have advanced significantly – for that matter, there isn't much good art in any medium in the newer neighborhoods.

4. "Creativity, Poetic Language, and the Computer," Marie Boroff. *Yale Review 60,* 481 (June, 1971). With grace, humor, sanity, and balance this Yale poet and English professor used a grant to tackle the computer, learning its language and processes from the ground up. Boroff finds computer poetry "startlingly and unpredictably effective," with good random lines and stimulus for "live" working ideas. However, she concludes, that to be really creative a computer would have to initiate, recognize saliency in verbal expression, make comparative judgments among alternative wordings. Admitting technological possibilities, the author notes that only humans can experience life, death, humor, fear, anger, sex, etc. – the stuff of existence. Even if ultimately a machine can experience and artfully express itself, "the value of that art for human beings must be assessed by human beings. Such assessment is the domain of the humanist."

5. "Science as a Humanistic Discipline," J. Bronowski. *Bull. Atomic Scientists 24,* No. 8, 33 (1968). The author of *Science and Human Values* here covers the history of humanism, values, choice, and the human being as a unique creature. It is the duty of science to transmit this sense of uniqueness, to teach the world that people are guided by self-created values and thus comfort it for loss of absolute purpose.

6. *Beyond Modern Sculpture: Effects of Science & Technology on the Sculpture of this Century.* Jack Burnham. (George Braziller Inc., N. Y. 1969). "Today's sculpture is preparing man for his replacement by information-processing energy." Burnham sees an argument for a mechanistic teleological interpretation of life in which culture, including art, becomes a vehicle for qualitative changes in man's biological status. [See review by Charlotte Willard in *Saturday Rev. 52,* No. 2, 19 (1969).]

7. "The Mythos of the Electronic Revolution," James W. Carey and John J. Quirk. *American Scholar 39,* No. 2, 219; No. 3, 395 (1970). A two-part article which criticizes literary neo-Luddite activity, but also notes that "electronics is neither the arrival of Apocalypse nor the dispensation of grace." Encourages positive promotion of the values of the arts in place of negativistic attitudes toward technology.

8. "The Computer and the Poet," Norman Cousins. *Saturday Rev. 49,* No. 30, 42 (23 July 1966). Suggests editorially (and movingly) that poets and programmers should get together to "see a larger panorama of possibilities than technology alone may inspire," and warns against the "tendency to mistake data for wisdom."

9. *Engineering: Its Role and Function in Human Society.* William H. Davenport and Daniel Rosenthal, Eds. (Pergamon Press, Inc., New York, 1967). An anthology with four sections on the viewpoint of the humanist, the attitudes of the engineer, human and machine, and technology and the future. Many of the writers in this bibliography are represented in an effort to present historical and contemporary perspectives on technology and society.

10. "Art and Technology – The New Combine," Douglas M. Davis. *Art in Amer. 56,* 28 (Jan.- Feb. 1968). Notes a new enthusiasm among many modern artists because of the forms, effects, and materials made possible by the new technology. Envisions full partnership between artist and machine in the creative process.

11. "The Artist and the Computer," Douglas Davis. *Newsweek 78,* No. 11, 78 (Sept. 13, 1971). Theorizes that there are now no images which people cannot make, especially with a reserve store locked away in electronic circuits.

12. *So Human an Animal.* René Dubos. (Charles Scribner's & Sons, N. Y., 1968). Dubos, a prominent microbiologist, won a Pulitzer Prize for his work, and it deserves wide reading. Motivated by humanistic impulses, writing now like a philospher and again like a poet, he discusses dehumanization under technological advance. People can adjust, Dubos says – at a price. But first they must understand themselves as creatures of heredity and environment and then learn the science of life, not merely science.

13. *The Theatre of the Absurd.* Martin Esslin. (Anchor Books – Doubleday and Co., Inc., Garden City, N.Y., 1961). The drama director for the British Broadcasting Company explains the work of Beckett, Ionesco, Albee, and others as a reaction to loss of values, reason, and control in an age of totalitarianism and of that technological development, the Bomb.

14. *Engineering and the Liberal Arts.* Samuel C. Florman. (McGraw-Hill Book Co., New York, 1968). The subtitle tells the story: *A technologist's Guide to History, Literature, Philosophy, Art, and Music.* Explores the relationships between technology and the liberal arts – historical, aesthetic, functional. Useful reading lists are included.

15. *The Creative Process.* Brewster Ghiselin, Ed. (University of California Press, Berkeley, 1952; Mentor Books, The New American Library, Inc., New York, paperback, 1961). Mathematicians, musicians, painters, and poets, in a symposium on the personal experience of creativity. Of use to those interested in the interplay between science and art.

16. *The Poet and the Machine.* Paul Ginestier. Martin B. Friedman, Transl. (University of North Carolina Press, Chapel Hill, 1961; College and University Press, New Haven, Conn., paperback, 1964). Considers through analysis of generous examples from modern and contemporary poetry the effect of the machine on subject matter, form, and attitude. An original approach to the value, meaning, and influence, as the author puts it, of the poetry of our technology-oriented era.

17. "The Secret War Between Science and Poetry," Robert Graves. *New Scientist 52,* No. 772, 34 (2 Dec. 1971). "The dean of English poets" finds

that "technology produces millions of identical and spiritually dead objects" and that modern science "lacks a unified conscience." Fellow English poet Roy Fuller, however, ("The Osmotic Sap," *Times* (London) *Literary Supplement,* No. *3611,* 559, May 14, 1971) believes that "a blind or neutral attitude to science tends to insulate the poet from the spirit of the age," leading to sentimentalism.

18. "Automation and Imagination," Jacquetta Hawkes. *Harper's 231,* 92 (Oct. 1965.) A prominent archaeologist fears the loss of human imagination under years of technical training. While the technological revolution sweeps on toward a total efficiency of means, she says, we must control the ends and not forget the significance of the individual.

19. *The Future as Nightmare.* Mark R. Hillegas. (Oxford University Press, New York, 1967). A study that begins with Wells and ends with recent science fiction by Ray Bradbury, Kurt Vonnegut, and Walter Miller, Jr. The latter three are worried about the mindless life of modern humans with radio, TV, and high-speed travel; the need to learn nothing more than how to press buttons; the machine's robbing us of the pleasure of working with our hands, leaving us nothing useful to do, and lately making decisions for us; and, of course, the possibility of a nuclear holocaust.

20. "Computer Music," Lejaren A. Hiller, Jr. *Scientific American 201,* No. 6, 109 (Dec. 1959). Thesis: "Information theory makes possible the programming of a computer to compose music. The process by which the machine does so throws light on musical structure and on the methods of human composers." Among discussable points is the assertion that "acoustics reduces the definition of musical sound to a plot of waveform amplitude versus time."

21. *Science and Culture.* Gerald Holton, Ed. (Beacon Press, Boston, 1967). Almost all of the 15 essays in this outstanding collection appeared, several in different form, in the Winter 1965 issue of the quarterly journal *Daedalus.* Of particular relevance to the area of this bibliography are Herbert Marcuse's view of science as ultimately just technology; Gyorgy Kepes' criticism of modern artists for missing vital connections with technological reality; René Dubos' contention that technological applications are becoming increasingly alienated from human needs; and Oscar Handlin's documentation of the ambivalent attitude of modern society toward technology.

22. *Thematic Origins of Scientific Thought.* Gerald Holton. (Harvard University Press, Cambridge, 1973). In this fine collection of essays and addresses ranging from Kepler to Einstein, Chapter 10 ("On Trying to Understand Scientific Genius") engagingly discusses Einstein's playful combining of objects of imagination which were real to him – an exercise which recalls the poet Wallace Stevens' assertion that the world of the imagination is the true reality – and Chapter 15 shows relevance to our present theme in its title, "Physics and Culture: Criteria for Curriculum Design."

23. "The Fiction of Anti-Utopia," Irving Howe. *New Republic 146,* 13 (23 Apr. 1962). An analysis of the effect on modern fiction of the splitting apart of technique and values and the appearance of technical means to alter human nature, both events leading to the American dream's becoming a nightmare.

24. *The Divine Proportion: A Study in Mathematical Beauty.* H. E. Huntley. (Dover, N. Y., 1970). The section on "Surprise, Wonder, Curiosity" is particularly pertinent. Discussing ratios and sequences: "A *pretty* result? What constitutes the essence of the aesthetic appeal of this outcome of simple mathematics? It appears to be

compounded of a mixture of archaic emotions. There is surprise at the unexpected encounter; there is also both curiosity and wonder – making three of the flavors included in the idea of beauty." Elsewhere Hartley says that mathematics reads like poetry to a mathematician who is aesthetically minded.

25. *Literature and Science.* Aldous Huxley. (Harper & Row, Publishers, New York, 1963). A literary and highly literate attempt to show bridges between the two cultures. Technological know-how tempered by human understanding and respect for nature will dominate the scene for some time to come, but only if men and women of letters and scientists respect each other's contributions.

26. *The Sciences and the Humanities.* W. T. Jones. (University of California Press, Berkeley, 1965). A professor of philosophy discusses conflict and reconciliation between the two cultures, largely in terms of the nature of reality and the need to understand each other's language.

27. *New Landscape in Science and Art.* Gyorgy Kepes. (Paul Theobald, Chicago, 1967). Like the earlier *Vision in Motion* by L. Moholy-Nagy (Paul Theobald, Chicago, 1947), this work will make the reader see more, better, and differently. Essays and comments by Gabo, Giedion, Gropius, Rossi, Wiener, and others plus lavish illustration assist Kepes, author of the influential *Language of Vision* and head of the program on advanced visual design at the Massachusetts Institute of Technology, to discuss morphology in art and science, form in engineering, esthetic motivation in science – in short, to demonstrate that science and its applications belong to the humanities.

28. *The Scientist vs. the Humanist.* George Levine and Owen Thomas, Eds. (W. W. Norton, New York, 1963). Among the most relevant items are I. I. Rabi's "Scientist and Humanist"; Oppenheimer's "The Tree of Knowledge"; Howard Mumford Jones's "The Humanities and the Common Reader" (which treats technological jargon); and P. W. Bridgman's "Quo Vadis."

29. "The New Poetry," Frank MacShane. *Amer. Scholar 37,* 642 (Autumn, 1968). Frequently, the modern poet writes of confrontation of humanity and machine. The poet is both attracted and repelled by technological change, which both benefits and blights.

30. *The Machine in the Garden: Technology and the Pastoral Ideal in America.* Leo Marx. (Oxford University Press, New York, 1964; Galaxy, Oxford Univ. Press, New York, paperback, 1967). One of the three most significant contemporary works on the interplay of literature and technology [along with Sussman (45) and Sypher (47)], this study concentrates on 19th-century American authors and their ambivalent reactions to the sudden appearance of the machine on the landscape. Whitman, Emerson, Thoreau, Hawthorne, Melville, and others reveal, under Marx's scrutiny, the meaning inherent in productivity and power. Whitman assimilated the machine, Emerson welcomed it but disliked ugly mills, Thoreau respected tools but hated the noise and smoke, Hawthorne and Melville noted humanity's growing alienation with the green fields gone, Henry Adams set the theme for the "ancient war between the kingdom of love and the kingdom of power. . .waged endlessly in American writing ever since." The domination of the machine has divested of meaning the older notions of beauty and order, says Marx, leaving the American hero dead, alienated, or no hero at all. Aptly used quotations, chronological order, and clarity of perspective and statement (with which not all may agree) make this a "must" for basic reading in this special category. Furthermore, there are links to Frost, Hemingway, Faulkner, and other modern writers.

31. "Science and Literature," P. B. Medawar. *Encounter 32,* No. 1, 15 (January, 1969). A frequently published British scientist finds holes in the literary opponent's game plan: a suspect claim to deep insight, a use of imagination without self-criticism, and an emphasis on too-often obscure style.

32. *The Science of Art.* R. E. Mueller. (John Day. N.Y., 1967). A veritable textbook on the subject which discusses technology as a force in art, cybernetics and art, and the meaning of art for science, among other topics. Sub-topics include new media, materials, revelations of nature, devices and tools, processes, and knowledge of human functioning.

33. *The Myth of the Machine.* Lewis Mumford. (Harcourt, Brace & World, Inc., New York, 1967). Important historical study of human cultural development, that shows a major shift of emphasis from human being to machine, questions our commitment to technical progress, and warns against the down-playing of literature and fine arts so vital to complete life experience. See also his earlier *Art and Technics* (Columbia University Press, New York, 1952), and *Technics and Civilization.*

34. "Design, Technology, and the Pursuit of Ugliness," George Nelson. *Saturday Review 54,* No. 40, 22 (Oct. 2, 1971). Technology as an extension of tools originally brought blessings, but now, a blind Moloch under no controls, it overrides "all needs of the human spirit, all traditions, custom, languages, races, ideologies." This discussion of design, mostly industrial, condemns us for junkpiles, roadside strips, billboards – which are our portraits. Technology plus design, a bridge between technology and humanity, can clean up the mess.

35. "Speculative Equations: Poems, Poets, Computer," Howard Nemerov. *American Scholar 36,* No. 3, 394 (Summer, 1967). Sometime Consultant in Poetry to the Library of Congress, Nemerov faces the issue of mechanical perfection vs. human, often flawed, work. If computer poetry eventually receives love and praise, he fears that this would mean "obeisance to its idol the machine" by the human mind, not intrinsic value in the poetry. (Compare Boroff [4]). He recalls Hannah Arendt's gloomy prognostication that the "modern age may end in the deadliest, most sterile passivity history has ever known."

36. *Aesthetics and Technology in Building.* Pier Luigi Nervi. (Harvard University Press, Cambridge, Mass., 1965). "Nervi's thesis is that good architecture is a synthesis of technology and art," according to an expert review by Carl W. Condit, in *Technology and Culture 7,* No. 3, 432 (Summer, 1966), which we also recommend.

37. "Notes on the Future of an Esthetic," Carter Ratcliff. *Art International 16,* No. 10, 81 (December, 1972). Feels that attempts to "esthetize" bits of the world by calling on science and technology (as do Gyorgy Kepes and other workers in advanced visual design) produce results "in pathetic disproportion to the grandiose forecasts." This occasionally rude attack on such enthusiasts as Douglas Davis (11) relies on the thesis that their work projects only dream worlds, that artists using computers are not really doing anything new, and that lack of taste makes their creations acceptable mostly "to the freaky side of the new humanism." Biased, but provocative.

38. "Art and Life," Sir Herbert Read. *Saturday Evening Post 232,* 34 (26 Sept. 1959). Modern violence and restlessness stem in great part from a neurosis in humans who have stopped making things by hand. Production, not grace or beauty, is the guiding force of technological civilization. Recommends the activity of art to re-

lease creative, rather than destructive, forces.

39. *Cybernetic Serendipity: The Computer and the Arts.* Jasia Reichardt, ed. (Praeger, N. Y., 1969). A special issue of *Studio International* in book form showing how the computer can extend creativity; the title is that of an exhibition at the Institute of Contemporary Arts, London, 1968. The volume serves as a useful introduction to the field, containing 100 illustrated pages of specialist essays on computer music, dance, poetry, painting, graphics, and film. (See also Ms. Reichardt's *Cybernetics, Art and Ideas,* 1972).

40. "Analysis of Musical Instrument Tones," J-C Risset and M. V. Mathews. *Physics Today 22,* No. 2, 23 (February, 1969). Thesis: "With computers we can not only analyze the sound of a musical instrument but also build up a synthesized copy of the sound. Comparison of real and synthetic tones tells which are the important parameters that lead to recognition of timbre."

41. "Art and Science: Analysis and Communication of Biological Form," Philip C. Ritterbush. *Science 162,* 1307 (Dec. 13, 1968). In an exposition of the influence of biological concepts of form on modern artists, the author notes that "Paul Klee's careful studies of the architectural principles underlying plant form and his interest in analogies between music and rhythms of growth played a very large role in his artistic development and are reflected in much of his work."

42. "Is Technology Taking Over?" Charles E. Silberman. *Fortune 73,* No. 2. 112 (February, 1966). A brisk discussion of familiar topics: art as defense; technology as an end; dehumanization and destruction; mass idleness; meaninglessness. Technology may not determine our destiny, but it surely affects it and, in enlarging choice, creates new dangers. As the author points out, however, borrowing from Whitehead, the great ages have been the dangerous and disturbed ones.

43. "Science as Art." Beatrice Stegman. *Bulletin of the Atomic Scientists 25,* No. 4, 27 (April, 1969). Philosophical discussion of the aesthetics of science, particularly the resemblances between acts of creativity in science and in art. Suggests analysis of a scientific theory be done as one would analyze a poem, via elements, form, central image, since "the elements of a scientific theory are human constructions rather than physical things."

44. "A Future Literacy," George Steiner. *Atlantic 228,* No. 2, 41 (Aug. 1971). Treats other literacies – music, mathematics, biomedical engineering, electronics – boosts science, criticizes humanists for looking to the past, and flatly states that indifference to current technological phenomena is "to opt out of reason." Steiner finds science rich in metaphor, myth, and laughter, citing the "deep elegance" and "quickness and merriment of the spirit" in the Banach-Tarski theorem of the sun and a pea, and the Penrose theory in cosmology. Points to Musil, Nabokov, Valery, Borges and others whose writing owes much to science training. Challenging and fresh.

45. *Victorians and the Machine: The Literary Response to Technology.* Herbert L. Sussman. (Harvard University Press, Cambridge, Mass., 1968). Does for English writers of the 19th century what Leo Marx (30) did for the Americans, with substantially similar conclusions. Writers stressed are Carlyle, Butler, Dickens, Wells, Ruskin, Kipling, and Morris, whose thought and art centered on the effects of mechanization on the intellectual and aesthetic life of their day. A major study of the machine as image, symbol, servant, and god –

something feared and respected, ugly and beautiful, functional and destructive – as seen by the significant Victorian literary figures, this work also helps explain the thrust of much contemporary writing.

46. "The Poet as Anti-Specialist," May Swenson. *Saturday Review 48,* No. 5 16 (40 Jan. 1965). A poet tells how her art can show us how to stay human in a technologized age, compares and contrasts the languages of science and poetry, wonders about the denerving and desensualizing of astronauts "trained to become a piece of equipment."

47. *Literature and Technology.* Wylie Sypher. (Random House, Inc., N.Y., 1968). The best, almost the only, general study of its kind, to be required reading along with Leo Marx [30] and Herbert Sussman [45]. Develops the thesis that technology dreads waste and, being concerned with economy and precaution, lives by an ethic of thrift. The humanities, including art, exist on the notion that every full life includes waste – of virtue, intention, thinking, and work. The thesis is illustrated by examples from literature and art. Although, historically, technology minimizes individual participation and resultant pleasure, Sypher concedes that lately "technology has been touched by the joy of finding in its solutions the play of intellect that satisfies our need to invent."

48. "The Poet in the Machine Age," Peter Viereck. *J. History Ideas 10,* No. 1, 88 (Jan., 1949). A classification of antimachine poets, who for esthetic, pious, instinctual, or timid reasons have backed away, and promachine poets, who, as materialists, cultists, or adapters, have used the new gadgets to advantage. We must try to unite the world of machinery and the world of the spirit, or "our road to hell will be paved with good inventions."

49. *Behind Appearance.* C. H. Waddington. (MIT Press, Cambridge, 1970). This "study of relations between painting and the natural sciences in this century" is large, lavishly illustrated, and expensive. Its author, professor of animal genetics in the University of Edinburgh and author of *The Scientific Attitude,* traces the influence of modern scientific concepts of space, time, and uncertainty on the philosophy of modern art, particularly in such movements as Cubism, constructivism, Dada, and Surrealism, and the specific bearing of mathematics on the content and form of art works by Naum Gabo, Mondrian, and Max Bill. Though all will not agree with all of his conclusions *(e.g.,* that connections between painting and science are stronger than between painting and literature), Waddington has put together a fascinating and stimulating presentation for student and teacher alike.

50. *Reflections on Big Science.* Alvin Weinberg. (The MIT Press, Cambridge, Mass., 1967). The former director of Oak Ridge National Laboratory devotes his first chapter, "The Promise of Scientific Technology; The New Revolutions," to nuclear energy, cheap electricity, technology of information, the Bomb, and dealing with nuclear garbage. He calls upon the humanists to restore meaning and purpose to our lives.

51. *Flesh of Steel: Literature and the Machine in American Culture.* Thomas Reed West. (Vanderbilt University Press, Nashville, Tenn., 1967). A consideration of the writings of Sherwood Anderson, Dos Passos, Sandburg, Sinclair Lewis, Mumford, and Veblen. While conceding that most of them are antimachine most of the time, West preaches the positive virtues of the Machine: law, order, energy, discipline, which, at a price, produce a city like New York,

where artists and writers may live and work on their own terms.

52. "A Computer Art for the Video Picture Wall," John H. Whitney. *Art International 15,* No. 7, 35 (September, 1971). Praises the power of the computer to bring visual enlightenment to much "that was formerly abstruse mathematical data." Welcomes the challenge that the computer "can become the universal musical instrument" if we acquire a knowledge of psychoacoustics. Draws analogies between the effects of wonder caused by periodic aspects of the world of mathematics and those aroused by music. Describes using the computer as a kind of piano "to generate periodic visual action, with a mind to reveal harmonic, juxtaposed against enharmonic, phenomena." The article is enhanced by color illustrations of the art of this well-known maker of experimental films.

III. Postscript

■ Since most of the foregoing material is critical or expository, except for quoted illustration, readers may wish to make a start with firsthand creative literary pieces. Here are some suggestions available in various paperback editions or standard anthologies.

Plays

On the theme of machine replacing man, there are two early modern classics for background:

53. *R.U.R.* Karel Capek.
54. *The Adding Machine.* Elmer Rice.

Three British plays deal directly with the Bomb, and the fourth, the only one available in paper, alludes to it:

55. *The Tiger and the Horse.* Robert Bolt, In *Three Plays* (Mercury Books, London, 1963).
56. *The Offshore Island.* Marghanita Laski. (Cresset Press, London, 1959).
57. *Each His Own Wilderness.* Doris Lessing. In *New English Dramatists,* E. Martin Browne, Ed. (Penguin Plays, London).
58. *Look Back in Anger.* John Osborne.

Two recent plays dealing with physicists:

59. *The Physicists.* Friedrich Dürrenmatt.
60. *In the Matter of J. Robert Oppenheimer.* Heinar Kipphardt.

Fiction

A quartet of Utopian or anti-Utopian novels:

61. *Brave New World.* Aldous Huxley.
62. *Nineteen Eighty-Four,* George Orwell.
63. *Walden II.* B. F. Skinner.
64. *We.* E. Zamiatan.

A quartet of science fiction:

65. *Fahrenheit 451.* Ray Bradbury.
66. *Canticle for Leibowitz.* Walter Miller, Jr.
67. *Player Piano.* Kurt Vonnegut, Jr.
68. *Cat's Cradle.* Kurt Vonnegut, Jr.

A trio of short stories:

69. "By the Waters of Babylon," Stephen V. Benet.
70. "The Portable Phonograph," Walter Van Tilburg Clark.
71. "The Machine Stops," E. M. Forster.

Poetry

See Ginestier above. Also:

72. *The Modern Poets.* John M. Brinnin and Bill Read, Eds. (McGraw-Hill Book Co., New York, 1963). Contains poems by Hoffman, Lowell, Moss, and Nemerov pertaining to the Bomb.
73. *Inside Outer Space: Poems.* Robert vas Dias, Ed. (Doubleday Anchor, 1970).
74. *Weep Before God.* John Wain. (The Macmillan Company, London, 1961). Sections VI-VII consider the Machine.

Authors

Jacob Bronowski, creator of and performer in the television series "The Ascent of Man", received his PhD from Cambridge University in 1933. At his death he was a Fellow of the Salk Institute of Biological Studies in California. Previously he had served as Director of General Process Development for the National Coal Board of England, as the Science Deputy to the British Chiefs of Staff, and as head of the Projects Division of UNESCO. He wrote extensively on the nature of science and its social consequences.

William H. Davenport, born in Connecticut in 1908, has been professor of English at various colleges, most recently at the Harvey Mudd College in Claremont, California. He studied at Dartmouth College, Tufts University, and Yale. His concerns for the role of science in society are illustrated by his co-authorship in 1967 of the book "Engineering: Its Role in Society".

Engineering Concepts Curriculum Projects developed a course, ***"The Man-Made World"***, for study in schools and colleges. The staff included numerous well known scientists and engineers concerned about the role of engineering and technology in the world.

John M. Fowler was born in Alabama in 1926 and studied at Earlham College, the University of Oklahoma, and the Johns Hopkins University. His scientific studies are in nuclear physics. In addition, his pedagogical interests have led him to be prominent in the instructional programs sponsored by the American Association of Physics Teachers. He is professor of physics at the University of Maryland.

Werner Heisenberg received the Nobel Prize for his pioneering contributions to the development of quantum mechanics. He was born in Würzburg, Germany in 1901 and studied at the University of Munich and Göttingen. After a professorship at the University of Leipzig, he was Director of the Kaiser Wilhelm Institute for Physics in Berlin, then Director of the Max Planck Institute for Physics in Göttingen, and later of the Max Planck Institute in Munich.

Donald F. Holcomb and **Philip Morrison** are professors of physics; Holcomb at Cornell University and Morrison at the Massachusetts Institute of Technology. Holcomb's studies have dealt with solid state physics. Morrison is concerned with the application of physics to astronomy and also with the interrelation of science and society.

Dorothy Michelson Livingston, the daughter of Albert Michelson, America's first Nobel Prize winner, has written a documentary — a biography of her father and his many scientific studies. The book, entitled ***The Master of Light*** is the source from which the essay reproduced in this Reader was drawn.

The Physics Survey Committee of the National Research Council and the **National Academy of Science** functioned under the leadership of the physicist, D. Bromley of Yale University. The report reappraises the nature of physics and its role in society and in education.

Vincent J. Schaefer is the discoverer and developer of methods of seeding clouds to produce rain. Born in Schenectady, New York in 1908, Schaefer graduated from Union College and later from the Davey College of Tree Surgeons. At the General Electric Laboratories he began as an assistant to Irving Langmuir.

Dietrich Schroeer is a physicist at the University of North Carolina, Chapel Hill. He was born in Berlin in 1938 and studied at Ohio State University. His range of interests is illustrated by his award of a Humanities fellowship in 1972-73.

Walter Sullivan, science writer for the *New York Times,* was born in New York City in 1918. After graduating from Yale University, he joined the staff of the *Times* and served as correspondent in the Far East, in Germany, and at the United Nations. For his journalistic writing about science he has received numerous prizes and awards.

Masao Watanabe is professor of the history of science at the University of Tokyo, Japan. He is known for his studies in the history of science, and also for his involvement in social and educational work.

Steven Weinberg, born in 1933, is Higgins Professor of Physics at Harvard University and Senior Scientist at the Smithsonian Astrophysical Observatory. He studied at Cornell University, the Copenhagen Institute of Theoretical Physics, and Princeton University. He has been professor of physics at the University of California and the Massachusetts Institute of Technology. His researches deal with elementary particles and cosmology. Also he has served as consultant to the U.S. Arms Control and Disarmament Agency.

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