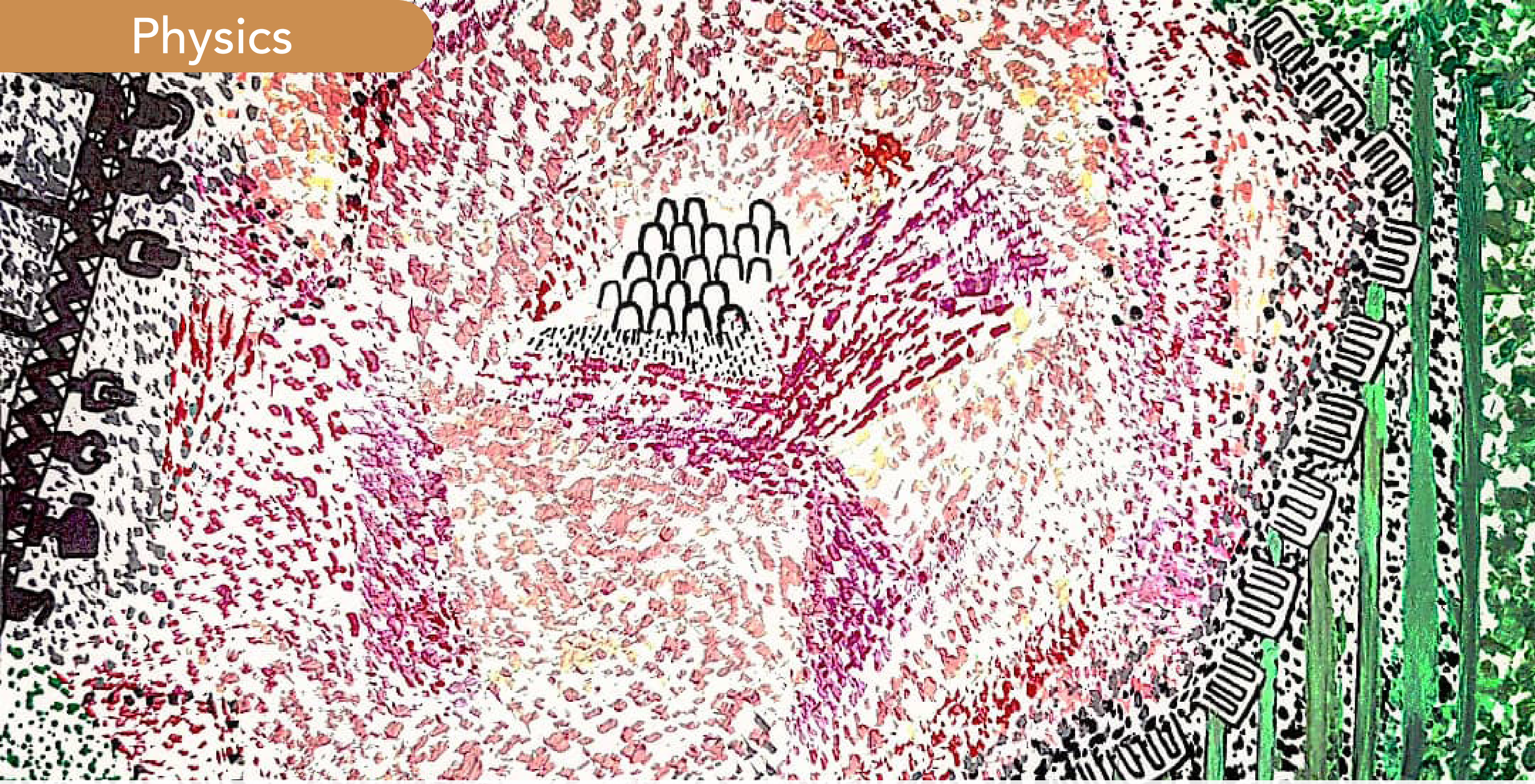
The Synapse: Intercollegiate science magazine

Volume 30 | Issue 1 Article 9

2022

The Acoustics of Concert Halls: Where Science, Music, & Visual Arts Meet

Norah Han



The Acoustics of Concert Halls

Where Science, Music, & Visual Arts Meet

Written by Norah Han
Illustrated by Seyeong Hanlim

Music, an expression of emotions through melodies and stories, might have little to do with science at first glance. However, the process of producing and performing music is fundamentally connected to science. A fundamental component of music is sound waves, which essentially work to transmit the noise from the instrument to your ears. A wave is created when a disturbance results in energy transferring across a medium, vibrating the medium's molecules as the wave propagates across, in this case, air. Sound waves are a type of compression or longitudinal wave, where the medium's molecules vibrate along the same direction of the wave propagation. The properties of these sound waves determine what you hear. Fortissimo and pianissimo can be distinguished by differences in the amplitudes of waves, and the distinct pitches of the notes correspond to the frequency. Other components of music performance are also fundamentally scientific in nature. For example, the tuning of instruments follows a mathematical structure. To further explore the interconnection between science and music, we are going to look into a specific example: the design of concert halls. The design of the concert hall is an ingenious amalgamation of artistic finesse and mathematically reliable designs. For centuries, architects have approached the design of concert halls with artistic intuition and slight technical consideration. Only recently has the field of concert hall design gone through a development. Physicist Wallace Clement Sabine proposed a more precise, conclusive mathematical equation that gauges the quality of the halls' acoustics.

History: Looking Back

Concert halls are typically designed for live music events, particularly symphonic works. Usually, a hall's audience capacity ranges from 300 to 2500 seats. The earliest concert halls that played western music took form as medieval churches, where the tall stone structures would resonate with resounding religious chants. The nature of the music developed to be performed in these churches specifically was inevitably shaped by the architecture—particularly, its acoustics and size. Further highlighting the intangible yet steadfast connection between music and the space that it is made for and performed in. Moreover, composers such as Richard Strauss and Hector Berlioz have emphasized that when composing a piece of music, it is crucial for one to gain a firm understanding of the nature of acoustics, and how different architectural structures are more beneficial for various musical genres. Another example is when Johann Sebastian Bach, patronized by Prince Leopold of Cöthen, composed his Brandenburg Concertos with the performance space in mind (the Prince's court). His concertos were composed for a relatively small-size orchestra and had intricate counterpoints that fit the limited room space with a relatively low reverberation time, which is the time that a sound takes to become imperceptible.

Concert Halls in the Real World

Among the numerous concert halls worldwide, Großer Musikvereinssaal in Vienna, Concertgebouw in Amsterdam, and the Boston Symphony Hall might be among the most famous and long-standing. The former two halls represent typical historical halls designed with an approach that emphasizes aesthetics, while the latter epitomizes the application of mathematical calculations for concert hall design. The three most common concert hall design styles are the shoebox, the fan-shaped, and the vineyard style. They stand out as popular models adopted by architects as they each have their advantage in aesthetics, acoustical efficiency, or both. The shoebox style enjoys the longest history and is widely adopted by both past and modern architects. As its name implies, a shoebox-style concert hall consists of a high-ceiling rectangular space, typically with seats on the first floor and upper-floor balconies built along the three parallel walls. This results in acoustics where the hall's sidewalls reverberate and enhance sounds in such a way that they are delivered to listeners from an angle that ensures maximal aural sensitivity. One disadvantage to this kind of design is flutter echoes. Flutter echoes are created when a sound is trapped between two parallel surfaces. Its movement, which happens in a relatively small period, generates a mini energy "tornado" between the two surfaces thus distorting the sound when delivered to the listeners' ears. Another type that is commonly adopted in modern period concert halls is the fan-shaped style. The fan-shaped style takes the form of a fan, with the stage at the fan's handle tip and the seating sections arranged in an arc shape along its edge. The hall's spacious shape ensures that the sound can be reflected and transmitted through the air effectively. Moreover, this design ensures that the problem with flutter echoes is effectively prevented, as the parallel walls are nonexistent. However, this can be a double-edged sword. As the fan-shaped hall filters out the lateral reflections, it prevents adequate transmission of the music's nuanced dynamics. Subsequently, the music might lack the enveloped and warm characteristics of pleasant acoustic sounds. The third common type of concert hall, the vineyard style, is the most novel among them all. In a vineyard-style hall, audience seatings are arranged in a way that is visually tantamount to vineyard slopes. Such an arrangement is quite visually pleasing and the seat sections circumscribe the stage partially from the side. One advantage of this style is that the irregular shape helps to hinder any potential flutter echoes. The downside is that it is complicated to design and not as cost-effective. In addition, without parallel walls that result in lateral reflections in the sound waves, the perceived dynamic range and expression will not be as enhanced, somewhat limiting the quality of the music.

> With formerly undesirably high reverberation time, if the area of sound-absorbing materials is increased, the lecture hall would then have a smaller reverberation time value.

Sabine's Model: A New Milestone

What marks a new milestone in the field of concert hall design and establishes acoustics as a formal field in modern science is a mathematical model proposed by physicist Wallace Clement Sabine. This model gauges a room's acoustical quality and was created under unexpected circumstances. Initially, Sabine started a project that aimed to turn an acoustically disastrous Harvard lecture hall into a functional space. To find a solution, Wallace started by designing and carrying out controlled experiments. With the presence of different materials, Sabine and his co-workers used organ pipes and a stopwatch to measure the amount of time that sounds with different frequencies took to decay to an inaudible level. Subsequently, from his experimental data, Sabine was able to derive a definite relationship between a space's size, total area of sound-absorbing materials, and acoustic quality.

Sabine's model

$T = V \div A \times 0.16$ seconds per meter

This mathematical model enables designers to predetermine the reverberation time of a room, a parameter that gauges the quality of room acoustics, denoted as T in the above equation. The reverberation time approximates the time that a sound takes to become inaudible after the noise source has been turned off. This value will vary for different sounds - for example, a sneeze might only take half a second to decay, while the whistle of a delivery truck might take a longer time. To calculate the reverberation time, one needs to measure V, the size of the space, and A, the total area of the room's surfaces that absorb sounds. This model serves as a fresh mark on the brand new page of the book of acoustics. Since then, acoustics has been studied as a rigorous field in modern science.

The Science Behind Sabine's Model

With his formula in hand, Sabine was able to tackle the inaudible Harvard lecture hall problem — it was because the reverberation time value (5.5 seconds) was too large. With this large reverberation time value, as the speaker lectures on in the hall, the echoes of their words render the speech inaudible. Sabine's solution for this problem is to increase the hall's effective absorption area. Referring to Sabine's model from above, increasing the absorption area means increasing the denominator A in the equation. Since the size of the space, V, remains unchanged, the value of T subsequently decreases. With formerly undesirably high reverberation time, if the area of sound-absorbing materials is increased, the lecture hall would then have a smaller reverberation time value. Thus, the lecture hall's problem with echoes was able to be resolved. Because of his pioneering research in acoustics, Sabine was invited to be the acoustic consultant for the then newly planned construction of the Boston Symphony Hall. Sabine used his formula to set the ideal reverberation time beforehand (1.9 to 2.1 seconds) to achieve maximum acoustic quality. With Sabine's help, the Boston Symphony Hall became the first concert hall designed with mathematical precision in mind.

As is the case with concert hall designs, there are innumerable instances where science and music converge. Since ancient times, musicians and scientists have been trying to unravel the interconnections between the two fields. For example, the ancient Greek mathematician Pythagoras' tuning system produces musical scales and defines the mathematical ratio between the 12 chromatic musical notes. The music composition technique developed in the early 20th century, the 12-tone serialism, requires one to compose a musical piece by carrying out variations on a set of notes and morphing them in an orderly, mathematical way. Chinese polymath Zhu Zaiyu (Ming Dynasty) is arguably the first person who did an exact calculation of the 12-tone equal temperament system, which divides an octave into 12 equal parts on a logarithmic scale . Moreover, questions like why certain combinations of musical notes are pleasing to the ear, why the piano has a broader pitch range than the guitar, and how players follow a piece's tempo and time signature can all be answered through mathematical explanation. Though science and music have distinct characteristics, both intertwine frequently. Science views the world through objective rationality, while music takes a subjective perspective and utilizes the expression of emotions. However, when the two meet, it produces beautiful and enthralling results.