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L'Enfant, Roger Bloch, Sculptor, 1958

Memorial to Henry Charles Lea, Historian, Laurel Hill Cemetery, Philadelphia, A. Stirling Calder, Sculptor, 1959

Monument to Claude Lorrain, Auguste Rodin, Sculptor, 1958

Monument to Rabelais, Montpelier, J. Villeneuve, Sculptor, 1958

National Maine Monument, Central Park, N. Y. C., H. Van Buren Magonigle, Architect, Attilio Piccirilli, Sculptor, 1959

Sphinx, The, M. Bistolli, Sculptor, 1958

Seasons, The, Auguste Rodin, Sculptor, 1958

THEATRES

Blackstone Theatre, Chicago, Ill., Marshall & Fox, Architect, 1984

Colonial Theatre, Chicago, Ill., Marshall & Fox, Architects, 1984

National Theatre, Louisville, Ky., Albert Kahn & Ernest Wilby, Architects, 1984

Shubert Theatre, W. 44th Street, N. Y. C., Henry B. Herts, Architect, 1978

RESIDENTIAL

Cottage, Alterations to a—Mere Point, Me., John Calvin Stevens and John Howard Stevens, Architects, 1967

477 Madison Avenue, N. Y. C., Hunt & Hunt, Architects, 1972

House in Azusa, Cal., Robert David Farquhar, Architect, 1968

House of J. H. Boston, Marietta, Ga., Hentz & Reid, Architects, 1973

House of Mrs. Mary C. Russell, Hollywood, Cal., Elmer Gray, Architect, 1958

House of Thomas R. Young, Chestnut Hill, Mass., Frank Chouteau Brown, Architect, 1958

House of Von Bernuth, Esq., Alterations to, Stratford, Pa., George S. Idell, Architect, 1970

House in Los Angeles, Cal., Robert David Farquhar, Architect, 1971

House of E. P. Rowe, Brookline, Mass., Henry W. Rowe, Architect, 1958

House at Cape Elizabeth, Me., John Calvin Stevens and John Howard Stevens, Architects, 1967

House of A. P. Champlain, Portland, Me., John Calvin Stevens and John Howard Stevens, Architects, 1967

House in Sierra Madre, Cal., Robert David Farquhar, Architect, 1971

House of Newbold Morris, Lenox, Mass., Hoppins & Koen, Architects, 1974

House of Harris Fahenstock, Lenox, Mass., Hoppins & Keon, Architects, 1974

House of C. E. Van Vleck, Montclair, N. J., Van Vleck & Goldsmith, Architects, 1977

House of C. J. Warren, Winchester, Mass., C. J. Warren, Architect, 1975

House of Ferdinand Witt, Hastings-on-Hudson, N. Y., Ferdinand Witt, Architect, 1975

House of B. D. Watkins, Druid Mills, Atlanta, Ga., Hentz & Reid, Architects, 1977

Mappa House, Trenton, N. Y., 1964

Rogers Model Dwellings, 250 W. 44th St., N. Y. C., Grosvenor Atterbury, Architect, 1975

PLATE SECTION

ILLUSTRATIONS ACCORDING TO LOCATION

The figures refer to the number of the issue, not to the text pages.

CALIFORNIA:—

Azusa—

House in, L. D. Farquhar, Architect, 1968

Hollywood—

House of Mrs. Mary C. Russell, Elmer Gray, Architect, 1958

Los Angeles—

House in, Robert David Farquhar, Architect, 1971

San Francisco—

Festal Court Panama-Pacific International Exposition, Louis Christian Mullgardt, Architect, 1980

First Church of Christ Scientist, Edgar A. Mathews, Architect, 1962

U. S. Custom House, Eames & Young, Architects, 1970

Sierra Madre—

House in, Robert David Farquhar, Architect, 1971

GEORGIA:—

Atlanta—

House of B. D. Watkins, Druid Hills, Hentz & Reid, Architects, 1977

Lodge at Peachtree Heights, Carrere & Hastings, Architects, 1968

Marietta—

House of J. H. Boston, Hentz & Reid, Architects, 1973

ILLINOIS:—

Chicago—

Blackstone Theatre, Marshall & Fox, Architects, 1984

Colonial Theatre, Marshall & Fox, Architects, 1984

KENTUCKY:—

Louisville—

National Theatre, Albert Kahn & Ernest Wilby, Architects, 1984

MAINE:—

Cape Elizabeth—

House at, John Calvin Stevens and John Howard Stevens, Architects, 1967

Mere Point—

Alterations to a Cottage at, John Calvin Stevens and John Howard Stevens, Architects, 1967

Portland—

House of A. P. Champlain, John Calvin Stevens and John Howard Stevens, Architects, 1967

L. D. M. Sweat Memorial, John Calvin Stevens and John Howard Stevens, Architects, 1969

MASSACHUSETTS:—

Brookline—

Block of Stores, Coolidge Corner, Arthur H. Bowditch, Architect, 1961

House of E. P. Rowe, Henry W. Rowe, Architect, 1958

Chestnut Hill—

House of Thomas R. Young, Frank Chouteau Brown, Architect, 1958

Lenox—

House of Harris Fahenstock, Hoppins & Koen, Architects, 1974

House of Newbold Morris, Hoppins & Koen, Architects, 1974

Northampton—

St. John Cantius Church, John William Donohue, Architect, 1977

Pittsfield—

Windows in First Church of, Designed by C. M. Burd, 1971

West Roxbury—

Old Meeting House, 1981

West Springfield—

Church of the Immaculate Conception, John William Donohue, Architect, 1977

Winchester—

House of C. J. Warren, C. J. Warren, Architect, 1975

Winchendon—

Church of the Immaculate Heart of Mary, John William Donohue, Architect, 1977

MICHIGAN:—

Ann Arbor—

Hill Memorial Hall, University of Michigan, Albert Kahn, Architect, Ernest Wilby, Associate, 1963

MISSOURI:—

University City—

Studio Building, Eames & Young, Architects, 1983

NEW JERSEY:—

Montclair—

House of C. E. Van Vleck, Van Vleck & Goldsmith, Architects, 1977

D., L. & W. R. R. Station, F. J. Nies, Architect, 1978

Newark—

Kinney Building, Cass Gilbert, Architect, 1983

Station on Lehigh Valley, R.R., Kenneth M. Murchison, Architect, 1968

Princeton—

Graduate College and Cleveland Memorial Tower, Princeton University, Cram, Goodhue & Ferguson, Architects, 1979

NEW YORK:—

Chatham—

Tracy Memorial Village Hall, Horace W. Peaslee, Architect 1961

Elmira—

Station on D. L. & W. R. R., Kenneth M. Murchison, Architect, 1968

Far Rockaway—

St. Mary's Parochial School, Edward A. Lehmann and Thomas O'Kane, Jr., Architects, 1959

Hastings-on-Hudson—

House of Ferdinand Witt, Ferdinand Witt, Architect, 1975

New York City—

Cathedral of St. John The Divine, Design for the Competition of the, Ralph Adams Cram, Consulting Architect, 1982

Columbia University, School of Journalism, McKim, Mead & White, Architects, 1966

Factory Building, Westwood Ave. and 63rd St., Joseph A. Schaeffler, 1983

First Precinct Police Station, Old Slip, Hunt & Hunt, Architects, 1970

477 Madison Avenue, Hunt & Hunt, Architects, 1972

Montefiore Home for Invalids, Arnold W. Brunner and Buchman & Fox, Associated Architects, 1976

National Main Monument, Central Park, H. Van Buren Magonigle, Architect, Attilio Piccirilli, Sculptor, 1959

Nurses' Home for Manhattan Maternity Hospital and Dispensary, E. 60th Street, Ludlow & Peabody, Architects, 1973

Rogers Model Dwellings, W. 44th Street, Grosvenor Atterbury. Architect, 1975

Shubert Theatre, W. 44th Street, Henry B. Herts, Architect, 1978

Stained Glass Window for West End Collegiate Church, Designed by C. M. Burd, 1961

Synod House, Cathedral of St. John The Divine, New York, Cram, Goodhue & Ferguson, Architects, 1982

Trenton—

The Mappa House, W. S. Wicks, Architect, 1964

White Plains—

Gedney Farm Hotel, Kenneth M. Murchison, Architect, 1981

OHIO:—

Cincinnati—

Hamilton County Court House, Rankin, Kellogg & Crane, Architects, 1965

Hebrew Union College, A. Lincoln Fechheimer, Architect, 1960

PENNSYLVANIA:—

Kittanning—

St. Paul's Church, Brazer & Robb, Architects, 1973

Philadelphia—

Memorial to Henry Charles Lea, Historian, Laurel Hill Cemetery, A. Stirling Calder, Sculptor, 1959

Stratford—

Alterations to House of Von Bernuth, George S. Idell, Architect, 1970

FOREIGN:—

England, London—

Pall Mall, S. W.—
Building for Morel Bros., Cobbett & Son, Ltd., Henry Tanner, Architect, 1971

Cuba, Havana—

Union Station, Kenneth M. Murchison, Architect, 1968

STUDENT WORK
SOCIETY OF BEAUX-ARTS ARCHITECTS

The figures refer to the number of the issue, not to the text pages.

Paris Prize Competition: The Monumental Treatment of the Lower End of Manhattan Island, 1962—Placed First, Grant Miles Simon, Philadelphia Atelier, U. of Penn.; Placed Second, B. Hoyt, Atelier Ware-Wagner; Placed Third, Thomas J. Raguere, Carnegie Institute; Placed Fourth, J. Moscowitz, Atelier Bosworth.

Academy in Rome Scholarships: 1964—First Prize in Architecture, Walter L. Ward; In Sculpture, "Work," Leo Friedlander; In Painting, "Work," George Davidson.

Class "A" I. (Problem in Design), Administration Building for the National Academy, 1983; H. J. Beshgetoorian, First Medal, Columbia University; L. Fentnor, Second Medal, Ware-Wagner, Atel.

Archaeology, I. (Problem in Design), A Corner Balcony; J. F. Harbeson, Third Medal, Phila. Atel.; A. S. Hildebrand, Third Medal, Columbia University, 1983

Warren Price Competition, Civic Group, R. M. Johnson, First Prize, Ware-Wagner; T. D. Fitzgibbon, Second Prize, Carnegie Inst., 1983

Class "B" I. Order Problem, An Entrance to Office Building, P. S. Knoblock, First Mention Placed, Atel., Hirons; S. Vosper, First Mention Placed, Atel. Corbett, 1983

Class "B" I. Problem in Design, A Public Comfort Station; F. Bigelow, First Mention Placed, Atel. Corbett, J. F. Mahon, First Mention Placed, Atelier Licht., 1983

FRONTISPIECES

The figures refer to the number of the issue, not to the text pages.

Alley in Florence, Italy, An, 1968

Andreas-Platz, Hildesheim, Germany (From original water color by Cass Gilbert), 1964

Arch of Constantine, Rome, Italy, 1959

Capital and Frieze, Temple of Vesta, Tivoli, Italy, 1969

Doorway, Church of St. Michael, Fano, Italy, 1971

Façade, Church of St. Michael, Lucca, Italy, 1982

Frieze and Cornice of Temple of Antonius and Faustina, Rome, Italy, 1966

Mantel in a House in Richmond Terrace, London, George Dewey, Architect, 1958

Measured Drawings, By John W. English, Entered in the Glover Gold Medal Studentship Competition. Mr. English's drawings were placed second: Sketch of North Transept, Hexham Abbey, 1975; North Transept from Nave, Hexham Abbey, 1976; The Abbot's Door, S. Albans Cathedral, Hertfordshire, 1978; Pulpit in S. Michael's Church S. Albans, 1979; The Rood Screen, Hexham Abbey, 1981

Municipal Palace, The, Pesaro, Italy, 1977

Palace of Lucretia Borgia, Venice, 1960

Palazzo Barberini, Rome, 1965, 1967

Pantheon, Rome, Italy, Capital of the Portico, 1962, 1963

Pulpit, Out-of-Doors, Cathedral, Prato, Italy, 1983

Temple of Mars Ultor, Rome, Italy, 1970, 1972

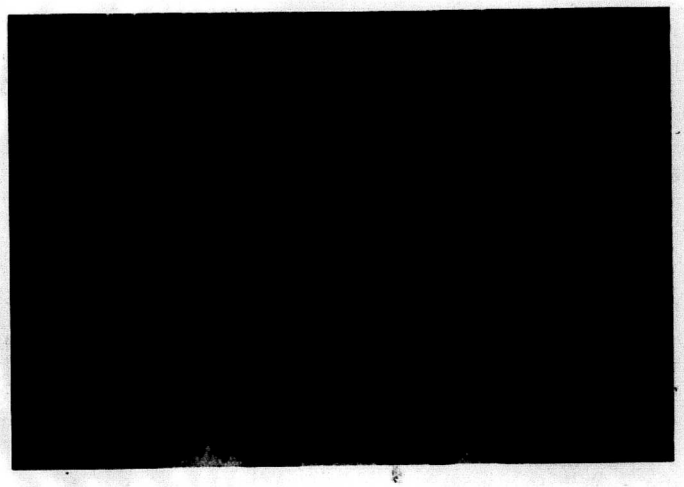
Temple of Jupiter Tonans, Rome, Italy, 1973

Temple of Jupiter Stator, Rome, Italy, 1974

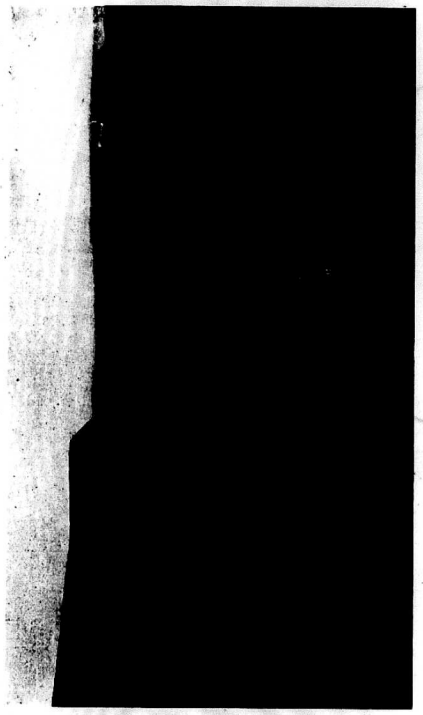
Temple of the Sibyls, Tivoli, Italy, 1980

Theatre, Roman, at Orange, 1984

XII Century. Central Doorway in the Abbey Church of St. Denis, France, 1961



THE AMERICAN ARCHITECT



ROMAN THEATRE AT ORANGE

THE AMERICAN ARCHITECT

VOLUME CIV WEDNESDAY, DECEMBER 31, 1913 NUMBER 1984



FIG 2. GREEK THEATRE AT THE UNIVERSITY OF CALIFORNIA.
MR. JOHN GALEN HOWARD, *ARCHITECT*
(SEE PAGE 276)

THEATRE ACOUSTICS

By WALLACE C. SABINE, HARVARD UNIVERSITY

VITRUVIUS, De Architectura, Liber V. Cap. VIII. (*De locis consonantibus ad theatra eligendis*). "All this being arranged, we must see with even greater care that a position has been taken where the voice falls softly and is not so reflected as to produce a confused effect on the ear. There are some positions offering natural obstructions to the projection of the voice, as for instance the dissonant, which in Greek are termed κατηχοῦντες; the circumsonant, which with them are named περιηχοῦντες; and again the resonant, which are termed ἀντηχοῦντες. The consonant positions are called by them συνηχοῦντες."

"The dissonant are those places in which the sound first uttered is carried up, strikes against solid bodies above, and, reflected, checks as it falls the rise of the succeeding sound."

This paper, which follows a number of papers printed in THE AMERICAN ARCHITECT and elsewhere during the past fifteen years on the general problem of architectural acoustics, is the beginning of a series of articles dealing with the application of the principles and the data thus produced to a number of classified problems.

The preceding papers were published in the Proceedings of the American Institute of Architects, 1898, the Dictionary of Architecture, THE AMERICAN ARCHITECT, 1900, the *Engineering Record*, 1900 and 1910, the Proceedings of the American Academy of Arts and Sciences, 1906, and in the *Harvard Architectural Quarterly*, 1912. These references are given because of frequent inquiries for reprints the supply of which is exhausted. Material for three other general papers dealing with "Coefficients of Absorption," "Loudness," "Interference and Resonance" has already been gathered, and should shortly appear.

Other articles to follow this will deal separately with the modern opera house, music halls for choral and orchestral concerts, private music rooms, large municipal auditoriums, and, perhaps the most difficult and varied of all, the church auditorium.

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"The circumsonant are those in which the voice spreading in all directions is reflected into the middle, where it dissolves, confusing the case endings, and dies away in sounds of indistinct meaning."

"The resonant are those in which the voice comes in contact with some solid substance and is reflected, producing an echo and making the case terminations double."

"The consonant are those in which the voice is supported and strengthened, and reaches the ear in words which are clear and distinct."

This is an admirable analysis of the problem of theatre acoustics. But to adapt it to modern nomenclature, we must substitute for the word dissonance, interference; for the word circumsonance, reverberation; for the word resonance, echo. For consonance, we have unfortunately no single term, but the conception is one which is fundamental.

It is possible that in the above translation and in the following interpretation I have read into the text of Vitruvius a definiteness of conception and an accord with modern science which his language only fortuitously permits. If so, it is erring on the better side, and is but a reasonable latitude to take under the circumstances. The only passage whose interpretation is open to serious question is that relating to dissonant places. If Vitruvius knew that the superposition of two sounds could produce silence, and the expression "*opprimit insequentis vocis elationem*" permits of such interpretation, it must stand as an observation isolated by many centuries from the modern knowledge of the now familiar phenomenon of interference.

Interference

Interference is a phenomenon common to all types of wave motion. The best introduction to its discussion is by reference to water waves and in particular to an interesting example of tidal interference on the Tongking Peninsula. The tide of the Pacific Ocean enters the Chinese Sea through two channels, one to the north of the Philippine Islands, between Luzon and Formosa, and the other through the Sulu Archipelago between Mindanao and Borneo. The northern channel is short and deep; and the tide enters with very little retardation. The other channel, although broad, is shallow, tortuous, and broken by many small islands; and the tide in passing through is much retarded. The two tides thus entering the Chinese Sea produce an effect which varies from point to point. At one port on the Tongking Peninsula, these tides are so retarded relatively to each other as to be six hours apart. It is high tide by one when it is low tide by the other. It also so happens that at this point the two tides are equal. Being equal and exactly opposite in phase, they neutralize each other.

Because tidal waves are long in comparison with the bodies of water in which they are propagated, their interference phenomena are obscure except to careful analysis. When, however, the waves are smaller than the space in which they are being propagated, the interference system becomes more marked, more complicated, and more interesting. Under such circumstances, there may be regions of perfect quiet near regions of violent disturbance.

Subjecting the parallel to a more exact statement, whenever two water waves come together the resulting disturbance at any instant is equal to the algebraic sum of the disturbances which each would produce separately. If their crests coincide, the joint effect is equal to the sum of their separate effect. If crest and trough coincide, their joint effect is the difference between them. If their relative retardation is intermediate, a wave results which is intermediate between their sum and their difference and whose time of maximum does not occur simultaneously with the maximum of either of the components.

The phenomenon is one which may be produced accurately on any scale and with any type of wave motion. Thus sound consists of waves of alternate condensation and rarifaction in the air. If two trains of sound waves cross each other so that at a given point condensation in the two trains arrive simultaneously, the rarifactions will also arrive simultaneously, and the total disturbance is a train of waves of condensation and rarifaction equal to the sum of the two components. If one train is retarded so that its condensations coincide with the other's rarifactions, the disturbance produced is the difference between that which would be produced by the trains of waves separately. Just as a tidal wave, a storm wave, or a ripple may be made to separate and recross by some obstacle round which it diffracts or from which it is reflected, and recombining produce regions of violent and regions of minimum disturbances, so sound waves may be diffracted or reflected, and recombining after travelling different paths, produce regions of great loudness and regions of almost complete silence. In general, in an auditorium the phenomenon of interference is produced not by the crossing of two trains of waves only, but by the crossing of many, reflected from the various walls, from the ceiling, from the floor, from any obstacle whatever in the room, while still other trains of waves are produced by the diffraction of the sound around columns and pilasters.

A source of sound on whose steadiness one can rely is all that is necessary in order to make the phenomenon of interference obvious. A low note on a pure toned stop of a church organ will serve the purpose admirably. The observer can satisfy himself that the note is sounding steadily by remaining in a fixed position. As soon, however, as he begins to move from this position by walking up and down the aisle he will observe a great change in loudness. Indeed, he may find a position for one ear which, if he closes the other, will give almost absolute silence, and this not far from positions whe e the sound is loud to the extent of being disagreeable. The observer in walking about the church will find that the phenomenon is complicated. It is, however, by no means random in its character, but definite, permanent, and accurate in its recurrence, note for note. The phenomenon while difficult is by no means impossible of experimental investigation or of theoretical solution. Indeed this has been done with great care in connection with the study of another problem—that of the Central Criminal Court Room in London known as Old Bailey. The full primary explanation of the methods and results of this general investigation would be inappropriately long in an article dealing with the acoustics of theatres; for while interference is a factor in every auditorium, it is on the whole not the most seriously disturbing factor in theatre design.

The subject of interference would not have been given even so extended a discussion as this in a paper dealing with theatres were it not that recently there has been proposed in Germany a form of stage setting known as the Kuppel-horizont for sky and horizon effects, to accompany the Fortuny system of stage lighting, in which interference may be a not inconsiderable factor unless guarded against. The Fortuny system, which in the opinion of some competent judges is an effective form of stage lighting, consists primarily in the use of indirect illumination, softened and colored by reflection from screens of silk. As an adjunct to the system, and in an endeavor to secure a considerable depth to the stage without either great height or an excessive use of sky and wing flies, a cupola is recommended to go with the Fortuny lighting as shown in the accompanying figures taken from the publications of the *Berliner Allegemeine Electricitäts Gesellschaft*. In Figures 3 and 4, the cupola is shown in section and in plan. Lights A and B illuminate the interior of the cupola; C and E light the area of the stage on which the principal action occurs. Cloud effects, either stationary or moving, are projected on the surface of the cupola by a stereopticon. The great advantage claimed for this form of stage setting is the more natural arrangement of stage properties which it makes possible, and the elimination of numerous flies. On the other hand there is some criticism that this lighting results in an unnatural silhouetting.

So detailed an explanation of the diagrams and the purpose of the several parts is necessitated by the fact that it is as yet an unfamiliar device in this country. It has been introduced recently in a number of theatres in Germany, although I believe not elsewhere, unless possibly in one theatre in England. It has been called to my attention by Professor Baker as a possible equipment of the theatre which is proposed

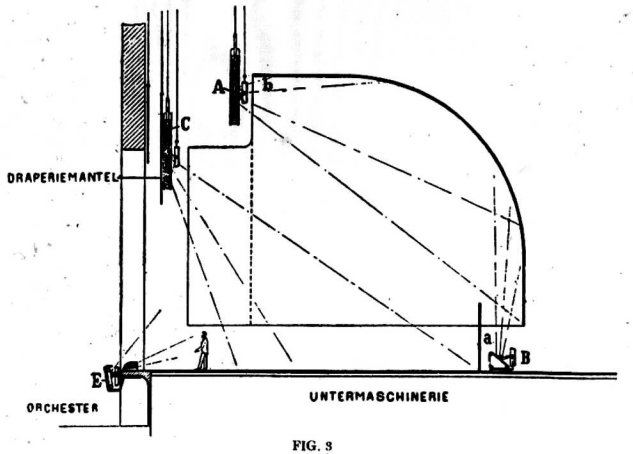


FIG. 3

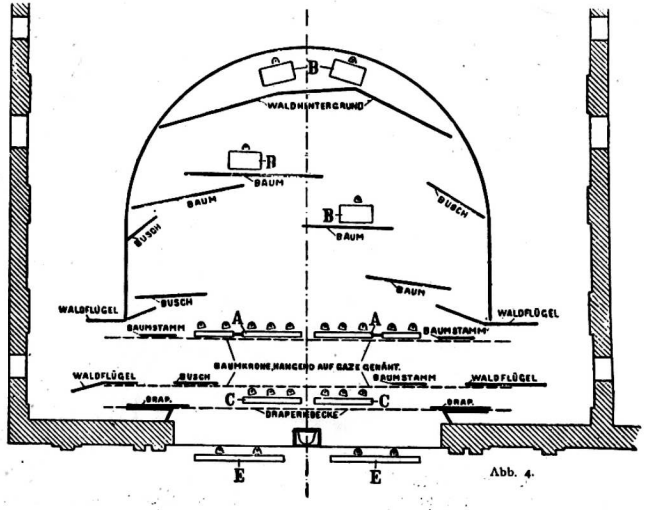


FIG. 4

SECTION AND PLAN OF THE KUPPEL-HORIZONT WITH FORTUNY SYSTEM OF LIGHTING

for the dramatic department of Harvard University, and it is reasonable to regard it as a probable factor in theatre design in other countries than Germany.

In Figure 5 is plotted the interference system established in this space, on a standing head level of five feet from the floor of the stage, by a sustained note tenor C in pitch. The intensity of the sound is indicated by contour lines very much as land elevation is indicated on the maps of the Geodetic Survey. In this plot, account has been taken of the sound reflected from the cupola and from the floor. No account has been taken of the reflection from the walls of the main auditorium since this would be a factor only for sounds prolonged beyond the length of any single element in articulate speech. Even in the case of a very prolonged sound the modification of the interference system of the stage and cupola by the rest of the auditorium would be very slight.

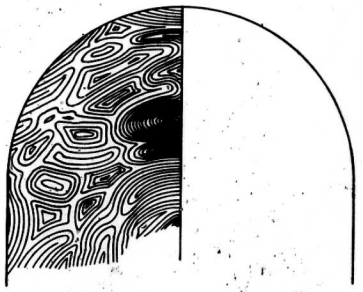


FIG. 5. INTERFERENCE SYSTEM FOR TENOR C IN THE KUPPEL-HORIZONT, HAVING A THIRTY-SIX FOOT PROSCENIUM OPENING. THE INTENSITY OF SOUND IS REPRESENTED BY CONTOUR LINES, THE MAXIMUM VARIATION BEING FORTY-SEVEN FOLD.

The interference system on the stage in question being determined wholly by the floor and cupola, it may be computed, and in the preparation of the chart was computed, by the so-called method of images. The sound reflected from the floor comes as from a virtual image as far beneath the floor as the mouth of the speaker is above it. Each of these produce real images by reflection from the interior of the cupola. Bearing in mind that these real images show the phenomenon of diffraction and some astigmatism, and taking into account the phase of the sound as determined by reflection and by distance, the calculation is laborious but not difficult. It involves but the most familiar processes of geometrical optics.

The disturbing effect of this interference system is not so great when the speaker is well in front of the center of curvature of the cupola, and of course it is almost always more or less broken by the stage properties, as indicated in Figures 3 and 4. Nevertheless, it is well to bear in mind that the quarter sphere form, as indicated in the diagrams, is neither necessary from the standpoint of illumination nor desirable from the standpoint of acoustics. Acoustically a flatter back with sharper curvature above and at the sides is preferable.

It should be repeated that the interference system is established only when the tones are sustained, in this case over one-tenth of a second, and is more of an annoyance to the actor on the stage than to the audience. With shorter tones it becomes an echo, and in this form is quite as annoying to the audience as to the actor. It should be added that the interference changes with change of pitch, but preserves extreme maxima and minima for a central position in a spherical or partly spherical surface. Finally in music, since sustained tones occur more than in speech, the interference is more disturbing. The effect of such spherical stage recesses on music is shown by those otherwise unusually excellent auditoriums, Orchestra Hall in Chicago, and the Concert Hall at Willow Grove Park near Philadelphia.

Reverberation

"Circumsonant places" were rare and almost wholly negligible difficulties in Greek and Roman theatres. However, they were common in the temples, and were even more pronounced in some of the older Roman palaces. It must have been in the experience of such conditions, wholly foreign to the theatre of which he was

writings, that Vitruvius made this portion of his analysis of the acoustical problem. Given the fundamental form of the Greek theatre it required no special consideration and little or no skill to avoid such difficulties. However, this is not true of the modern theatre, in which excessive reverberation is more often the defect than any other factor.

If a sound be produced briefly in a wholly empty, wholly closed room, having perfectly rigid walls, it will be reflected at each incidence with undiminished intensity, and travelling to and fro across the space, will continue audible almost indefinitely. Of course no theatre, ancient or modern, satisfies these conditions and the sound loses at each reflection, diminishing in intensity, until in the course of time it crosses what the experimental psychologist calls the "threshold of audibility." In the Greek theatres the duration of audibility of the residual sound after the cessation of a source of ordinary loudness was never more than a few tenths of a second, in a modern theatre it may be several seconds. The rapidity with which the sound dies away depends on the size of the theatre, on its shape, on the materials used for its walls, ceiling, and furnishings, and on the size and distribution of the audience. The size and shape of the theatre determines the distance travelled by the sound between reflections, while the materials determine the loss at each reflection. No actual wall can be perfectly rigid. Wood sheathing, plaster on wood lath, plaster on wire lath, plaster applied directly to the solid wall, yield under the vibrating pressure of sound and dissipate its energy. Even a wall of solid marble yields slightly, transmitting the energy to external space or absorbing it by its own internal viscosity.

Absorption by the walls and other objects in the process of reflection, including in this transmission through all openings into outer space as equivalent to total absorption, boundary condition in other words, are practically alone to be credited with the dissolution of the residual sound. But Vitruvius' statement that the sound "is reflected into the middle, where it dissolves" challenges completeness and at least the mention of another factor, which, because of its almost infinitesimal importance, would otherwise be passed without comment.

Assuming, what is of course impossible, a closed room of absolutely rigid and perfectly reflecting walls, a sound once started would not continue forever, for where the air is condensed by the passing of the wave of sound, it is heated, and where it is rarified, it is cooled. Between these unequally heated regions and between them and the walls, there is a continual radiation of heat, with a resulting dissipation of available energy. In the course of time, but only in the course of a very long time, the sound would even thus cease to be of audible intensity. This form of dissipation might well be called in the language of Vitruvius "*solvens in medio*;" but, instead of being an important factor, it is an entirely negligible factor in any actual auditorium.

Practically the rapidity with which the sound is absorbed is dependent solely on the nature of the reflecting surfaces and the length of the path which the sound must traverse between reflections, the latter depending on the shape and size of the auditorium. It was shown in a series of papers published in THE AMERICAN ARCHITECT in 1900, and in another paper published in the Proceedings of the American Academy of Arts and Sciences in 1906, that given the plans of an auditorium and the material of which it is composed, it is possible to calculate with a very high degree of accuracy the rate of decay of a sound in the room and the duration of its audibility. In the first of the above papers there was given the complete theory of the subject, together with tables of experimentally determined coefficients of absorption of sound for practically all the materials that enter into auditorium construction, for sounds having a pitch one octave above middle *c* (vibration frequency 512). In the second of the above papers there were given the coefficients of absorption of building materials for the whole range of the musical scale.

In the careful design of a room for musical purposes, the problem obviously must include the whole range of the musical scale, at least seven octaves. It is not so obvious that the study must cover so great a range when the primary use is to



FIG. 6. THE LITTLE THEATRE, NEW YORK
MESSRS. INGALLS AND HOFFMAN, *ARCHITECTS*

be with the spoken voice. The nearest study to architectural acoustics is the highly developed science of telephony, and in this it is apparently sufficient for much of the work to adapt the theory and design to the single frequency of 800, approximately *a* in the second octave above middle *c*. But for some problems the investigation must be extended over a considerable range of pitch. Similarly experience in the architectural problem shows that with some of the materials entering into building construction there occurs a sharp resonance within a not great range of pitch. It is therefore necessary to determine the reverberation even for the speaking voice, not for a single pitch but for a considerable range and the quality of a theatre with respect to reverberation will be represented by a curve in which the reverberation is plotted against the pitch.

Without undertaking to give again a complete discussion of the theory of reverberation, and referring the reader to the earlier (1900) numbers of THE AMERICAN ARCHITECT, it will suffice to give a single illustration. For this I have selected Mr. Winthrop Ames' "Little Theatre" in New York, designed by Messrs. Ingalls and Hoffman, because the purpose and use of this auditorium was defined from the beginning with unusual precision. The purpose was the production of plays which could be adequately rendered only by the most delicate shades of expression, which would be lost in considerable measure if the conditions were such as to necessitate exaggeration of feature or of voice. The definition of its use was that it should seat just less than 300, and that all the seats were to be as nearly as possible of equal excellence, with the important assurance that every seat would be occupied at every performance.

The final plans and elevations of the Little Theatre are shown in Figures 7 and 8. The initial pencil sketch was of an auditorium differing in many architectural details, acoustical considerations sharing in, but by no means alone dictating, the steps leading to the final solution of the problem. The first calculations, based on the general lines of the initial sketch, and assuming probable materials and plausible details of construction (plaster on tile

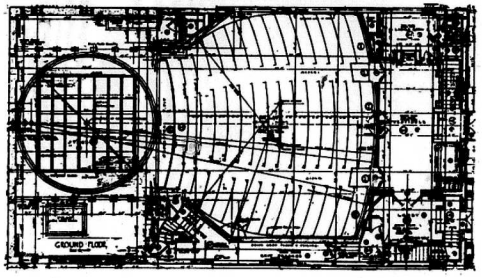


FIG 7

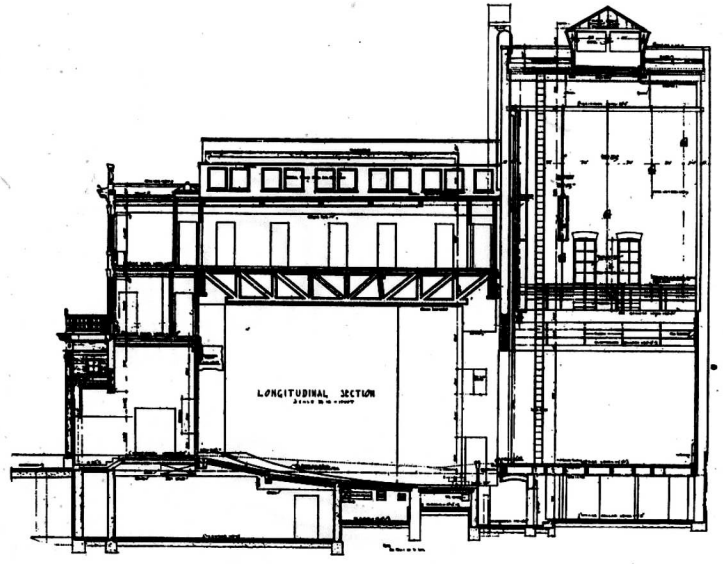


FIG. 8

PLAN AND SECTION OF THE LITTLE THEATRE, NEW YORK
MESSRS. HOFFMAN AND INGALLS, *ARCHITECTS*

walls, plaster on wire lath ceiling, solid plaster cornices and moulding), gave a reverberation as shown in Curve 1 in Figure 9. This would not have been in excess of that in many theatres whose acoustical qualities are not especially questioned. But the unusual requirements of the plays to be presented in this theatre, and the tendency of the public to criticize whatever is unconventional in design, led both Mr. Ames and the architects to insist on exceptional quality. The floor was therefore lowered at the front, the ceiling was lowered, and the walls near the stage brought in and reduced in curvature, with, of course, corresponding changes in the architectural treatment. The rear wall, following the line of the rear seats, remained unchanged in curvature. The side walls near the stage were curved. The net effect of these changes was to give an auditorium twenty-eight feet high in front, twenty-three feet high at the rear, forty-eight feet long and forty-nine feet broad, with a stage opening eighteen by thirty-one, and having a reverberation as shown by Curve 2. In order to reduce still further the reverberation, as well as to break acoustically the curvature of the side and rear walls, "acoustic felt". was applied in panels. There were three panels, six feet by thirteen feet, on each of the side walls, and seven panels, two four feet five inches by thirteen feet, two five feet by ten feet, two two feet by four feet, and one eight feet by seven feet, on the rear wall. The resulting reverberation is shown by Curve 3 in the diagram. Throughout, consideration was had for the actual path of the sound in its successive reflections, but the discussion of this phase of the general problem comes in the next section and will be illustrated by other theatres.

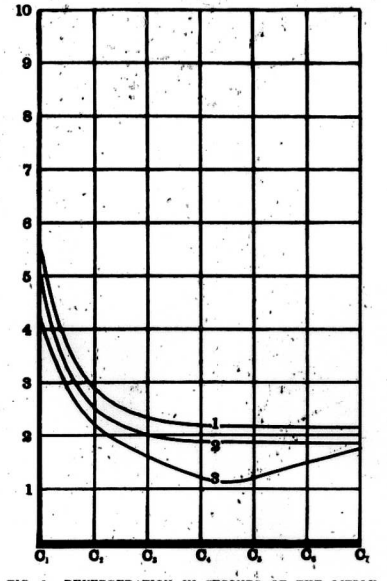


FIG. 9. REVERBERATION IN SECONDS OF THE LITTLE THEATRE, FOR NOTES OF DIFFERENT PITCH, C, BEING MIDDLE C, CURVE 1 FOR THE FIRST DESIGN, CURVE 2 FOR THE SECOND, AND CURVE 3 FOR THE THIRD AND AS BUILT.

It should be said, parenthetically but none the less emphatically, that throughout this paper by theatre is meant an auditorium for the spoken drama.

Echo

When a source of sound is maintained constant for a sufficiently long time, a few seconds will ordinarily suffice, the sound becomes steady at every point in the room. The distribution of the intensity of sound under these conditions, is called the interference system, for that particular note, of the room or space in question. If the source of sound is suddenly stopped, it requires some time for the sound in the room to be absorbed. This prolongation of sound after the source has ceased is called reverberation. If the source of sound, instead of being maintained, is short and sharp, it travels as a discreet wave or group of waves about the room, reflected from wall to wall, producing echoes. In the Greek theatre there was ordinarily but one echo, "doubling the case ending," while in the modern theatre there are many, generally arriving at a less interval of time after the direct

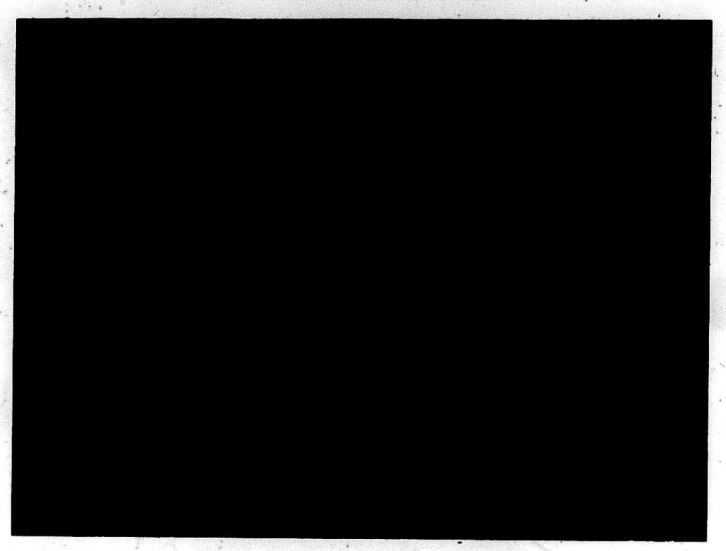


FIG. 10. THE NEW THEATRE, NEW YORK
MESSRS. CARRERE AND HASTINGS, *ARCHITECTS*

sound and therefore less distinguishable, but stronger and therefore more disturbing.

This phase of the acoustical problem will be illustrated by two examples, the New Theatre, the most important structure of the kind in New York, and the plans of the theatre now building for the Scollay Square Realty Company in Boston.

Notwithstanding the fact that there was at one time criticism of the acoustical quality of the New Theatre, the memory of which still lingers and still colors the casual comment, it was not worse in proportion to its size than several other theatres in the city. It is therefore not taken as an example because it showed acoustical defects in remarkable degree, but rather because there is much that can be learned from the conditions under which it was built, because such defects as existed have been corrected in large measure, and above all in the hope of aiding in some small way in the restoration of a magnificent building to a dignified use for which it is in so many ways eminently suited. The generous purpose of its founders, the high ideals of its manager in regard to the plays to be produced, and the perfection otherwise of the building directed an exaggerated and morbid attention to this feature. Aside from the close scrutiny which always centers on a semi-public undertaking, the architects, Messrs. Carrere and Hastings, suffered from that which probably every architect can appreciate from some similar experience of his own, an impossible program. They were called on to make a large "little theatre," as a particular type of institution is called in England; and, through a division of purpose on the part of the founders and advisers, for the Director of the Metropolitan Opera was a powerful factor, they were called on to make a building adapted to both the opera and the drama. There were also financial difficulties, although very different from those usually encountered, a plethora of riches. This necessi-

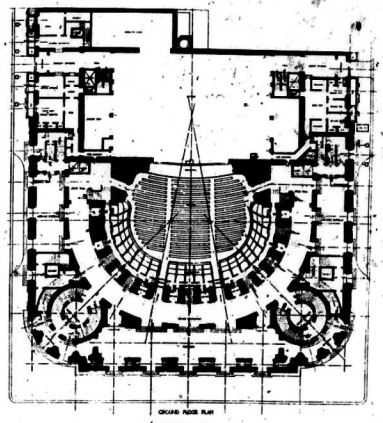


FIG. 11

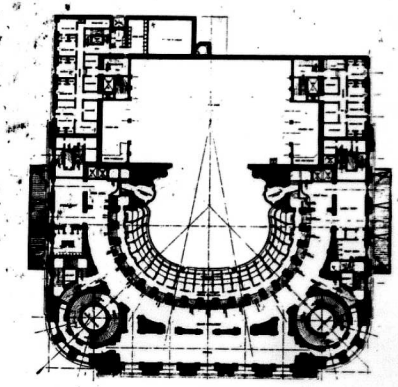


FIG. 12

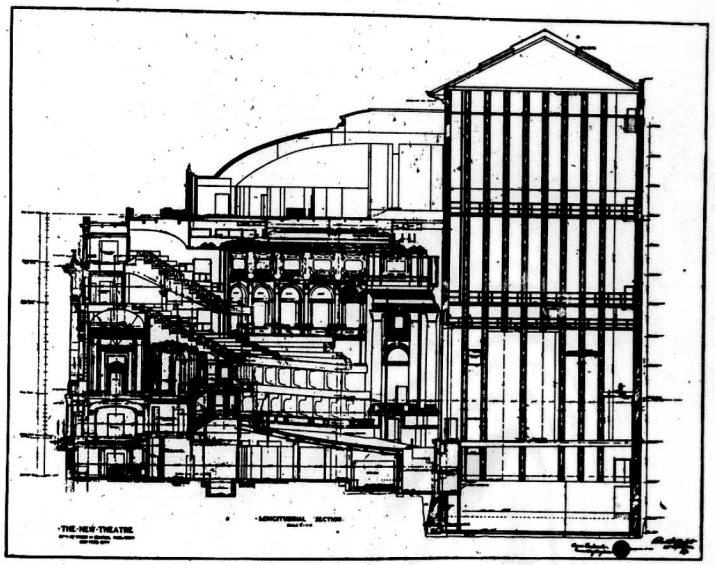


FIG. 13

PLANS AND SECTION OF THE NEW THEATRE, NEW YORK
MESSRS. CARRERE AND HASTINGS, *ARCHITECTS*

tated the provision of two rows of boxes, forty-eight originally, equally commodious, and none so near the stage as to thereby suffer in comparison with the others. Finally there was a change of program when the building was almost complete. The upper row of boxes was abandoned and the shallow balcony thus created was devoted to foyer chairs which were reserved for the annual subscribers. As will be shown later these seats were acoustically the poorest in the house.

Encircling boxes are a familiar arrangement, but most of the precedents, especially those in good repute, are opera houses and not theatres, the opera and the drama being different in their acoustical requirements. In the New Theatre this arrangement exerted a three-fold pressure on the design. It raised the balcony and gallery twelve feet. It increased both the breadth and the depth of the house. And, together with the requirement that these boxes should not extend near the stage, it led to side walls whose most natural architectural treatment was such as to create sources of not inconsiderable echo.

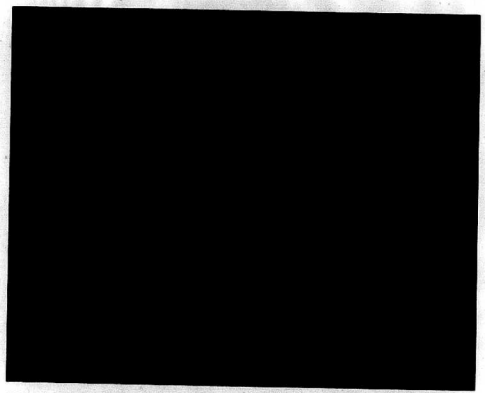


FIG. 14. PHOTOGRAPH OF A SOUND WAVE, *W W*, ENTERING A MODEL OF THE NEW THEATRE, AND OF THE ECHOES a_1, PRODUCED BY THE ORCHESTRA SCREEN, a_2 FROM THE MAIN FLOOR, a_3 FROM THE FLOOR OF THE ORCHESTRA PIT, a_4 THE REFLECTION FROM THE ORCHESTRA SCREEN OF THE WAVE a_5, a_5 THE WAVE ORIGINATING AT THE EDGE OF THE STAGE.

The immediate problem is the discussion of the reflections from the ceiling, from the side walls near the stage, from the screen and parapet in front of the first row of boxes and from the wall at the rear of these boxes. To illustrate this I have taken photographs of the actual sound and its echoes passing through a model of the theatre by a modification of what may be called the Toeppler-Boys-Foley method of photographing air disturbances. The details of the adaptation of the method to the present investigation will be explained in another paper. It is sufficient here to say that the method consists essentially of taking off the sides of the model, and, as the sound is passing through it, illuminating it instantaneously by the light from a very fine and somewhat distant electric spark. After passing through the model the light falls on a photographic plate placed at a little distance on the other side. The light is refracted by the sound waves, which thus act practically as their own lens in producing the photograph.

In the accompanying illustrations reduced from the photographs the enframing silhouettes are shadows cast by the model, and all within are direct photographs of the actual sound wave and its echoes. For example, Figure 14 shows in silhouette the principal longitudinal section of the main auditorium of the New Theatre. *WW* is a photograph of a sound wave which has entered the main auditorium from a point on the stage at an ordinary distance back of the proscenium arch; a_1, is the reflection from the solid rail in front of the orchestra pit, and a_2, the reflection from the floor of the sound which has passed over the top of the rail; a_3 is the reflection from the floor of the pit, and a_4 the reflection of this reflected wave from the rail; while a_5 originated at the edge of the stage. None of these reflections are important factors in determining

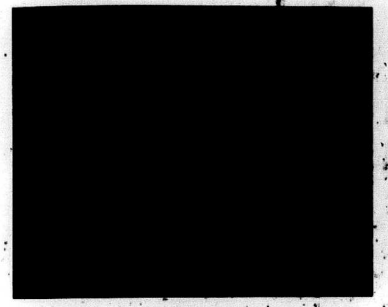


FIG. 15

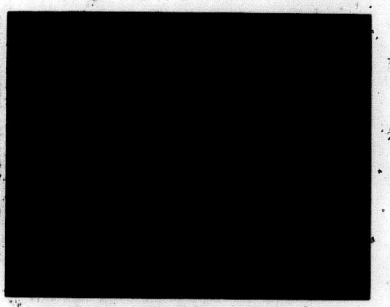


FIG. 18

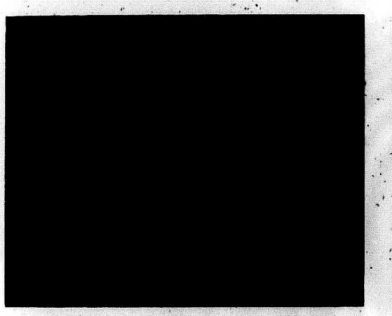


FIG. 16

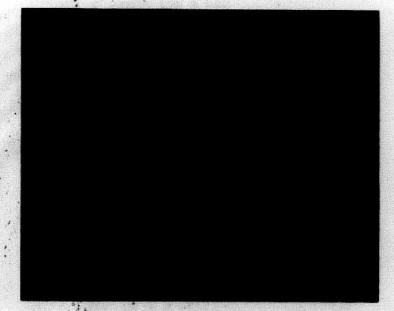


FIG. 19

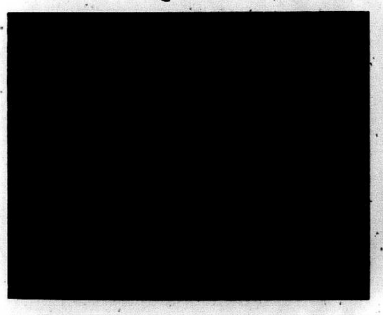


FIG. 17

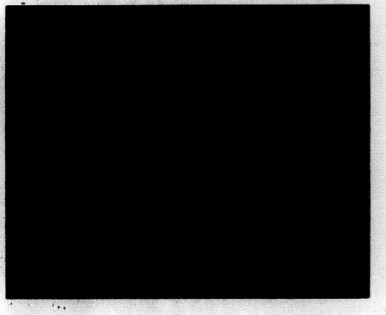


FIG. 20

TWO SERIES OF PHOTOGRAPHS OF THE SOUND AND ITS REFLECTIONS IN THE NEW THEATRE—15 TO 17 BEFORE, 18 TO 20 AFTER THE INSTALLATION OF THE CANOPY IN THE CEILING. THE EFFECT OF THE CANOPY IN PROTECTING THE BALCONY, FOYER CHAIRS, BOXES, AND THE ORCHESTRA CHAIRS BACK OF ROW L IS SHOWN BY COMPARING FIGURES 19 AND 20 WITH FIGURES 16 AND 17.

the acoustical quality of the theatre, but the photograph affords excellent opportunity for showing the manner in which reflections are formed, and to introduce the series of more significant photographs on the preceeding page.

Figures 15, 16 and 17 show the advance of the sound through the auditorium at .07, .10 and .14 second intervals after its departure from the source. In Figure 15, the waves which originated at the orchestra pit can be readily distinguished, as well as the nascent waves where the primary sound is striking the ceiling cornice immediately over the proscenium arch. The proscenium arch itself was very well designed, for the sound passed parallel to its surface. Otherwise reflections from the proscenium arch would also have shown in the photograph. These would have been directed toward the audience and might have been very perceptible factors in determining the ultimate acoustical quality.

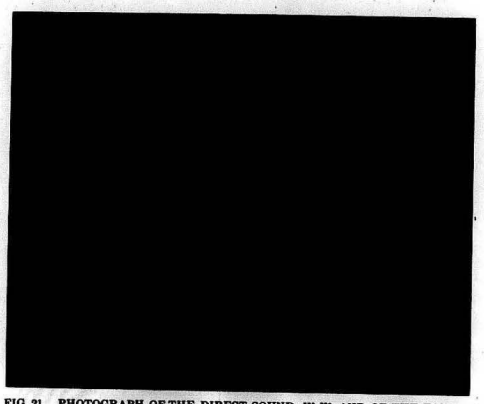


FIG. 21. PHOTOGRAPH OF THE DIRECT SOUND, *W W*, AND OF THE ECHOES FROM THE VARIOUS SURFACES; $a_{1,2}$, A WAVE, OR ECHO, DUE TO THE COMBINATION OF TWO WAVES WHICH ORIGINATED AT THE ORCHESTRA PIT; c_1 FROM THE OVAL PANEL IN THE CEILING; c_2 AND c_3, FROM THE CEILING MOULDINGS AND CORNICE OVER THE PROSCENIUM ARCH; c_4, A GROUP FROM THE MOULDING SURROUNDING THE PANEL; c_5, FROM THE PROSCENIUM ARCH; b_1, b_2, b_3 FROM THE SCREENS IN FRONT, AND THE WALLS IN THE REAR OF THE BOXES, BALCONY AND GALLERY.

The system of reflected waves in the succeeding photograph in the series is so complicated that it is difficult to identify the several reflections by verbal description. The photograph is therefore reproduced in Figure 21, lettered and with accompanying legends. It is interesting to observe that all the reflected waves which originated at the orchestra pit have disappeared with the exception of waves a_2 and a_3. These have combined to form practically a single wave. Even this combined wave is almost negligible.

The acoustically important reflections in the vertical section are the waves c_1, c_2 and c_3. The waves b_1 and b_2 from the screen in front of the boxes and from the back of the boxes are also of great importance, but the peculiarities of these waves are better shown by photographs taken vertically through a horizontal section.

The waves c_1, c_2, c_3 and b_1 and b_2 show in a striking manner the fallacy of the not uncommon representation of the propagation of sound by straight lines. For example, the wave c_1 is a reflection from the oval panel in the ceiling. The curvature of this panel is such that the ray construction would give practically parallel rays after reflection. Were the geometrical representation by rays an adequate one the reflected wave would thus be a flat disc equal in area to the oblique projection of the panel. As a matter of fact, however, the wave spreads far into the geometrical shadow, as is shown by the curved portion reaching well out toward the proscenium arch. Again, waves c_2 and c_3 are reflections from a cornice whose irregularities are not so oriented as to suggest by the simple geometrical representation of rays the formation of such waves as are here clearly shown. But each small cornice moulding originates an almost hemispherical wave, and the mouldings are in two groups, the position of each being such that the spherical waves conspire to form these two master waves. The inadequacy of the discussion

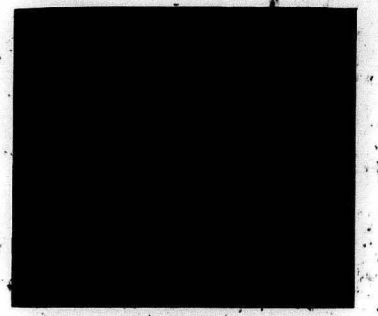


FIG. 22

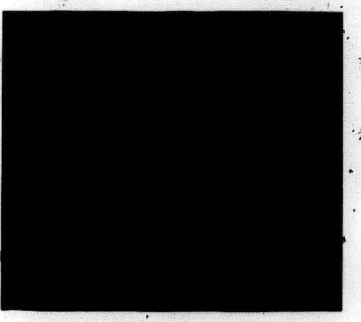


FIG. 25

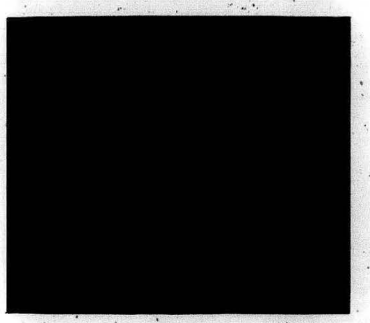


FIG. 23

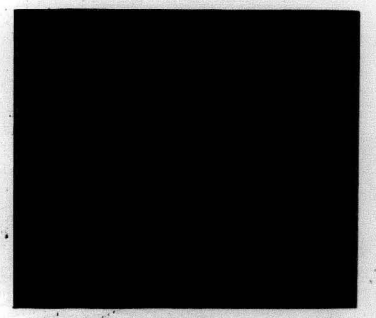


FIG. 26

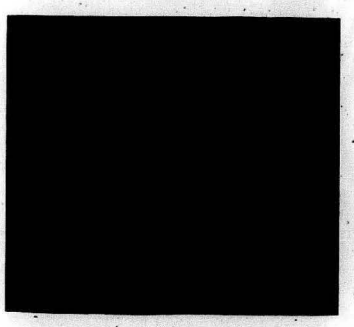


FIG. 24

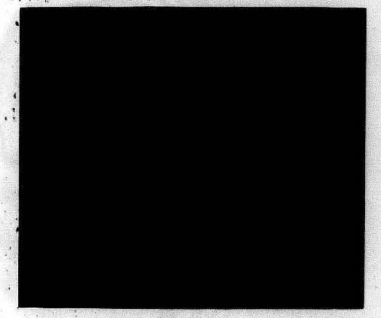


FIG. 27

PHOTOGRAPHS SHOWING THE REFLECTIONS, IN A VERTICAL PLANE, FROM THE SIDES OF THE PROSCENIUM ARCH, THE PLANE WALL BELOW THE ACTORS' BOX, AND THE RAIL OR SCREEN IN FRONT OF THE BOXES. THE PHOTOGRAPH TAKEN IN NUMERICAL SEQUENCE SHOW THE PROGRESS OF A SINGLE SOUND WAVE AND ITS REFLECTIONS.

of the subject of architectural acoustics by the construction of straight lines is still further shown by the waves reflected from the screens in front of the boxes, of the balcony, and of the gallery. These reflecting surfaces are narrow, but give, as is clearly seen in the photograph, highly divergent waves. This spreading of the wave beyond the geometrical projection is more pronounced the smaller the opening or the reflecting obstacle and the greater the length of the wave. The phenomenon is called diffraction and is of course one of the well known phenomena of physics. It is more pronounced in the long waves of sound than in the short waves of light, and on the small areas of an auditorium than in the large dimensions of out of door space. It cannot be ignored, as it has been heretofore ignored in all discussion of this phase of the problem of architectural acoustics, with impunity. The method of rays, although a fairly correct approximation with large areas, is misleading under most conditions. For example, in the present case it would have predicted almost perfect acoustics in the boxes and on the main floor.

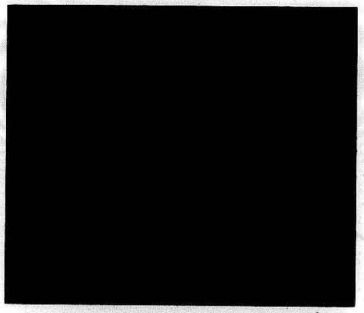


FIG. 28. A PHOTOGRAPH, ONE OF MANY TAKEN, SHOWING IN VERTICAL SECTION ONE STAGE OF THE REFLECTION b_3, FIG. 21. THESE REFLECTIONS WERE ELIMINATED BY THE ARCHITECTS IN THE SUMMER FOLLOWING THE OPENING OF THE THEATRE, BUT HAVE BEEN IN PART RESTORED BY SUBSEQUENT CHANGES.

The third photograph in the series shows the condition in the room when the main sound wave has reached the last seat in the top gallery. The wave c_1 has advanced and is reaching the front row of seats in the gallery, producing the effect of an echo. A little later it will enter the balcony, producing there an echo greater in intensity, more delayed, and affecting more than half the seats in the balcony, for it will curve under the gallery, in the manner just explained, and disturb seats which geometrically would be protected. Still later it will enter the foyer seats and the boxes. But the main disturbance in these seats and the boxes, as is well shown by the photograph, arises from the wave c_2, and in the orchestra seats on the floor from the wave c_3.

In the summer following the opening of the theatre, a canopy, oval in plan and slightly larger than the ceiling oval, was hung from the ceiling surrounding a central chandelier. The effect of this in preventing these disturbing reflections is shown by a comparison, pair by pair, of the two series of photographs, Figures 15 to 17 and Figures 18 to 20. It is safe to say that there are few, possibly no modern theatres, or opera houses, equal in size and seating capacity, which are so free from this particular type of disturbance as the New Theatre at the present time.

In the study of the New Theatre photographs were taken through several horizontal sections. It will be sufficient for the purposes of the present paper to illustrate the effect of curved surfaces in producing converging waves by a few photographs showing the propagation of sound through a single section in a plane passing through the parapet in front of the boxes. The reflected waves shown in Figure 22 originating from the edge of the proscenium arch and from the base of the column can be followed throughout all the succeeding photographs. In Figure 23 are shown waves originating from the plain wall beneath the actor's box and the beginning of some small waves from the curved parapet. It is easily possible, as it is also interesting and instructive, to follow these waves through the succeeding photographs. In Figure 25 the sound has been reflected from the rear of the parapet; while in Figure 26 it has advanced further down the main floor of the auditorium, narrowing as it

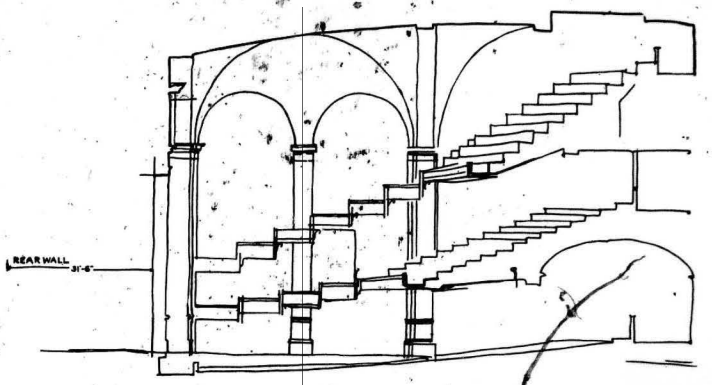


FIG. 29. SECTION IN PENCIL SKETCH OF SCOLLAY SQUARE THEATRE, IN BOSTON
MR. C. H. BLACKALL, *ARCHITECT*

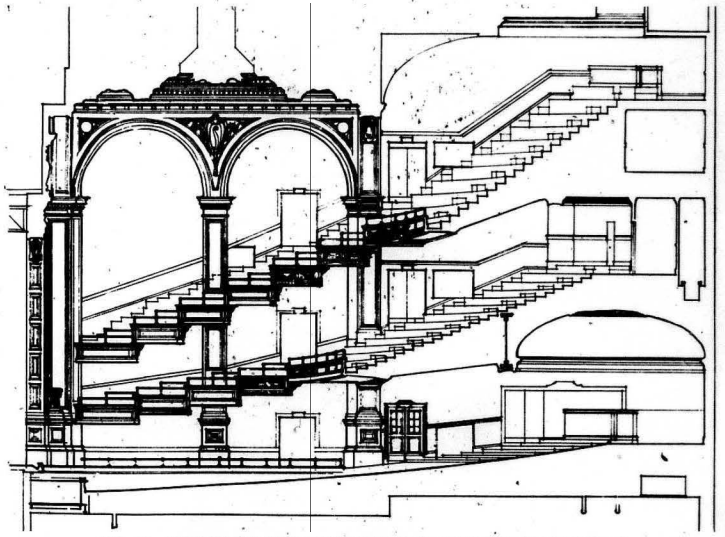


FIG. 30. FINISHED SECTION OF SCOLLAY SQUARE THEATRE BOSTON
MR. C. H. BLACKALL, *ARCHITECT*

proceeds and gaining in intensity. The waves reflected from the parapet outside of the aisles are here shown approaching each other behind the wave which has been reflected from the parapet between the aisles. Waves are also shown in Figure 26 emerging from the passages between the boxes. Indeed, it is possible to trace the waves arising from a second reflection from the proscenium arch of the sound which, first reflected from the corresponding surfaces on the other side, has crossed directly in front of the stage. With a little care, it is possible also to identify these waves in the last photograph.

Although many were taken, it will suffice to show a single photograph, Figure 28, of the reflections in the plane passing through the back of the boxes. These disturbing reflections were almost entirely eliminated in the revision of the theatre by the removal of the boxes from the first to the second row and by utilizing the space vacated together with the anterooms as a single balcony filled with seats.

An excellent illustration of the use of such photographs in planning, before construction and while all the forms are still fluid, is to be found in one of the theatres now being built in Boston by Mr. C. H. Blackall, who has had an exceptionally large and successful experience in theatre design. The initial pencil sketch, Figure 29, gave in the model test the waves shown in the progressive series of photographs, Figures 31 to 33. The ceiling of interpenetrating cylinders was then changed to the form shown in finished section in Figure 30, with the results strikingly indicated in the parallel series of photographs, Figures 34 to 36. It is of course easy to identify all the reflections in each of these photographs—the reflections from the ceiling and the balcony front in the first; from the ceiling and from both the balcony and gallery front in the second; and in the third photograph of the series, the reflections of the ceiling reflection from the balcony and gallery fronts and from the floor. But the essential point to be observed in comparing the two series pair by pair, is the almost total absence in the second series of the ceiling echo and the relatively clear condition back of the advancing sound wave.

Consonance

Consonance is the process whereby, due to suitably placed reflecting walls, "the voice is supported and strengthened." It is the one acoustical virtue that is positive. It is also the characteristic virtue of the modern theatre, and that through which this complicated auditorium surmounts the attendant evils of interference, reverberation and echo. Yet such is our modern analysis of the problem that we do not even have for it a name. On the other hand, it is the virtue which the Greek theatre has in least degree. It is therefore all the more interesting that it should have been included in the analysis of Vitruvius, and should have received a name so accurately descriptive. Indeed, one can hardly make explanation of the phenomenon better than through the very type of theatre in which its lack is the one admitted defect.

The Greek theatre enjoys a not wholly well founded reputation for extremely good acoustics. In most respects it is deserved; but the careful classical scholar, however gratified he may be by this praise of a notable Greek invention, regards himself as barred by contemporaneous evidence from accepting for the theatre unqualified praise. Every traveller has heard of the remarkable quality of these theatres, and makes a trial wherever opportunity permits, be it at beautiful Taormina, in the steep sloped theatre at Pompeii, the great theatre at Ephesus, or the "little theatre" on the top of Tusculum—always with gratifying results and the satisfaction of having confirmed a well known fact. Perhaps it is useless to try to traverse such a test. But there is not a theatre in Italy or Greece which is not in so ruined a condition today that it in no way whatever resembles acoustically its original form. If its acoustics are perfect today, they certainly were not originally. Complete "scaena" and enclosing walls distinctly altered the acoustical conditions. The traveller has in general tested what is little more than a depression in the ground, or a hollow in a quiet country hillside. As a matter of fact, the theatre in its original form was better than in its ruined state. Still, with all its excellencies it was not wholly good. Its acoustical

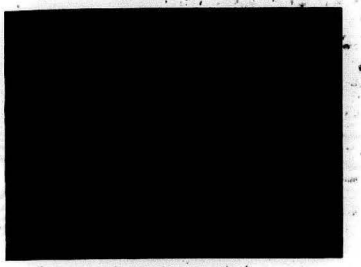


FIG. 31

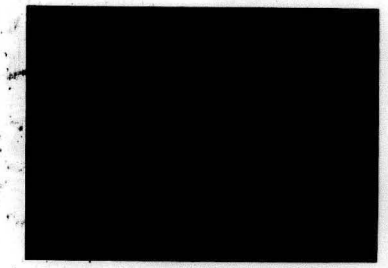


FIG. 34

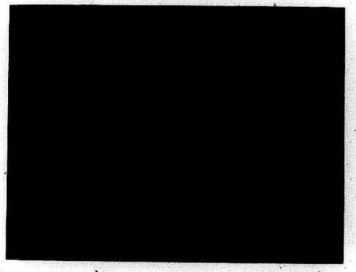


FIG. 32

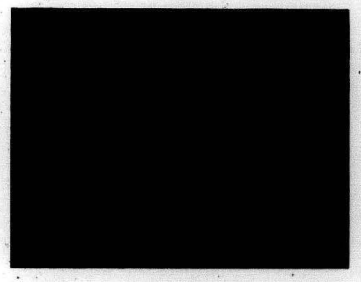


FIG. 35

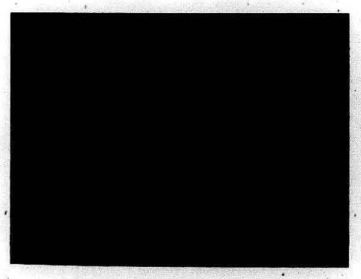


FIG. 33

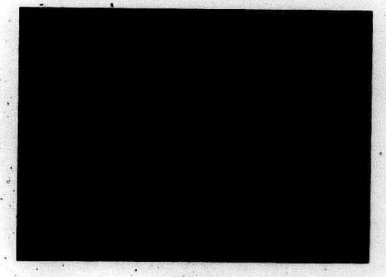


FIG. 36

TWO SERIES OF PHOTOGRAPHS SHOWING, FIGURES 31 TO 33, THE REFLECTIONS WHICH WOULD HAVE RESULTED FROM THE EXECUTION OF THE FIRST PENCIL SKETCH OF THE SCOLLAY SQUARE THEATER (FIGURE 29), AND, FIGURES 34 TO 36, FROM THE EXECUTION OF THE SECOND SKETCH BY MR. BLACKALL (SHOWN IN FINISHED SECTION IN FIGURE 30).

qualities were not wholly acceptable to its contemporaries, and would be less acceptable in a modern theatre, and for modern drama.

The difficulty with such casual evidence is that it is gathered under wholly abnormal conditions. Not only are the ruins but scant reminders of the original structure, but the absence of a large audience vitiates the test, as it would vitiate a test of any modern theatre. But while in a modern auditorium the presence of an audience almost always, though not invariably, improves the acoustics, in the classical theatre the presence of an audience, in so far as it has any effect, is disadvantageous. The effect of an audience is always twofold—it diminishes the reverberation, and it diminishes the loudness or intensity of the voice. In general, the one effect is advantageous, the other disadvantageous. But in the Greek theatre, occupied or unoccupied, ruined or in its original form, there was very little reverberation. In fact, this was its merit. On the other hand, the very fact that there was little reverberation is significant that there was very slight architectural reënforcement of the voice. One might well be unconvinced by such *a priori* considerations were there not excellent evidence that these theatres were not wholly acceptable acoustically even in their day, and for drama written for and more or less adapted to them. Excellent evidence that there was insufficient consonance is to be found in the megaphone mouthpieces used at times in both the tragic and the comic masks, and in the proposal by Vitruvius to use resonant vases to strengthen the voice.

The doubt is not as to whether a speaker, turned directly toward the audience and speaking in a sustained voice, could make himself heard in remote parts of a crowded Greek theatre. It is almost certain that he could do so, even in the very large and more nearly level theatres, such as the one at Ephesus. Better evidence of this than can be found in the casual test of a lonely ruin is the annual performance by the staff of the Comédie Française in the theatre at Orange. But even this, the best preserved of either Greek or Roman theatres, is but a ruin, and its temporary adaptation for the annual performance is more modern than classical. A much better test is in the exercises regularly held in the Greek Theatre of the University of California, designed by Mr. John Galen Howard, of which President Wheeler speaks in most approving terms. The drama, especially modern drama, differs from sustained speech and formal address in its range of utterance, in modulation, and above all in the requirement that at times it reach the audience with great dynamic quality but without strain in enunciation. Mere distinctness is not sufficient. It was through a realization of this that the megaphone mouthpiece was invented—awkward in use and necessarily destructive of many of the finer shades of enunciation. That it was only occasionally used proves that it was not a wholly satisfactory device, but does not detract its evidence of weakness in the acoustics of the theatre.

The megaphone mouthpiece bears to the acoustics of the Greek theatre the same evidence, only in a reciprocal form, that the mask itself bears to the theatre's illumination. It was not possible to see in bright daylight, particularly in the bright sunlight of the Mediterranean atmosphere, with anything like the accuracy and detail possible in a darkened theatre with illuminated stage. The pupil of the eye was contracted, and the sensitiveness of the retina exhausted by the brilliancy of the general glare. Add to this that the distance from the stage was very much greater in the Greek than in the modern theatre, audience for audience, and one can realize the reason for the utter impossibility of facial expression in Greek dramatization except by artificial exaggeration. The heaviness and inflexibility of these devices, and therefore their significance as proof of some inherent difficulty in dramatic presentation, is emphasized by the delicacy of line and fine appreciation of the human form shown in other contemporaneous art.

Not less significant in regard to the acoustics of the Greek theatre are the directions given by Vitruvius for the reënforcement of the voice by the use of resonant vases:

"Accordingly bronze vessels should be made, proportional in size to the size of the theatre, and so fashioned that when sounded they produce with one another

the notes of the fourth, the fifth, and so on to the double octave. These vessels should be placed in accordance with musical laws in niches between the seats of the theatre in such position that they nowhere touch the wall, but have a clear space on all sides and above them. They should be set upside down and supported on the side facing the stage by wedges not less than half a foot high. . . . With this arrangement, the voice, spreading from the stage as a center and striking against the cavities of the different vessels, will be increased in volume and will wake an harmonious note in unison with itself."

There is good reason for believing that this device was but very rarely tried. This, and the fact that it could not possibly have accomplished the purpose as outlined by Vitruvius, is not germane. The important point is that its mere proposal is evidence that the contemporaries of the Greek theatres were not wholly satisfied, and that the defect was in lack of consonance.

It would be inappropriately elaborate and beyond the possible length of this paper to give in detail the method of calculating the loudness of sound in different parts of an auditorium. That subject is reserved for another paper in preparation in which will be given not merely the method of calculation but the necessary tables for its simplification. It is, however, possible and proper to give a general statement of the principles and processes involved.

In this discussion I shall leave out as already adequately discussed the phenomenon of interference, or rather shall dismiss the subject with a statement that when two sounds of the same pitch are superposed in exact agreement of phase, the intensity of the sound is the square of the sum of the square roots of their separate intensities; when they are in opposite phases, it is the square of the difference of the square roots of their intensities; but when several sounds of the same pitch arrive at any point in the room with a random difference of phase their probable intensity is the simple numerical sum of their separate intensities. It is on the assumption of a random difference of phase and an average probable loudness that I shall here consider the question. This has the advantage of being the simpler and also a first approximation in an auditorium designed for articulate speech.

When sound spreads from a spherically symmetrical source it diminishes as the square of the distance. When the sound is being propagated, still in space unrestricted by walls or ceiling, but over the heads of a closely seated audience, the law of the diminution of the sound is more rapid than the law of the inverse square. This more rapid diminution of the sound is due to the absorption of the sound by the audience. It is a function of the elevation of the speaker and the angle of inclination of the floor—in other words, the angle between the sight lines. The diminution of the intensity of the sound due to distance is less the greater this angle.

If the auditorium be enclosed by not too remote walls, the voice coming directly from the speaker is reënforced by the reflection from the retaining walls. However, it is obvious that the sounds reflected from the walls and ceilings have traversed greater paths than the sound of the voice which has come directly. If this difference of path length is great, the sounds will not arrive simultaneously. If, however, the path differences are not great, the reflected sounds will arrive in time to reënforce the voice which has come directly, each syllable by itself, or, indeed, in time for the self support of the sub-syllabic components. It is to this mutual strengthening of concurrent sounds within each element of articulate speech that Vitruvius has given the name "consonance."

Thus in the computation of the intensity of the voice which has come directly from the speaker across the auditorium it is necessary to take into consideration not merely the diminution of intensity according to the law of the inverse square of the distance and the diminution of the intensity due to the absorption by the clothing of the audience, but also, as a compensating factor for the latter, the diffraction of the sound from above which is ever supplying the loss due to absorption, while in computing the intensity of the sound reflected from any wall or other surface one must take into consideration all this, and also the coefficient of reflection

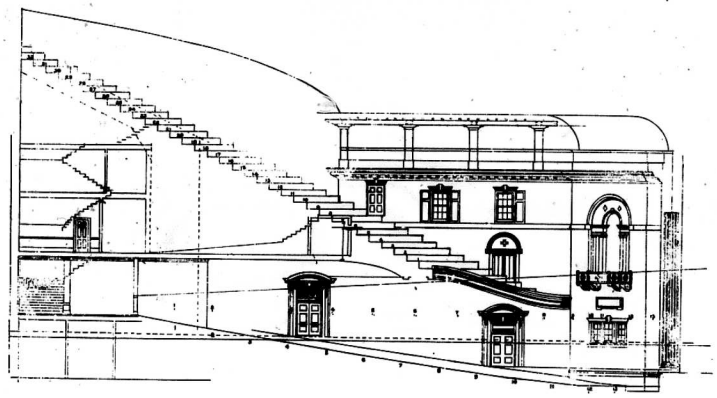


FIG. 37. THE HARRIS THEATRE, MINNEAPOLIS, FIRST DESIGN.
MESSRS. CHAPMAN & MAGNEY, *ARCHITECTS*

of the wall and the diffraction due to the restricted area of the reflecting element.

Abstract principles are sometimes tedious to follow even when not difficult. In Figure 38 is shown a photograph taken in an investigation for the architects, Messrs. Chapman and Magney, of the Harris Theatre, to be erected in Minneapolis, which affords an excellent example of both favorable and unfavorable conditions in respect to consonance. The initial sketch for this theatre offered no problems either of interference or reverberation, and of echo only in the horizontal section. The only very considerable question presented by the plans was in respect to consonance and there in regard only to the more remote parts of the floor and of the balcony. The particular photograph here reproduced records the condition of the sound in the room at such an instant as to bring out this aspect of the problem in marked degree.

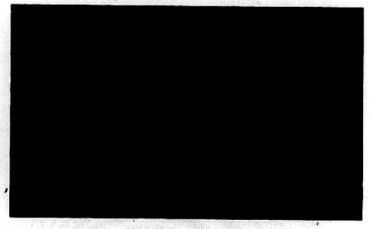


FIG. 38. SHOWING THE CONSONANCE IN THE BALCONY OF THE HARRIS THEATRE. THIS RELATES ONLY TO CONSONANCE IN THE VERTICAL SECTION.

The forward third of the balcony in this theatre affords an excellent example of consonance, for the reflection from the ceiling arrives so nearly simultaneously with the sound which has come directly from the stage as to "strengthen and support" it and yet "leave the words clear and distinct." The interval between the two, the direct and the reflected voice, varies from .01 seconds to .03 seconds. Back of the first third, however, the consonance from the ceiling gradually diminishes and is practically imperceptible beyond the middle of the gallery. Back of that point the direct voice diminishes rapidly since it is passing in a confined space over the highly absorbent clothing of the audience. The loss of intensity at the rear of the gallery is increased by the carrying of the horizontal portion of the ceiling so far rearward. While the effect of this is to throttle the rear of the gallery it obviously strengthens the voice in the forward third. Although there is thus some compensation, on the whole the forward part of the gallery does not need this service so much as the rear seats. The photograph shows this process clearly: the main sound wave can be seen advancing after having passed the angle in the ceiling. The wave reflected from the ceiling can be seen just striking the gallery seats. It is evident that at the instant at which the photograph was taken the sound wave was receiving the last of this support by the sound reflected from the ceiling.

The photograph also shows how the sound after passing the ceiling angle spreads into the space above, thus losing for the moment thirty per cent. of its intensity, a loss, however, to be regained in considerable part later.

On the main floor the reflection from the ceiling strengthens the direct voice only for the long syllabic components. Nevertheless, in comparison with other theatres the forward part of the floor of this theatre will be excellent. There will be just a trace of echo immediately under the front of the balcony, but this will be imperceptible beyond the first four rows of seats under the balcony. It is obvious from the photograph that there is no consonance in the rear of the main floor of the auditorium under the balcony.

A not unnatural, certainly a not uncommon, inquiry is for some statement of the best height, the best breadth, and the best depth for a theatre, for a list of commended and a list of prohibited forms and dimensions. A little consideration, however, will show that this is neither a possible nor the most desirable result of such an investigation.

For a simple rectangular auditorium of determined horizontal dimensions there is a best height. When, however, the horizontal dimensions are changed the desirable height changes, although by no means proportionally. When the floor is inclined, when the walls are curved, when there are galleries and connecting corridors, when the material of construction is varied in character, the problem becomes somewhat more intricate, the value of each element being dependent on the others. Moreover it is futile to attempt to formulate a standard form even of a single type of auditorium. How greatly the design must vary is well illustrated in the four theatres which have been taken as examples—the Little Theatre with all the seats on the main floor, the Harris Theatre, very long, very broad, and with but a single gallery, the Scollay Theatre with two galleries, and the New Theatre with two rows of boxes and two galleries. The fundamental conditions of the problem, not the entirely free choice of the architect, determined the general solution in each case. Acoustical quality is never the sole consideration; at best it is but a factor, introduced sometimes early, sometimes late, into the design.