Fogg Art Museum Lecture Room,  
A calibrated recreation of the birthplace of Room Acoustics

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At the end of the 19th century, an assistant professor of physics at Harvard University named Wallace Clement Sabine undertook the task of correcting the acoustics of the Fogg Art Museum Lecture Hall. Rather than merely correcting the acoustics, Sabine’s work on this acoustically difficult space (semicircular, domed, with arched perimeter) formed the basis for his monumental research on reverberation time and absorption. This work and its subsequent publication established Room Acoustics as a real science, rather than guesswork and luck. During the next 70 years the room underwent several large renovations, and was demolished to make space for student housing in 1973. Learning of the impending demolition, one of the authors was fortunately able to access the room, making several room impulse response measurements the day prior to its final destruction. A computational room acoustics model has been created using architectural plans and the few available photographs. The historically important impulse response measurements of the room provide a reference calibration for the model. The geometrical model includes the various architectural phases of the room during its lifetime. Through simulation and auralization these versions of the room are restored in acoustical terms, allowing one to “experience” an educated rendering of the original acoustics as Sabine found it in 1895. The results of this study, in particular the geometrical model, will be made available for public use, to allow future room acoustics students and researchers the opportunity to aurally follow in Sabine’s footsteps.

In 1973 a significant building in the history of acoustics was destroyed. Harvard University’s first Fogg Art Museum, which housed the lecture room that prompted Wallace Clement Sabine’s interest in architectural acoustics, was demolished. However, a link to this space was preserved so its acoustical characteristics can be explored again. As computer models and auralization become ubiquitous for projects, the use of the computer model for renovation as a yardstick for comparing various options is an attractive supposition. But, this can only be the case if the “original” model can be considered “accurate”. In this study, an attempt is made to create a calibrated model, based on historical measurements and post renovation measurements, turning back the clock to recreate and hence revisit this historical room.

1 Fogg Art Museum – History

Opened in 1894, the museum was designed by a leading architect, Richard Morris Hunt. It was soon found that the semicircular, domed lecture room was acoustically unsatisfactory. Its most vocal critic was the senior lecturer in fine arts, Charles Eliot Norton, who was also a cousin of the University president. Because of the widespread criticism elicited largely by Norton’s comments, President Eliot instructed Wallace Clement Sabine, a young assistant professor of physics, to address the acoustics with (in his words) “…the end in view of correcting the lecture-room which had been found impractical and abandoned as unusable.” [1]

Sabine’s analysis of the lecture room is best described in his 1898 presentation [2] and in the numerous letters published in W.D Orcutt’s 1933 biography of Sabine. [3] Sabine stated that following his acoustic treatments the lecture room was “…not excellent, but entirely serviceable… without serious complaints.” [2] Why his opinion was not shared by others is not clear, but in 1911-12 the lecture room was reduced from over 400 seats to around 200. In the words of the museum director: “We hope for a… roof that does not leak (and) a medium-sized lecture hall instead of a large one in which you cannot hear.” [4]

No records have been found on the lecture room from the 1911-12 remodeling to 1927 when the new Fogg Art Museum was opened and the old building became an annex to the school of architecture. However, the drawings for the remodeling showed a new inner semicircular wall with no sound absorbing material.

In 1935, the year that the Faculty of Design was established, the building was renamed Hunt Hall in honor of its architect. Around this time a layer of hair felt covered by a perforated asbestos board was installed on the lower two thirds of the inner wall. Little additional information prior to 1965, when the room was first carpeted, could be elicited either from available documents or former occupants.
In 1972 the museum was returned to the Fine Arts faculty and some inexpensive changes were made to the lecture room. A flat canopy was added over the raised lecturer’s platform and an eight foot high band of highly absorptive material was added around the semi-circular inner wall. In 1973 a student report described the acoustical changes in the following manner: Before remodeling, focused reflections from walls and ceiling created locations at which “…the sound was reinforced making hearing very easy (assuming the speaker did not move). Conversely there were dead spots where hearing was often extremely difficult.” After the remodeling, the student report concluded that “Having attended two classes a week since these corrections were made, I can say that the hearing conditions … have been drastically improved. A speaker anywhere to the front of the room can be heard clearly throughout the hall.”[5]

The building was demolished in 1973 to make way for a student dormitory. So, for at least its final year, speech intelligibility in the room seemed to be relatively acceptable.

2 Acquisition of information

Acoustic reconstruction of an historical building, especially one that is no longer standing, begins with the accumulation of documentation concerning not only the geometry but also the construction materials. The documents found describing this room cover over 70 years, as the building underwent a series of renovations. Documents include original publications by Sabine himself, various architectural drawings, photographs, and several acoustical measurements.

2.1 Sabine’s papers

In Sabine’s important work, “Reverberation”, the Fogg Art Museum was introduced. [2] His drawing is reproduced here in Figure 1. In addition to the drawing, a number of acoustical and construction details are given, summarized in Table 1. Subsequent to the fundamental research efforts in the room, establishing the relationship between absorption and reverberation time (first in terms of theatre seating cushions, then in terms of open window area) the room was modified from its original design through the addition of an absorbing material. According to Sabine, “…hair-felt one inch in thickness was glued to the walls in the rectangular spaces between the windows and on the recessed lunettes in the ceiling. Over this was stretched asbestos cloth, also of moderately high absorbing power...The asbestos was placed in contact with the felt, and held against it by an office-wire grating. The use of this construction was immediately successful, and it has remained untouched, the lecture room being used constantly, not merely for classes, but for public lectures and musical concerts.”[3]

The absorption coefficients for 1-inch felt and Sabine’s seat cushions are found in two other papers, “Musical Pitch” and “Architectural Acoustics” respectively (see Table 1). [6] These publications provided the only reference for the original acoustical state of the room. While there are a great deal of data concerning the experiments with cushions, no data were found regarding the post-treatment conditions.

Table 1. Sabine’s construction and acoustical data. [6]

<table>
<thead>
<tr>
<th>Volume</th>
<th>2740 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation Time (512 Hz)</td>
<td>5.61 sec</td>
</tr>
<tr>
<td>Total abs. (open window area): room empty</td>
<td>75.5 m²</td>
</tr>
<tr>
<td>Walls, plaster on tile (α at 512 Hz)</td>
<td>0.025</td>
</tr>
<tr>
<td>Dome, plaster on lath (α at 512 Hz)</td>
<td>0.033</td>
</tr>
</tbody>
</table>

α vs. freq: 1-inch thick hair felt and Sanders Theatre seat cushion.

Table 1. Sabine’s construction and acoustical data. [6]

<table>
<thead>
<tr>
<th>Organ Note</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>~Freq (Hz)</td>
<td>31</td>
<td>63</td>
<td>125</td>
<td>250</td>
<td>500</td>
<td>1k</td>
<td>2k</td>
</tr>
<tr>
<td>Felt (1 inch)</td>
<td>0.12</td>
<td>0.14</td>
<td>0.23</td>
<td>0.54</td>
<td>0.64</td>
<td>0.56</td>
<td>0.52</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.24</td>
<td>0.28</td>
<td>0.39</td>
<td>0.54</td>
<td>0.59</td>
<td>0.53</td>
<td>0.46</td>
</tr>
</tbody>
</table>

2.2 Architectural drawings

It was not learned until after the start of demolition that the University had no drawings of the museum prior to 1900. This discovery prompted a search, probably still incomplete, lasting three years for sources of information. Drawings were compiled from several sources, primarily based on a plan and section found in the archives of the city building department. Resulting plans and sections were published in [7]. While consistent with Sabine’s drawings, later investigation has confirmed some inconsistencies with other drawings discovered later (see Figure 2 and discussion in section 3.1).
Following a presentation in 1973 [9], copies of the paper were sent to many people whose names had surfaced in discussions with former faculty and staff familiar with the original Fogg Art Museum, with requests for any information that could be added. It is gratifying to re-read the correspondence from librarians, retired faculty, researchers and others who were very generous with time and recollections. One person suggested a check of records at the new Fogg, where a staff member not only found a photograph of the original room but also introduced a retired professor whose class notes from Sabine’s course in architectural acoustics are now in Harvard’s Pusey Library. This photo, shown in Figure 3, was used for the proceedings’ cover of the Sabine Centennial Symposium. [10] Some information acquired after the 1973 presentation was presented in 1976. [11]

The re-examination of correspondence and notes prompted by the current study elicits distinct regret for the many questions that, in hindsight, could have been asked of several elderly correspondents from 1973 to 1976. A particular regret is that, had the dearth of information been apparent, more photographs could have been taken and interior dimensions could have been verified. However, this loss may in some ways be offset by the vastly improved communications afforded by computer resources. A sample of Sabine’s original sound absorbing material should also have been saved from one of the lunettes, or arched recesses, in the dome. It is hoped that continued study of the records will shed further light on the Fogg Art Museum.

To summarize, the lecture room can be characterized as having gone through two architectural modifications since its completion in 1895: in 1912 (volume reduction, flat floor) and 1972 (addition of canopy). In addition, there were three purely acoustic modifications: 1898 (Sabine’s acoustic treatment), c.1930 (acoustic panels added on lower portion of rear wall) and c.1965 (floor carpeted).

The demolition of the original Fogg Art Museum began on 16-June-1973. In the preceding weeks, with the support of several University departments, acoustical measurements were made on two occasions. On 5-June, with the room in its final configuration, tape recordings were made of sound decay, impulse response, and sound distribution using noise bursts (1/3rd octave) and balloon bursts. Then the canopy was substantially demolished and on 15-June the measurements were repeated. The second set of measurements came perilously close to not taking place because of end-of-year administrative changes.

Using the collection of architectural, photographic, and acoustical details the task of constructing an acoustical model for study and subsequent auralization was possible. As the room had undergone various architectural and acoustic modifications, the goal was to have valid models for the various phases. The primary goal was to arrive at the 1895 and 1898 conditions, those on which Sabine actually worked. In total, three conditions have been considered here: 1895 (pre-Sabine), 1898 (post-Sabine) and 1972, in which the 1912 remodeling, the c.1930 acoustic treatment, and the c.1965 carpet are included. The 1972 canopy has not been included.

Among the general assumptions necessary to make the transition from ink drawings to computer model, the lack of a lateral section and reflected ceiling plan made

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**Figure 2. Architectural section, colorized to better visualize the building structure.**

**Figure 3. Interior photo of lecture-room after 1898. Courtesy of Fogg Art Museum, Harvard University.**
creation of the dome and skylight areas difficult and posed many questions. In addition, the majority of photos taken do not show the ceiling or higher elevations or were taken with the large canopy in place, masking the dome and arches. For this part of the model, the 1898 photo (Figure 3) was the only real source of information. A great number of assumptions have been based on this photo.

### 3.1 Conflict between drawings

Several discrepancies were found when comparing the various section drawings (see Figure 1 and Figure 2). First, regarding the curvature of the dome and arch above the platform; in Sabine’s drawings these curved surfaces are circular. In contrast, Figure 2 shows a composite curve. While the authors have great respect for Sabine’s acoustical work, they have more faith in the architectural study in terms of determining the actual geometry of the room. Inspection of Figure 3 supports the non-circular form.

The second major discrepancy was the determination of the height of the room. In using Figure 2, it was found that the noted height was inconsistent with the other dimensions of the room, being 9% smaller. As Sabine’s drawing did not include dimensions, a calibration between the drawings would be necessary. Comparisons of other dimensions on the drawing showed the single inconsistent dimension was the height. This was shown as referenced to an external measure on the outside of the building. A final comparison was performed using photographs taken during the 1973 measurement sessions. These supported the hypothesis that the height was erroneously labeled and it was decided to discount this single noted dimension. These decisions result in the final model being based on a combination of dimensions from drawings of various sources.

### 3.2 Geometrical Model 1972

A base model was created which contained architectural elements constant between the eras: the platform wall and arc and the dome. Most of the model was parameterized using circle and ellipse equations approximated from the architectural drawings. The dome section also has rotational symmetry, so there was need for only one “pie slice” to be modeled, then simply duplicated. The model is shown in Figure 4. Source, $A_1$, and receiver positions, $O_1$ and $O_2$, for the measurement session (see section 2.3) are also shown.

### 3.3 Geometrical Model 1895

The earlier era model was created by replacing the flat floor and rear wall (installed in the 1912 renovation) by the original architecture. The model is shown in Figure 5, including a surface representing the original seating.

During model construction, one of the main resources for verification of the architecture was the singular photo shown in Figure 3. Comparisons were possible through renderings of the model, where the approximate camera position was recreated (see example in Figure 6). While the camera properties are not perfectly recreated, one can make certain judgments on the model. The red shaded surfaces, back of the lunettes and between the windows, are those on which Sabine installed acoustic treatment. Certain aspects appear to be slightly in error, though are not considered crucial, such as the tip intersection of the lunettes and dome. A final comparison of interest is with regard to the room volume. The model has an interior volume of 2632 m³. This is approximately 4% smaller than Sabine’s estimate (see Table 1).
4 Acoustic model calibration

Aside from the collection of architectural and anecdotal details on the lecture-room, this study includes actual acoustical measures in the room (albeit after several renovations). The approach for this study was to work backwards, from the 1972 room with the corresponding measured data back through the renovations to arrive at the earlier states. Agreement between the model predictions and measurements should provide some confidence in the reconstruction.

Replicating the measurement positions of 1973, the reverberation time (RT) was compared with the model. The measured data exhibited a dip in RT at 500 Hz. Some minor adjustments were made to absorption coefficients (particularly for the ventilation grilles near the skylight) and the diffusion coefficients (to account for the debris of the canopy on the floor during the measurements). The final state of the model using ray tracing techniques (T15 and T30) and traditional Sabine Reverberation Time calculation are compared to the measured data (typically T15 due to low S/N ratios), with results shown in Figure 7. The T15 calculation matches extremely well, with small variations at lower frequencies for T30. Sabine’s diffuse field prediction equation is slightly less consistent with the measurement results.

While reverberation time is a good descriptor, it is statistical in nature, and does not represent the fine structure of the impulse response (IR). A final, more specific comparison was also made between the measured IR (balloon burst recordings) and calculated IR from the acoustical model. The magnitude of the IR, smoothed using a 12 msec Gaussian window, was used. An example is shown in Figure 8. The alignment and magnitude of the major features is very good. The first major feature, near 0.05 sec, corresponds to reflections from the skylight and dome. The second cluster of reflections, 0.17 sec, is attributed to multiple clusters of reflections generated from the circular form in plan of the room.

5 Comparison 1895 & 1898

Using the model characteristics established through the calibration procedure (refinement of the acoustical properties of materials), it was now possible to undo the series of renovations occurring over the time span 1910 – 1973. Using the pre-renovation models, numerous acoustical parameters can be predicted, as well as the generation of IRs for auralization. While the latter is the goal, it is difficult to include them in a printed article. For that reason, several of the acoustical parameter results are presented.

5.1 Comparison with Sabine’s data

The fundamental room acoustic parameter is Sabine’s reverberation time. Predicted RT values for the models are given in Table 2. These can be compared to Sabine’s pure-tone measurement of 5.61 sec at 512 Hz for the 1895 state, representing a difference of only 4%, which is within the tolerance for perceptual and
There is also a clear reduction in reverberation time following Sabine’s treatment. But, one must note that it does not approach the low values obtained during his scientific study using cushions where he obtained 2.03 sec with all seats covered, and a notable 1.14 sec with 1500 cushions placed throughout the room. [2]

Table 2. Predicted reverberation time: 1895 & 1898.

<table>
<thead>
<tr>
<th>T15</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1k</th>
<th>2k</th>
<th>4k</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895</td>
<td>3.85</td>
<td>4.49</td>
<td>5.40</td>
<td>5.93</td>
<td>4.77</td>
<td>2.95</td>
</tr>
<tr>
<td>1898</td>
<td>3.5</td>
<td>3.26</td>
<td>3.49</td>
<td>3.76</td>
<td>3.34</td>
<td>2.32</td>
</tr>
</tbody>
</table>

### 5.2 Intelligibility measures

A parameter of great interest in the context of this room and its use is that of intelligibility. This was cited as the major fault of the room, and the reason for Sabine’s involvement. A comparison of the intelligibility before and after Sabine’s intervention is presented in Figure 9. The lack of homogenity as mentioned by the accounts is clear. While Sabine’s treatment seems to have improved the intelligibility near the center of the room (particularly at the rear), there still remained a section of seating (dome radial angle region 20°-40°) with a consistently BAD/POOR intelligibility rating. In general, the room would still be classified as having POOR intelligibility.

![Figure 9. STI Comparison: 1895 & 1898.](image)

### 6 Summary

This study presents the documentary work, as well as the acoustical modeling method, adopted in an attempt to acoustically reconstruct the Fogg Art Museum Lecture-room. Using measured data and related published data by Sabine, a calibrated prediction and simulation model has been created. Comparisons of acoustical parameters and impulse responses indicate a valid model. Initial analysis of intelligibility through predictions appears to corroborate the anecdotal evidence for the poor acoustic functioning of the hall and its strong lack of homogeneity.

As the goal of this study has been to acoustically explore this historic building, through simulation and auralization, the authors have chosen to make the model files available for educational and academic use. The authors would like to thank Harvard University and Boston Public Library for continued support and Bengt-Inge Dalenbäck of CATT for making the model accessible to the general public (available at [www.catt.se/FoggArtMusum.htm](http://www.catt.se/FoggArtMusum.htm)). All computer models and simulations were performed using CATT-Acoustic v.8.0c. [13] The authors would also like to thank Kurt Graffy and Larry Tedford for their assistance and particularly for introducing the authors with the purpose of realizing this study.

### References


