
Reverberation and the Art of Architectural Acoustics

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In 1895 Harvard University, that *other* school situated on the Charles River, opened its Fogg Art Museum. This wonderful building, still much used today, contained an equally wonderful, large lecture hall. Audiences flocked in, eager to experience intellectual enlightenment in beautiful new surroundings.

But there was a large, ugly fly in this intellectual ointment: No one could understand any of the lectures that were given in Fogg lecture hall. And it wasn't because the lectures were too esoteric, or because the lecturers mumbled into their beards, or because the students were too distracted. The problem was acoustics and hearing.

For help, Harvard turned to one of its own, **Wallace Clement Sabine** (photo), then a 27 year-old Assistant Professor of Physics. To that point in his career, Sabine had distinguished himself primarily through his teaching; research productivity was not his strongest suit. Even though Sabine had not previously worked with this sort of problem, his writings show that he was a remarkably quick study and a truly dedicated scientist. His published work also provides a model of good, clear scientific prose. After diagnosing and then solving Harvard's problem with the Fogg lecture room, Sabine devoted the rest of his career to the new field that he had virtually created in the process: architectural acoustics.

First, Sabine noted that when anyone spoke in the Fogg Museum lecture room, even at normal conversational levels, the sound of his or her voice remained audible in the room for several seconds thereafter. You can imagine how difficult this made it to comprehend what the speaker was saying. The speaker's words first reached the listener directly. Then several, successive acoustic "copies" of the speaker's words reached the listener. These "copies" were produced by strong sound reflections from various hard surfaces in the room. If enough surfaces produced strong, audible reflections, listeners would be bombarded by several versions of lecture, each version only slightly delayed in time relative to its predecessors.

Sabine found that when a lecturer spoke at a normal conversational level and then stopped, his or her last words remained audible for about 5.5 seconds. During these 5.5 seconds, if the speaker had not stopped, he or she might have uttered an additional 12-15 words. A listener, then, had to contend with a real jumble: a mixture of i) what the speaker was saying right now, and ii) everything else that the speaker had said during the previous 5.5 seconds.

This was a definitely low-tech operation. With just a stop watch, highly trained auditors, and a portable pipe organ pipe for equipment, Sabine used compressed air to create sounds of any steady level. Upon shutting off the compressed air flowing through the organ pipe, he measured how long it took for the sound to become inaudible. He found first that it didn't make much difference where the auditor stood, or where in the hall the sound source was. As a result, his findings had considerable generality.

We can translate Sabine's basic finding into modern units. Recall that normal conversational-level speech remained audible for 5.5 seconds. Since normal conversational level is about 1,000,000 times above threshold intensity, Sabine's measurements meant that it took 5.5 seconds for the sound level to drop by a factor of 1,000,000 (60 db).

Sabine made thousands of measurements in Fogg Hall. And he made similar numbers of measurements in other rooms at Harvard. He found that in different rooms, sound took different amounts of time to die away --to drop by 60 db. Sabine used the term **reverberation time** to signify the time that is needed for a sound's intensity to drop by 60 db. Sabine discovered that reverberation time increased with a hall's volume; he also found that a hall's reverberation time could be drastically changed by the hall's contents and building materials.

In October 29, 1898, Sabine derived the expression that relates reverberation time to two key variables. In his expression, T is the time required for the residual sound to decay below audible intensity, starting from a 1,000,000 times higher initial intensity:

$$T = 0.161 V/A$$

where V is the room's volume in cubic meters, and A is the total absorption in square meters. More than a century later, Sabine's equation remains a foundation of architectural acoustics.

Studying various rooms that had been judged to be acoustically good, Sabine discovered that good concert halls tended to have reverberation times of 2-2.25 seconds (at shorter reverberation times, a hall would seem too "dry" to a listener's ears); and that good lecture rooms had reverberation times of slightly under 1 second (at longer reverberation times, speech became too blurred and confused).

Sabine's studies of reverberation time in Fogg Hall are models of careful science. In one set of studies, he brought in seat cushions from another Harvard building, Sanders Theater. With various numbers of cushions inside Fogg, Sabine discovered that reverberation time decreased as a function of the number of cushions. He also tested reverberation time with several different types of Oriental rugs inside Fogg, and with various numbers of people occupying its seats. He discovered that the body of an average person decreased reverberation time by about as much as did slightly more than six seat cushions.

After experimenting with several different substances, Sabine discovered that felt, used as a wall covering, reduced the

reverberation time down to the point at which speakers would be intelligible. Felt coverings later became a fixed part of the hall's permanent decor.

Later, Sabine helped to design Symphony Hall in Boston, home to the Boston Symphony Orchestra, and one of the world's great concert halls. On the basis of Symphony Hall's volume, and knowing what materials the hall would contain, Sabine made a remarkably accurate prediction of what the future hall's reverberation time would be. Reverberation time is not the only variable that controls the acoustic quality of a concert hall, the hall's overall shape is quite important, too. For a discussion of this variable, and of why no recent concert hall can match the acoustic quality of Symphony Hall, you can read==> read an article by Nicholas Edwards that appeared in Architectural Record (1984).

It's definitely not convenient to base scientific measurements, no matter how carefully made, upon units such as seat cushions. It is more convenient to base these particular measurements upon an easily obtained, near-perfect absorber of sound --an open window. A unit of absorption, known as the Sabin, is defined by the sound absorbing ability of an open window that is one foot square in area. Here are some examples of this measurement:

- one square foot of thick Oriental carpet equals 0.25 Sabins
- four square feet of the same carpet equals one Sabin
- a seat cushion from Sanders Theater equalled 0.7 Sabins
- one square foot of brick or plaster, either of which absorbs very little sound, equals about 0.02 Sabins
- one adult human, sitting in an audience equals about 4.7 Sabins
- a pair of adult humans equals about 9.4 Sabins.

Finally, Sabine realized that the total acoustic disturbance produced by any ensemble's instruments must be intense enough to overcome the concert hall's tendency to absorb sound. Otherwise, the hall will "soak up" much of the available sound, leaving little for the the audience to hear, and causing the audience to complain that the music lacks "body." If the ensemble produces too much sound for that room, the effect would be overpowering and unpleasant. In fact, Sabine's successors have developed quantitative expressions that match the size and makeup of any musical ensemble to the sound absorption of the concert hall. This precision is a far cry from the crudity of Sabine's original, emergency rescue effort at the Fogg Museum.