1 HISTORICAL INTRODUCTION

The arts of music, drama, and public discourse have both influenced and been influenced by the acoustics and architecture of their presentation environments. It is theorized that African music and dance evolved a highly complex rhythmic character due, in part, to its being performed outdoors-rather than the melodic line of early European music. Wallace Clement Sabine (1868–1919), an early pioneer in architectural acoustics, felt that the development of a tonal scale in Europe rather than in Africa could be ascribed to the differences in living environment. In Europe, prehistoric tribes sought shelter in caves and later constructed increasingly large and reverberant temples and churches. Gregorian chant grew out of the acoustical characteristics of the gothic cathedrals, and subsequently Baroque music was written to accommodate the churches of the time. In the latter half of the twentieth century both theater design and performing arts became technology driven, particularly with the invention of the electronic systems that made the film and television industries possible. With the development of computer programs capable of creating the look and sound of any environment, a work of art can now not only influence, but also define the space it occupies.

1.1 GREEK AND ROMAN PERIOD (650 BC - AD 400)

Early Cultures

The origin of music, beginning with some primeval song around an ancient campfire, is impossible to date. There is evidence (Sandars, 1968) to suggest that instruments existed as early as 13,000 BC. The understanding of music and consonance dates back at least to 3000 BC, when the Chinese philosopher Fohi wrote two monographs on the subject (Skudrzyk, 1954).

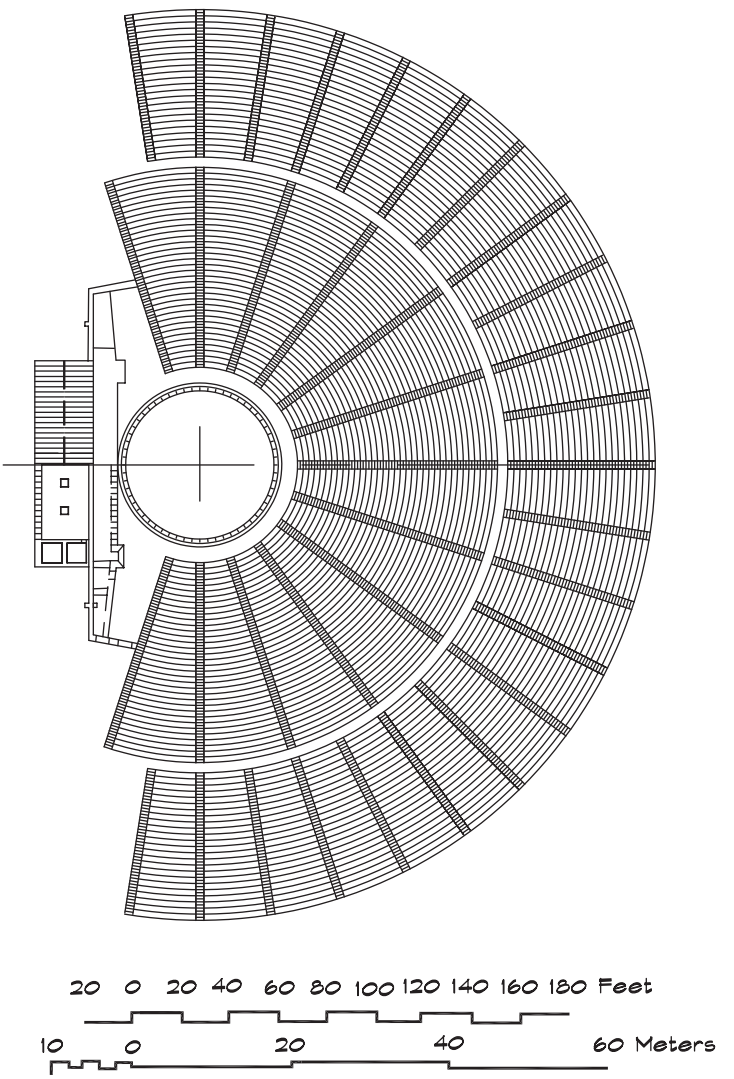
The earliest meeting places were probably no more than conveniently situated open areas. Their form was whatever existed in nature and their suitability to purpose was haphazard. As the need arose to address large groups for entertainment, military, or political purposes it became apparent that concentric circles brought the greatest number of people close to the central area. Since the human voice is directional and intelligibility decreases as the listener moves off axis, seating arrangements were defined by the vocal polar pattern and developed naturally, as people sought locations yielding the best audibility. This led to the construction of earthen or stone steps, arranging the audience into a semicircle in front of the speaker.

The need to improve circulation and permanence evolved , in time, to the construction of dedicated amphitheaters on hillsides based on the same vocal patterns.

Greeks

The Greeks, perhaps due to their democratic form of government, built some of the earliest outdoor amphitheaters. The seating plan was in the shape of a segment of a circle, slightly more than 180°, often on the side of a hill facing the sea. One of the best-preserved examples of the Greco-Hellenistic theater is that built at Epidaurus in the northeastern Peloponnese in 330 BC, about the time of Aristotle. A sketch of the plan is shown in Fig. 1.1. The seating was steeply sloped in these structures, typically 2:1, which afforded good sight lines and reduced grazing attenuation. Even with these techniques, it is remarkable that this theater, which seated as many as 17,000 people, actually functioned.

FIGURE 1.1 Ancient Theater at Epidaurus, Greece (Izenour, 1977)



The ancient Greeks were aware of other acoustical principles, at least empirically. Chariot wheels in Asia Minor were heavy, whereas those of the Greeks were light since they had to operate on rocky ground. To achieve high speed, the older Asian design was modified, so that the four-spoke wheels were smaller and the wooden rims were highly stressed and made to be very flexible. They were so light that if left overnight under the weight of the chariot they would undergo deformation due to creep. Telemachus, in Homer's story of the Odyssey, tipped his vehicle vertically against a wall, while others removed their wheels in the evening (Gordon, 1978) to prevent warping. The wheels were mounted on light cantilevered shafts and the vehicle itself was very flexible, which helped isolate the rider from ground-induced vibrations.

Greek music and dance were also highly developed arts. In 250 BC at a festival to Apollo, a band of several hundred musicians played a five-movement piece celebrating Apollo's victory over Python (Rolland et al., 1948). There is strong evidence that the actors wore masks that were fitted out with small megaphones to assist in increasing the directivity of the voices. It is not surprising that the Greek orator Demosthenes (c 384–322 BC) was reputed to have practiced his diction and volume along the seashore by placing pebbles in his mouth. Intelligibility was enhanced, not only by the steeply raked seating, but also by the naturally low background noise of a preindustrial society.

The chorus in Greek plays served both as a musical ensemble, as we use the term today, and as a group to chant the spoken word. They told the story and explained the action, particularly in the earlier plays by Aeschylus (Izenour, 1977). They may have had a practical as well as a dramatic purpose which was to increase the loudness of the spoken word through the use of multiple voices.

Our knowledge of the science of acoustics also dates from the Greeks. Although there was a general use of geometry and other branches of mathematics during the second and third millennia BC, there was no attempt to deduce these rules from first principles in a rigorous way (Dimarogonas, 1990). The origination of the scientific method of inquiry seems to have begun with the Ionian School of natural philosophy, whose leader was Thales of Miletos (640–546 BC), the first of the seven wise men of antiquity. While he is better known for his discovery of the electrical properties of amber (*electron* in Greek), he also introduced the logical proof for abstract propositions (Hunt, 1978), which led in time to the formal mathematics of geometry, based on the theorem-proof methods of Euclid (330–275 BC).

Pythagoras of Samos (c 570–497 BC), a contemporary of Buddha, Confucius, and Lao-Tse, can be considered a student of the Ionian School. He traveled to Babylon, Egypt, and probably India before establishing his own school at Crotone in southern Italy. Pythagoras is best known for the theorem that bears his name, but it was discovered much earlier in Mesopotamia. He and his followers made important contributions to number theory and to the theory of music and harmony. The word *theorii* appeared in the time of Pythagoras meaning "the beauty of knowledge" (Herodotos, c 484–425 BC). Boethius (AD 480–524), a Roman scholar writing a thousand years later, reports that Pythagoras discovered the relationship between the weights of hammers and the consonance of their natural frequencies of vibration. He is also reported to have experimented with the relationship between consonance and the natural frequencies of vibration of stretched strings, pipes, shells, and filled vessels. The Pythagorean School began the scientific study of harmony and acoustics through these studies. They understood the mechanisms of generation, propagation, and perception of sound (Dimarogonas, 1990). Boethius describes their knowledge of sound in terms of waves generated by a stone falling into a pool of water. They probably realized that sound

was a wave propagating through the air and may have had a notion of the compressibility of air during sound propagation.

Aristotle (384–322 BC) recognized the need for a propagation medium and stated that the means of propagation depended on the properties of the medium. There was some confusion concerning the relationship between sound velocity and frequency, which was clarified by Theophrastos of Eresos (370–285 BC): "The high note does not differ in speed, for if it did it would reach the hearing sooner, and there would be no concord. If there is concord, both notes must have the same speed." The first monograph on the subject, *On Acoustics*, is attributed to Aristotle, although it may have been written by his followers. Whoever wrote it, the author had a clear understanding of the relationship between vibration and sound: "bodies that are capable of vibrating produce sounds . . . strings are examples of such bodies."

Romans

The Roman and the late Hellenistic amphitheaters followed the earlier Greek seating pattern, but limited the seating arc to 180°. They also added a stagehouse (*skene*) behind the actors, a raised acting area (*proskenion*), and hung awnings (*valeria*) overhead to shade the patrons. The chorus spoke from a hard-surfaced circle (*orchestra*) at the center of the audience. A rendering of the Roman theater at Aspendius, Turkey is shown in Fig. 1.2. The Romans were better engineers than the early Greeks and, due to their development of the arch and the vault, were not limited to building these structures on the natural hillsides.

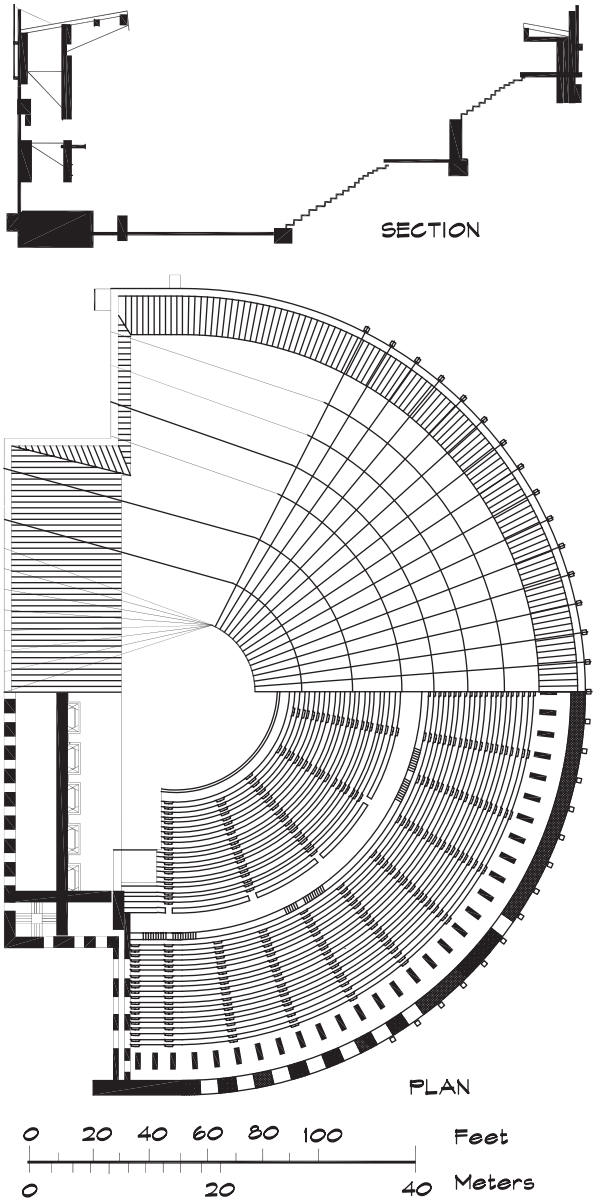
The most impressive of the Roman amphitheaters, the Flavian amphitheater was built between AD 70 and 81, and was later called the Colosseum, due to its proximity to a colossal statue of Nero. With a total seating capacity of about 40,000 it is, except for the Circus Maximus and the Hippodrome (both racecourses), the largest structure for audience seating of the ancient world (Izenour, 1977). Its architect is unknown, but his work was superb. The sightlines are excellent from any seat and the circulation design is still used in modern stadia. The floor of the arena was covered with sand and the featured events were generally combats between humans, or between humans and animals. This type of spectacle was one of the few that did not require a high degree of speech intelligibility for its appreciation by the audience. The floor was sometimes caulked and filled with water to a depth of about a meter for mock sea battles.

Smaller indoor theaters also became a part of the Greek and Roman culture. These more intimate theaters, called *odea*, date from the age of Pericles (450 BC) in Greece. Few remain, perhaps due to their wood roof construction. The later Greek playwrights, particularly Sophocles and Euripides, depended less on the chorus and more on the dialogue between actors to carry the meaning of the play, particularly in the late comedies. These dramatic forms developed either because of the smaller venues or to accommodate the changing styles.

In the Roman theater the chorus came out only at intermission so the *orchestra* shrunk to a semicircle with seats around it for the magistrates and senators. The front wall or *scaena* extended out to the edges of the semicircle of seats and was the same height as the back of the seating area. It formed a permanent backdrop for the actors with a palace decor. The *proskenium* had a curtain, which was lowered at the beginning of the performance and raised at the end. (Breton, 1989)

The Odeon of Agrippa, a structure built in Athens in Roman times (12 BC), was a remarkable building. Shown in Fig. 1.3, it had a wood-trussed clear span of over 25 meters (83 feet). It finally collapsed in the middle of the second century. Izenour (1977) points out that these

FIGURE 1.2 Roman Theater at Aspendus, Turkey (Izenour, 1977)

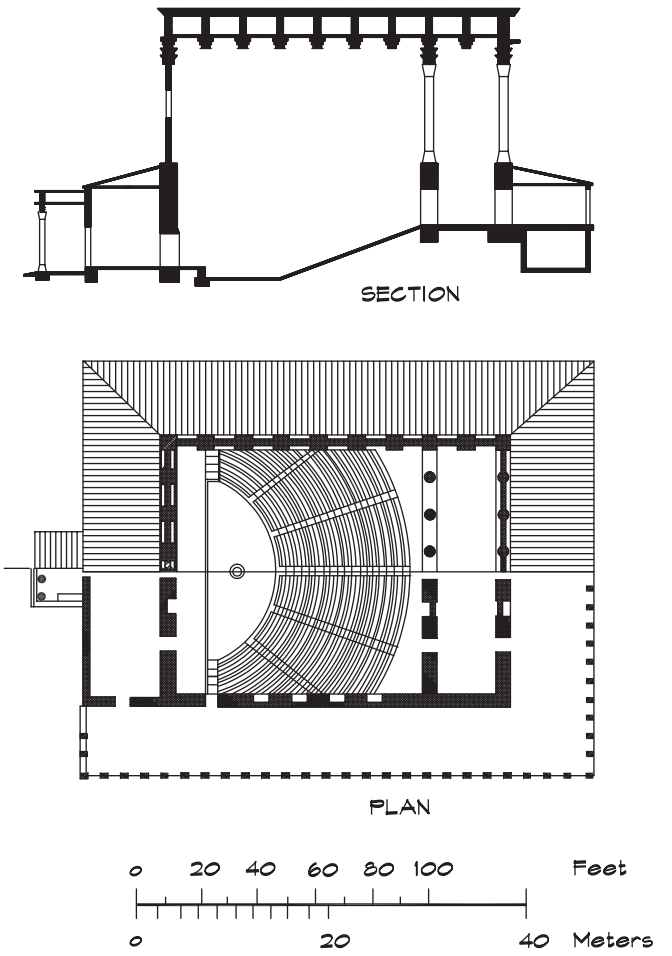


structures, which ranged in size from 200 to 1500 seats, are found in many of the ancient Greek cities. He speculates that, "during the decline of the Empire these roofed theaters, like the small noncommercial theaters of our time, became the final bastion of the performing arts, where the more subtle and refined stage pieces—classical tragedy and comedy, ode and epoch—were performed, the latter to the accompaniment of music (lyre, harp, double flute and oboe) hence the name odeum, 'place of the ode'."

Vitruvius Pollio

Much of our knowledge of Roman architecture comes from the writings of Vitruvius Pollio, a working architect of the time, who authored *De Architectura*. Dating from around 27 BC,

FIGURE 1.3 Odeon of Agrippa at Athens, Greece (Izenour, 1977)



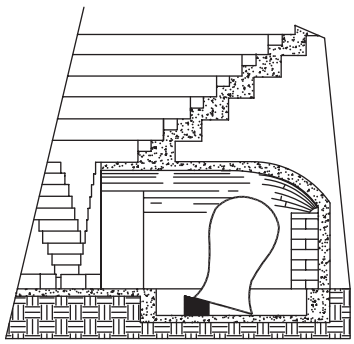
this book describes his views on many aspects of architecture, including theater design and acoustics. Some of his ideas were quite practical, such as his admonition to locate theaters on a "healthy" site with adequate ventilation (away from swamps and marshes). Seating should not face south, causing the audience to look into the sun. Unrestricted sightlines were considered particularly important, and he recommended that the edge of each row should fall on a straight line from the first to the last seat. His purpose was to assure good speech intelligibility as well as good sightlines.

Vitruvius also added one of the great historical mysteries to the acoustical literature. He wrote that theaters should have large overturned amphora or sounding vases placed at regular intervals around the space to improve the acoustics.

These were to be centered in cavities on small, 150 mm (6") high wedges so that the open mouth of the vase was exposed to the stage, as shown in a conjectural restoration by Izenour in Fig. 1.4, based on an excavation of a Roman theater at Beth Shean in Israel. The purpose, and indeed the existence of these vases, remains unclear. Even Vitruvius could not cite an example of their use, though he assures us that they existed in the provinces.

FIGURE 1.4 Hypothetical Sounding Vases (Izenour, 1977)

A conjectural restoration in section of sounding vases in a cavity found at a Roman theater at Beth Shean, Israel.



1.2 EARLY CHRISTIAN PERIOD (AD 400–800)

Rome and the West

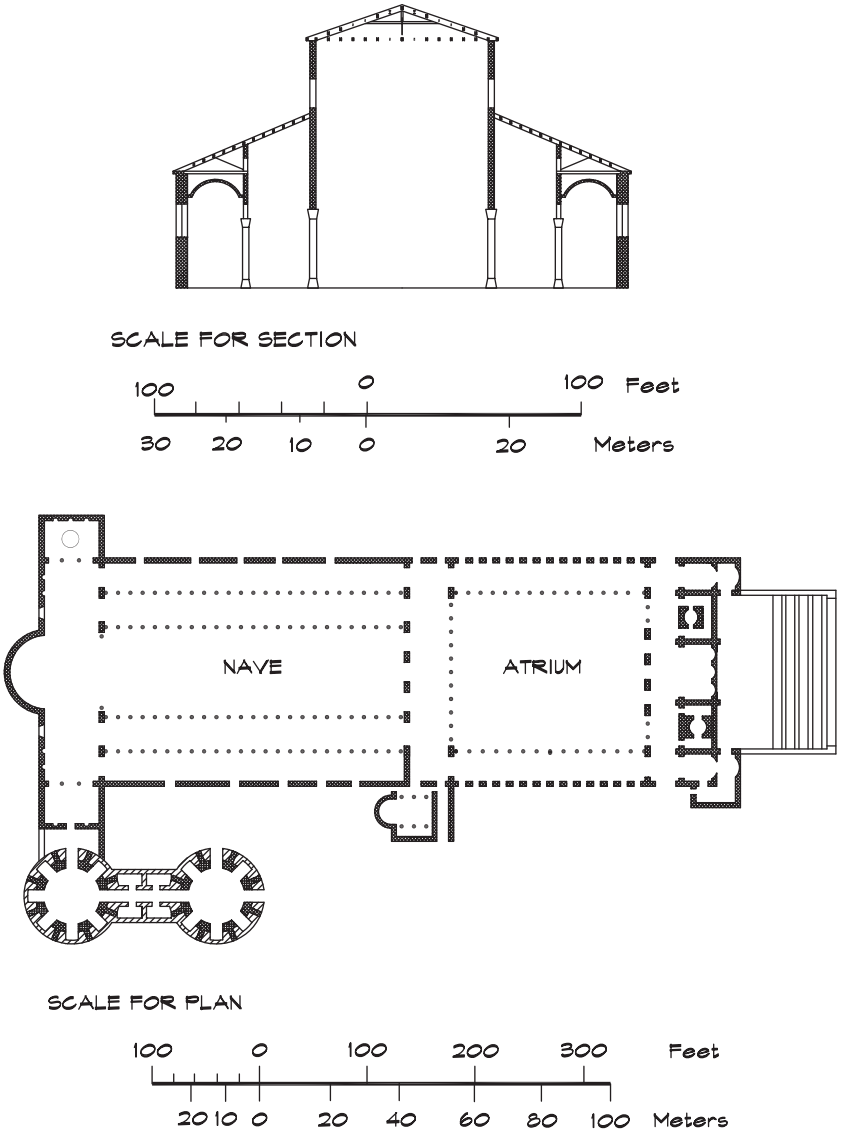
The early Christian period is dated from the Roman emperor Constantine to the coronation of Charlemagne in 800. Following the official sanction of Christianity by Constantine in 326 and his relocation from Rome to Byzantium in 330, later renamed Constantinople, the age was increasingly dominated by the church, which provided the structural framework of everyday life as the Roman and then the Byzantine empires slowly decayed. Incursions by the Huns in 376 were followed by other serious invasions. On the last day of December in the winter of 406, the Rhine river froze solid, forming a bridge between Roman-controlled Gaul and the land of the Germanic tribes to the east (Cahill, 1995). Across the ice came hundreds of thousands of hungry Germans, who poured out of the eastern forests onto the fertile plains of Gaul. Within a few years, after various barbarian armies had taken North Africa and large parts of Spain and Gaul, Rome itself was sacked by Alaric in 410.

In these difficult times, monasteries became places of refuge, which housed small self-sustaining communities—repositories of knowledge, where farming, husbandry, and scholarship were developed and preserved. These generally were left unmolested by their rough neighbors, who seemed to hold them in religious awe (Palmer, 1955). In time, the ablest inhabitants of the Empire became servants of the Church rather than the state and "gave their loyalty to their faith rather than their government" (Strayer, 1955). "Religious conviction did not reinforce patriotism and men who would have died rather than renounce Christianity accepted the rule of conquering barbarian kings without protest." Under the new rulers a Romano-Teutonic civilization arose in the west, which eventually led to a division of the land into the states and nationalities that exist today.

After the acceptance of Christianity, church construction began almost immediately in Rome, with the basilican church of St. Peter in 330 initiated by Constantine himself. The style, shown in Fig. 1.5, was an amalgam of the Roman basilica (hall of justice) and the Romanesque style that was to follow.

The basic design became quite popular—there were 31 basilican churches in Rome alone. It consisted of a high central nave with two parallel aisles on either side separated by colonnades supporting the upper walls and low-pitched roof, culminating in an apse and preceded by an atrium or forecourt (Fletcher, 1963). The builders generally scavenged columns from older

FIGURE 1.5 Basilican Church of St. Peter, Rome, Italy (Fletcher, 1963)

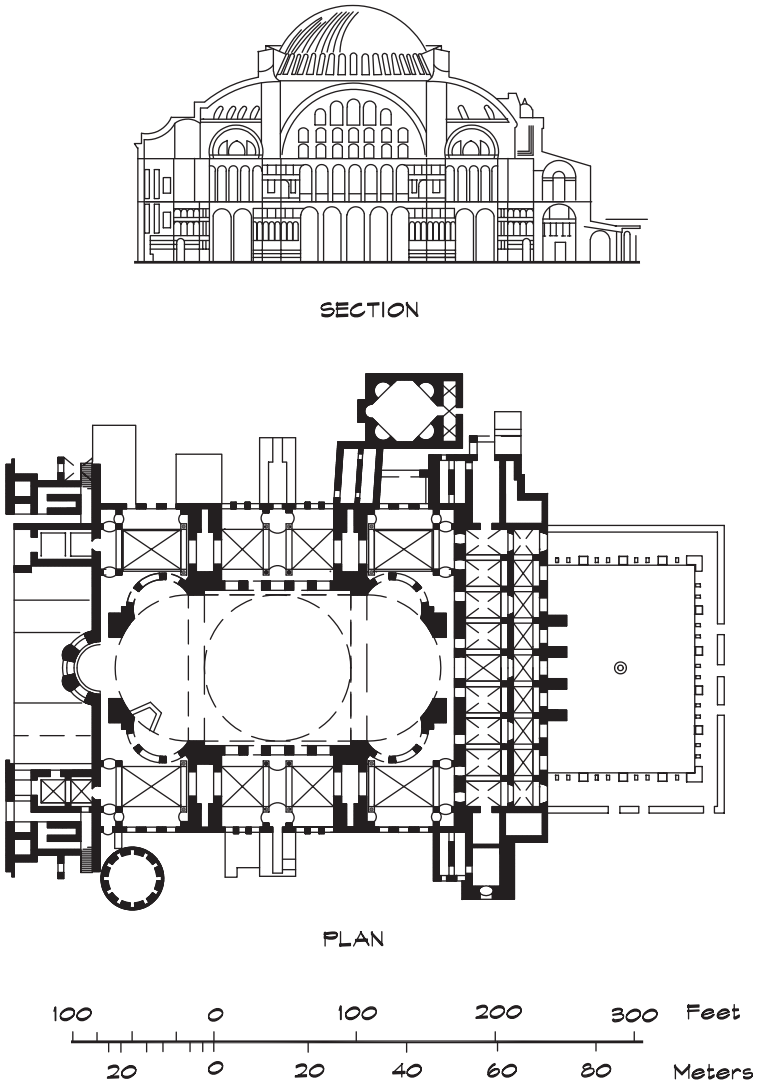


Roman buildings that they could not match or maintain, and which had therefore fallen into decay. The basilica style became a model for later church construction throughout Western Europe, eventually leading to the Gothic cathedrals.

Eastern Roman Empire

In the Eastern Roman Empire the defining architectural feature was the domed roof, used to cover square or polygonal floor plans. This form was combined with classical Greek columns supporting the upper walls with a series of round arches. The primary construction material was a flat brick, although marble was used as a decorative facade. The best known building of the time was St. Sophia (532–537) (*Hagia Sophia*, or divine wisdom) in Constantinople. This massive church, still one of the largest religious structures in the world, was built for

FIGURE 1.6 St. Sophia, Constantinople, Turkey (Fletcher, 1963)



Emperor Justinian by the architects Anthemius of Tralles and Isodorus of Miletus between 532 and 537. Its enormous dome, spanning 33 meters (107 feet) in diameter, is set in the center of a 76 meter (250 foot) long central nave. St. Sophia, shown in Fig. 1.6, was the masterpiece of Byzantine architecture and later, following the Turkish capture of the city in 1453, became the model for many of the great mosques.

In the sixth century the regions of the former Roman Empire continued to divide. The Mediterranean world during this period was separated into three general regions: 1) the Byzantine empire centered in Asia minor, which controlled the Balkans, Greece, and eventually expanded into Russia; 2) the Arab world of Syria, Egypt, and North Africa, which under the leadership of Mohammed (570–632) swept across Africa and into southern Italy, Sicily, and Spain; and 3) the poorest of the three, Western Europe, an agricultural backwater with basically a subsistence economy. Holding the old empire together proved to be more than the Byzantine emperors could afford. Even the reign of the cautious Justinian (527–565), whose

generals temporarily recaptured Italy from the Ostrogoths, North Africa from the Vandals, and southeastern Spain from the Visigoths, did so on the backs of heavy taxation and loss of eastern provinces. The Lombards soon recaptured much of Italy, but the Byzantine representatives managed to hang onto Rome and the neighboring territories. The troubled sixth century closed with the successful pontificate of Pope Gregory I, who strove to standardize the liturgy and is traditionally regarded as the formulator of the liturgical chant, which bears his name.

Gregorian chant or plainsong, which became part of the liturgy in the Western Church, had antecedents in the rich tradition of cantillation in the Jewish synagogues, as well as the practices in the Eastern Church. Plainsong combined the simple melody and rhythm that dominated church music for several centuries.

Until a common system of musical notation was developed in the ninth century, there was little uniformity or record of the music. The early basilican churches were highly reverberant, even with open windows, and the pace and form of church music had to adjust to the architecture to be understood. Even with a simple monodic line, the blending of sounds from chants in these reverberant spaces is hauntingly beautiful.

The eastern and western branches of the Christian church became divided by ideological differences that had been suppressed when the church was clandestine. An iconoclastic movement resulted from a decree from the eastern emperor, Leo III (717–741), forbidding any representation of human or animal form in the church. Subsequently many Greek artisans left Constantinople for Italy, where they could continue their professions under Pope Gregory II. This artistic diaspora caused Leo to relent somewhat and he allowed painted figures on the walls of eastern churches but continued the prohibition of sculpture. His decrees led, in part, to the Byzantine style—devoid of statuary, and unchanging in doctrine and ritual. In contrast, the western church embraced statuary and sculpture, which in time begot the highly ornamented forms of the Baroque period and the music that followed. The split between the eastern and western branches, which had begun in the ninth century with a theological argument over the nature of the divine spirit, finally ended with a formal schism in 1054 when the two churches solemnly excommunicated each other.

1.3 ROMANESQUE PERIOD (800–1100)

The Romanesque period roughly falls between the reign of Charlemagne and the era of the Gothic cathedrals of the twelfth century. In the year 800 it was rare to find an educated layman outside of Italy (Strayer, 1955). The use of Latin decreased and languages fragmented according to region as the influence of a central authority waned. The feudal system developed in its place, not as a formal structure based on an abstract theory of government, but as an improvisation to meet the incessant demands of the common defense against raiders.

The influence of both Roman and Byzantine traditions is evident in the architecture of the Romanesque period. From the Roman style, structures retained much of the form of the basilica; however, the floor plans began to take on the cruciform shape. The eastern influence entered the west primarily through the great trading cities of Venice, Ravenna, and Marseilles and appeared in these cities first. Romanesque style is characterized by rounded arches, domed ceilings that developed from the spherical shape of the east into vaulted structures in the west. The narrow upper windows, used in Italy to limit sunlight, lead to larger openings in the north to allow in the light, and the flat roofs of the south were sharpened in the north to throw off rain and snow. Romanesque structures remained massive until the introduction of

buttresses, which allowed the walls to be lightened. Construction materials were brick and stone and pottery, as well as materials scavenged from the Roman ruins. The exquisite marble craftsmanship characteristic of the finest Greek and Roman buildings had been lost and these medieval brick structures seemed rough and plain compared with the highly ornamented earlier work.

One notable exception was St. Mark Cathedral in Venice. It was built on the site of the basilica church, originally constructed to house the remains of St. Mark in 864. The first church burned in 976 and was rebuilt between 1042 and 1085. It was modeled after the Church of the Apostles in Constantinople as a classic Romanesque structure in a nearly square cruciform shape, with rounded domes reminiscent of the later Russian orthodox churches. St. Mark, illustrated in Fig. 1.7, was later home to a series of brilliant composers including Willaert (1480–1562), Gabrielli (1557–1612), and Monteverdi (1567–1643).

The music, which we now associate with Gregorian chant, developed as part of the worship in the eighth and ninth centuries. The *organum*, a chant of two parts, grew slowly from the earlier monodic music. At first this form consisted of a melody that was sung (held) by a tenor (*tenere*, to hold) while another singer had the same melodic line at an interval a forth above. True polyphony did not develop until the eleventh century.

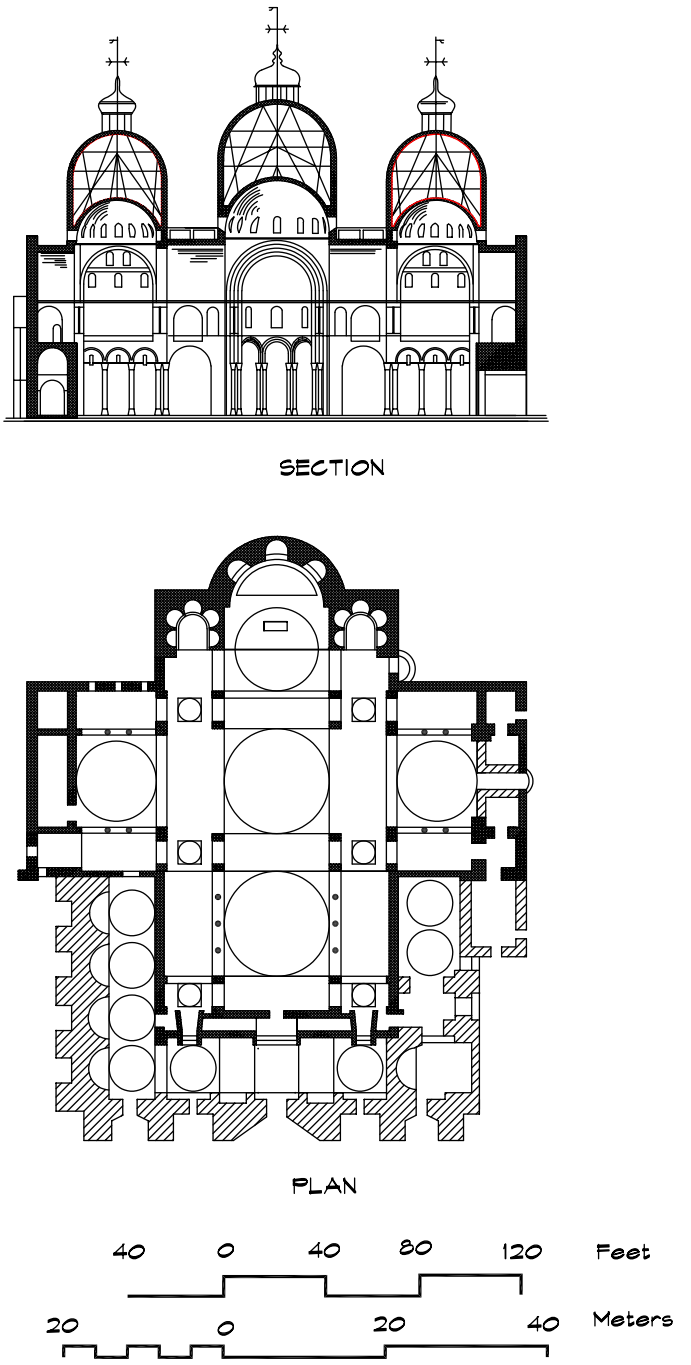
1.4 GOTHIC PERIOD (1100–1400)

Gothic Cathedrals

Beginning in the late middle ages, around 1100, there was a burst in the construction of very large churches, the Gothic cathedrals, first in northern France and later spreading throughout Europe. These massive structures served as focal points for worship and repositories for the religious relics that, following the return of the crusaders from the holy lands, became important centers of the valuable pilgrim trade. The cathedrals were by and large a product of the laity, who had developed from a populace that once had only observed the religious forms, to one that held beliefs as a matter of personal conviction. Successful cities had grown prosperous with trade and during the relatively peaceful period of the late middle ages the citizens enthusiastically supported their construction. The first was built by Abbot Suger at St. Denis near Paris between 1137 and 1144 and was made possible by the hundreds of experiments in the building of fortified towns and churches, which had produced a skilled and knowledgeable work force. Suger was a gifted administrator and diplomat who also had the good fortune to attend school and become best friends with the young prince who became King Louis VI. When the king left on the Second Crusade he appointed Suger regent and left him in charge of the government. Following the success of St. Denis, other cathedrals were soon begun at Notre Dame (1163–c1250), Bourges (1192–1275), Chartes (1194–1260), and Rheims (1211–1290). These spectacular structures (see Fig. 1.8) carried the art and engineering of working in stone to its highest level. The vaulted naves, over 30 meters (100 feet) high, were lightened with windows and open colonnades and supported from the exterior with spidery flying buttresses, which gave the inside an ethereal beauty. Plain chant was the music of the religious orders and was suited perfectly to the cathedral. Singing was something that angels did, a way of growing closer to God. It was part of the every day religious life, done for the participants rather than for an outside listener.

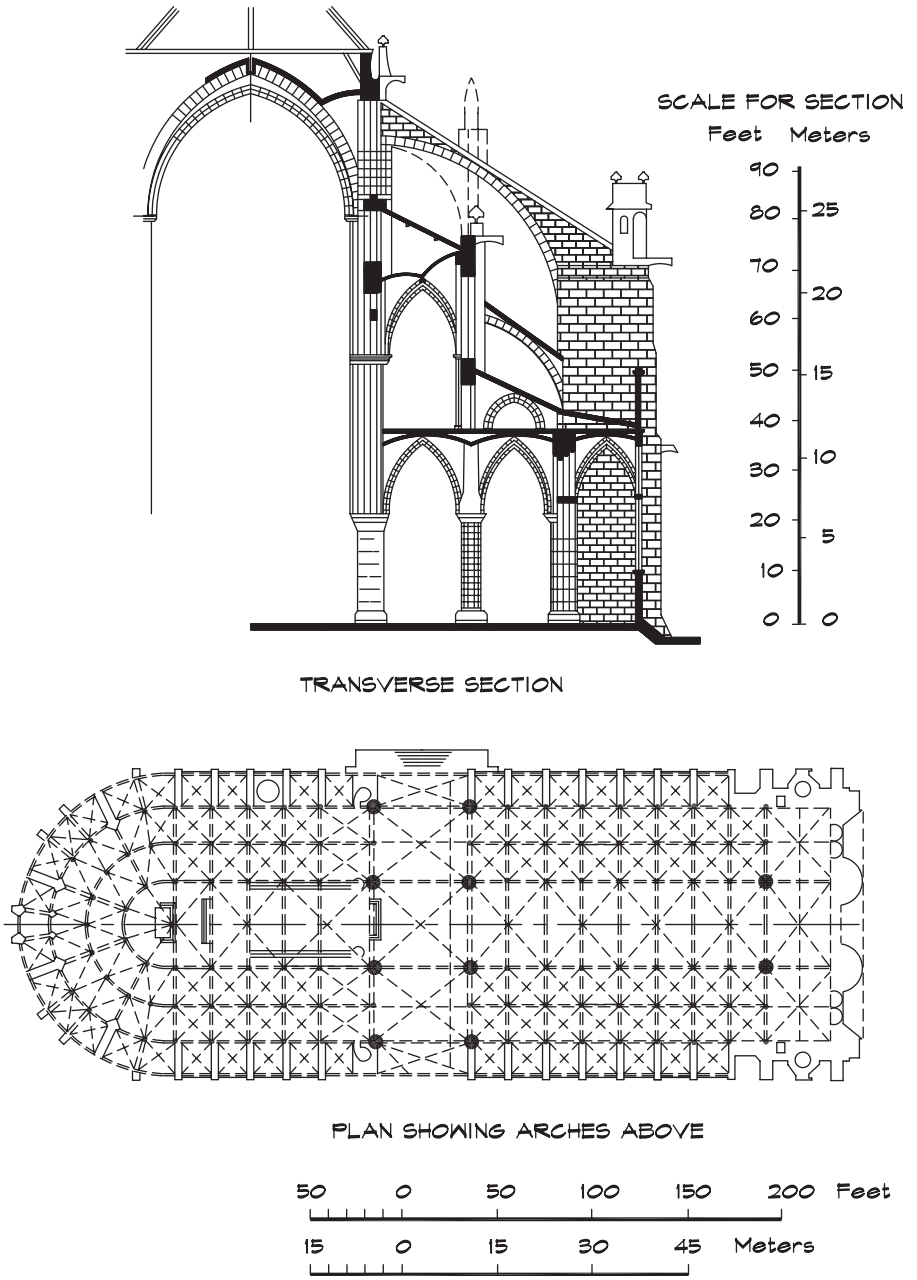
In the second half of the twelfth century the beginnings of polyphony developed in the School of Notre Dame in Paris from its antecedents in the great abbey of St. Martial in Limoges. The transition began with the two-part *organum* of Leonin, and continued with the three

FIGURE 1.7 St. Mark Cathedral, Venice, Italy (Fletcher, 1963)



and four-part *organum* of his successor Perotin. The compositions were appropriate for the large reverberant cathedrals under construction. A slowly changing plainsong pedal note was elaborated by upper voices, which did not follow the main melody note for note as before. This eventually led, in the thirteenth and fourteenth centuries, to the polyphonic motets in which different parts also might have differing rhythms. Progress in the development of

FIGURE 1.8 Notre Dame Cathedral, Paris, France (Fletcher, 1963)



serious music was laborious and slow. Outside the structured confines of church music, the secular troubadours of Provence, the trouveres of northern France and southern England, the story-telling jongleurs among the peasantry, and the minnesingers in Germany also made valuable contributions to the art.

The influence of the Church stood at its zenith in the thirteenth century. The crusades, of marginal significance militarily, had served to unite Western Europe into a single religious community. An army had pushed the Muslims nearly out of the Iberian peninsula.

Beginning in the fourteenth century, however, much of the civilized world was beset by the ravages of the bubonic plague. Between the years 1347 and 1350 it wiped out at least one third of the population. The Church was hit harder than the general populace, losing more than half its members. Many men, largely illiterate, had lost their wives to the plague and sought to join the religious orders. Lured by offers of money from villages that had no priest, others came to the church for financial security. Money flowed into Rome and supported a growing bureaucracy and opulence, which ultimately led to the reformation. This worsened a problem already confronting the religious leadership, "the danger of believing that the institution exists for the benefit of those who conduct its affairs."(Palmer, 1955)

With the rise of towns and commerce, public entertainment became more secular and less religious in its focus. Theater in the late middle ages was tolerated by the Church largely because it had been co-opted as a religious teaching aid. Early plays, dating from the tenth century, were little more than skits based on scripture, which were performed in the streets by troupes. These evolved, in the thirteenth and fourteenth centuries, into the miracle and mystery plays that combined singing and spoken dialogue. The language of the early medieval theater was Latin, which few understood. This changed in time to the local vernacular or to a combination of Latin and vernacular. The plays evolved from a strictly pedagogical tool to one that contained more entertainment. As the miracle plays developed, they were performed in rooms that would support the dialogue and make it understandable. By 1400, the pretext of the play remained religious, but the theater was already profane (Hindley, 1965).

1.5 RENAISSANCE PERIOD (1400–1600)

Renaissance Churches

The great outpouring of art, commerce, and discovery that was later described as the Renaissance or rebirth, first started in northern Italy and gradually spread to the rest of Europe. The development of new music during these years was rich and profuse. Thousands of pieces were composed and, while sacred music still dominated, secular music also thrived (Hemming, 1988).

Church construction still continued to flourish in the early years of the Renaissance. St. Peter's Cathedral in Rome, the most important building of the period, was begun in 1506 and was created by many of the finest architects and artists of the day. A competition produced a number of designs, still preserved in the Uffizi Gallery in Florence, from which Bramante (1444–1514) was selected as architect (Fletcher, 1963). After the death of Pope Julius II a number of other architects, including Raphael (1483–1520), worked on the project—the best known being Michelangelo (1475–1564). He began the construction of the dome, which was completed after his death, from his models. Some time later Bernini erected (1655–1667) the immense piazza and the baroque throne of St. Peter.

The construction of this great cathedral in Rome also reached out to touch an obscure professor of religion at the university in Whitenberg. In 1517, a friar named Tetzel was traveling through Germany selling indulgences to help finance it. Martin Luther felt that the people were being deluded by this practice and, in the manner of the day, posted a list of 95 theses on the door of the castle church in protest (Palmer, 1955). By 1560, most of northern Europe including Germany, England, Netherlands, and the Scandinavian countries had officially adopted some form of Protestantism.

Renaissance Theaters

Theater construction began again in Italy in the early Renaissance, more or less where the Romans had left it a thousand years earlier. In 1580, the Olympic Academy in Vicenza engaged Palladio (1518–1580) to build a permanent theater (Fig. 1.9), the first since the Roman Odeon's. The seating plan was semi-elliptical, following the classical pattern, and the stage had much the same *orchestra* and *proskenium* configuration that the old Roman theaters had. Around the back of the audience was a portico of columns with statues above. The newly discovered art of perspective captured the imagination of designers and they crafted stages, which incorporated a rising stage floor and single point perspective. The terms upstage and downstage evolved from this early design practice. After the death of Palladio, his pupil Scamozzi added five painted streets in forced perspective angling back from the *scaena*.

In 1588, Scamozzi further modified the Roman plan in a new theater, the Sabbioneta. The semi-elliptical seating plan was pushed back into a U shape, the stage wall was removed, and a single-point perspective backdrop replaced the earlier multiple-point perspectives. This theater is illustrated in Fig. 1.10. Its seating capacity was small and there was little acoustical support from reflections off the beamed ceiling.

In mid-sixteenth century England, traveling companies of players would lay out boards to cover the muddy courtyards of inns, while the audience would stand around them or line the galleries that flanked the main yard (Breton, 1989). Following the first permanent theater built in 1576 by James Burbage, this style became the model for many public theaters, including Shakespeare's Globe. The galleries surrounding the central court were three tiers high with a roofed stage, which looked like a thatched apron at one end. Performances were held during the day without a curtain or painted backdrop. The acoustics of these early theaters was probably adequate. The side walls provided beneficial early reflections and the galleries yielded excellent sightlines. The open-air courtyard reduced reverberation problems and outside noise was shielded by the high walls. It is remarkable that such simple structures sufficed for the work of a genius like Shakespeare. Without good speech intelligibility provided by this type of construction, the complex dialogue in his plays would not only have been lost on the audience, it would probably not have been attempted at all.

FIGURE 1.9 Teatro Olimpico, Vicenza, Italy (Breton, 1989)

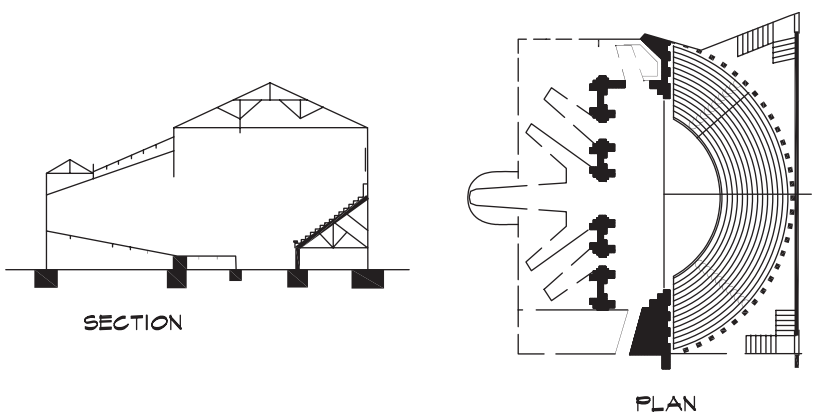
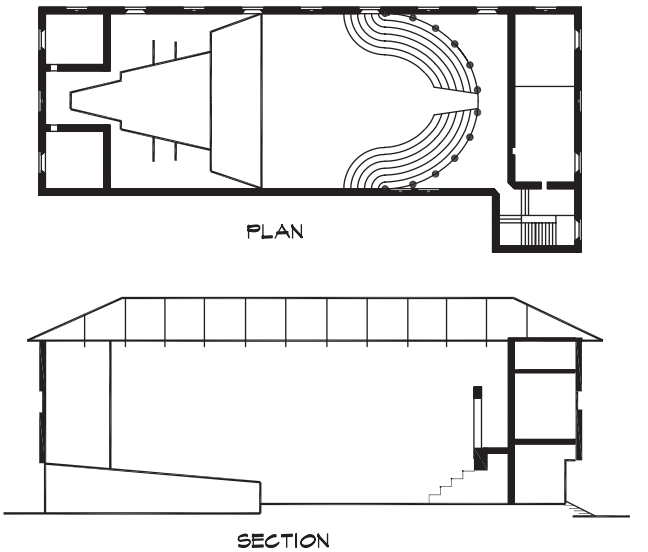


FIGURE 1.10 Sabbioneta Theater, Italy (Breton, 1989)



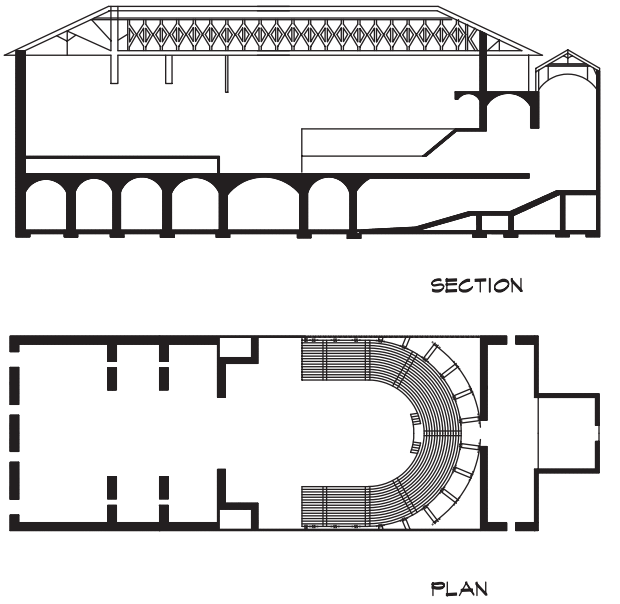
1.6 BAROQUE PERIOD (1600–1750)

Baroque Churches

The first half of the seventeenth century was dominated by the Thirty Years War (1618–1648), which ravaged the lands of Germany and central Europe. This confusing struggle was one of shifting alliances that were formed across religious and political boundaries (Hindley, 1965). The end result was a weakening of the Hapsburg empire and the rise of France as the dominant power in Europe. Italy became a center for art and music during that period, in large part because it was relatively unscathed by these central European wars. In northern Italy a style, which became known as the Baroque (after the Portuguese *barocco*, a term meaning a distorted pearl of irregular shape), grew out of the work of a group of Florentine scholars and musicians known as the *Camerata* (from the Italian *camera*, or chamber). This group abandoned the vocal polyphony of Renaissance sacred music and developed a new style featuring a solo singer with single instrumental accompaniment (the *continuo*) to provide unobtrusive background support for the melodic line. The new music was secular rather than sacred and dramatic and passionate rather than ceremonial (Hemming, 1988), and allowed for considerably more freedom by the performer.

Both the music and the architecture of the Baroque period was more highly ornamented than that of the Renaissance. Composers began writing in more complicated musical forms such as the fugue, chaconne, passacaglia, toccata, concerto, sonata, and oratorio. Some of the vocal forms, such as the cantata, oratorio, and opera, grew out of the work of the Camerata. Others developed from the architecture and influence of a particular space. The St. Mark Cathedral in Venice was shaped like a nearly square cross with individual domes over each arm and above the center (see Fig. 1.7). These created localized reverberant fields, which supported the widely separated placement of two or three ensembles of voices and instruments that could perform as separate musical bodies. Gabrielli (1557–1612), who was organist there for 27 years, exploited these effects in his compositions, including separate

FIGURE 1.11 Theatro Farnese, Parma, Italy (Breton, 1989)



instrument placement, call and response sequences, and echo effects. In less than 100 years this style had been transformed into the concerto grosso (Burkat, 1998).

Baroque Theaters

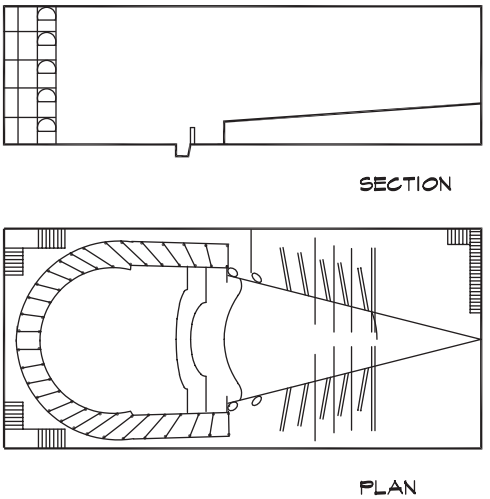
The progress in theater construction in Northern Italy was also quite rapid. The illusion stages gave way to auditoria with horizontally sliding flats, and subsequently to moveable stage machinery. The *Theatro Farnese* in Parma, constructed between 1618 and 1628 by Giovanni Battista Aleotti, had many features of a modern theater. Shown in Fig. 1.11, it featured horizontal set pieces, which required protruding side walls on either side of the stage opening to conceal them. This allowed set changes to be made and provided entrance spaces on the side wings for the actors to use without appearing out of scale. The U-shaped seating arrangement afforded the patrons a view, not only of the stage, but also of the prince, whose box was located on the centerline.

In Florence at the Medici court, operas were beginning to be written. The first one was *Dafne*, which is now lost, written between 1594 and 1598 by Peri (Forsyth, 1985). The first known opera performance was Peri's *Euridice*, staged at a large theater in the Pitti Palace to celebrate the wedding of Maria de'Medici and King Henri IV of France in 1600. This was followed by Monteverdi's *Orfeo*, first performed in 1607 in Mantua, which transformed opera from a somewhat dry and academic style to a vigorous lyric drama.

Italian Opera Houses

By 1637, when the first public opera house was built in Venice (see Fig. 1.12), the operatic theater had become the multistory U-shaped seating arrangement of the Theatro Farnese, with boxes in place of tiers. Later the seating layout further evolved from a U shape into a truncated elliptical shape. The orchestra, which had first been located at the rear of the stage and then in the side balconies, was finally housed beneath the stage as is the practice today

FIGURE 1.12 Theater of SS. Giovanni e Paolo, Venice, Italy (Forsyth, 1985)



(Breton, 1989). The stage had widened further and now had a flyloft with winches and levers to manipulate the scenery. This became the typical Baroque Italian opera house, which was the standard model replicated throughout Europe with little variation for 200 years.

Italy immediately became the center of opera in Europe. In the years between 1637 and the end of the century, 388 operas were produced in Venice alone. Nine new opera houses were opened during this period, and after 1650, never fewer than four were in simultaneous operation (Grout, 1998). These early opera houses served as public gathering places. For the equivalent of about 50 cents, the public could gain entry to the main floor, occupied by standing patrons who talked and moved about during the performances. The high background noise is documented in many complaints in writings of the time. It led to the practice of loudly sounding a cadential chord to alert the audience of an impending aria. In a forerunner of contemporary films, special effects became particularly popular. As the backstage equipment grew more complicated and the effects more extravagant, the noise of the machines threatened to drown out the singing. Composers would compensate by writing instrumental music to mask the background sounds. The popularity of these operas was so great that the better singers were in considerable demand. Pieces were written to emphasize the lead singer's particular ability with the supporting roles de-emphasized.

Baroque Music

The seventeenth century also saw the rise of the aristocracy and with it, conspicuous consumption. Churches and other public buildings became more ornate with applied decorative elements, which came to symbolize the Baroque style. Music began to be incorporated into church services in the form of the oratorio, a sort of religious opera staged without scenery or costumes. In Rome the Italian courts were opulent enough to embrace opera as a true spectacle. Pope Urban VII commissioned the famous Barberini theater based on a design of Bernini, which held 3000 people and opened in 1632 with a religious opera by Landi.

In the Baroque era instrumental music achieved a status equal to vocal music. Musical instruments became highly sophisticated in the seventeenth and eighteenth centuries and in some cases achieved a degree of perfection in their manufacture that is unmatched today.

The harpsichord and the instruments of the violin family became the basic group for ensemble music. Violins fashioned by craftsmen such as Nicolo Amati (1569–1684), Giuseppi Guarneri (1681–1742) and Antonio Stradivari (1644–1737) are still the best instruments ever made. The lute, which was quite popular at the beginning of the period, rarely was used at the end. Early wind instruments had been mainly shawms (later oboes), curtals (later bassoons), crumhorns, bagpipes, fifes and drums, cornets, and trumpets. New instruments were developed, specifically the recorder, the transverse flute, oboe, and bassoon. The hunting horn, having a fiveandonehalffoot tube wound into four or five loops before flaring into a bell, was improved in France by reducing the number of loops and enlarging the bell. When it became known in England, it was given the name French horn. By the early 1600s, the pipe organ had developed into an instrument of considerable technical development.

Antonio Vivaldi (1678–1741), now recognized as one of the foremost Baroque composers, first learned violin from his father, who was a violinist at St. Mark in Venice. He was a priest and later (1709) music director at a school for foundling girls, the Seminario dell'Ospitale della Pieta. His intricate compositions for the violin and other instruments of the time feature highly detailed passages characteristic of what is now known as chamber music, written for small rooms or salons.

Protestant Music

In Protestant northern Europe the spoken word was more important to the religious service than in the Catholic south. The volume of the northern church buildings was reduced to provide greater clarity of speech. The position of the pulpit was centrally placed and galleries were added to the naves and aisles. Many existing churches, including Thomaskirche in Leipzig, were modified by adding hanging drapes and additional seating closer to the pulpit (Forsyth, 1985). Johann S. Bach (1685–1750) was named cantor there in 1722, to the disappointment of the church governors. He was their second choice behind Georg Philip Telleman (1681–1767). Bach was influenced by the low reverberation time of the church, which has been estimated to have been about 1.6 seconds (Bagenal, 1930). His B-Minor Mass and the St. Matthew Passion were both composed for this space.

Bach wrote music for reverberant spaces as well as for intimate rooms. During his early years in Weimar (1703–1717) he composed mostly religious music including some of his most renowned works for organ, the Passacaglia and double Fugue in C minor and the Toccata and Fugue in D minor. His Brandenberg Concertos, composed for the orchestra at the little court of Anhalt-Cothen, were clearly meant to be played in a chamber setting, as were the famous keyboard exercises known as the *Well Tempered Clavier*, which were written for each of the 24 keys in the system of equal-tempered tuning, completed about the same time.

Baroque music was performed in salons, drawing rooms, and ballrooms, as well as in churches. In general the former were not specifically constructed for music and tended to be small. The orchestras were also on the smallish side, around twenty-five musicians, much like chamber orchestras today. As rooms and audiences grew larger, louder instruments became more popular. The harpsichord gave way to the piano, the viola da gamba to the cello, and the viol to the violin. The problem of distributing the sound evenly to the listener was soon recognized, but there were few useful guidelines. In England Thomas Mace published (1676) suggestions for the designer in his *Musick's Monument or a Rememberancer of the best practical Musick*. He recommended a square room with galleries on all sides surrounding the musicians, much like a theater in the round. Mace advocated piping the sound from the musicians to the rear seats through tubes beneath the floor, a device that was used

extensively in the Italian opera houses of the day, and contemporaneously in loud-speaking trumpets, which were employed as both listening and speaking devices (Forsyth, 1985).

1.7 ORIGINS OF SOUND THEORY

The understanding of the theory of fluids including sound propagation through them made little progress from the Greeks to the Renaissance. Roman engineers did not have a strong theoretical basis for their work in hydraulics (Guillen, 1995). They knew that water flowed downhill and would rise to seek its own level. This knowledge, along with their extraordinary skills in structural engineering, was sufficient for them to construct the massive aqueduct systems including rudimentary siphons. However, due to the difficulty they had in building air-tight pipes it was more effective for them to bridge across valleys than to try to siphon water across the valley floors. Not until Leonardo da Vinci (1452–1519) studied the motion and behavior of rivers did he noticed that, "A river of uniform depth will have more rapid flow at the narrower section than at the wider." This is what we now call the equation of continuity, one of the relationships necessary for the derivation of the wave equation.

Galileo Galilei (1564–1642) along with others noted the isochronism of the pendulum and was aware, as was the French Franciscan friar Marin Mersenne (1588–1648), of the relationship between the frequency of a stretched string and its length, tension, and density. Earlier Giovanni Battista Benedetti (1530–1590) had related the ratio of pitches to the ratio of the frequencies of vibrating objects. In England Robert Hooke (1635–1703), who had bullied a young Isaac Newton (1642–1727) on his theory of light (Guillen, 1995), published in 1675 the law of elasticity that now bears his name, in the form of a Latin anagram CEIIINOSSSTTUV, which decoded is "ut tensio sic vis" (Lindsay, 1966). It established the direct relationship between stress and strain that is the basis for the formulas of linear acoustics. The first serious attempt to formalize a mathematical theory of sound propagation was set forth by Newton in his second book (1687), *Philosophiae Naturalis Principia Mathematica*. In this work he hypothesized that the velocity of sound is proportional to the square root of the absolute pressure divided by the density. Newton had discovered the isothermal velocity of sound in air. This is a less generally applicable formula than the adiabatic relationship, which was suggested later by Pierre Simon Laplace (1749–1827) in 1816. A fuller understanding of the propagation of sound waves had to wait until more elaborate mathematical techniques were developed.

Daniel Bernoulli (1700–1782), best known for his work in fluids, set forth the principle of the coexistence of small amplitude oscillations in a string, a theory later known as superposition. Soon after, Leonhard Euler (1707–1783) published a partial differential equation for the vibrational modes in a stretched string. The stretched-string problem is one that every physics major studies, due both to its relative simplicity and its importance in the history of science. The eighteenth century was a time when mathematics was just beginning to be applied to the study of mechanics. Prizes were offered by governments for the solution of important scientific problems of the day and there was vigorous and frequently acrimonious debate among natural philosophers in both private and public correspondence on the most appropriate solutions.

The behavior of sound in pipes and tubes was also of interest to mathematicians of the time. Both Euler (1727) and later J. L. Lagrange (1736–1830) made studies of the subject. Around 1759 there was much activity and correspondence between the two of them (Lindsay, 1966).

In 1766, Euler published a detailed treatise on fluid mechanics, which included a section entirely devoted to sound waves in tubes.

The tradition of offering prizes for scientific discoveries continued into the nineteenth century. The Emperor Napoleon offered, through the Institute of France, a prize of 3000 francs for a satisfactory theory of the vibration of plates (Lindsay, 1966). The prize was awarded in 1815 to Sophie Germain, a celebrated woman mathematician, who derived the correct fourth-order differential equation. The works of these early pioneers, along with his own insights, ultimately were collected into the monumental two-volume work, *Theory of Sound*, by John W. Strutt, Lord Rayleigh (1842–1919) in 1877. This classic work contains much that is original and insightful even today.

1.8 CLASSICAL PERIOD (1750–1825)

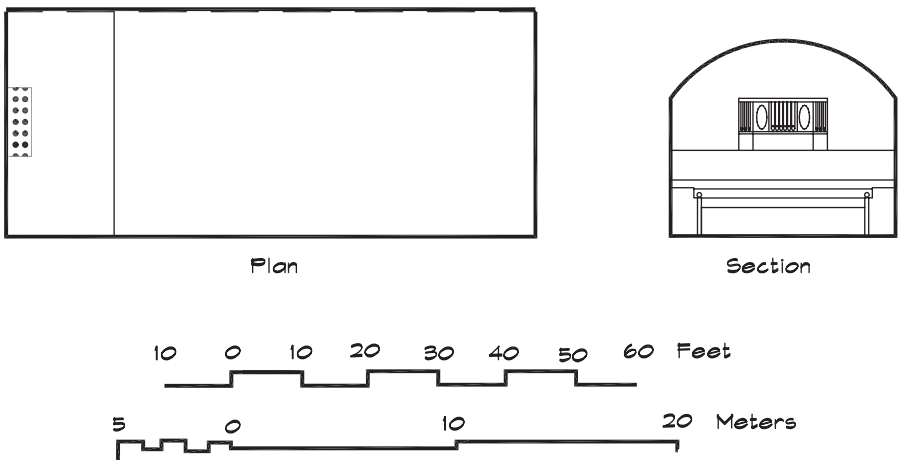
The eighteenth century in Europe was a cosmopolitan time when enlightened despots (often foreign born) were on the throne in many countries, and an intellectual movement known as the Enlightenment held that knowledge should evolve from careful observation and reason. The French *philsophes*, Rousseau, Montesquieu, and Voltaire reacted to the social conditions they saw and sought to establish universal rights of man. In both the visual and performing arts, there was a classic revival, a return to the spirit of ancient Greece and Rome. The paintings of Jacques Louis David, such as the *Oath of the Horatii* (1770), harkened back to Republican Rome and the virtues of nobility, simplicity, and perfection of form. The excavations of Pompeii and Herculeum had created public interest in the history of this earlier era and, with the American Revolution in 1776 and the French revolution in 1789, the interest took on political overtones.

The period referred to as Classical in music occurred during these years, though some historians, such as Grout and Palisca (1960) date it from 1720 to 1800. Classical refers to a time when music was written with careful attention to specific forms. One of these had a particular three-part or ternary pattern attributed to J. S. Bach's son, Carl Philipp Emanuel Bach (1714–1788), which is now called sonata form. Others included the symphony, concerto, and rondo. Compositions were written within the formal structure of each of the types. The best known composers of that time were Franz Joseph Haydn (1732–1809), Wolfgang A. Mozart (1756–1791), and later Ludwig Beethoven (1770–1827). During the Classical period musical pieces were composed for the first time with a formal concert hall performance in mind. Previously rooms that were used for musical concerts were rarely built specifically for that sole purpose.

In England in the middle of the eighteenth century, buildings first were built for the performance of nontheatrical musical works. Two immigrant musicians, Carl Fredrick Abel (1723–1787) and Johann (known as John) Christian Bach (1735–1782), the eighteenth child of J. S. Bach, joined forces with Giovanni Andrea Gallini, who provided the financing, to build between 1773 and 1775 what was to become the best-known concert hall in London for a century, the Hanover Square Rooms. The *Illustrated London News* of 1843 showed an engraving of the main concert hall (Forsyth, 1985) from which Fig. 1.13 was drawn.

When Haydn came to England in 1791–1792 and 1793–1794, he conducted his London Symphonies (numbers 93 to 101), which he had written specifically for this room. The main performance space was rectangular and, according to the London *General Evening Post* of February 25, 1794 (Forsyth, 1985), it measured 79 ft (24.1 m) by 32 ft (9.7 m). The height has been estimated at 22 to 28 ft. (6.7 to 8.5m). In Victorian times, it was lengthened to between

FIGURE 1.13 Hanover Square Room, London, England (Forsyth, 1985)

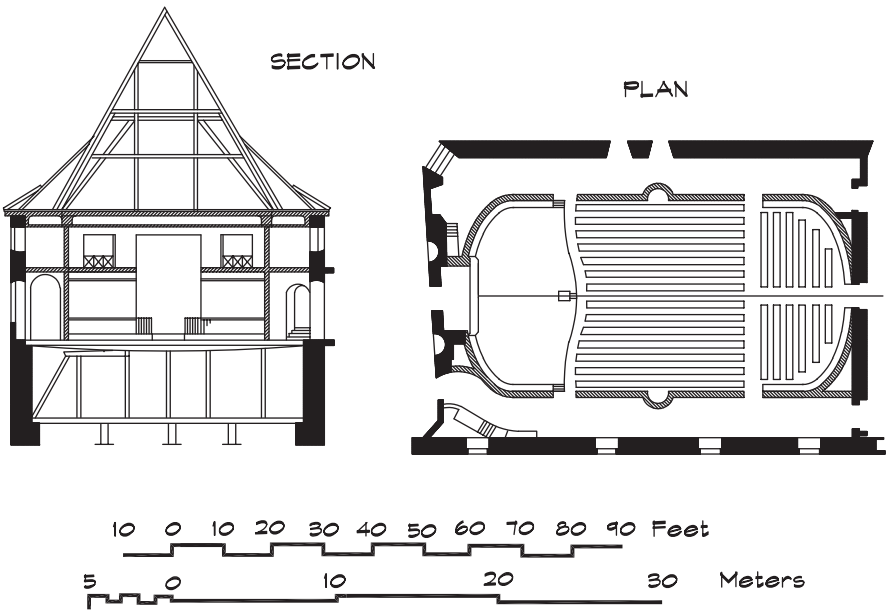


90 and 95 ft (Landon, *Haydn in England*). It was somewhat small for its intended capacity (800) and probably had a reverberation time of less than one second when fully occupied (J. Meyer, 1978). The low volume and narrow width would have provided strong lateral reflections and excellent clarity, albeit a somewhat loud overall level. The room was well received at the time. The *Berlinische Musikalische Zeitung* published a letter on June 29, 1793 describing a concert there by a well-known violinist, Johann Peter Salomon (1745–1815): "The room in which [the concert] is held is perhaps no longer than that in Stadt Paris in Berlin, but broader, better decorated, and with a vaulted ceiling. The music sounds, in the hall, beautiful beyond any description." (Forsyth, 1985)

In the eighteenth century the center of gravity of the music in Europe shifted northward from Italy. Orchestras in London, Paris, Mannheim, Berlin, and Vienna were available to composers of all nationalities. Halls were built in Dublin, Oxford, and Edinburgh, many years before they appeared in cities on the continent. The Holywell Music Room at Oxford, which opened in 1748, still stands today. These halls were relatively small by today's standards with seating capacities ranging from 400 to 600, and reverberation times were generally less than 1.5 seconds (Bagenal and Wood, 1931). Music was also played at public concerts held outdoors in pleasure gardens. In 1749 some 12,000 people paid two shillings sixpence each to hear Handel's 100-piece band rehearse his *Royal Fireworks Music* at Vauxhall Gardens (Forsyth, 1985).

In continental Europe in the mid eighteenth century there was not yet a tradition of public concerts open to all. Concert-goers were, by and large, people of fashion and concerts were usually held in rooms of the nobility, such as Eisenstadt Castle south of Vienna or Eszterhaza Castle in Budapest, which was the home of Haydn during his most productive years. It was not until 1761 that a public hall was built in Germany, the Konzert-Saal auf dem Kamp in Hamberg. In Leipzig, perhaps because it did not have a royal court, the architect Johann Carl Friedrich Dauthe converted a Drapers' Hall or Gewandhaus into a concert hall in 1781 (see Figure 1.14). Later known as the Altes Gewandhaus, it seated about 400 with the orchestra located on a raised platform at one end occupying about one quarter of the floor space. The room had a reverberation time of about 1.3 seconds (Bagenal and Wood, 1931) and was lined with wood paneling, which reduced the bass build up. Recognized for

FIGURE 1.14 Altes Gewandhaus, Leipzig, Germany (Bagenal and Wood, 1931)



its fine acoustics, particularly during Felix Mendelssohn's directorship in the mid-nineteenth century (1835–1847), it was later replaced by the larger Neus Gewandhaus late in the century.

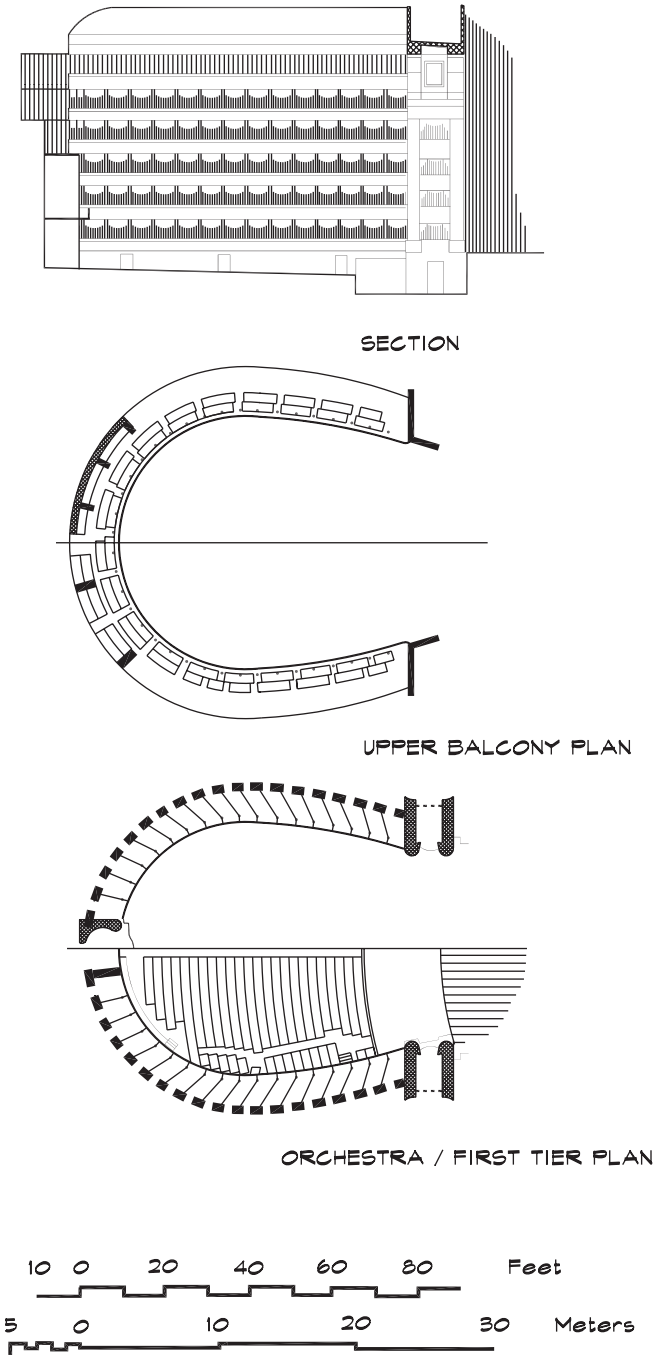
Vienna became an international cultural center where artists and composers from all over Europe came to work and study, including Antonio Salieri (1750–1825), Mozart, and Beethoven. Two principal concert halls in Vienna at the time were the Redoutensaal at Hofburg and the palace of the Hapsburg family. Built in 1740, these two rooms, seating 1500 and 400, respectively, remained in use until 1870. The larger room was rectangular, had a ceiling height of about 30 ft, and side galleries running its full length. The reverberation time was probably slightly less than 1.6 seconds when fully occupied. The rooms had flat floors and were used for balls as well as for concerts. Haydn, Mozart, and Beethoven composed dances for these rooms, and Beethoven's Seventh Symphony was first performed here in 1814 (Forsyth, 1985).

Meanwhile in Italy little had changed. Opera was the center of the cultural world and opera-house design had developed slowly over two centuries. In 1778 La Scalla opened in Milan and has endured, virtually unchanged, for another two centuries. Shown in Fig. 1.15, it has the form of a horseshoe-shaped layer cake with small boxes lining the walls. The sides of the boxes are only about 40% absorptive (Beranek, 1979) so they provide a substantial return of reflected sound back to the room and to the performers. The orchestra seating area is nearly flat, reminiscent of the time when there were no permanent chairs there. The seating arrangement is quite efficient (tight by modern standards), and the relatively low (1.2 sec) reverberation time makes for good intelligibility.

1.9 ROMANTIC PERIOD (1825–1900)

The terms Classic and Romantic are not precisely defined nor do they apply strictly to a given time period. Music written between about 1770 and 1900 lies on a continuum, and every composer of the age employed much the same basic harmonic vocabulary (Grout and

FIGURE 1.15 Theatro Alla Scalla, Milan, Italy (Beranel, 1979)



Palisca, 1996). Romantic music is more personal, emotional, and poetic than the Classical and less constrained by a formal style. The Romantic composers wanted to describe thoughts, feelings, and impressions with music, sometimes even writing music as a symphonic poem or other program to tell a story. Although Beethoven lived during the Classical time period, much of his music can be considered Romantic, particularly his sixth and ninth symphonies.

Clearly he bridged the two eras. The best known Romantic composers were all influenced by Beethoven including Franz Schubert (1797–1828), Hector Berlioz (1803–1869), Felix Mendelssohn (1809–1847), Johannes Brahms (1833–1897), and Richard Wagner (1813–1883).

A common characteristic of Classical composers was their familiarity with the piano, which had become the most frequently used instrument. Some Romantic composers were also virtuoso pianists including Franz Liszt (1811–1886), Edvard Grieg (1843–1907), Frederic (1810–1849), and of course Beethoven. The wide dynamic range of this instrument originally led to its name, the forte (loud) piano (soft), and socially prominent households were expected to have one in the parlor.

As musical instruments increased in loudness they could be heard by larger audiences, which in turn encouraged larger concert halls and the use of full orchestras. As performance spaces grew larger there arose an incentive to begin thinking more about their acoustical behavior. Heretofore room shapes had evolved organically, the Italian opera from the Greek and Roman theaters, and the Northern European concert halls from basilican churches and rectangular ballrooms. Many of these rooms were enormously successful and are still today marvels of empirical acoustical design, although there were also those that were less than wonderful. The larger rooms begat more serious difficulties imposed by excessive reverberation and long delayed reflections.

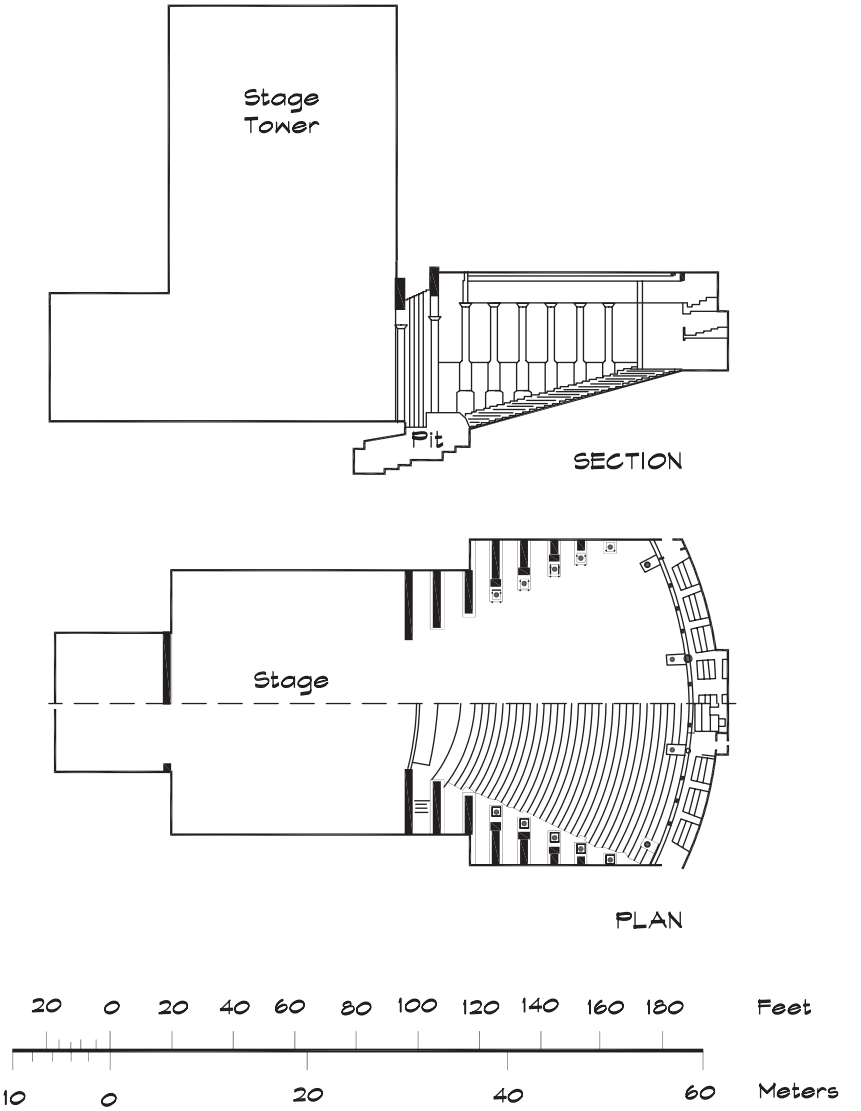
Concerts were performed, for example, in the famous Crystal Palace designed by Joseph Paxton, which had housed the Great Exhibition of 1851 and was later moved to Hyde Park in 1854. This huge structure was built of glass, supported by a cast iron framework, and became a popular place for weekly band concerts. Occasionally mammoth festival concerts were held there, which, for example, in 1882 played to an audience of nearly 88,000 people using 500 instrumentalists and 4000 choir members (Forsyth, 1985).

Knowledge of the acoustical behavior of rooms had not yet been set out in quantitative form. Successful halls were designed using incremental changes from previously constructed rooms. The frustration of many nineteenth-century architects with acoustics is summarized in the words of Jean Louis Charles Garnier (1825–1898), designer of the Paris Opera House, "I gave myself pains to master this bizarre science [of acoustics] but . . . nowhere did I find a positive rule to guide me; on the contrary, nothing but contradictory statements . . . I must explain that I have adopted no principle, that my plan has been based on no theory, and that I leave success or failure to chance alone . . . like an acrobat who closes his eyes and clings to the ropes of an ascending balloon." (Garnier, 1880)

One of the more interesting theatrical structures to be built in the century, Wagner's opera house, the Festspielhaus in Bayreuth, Germany built in 1876, was a close collaboration between the composer and the architect, Otto Brueckwald, and was designed with a clear intent to accomplish certain acoustical and social goals. The auditorium is rectangular but it contains a fan-shaped seating area with the difference being taken up by a series of double columns supported on wing walls. The plan and section are shown in Fig. 1.16. The seating arrangement in itself was an innovation, since it was the first opera house where there was not a differentiation by class between the boxes and the orchestra seating. The horseshoe shape with layered boxes, which had been the traditional form of Italian opera houses for three centuries, was abandoned for a more egalitarian configuration.

Most unusual, however, was the configuration of the pit, which was deepened and partially covered with a radiused shield that directed some of the orchestral sound back toward

FIGURE 1.16 Festspielhaus, Bayreuth, Germany (Beranek, 1979)

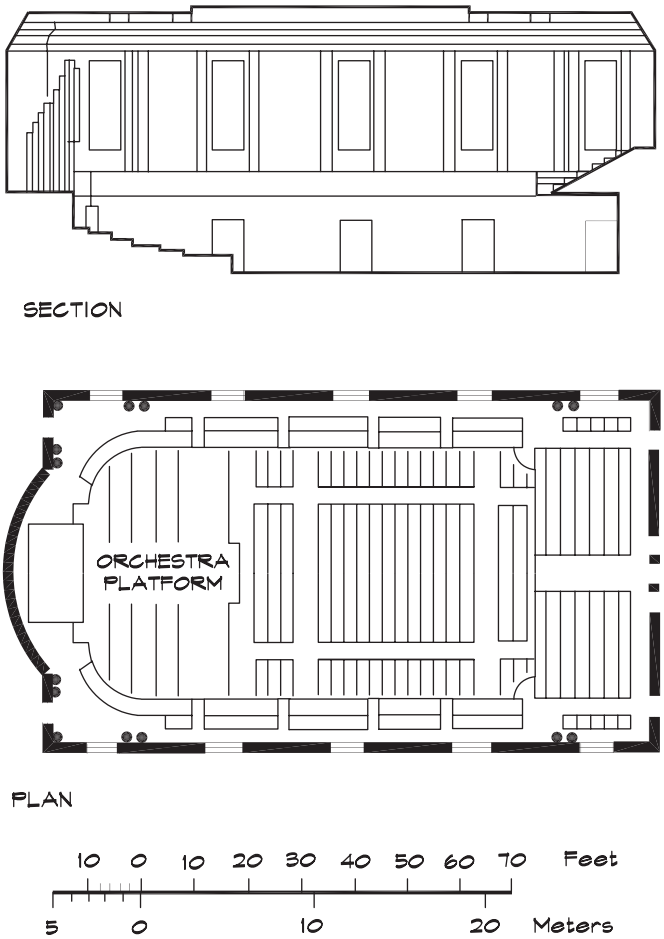


the actors. This device muted the orchestral sound heard by the audience, while allowing the musicians to play at full volume out of sight of the audience. It also changed the loudness of the strings with respect to the horns, improving the balance between the singers and the orchestra. The reverberation time, at 1.55 seconds (Beranek, 1996), was particularly well suited to Wagner's music, perhaps because he composed pieces to be played here, but the style has not been replicated elsewhere.

Shoebox Halls

Several of the orchestral halls constructed in the late eighteenth and early nineteenth centuries are among the finest ever built. Four of them are particularly noteworthy, both for their fine acoustics and for their influence on later buildings. They are all of the shoebox type with high ceilings, multiple diffusing surfaces, and a relatively low seating capacity. The oldest

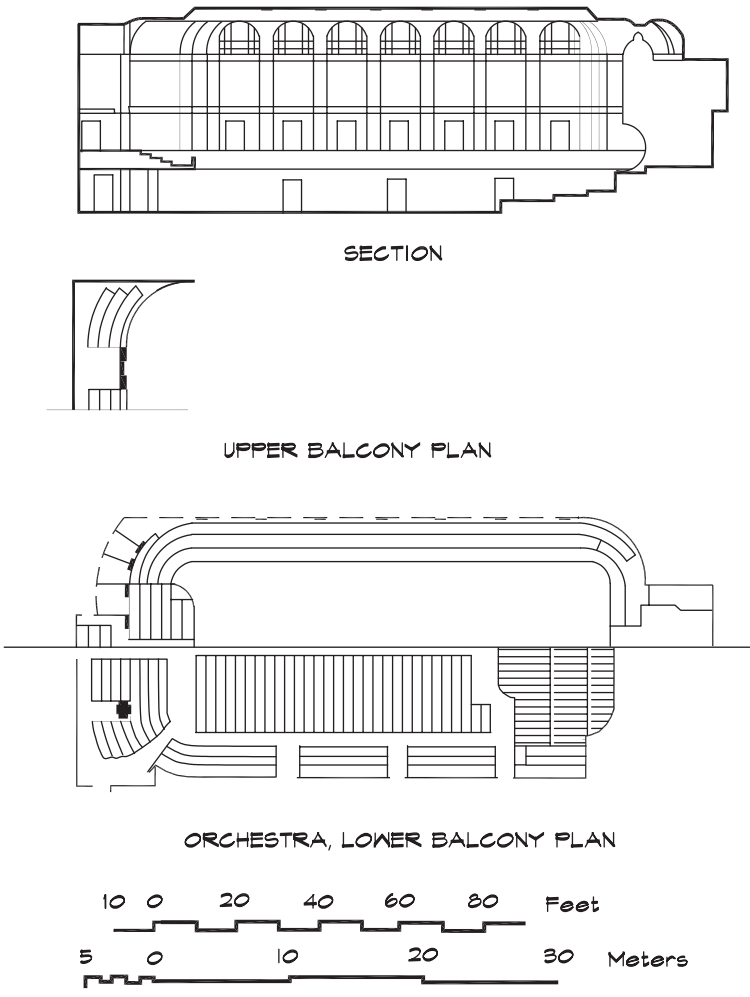
FIGURE 1.17 Concert Hall, Stadt Casino, Basel, Switzerland (Beranek, 1979)



is the Stadt Casino in Basel, Switzerland, which was completed in 1776. Shown in Fig. 1.17, it is very typical of the age with a flat floor reminiscent of the earlier ballrooms, small side and end balconies, and a coffered ceiling. The orchestra was seated on a raised platform with risers extending across its width. Above and to the rear of the orchestra was a large organ. The hall seated 1448 people and had a mid-frequency reverberation time of about 1.8 seconds (Beranek, 1996) making it ideal for Classical and Romantic music.

Ten years later the Neues Gewandhaus was built to provide a larger space for concerts in Leipzig. After it was completed, the old Altes Gewandhaus was torn down. The building was based on a design by the architects Martin K. P. Gropius (1824–1880) and Heinrich Schmieden (1835–1913) and was finally completed in 1882 after Gropius' death, remaining extant until it was destroyed in World War II. A sketch of the hall is shown in Fig. 1.18. Its floor plan is approximately two squares, side by side, measuring 37.8 m (124 ft) by 18.9 m (62 ft) with a 14.9 m (49 ft) high ceiling. The new room housed 1560 in upholstered seats and its reverberation time at 1.55 seconds was less than that of the other three, making it ideal for the works of Bach, Mozart, Haydn, and other Classical chamber music. The upper walls were pierced with arched clerestory windows, looking like the brim of a baseball cap, which let in light and helped to control the bass reverberation. The structural interplay of the

FIGURE 1.18 Neues Gewandhaus, Leipzig, Germany (Beranek, 1979)

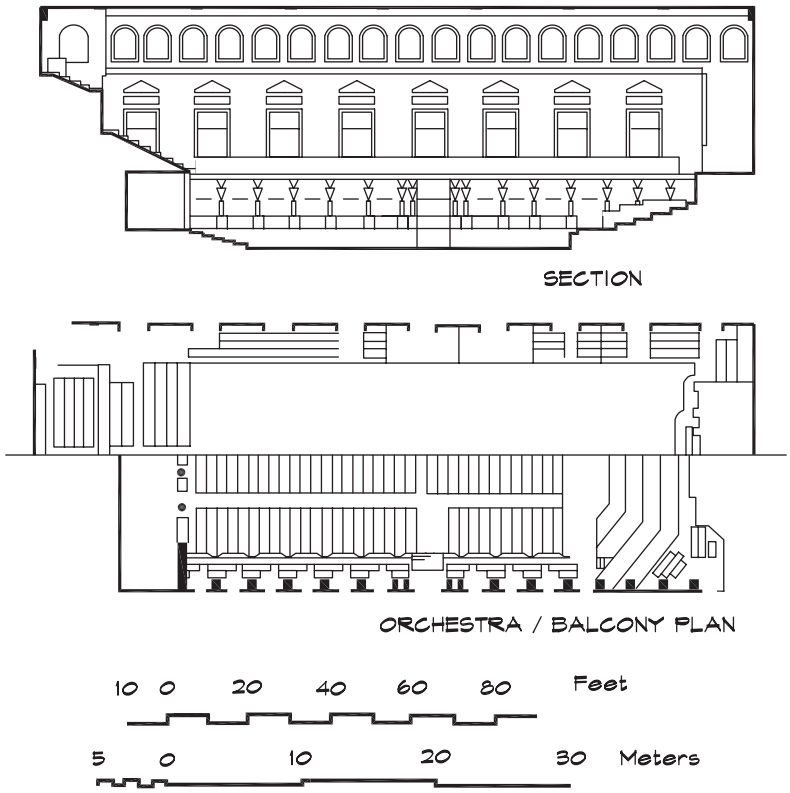


curved transition to the ceiling yielded a highly dramatic form, which, along with three large chandeliers, added diffusion to the space. Like the other halls of this type it had a narrow balcony around its perimeter of about three rows of seating, with a large organ towering over the orchestra.

Grosser Musikvereinssaal (see Fig. 1.19) in Vienna, Austria, which is still in use today, is considered one of the top three or four concert halls in the world. It was opened in 1870 and has a long (50.3 m or 185 ft) and narrow (19.8 m or 65 ft) rectangular floor plan with a high (15 m or 50 ft), heavily beamed ceiling. The seating capacity, at 1680 in wooden seats, is relatively small for so long a room.

The single narrow balcony is supported by a row of golden caryatids, much like giant Oscars, around the side of the orchestra seating. Reflections from the underside of the balcony and the statuary are particularly important in offsetting the grazing attenuation due to the audience seated on a flat floor. The high windows above the balcony provided light for afternoon concerts and reduced the bass buildup.

FIGURE 1.19 Grosser Musikvereinssaal, Vienna, Austria (Beranek, 1979)

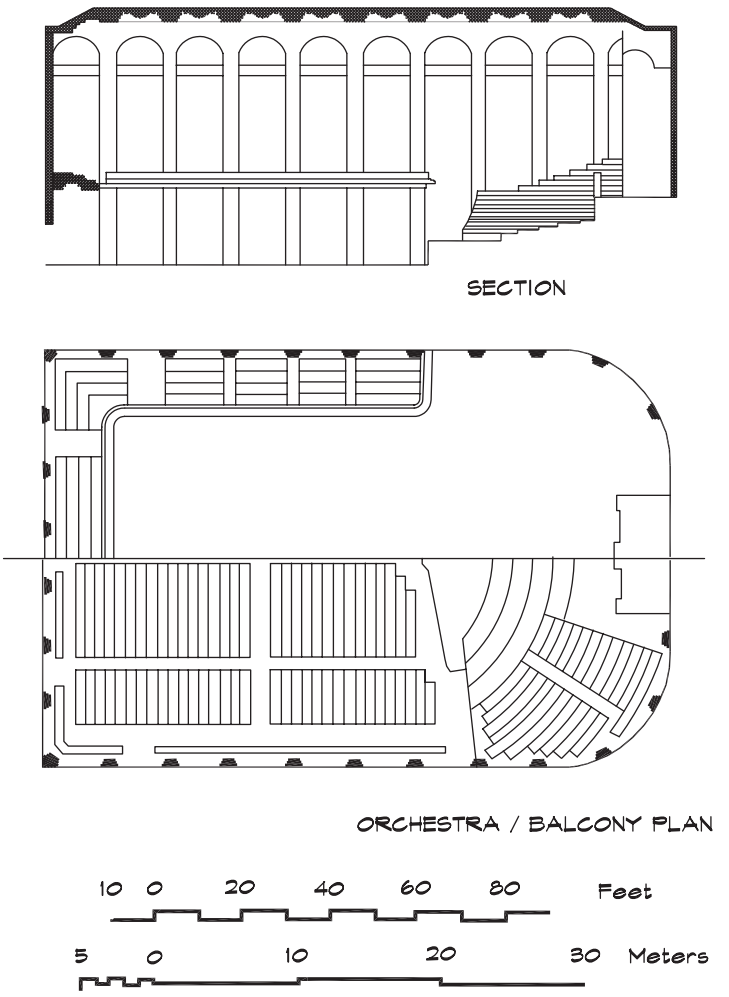


Grosser Musikvereinssaal also was known as the Goldener Saal, since its interior surfaces are covered by meticulously applied paper-thin sheets of gold leaf. The sound in this hall is widely considered ideal for Classical and Romantic music. Its reverberation time is long, just over 2 seconds when fully occupied, and the narrowness of the space provides for strong lateral reflections that surround or envelop the listener in sound. The walls are constructed of thick plaster that supports the bass, and the nearness of the reflecting surfaces and multiple diffusing shapes gives an immediacy and clarity to the high strings. It is this combination of clarity, strong bass, and long reverberation time that is highly prized in concert halls, but rarely achieved.

Concertgebouw in Amsterdam, Netherlands (see Fig. 1.20) is the last of the four shoebox halls. Designed by A. L. Van Gendt, it opened in 1888. Like the others it is rectangular; however, at 29 m (95 ft) it is wider than the other three and seats 2200 people on a flat floor. Consequently it is more reverberant at 2.2 seconds and has somewhat less clarity than Grosser Musikvereinssaal. It is best suited to large-scale Romantic music, providing a live, full, blended tone.

The four halls cited here have similar features that contribute to their excellent acoustics. They are all rectangular and relatively narrow (except in the case of Concertgebouw). The construction is of thick plaster and heavy wood with a deeply coffered ceiling about 15 meters high. The floors are generally flat and the orchestra is seated above the heads of the patrons on a high, raked, wooden platform. The orchestra is located in the same room as the audience rather than being set back into a stage platform. All these rooms are highly ornamented with

FIGURE 1.20 Concertgebouw, Amsterdam, Netherlands (Beranek, 1979)



deep fissures, statuary, recessed windows, organs, and overhanging balconies to help diffuse the sound. They all had highly ornate chandeliers that also scatter the sound.

The capacity of these rooms is not great by modern standards and the seating is tight. No seat is far from a side wall or from the orchestra. The orchestra is backed by a hard reflecting surface to help project the sound, particularly the bass, out to the audience. There is a notable absence of thin wood paneling in these structures. Paneling at one time was considered acoustically desirable in accordance with the hall as a musical instrument theory. These rooms provided excellent acoustics and became the examples to be emulated in the scientific approach to concert hall performance, begun early in the following century.

1.10 BEGINNINGS OF MODERN ACOUSTICS

The nineteenth century produced the beginnings of the study of acoustics as a science and its dissemination in the published literature via technical books and journals. Heretofore scientific ideas had a relatively limited audience and were often distributed through personal correspondence between leading scholars of the day. Frequently written in Latin they were

not generally accessible to the public. In the nineteenth century, books written in English or German, such as Hermann von Helmholtz (1821–1894) *Sensations of Tone* in 1860, established the field as a science where measurement, observation, and a mathematical approach could lead to significant progress. Later in the century (1877) John W. Strutt, Lord Rayleigh published the first of his two-volume set, *Theory of Sound*, followed by the second between 1894 and 1896, which was one of the most important books ever written in the field. In it he pulled together the disparate technical articles of the day and added many valuable contributions of his own. It is remarkable that such a clear presentation of acoustical phenomena was written before careful experimental work was possible. In Rayleigh's time the only practical sound source was a bird whistle (Lindsay, 1966) and the most sensitive detection device (besides the ear) was a gas flame.

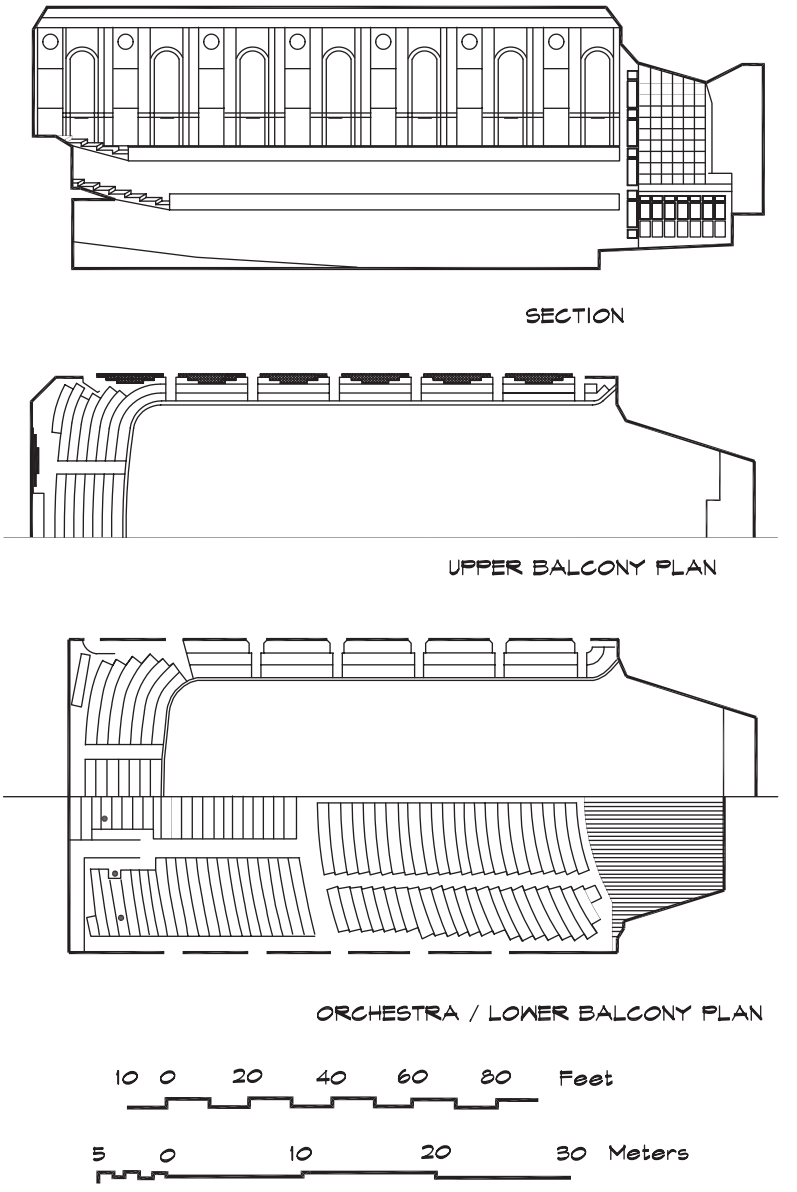
About the same time, in the remarkable decade of the 1870s, there was a surge in the development of practical electroacoustic devices. In Germany, Ernst W. Siemens patented in 1874 the moving coil transducer, which eventually led to today's loudspeaker. In 1887 the U.S. Supreme Court held in favor of the patent, originally filed in 1876, and probably the single most valuable patent ever issued, of Alexander Graham Bell (1847–1922) for the telephone. It incorporated the granular carbon microphone, the first practical microphone, and one of the few instruments that is improved by banging it on a table. Within a year (1877), Thomas A. Edison had patented the phonograph and somewhat later, in 1891, motion pictures. Thus within a decade the technical foundation for the telephone, sound recording, music reproduction, and motion-picture industries had been developed.

In the late nineteenth and early twentieth centuries, the theoretical beginnings of architectural acoustics were started by a young physics professor at Harvard College, W. C. Sabine. Sabine's work began inauspiciously enough following a request by president Elliot to "do something" about the acoustical difficulties in the then new Fogg Art Museum auditorium, which had been completed in 1895 (Sabine, 1922). Sabine took a rather broad view of the scope of this mandate and commenced a series of experiments in three Harvard auditoria with the goal of discovering the reasons behind the difficulties in understanding speech. By the time he had completed his work, he had developed the first theory of sound absorption of materials, its relationship to sound decay in rooms, and a formula for the decay (reverberation) time in rooms. His key discovery was that the product of the total absorption and the reverberation time was a constant.

Soon after this discovery in 1898 he helped with the planning of the Boston Music Hall, now called Symphony Hall. He followed the earlier European examples, using a shoebox shape and heavy plaster construction with a modest ceiling height to maintain a reverberation time of 1.8 seconds. Narrow side and rear balconies were used to avoid shadow zones and a shallow stage enclosure, with angled walls and ceiling, directed the orchestra sound out to the audience. The deeply coffered ceiling and wall niches containing classical statuary helped provide excellent diffusion (Hunt, 1964). The auditorium, pictured in Fig. 1.21, opened in 1900 and is still one of the three or four best concert halls in the world.

While the designers of Boston Symphony Hall followed one European design tradition, the designers of New York's Metropolitan Opera House (see Fig. 1.22) followed another, that of the Italian opera houses. Opening in 1883 the Met, seating over 3600, is one of the largest opera houses in the world. Despite its size it has reasonably good acoustics in the middle balconies; however, the orchestra seats and the upper balcony seats are less satisfactory (Beranek, 1979). With a volume nearly twice that of La Scalla, it is difficult for singers to sound as loud as in Milan. The hall, with some ceiling and balcony front additions by

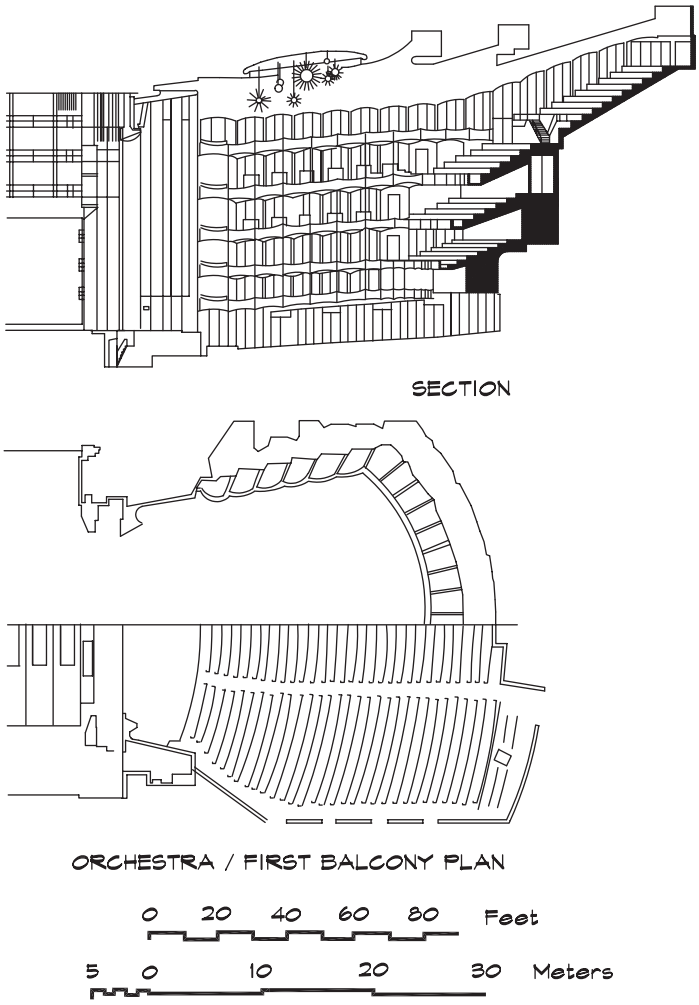
FIGURE 1.21 Symphony Hall, Boston, MA, USA (Beranek, 1979)



architect Wallace K. Harrison and acousticians Cyril Harris and Vilhelm Jordan to increase diffusion and the sound in the balconies, is in active use today.

Another American hall, constructed around the turn of the century, was Carnegie Hall (see Fig. 1.23) in New York. Andrew Carnegie, an entrepreneur and steel baron, was fishing at his vacation home in Scotland with a young American musician, Walter Damrosch, whose father Leopold was director of the New York Symphony Society. The idea to provide a permanent building to house its activities arose while the two were casting in midstream (Forsyth, 1985). The plans were prepared by architect William B. Turnhill and the hall opened in 1891. Carnegie Hall was designed as a shoebox hall but like a theater. The orchestra was

FIGURE 1.22 Metropolitan Opera House, New York, NY, USA (Beranek, 1979)

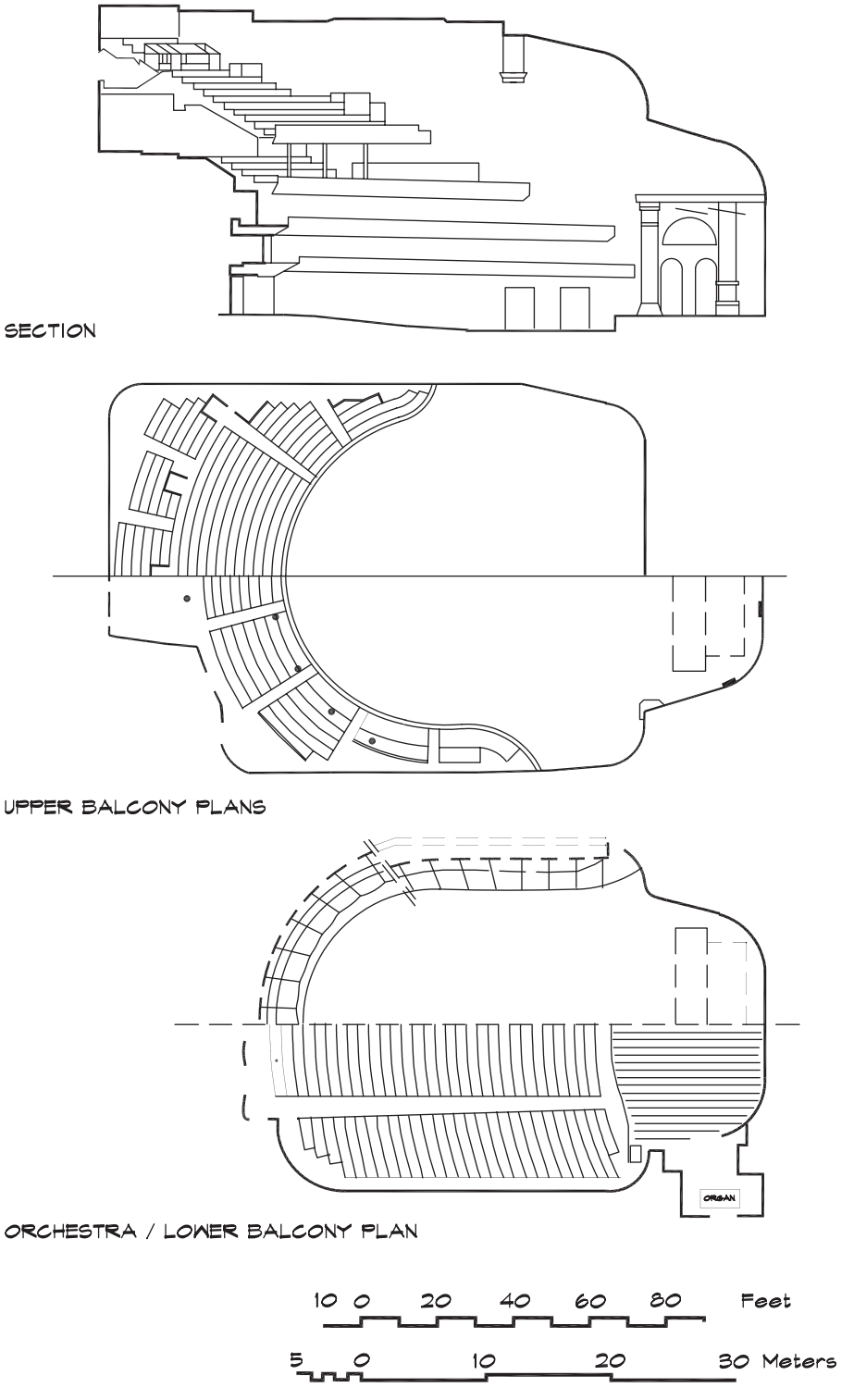


located on stage behind a proscenium arch under a curved orchestra shell. The audience is seated on a nearly flat floor and in four balconies, whose rounded front faces are stacked on an imaginary cylinder. Each balcony flares out into side balconies, which almost reach the stage at the lowest level. Carnegie Hall is known for the clarity of its high frequency sound. At 1.7 seconds it has a slightly dry reverberation with less bass support than in Boston. It was recently refurbished with the stated objective of leaving the acoustical properties unchanged.

1.11 TWENTIETH CENTURY

In the twentieth century, architectural acoustics came to be recognized as a science as well as an art. Although the number and quality of the published works increased, our understanding of many of the principles of acoustical design did not in all cases lead to improvements in concert halls. The more routine aspects of room acoustics, including noise and vibration control and development of effective acoustical materials, experienced marked improvements.

FIGURE 1.23 Carnegie Hall, New York, NY, USA (Beranek, 1979)



The development of electroacoustic devices including microphones, amplifiers, loudspeakers, and other electronic processing instruments flourished. The precision, which is now available in the ability to record and reproduce sound, has in a sense created an expectation of excellence that is difficult to match in a live performance. The high-frequency response in a hall is never as crisp as in a close-miked recording. The performance space is seldom as quiet as a recording studio. The seats are never as comfortable as in a living room. Ironically, just as we have begun to understand the behavior of concert halls and are able to accurately model their behavior, electroacoustic technology has developed to the point where it may soon provide an equivalent or even superior experience in our homes.