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ACOUSTICS OF AUDITORIUMS

BY

F. R. WATSON

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Fig. 1. Auditorium, University of Illinois.

ACOUSTICS OF AUDITORIUMS

An Investigation of the Acoustical Properties of the Auditorium at the University of Illinois.

I. Introduction.

Much concern has arisen in late years in the minds of architects because of the faulty acoustics that exist in many auditoriums. The prevalence of echoes and reverberations with the consequent difficulty in hearing and understanding on the part of the auditor defeats the purpose of the auditorium and diminishes its value.

The Auditorium at the University of Illinois presents such a case. The building is shaped nearly like a hemisphere, with several large arches and recesses to break up the regularity of its inner surface. The original plans of the architect were curtailed because of insufficient money appropriated for the construction. The interior of the hall, therefore, was built absolutely plain with almost no breaking up of the large, smooth wall surfaces; and, at first, there were no furnishings except the seats and the cocoa matting in the aisles. The acoustical properties proved to be very unsatisfactory. A reverberation or undue prolongation of the sound existed, and in addition, because of the large size of the room and the form and position of the walls, echoes were set up.

If an observer stood on the platform and clapped his hands, a veritable chaos of sound resulted. Echoes were heard from every direction and reverberations continued for a number of seconds before all was still again. Speakers found their utterances thrown back at them, and auditors all over the house experienced difficulty in understanding what was said. On one occasion the University band played a piece which featured a xylophone solo with accompaniment by the other instruments. It so happened that the leader heard the echo more strongly than the direct sound and beat time with it. Players near the xylophone kept time to the direct sound, while those farther away followed the echo. The confusion may well be imagined.

Thus it seemed that the Auditorium was doomed to be an acoustical horror; that speakers and singers would avoid it, and that auditors would attend entertainments in it only under protest. But the apparent misfortune was in one way a benefit since it provided an opportunity to

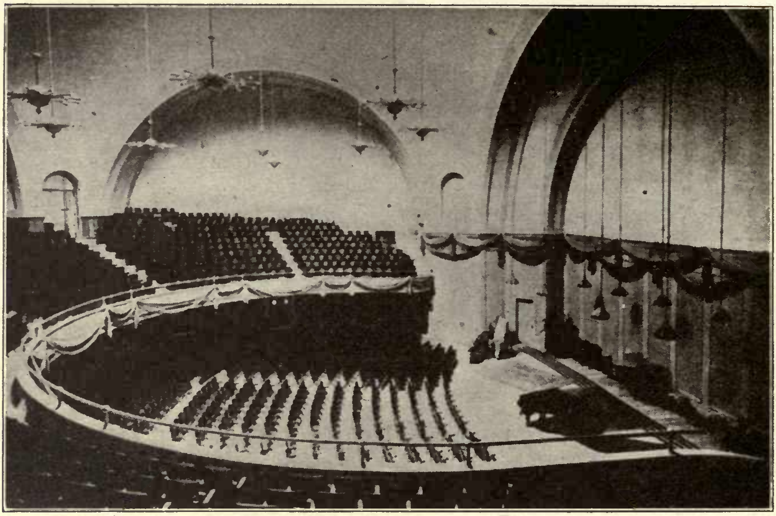

FIG. 2. PHOTOGRAPH OF INTERIOR. VIEW OF STAGE.

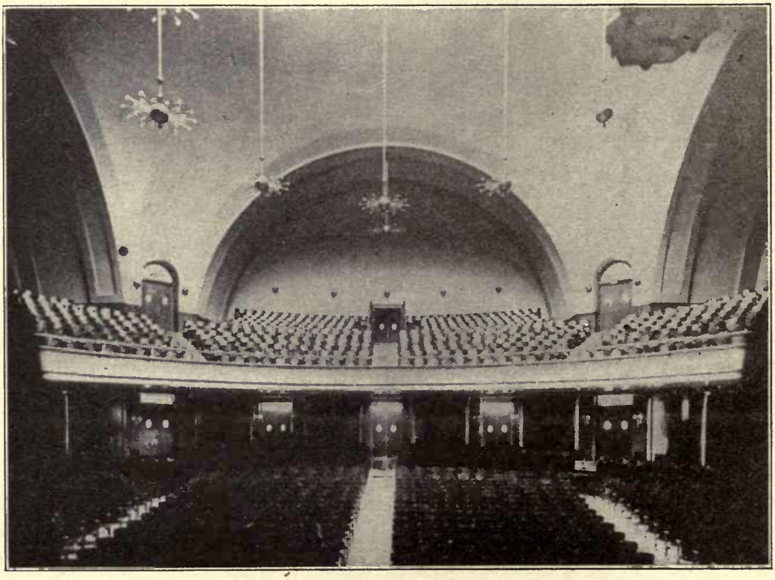

FIG. 3. PHOTOGRAPH OF INTERIOR. VIEW TOWARD BALCONY.

study defective acoustics under exceptionally good conditions and led to conclusions that not only allowed the Auditorium to be improved but also indicate some of the pitfalls to be avoided in future construction of other halls.

An investigation of the acoustical properties of the Auditorium was begun in 1908 and has continued for six years. It was decided at the outset not to use "cut and try" methods of cure, but to attack the problem systematically so that general principles could be found, if possible, that would apply not only to the case being investigated but to auditoriums in general. This plan of procedure delayed the solution of the problem, since it became necessary to study the theory of sound and carry out laboratory investigations at the same time that the complex conditions in the Auditorium were being considered. The author spent one year of the six abroad studying the theory of acoustics and inspecting various auditoriums.

The main echoes in the Auditorium were located by means of a new method for tracing the path of sound, the time of reverberation was determined by Sabine's method, and a general diagnosis of the acoustical defects was made. Hangings and curtains were installed in accordance with the results of the study so that finally the acoustical properties were improved.

Acknowledgment.—The author desires to express his great appreciation of the advice and encouragement given by President E. J. James, Supervising Architect J. M. White, and Professor A. P. Carman of the Physics Department. He desires also to acknowledge the material assistance cheerfully rendered by the workmen at the University, which contributed in no small degree to the successful solution of the problem.

II. Behavior of Sound Waves in a Room.

When a speaker addresses an audience, the sounds he utters proceed in ever widening spherical waves until they strike the boundaries of the room. Here the sound is partly reflected, partly transmitted, and the rest absorbed. The amounts of reflection, absorption and transmission depend on the character of the walls. A hard, smooth wall reflects most of the sound so that but little is transmitted or absorbed. In the case of a porous wall or a yielding wall, the absorption and transmission are greater, and the reflection is less. After striking a number of reflecting surfaces, the energy is used up and the sound dies out.

The reflection of sound produces certain advantages and disadvantages for the acoustics. When it is considered that sound travels about 1100 feet a second it may be seen that a room of ordinary size is almost immediately filled with sound because of the many reflections. In a room 40 feet square, for instance, the number of reflections per second between opposite walls is $1100 \div 40$, or approximately 27. The number is really greater than this, since the sound that goes into the corners is reflected much more frequently than out in the middle where the distances between walls are greater. The result is that the sound mixes thoroughly in all parts of the room so as to give the same average intensity; that is, the sound is of the same average *loudness* for all auditors, even for those in the remotest corners.

Though the reflection of sound has the advantage of fulfilling the conditions for loudness, it introduces at the same time possibilities for setting up defective acoustics. For instance, when the walls of the room are hard and smooth very little energy is lost at each impact of the sound and many reflections take place before it finally dies out. This slow decadence of the sound, or *reverberation* as it is called, is the most common defect in auditoriums.

If a speaker talks in such a hall the auditors have difficulty in understanding. Each sound, instead of dying out quickly, persists for some time so that the succeeding words blend with their predecessors and set up a mixture of sounds which produces confusion. The cure for the trouble is brought about by the introduction of materials such as carpets, tapestries, and the like, which act as absorbers of sound and reduce the time of reverberation.

When music is played in an auditorium with a prolonged reverberation, the tones following one another blend and produce the same effect as that of a piano when played with the loud pedal in use. A reverberation is more advantageous for music than for speech, since the prolongation and blending of the musical tones is desired, but the mixing of the words in a speech is a distinct disadvantage. When curing this defect for halls used for both music and speaking, a middle course must be steered, so that the reverberation is made somewhat long for speaking and somewhat short for music, yet fairly satisfactory for both.

Going back to the consideration of the reflection of sound, it is found that another defect may be produced, namely, an *echo*. This is the case when a wall at some distance reflects the sound to the position of the auditor. He hears the sound first from the speaker, then later by reflection from the wall. The time interval between the direct and reflected sound must be great enough to allow two distinct impressions to be made. This time is about 1/15 of a second, but varies with the acuteness of the observer. The farther off the wall is, the greater is the time interval and the more pronounced is the echo. If the wall is not very distant, the time interval is too short to allow two distinct impressions to be made, and the effect on the auditor is then much the same as if his neighbor at his side speaks the words of the discourse in his ear at the same time that he gets them directly from the speaker. In case the reflecting wall is curved so as to focus the sound the echoes are much more pronounced. A curved wall wherever it may be placed in an auditorum is thus always a menace to good acoustics.

There are other actions of the sound that may result in acoustical defects. The phenomena of *resonance,* for instance, may cause trouble. Suppose that the waves of sound impinge on an elastic wall, not too rigid. If these waves are timed right they set the wall in vibration in the same way that the bell ringer causes a bell to ring by a succession of properly timed pulls on the bell rope. The wall of the room will then vibrate under the action of this sound with which it is in tune and will reinforce it. Now suppose a band is playing in a room. Certain tones are reinforced, while the others are not affected. The original sound is then distorted. The action is the same on the voice of the speaker. The sounds he utters are complex and as they reach the walls certain components are reinforced and the quality of the sound is changed. This action of resonance may also be caused by the air in a room. Each room has a definite pitch to which it responds, the smaller the volume of the room the higher being the pitch. A large auditorium would respond to the very low pitch of the bass drum. In small rooms and alcoves the response is made to higher pitched tones, as may be observed by singing the different notes of the scale until a resonance is obtained.

Another action of sound causes the *interference* of waves. Thus the reflected waves may meet the oncoming ones and set up concentrations of sound in certain positions and a dearth of sound in others.

Summing up, it is seen that the effects of sound which may exist in a room are *loudness, reverberation, echoes, resonance,* and *interference,* and that the most common defects are reverberation and echoes. We now turn to the discussion of the methods of cure.

III. Methods of Improving Faulty Acoustics.

A. Reverberation and its Cure.

Everyone has doubtless observed that the hollow reverberations in an empty house disappear when the house is furnished. So, in an auditorium, the reverberation is lessened when curtains, tapestries, and the like are installed in sufficient numbers. The reason for this action is found when we inquire what ultimately becomes of the sound.

Sound is a form of energy and energy can not be destroyed. When it finally dies out, the sound must be changed to some other form of energy. In the case of the walls of a room, for instance, it has been shown in a preceding paragraph that the sound may be changed into mechanical energy in setting these walls in vibration. Again, some of the sound may pass out through open windows and thus disappear. The rest of the sound, according to Lord Rayleigh, is transformed by friction into heat. Thus[1] a high pitched sound, such as a hiss, before it travels any great distance is killed out by the friction of the air. Lower pitched sounds, on reaching a wall, set up a friction in the process of reflection between the air particles and the wall so that some of the energy is converted into heat.[2] The amount of sound energy thus lost is small if the walls are hard and smooth. The case is much different, however, if the walls are rough and porous, since it appears that the friction in the pores dissipates the sound energy into heat. In this connection, Lamb[3] writes: "In a sufficiently narrow tube the waves are rapidly stifled, the mechanical energy lost being of course converted into heat. * * * * When a sound wave impinges on a slab which is permeated by a large number of very minute channels, part of the energy is lost, so far as the sound is concerned, by dissipation within these channels in the way just explained. The interstices in hangings and carpets act in a similar manner, and it is to this cause that the effect of such appliances in deadening echoes in a room is to be ascribed, a certain proportion of the energy being lost at each reflection. It is to be observed that it is only through the action of true dissipative forces, such as viscosity and thermal conduction, that sound can die out in an enclosed space, no mere modifications of the waves by irregularities being of any avail."

It should be pointed out in this connection that any mechanical breaking up of the sound by relief work on the walls or by obstacles in the room will not primarily diminish the energy of the sound. These

1. "Theory of Sound," Vol. II, p. 316.
2. "Theory of Sound," Vol. II, § 351.
3. "Dynamical Theory of Sound," p. 196.

may break up the regular reflection and eliminate echoes, but the sound energy as such disappears only when friction is set up.

The following quotation from Rayleigh[1] emphasizes these conclusions: "In large spaces, bounded by non-porous walls, roof, and floor, and with few windows, a prolonged resonance seems inevitable. The mitigating influence of thick carpets in such cases is well known. The application of similar material to the walls and roof appears to offer the best chance of further improvement."

Experimental Work on Cure of Reverberation.—The most important experimental work in applying this principle of the absorbing power of carpets, curtains, etc., has been done by Professor Wallace C. Sabine of Harvard University.[2] In a set of interesting experiments lasting over a period of four years, he was able to deduce a general relation between t, the time of reverberation, V, the volume of the room, and a, the absorbing power of the different materials present. Thus:

$$t = 0.164\, V \div a \tag{1}$$

For good acoustical conditions, that is, for a short time of reverberation, the volume V should be small and the absorbing materials, represented by a, large. This is the case in a small room with plenty of curtains and rugs and furniture. If, however, the volume of the room is great, as in the case of an auditorium, and the amount of absorbing materials small, a troublesome reverberation will result.

Professor Sabine determined the absorbing powers of a number of different materials. Calling an open window a perfect absorber of sound, the results obtained may be written approximately as follows:

One square meter of open window space	1.000
One square meter of glass, plaster, or brick	.025
One square meter of heavy rugs, curtains, etc.	.25
One square meter of hair felt, 1 inch thick	.75
One square meter of audience	.96

These values, together with the formula, allow a calculation to be made in advance of construction for the time of reverberation. This pioneer work cleared the subject of architectural acoustics from the fog of mystery that hung over it and allowed the essential principles to be seen in the light of scientific experiment.

In a later investigation[3] Sabine showed that the reverberation depended also on the pitch of sound. As a concrete example, the high

1. "Theory of Sound," p. 333.
2. "Architectural Acoustics." A series of articles in the Engineering Record, 1900; also the American Architect, 1900.
3. "Architectural Acoustics," Proc. of Amer. Acad. of Arts and Sciences. Vol. 42, pp. 49-84, 1906.

notes of a violin might be less reverberant with a large audience than the lower tones of the bass viol, although both might have the same reverberation in the room with no audience. Again, the voice of a man with notes of low pitch might give satisfactory results in an auditorium while the voice of a woman with higher pitched notes would be unsatisfactory.

These considerations show that the acoustics in an auditorium vary with other factors than the volume of the room and the amount of absorbing material present. The audience may be large or small, the speaker's voice high or low, the entertainment a musical number or an address. The best arrangement for good acoustics is then a compromise where the average conditions are satisfied. The solution offered by Professor Sabine is such an average one, and has proved satisfactory in practice.

The problem of architectural acoustics has been attacked experimentally by other workers. Stewart[1] proposed a cure for the poor acoustical conditions in the Sibley Auditorium at Cornell University. His experiments confirmed the work of Sabine. Marage[2], after investigating the properties of six halls in Paris, approved Sabine's results and advocated a time of reverberation of from ½ to 1 second for the case of speech.

Formulae for Reverberation of Sound in a Room.—On the theoretical side, Sabine's formula has been developed by Franklin,[3] who obtained the relation $t = 0.1625\, V \div a$, an interesting confirmation, since Sabine's experimental value for the constant was 0.164.

A later development has been given by Jäger,[4] who assumes for a room whose dimensions are not greater than about 60 feet, that the sound, after filling the room, passes equally in all directions through any point, and that the average energy is the same in different parts of the room. By using the theory of probability and considering that a beam of sound in any direction may be likened to a particle with a definite velocity, he was able to deduce Sabine's formula and write down the factors that enter into the constants. Applying his results to the case of reflection of sound from a wall, he showed that sound would be reflected in greater volume when the mass of the wall was increased and

1. G. W. Stewart. "Architectural Acoustics," Sibley Journal of Engineering, May, 1903. Published by Cornell University, Ithaca, N. Y.
2. "Qualités acoustiques de certaines salles pour la voix parlée." Comptes Rendus, 142, 878, 1906.
3. W. S. Franklin. "Derivation of Equation of Decaying Sound in a Room and Definition of Open Window Equivalent of Absorbing Power." Physical Review, Vol. 16, pp. 372-374, 1903.
4. G. Jäger. "Zur Theorie des Nachhalls." Sitzungsberichte der Kaiserliche Akad. der Wissenschaften in Wien, Math-naturw. Klasse; Bd. CXX. Abt. 11 a. Mai, 1911.

the pitch of the sound made higher. He showed also that when sound impinges on a porous wall, more energy is absorbed when the pitch of the sound is high than when it is low, since the vibrations of the air are more frequent, and more friction is introduced in the interstices of the material.

B. ECHOES AND THEIR REMEDY.

An echo is set up by a reflecting wall. If an observer stands some distance from the front of a cliff and claps his hands, or shouts, he finds that the sound is returned to him from the cliff as an echo. So, in an auditorium, an auditor near the speaker gets the sound first directly from the speaker, then, an instant later, a strong repetition of the sound by reflection from a distant wall. This echo is more pronounced if the wall is curved and the auditor is at the point where the sound is focused.

To cure such an echo, two methods may be considered. One method consists in changing the form of the wall so that the reflected sound no longer sets up the echo. That is, either change the angle of the wall, so that the reflected sound is sent in a new direction where it may be absorbed or where it may reinforce the direct sound without producing any echoes, or else modify the surface of the wall by relief work or by panels of absorbing material, so that the strong reflected wave is broken up and the sound is scattered. The second method is to make the reflecting wall a "perfect" absorber, so that the incident sound is swallowed up and little or none reflected. These methods have been designated as "surgical" and "medicinal" respectively. Each method has its disadvantages. Changing the form of the walls in an auditorium is likely to do violence to the architectural design. On the other hand, there are no perfect absorbers, except open windows, and these can seldom be applied. The cure in each case is, then, a matter of study of the special conditions of the auditorium. Usually a combination of the surgical and the medicinal cures is adopted. For instance, coffering a wall so that panels of absorbing material may be introduced has been found to work well in bettering the acoustics, and also, in may cases, it fits in with the architectural features.

C. POPULAR CONCEPTION OF CURES.—USE OF WIRES AND SOUNDING BOARDS.

A few words should be written concerning the popular notion that wires and sounding boards are effective in curing faulty acoustics. Experiments and observations show that wires are of practically no benefit, and sounding boards can be used only in special cases. Wires stretched in a room scarcely affect the sound, since they present too small a surface to disturb the waves. They have much the same effect on sound waves that a fish line in the water has on water waves. The idea has, perhaps, grown into prominence because of the action of a piano in responding to the notes of a singer. The piano has every advantage over a wire in an auditorium. It has a large number of strings tuned to different pitches so that it responds to any note sung. It also has a sounding board that reinforces strongly the sound of the strings. Finally, the singer is usually near the piano. The wire in the auditorium responds to only one tone of the many likely to be present, it has no sounding board, and the singer is some distance away. But little effect, therefore, is to be expected.

The author has visited a number of halls where wires have been installed, and has yet to find a case where pronounced improvement has resulted.[1] Sabine[2] cites a case where five miles of wire were stretched in a hall without helping the acoustical conditions. It is curious that so erroneous a conception has grown up in the public mind with so little experimental basis to support it.

Sounding Boards.—Sounding boards or, more properly, reflecting boards, have value in special cases. Some experiments are described later where pronounced effects were obtained. The sounding board should be of special design to fit the conditions under which it is to be used.

Modeling New Auditoriums after Old Ones with Good Acoustics.—Another suggestion often made is for achitects to model auditoriums after those already built that have good acoustical properties. It does not follow that halls so modeled will be successful, since the materials used in construction are not the same year after year. For instance, a few years ago it was the usual custom to put lime plaster on wooden lath; now it is frequently the practice to put gypsum plaster on metal lath, which forms an entirely different kind of a surface. This latter arrangement makes hard, non-porous walls which absorb but little sound, and thus aggravate the reverberation. Further, a new hall usually is changed somewhat in form from the old one, to suit the ideas of the architect, and it is very likely that the changes will affect the acoustics.

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1. Science, Vol. 35, p. 833, 1912.
2. Arch. Quarterly of Harvard University, March, 1912.

D. THE EFFECT OF THE VENTILATION SYSTEM ON THE ACOUSTICS.

At first thought it might seem that the ventilation system in a room would affect the acoustical properties. The air is the medium that transmits the sound. It has been shown that the wind has an action in changing the direction of propagation of sound.[1] Sound is also reflected and refracted at the boundary of gases that differ in density and temperature.[2] It is found, however, that the effect of the usual ventilation currents on the acoustics in an auditorium is small. The temperature difference between the heated current and the air in the room is not great enough to affect the sound appreciably, and the motion of the current is too slow and over too short a distance to change the action of the sound to any marked extent.[3]

Under special circumstances, the heating and ventilating systems may prove disadvantageous.[4] A hot stove or a current of hot air in the center of the room will seriously disturb the action of sound. Any irregularity in the air currents so that sheets of cold and heated air fluctuate about the room will also modify the regular action of the sound and produce confusion. The object to be striven for is to keep the air in the room as homogeneous and steady as possible. Hot stoves, radiators, and currents of heated air should be kept near the walls and out of the center of the room. It is of some small advantage to have the ventilation current go in the same direction that the sound is to go, since a wind tends to carry the sound with it.

IV. The Investigation in the Auditorium at the University of Illinois.

A. PRELIMINARY WORK.

As already stated, a chaos of sound was set up when an observer in the Auditorium spoke or shouted or clapped his hands. Both echoes and reverberations were present and could be heard in all parts of the room, though the echoes seemed to be strongest on the stage and in the balcony. The prospects for bettering the acoustics were not very encouraging. Luckily, the cure for the reverberation was fairly simple, since Sabine's method gave a definite procedure that could be applied to this case. The cure for the echo, however, was yet to be found. It was first necessary to find out which walls set up the defect.

1. Osborne Reynolds. Proc. of Royal Soc., Vol. XXII, p. 531, 1874.
2. Joseph Henry, "Report of the Lighthouse Board of the United States for the year 1874."
   J. Tyndall, Phil. Trans., 1874.
3. Sabine, Engineering Record, Vol. 61, p. 779, 1910.
   Watson, Engineering Record, Vol. 67, p. 265, 1913.
4. Sabine and Watson. Ibid.

The attempt to locate echoes by generating a sound and listening with the ear met with only partial success. The ear is sensitive enough but becomes confused when many echoes are present, coming apparently from every direction, so that the evidence thus obtained is not altogether conclusive. It became apparent that the successful solution lay in fixing the attention on the sound going in a particular direction and finding out where it went after reflection; then tracing out the path in another particular direction, and so on until the evidence obtained gave some hint of the general action of the sound.

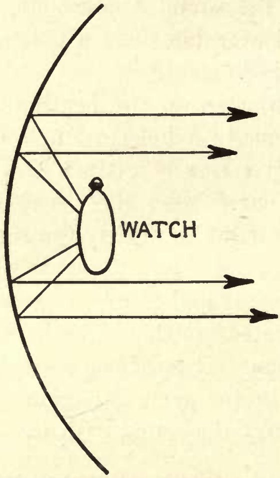

FIG. 4. WATCH AS SOURCE OF SOUND, BACKED BY A CONCAVE REFLECTOR.

The first step in the application of this principle was to use a faint sound which could not be heard at any great distance unless reinforced in some way. The ticks of a watch were directed, by means of a reflector (Fig. 4) to certain walls suspected of giving echoes. Using the relation that the angle of incidence equals the angle of reflection, the reflected sound was readily located, and the watch ticks heard distinctly after they had traveled a total distance as great as 70 to 80 feet from the source.

In a later experiment, a metronome was used which gave a louder sound. It was enclosed in a sound-proof structure (Fig. 5) with only one opening, so that the sound could be directed by means of a horn. This method was suggested by the work of Gustav Lyon in the Hall of the Trocadero at Paris,* where a somewhat similar arrangement was used. The method was successful and verified the observations taken previously.

*La Nature (Paris), April 24, 1909.

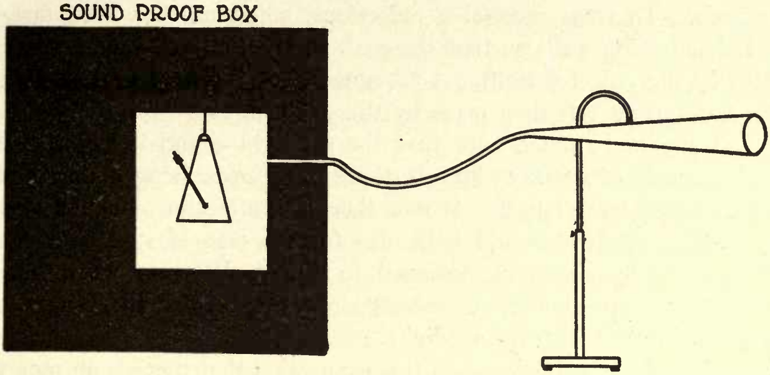

FIG. 5. METRONOME AS SOURCE OF SOUND.

Though the results obtained with the watch and metronome seemed conclusive, yet the observer was not always confident of the results. A further method was sought, and a more satisfactory one found by using an alternating current arc-light at the focus of a parabolic reflector (Fig. 6). In addition to the light, the arc gave forth a hissing sound, which was of short wave length and therefore experienced but little diffraction. The bundle of light rays was, therefore, accompanied by a bundle of sound, both coming from the same source and

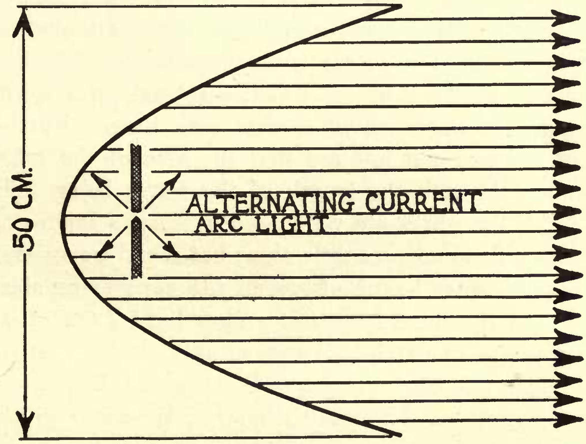

FIG. 6. ARC-LIGHT AS SOURCE OF SOUND.

subject to the same law of reflection. The path of the sound was easily found by noting the position of the spot of light on the wall. The reflected sound was located by applying the relation that the angles of incidence and reflection are equal. The arc-light sound was intense and gave the observer confidence in results that was lacking in the other methods. To trace successive reflections, small mirrors were fastened to the reflecting walls so that the path of the reflected sound was indicated by the reflected light. A "diagnosis" of the acoustical troubles of the Auditorium was then made by this method.

It should be noted here that the arc-light sound is not the same as the sounds of music or speech, these latter ones being of lower pitch and of longer wave length. It was, therefore, a matter of doubt whether the results obtained would hold also for the case of speech or music. Tests made by observers stationed in the Auditorium when musical numbers and speeches were rendered, however, verified the general conclusions obtained with the arc-light.

It should be pointed out in this connection that there is an objection to applying the "ray" method of geometrical optics to the case of sound. It is much more difficult to get a ray of sound than it is to get a ray of light.* This is due to the difference in the wave lengths in the two cases. It appears that the waves are diffracted, or spread out, in proportion to their length, the longer waves being spread out to a greater extent. The short waves of light from the sun, for instance, as they come through a window mark out a sharp pattern on the floor, which shows that the waves proceed in straight lines with but little diffraction or spreading. Far different is it with the longer waves of sound. If the window is open, we are able to hear practically all the sounds from outdoors, even that of a wagon around the corner, although we may be at the other end of the room away from the window. The longer sound waves spread out and bend at right angles around corners, so that it is almost impossible to get a sound shadow with them. Furthermore, in the matter of reflection, it appears that the area of the reflecting wall must be comparable with the length of the waves being reflected. In the case of light, the waves are very minute, hence a mirror can be very small and yet be able to set up a reflection; but sound waves are of greater length, the average wave length of speech (45 cm.) being about 700 000 times longer than the wave length of yellow light (.00006 cm.), hence the reflecting surface must be correspondingly larger. An illustration will perhaps make this clearer. Suppose a post one foot square projects through a water surface. The small ripples on the water will be reflected easily from the post, but the large water waves pass by almost as if the post were not there. The reflecting surface must have an area comparable with the size of the wave if it is to cause an effective reflection. Relief work in auditoriums, if of small dimensions, will affect only the high pitched sounds, i. e., those of short wave length, while the low

*Rayleigh "Theory of Sound," Vol. II, § 283.

pitched sounds of long wave length are reflected much the same as from a rather rough wall. It is also shown that the area of the reflecting surface is dependent on its distance from the source of sound and from the observer; the greater these distances are the larger must be the reflecting surface.*

These considerations all show that the reflection of sound is a complicated matter. The dimensions of a wall to reflect sound, or of relief work to scatter it, are determined by the wave length and by the various other factors mentioned. It should be said with caution that a "ray" of sound is reflected in a definite way from a small bit of relief work. We must deal with *bundles* of sound, not too sharply bounded, and have them strike surfaces of considerable area in order to produce reflections with any completeness.

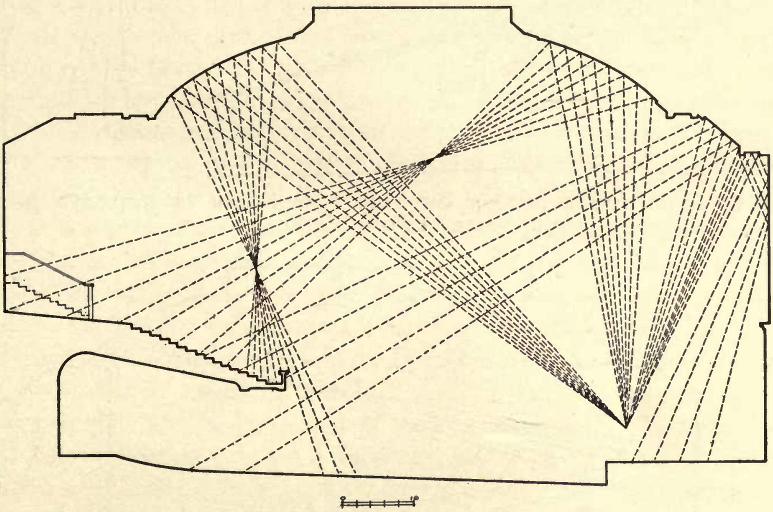

FIG. 7. LONGITUDINAL SECTION SHOWING THE CHIEF CONCENTRATIONS OF SOUND, THE DIFFRACTION EFFECTS BEING DISREGARDED.

B. DETAILS OF THE ACOUSTICAL SURVEY IN THE AUDITORIUM.

The general effect of the walls of the Auditorium on the sound may be anticipated by considering analogous cases in geometrical optics, but with the restrictions on "rays" described in the preceding paragraph. The sound does not actually confine itself to the sharp boundaries shown. The diagrams are intended to indicate the main effect of the sound in the region so bounded. Fig. 7 gives such an idea for the concentration of sound in the longitudinal section of the Auditorium.

*Rayleigh, ibid, 283.

The plan followed in the experimental work was to anticipate the path of the sound as indicated in Fig. 7, then to verify the results with the arc-light reflector. Figs. 8 and 9 show the effect of the rear wall in the balcony in forming echoes on the stage. The speaker was particularly unfortunate, being afflicted with no less than ten echoes.

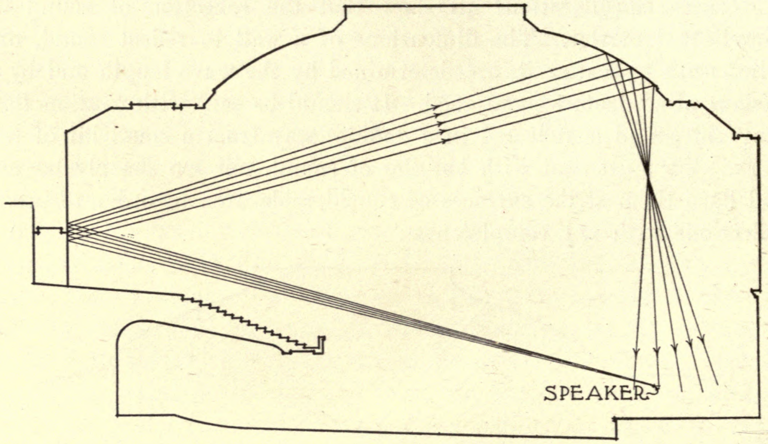

Fig. 8. Longitudinal Section Showing how Sound Is Returned to the Stage to Form an Echo.

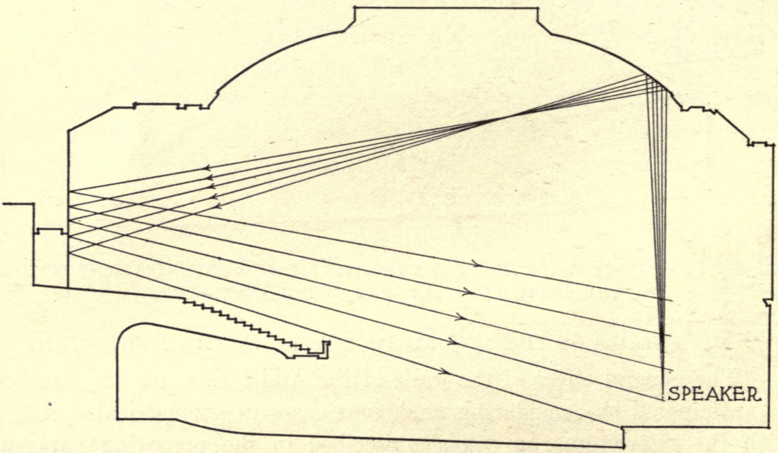

Fig. 9. Longitudinal Section Showing Formation of Echo on the Stage.

The hard, smooth, circular wall bounding the main floor under the balcony gave echoes as shown in Fig. 10, the sound going also in the reverse direction of the arrows.

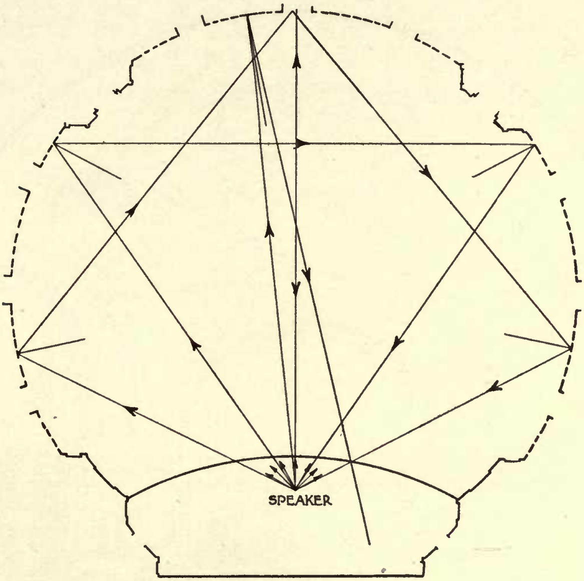

FIG. 10. PLAN OF AUDITORIUM SHOWING ACTION OF REAR WALL ON THE SOUND.

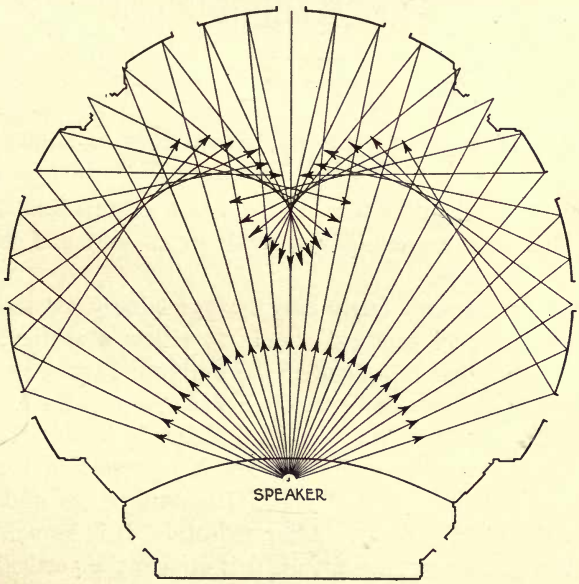

FIG. 11. PLAN OF AUDITORIUM SHOWING CONCENTRATION OF SOUND BY THE REAR WALL.

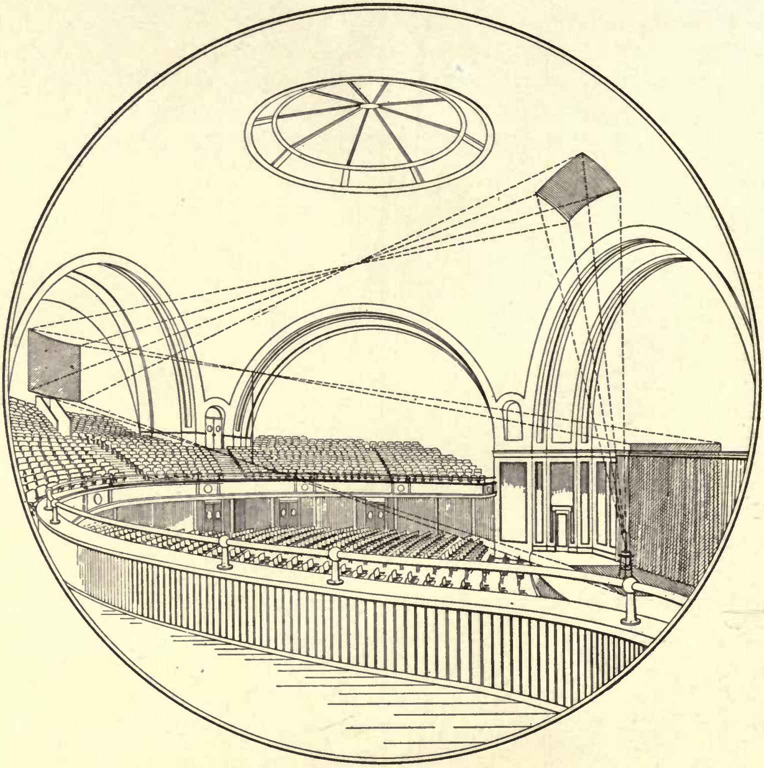

FIG. 12. THIS FIGURE TAKEN WITH FIG. 9 SHOWS HOW AN ECHO IS SET UP ON THE STAGE.

A more comprehensive idea of the action of this wall is shown in Fig. 11. This reflected sound was small in amount and therefore not a serious disadvantage.

The cases cited were fairly easy to determine since the bundles of sound considered were confined closely to either a vertical or a horizontal plane for which the plans of the building gave some idea of the probable path of the sound. For other planes, the paths followed could be anticipated by analogy from the results already found. Fig. 12 shows in perspective the development of the result expressed in Fig. 9.

A square bundle of sound starts from the stage and strikes the spherical surface of the dome. After reflection, it is brought to a point focus, as shown, and spreads out until it strikes the vertical cylindrical wall in the rear of the balcony. This wall reflects it to a line focus, after which it proceeds to the stage. Auditors on all parts of the stage complained of hearing echoes.

Referring to Fig. 7, it is seen that the arch over the stage reflects sound back to the stage. Fig. 13 shows in perspective the focusing action of this overhead arch. Fig. 14 shows the effect of the second arch.

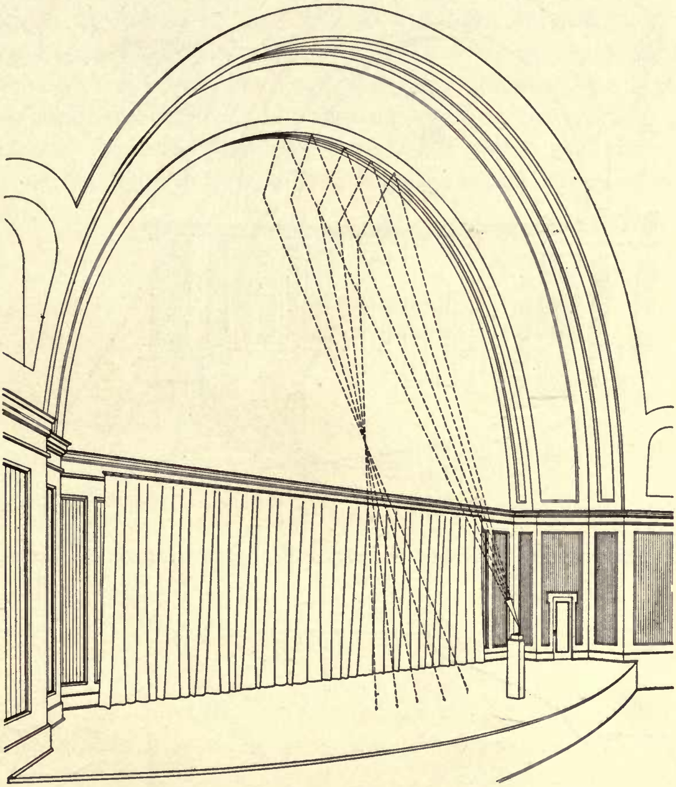

Fig. 13. Perspective of Stage Showing Focusing Action of Arch on Sound.

Some of this sound is reflected to the stage and to the seats in front of the stage; other portions, striking more nearly horizontally, are reflected to the side balconies. The echoes are not strong except for high pitched notes with short wave lengths, since the width of the arch is small.

Passing now to the transverse section, Fig. 15, we find the most pronounced echoes in the Auditorium. If an observer generates a sound in the middle of the room directly under the center of the skylight, distinct echoes are set up. A bundle of sound passes to the concave surface which converges the sound to a focus, after which it spreads out again to the other concave surface and is again converged to a focus

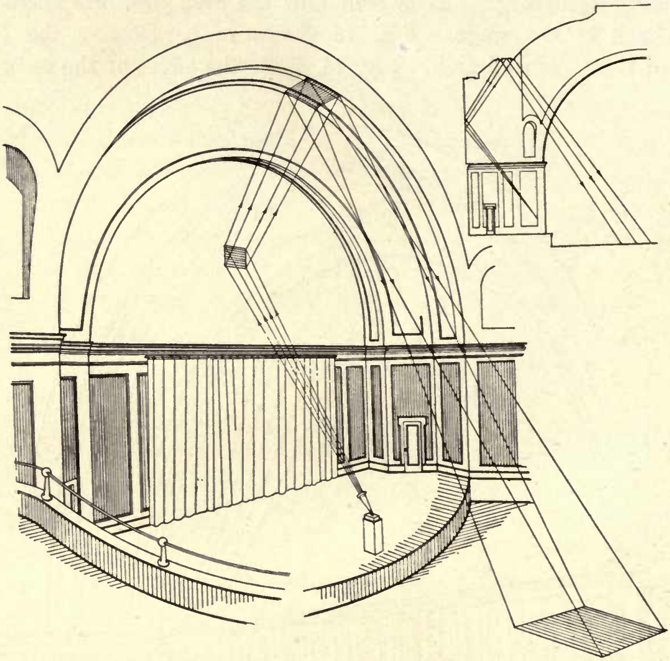

FIG. 14. PERSPECTIVE OF STAGE SHOWING FOCUSING ACTION OF SECOND ARCH

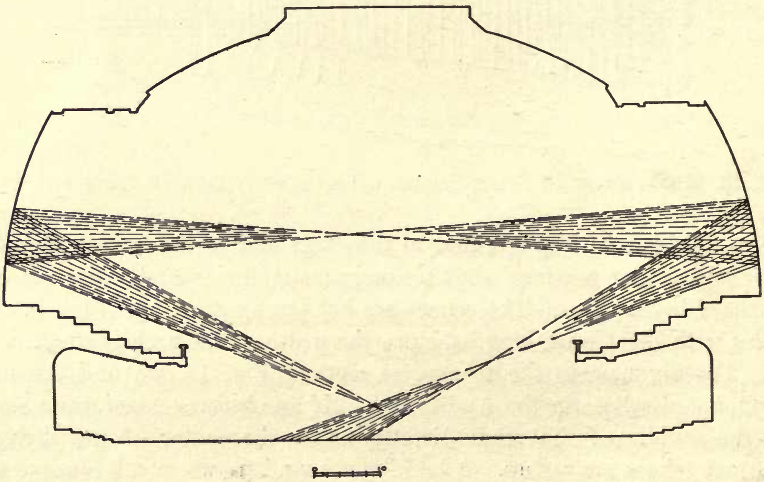

FIG. 15. TRANSVERSE SECTION SHOWING HOW MOST PRONOUNCED ECHOES ARE SET UP BY THE TWO CONCAVE SURFACES.

nearly at the starting point. The distance traveled is about 225 feet, taking about ¼ second, so that the conditions are right for setting up a strong echo. This echo is duplicated by the sound which goes in the reverse of the path just described. Another echo, somewhat less strong, is formed by the sound that goes to the dome overhead and which is reflected almost straight back, since the observer is nearly at the center of the sphere of which the dome is a part. These echoes repeat themselves, for the sound does not stop on reaching the starting point but is reflected from the floor and repeats the action just described. As many as ten distinct echoes have been generated by a single impulse of sound.

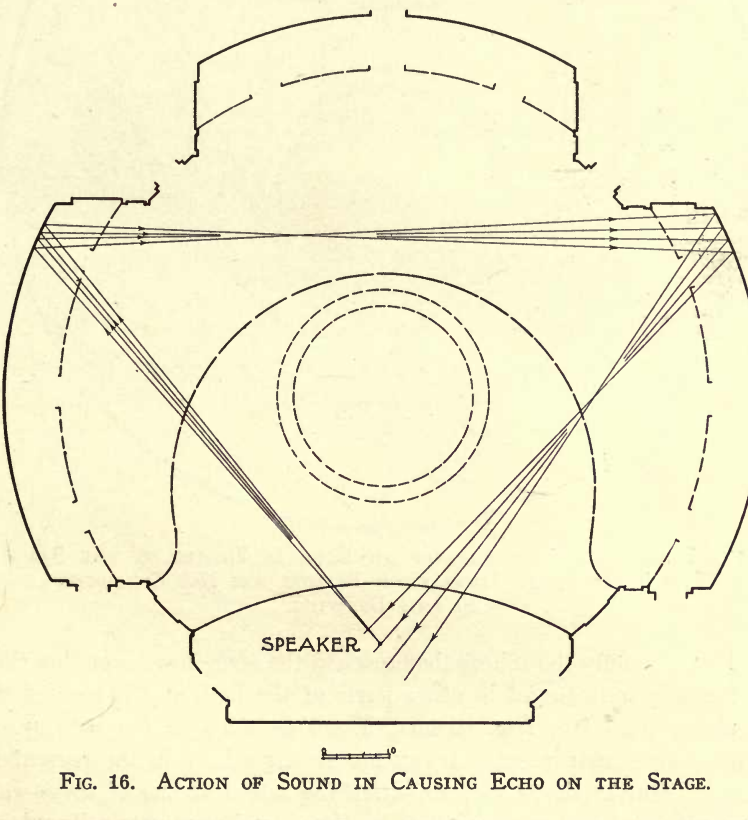

FIG. 16. ACTION OF SOUND IN CAUSING ECHO ON THE STAGE.

The echo shown in Fig. 15 is repeated in a somewhat modified form for a sound generated on the stage by a speaker. Fig. 16 shows the path taken by the sound. This echo is duplicated by the sound that goes in the reverse direction of the arrows, so the speaker is greeted from both sides. Fig. 17 is a perspective showing the path. The sound does not confine itself closely to a geometrical pattern, as shown in the picture, but spreads out by diffraction. The main effect is shown by the figure.

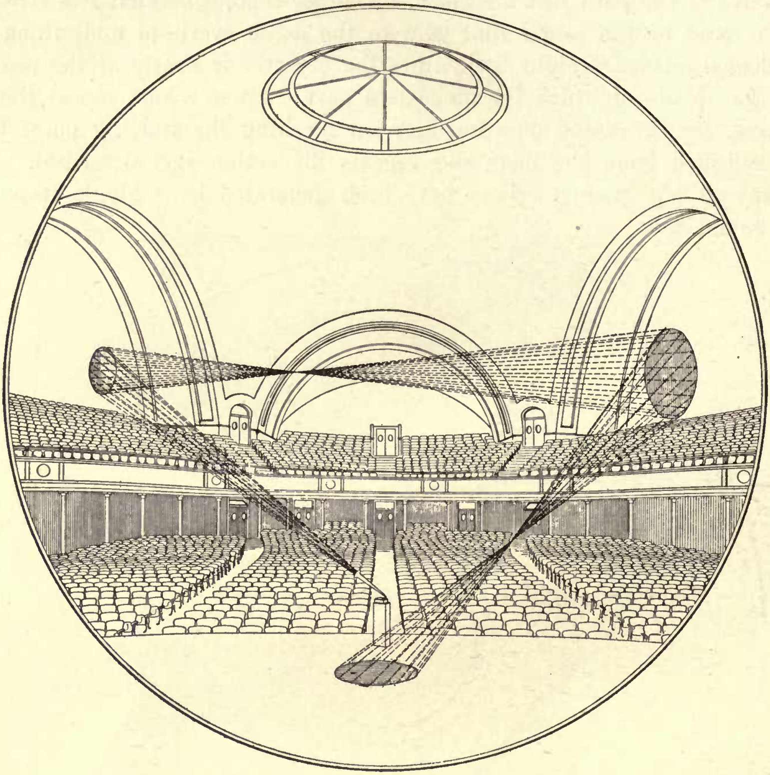

FIG. 17. PERSPECTIVE SHOWING HOW AN ECHO IS FORMED ON THE STAGE BY TWO REFLECTIONS. DIFFRACTION EFFECTS ARE NOT CONSIDERED IN THIS DRAWING.

Thus far only the echoes that reached the stage have been described. Other echoes were found in other parts of the hall, and it seemed that few places were free from them. The side walls in the balcony, for instance, were instrumental in causing strong echoes in the rear of the balcony. Fig. 18 shows in perspective the action of one of these walls. These two surfaces were similar in shape and symmetrically placed. Each was the upper portion of a concave surface with its center of curvature in the center of the building under the dome. The general effect of the left hand wall was to concentrate the sound falling on it in the right hand seats in the balcony. Some of the sound struck the opposite wall and was reflected to the stage, as shown in Fig. 17. Auditors who sought the furthermost rear seats in the balcony to escape echoes were thus caught by this unexpected action of the sound. The right hand wall acted in a similar way to send the sound to the upper left balcony.

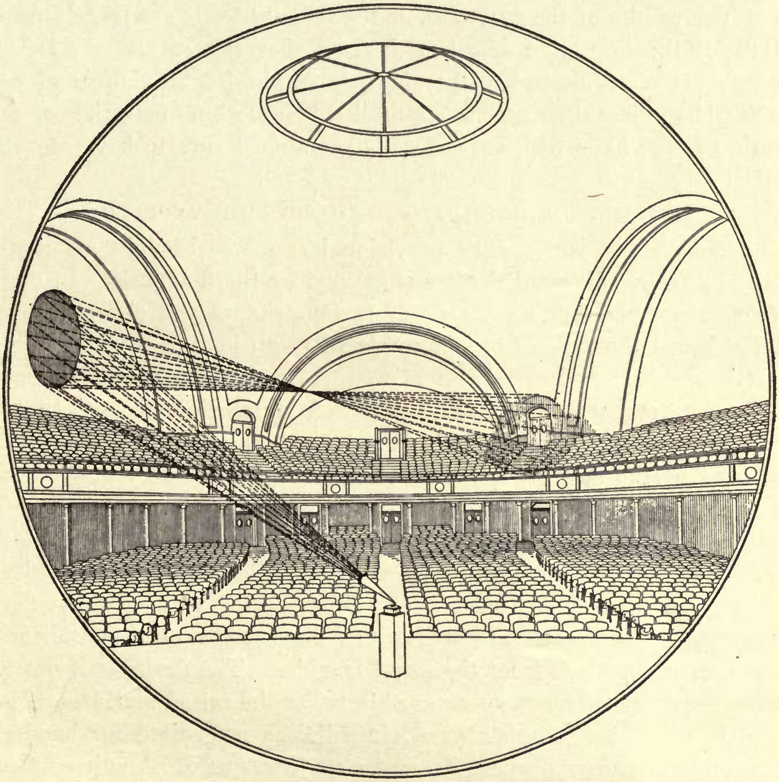

Fig. 18. Perspective Showing Sound Reflected from Concave Wall in Balcony. Diffraction Not Considered.

The dome surface concentrates most of its sound near the front of the central portion of the balcony and the ground floor in front of the balcony in the form of a caustic cone. Figs. 7, 9 and 11 give some conception of how a concentration of sound is caused by this spherical surface. The echo in the front portion of the balcony was especially distinct. On one occasion, in this place, the author was able to hear the speaker more clearly from the echo than by listening to the direct sound.

Minor echoes were set up by the horizontal arch surfaces in the balcony. The sound from the stage was concentrated by reflection from these surfaces and then passed to a second reflection from the concave surfaces back of them. Auditors in the side balcony were thus disagreeably startled by having sound come from overhead from the rear.

C. CONCLUSION DRAWN FROM THE ACOUSTICAL SURVEY.

The results of the survey show that curved walls are largely responsible for the formation of echoes because they concentrate the reflected sound. It seems desirable, therefore, to emphasize the danger of using such walls unless their action is annulled by absorbing materials or relief work. Large halls with curved walls are almost sure to have acoustical defects.

D. METHODS EMPLOYED TO IMPROVE THE ACOUSTICS.

Reflecting Boards.—The provisional cure was brought about gradually by trying different devices suggested by the diagnosis. In one set of experiments sounding boards of various shapes and sizes were used. A flat board about five feet square placed at an incline over the position of the speaker produced little effect. A larger canvas surface, about 12 by 20 feet, was not much better. A parabolic reflector, however, gave a pronounced effect. This reflector was mounted over a pulpit at one end of the stage and served to intercept much of the sound that otherwise would have gone to the dome and produced echoes. The path of the reflected sound was parallel to the axis of the paraboloid of which the reflector was a quarter section. There was no difficulty in tracing out the reflected sound. Auditors in the path of the reflected rays reported an echo, but auditors in other parts of the Auditorium were remarkably free from the usual troubles. The device was not used permanently, since many speakers objected to the raised platform. Moreover, it was not a complete cure, since it was not suited for band concerts and other events, where the entire stage was used. Another reflector similar in shape to the one just described is shown in Figs. 21 and 22.

Sabine's Method.—The time of reverberation was determined by Sabine's method. An organ pipe making approximately 526 vibrations a second was blown for about three seconds and then stopped. An auditor listened to the decreasing sound, and when it died out made a record electrically on a chronograph drum. The time of reverberation was found to be 5.90 seconds, this being the mean of 19 sets of measurements, each of about 20 observations. The reverberation was found also by calculation from Sabine's equation (see Section III), taking the volume of the Auditorium as 11 800 cubic meters and calculating the

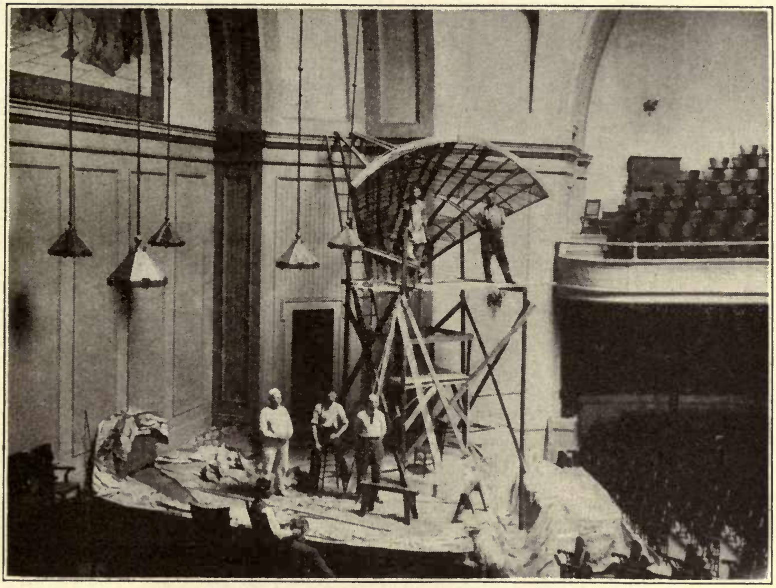

FIG. 19. REFLECTING BOARD IN PROCESS OF CONSTRUCTION.

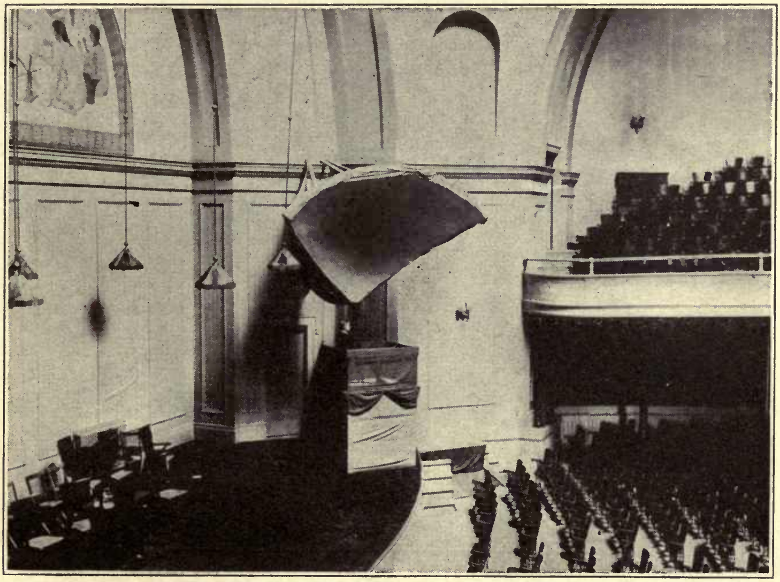

FIG. 20. FINISHED REFLECTOR. HARD PLASTER ON WIRE LATH.

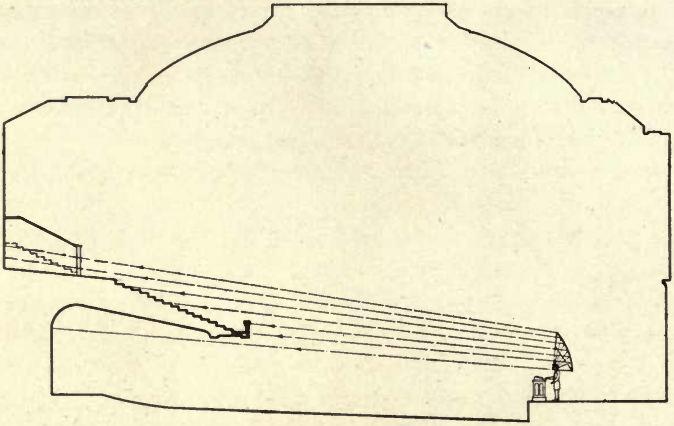

FIG. 21. PARABOLIC REFLECTOR SHOWING ITS ACTION ON SOUND.

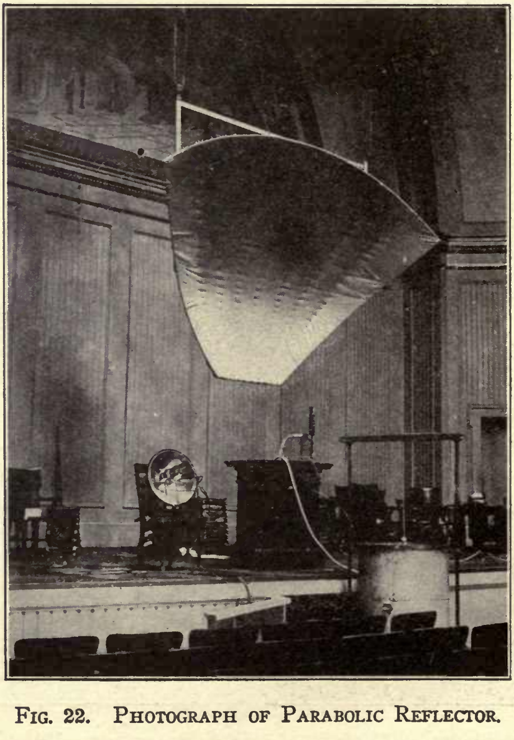

FIG. 22. PHOTOGRAPH OF PARABOLIC REFLECTOR.

absorbing power of all the surfaces in the room. This calculation gave 6.4 seconds. The agreement between the two results is as close as could be expected, since neither the intensity of the sound nor the pitch used by the author was the same as those used by Professor Sabine, and both of these factors affect the time of reverberation.

Several years later the time of reverberation was again determined after certain changes had been made. A thick carpet had been placed on the stage, heavy velour curtains 18 by 32 feet in area hung on the wall at the rear of the stage, a large canvas painting 400 square feet in area was installed, and the glass removed from the skylight in the ceiling. The time of reverberation was reduced to 4.8 seconds. With an audience present this value was reduced still more, and when the hall was crowded at commencement time the reverberation was not troublesome.

Method of Eliminating Echoes.—Although the time of reverberation was reduced to be fairly satisfactory, as just explained, the echoes still persisted, and were very annoying. Attempts were made to reduce individual echoes by hanging cotton flannel on the walls at critical points. Thus the shaded areas in Fig. 17 were covered and also the entire rear wall in the balcony. Pronounced echoes still remained, and it was evident that some drastic action was necessary to alleviate this condition. Four large canvases, shown in Figs. 23 and 24, were then hung in the dome in position suggested by the results of the diagnosis. A very decided improvement followed. For the first time the echoes were reduced to a marked degree and speakers on the stage could talk without the usual annoyance. This arrangement eliminated the echoes not only on the stage, but generally all over the house. A number of minor echoes were still left, but the conditions were much improved, especially when a large audience was present to reduce the reverberation.

Proposed Final Cure.—The state of affairs just described is the condition at the time of writing. Two propositions were considered in planning the final cure. One proposition involved a complete remodeling of the interior of the Auditorium. Plans of an interior were drawn in accordance with the results of the experimental work that would probably give satisfactory acoustics. This proposition was not carried out because of the expense and because it was thought desirable to attempt a cure without changing the shape of the room. The latter plan is the one now being followed. It is proposed to replace the present unsightly curtains with materials which will conform to the architectural features of the Auditorium and which will have a pleasing color scheme. At the same time, it will be necessary to hold to the features which have improved the acoustics.

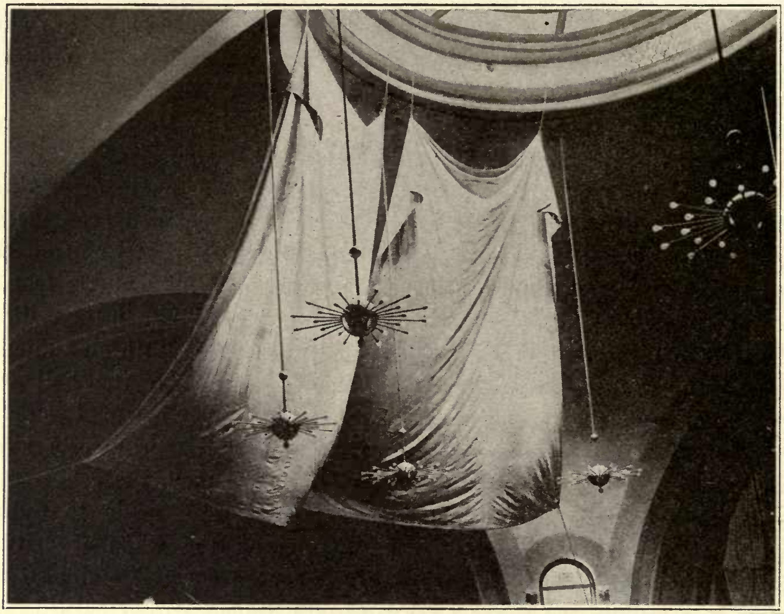

Fig. 23. Photograph of Two of the Canvas Curtains in the Dome of the Auditorium. Note also the Absorbing Materials under the Arches.

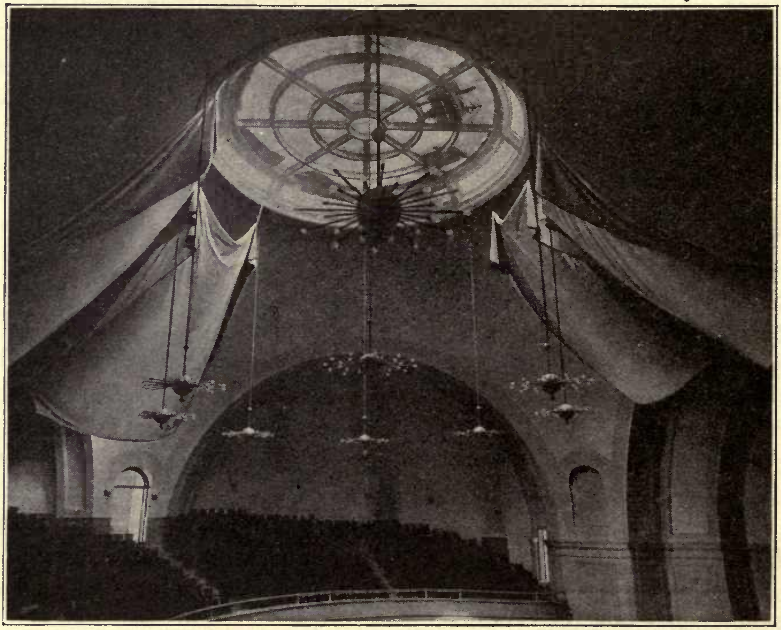

Fig. 24. Photograph of Dome of Auditorium Showing the Canvases Installed to Eliminate Echoes.

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