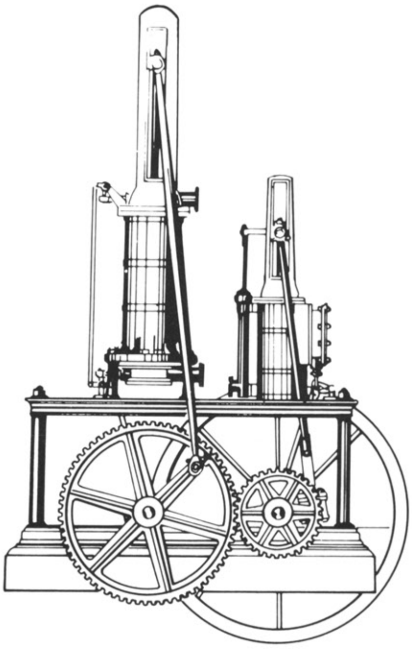
chilled to become ice, the brine recirculated to the evaporator where the ether once more lowered its temperature.[8] Perkins's invention did not gain wide commercial application, but an engineer in East London is said to have operated a Perkins compressor for a time and sold the ice it produced.

Years later John Gorrie, a physician in the busy cotton port of Apalachicola, Florida, became so absorbed in his theory that malarial fever could be cured or prevented by cooling the air of sickrooms that he abandoned his medical practice, which had included a government contract to care for sick sailors in a local hospital.[9] Written under a pseudonym, Gorrie's articles in the local newspaper show that he was fully aware of the nonmedical potential of his invention for producing cold:

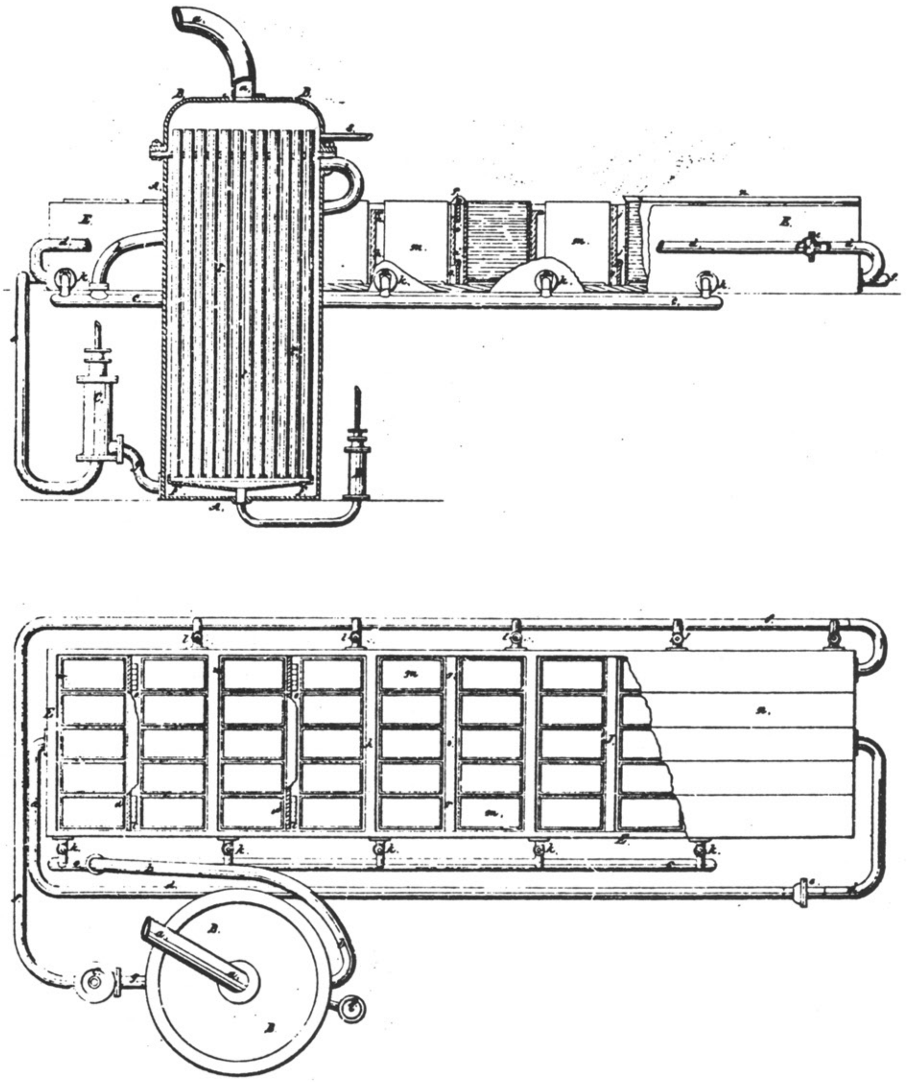
> There are advantages to be derived from the generation of cool air within any building and this is equally applicable to ships as well. It might enable the hardy mariner to better serve mankind, he who contributes so much to our wealth and pleasure by transporting for us, from shore to shore, the rich production of the tropics—as animals when divested of life, and fruits which may be preserved entirely with all of their juices in a low temperature. This principle of producing and maintaining cold might be made instrumental in preserving organic matter for an indefinite time and thus become an accessory to the extension of commerce.[10]

His invention, patented in 1851 with the assistance of a Boston investor, was a compression design, releasing air at high pressure into a cooling chamber that was surrounded by water (fig. 12.3). Gorrie demonstrated his ice machine publicly, but he could not find sufficient financial backing to establish a commercial application.



The air cycle compression system was clearly less efficient than others that used chemical agents, but air had the obvious advantage of being odorless, nonflammable, and readily available everywhere. It was natural that hospitals should prefer a cooling system that employed a harmless substance. Lloyd's, the London international market for marine insurance, and its underwriters gave their approval to no other system of refrigeration.

With the metropolitan population of Europe growing, the cattle and sheep that grazed on broad plains in Australia, Argentina, and the United States awaited a ready market. Shipping meat across stretches of equatorial water demanded a mass of natural ice that occupied much of a ship's hold, usually making the venture uncertain and unprofitable (fig. 12.4). In 1878 the steamship *Strathclyde*,



12.5 Alexander C. Twining's ice machine, patented in England (1850) and the U.S. (1850, 1862), was put in commercial operation in Cleveland, Ohio. This last patent uses a single tank of chilled brine to freeze 50 blocks of ice. Although the price of its product was almost competitive with natural ice, Twining's ice plant did not survive. (U.S. Patent no. 34,993.)

which had been outfitted with an air cycle system, sailed from Europe to Australia and returned with a load of beef and mutton in her cargo. Thereafter the air cycle system dominated in the marine transportation of foods, as well as in hospital installations. Air cycle equipment reigned until the 1890s, with many improvements being made upon the original models.

In 1853 Alexander C. Twining, an engineer living in New Haven, Connecticut, invented and patented a liquid vapor compression machine to make ice (fig. 12.5). Twining had studied engineering at West Point, and his early work laying out the northerly routes of the Hartford and New Haven Railroad led to a lucrative position as consulting engineer for other railroad companies that were engaged in westward expansion. After Twining resigned the chair of mathematics at Middlebury (Vermont) College in 1849, he devoted much of his time to development of his ice machine. The machine employed a system much like that used some 20 years before by Jacob Perkins. In the ice plant that Twining built in Cleveland, Ohio, a logical point to originate shipments of ice down the Ohio and Mississippi rivers, volatile sulphuric ether was employed.[11] The plant's output was said to have been 1,600 pounds of ice per day. For a time this type of machine was the most prevalent form of refrigeration, for it involved lightweight machinery, less expensive and more easily maintained than that of other systems.

The aqua ammonia system of refrigeration used as its refrigerant a mixture of water and ammonia, the latter usually procured from plants that manufactured illuminating gas.[12] A Frenchman, Ferdinand Carré, patented his machine before the Civil War began in the United States. New Orleans businessmen had a Carré machine shipped from France through the Union blockade, and it was set up at the military hospital in Augusta, Georgia, for the benefit of soldiers who suffered from fevers. This machine was small, producing only about 500 pounds of ice per day, and the process could be regulated only by stoking or banking the fire. Three more Carré machines were imported by these New Orleans investors, and they were shipped through Mexico in order to circumvent the Yankee blockade. One of the machines was purchased by a firm in San Antonio, Texas, where it was fitted with a steam coil to better regulate the process.[13] Because it could not provide clear ice from the city's water, the firm froze distilled water, producing transparent blocks that were considered superior to the natural ice shipped from Boston. In spite of such pioneer activity, in 1867 there were only five ice plants operating in the United States. It was the "great ice famine," caused by a very warm winter in 1890, that provided a major impetus for the American ice trade to convert to mechanical refrigeration.[14]

By the 1860s, refrigeration with natural ice had been adopted in most American slaughterhouses. In the next two decades, refrigerated railroad cars came into general use for shipping meat from the stockyards in Chicago. Shipments across oceans, the key that would open European markets, were attempted in the same period. Natural ice and a manually operated fan were used in 1875 to chill meat on the trip from New York to England. It was more than four times that distance to England from Australia and New Zealand, where wool had been the most marketable part of the sheep that grazed on rich grasslands. In 1879 two shipments of frozen meat reached England from Australia, and three years later a successful shipment was made from New Zealand, winning a prize that had been offered by the colonial government. By 1890 the number of sheep in Australia had greatly increased, and land values in both colonies had risen appreciably.

* * *

Early mechanical refrigeration found little application to the provision of human comfort, except for the cooling of feverish hospital patients. To some extent this may have been due to the fact that air cooling with ice had already been provided in some spaces intended for human occupancy, particularly places of assembly. The ventures into air conditioning were at first dominated by demands of industries in which there was a need for humidity control.

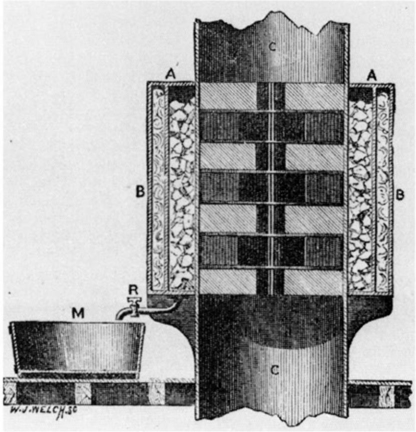
The French scientist Jouglet in the 1870s reported several attempts that others had made to bring cooler air into rooms that were intolerable for gatherings during the heat of summer. He described the frustrations that had been acknowledged in assemblies of the Académie des Sciences:

> On that day the heat was suffocating, and the rays of the afternoon sun were glowing through the windows. Unable to control himself, Velpeau rose with protestations against the orb of day, and called upon the

> physical [science] section of the assembly to find some method of putting an end to such a state of things. General Morin, moved by the burning eloquence of his illustrious associate, rose, and stated that hitherto it had been found impossible to abate the nuisance . . . in fact, the brave general confessed himself vanquished by the rays of the sun itself.[15]

One design was tried in the very hall that had occasioned Velpeau's outburst. A vertical cylinder was placed on the roof and within it were set 104 pipes of 1½-inch diameter through which chilled water flowed. Air, cooled by contact with the pipes, descended into the room. This invention was found to be inadequate, and another experimenter made a futile attempt to improve it by wetting the external surfaces of the pipes.[16] A few years later a similar device was described to a meeting of the Institution of Civil Engineers in England. In this design, cool water from a nearby brook streamed over the surface of a perforated panel through which a fan blew air. It was reported that the temperature of the air going through this contrivance was lowered from 70° F to 56° F.

Another method of obtaining cool air was the use of underground sources. At the Necker Hospital in Paris a large masonry tunnel over 180 feet long ran 13 feet under the building's cellars, and it was reported to cool the air more than 8° F when outside air was 80° in the shade. The Conservatoire des Arts et Métiers simply drew air from the building's deep cellars; however, suggestions to use the air in the catacombs beneath Paris (which was said to be about 58° F) were rejected, because air from sewers and cemeteries was not considered healthful in a world that still believed in the miasmic principle of disease. As late as 1900 a more extensive system was used to cool the Court Theater in Vienna. An underground channel was divided by a center wall running its entire length. On one side water sprayed over 276 metal trays; on the other side were the cool moist walls of the tunnel. At the end of these two channels the air was directed to those spaces in the building that were at the time most urgently in need of cooling.[17]

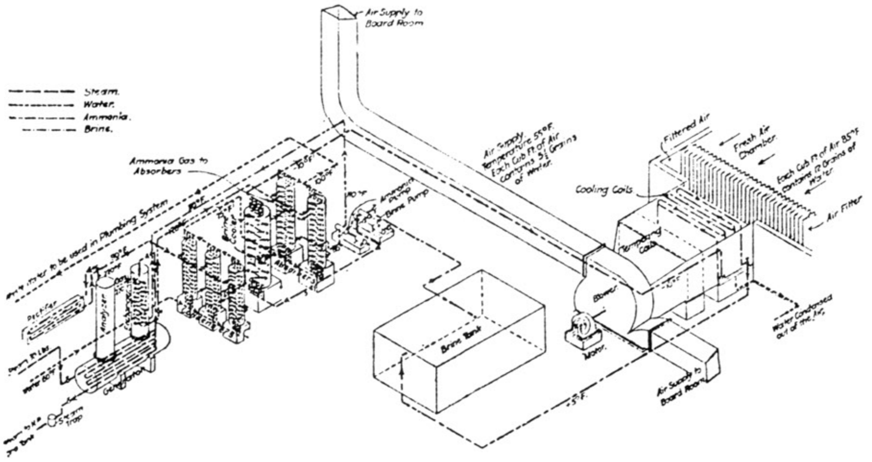


12.6 This double-jacketed flue, developed in France, was typical of many late nineteenth-century cooling experiments. The outermost cylinder was packed with an insulation material; the next held ice and salt. Metal fins within the flue increased the amount of chilled surface over which air passed. In the view of one writer, the high cost of natural ice limited the system to use as an "instrument of medical practice." (*Practical Magazine*, no. 6, 1873.)

12.7 Alfred Wolff, an American pioneer of air conditioning, designed this system for the New York Stock Exchange. Air entered at the right; after being filtered, it passed over coils that heated or cooled it. At the left an ammonia absorption machine chilled brine to be stored in a subterranean tank (center), allowing nighttime operation in anticipation of the daytime hours of frenzied trading in the Board Room. (*Metal Worker, Plumber, and Steam Fitter*, 5 August 1905.)

12.8 In spite of the windows and skylight, it was calculated that almost two-thirds of the heat in the Board Room of the New York Stock Exchange would rise from about 1,000 workers on the trading floor. (*Century Magazine*, November 1903.)

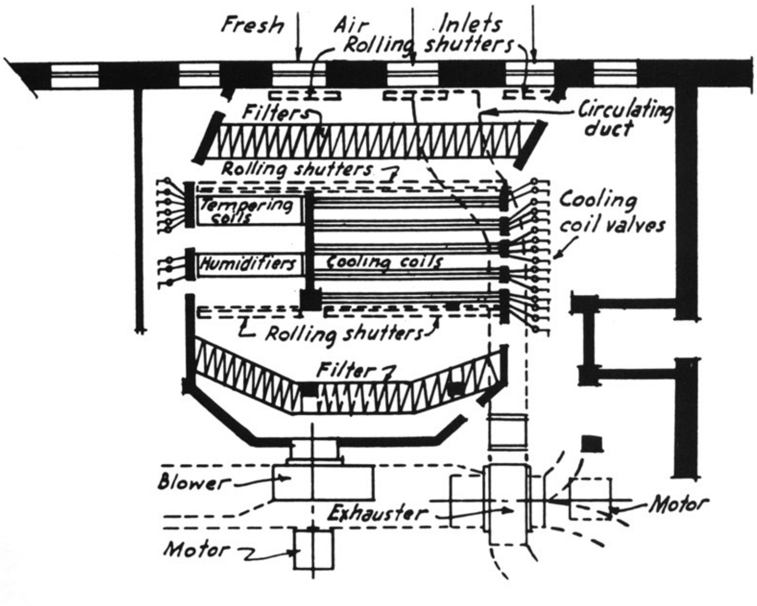
Once machine-made ice was available, another option was considered, that of cooling air by passing it over ice or some surface chilled by ice. A French invention drew air through a round metal duct surrounded by a container filled with ice and salt (fig. 12.6). Metal vanes inside the duct insured that the air traveled a route long enough for it to be sufficiently cooled. An estimate indicated that cooling the wards of a Paris hospital by this method would cost fully as much as heating them through the winter, and therefore the proposal was rejected.[18] It is reported, however, that in 1880 an ice cream maker who had built a hotel in Staten Island, New York, began cooling his hotel dining room through ducts set in ice and salt. Three years later a restaurant at the Hygiene Exhibition in Berlin was cooled by air blown over ice, but the flimsy construction of this temporary building prevented the cooling system's being fully effective.


Air Supply to Board Room
Steam.
Water.
Ammonia.
Brine.
Ammonia Gas to Absorbers
Water to be used in Plumbing System
Rectifier
Analyzer
Generator
Steam Trap
Water 80°F
Absorbers
Brine Cooler
Ammonia Pump
Brine Pump
Brine Tank
+5°F.
Air Supply. Temperature 55°F. Each Cub Ft. of Air Contains 5¼ Grains of Water.
Cooling Coils
Filtered Air
Fresh Air Chamber.
Each Cub Ft of Air 85°F contains 12 Grains of Water
Air Filter
Tempering Coils
Blower
Motor.
Water Condensed out of the Air.
Air Supply to Board Room


Otto H. Bacher . 03

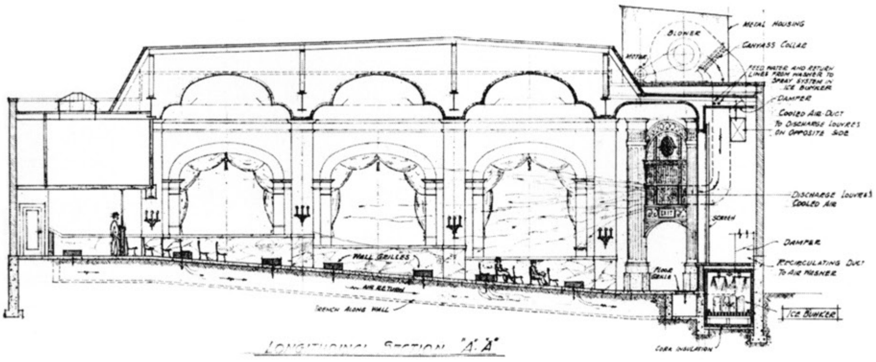
When Carnegie Hall in New York was built in 1889, the architect, William B. Tuthill, and his young consulting engineer, Alfred R. Wolff, provided in its basement a large rack on which blocks of ice were placed. Air was brought from an intake above the building's roof and drawn across racks of ice by four steam-powered blowers that stood 12 feet high. The blowers were necessarily powerful, for they forced the air again to the roof structure of the building, where it entered the concert hall through grilles in the ceiling.[19] Less complicated installations were used for some theaters and auditoriums. In fact, the 1901 high school graduation exercises in Scranton, Pennsylvania, were cooled by about 8 tons of ice, mounted on a wooden rack. Though temporary, this makeshift solution was reported to have lowered air temperature in the auditorium from the 90° F outside temperature to a moist 76° F.[20]

Systems remained much the same when mechanical refrigeration began to replace ice in cooling installations. An Indian rajah's palace was to have been cooled around 1890 by a mechanical refrigeration system planned by a Canadian company. Later a residence in Frankfurt, Germany, and a private library in St. Louis, Missouri, had mechanical cooling apparatuses installed. Even when a more complete treatment of air was provided for certain industrial purposes, gatherings of people were at best forced to rely on simple air cooling systems in which ventilating fans blew over refrigerated coils.



12.9 The system Alfred Wolff designed in 1907 for the Metropolitan Museum of Art in New York provided for warming, moistening, or cooling air as needed for the preservation of works of art. Fresh or recirculated air passed through cheesecloth filters before and after treatment, the route being determined by shutters that controlled the openings. The cooling equipment was used only a few years, because museum management felt that winter control of temperature and humidity was sufficient without cooling and dehumidification in the summer. (*Heating, Piping and Air Conditioning*, June 1936.)

When it was announced that the New York Stock Exchange would be air-cooled, it was recalled that a frustrated proponent of cooling hospitals had bitterly commented years before, "If they can cool dead hogs in Chicago, why not live bulls and bear in the New York Stock Exchange?"[21] In New York's hot and muggy summer weather, the expanse of windows that opened into the trading room of George B. Post's design was responsible for about 25 percent of the heat in the room (figs. 12.7, 12.8). But this was a small matter when compared with the heat generated by the bodies of around 1,000 anxious traders in the market, which contributed, at maximum condition, at least 66 percent of the design load considered by Alfred R. Wolff, the mechanical engineer who had designed the ice-cooling system for Carnegie Hall.[22] The Stock Exchange's system, which used ammonia as its refrigerant, was the same that had been successfully applied by Wolff a short time before in the Hanover National Bank. In the Stock Exchange, as it was completed in 1904, air was taken in at roof level, drawn down a shaft to the basement, and went through a filter of 5,400 square feet of cheesecloth hanging in a zigzag pattern.[23] The refrigeration equipment was powered by exhaust steam from the electric generators that supplied the building's lighting system. Brine from a basement tank was chilled and then passed through coils



DIAGRAMMATIC VIEW OF ICE COOLING SYSTEM INSTALLED IN THEATER

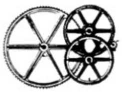
12.10 In a Philadelphia movie house, the air-cooling system sprayed water over ice kept in an insulated "bunker" beneath the screen, and the chilled water was then pumped to an air washer on the building's roof. The ice company that installed this system around 1932 warned against engineers' insistence on "complete engineering systems" and stoutly declared that "the progress of air cooling will take place not by the attainment of perfection and complete systems but by makeshifts and partial jobs." (*Refrigerating Engineering*, November 1932.)

located between the cheesecloth filters and the blower. One of the first large installations of air cooling outside industry, the Stock Exchange led to the application of cooling in theaters and department stores, where other crowds contributed body heat.

At about the same time, a theater in Cologne, Germany, installed a refrigeration machine to cool its audiences. During daytime hours the theater was cooled in preparation for the evening's performance by circulating cool well water through the coils of the system, and at the same time the refrigeration plant chilled brine, which was retained in a large storage tank. Once an audience filled the theater, cold brine circulated through the coils so that its lower temperature could compensate for the heat given off by bodies and lights.

A flourish of activity in cooling theaters began in the 1910s (fig. 12.10). The rapid development of cooled theaters was the result of a highly competitive business structure that came with the introduction of motion pictures. In 1917 the Empire theater in Montgomery, Alabama, installed a year-round cooling system. In the years that followed World War I, two Chicago movie houses led the way by installing air-cooling systems using mechanical refrigeration, and Grauman's Metropolitan Theater in Los Angeles, California, provided full air conditioning (fig. 12.11). It has been estimated that by 1931 about 400 movie houses, vaudeville palaces, and legitimate theaters were cooled.

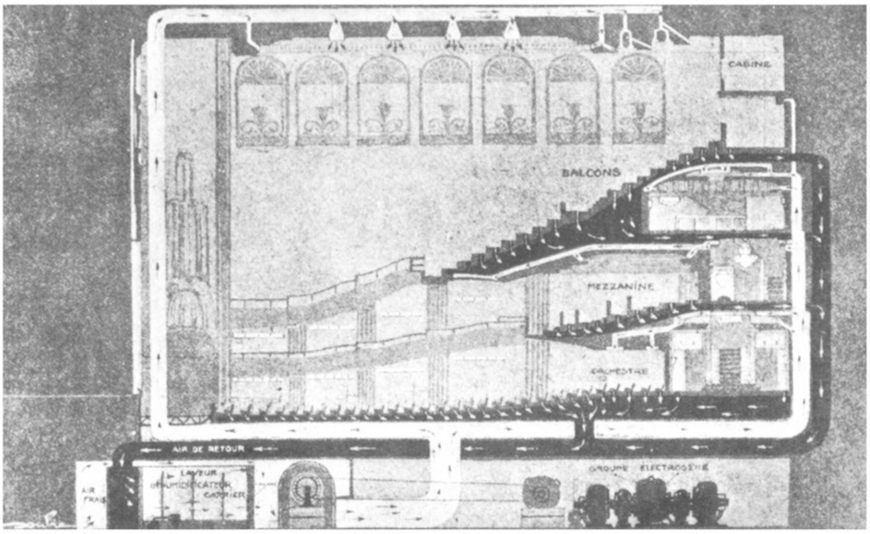
Air-cooled interiors still had the problem of high humidity, and this was particularly true of systems that blew the air over melting blocks of ice. At the turn of the century it was not uncommon that beyond the ice racks would be placed shallow trays filled with calcium chloride, a by-product of the manufacture of soda ash that could absorb roughly three times its weight in moisture before dissolving. This was the same chemical used by Carrier in his first attempts to solve the problems of excessive humidity.



In 1901 Willis Haviland Carrier graduated in engineering from Cornell University and took a position with the Buffalo Forge Company, a manufacturer of coils and fans for heating installations.[24] After only a year with the company, Carrier was assigned to solve the problems of the Sackett-Wilhelms Lithographing and Publishing Company of Brooklyn, New York, printers for *Judge*, the country's leading humor magazine, and other publications. Color lithography, which had only a short time before advanced to incorporate the half-tone process, demanded precise register of the several individual printings that might be required for a single colored picture. Fluctuations of humidity in the hot pressroom of the printer could cause paper to expand or contract and result in faulty register of the different colors of ink, and excessive moisture in the air impeded drying of inks and delayed the entire process. Sackett-Wilhelms had a dire need for humidity control, especially after the unusually hot and steamy summers of 1900 and 1901.

Carrier's first move was an experiment of drawing air through burlap soaked with a saturated solution of calcium chloride. This removed moisture from the air, but air coming from it seriously corroded the printing presses. In a second attempt Carrier carefully selected the dewpoint temperature at which the air retained the correct amount of water vapor for printing. For this purpose he used psychrometric tables provided by the Weather Bureau, charts that indicated the relationship of air temperature and the maximum amount of water vapor that it could retain. With this data, he determined the amount of coil surface, the required temperature of the coils, and the velocity of air movement that would be needed to accomplish his task. Money was saved the first summer by using cool water from an artesian well, rather than from city mains, but the second summer saw the addition of a refrigerating system. For winter months, when the heated air tended to be too dry, a spray of low-pressure steam was added. Having established the relationship of temperature and water vapor as the key to successful air conditioning, Carrier came upon the principle that was the basis of his work:

> Here is air approximately 100% saturated with moisture. The temperature is low so, even though saturated, there is not much actual moisture. There could not be at so low a temperature. Now, if I can saturate



12.11 Although early application of air conditioning centered in the United States, major European movie houses soon installed systems. By the late 1920s the "Paramount" in Paris had a Carrier machine in the basement. Cool air entered the auditorium through its ceiling and the undersides of balconies, and it returned to the basement through "mushroom" fixtures beneath the seats. (*Science et Vie*, February 1928.)

> air and control its temperature at saturation, I can get air with any amount of moisture I want in it. I can do it, too, by drawing the air through a fine spray of water to create actual fog. By controlling the water temperature I can control the temperature at saturation. When very moist air is desired, I'll heat the water. When very dry air is desired, that is, air with a small amount of moisture, I'll use cold water to get low temperature saturation. The cold spray water will actually be the condensing surface. I certainly will get rid of the rusting difficulties that occur when using steel coils for condensing vapor in air. Water won't rust.[25]

One problem was that of finding a spray that would send out particles of water as fine as mist, and the solution lay in nozzles that had been designed to spread a fog of insecticide on plants. A U.S. patent for Carrier's "Apparatus for Treating Air" was issued in 1906. The first installation was made at the LaCrosse National Bank in Wisconsin, but there the system was used only to wash air in the ventilation system.

Carrier's work was first directed toward factory problems, just as refrigeration had been first used in meat packing, brewing, and other industries. Mills for cotton, rayon, and silk; factories making gelatin capsules for pharmaceutical companies and celluloid for movie film; and workshops where tobacco leaves were hand-rolled into cigars—there was a seemingly endless list of manufacturers who had for years tolerated waste, inefficiency, or imperfections that might now be avoided through control of temperature, humidity, and airborne particles of the materials used.

Factories and theaters had specific needs for cooling, and most of their problems of cooling centered on one or perhaps two large undivided spaces. Buildings that were subdivided into many separate spaces presented new questions. The Travis Investment Company of San Antonio, Texas, in January 1928 opened its new 21-story office structure, the Milam Building (figs. 12.12, 12.13). Although several earlier office buildings had been air-conditioned, the Milam Building was heralded as the tallest of these and the "most completely equipped." Eleven air conditioning units were distributed through the building. Each two typical floors of office space, arranged in a C-shaped plan that was common at the time, were served by a single air conditioning plant. In the basement, a refrigerating plant chilled water, which was stored in a tank beneath the basement floor. This tank provided the advantage of being able to operate the refrigerating plant, whose maximum daily load was the equivalent of 375 tons of ice, during the hours when electric rates were lowest. Cold water was pumped to each of the conditioning units, where fans pulled air through fine sprays of water and sent it down ducts above the corridor ceilings.

It was estimated that savings effected by the Milam Building's air conditioning system would compensate for about 40 percent of the cost of the system. Transoms over office doors could be eliminated, along with the ceiling fans that were customary in southern states. Other advantages that were put forth at the time included the office workers' escape from street noises, janitorial costs saved by preventing dust blowing into offices, and the tenants' willingness to pay higher rents for cool and comfortable offices. In addition, it was recommended that the occupants be allowed to control the volume of air entering their spaces, both because an excess of automatic controls would demand too much attention and the conviction

12.12 In addition to being the tallest reinforced concrete building of its time, the Milam Building, San Antonio, Texas, was also the most completely air-conditioned. In the city's sunny summers the highest cooling needs occurred around four o'clock in the afternoon, but that requirement was adjusted on the assumption that Texans were comfortable at temperatures slightly higher than those preferred by natives of other areas. (*Heating, Piping and Air Conditioning*, July 1929.)

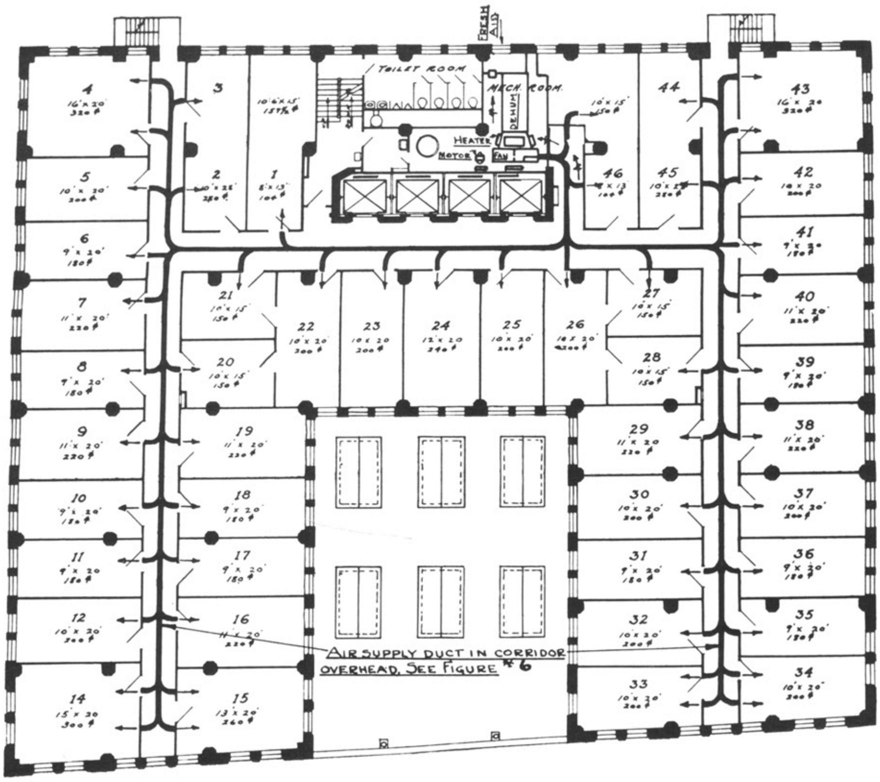
12.13 From the mechanical rooms behind the elevators of the Milam Building (top of drawing), flat ducts ran above corridors, bringing warm or cool air to each office. Air returned through grilles in office doors, traveling through the corridors to reach the mechanical rooms. (*Heating, Piping and Air Conditioning*, July 1929.)

12.14 When *Fortune* magazine published this diagram explaining the air conditioning of office buildings in 1938, few skyscrapers were cooled. World War II delayed the construction of office buildings, but once the war ended air-conditioned office space rapidly became the standard in the United States. (*Fortune*, April 1938. Copyright 1938 Time, Inc. All rights reserved.)

that the office tenant "is considerably relieved merely to feel that he has taken some action, more or less regardless of the results." The journal *Heating, Piping and Air Conditioning* viewed the building's air conditioning system with enthusiasm:

> The windowless skyscraper, already envisioned by others and made possible by air-conditioning plus artificial illumination, will surely become a reality since, for one thing, it can be erected on relatively inexpensive property. Let those who cry for "fresh" air through open windows from the out-of-doors be reminded that it doesn't exist in the congested city. . . . So air-conditioning has come to make available every day the best in atmospheric comfort that nature offers so spasmodically.[26]

The second skyscraper to be so fully air-conditioned was probably the Philadelphia Savings Fund Society, a landmark of modern architecture built in the midst of the Great Depression, four years after the Milam Building.


FRESH AIR
TOILET ROOM
MECH. ROOM
DEHUM
HEATER
MOTOR
FAN
1
8'x 13'
104#
2
10'x 25'
250#
3
10'6"x 15'
157½#
4
16'x 20'
320#
5
10'x 20'
200#
6
9'x 20'
180#
7
11'x 20'
220#
8
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11'x 20'
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260#
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10'x 20'
200#
23
10 x 20
200#
24
12'x 20
240#
25
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26
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200#
27
10'x 15'
150#
28
10'x 15'
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11'x 20
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40
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41
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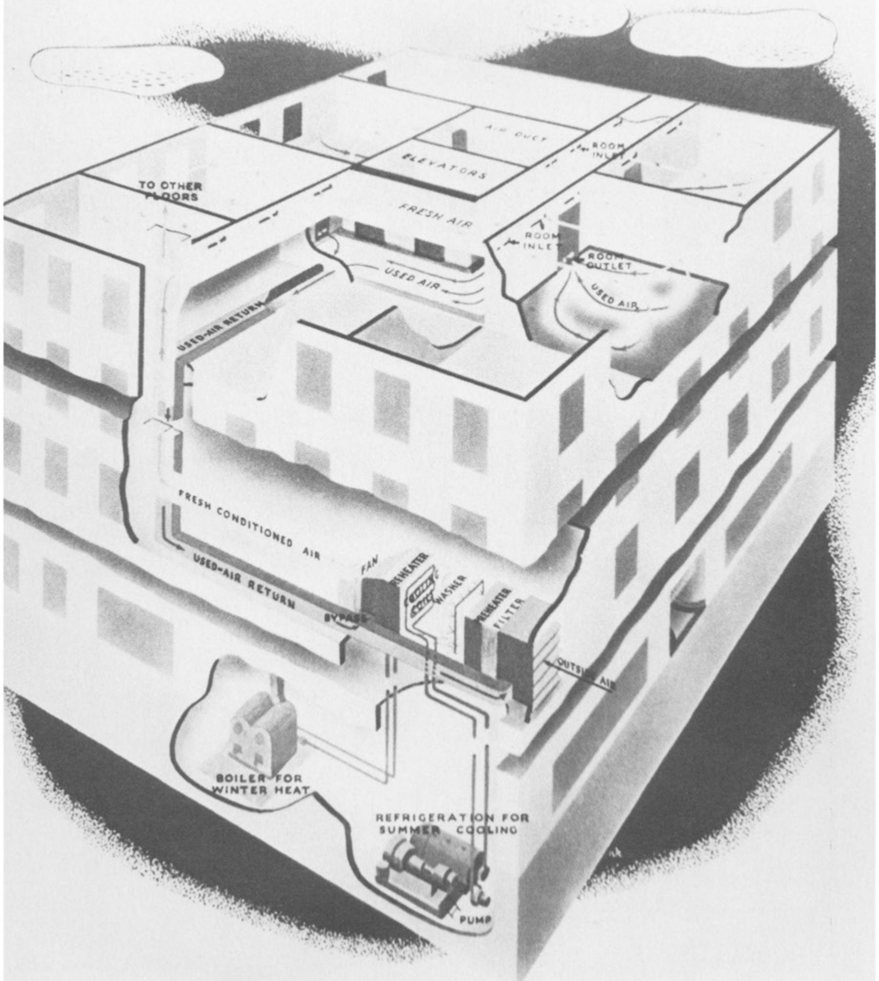
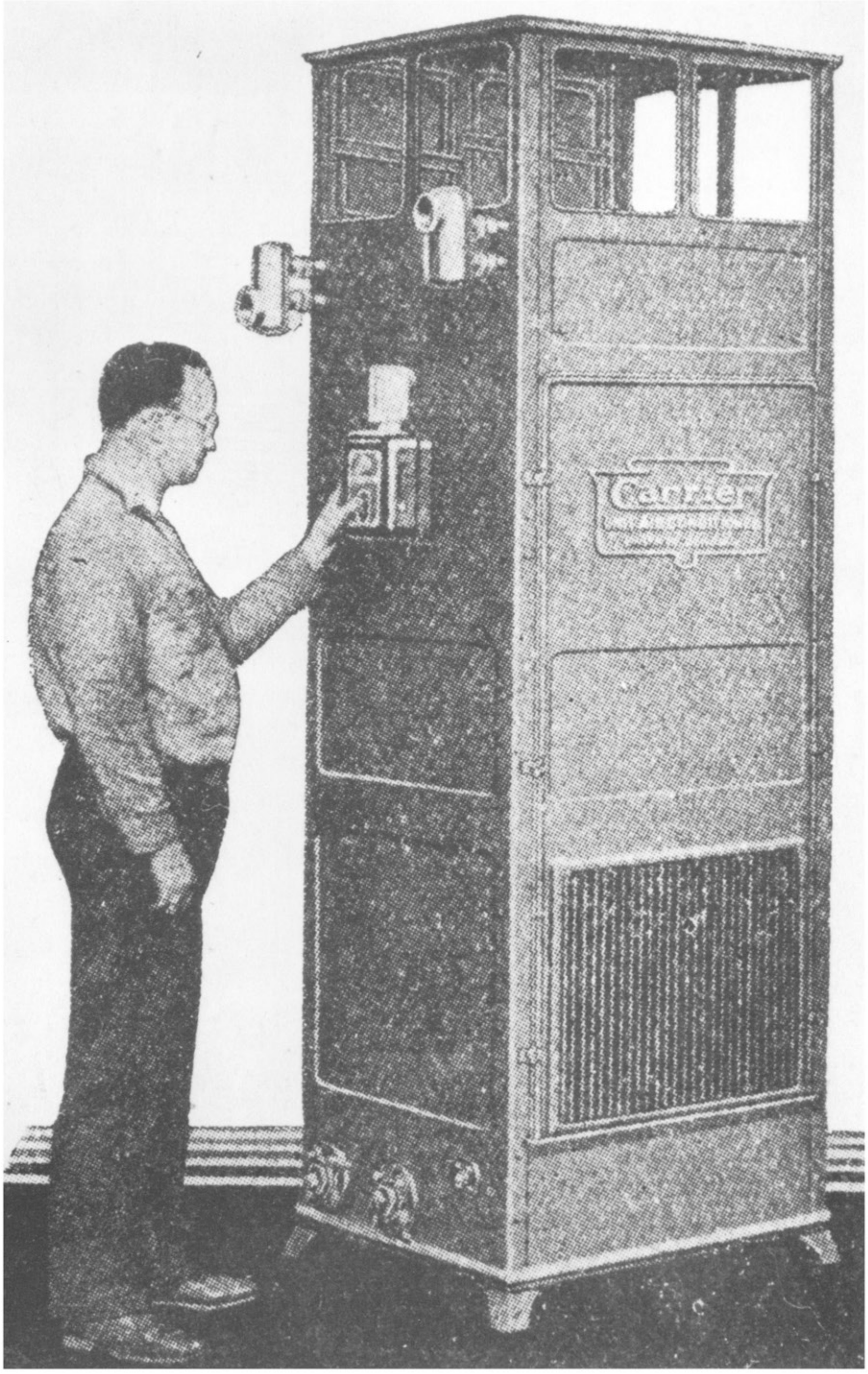
180#
42
10 x 20
200#
43
16'x 20
320#
44
10'x 15'
150#
45
10'x 25'
250#
46
8'x 13
104#
AIR SUPPLY DUCT IN CORRIDOR OVERHEAD. SEE FIGURE #6


TO OTHER FLOORS
AIR DUCT
ELEVATORS
ROOM INLET
FRESH AIR
ROOM INLET
ROOM OUTLET
USED AIR
USED AIR
USED-AIR RETURN
FRESH CONDITIONED AIR
USED-AIR RETURN
BYPASS
FAN
REHEATER
COOLING COILS
WASHER
PREHEATER
FILTER
OUTSIDE AIR
BOILER FOR WINTER HEAT
REFRIGERATION FOR SUMMER COOLING
PUMP



12.15 By the late 1920s, major companies were manufacturing unit air conditioners, such as this one produced by Carrier. When several were spaced about a large room, they governed temperature and humidity without the expense of installing a system of ductwork. (*Mémoires, Sociétés des Ingénieurs Civiles*, 1929.)

Originally it had been planned to air-condition only the four lowest floors and a penthouse, the levels in which public spaces and executive offices were located. However, the desire to compete with other office buildings—and a sweltering summer during construction—caused bank officials to reconsider. With the steel frame completed to the twentieth floor, over half the building's height, it was decided that the entire PSFS building should be air-conditioned (fig. 12.14).

* * *

A Philadelphia newspaper in 1859 published an advertisement for a chair with an ice chest beneath the seat that offered a solution to the discomforts of hot summer days:

> KAHNWEILER'S PATENT VENTILATING ROCKING CHAIR
>
> This is a novelty that commends itself to all who value health and comfort. The invalid will recognize it as an invention especially conducive to his well being, inasmuch as with the addition of, say two cents worth of ice per day, the luxury of pure air may be fully enjoyed within doors, and the heat of the summer, or the vitiated atmosphere of a closed apartment, defied. Sold at the Manufacturer's Depot, Masonic Hall, No.. 715, Chestnut Street, by James Wilcox.[27]

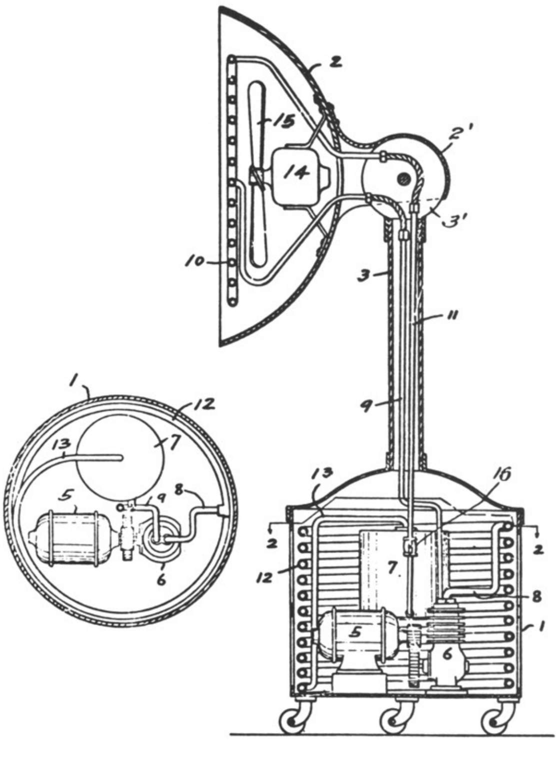
Even with cooling later provided in some movie houses, restaurants, and department stores, long hot summers made people long for some means of cooling the offices and shops in which they worked and the rooms in which they endured steamy nights. In the first decades of this century most office buildings were heated by steam radiators and most central-heated houses had gravity hot-water or warm-air systems. There was little possibility of adapting those systems to cooling. Ice companies in the early 1930s saw their markets rapidly vanishing. Most of their industrial customers were installing mechanical systems to make their own ice and the household refrigerator was rapidly replacing the icebox. A faint and desperate hope of the ice industry centered on cooling buildings with ice. Small portable coolers, a fan and a chest that had to be filled with ice once a day, were introduced without great success.[28] Larger systems chilled water in an iced space and pumped it to fan units distributed about the building. More hope seemed to lie in systems still larger, such as those for restaurants and theaters, for which the ice industry valiantly claimed three advantages: low installation cost, flexibility to match varying loads, and the remarkable virtue of being "unautomatic."

Leadership in the development of small cooling units was provided by the railroad industry. Summer travelers had been forced to endure hours inside sun-baked cars, the open windows admitting blasts of hot air bearing granules of soot from coal-burning locomotives. In 1907 a company undertook the manufacture of passenger cars in which air passed over 600 feet of ice-covered tubes before entering the car, but it was the 1930s before successful cooling was provided in the Baltimore and Ohio Railroad's dining car, the *Martha Washington.* The following year an entire air-conditioned train was regularly scheduled between New York and Washington. Systems were quickly converted from ice-cooling to mechanical refrigeration, and by 1934 only slightly more than a third of the 2,494 air-conditioned railroad cars in the United States were still using ice.[29] Railroads that provided cooled cars had a distinct advantage in a competitive industry, and the president of the Baltimore and Ohio stated that air conditioning had done more than any other factor to increase that line's business.

By the 1920s, the design of small vapor compressors had advanced to the point that room air conditioners could be proposed. The introduction of household refrigerators had found an enthusiastic market, anxious to rid itself of the iceman's daily visit. By 1925, 75,000 electric refrigerators had been placed in homes in the United States, and that year they were first available in Britain.[30] A portable "cooling device" was patented in 1926 but never went into commercial production (fig. 12.16). Its cylindrical base housed a motor, compressor, and condenser, and at the top a fan blew across the cooling coil.[31] In the same year, application was made for a patent on an air conditioning console with intake and exhaust ducts that could extend to the outside through a window sash.

When the breakthrough in residential cooling came in the 1930s, many levels of complexity were included, but all depended on discoveries that had been made in the development of household refrigerators.[32] That decade saw unusually hot and dry summer weather in much of the United States. In some areas attic fans were effective at day's end to draw cool air into the house, thereby cooling the occupants and lowering the heat that radiated from walls and ceilings. Evaporative coolers, the first method studied by Willis H. Carrier early in the century, were constructed in their crudest form with water dripping over a layer of excelsior (curls of wood used for crating fragile objects) and a low-speed fan drawing air through this evaporative screen. In the drought years of the Great Depression those methods were effective, and their technological crudity was offset by their extremely low cost.

A more sophisticated product, though large and ugly, was the console water-cooled air conditioners introduced in the United States by the Frigidaire Corporation in 1929. Soon several other companies brought out competing models. Air-cooled models with humidity and temperature controls were on the market during the 1930s and found their way into many executive offices (fig. 12.17). In 1932 the Thorne company advertised a window-mounted room air conditioner, but it is doubtful that this design was ever actually put in production. It was four more years before an acceptable model was brought on the market by Philco Corporation. It did not provide a fresh-air intake, but a single motor drove the compressor, condenser fan, and evaporator fan to produce a capacity of 3,675 BTUs per hour. The Westinghouse Electric Corporation's design five years later had a capacity more than 50 percent greater. It offered a reverse cycle for heating and, as an additional advantage, was sold with a five-year warranty.



12.16 A 1926 patent for a room air conditioner was a harbinger of unitized cooling. With a water-cooled condenser the unit could have been easily moved about (had it ever been manufactured in quantity); however, no provision was made for the condensation that would form on the cooling coils. (U.S. Patent no. 1,831,825.)

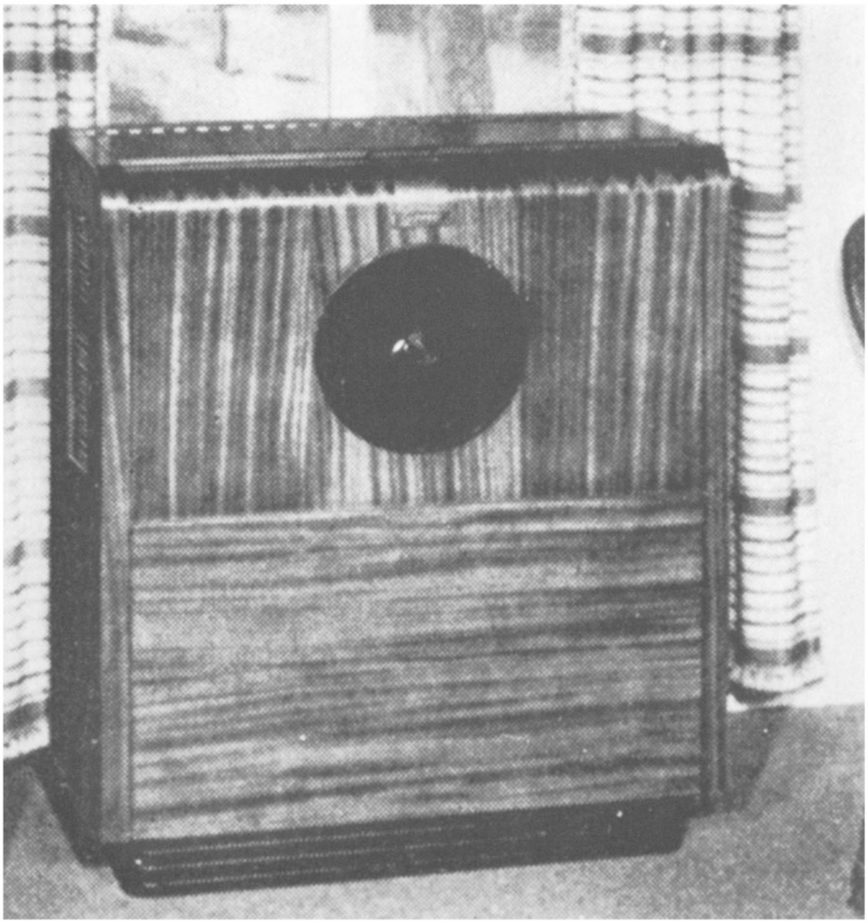
12.17 Room air conditioners that were available after World War II often assumed the appearance of furniture. This ¾-horsepower console, manufactured by Fedders, disguised the machine with a jacket imitating mahogany. (*Refrigerating Engineering*, January 1950.)

Little progress in the development of unit air conditioners was made during World War II, but immediately afterward window-mounted air conditioners were placed on the market by almost all American manufacturers in the field. Sizes were somewhat smaller than before, and the greater part of the chassis projected outside the window, thus eliminating the supporting legs and brackets that had been required by some earlier models. By this time, the same motor power obtained almost three times as great a capacity as in the first unit sold by Philco.

* * *

After World War II, applications of air conditioning were extended to include housing, schools, and nearly all other building types. Because it was costly to install systems of ducts and fans exclusively for cooling, warm-air heating methods were customarily installed in buildings that were to be air-conditioned. The seminal installations of Wolff and Carrier using mechanical refrigeration in air conditioning followed patterns that had long before been established for warm-air heating—air blown over coils filled with the temperature-altering agent. Therefore the combination of cooling and heating was easily accomplished.

Installations of air conditioning from the first suggested the option of completely sealing buildings and eliminating the operable sash that had been necessary to admit summer breezes. Stuart W. Cramer, a U.S. engineer, originated the expression "air conditioning" as a term for the improvement of the atmosphere within textile mills. The objectives he presented in 1909 were: "(a) Heating. (b) Air Moistening. (c) Ventilating. (d) Air Cleansing. (e) Air Cooling. (f) Automatic Regulation of humidity and temperature to a predetermined standard." Systems of the past, with sprays of moisture, filters of cheesecloth, and carefully placed intakes for new air, sufficed for several decades. At present it is the fourth of Cramer's criteria that is most questioned. Sealed buildings in a polluted setting and subject to health-endangering emissions from their own interiors give rise to new definitions of "air cleansing."[33]




Hyde

Technics and Architecture

The Development of Materials and Systems for Building

OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

13

Elevators and Escalators

1830s	Hoists in mill buildings operated by steam power
1854	Elisha Graves Otis demonstrates his safety device at the New York World's Fair
1859	"Vertical screw railway" is installed in Fifth Avenue Hotel, New York
1870	The water balance elevator introduced by Cyrus W. Baldwin
1878	Vertical-cylinder hydraulic elevators introduced by Baldwin in the Boreel Building, New York; horizontal-cylinder elevators soon follow
1887	Electric elevator installed in Baltimore, Maryland
1892	Jesse W. Reno builds an experimental escalator in Brooklyn, New York
1900	Escalators of several makes operated at the Paris Exposition
1900–20	Popularity of air cushion safety systems
1903	Traction elevators introduced by Otis Elevator Company
1931	Two elevators per shaft installed in the Westinghouse office building, East Pittsburgh, Pennsylvania
1970	Double-deck arrangement of elevators revived in Time-Life Building, Chicago

13.1 The teagle elevators employed in English textile mills in the 1840s were powered by belts from the main shaft of a factory, the shaft that drove all the machinery. (*Pictorial Gallery of Arts*, circa 1845.)

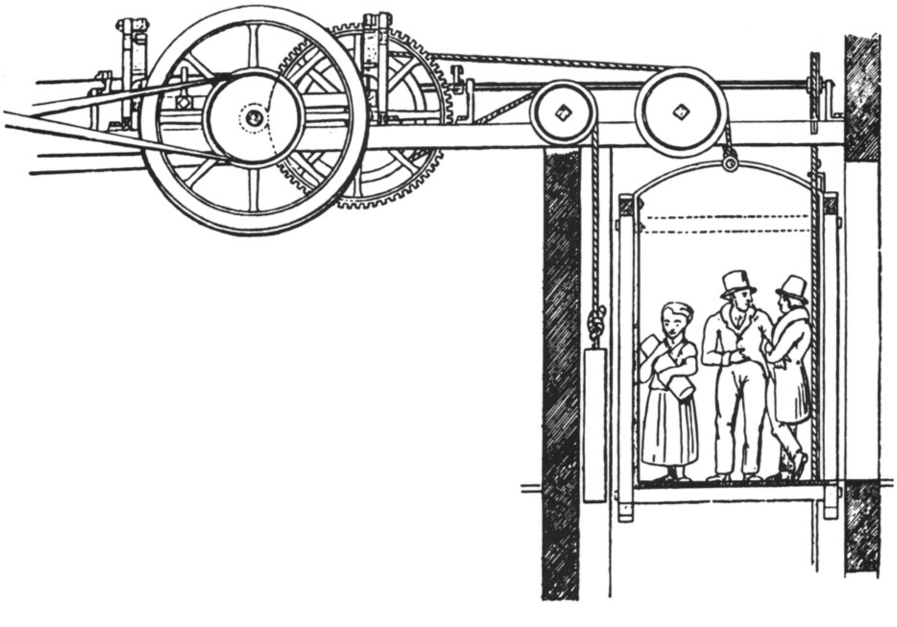
13.2 A short distance from the World's Fair, New York (1853), visitors could repair to the Latting Observatory and Ice Cream Parlor, in which an elevator would take them for a jerky trip to the top of the conical tower for a view of the city. (Courtesy Otis Elevator Company. Archive, United Technologies Corporation, Hartford, Connecticut.)

Hoists were used very early in history for mining, loading ships, and other activities in which heavy loads were to be lifted. With power supplied by workmen, animals, or water wheels, hawsers and chains were drawn over pulleys to lift weights. Hoists usually operated by manpower in the Roman period, since there was little incentive to develop costly mechanisms to replace the labor of the Roman hordes on the dole.[1] During medieval times, with the decline of massive projects, hoists advanced little beyond the mechanical simplicity of winches turned by hand or by a treadmill. Often counterweights were added to compensate for the weight of containers in which loads were lifted. With the addition of the ratchet and pawl, a system of restraint that had been known in ancient times, the essentials of all hoists were present, and only the improvement of motive power was needed.

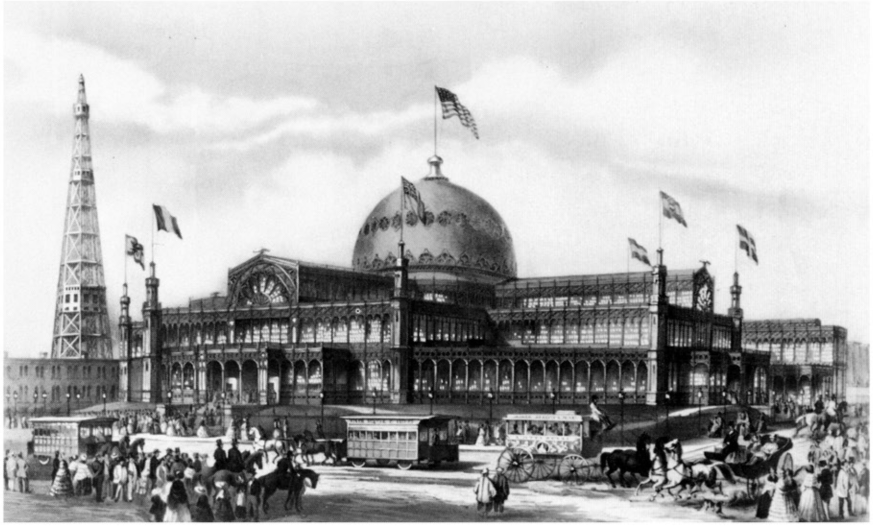
In English mills a hoist system, the teagle, was present early in the nineteenth century, and by 1835 power from the steam engines that ran spinning machines was used to operate teagles (fig. 13.1). The platform of the teagle was suspended by two ropes that went around a grooved pulley and supported counterweights at their opposite ends. Both the platform and the counterweights moved between vertical guide rails. The movement of the teagle platform was stopped by the operator's tugging a rope that shifted the belt onto a free-turning wheel.[2]

* * *

When the New York World's Fair opened in 1853, its displays were but a pallid imitation of the London event two years earlier. Visitors could leave the exhibition grounds and retire across Forty-second Street to Latting's Observatory and Ice Cream Parlor (fig. 13.2). Besides refreshments, this commercial appendage to the fair offered rides to the top of a slender conical structure from which one could view the Fair and the city, including the wooded tangle that would become Central Park.[3] Ascent was accomplished by a creaking elevator directly powered by a steam

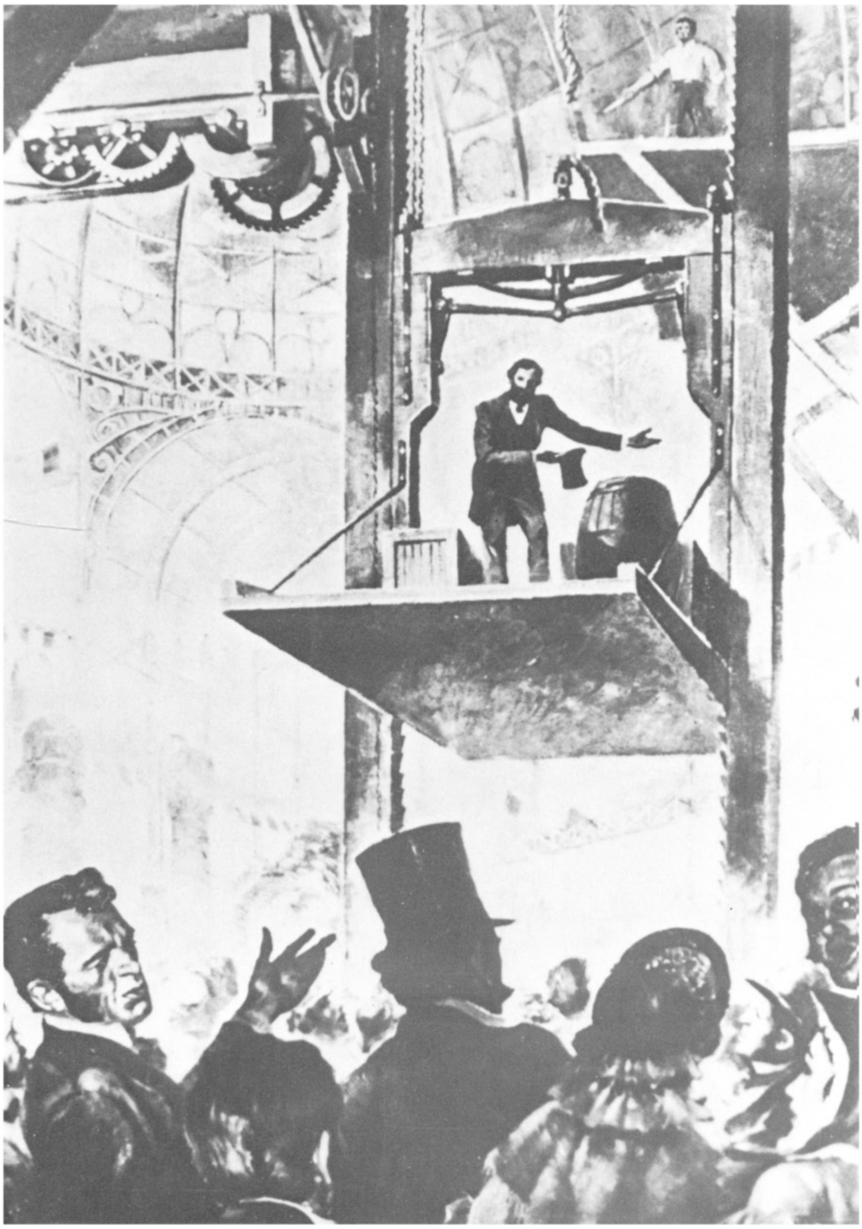


engine. During the second season of the fair, passengers traveling to the top of Latting's Observatory could hardly have been reassured by Elisha Graves Otis's prominent display in the Exhibition Hall, of his safety device for hoists and elevators (fig. 13.3). For each demonstration of his device, Otis mounted a hoist platform and was drawn upward. Once at the top of the hoist framework, the rope by which the platform hung was cut, frightening the onlookers and activating the safety device Otis had invented.



The Otis safety mechanism used toothed metal runners at the sides of the shaft and pawls attached to the car. When the car was suspended, tension in the supporting rope or cable held back the pawls, allowing the car to move freely up and down the runners. When the rope was cut, the pawls were unrestrained and springs drove them forward to catch the teeth of the side rails and quickly halt the car's fall. Forced by illness to abandon work in building construction and carriage making, Otis in 1948 had established a small machine shop in Albany. When the city expanded its water system and took over the creek that powered his machinery, Otis moved to New Jersey and became superintendent of a bedstead factory, with his 16-year-old son Charles as the engineer-in-charge of the factory steam engine. When his employers began construction of a new factory in Yonkers, New York, Otis devised a means of preventing the plant's hoist from falling, a frequent industrial accident of that period. Orders from other factory owners and the financial collapse of the Yonkers Bedstead Manufacturing Company led Otis to establish his own business of building industrial hoists and to demonstrate his design at the World's Fair. The first order came from a New York furniture manufacturer whose hoists had recently fallen and killed two workmen.[4] Within two years Otis's workshop had produced over 40 elevators, all for installation in industrial buildings.

In a steam-powered factory, the engine drove an overhead shaft from which belts conveyed rotational force



13.3 In his World's Fair exhibition, Elisha Graves Otis had himself lifted on the platform of a factory hoist. When an assistant overhead cut the rope, the Otis safety device held the platform securely in place. (Courtesy Otis Elevator Company. Archive, United Technologies Corporation, Hartford, Connecticut.)

to individual machines. Adding a hoist to the array of equipment was a relatively simple matter, and shifting its belt to a neutral position would stop the hoist in the same way other machines were stopped. Provision of a counterweight was, of course, customary for factories' hoisting mechanisms. All of the elements of a passenger elevator—power, control, and balance—were present at a primitive level in factory hoists early in the nineteenth century. Only the improvement of comfort, distance, speed, safety, and economy remained as challenges.

For his industrial hoists Otis introduced a two-cylinder steam engine that could be powered by steam piped from a factory's boilers, and this compact unit proved to have many advantages over belt-driven machines connected to the factory's drive shaft.[5] Once the factory hoist became relatively independent in location and power, its adaptation to use for passengers was an obvious step. In 1857 the Otis Steam Elevator Company installed a passenger elevator, probably the first to be made, in the building of E. V. Haughwout and

Company, at the corner of Broadway and Broome Street in New York. The Haughwout Company's five-story building was crowded with displays of silver plate, gas-lit chandeliers, and the imported French china and clocks for which the store was famous. A store with a valuable location generously served by the city's transit systems, the Haughwout Company needed a means of attracting buyers to every corner of every floor of its building to see the full range of its merchandise. Hence, an elevator.

Elisha Graves Otis died in 1861, the same year in which he obtained the patent that would be the basis for his company's later growth. Reorganized as Otis Brothers and Company, the firm in 1871 secured a reissue of the fundamental patent that it had used for ten years. Under the direction of Charles R. Otis, who had worked alongside his father from the age of 13, the firm began to transfer its attention from steam-powered elevators to those driven by hydraulic systems, but recurrent depressions and economic panics made expansion difficult.

In 1859 the Fifth Avenue Hotel had been built facing New York's Madison Square. It was a splendid six-story structure of white marble in the classical style, a center of political intrigue, and it offered guests the convenience of the "vertical screw railway" installed by Otis Tufts, a Boston engineer. The *New York Times* admired "the car, or little parlor," which differed greatly from industrial hoists that were suspended on chains or cables, and described its equipment in detail:

> An open vertical space, some 10 feet square, extends through the house from ground floor to top floor, with openings to the intermediate floors. The car, a covered room, nearly filling this space, or "well," forms the nut of a screw which extends from top to bottom; so that as the screw revolves to the right or left, the car ascends or descends. A guide-way at one corner of the well prevents the car from turning around with the screw. The screw is 90 feet long, 12 inches in diameter across the (hollow) stem, and some 18 inches diameter across the thread. The threads are two inches thick or deep. It is made of the best gun iron, and is in several sections or lengths—so long a casting could not be well made in one piece. The different lengths of screw are joined together by pins of wrought iron. . . . On the bottom of the screw, in the cellar, is a large gear which is moved by a smaller one on a horizontal shaft, which shaft is revolved by a belt directly from the steam engine. This belt may be shifted by a wire rope passing through the car from the driving pulley on the said shaft, to a loose pulley on the same shaft. When so shifted, the car begins to descend by its own weight—*i.e.*, it begins to turn the screw, the gears, and the horizontal shaft in an opposite direction. By pressing a brake on a third pulley on this horizontal shaft, by means of a second wire rope in the car, the whole mass is stopped at any required point.[6]

The car's descent was regulated by pistons in two water-filled cylinders. As the elevator car reached the top or bottom floor levels, the mechanism was automatically switched between the two systems, the engine-driven screw and the piston-controlled gravity descent.

The installation was expensive to operate, both in the provision of steam power and the frequent repairs required, and the large wood-sheathed shaft in the center of the car restricted the space available to passengers. According to most descriptions, movement—whether upward or downward—was extremely slow. This stately travel was punctuated by jolt-

13.4 Vertical, two-cylinder steam engines for elevators briefly followed the use of belts from the engines that powered the other systems of a factory. At the top and bottom of the shaft a tug on a rope could activate the controls (*L*) that reversed the direction of the engine. (*Appleton's Cyclopedia*, 1880, 1:594, 595.)

ing stops for the floor levels at which passengers wished to leave. In spite of the safety devices provided by Tufts, a trip in the "vertical screw railway" was an unsettling experience for many. The children of a wealthy banker, who lived in one of the mansions across from the Fifth Avenue Hotel, were firmly instructed never to enter the elevator apparatus.[7] Only minor improvements were made a few years later when a Tufts elevator was installed in Philadelphia's Continental Hotel. In spite of their shortcomings, the two hotel elevators continued to be used for almost 20 years.

In an outburst of prophecy, a reporter for the *New York Times* enumerated the advantages that might be expected from a profusion of elevators such as that in the Fifth Avenue Hotel. First, he wrote, space in the top floors of buildings would become more desirable than in lower floors, altering the "compromise between high prices, dust and noise, on the one hand, and excessive weariness in stair-climbing on the other hand," and this would make possible a more profitable utilization of the ground level of building sites. Second, the convenience of office building elevators would, in effect, place "all offices on a level with the street, as far as physical exertion is concerned," thereby improving their quality and accessibility. Third, efficient hoists would also permit the use of upper stories of buildings for retail establishments and manufacturing. Fourth, greater comfort could be brought to private houses. Scorning all notions of healthful exercise provided by the chores of housekeeping, the writer proposed that residential elevators be used to free time for outdoor forays by the "ladies of New York."[8]

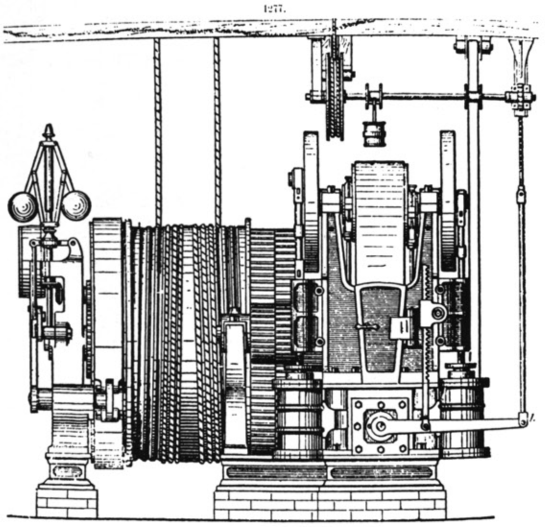
Few vertical screw elevators were built, and it was about 20 years before the William Miller Company of Cincinnati introduced a vertical screw elevator that eliminated the column in the center of the car. Up two sides of the elevator shaft were secured ridged strips of iron, each shaped like half a threaded hollow tube. At each side under the car floor, short threaded shafts turned within the guides, moving the elevator up or down. A mechanical system beneath the car was powered by a belt that ran the full height of the elevator shaft and was driven by a steam engine. This system was undoubtedly ingenious and safe, though the driving belt required frequent adjustments to keep it taut.[9] Miller's screw elevator proved impractical for tall buildings, but for almost 40 years it maintained a limited popularity for lifting heavy loads for short distances.

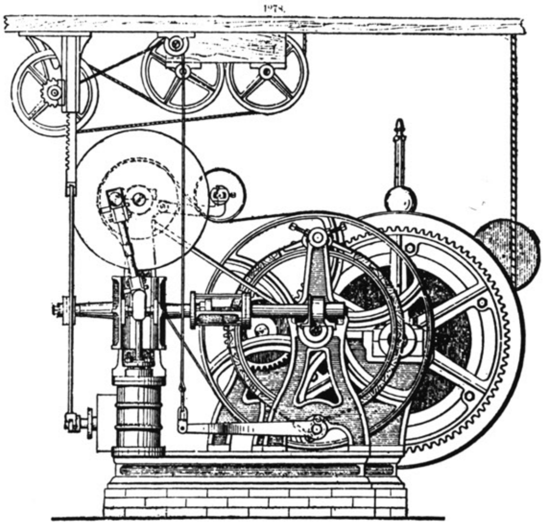
Early in the development of steam-driven passenger elevators, there were systems in which rope or cable was wound on a drum that was turned by a belt or gearing from the engine (fig. 13.4). Contemporary evaluations suggest that this system was not economically efficient, but its major drawbacks were of a practical nature.[10] Taller buildings required larger drums at the bottom of the elevator shaft, for the length of cable was necessarily equal to the maximum distance an elevator traveled. By increasing either the length of the drum or its diameter, more cable could be accommodated, but the size of the machine was often excessive and control became increasingly difficult. A drum elevator could seldom be used in a building higher than 10 stories. Direct use of a steam engine also meant that there was no simple method of limiting the movement of an elevator car at the top or bottom of its run. Safety devices could be placed at the ends of an elevator shaft, but if they failed and the elevator operator was not alert, a car might hurtle into the overhead structure or drop onto the bottom of the shaft.[11]

For warehouse and factory hoists, drum and direct-powered systems continued into the twentieth century, but they were seldom used for passengers after the introduction of hydraulic systems. The steam-powered elevator did not provide a ride that was either smooth or reassuring. In spite of many advances in the development of the machine, many of the chugs and lurches of the steam engine itself were transmitted to the elevator car and its passengers. Stops and starts were abrupt, and the public's fears were not greatly soothed by safety devices that were not visible to them.

An elevator system operated by water was patented in 1870 by Cyrus W. Baldwin, a Boston engineer (fig. 13.6). The Hale Elevator Company in Chicago, which undertook the manufacturing of the design, advertised it as the Hydro-Atmospheric Elevator, but it was more generally known as the water balance elevator. The principle was one that had been used in funicular railways in the Alps, where cars were drawn upward by filling a counterbalancing container with water.[12] In Baldwin's elevator the car was suspended by cables that ran over pulleys to a large iron bucket that weighed slightly less than the car. The bucket, traveling in a shaft beside that of the elevator, would be filled with water, and as the bucket descended the car and its passengers were drawn upward. As the bucket was emptied and rose from the bottom of its shaft, the car would descend. The only driving force required was a steam-powered pump to transfer water from the building's basement to a rooftop tank. Stops were made by applying pressure to the guide rails, and in most installations the springs that braked the car were so strong that the car probably moved more by release of the braking systems than by control of the water balance system.

The water balance elevator attained speeds as fast as 1,800 feet per minute (about 20 miles per hour).[13] Travel was smooth and operation of the system was economical. In practice, however, its high speed proved to be a disadvantage, even a danger. At the same time the ground area required for the water bucket was thought to be excessive. Although shafts for the several water buckets in a building's elevator system were much smaller than those required for the elevator cars themselves, when extended





13.5 **This elevator in Lord and Taylor's New York department store provided upholstered benches on which passengers rested, while an attendant tugged the rope that started and stopped the elevator. (Courtesy Otis Elevator Company. Archive, United Technologies Corporation, Hartford, Connecticut.)**

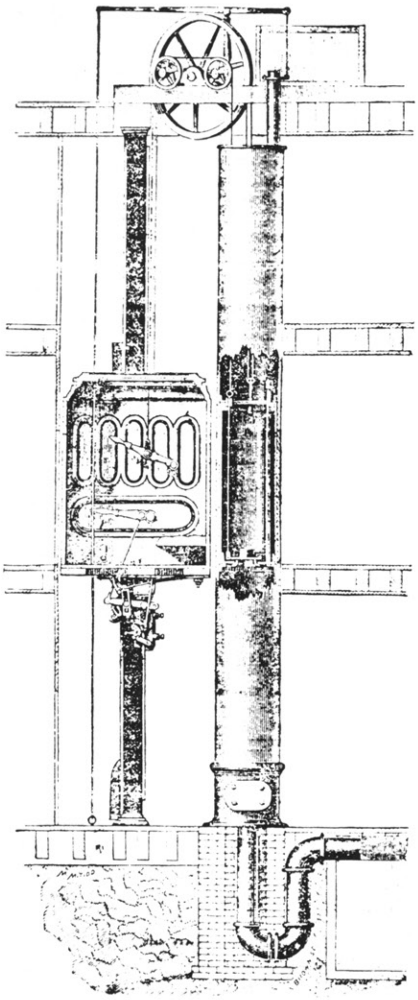
13.6 **The passenger car of the water balance elevator was linked to a sheet-iron bucket weighing slightly less. By adding or withdrawing water, speeds as high as 1,800 feet per minute could be attained, but it was necessary to provide for the metal tube a space as tall as the elevator shaft. (*U.S. Railroad and Mining Register*, 12 April 1873.)**

13.7 **Investors in Weehawken, New Jersey, built an elevator in 1891 to receive passengers off the ferry from New York and lift them to the elevation of the Palisades, where trains took them to the Eldorado amusement park and Gutenberg racetrack. Each of the three hydraulic elevators operating in this tower could carry 150 passengers 150 feet in 40 seconds. Within a few years the resort was bankrupt and the elevator tower was dismantled. (*Engineering Magazine*, June 1893.)**

through all the stories of a building they occupied a considerable amount of potentially rentable floor area.

Though its popularity was short-lived, the water balance elevator found a place in many new skyscrapers. The Western Union Building in New York, second highest in the city and only 30 feet below the Tribune Building, had its direct-action steam engine elevators replaced with a water balance system shortly after the building was completed in 1875. This installation remained in service until the building burned in 1891.[14] Advances in elevator design were so rapid that by the time of the fire, water balance systems had long been replaced by hydraulic equipment and the electric elevator had been introduced.

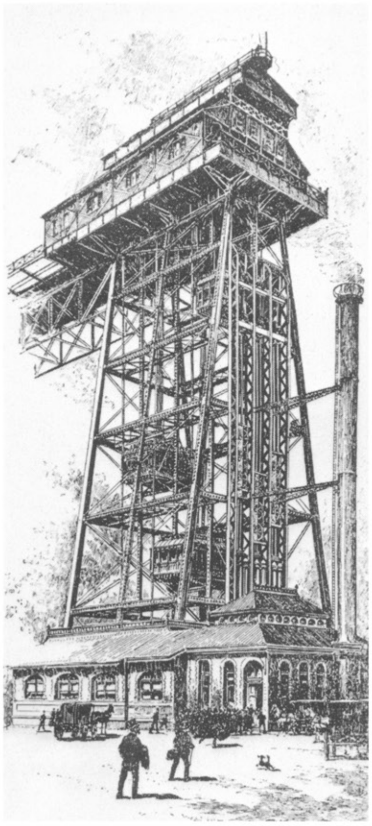
A hydraulic crane invented in 1846 by a British engineer employed the force of water pressure to move a pis-



ton within an iron cylinder and thereby lift heavy objects. Unlike water wheels and steam engines, which required conversion of rotary movement to linear movement, the hydraulic cylinder produced linear movement.[15] An additional advantage of hydraulic systems was the ease with which they could be regulated with simple valves.

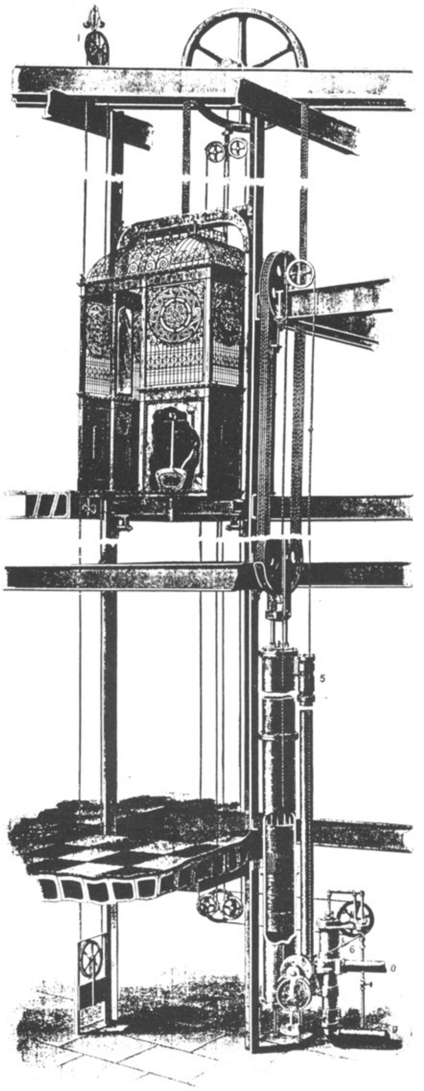
Cyrus W. Baldwin, inventor of the water balance elevator, was still associated with Chicago's Hale Elevator Company when in 1878 he introduced the vertical-cylinder hydraulic system in the Boreel Building in New York.[16] The vertical cylinder stood in the elevator shaft, directly behind the car, and to its piston was attached a frame bearing the traveling sheaves of the pulley system (fig. 13.8). Stationary sheaves were secured at the top of the elevator shaft. Water filled the vertical cylinder, entering under pressure near the top, and pushed the piston downward. As the piston moved, water was expelled from that portion of the cylinder beneath it, and the traveling sheaves of the pulley were drawn downward. Once the elevator had reached the top of the shaft, valves adjusted to stop water entering the cylinder and to open the way for water to move from the top of the cylinder to the bottom. The weight of the elevator slowly pulled the piston upward until the car reached the bottom of the shaft. With a counterweight somewhat lighter than the car itself, movement in either direction could be accomplished with relatively low water pressure. One distinct advantage of the vertical-cylinder hydraulic elevator was the ability to attach counterweights to the traveling sheaves of the pulley system. These weights had to be determined as the inverse of the gear ratio, so a pulley system producing three feet of car travel for each foot of piston movement would require a weight three times as great as that of an independent counterweight. Nevertheless, such counterweights had the distinct advantage of not requiring the installation of additional cables and pulleys.

On each floor, the vertical-cylinder hydraulic elevator required floor area above the cylinder. While the area needed was less than that for the water balance elevator, buildings were higher than they had formerly been, and astute landlords could not but covetously eye that small area reserved behind each elevator. The



13.8 For hydraulic elevators with vertical cylinders, the traveling sheaves of the cable system attached directly to the cylinder's piston. Safety provisions included the devices shown beneath the car and the governor at the upper left of this drawing. (*Scientific American Supplement*, 12 August 1899.)

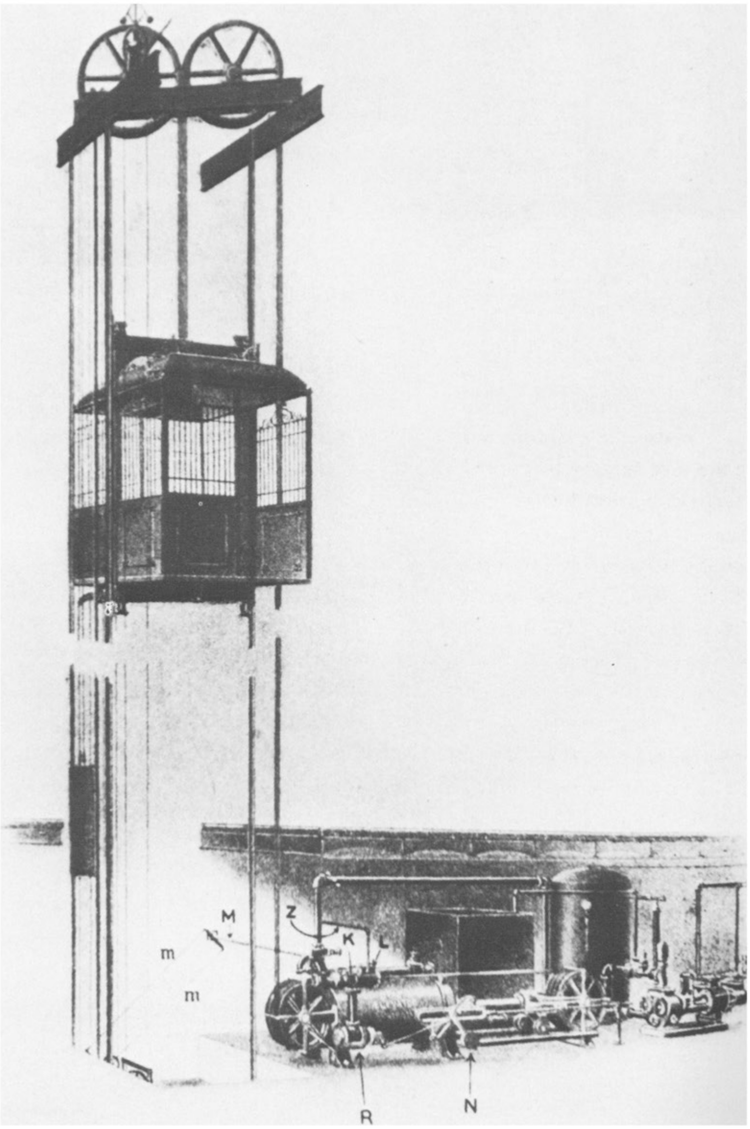
13.9 The horizontal hydraulic cylinder permitted a reduction of the area in elevator shafts. To save space in buildings' basements, often crowded with furnaces and generators of electricity for lighting, the cylinders could be stacked on steel frameworks. (Courtesy Otis Elevator Company. Archive, United Technologies Corporation, Hartford, Connecticut.)



horizontal-cylinder hydraulic elevator, introduced at about the same time as the vertical-cylinder system, was essentially the same but occupied basement floor area instead of rentable space in the upper stories (fig. 13.9). A piston rod moved horizontally with the traveling sheaves of the pulley system rolling on iron rails. Bending around a set of pulleys attached to the frame of the hydraulic engine, the cables extended upward to the pulleys at the top of the elevator shaft. Usually water was present only on the pressure side of the piston in a horizontal cylinder, and this permitted easy determination of the tightness of the piston's seal. In vertical cylinders, leakage around the piston could only be detected by comparing the readings of gauges that measured the pressure within the cylinder above and below the piston (fig. 13.10). The horizontal cylinder also avoided the differences of pressure that were present between the top and bottom of a vertical cylinder, which held a column of water that might be as tall as 40 feet.

Placed horizontally, the hydraulic mechanism occupied a great amount of floor area, but only in the building's basement. This location allowed walls to be constructed around the equipment, preventing the eerie sounds of creaking machinery from echoing throughout the elevator shaft. For installation of large numbers of elevators in a building, iron racks were constructed to stack the cylinders one above another, freeing basement area.

Both sorts of hydraulic elevator systems benefited from the use of the pulley. Pulleys could have been used in drum elevator systems, but they would have resulted in an awkward mechanism that magnified the unevenness of the movement. In the simplest form of hydraulic elevator, one end of the cable was secured to a crossbeam at the top of the elevator shaft. The cable extended down the shaft to turn through the traveling sheave fastened to the piston, then went back up the shaft to the top where it turned around a fixed sheave before turning down to be fastened to the elevator car. This allowed the car to travel two feet with only one foot of movement by the traveling sheave and the piston. Additional pulleys and more cable could increase this gearing ratio. Because of their locations, vertical cylinders tended to be made tall with small diameters and their gearing ratio seldom exceeded 4:1, four feet of elevator travel for each foot of piston movement. Horizontal cylinders were shorter and large in diameter, and consequently their ratio might be as high as 12:1. Longer piston travel offered advantages in smooth starting and stopping, but the choice between the two types of cylinder was more often made on the basis of the available water pressure and space allocations. A major improvement in the smooth operation of hydraulic equipment resulted from the use of valves that had been invented for the control of machinery in the manufacture of sugar.[17] By employing a series of openings, graduated in size, these valves produced a smooth acceleration and slowing of the elevator car's movement.



The simplest method of supplying power to a hydraulic elevator was the use of water from city mains. With relatively low pressures, ranging from 20 to 40 pounds per square inch, a horizontal cylinder was the necessary choice because of its larger piston head and the pressure variation that resulted from the height of the column of water contained in a vertical cylinder.[18] A more common procedure during the period of hydraulic elevators was the installation of a water tank on the top of the building. By pumping water from the basement into the tank, a high pressure could be obtained, although it was, of course, limited by the height of the building. Repeated use of the same water provided significant savings when several elevators were to be served. When the building's height did not afford sufficient water pressure, closed pressure tanks provided the pressure that was needed.[19] Most standard elevator

13.10 This drawing of a vertical cylinder hydraulic elevator shows a typical turn-of-the-century installation. Buttons in the car regulate valves that alter the admission of water and the flow of water from top to bottom in the cylinder. At the left, a governor and its cable control safety mechanisms beneath the car. (W. Baxter, Jr., *Hydraulic Elevators*, 1905.)

equipment was designed for a pressure of 150 pounds per square inch. As higher pressures were attained, smaller and less expensive tanks, cylinders, and pipes could be employed, but higher pressures demanded special and more expensive equipment.[20] Air trapped in the top 40 percent of a closed tank exerted pressure on the water below, and an automatically controlled pump maintained this pressure at a constant level.[21]

The plunger elevator was a hydraulic system in which the cylinder was placed in the ground directly beneath the car and the piston was directly attached beneath the car. The plunger had been employed in English factory hoists in the 1830s and had been admired for its safety and economy. Throughout much of the nineteenth century, plunger elevators were the dominant form in Europe for passenger service. With relatively few tall buildings being built there, the height limitations of the plunger elevator were of little significance, and consequently the European distrust of cars suspended by cables prevailed. With the assistance of a counterweight system, a plunger elevator could often operate on the water pressure available from city mains.

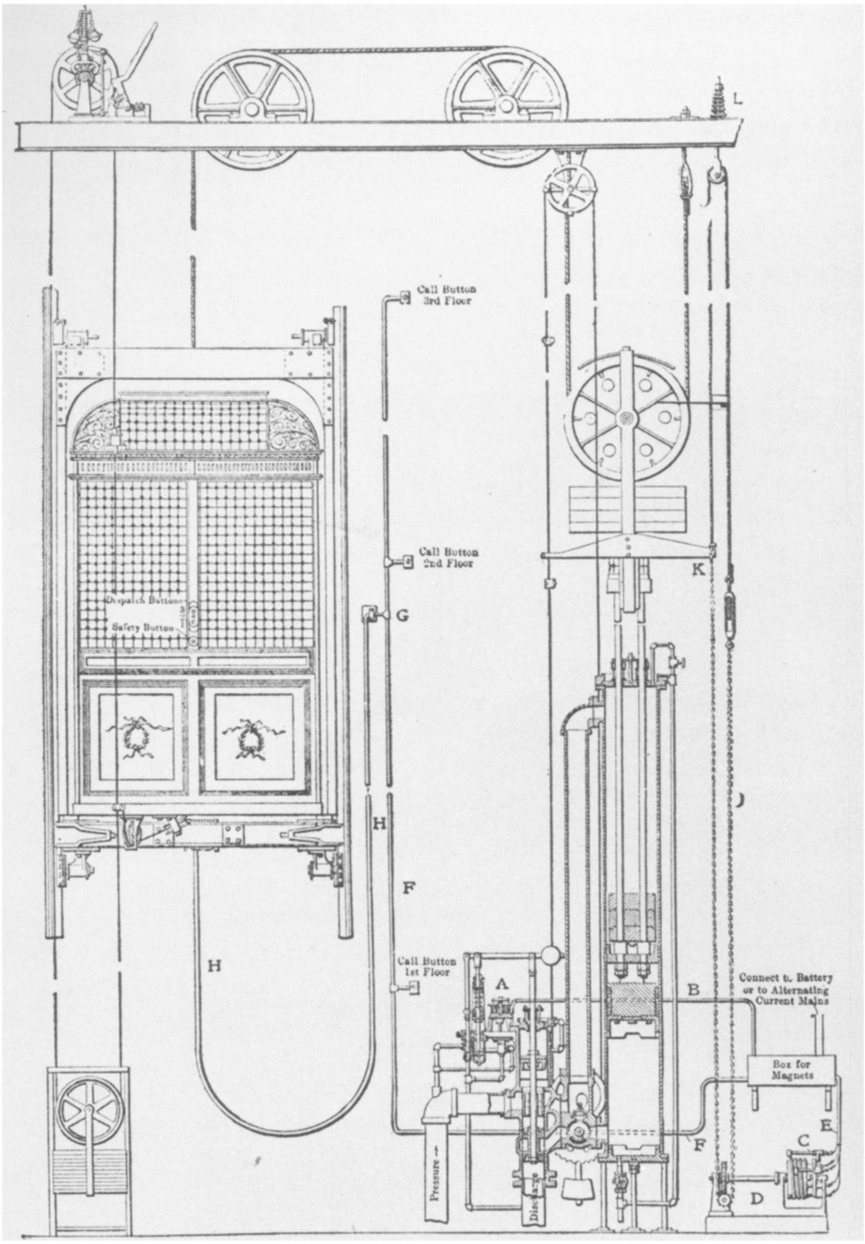
The increased use of plunger elevators in the United States late in the nineteenth century was influenced by the improvement of methods for drilling the holes into which hydraulic cylinders were inserted, a result of techniques developed in the oil industry. Advances in the manufacture of steel pipe brought about further improvements. A telescoping plunger was introduced, but it had little success. Although it required a much shallower cylinder, the difficulty of maintaining watertight connections between the telescoping sections made the system impractical.[22]

Plunger elevators at the end of the nineteenth century were installed with runs as high as 30 stories. Tests made by George I. Alden at Worcester (Massachusetts) Polytechnic Institute encouraged increased use of plunger installations. Although early plunger elevators had been slow, improved valves allowed speeds as high as 600 feet per minute. In 1904 a total of 110 plunger elevators were ordered for installation in the John Wanamaker stores in New York and Philadelphia.[23] In the end, electric elevators replaced plunger installations for all but relatively low runs and speeds not exceeding 200 feet per minute.

* * *

Once begun, the use of electrical power in passenger elevators advanced rapidly, greatly assisted by the development of electric motors for the streetcar. By 1873 both the Gramme dynamo and another manufactured by Siemens and Halske had been improved to the point of providing reliable and constant current. Many textile mills of the northeastern United States in the early 1880s installed hoists for which electric motors provided power to belt-driven winding drums, substituting electric power for steam power. Hoists of this sort were used for freight until the end of the nineteenth century.

Werner Siemens, the electrical wizard of Germany, exhibited an electric elevator in 1880 at the Industrial Exhibition in Mannheim. The system in many ways resembled the vertical screw elevator that had been developed by Otis Tufts about 20 years before. In the center of the shaft and the car, a notched steel column extended the full height of the elevator's run, providing the direct support usually demanded by the European public. Beneath the floor of the car,



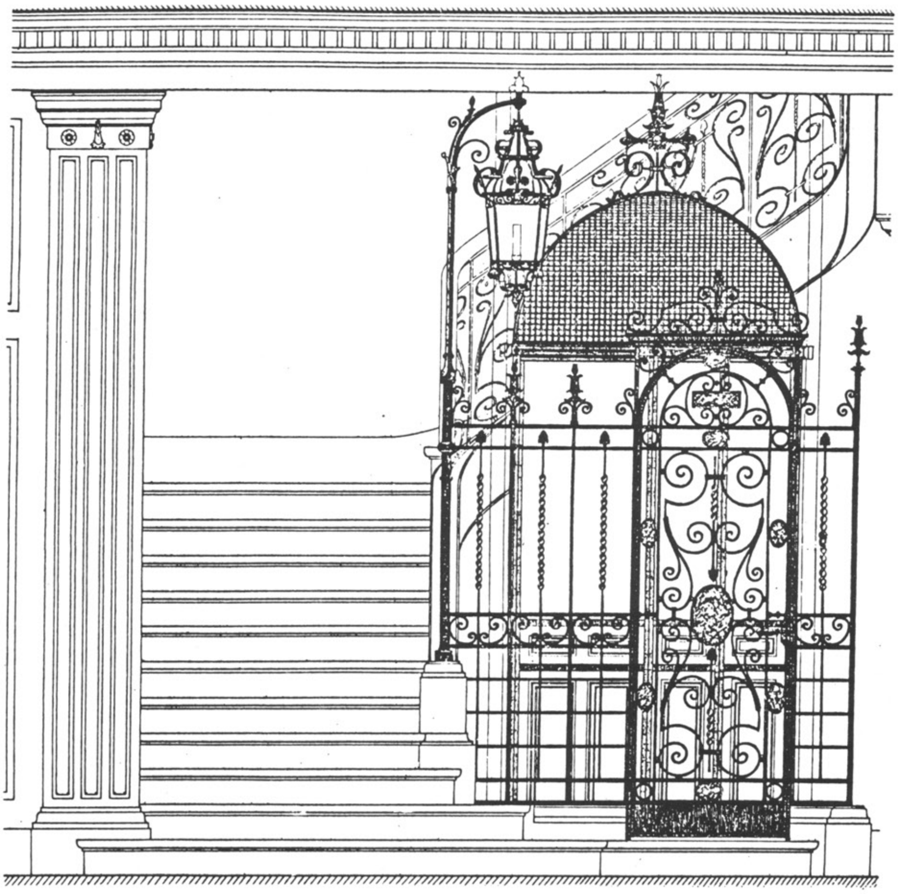
an electric motor turned cogwheels that raised or lowered it. Over 8,000 visitors at the Mannheim fair rode in Siemens's elevator at a speed of about 100 feet per minute, a jerky, thumping ride because the motion of the gears was transmitted directly to passengers.[24]

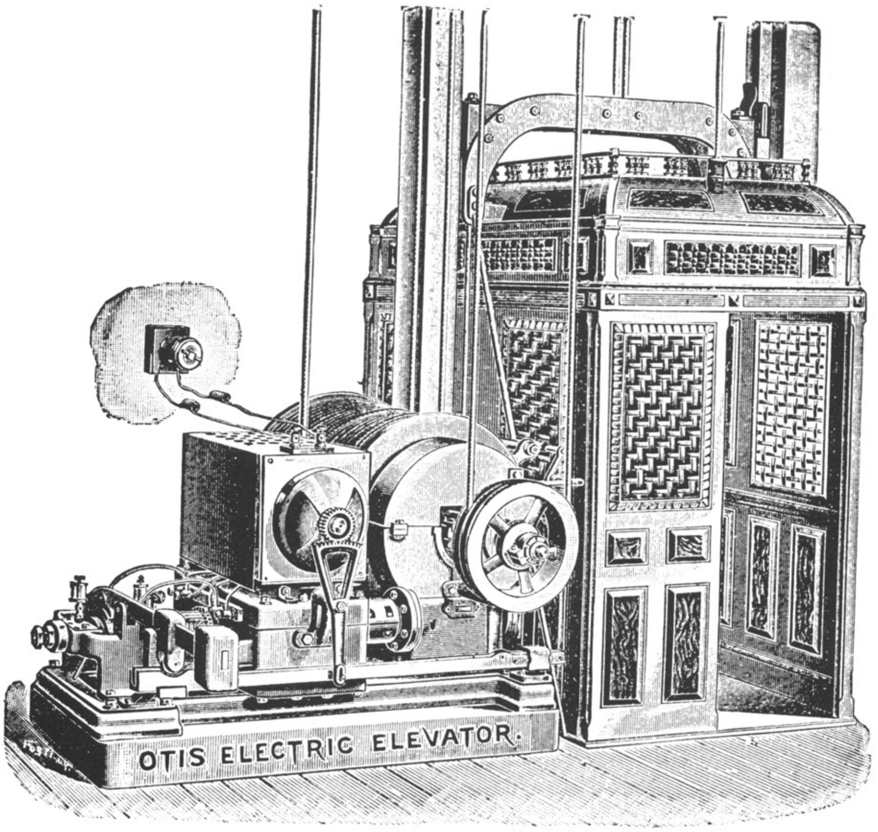
The first permanently installed electric elevator was designed by William Baxter, Jr., in 1887 for a Baltimore building. Power was supplied by a generator designed for arc lighting systems, and the electric motor was geared to a drum about which the cables were wound.[25] The whirling of a centrifugal governor controlled speed and, when the car descended with a full load, the governor could reverse the motor so it would act as a brake. Hand control was limited to a switch in the car that reversed the direction of the car's movement at the top and bottom of its run. Switches connected to the doors at every floor level stopped and started the motor, a

13.11 Open elevator cages gave an opportunity to explore the artistry of metalwork in the execution of grilles and gates. A French folio of 1898 shows an ornate design, set within a stairwell of more classical style. (T. Lambert, *Escaliers et Ascenseurs*, 1898.)

13.12 An electric elevator was developed by 1887, and nine years later the Otis Elevator Company reported that it had installed more than 4,000 of them. Acceptance of the electric elevator depended largely on determining its cost of operation. (*Electric Review*, 21 February 1896.)

13.13 The Sprague-Pratt elevator system substituted electric motors for hydraulic cylinders, threaded shafts taking the place of pistons. Like their hydraulic counterparts, these machines could be stacked in order to save basement floor area. (*Transactions, American Institute of Electrical Engineers*, 22 January 1896.)



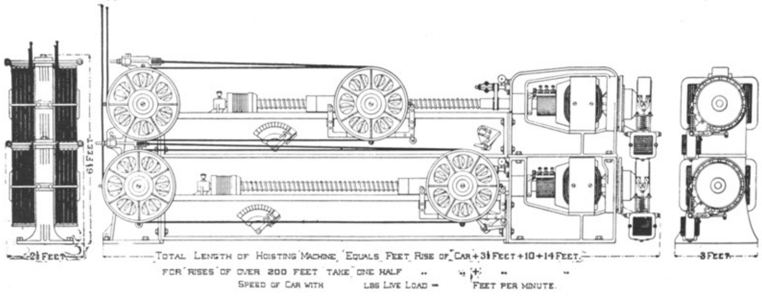


system that resulted in relatively slow speeds of travel. Because electric motors produced rotary motion, the use of a drum was the most practical solution, but drums large enough to hold great lengths of cable were difficult to control and required extremely large motors (fig. 13.12). For this reason, hydraulic elevators continued to dominate large installations until the end of the century.

The problems of acceleration and deceleration troubled early electric elevator systems as much as they had limited hydraulic systems. In the latter, a series of valves, graduated in size and opened sequentially, had served to avoid lurching starts and jolting stops. In the former, a series of electrical resistances were engaged or disengaged, one by one, to achieve the same objective. By the end of the century the Otis Elevator Company had introduced a "magnetic dash-pot" that provided an alternative system for cushioning the electric motor's action. An additional advantage of this device was the fact that it reduced the drain on a building's total electrical system when an elevator motor pulled quickly against the inertia of a car and its counterweight. Before controlled acceleration was introduced, if a building operated its own steam-powered generators, a rapid start of one elevator car could suddenly dim lighting throughout the building.[26]

Charles R. Pratt, the young chief engineer of the Sprague Electric Elevator Company, in 1888 invented a new form of electric elevator that was extremely eclectic in its design. Pratt had worked for two other elevator manufacturers before joining Frank J. Sprague, who had played a leading role in the development of the first electric streetcar systems. The Sprague-Pratt elevator, as it was called, used a long horizontal screw driven by an electric motor (fig. 13.13).[27] Threaded on the screw was a block to which was attached the traveling sheaves of a pulley system, much the same as those used for horizontal-cylinder hydraulic elevators. Because they occupied about as much basement area as horizontal hydraulic cylinders, Sprague-Pratt machines were also often stacked on metal frames. In use they were plagued with mechanical difficulties and, because smoothness of motion was their only significant contribution, the Sprague-Pratt elevators were not popular.

Toward the end of the nineteenth century, the comparative advantages of hydraulic and electric passenger elevators were carefully studied. Few of the experts writing on the relative efficiencies of available systems were without a bias toward their own inventions, their company's systems, or a recent installation that they had designed. Hydraulic elevators, whether using vertical or horizontal cylinders, profited from the long experience that made them simple to operate and low in initial cost. Using water under high pressure offered a degree of economy, especially in English cities such as London and Liverpool, where mains in the central portions of the city furnished water at a pressure of 700 pounds per square inch.[28] However, the small valves that were required in high-pressure systems were difficult to maintain, and when they leaked the elevator controls were inexact in their action. Some high-pressure installations were



replaced only a few years after being first put in service. A system that provided water at both low and high pressure, employing high pressure only when the elevator load required it, offered definite advantages, but it had only a short period of application.

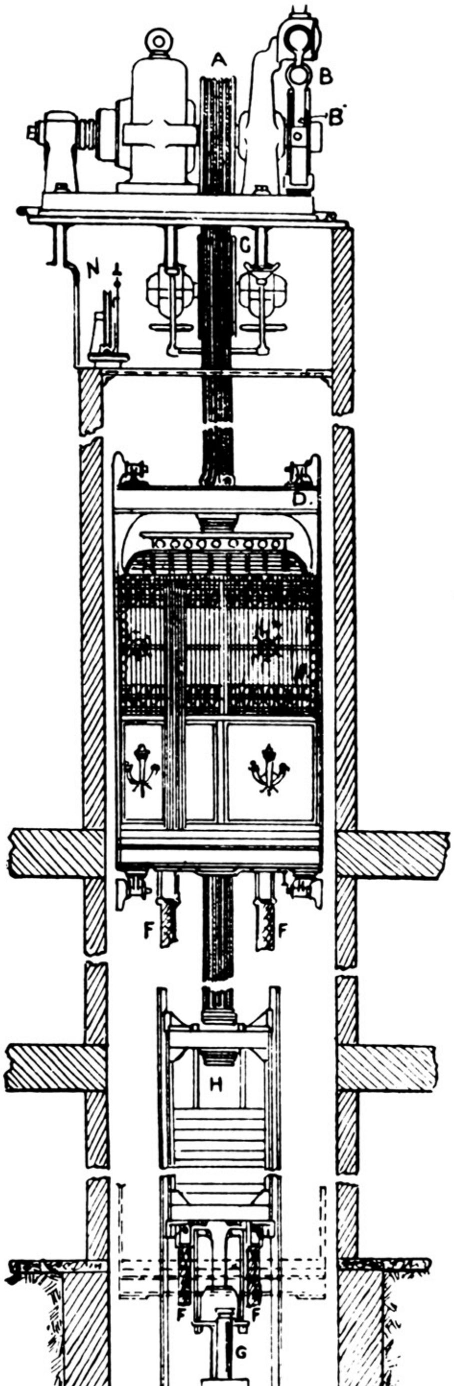
The electric drum elevator was so expensive to install that it was used only where the best of service was demanded. Such installations were unimpressive until improvements in the gearing almost tripled their efficiency.[29] The Sprague-Pratt electric machine had a reasonable efficiency, but the power used in starting it was costly. The power per mile traveled in the Marshall Field Building in Chicago when there were infrequent stops proved to be about two-thirds of that required when the cars stopped at every floor.[30] Weighing all the factors of maintenance, cost, and smooth control, it was extremely difficult at the turn of the century to make a choice among the available types of elevators.

13.14 The Otis traction elevator of 1909 had its motor and drum at the top of the shaft with a braking system (*B, B′*) provided. A governor (*N*) and an undercar system (*I*) provided additional safety. The counterweight (*H*) and compensating system (*F*) controlled the load. (*American Review of Reviews*, December 1909.)

Experiments at the Otis Elevator Company in 1903 led to the company's introducing the traction elevator system, which found a fresh combination of the customary elements in electric-powered elevators of that time (fig. 13.14). In all previous elevators, even the plunger elevator with its hydraulic cylinder beneath the car, counterweights served only the purpose of lightening the load to be moved by the driving mechanism. Theoretically, if sufficiently large motors were provided, these systems could have lifted and lowered their elevator cars without counterweights. The traction elevator abandoned the task of pulling up the elevator car and focused its attention on the balance between the car and its counterweight. Thus, there was no longer a need for the elaborate system of pulleys that had been used for both hydraulic and electric elevators, systems in which the pulleys, cables, and frames often weighed much more than the load to be moved. In its simplest terms, the traction elevator had cables attached from the car to the counterweight, and those cables passed over a drum that could be turned in either direction by an electric motor. The cables and the elevator car were moved by friction between the several cables employed and grooves in the drum, just as friction between wheels and steel rails moved locomotives and streetcars. One safety advantage of the traction elevator lay in the fact that if safety devices failed and the car or counterweights overran their limits at the bottom of the elevator shaft, the tension on cables would slacken, and the cables would no longer move as the drum turned.

Half-wrap traction systems had a single cylindrical drum at the top of the shaft with a series of V-shaped grooves cut into the drum to increase its friction with the cables (fig. 13.15). These grooves sometimes wore away after years of use, reducing the pinching action that grasped the cables, but the surfaces of drums were made in metal segments that allowed replacement. Full-wrap traction systems provided a second and smaller drum around which the cables ran before a second half-turn around the powered drum. The cables rested in grooves that were usually semicircular in shape, and they had twice the length of frictional surface provided by half-wrap traction designs.

The design of traction elevators permitted mounting the electric motor at the top of an elevator shaft, eliminating the congestion of basement areas that had resulted from the construction of towering office buildings needing many elevators on parcels of land that were extremely limited in area. By the turn of the century an increasing number of buildings in the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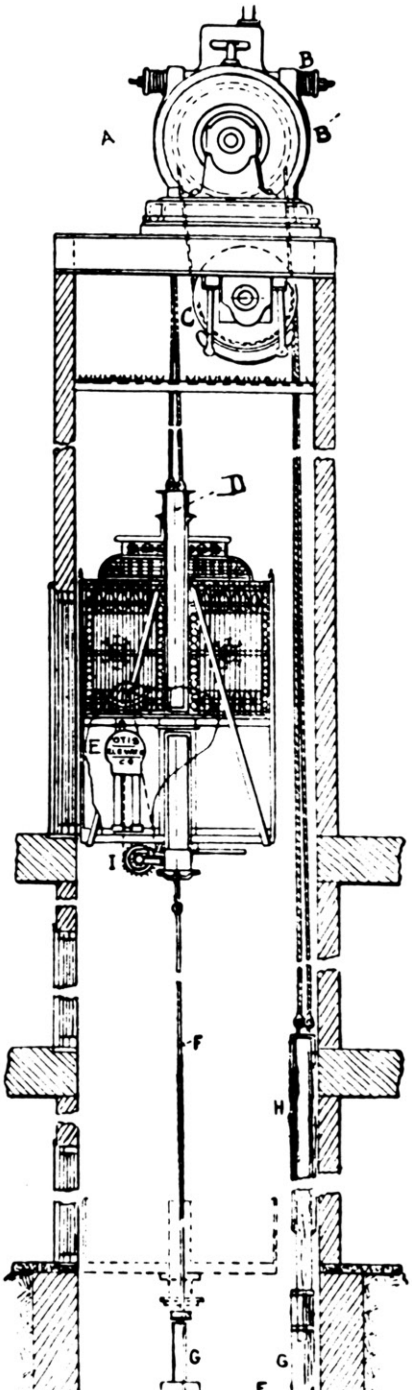
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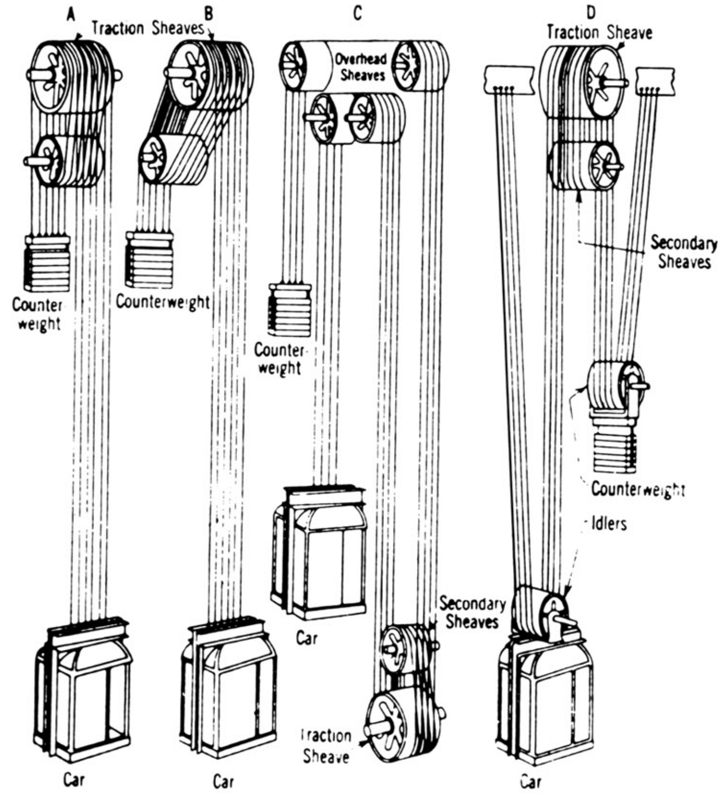
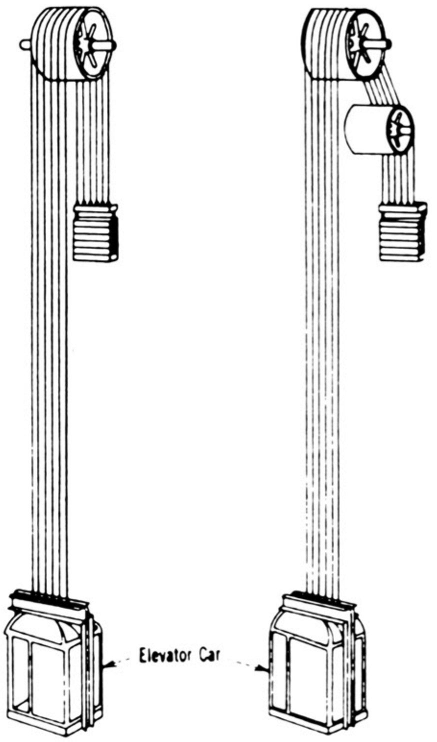




centers of cities had abandoned their individual steam-powered generating plants in favor of electrical supply from central plants, and basements were freed for other uses. By 1906 electric elevators comprised almost 90 percent of the new installations, and it was reported in 1922 that about 98 percent of new elevator installations in the United States were operated by overhead electric motors.[31]

Facilities for vertical traffic are the direct result of increased means of rapid transit on the level. While businessmen were

> restricted to the slow-moving horse-car or cab, business interests were scattered; the ship-owner had his office at the dock, the lawyer was at the courts, and the manufacturer at his factory; as a consequence, the building of five stories fulfilled all requirements, and the lift was a luxury. The advent of comfortable rapid transit and the telephone changes these conditions; the separate trades draw close to each other by means of business offices in the city, and the ensuing contraction causes the high building to spring up and the lift to become a necessary tool in the "manufacture of transportation."[32]

This comment, made in 1897, provides only one of the many reasons that have been given for nineteenth-century growth in the central portion of cities. There had long been systems of urban transportation, but none rapid or cheap enough to allow many to live far from their working place. Although many voices warned of the dangers of "high-building mania," it was inevitable once business had begun to concentrate at the cities' centers. A British journalist commented of New Yorkers, "They move almost as much on the perpendicular as on the horizontal plane. When they find themselves a little crowded, they simply tilt a street on end and call it a skyscraper."[33] This was in fact the image that excited many. The *Scientific American* reported with evident pride that "in the modern city the streets are often vertical. In a modern community like the Park Row Building in New York there are over six thousand inhabitants, with a vertical thoroughfare having twenty-five cross streets."[34]

No matter how much disapproval was expressed, the network of ground transportation spread farther and office buildings—and the elevators in them—climbed higher. At one time there had seemed a natural end to this quest for height, as the thick masonry walls required to support tall buildings began to fill the ground space that had become so valuable. Steel frame construction swept away this limitation, and the competitive craze for taller buildings was under way once more. By 1897 it could be said that in New York there were over 5,000 elevators of various kinds and that their daily travel was "as much, if not more, than the distance travelled horizontally by the various local cars and trains."[35]

If elevators were vertical streets, they also suffered from many of the psychological factors that could be observed in ground traffic. When the man in charge of the elevators of New York's Equitable Building was interviewed in 1924, he identified his principal problem: "Almost all of them [passengers] think they are in a hurry. Everyone rushes. . . . Men rush round a corner . . . so fast that they fairly pile into the cars. Once in, everyone feels cheated if the car does not start *at once*."[36] Most of this confusion occurred in the elevator lobby at the street level, where the ground floor of the building had become a frantic interchange between horizontal and vertical transportation systems.

Before World War I it could be said with accuracy that "one set of architects is wedded to the semicircular arrangement [of elevators]; another to their disposition in line; and another to divisions facing each other."[37] As long as a building did not require more than a dozen elevators, the semicircular array provided excellent visibility of all elevators arriving at the lobby level, but the open space in front of the arc of elevators was necessarily repeated on each floor, often at great cost of rentable office area. When a building site had one side abutting another structure, making that side unavailable for office windows, the curved bank of elevators could be placed there without much

13.15 In the full-wrap traction elevator (the four drawings at left) the bearings of the driving sheaves were heavily loaded, and this caused the system to be less efficient. The load on the bearings of the half-wrap machine (the two drawings at right) was half as great. Cables lasted longer on half-wrap machines, but the V-grooves on the sheaves, used to gain maximum friction, had to be replaced more often than the semicircular grooves of full-wrap machines. (*Journal, American Institute of Electrical Engineers*, April 1922.)

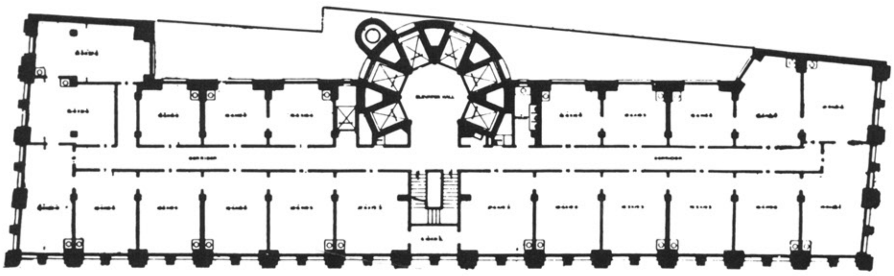
13.16 **In the Metropolitan Life Building, Minneapolis, Minnesota, elevators were caged in corners of a central sky-lighted space. The effect was heightened by thick glass slabs that were the flooring of the galleries around the light well. (Courtesy of the Minnesota State Historical Society.)**

13.17 **The Havemeyer Building in New York (1897) had a ring of six elevators opposite the entrance and jutting into a narrow open space against an adjacent building. Two were express elevators, particularly useful for access to a rooftop restaurant and promenade, "where superb views of the bay and surrounding country can be had from this height" (15 stories). (W. Birkmire, *Skeleton Construction,* 1894.)**

13.18 **Arrangements of cables and sheaves could allow efficient location of the hydraulic machinery in the basement, as shown in this partial plan of the Empire Building, New York (1897). Below the third floor, the individual shafts were separated by masonry walls that were part of the air-cushion safety system. (*Scientific American Supplement,* 12 August 1899.)**

floor area being wasted (fig. 13.17). For plans in which offices ran along both sides of corridors, whether C-shaped, E-shaped, or wrapped around a central light well, a linear arrangement was more desirable, since on upper floors little lobby area was required beyond that provided by the office corridors. Lines of elevators were limited to about seven cars, because a waiting passenger could not easily get to all of the cars in a longer line and the elevators farthest from the lobby entrance would not receive sufficient use (fig. 13.18). Later skyscraper towers often had parallel rows of elevators, a plan that was particularly appropriate when cars serving the same zones of height in the building could be placed facing each other. Also, when regulations required setbacks that reduced the area of upper floors of a skyscraper, rows of elevators could be eliminated as they reached the upper limit of their zone of service (fig. 13.19).

If saving floor area in an office building was a strong factor in elevator design, it was also vital to determine accurately the number of elevators that would be needed to serve a building. A British engineer stated the case in the 1920s: "I have said that, given the necessary particulars of a building, the lift engineer will be able to calculate the probable traffic. It must be admitted, however, that the lift engineer himself does not



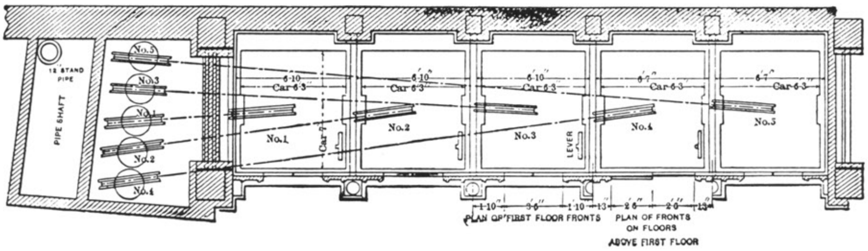
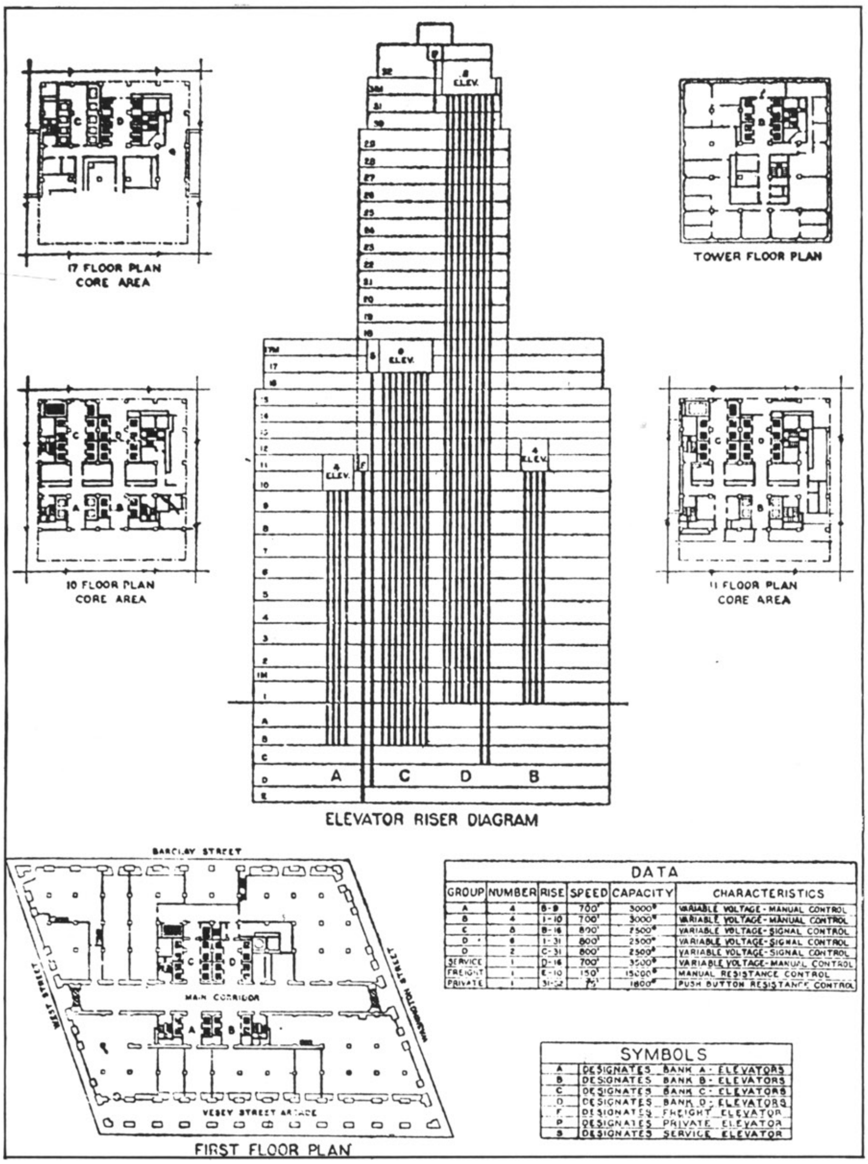


FIG. 8.

employ any scientific method in arriving at the number of passengers per minute which will require lift service on each particular floor during the busy part of the day. Each will draw upon his own experience and home-made formulae."[38] Like any form of transportation, elevators required a balancing of average and peak demands, with economy an inescapable consideration. Every type of building had a different relationship between floor area and the number of occupants to be accommodated, and there was much debate about the validity of comparing office building populations in London, New York, and other cities. Rapid elevator service was a marketable convenience, and the number of elevators might be greatly influenced by the level of rents to be charged in a building. All of these factors, subjective as they were, entered into the calculations by which elevators were selected. Unpredictable variations were so frequently encountered that at a Chicago convention one engineer warned against putting too much trust in estimated average conditions and concluded that "the psychology of it is more important than anything else."[39]

As early as 1898 the New York *Evening Post* reported that in "the dwelling houses of the rich" elevators were being provided for "men with money and a desire to be 'up to date'." In fact, elevators were so popular that "in cases where the elevator is not to be put in immediately provision is made for it either by space left for the shaft or by the actual construction of the shaft."[40] It was the electric elevator and push-button controls that made residential elevators practical; only five years after Baxter installed the first electric elevator in the United States, one company had installed 90



13.19 Zoning of the elevators in the New York Telephone Building (1926) is indicated in this drawing. The locations of elevator groups are exaggerated in the diagram and can be more clearly seen in the plans of the elevator core at different levels. (F. Mujica, *History of the Skyscraper*, 1930. Courtesy of Da Capo Press.)

DATA

GROUP	NUMBER	RISE	SPEED	CAPACITY	CHARACTERISTICS
A	4	B-9	700'	3000#	VARIABLE VOLTAGE - MANUAL CONTROL
B	4	1-10	700'	3000#	VARIABLE VOLTAGE - MANUAL CONTROL
C	8	B-16	800'	2500#	VARIABLE VOLTAGE - SIGNAL CONTROL
D	6	1-31	800'	2500#	VARIABLE VOLTAGE - SIGNAL CONTROL
D	2	C-31	800'	2500#	VARIABLE VOLTAGE - SIGNAL CONTROL
SERVICE	1	D-16	700'	3500#	VARIABLE VOLTAGE - MANUAL CONTROL
FREIGHT	1	E-10	150'	15000#	MANUAL RESISTANCE CONTROL
PRIVATE	1	31-32	75'	1800#	PUSH BUTTON RESISTANCE CONTROL

SYMBOLS

A	DESIGNATES BANK A - ELEVATORS
B	DESIGNATES BANK B - ELEVATORS
C	DESIGNATES BANK C - ELEVATORS
D	DESIGNATES BANK D - ELEVATORS
F	DESIGNATES FREIGHT ELEVATOR
P	DESIGNATES PRIVATE ELEVATOR
S	DESIGNATES SERVICE ELEVATOR

residential elevators in New York. Push-button controls and safety door locks made it possible for the residential elevator to be operated safely by the "hands of children and servants."[41]

Residential elevators, although large enough to carry only three to eight persons, were customarily decorated lavishly:

> The entire designing and construction of the elevator is done under the supervision of the elevator company, but the ornamentation is confided to the decorator and furniture makers. The elevator is almost never built of iron or steel, but of some handsome hard wood. Much carving sometimes goes into it, and the upholstery and other decoration are often very sumptuous.

> Elevators are found very useful at large balls and receptions, and the time is rapidly approaching when it will be considered "bad form" if guests are asked to walk up a pair of stairs.[42]

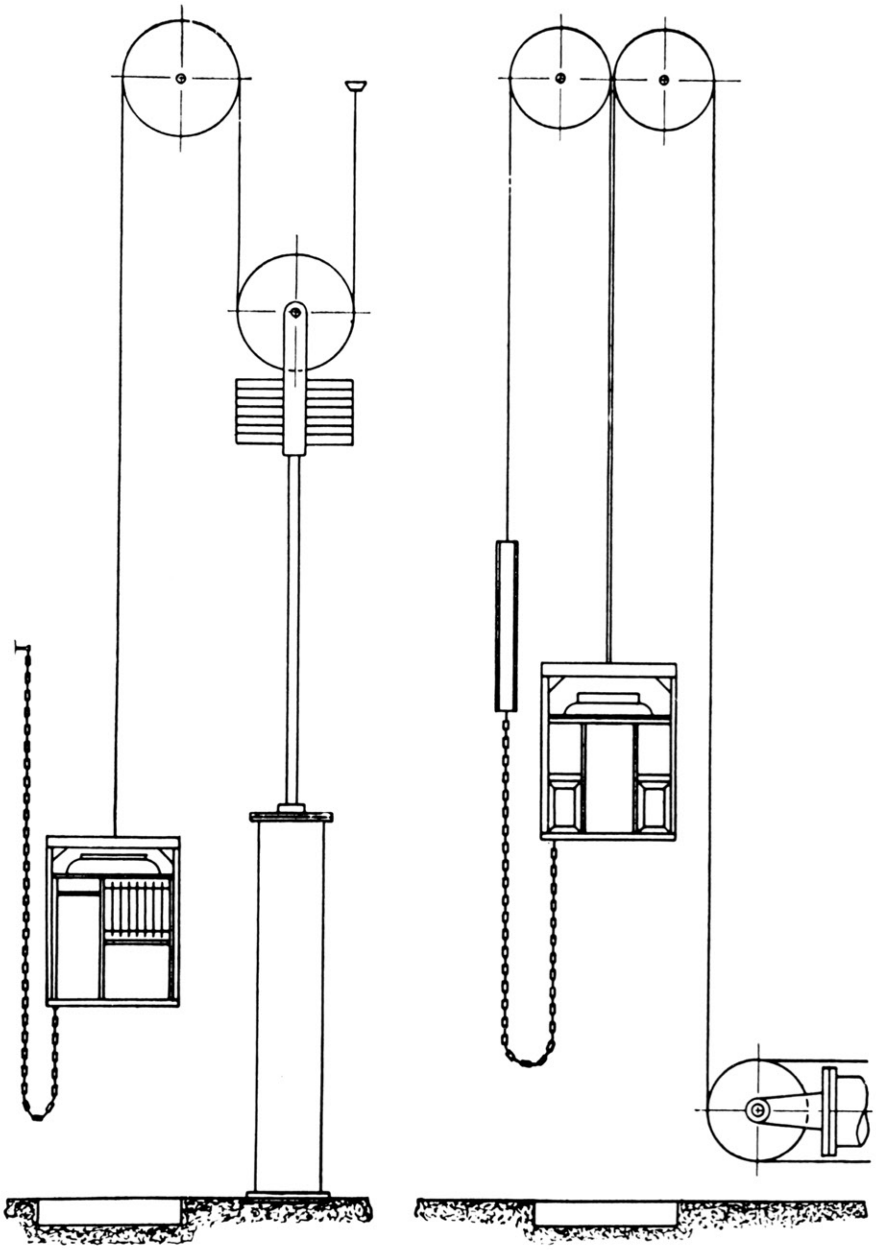
Settees, gilded mirrors, and thick carpets were natural decorations for elevators in the houses of the wealthy, but there was a temptation to add ornament on other occasions. In spite of the protests of safety engineers, architects tended to view the elevator doors of office buildings as something to be made esthetically acceptable by "expressing their architectural ambition in iron and bronze."[43]

* * *

Around 1880, elevator cars for hotels and some department stores in the United States contained upholstered seats and benches. "Some of these cars are gorgeously inlaid and decorated; mirrors are inserted in the small amount of surface available for that purpose, and rich chandeliers hang in the middle."[44] Gas was brought to the light fixtures by a flexible tube that coiled on the top of the car as it rose. Later, faster service obviated the need for comfort in transit, and office building installations limited embellishments to the doors that were visible in the building's lobby. It was essential that the elevator car be kept as light as possible, and therefore it was long assumed that wood construction was highly desirable, if not necessary. But there were many devices that had to be attached to the elevator car: cables connecting the top of the car with counterweights and the driving mechanism; fittings that controlled the car's movement along the guide rails at the sides of the shaft; and brakes and safety devices that were usually attached to the bottom of the car. For this reason, whether operating in a closed shaft or the open cage that was popular in the United States, the elevator car came to be constructed within a sling made of iron and steel. Across the top a sturdy beam held the cables and was connected to two vertical members that ran beside the guide rails. Across the bottom a beam bore the weight of the car and its passengers and the safety devices that were provided.

The typical early elevator shaft was undeniably a fire risk. In 1880 it was pointed out: "Until recently freight elevators were generally open and passenger elevators were enclosed. Now many of the former are enclosed and some of the latter open."[45] When enclosed, the shaft became a chimney by which flames could spread quickly from floor to floor, and it was at the same time a potential source of fire. "Even in so-called fireproof buildings [in the United State] the posts are almost always of pitch-pine, soaked with grease which is used to lubricate the guide strips." At each story the elevator shaft would be closed off from the hallway with thin barriers of varnished wood, glass, or simply metal grilles. All these materials were ready to spread a fire that might easily be started in "oily rags or shavings, or by hot ashes from the boiler" which were often near the bottom of the shaft.[46]

In Europe it was different, and American inattention to fire precautions might have been "considered criminal abroad." According to one observer, "On the continent, open hatchways are forbidden within the walls of buildings, and such elevator-wells as are placed there are always enclosed from bottom to top by stout brick or stone masonry, with doors at each story."[47] In fact, whether as a fire precaution or an uncomplicated



13.20 As buildings grew taller, it was necessary to compensate for the weight of cable in order to maintain a balance between the weight of the car and its counterweight. Compensator chains were attached to the car and to either the walls of the elevator shaft or the counterweight. The clank of chains could be reduced by weaving soft rope through the chain's links. (J. J. Jallings, *Elevators,* 1916.)

way of adding elevator service to existing buildings, elevator shafts in Europe were sometimes supported by an open framework of iron situated beside the building in a courtyard or areaway. Europeans were also inclined to construct their elevator cars of sheet metal, less flammable than their American counterparts.

A reason for open elevators may have been the early lack of lighted signals to warn passengers that a car was approaching. Many insisted it was essential that the waiting passenger see the elevator coming and that the operator in the car have a full view of every floor as he passed it. Other experts recommended that shafts should be built of solid masonry materials, extending above the building's roof and having a ventilator at the top. However, when Boston set about revising its building regulations, which had been enacted after the disastrous fire of 1872, the only requirement given serious consideration was one demanding that shafts should be separated from the remainder of the building by doors at each story.[48]

A smoother ride and more economical operation was possible through the use of counterweights. These could be calculated to have the desired weight in relation to the aggregate weight of the elevator car, parts of the pulley system, and pistons or other elements of the driving mechanism, but in tall buildings the weight of varying lengths of cables in the shaft with the elevator or on the side of the counterweight could become a significant factor in balancing the system to minimize the power required. An early method of compensating for the weight of cables consisted of heavy chains, one end fastened to the bottom of the elevator car and the other end to the wall of the elevator shaft (fig. 13.20). As the weight of the cables shifted, the proportion of the chain's weight hanging from the elevator car changed to equalize the system. Later a narrow upright pipe of water was placed near the vertical cylinder of hydraulic elevators and was connected to the water in the cylinder of the hydraulic system. As the piston rose or fell, the height of this column of water changed to provide a variable pressure that compensated for the shift of the cable's weight.

One factor that encouraged the abandonment of compensator chains was the clanking sounds they made, certainly not reassuring to nervous passengers. In their 1910 installation of electric traction elevators in the 44-story Metropolitan Life Building in New York, the Otis company substituted flat wire rope almost 4 inches wide in order to avoid the fearsome noises of chains.[49]

The earliest controls for steam-driven elevators were nothing more than loops of light cable that extended from the top to the bottom of the elevator shaft with one side of the loop running within the elevator car. By grasping the cable, an elevator operator caused the loop of cable to move with the car, and that movement activated a device that shifted the belt powering the elevator off the driving wheel and onto a freely spinning wheel. Another tug on the cable moved the belt back to its original position, and the elevator resumed its travel. More exact controls were needed. After all, if the elevator moved at 500 feet per minute, the maximum speed allowed in New York in 1913, a misjudgment of one-tenth of a second could result in the car's stopping almost one foot above or below the floor level intended. Obviously, many jolts and starts might be required for an inexpert operator to stop the car reasonably close to the desired floor level, and the warning "Watch your step, please!" was an essential part of the elevator operator's duties.

As speeds became greater and the hydraulic elevator came to dominate the field, the problems of control increased. At first, controls within the elevator car opened and closed a valve that governed the pressure of water against the piston, but the full force of water pressure made starting and stopping the elevator too abrupt. Similarly, electric elevator controls were relatively crude until around 1915, when an automatic leveling device was introduced that not only brought the floor of the car to the desired level, but also compensated for the cables' stretching when a large number of passengers caused a significant increase in the load. This advance allowed the night operation of office building elevators by late-working employees in the offices, sped the development of higher apartment buildings, and encouraged the installation of elevators in private residences (fig. 13.21).

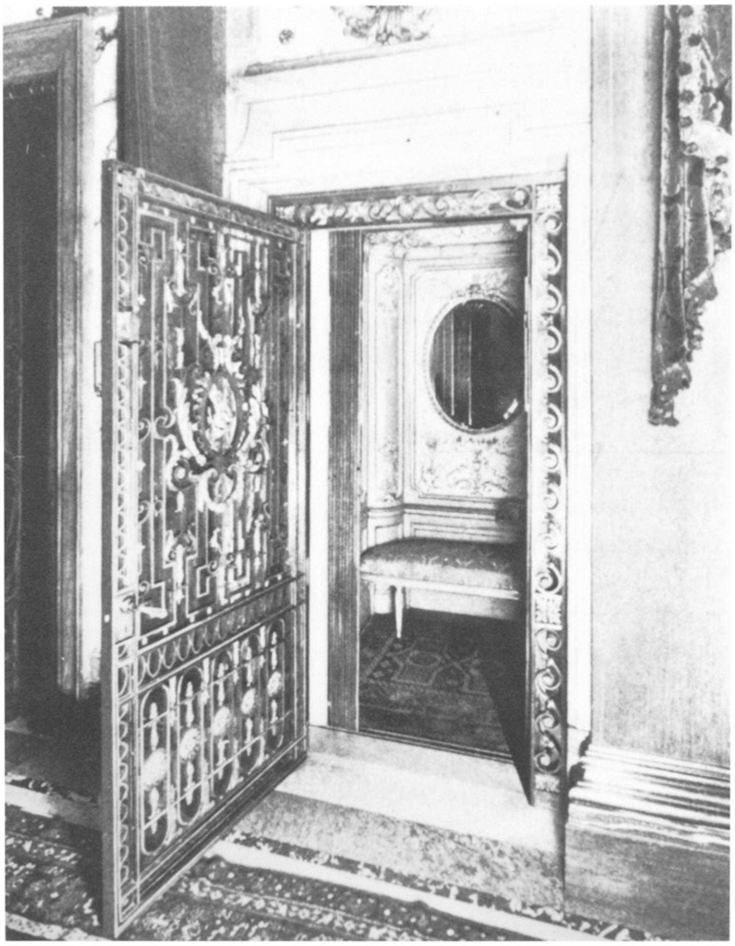
A major factor in the development of elevators was the public's fear of elevator accidents. In 1878 the Paris newspaper *Figaro* printed a description of an accident at the Grand Hotel that soon found its way into the press of other countries:

> The conductor touched the button, but instead of descending, the car began to mount with alarming rapidity. The casting which united the piston to the platform on which the car rested had broken. While the force of water was beneath the piston and the car was ascending, this was not felt, as the piston ran up and lifted the load as usual; but immediately the escape-valve was opened at the foot of the supply-pipe, the piston darted downward with fearful speed to the bottom, while counterweights, now much heavier than the car and its load, began to run down, and pulled the car up at a dizzy rate. Arriving at the top floor, the car was violently rammed against the top beam. The shock was so great that it broke the chains which held the counterweights, and the car went flying down to the basement. The weights fell with a report almost equal to a cannon-shot, attracting nearly every person in the building. The three occupants of the cage were dead, all bleeding from the mouth and ears, showing cerebral congestion. At the inquest it was ascertained that a "blister" in the casting was the cause of the disaster.[50]

The elevator was of the direct plunger type favored by Europeans for its apparent safety, and it had been installed only 18 months before the accident. The hydraulic cylinder and piston were located directly beneath the car, acting as a column of changing height, and a chain extended upward over a pulley to balance the car with a counterweight and thus reduce the work of the plunger system.[51] It had all seemed so safe that no safety devices were provided.

In 1857 a Boston freight elevator loaded with boxes of sugar fell to the bottom of its shaft, and the boxes were undamaged. Investigation showed that the car had been protected by relatively airtight construction at the bottom of the elevator shaft, the air entrapped there serving as a brake for the falling car. Several decades later the air cushion safety system became a common provision in elevator installations. The *Engineering News* in 1899 referred to the air cushion as having been "in considerable use some years ago" and explained that "a car falling freely down a 100-foot shaft, for example, would acquire a velocity at the bottom of about 80 feet per second, or 55 miles per hour, and unless a very deep shaft were made for the air cushion, the stop would be highly disastrous to the passengers."[52]

The year before these comments were made, there had been a demon-



13.21 Push-button controls, leveling devices, and safety systems at elevator doors encouraged the use of elevators in apartment buildings. (*American Architect and Architecture*, 6 August 1919.)

stration of one of the most extensive and elaborate applications of the elevator air cushion in the Empire Building at Broadway and Rector Street, New York. As in most such installations, the walls of the air cushion were sloped in order to ease the escape of trapped air, and air escape valves were installed at the bottom of the shaft. In the Empire Building test "a car weighing 2,000 pounds was dropped from the twentieth story. The efficiency of the cushion was shown by the fact that the eggs and incandescent lamps carried upon the floor of the car were uninjured."[53]

The air cushions for elevators in the Philadelphia City Hall were similarly tested in 1902. Although the building stood 500 feet tall from the shoes of William Penn's statue to the sidewalk, the test allowed a car of about 1,500 pounds to fall free for 290 feet (a greater height than any previous test) before entering an air cushion 75 feet deep. In the car were a lighted lantern, six rats, fifty incandescent light bulbs, and several dozen eggs. "A New York reporter begged for the privilege of accompanying the rats, but was refused." A few seconds after the car was cut loose there was a "cannon-like report." When the car was entered it was found that "the lantern was upset, and a few of the eggs were broken, the rats were unscathed . . . and the incandescent light bulbs were unbroken."[54] F. T. Ellithorpe, president of the Ellithorpe Safety Air Cushion Company and principal promoter of the safety device, calmly reported to the press that he had himself many times dropped six stories without injury.

The last major installation of air cushions seems to have been that in the Woolworth Building, for which the architect Cass Gilbert had the assistance of Thomas E. Brown, Jr., consulting engineer for the Otis Elevator Company. For this installation the lower part of each shaft was enclosed with walls of steel and concrete, airtight elevator entrance doors were installed at every floor level, special outlet valves at the bottom of the shaft released air during impact, and inlet valves reduced suction as the car rose again. In November 1912 an article titled "Parachuting Down an Elevator Shaft" announced: "A safety expert, F. T. Ellithorpe, is to drop in an elevator seven hundred feet. . . . Mr. Ellithorpe is going to call into use this air to check the downward course only toward the end and not at the beginning of the elevator's fall. This would seem to add to the peril because it gives the plunging car just so much more time in which to acquire dangerous momentum."[55] Perhaps Ellithorpe had the same misgivings, for his name is not mentioned in a later report: "On the night of October 16, 1913, one of the forty-six story cars, loaded to a weight of 7,500 lb., corresponding to a carful of passengers, was dropped freely from the forty-fifth floor and stopped safely by the action of the air cushion. It fell 470 feet to the top of the air cushion in 5½ seconds and came to rest safely at the bottom of the air cushion in about 1½ seconds more."[56]

By the 1920s the air cushion had been abandoned as an elevator safety device. Smoother starting and stopping and the more facile control provided by new power systems had calmed the public's fears, and 50 years of experience with elevators had brought new generations, accustomed to travel in automobiles and inclined to trust mechanical contrivances. Nevertheless, the air cushion safety system had always offered distinct advantages. It was costly to construct but was not plagued by deterioration of springs, maintenance costs, or the tampering of building engineers. Furthermore, it lent itself to dramatic demonstrations of its capabilities, and that had been a significant factor in elevator development since the days of Elisha Graves Otis.

13.22 The Chicago Time-Life Building (1971) was not large enough or tall enough to satisfy the usual criteria for the use of double-deck elevators. The prompt arrival of 2,800 clerical workers was the determining factor. (*Progressive Architecture*, December 1971.)

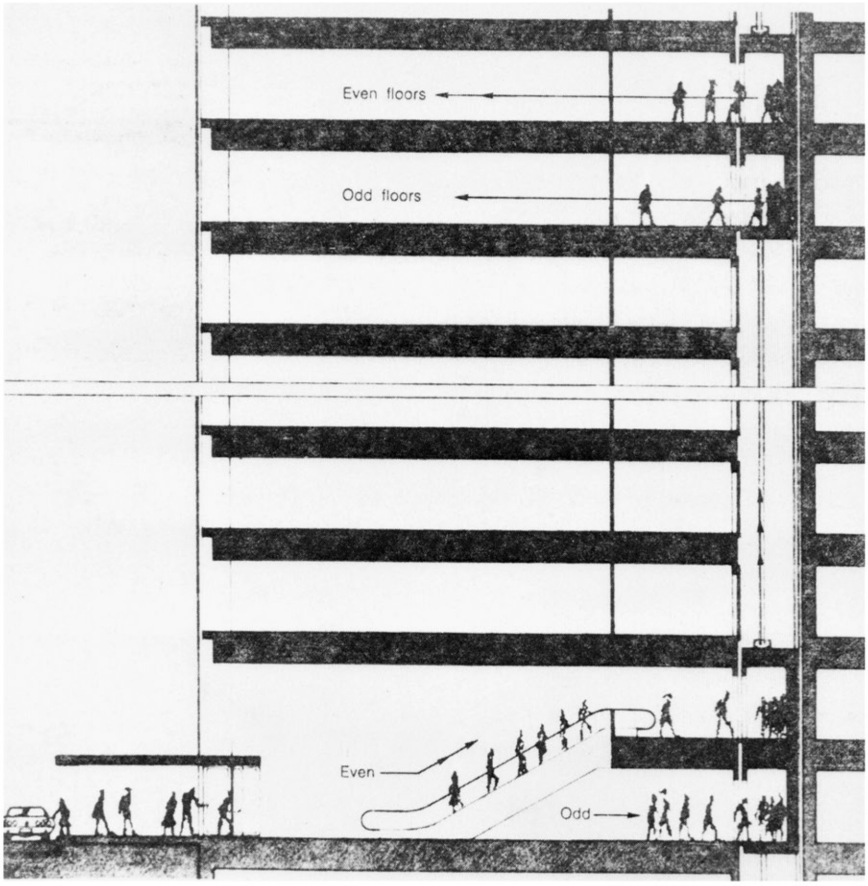
Almost 50 years after Otis had demonstrated his safety device at the New York World's Fair in 1854, elevator engineers were so confident as to refer to his invention as "a very pretty exhibition safety," because its action was triggered by a broken rope or chain, "the rarest cause of a car falling."[57] Once higher elevator speeds had been reached, the sudden shock that resulted from pawls engaging the ridges of the side rail was too great for the safety of passengers. Before steel rails replaced wood, this objection was somewhat alleviated by the fact that toothed pawls would gradually embed themselves in pine side rails, cutting deep gouges in the wood before bringing the car to a halt. Once the height of elevator shafts increased, the device was effective only when the cable broke near the car, for the weight of chain or cable in the shaft could maintain tension on the releasing mechanism.

Other means of stopping a falling car were triggered by a car's acceleration during a fall. In one system a cog rotated in a metal case, turned by the teeth of the metal side rail, and when the speed became too great the cog would be driven upward to wedge against the rail. Pneumatic devices included a pair of hinged boards on the bottom of the car that would be forced outward against the rails by the air pressure beneath the falling car, and a pneumatic piston applying restraint through its own cable attached to the car. At the end of the nineteenth century it was reported that "neither of these pneumatic devices is considered to be reliable."[58]

Many safeties were operated by centrifugal governors located on the top of the car or at the top of the shaft. A light cable attached to the car made a loop up and down the shaft, turning the governor. With excessive speed the spinning balls of the governor rose, and a safety device was activated. Multiple systems were common and there was always a buffer at the bottom of the shaft. For low speeds and shorter buildings the buffer was usually a simple, massive spring; for faster and higher installations the spring might be placed on an oil hydraulic piston and cylinder.

The fear of falling may have been a natural concern, but statistics indicate that other factors were a more common cause of accidents. Even a falling car could involve injuries from things other than its impact on the bottom of the shaft. Early counterweights were not always restrained to prevent their falling on a crashed car and, when the shaft was many stories in height, falling cables could themselves prove extremely dangerous.

There were repeated protestations of the safety of elevator transportation. In 1898 a Boston elevator inspector compared elevators to railroads: "Statistics of this country show that while one passenger among 166,000 is injured on railroads, only one out of 1,210,000 passengers, as nearly as can be determined, is injured and only one killed out of 2,000,000 passengers by reason of elevator operation."[59] Cables breaking or unwinding were responsible for only about 6 percent of elevator accidents. About 10 years later an 11-year study of fatal elevator accidents in Chicago and Manhattan showed that 85 percent took place at the elevator door and 15 percent in the shaft, whether from falling cars or workmen's activities.[60] Of the fatal doorway accidents, about half were a matter of the victims being crushed in



the doorway, and the other half were cases in which the victim fell through an open elevator door. Most of the accidents at the elevator door were the result of inadequate, broken, or unused safety devices that were intended to insure closure of the landing door until the car was level and prepared to be boarded.

> Mrs. Elizabeth Insman last night walked into the elevator shaft at St. James Hospital where she was a patient, sustaining injuries which caused her death. She mistook the door for that which led to the bathroom.
>
> Donald Meade, a clerk, couldn't understand why the elevator was so slow. He opened the safety gate and looked up the shaft. The descending car pushed down the gate, pinned him to the floor and crushed him to death.[61]

In most cases these accidents seem to have been related to human impatience and curiosity as much as they were to mechanical problems. As late as 1923, when mechanical and electrically controlled mechanical devices to prevent doorway accidents were well developed, it was reported that a check on the 56 elevator doors of the Film Building in New York showed

13.23 In the 1892 Reno patent, cast-iron strips moved along I-beam runners and turned on sprocket wheels at the top and bottom of the escalator. Reno's most significant feature was the comb plate (14 in the upper drawing), which extended into the grooves of the cast-iron strips (2 and 5 in the lower drawing). (U.S. Patent no. 470,918.)

that not one of the electro-mechanical safeties was in operating condition, and that in the second largest hotel in Richmond, Virginia, 17 of the 41 mechanical safeties were broken or dismantled.

Gradually municipalities enacted more stringent requirements for elevator safety at the door, but not without strong argument and the inclusion of exemptions for elevators already in operation. One safety engineer recalled a hearing in New York in which the official representative of building owners shouted to the aldermen, "Five million dollars, gentlemen—$5,000,000 for a lot of useless junk!"

* * *

A major economy in elevator systems was achieved in 1931 when the Westinghouse office building in East Pittsburgh, Pennsylvania, was designed to have two elevators operating in each shaft. The building's height required two elevator zones, the lower one running from the lobby to the eleventh floor and the upper zone starting at another lobby a half-story above street level, going directly to the twelfth floor, and thereafter serving the upper half of the building. The controls, in the design of which Frank J. Sprague took part, stopped either car at the top of its designated run until the other had also reached its top point. During the descent that was thus coordinated, safety devices prevented the cars from getting nearer to each other than a designated distance. The Westinghouse Electric Company estimated that this arrangement saved floor space that could have been rented at that time for a sum between $35,000 and $85,000 per year.[62] The electrical controls gave a degree of security, even in a period when elevators were run by operators at hand controls, but the fact that the lower elevator made more frequent stops on its downward trip, frequently bringing the express elevator to a complete stop, proved an irremediable disadvantage of the system.

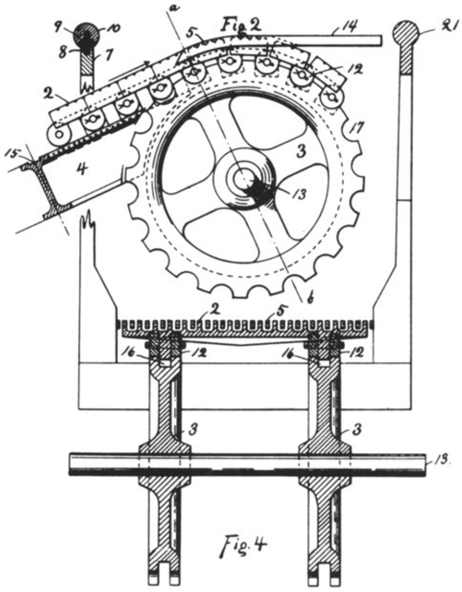
The following year a New York office building of 60 stories used stacked elevator cars. Passengers wishing to reach even-numbered floors entered the upper part of the car from the building's street-level lobby; those wanting to go to odd-numbered floors went to the basement, where they entered the lower part of the car. The lower level was meant principally to serve workers arriving through a proposed subway entrance, which was unfortunately never built.[63] Consequently, the system was soon converted to single-car operation.

In 1970 the idea of double-deck elevators was revived in the design of the Chicago office of the Time-Life publishing house (fig. 13.22). These offices were occupied by the magazine's subscription service, and management required that all workers observe the same office hours. Therefore, although the building had only 25 stories, it was necessary in a five-minute period to move almost twice the number of occupants as usual in office buildings.[64] Shortly afterward three other buildings were designed with double-deck elevators.

* * *

Elevators satisfied the needs of hotels and offices, accommodating a moderate number of people who desired to reach their destinations within moderate intervals of time. For railroad terminals and busy department stores the larger numbers of people led to inevitable comparisons with the methods of movement used in mining and manufacturing, conveyor belts that delivered ores and raw materials to the carts and bins from which they would be used. Assembly line principles, the "iron foreman" that set the pace for factory workers, could also speed and regulate the flow of the throngs that crowded into the booming centers of metropolitan areas. Furthermore, the advantages of eliminating queuing through continuous movement could be realized by "inclined elevators," "moving stairways," and "electric stair lifts," as escalators were called before the turn of the century.

A U.S. patent for "revolving stairs" was issued as early as 1859, but the first steps toward development of the escalator were taken in 1892 by Jesse W. Reno, who at the same time proposed an underground rapid transit system for New York. Reno, the son of the Civil War general for whom the Nevada city was named, had worked in western mining activities for seven years after graduating from Lehigh University in 1883. Coming east to join the staff of the Thomson-Houston Company, he worked alongside C. J. Van Depoele, the Belgian engineer who contributed to the development of streetcar systems and electric motors. Steam-driven conveyor belts used to load ore, interest in the movement problems of metropolitan centers, and the potential offered by heavy-duty electrical motors were combined in Reno's mind.



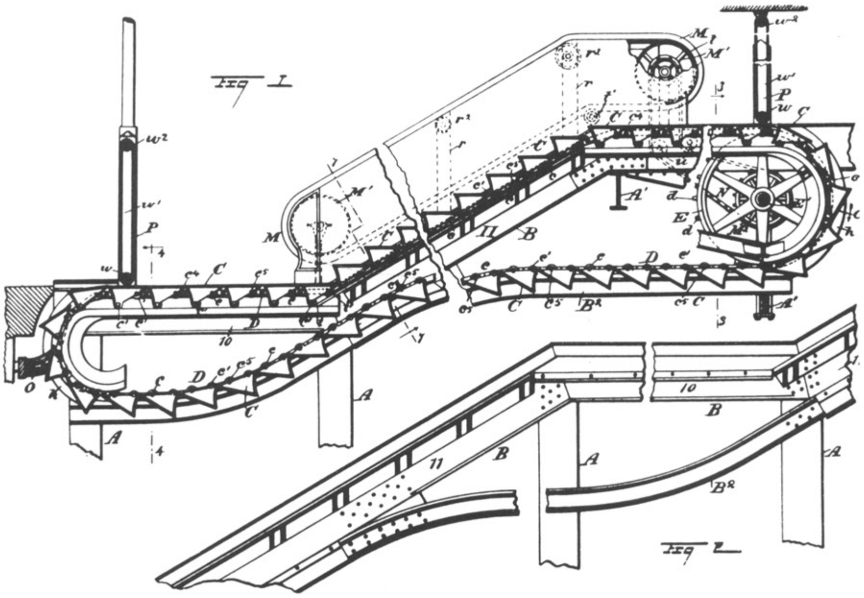
In 1892 the *Engineering News* reported that an experimental "continuous passenger elevator" had been built by Reno in Brooklyn, and it suggested that the device would be useful "in places where the traffic is quite continuous, as at the downtown stations of the elevated railways and on the Brooklyn Bridge," giving people access to the streetcars from levels lower than the bridge's approaches.[65] This design was simply an inclined plane that traveled at the speed of 70 feet per minute (fig. 13.23). The moving surface was made up of cast iron strips, 3½ inches wide, that rolled along tracks at each side of the moving belt. These segments were grooved in the direction of travel and bands of rubber assured that users' feet would not slip on the slope of about 1:2. At landings passengers stepped onto an iron plate with projections like the teeth of a comb, fitting between the ridges of the cast-iron strips. Reno machines were installed at approaches to the Brooklyn Bridge and at Coney Island. Their principal shortcoming was the steep angle of the moving surface on which passengers stood. For safety and reassurance a moving handrail was provided on one sided, although it was found necessary to mold large white circles in the rubber covering in order

13.24 The Reno inclined elevator required that passengers stand on a steep slope, as shown in this early installation in a department store. Note the white circles that made the movement of the handrail evident to boarding passengers. (*Electrical Engineering,* 7 July 1898.)

13.25 In the 1892 Wheeler patent, steps appeared out of the floor and disappeared into the floor. At these points it was proposed to place barriers (*P* at left and right), which were to consist of belts rotating in the direction that would push away incautious toes. (U.S. Patent no. 479,864.)

to make it apparent that the handrail moved (fig. 13.24).[66]

In the same year that Reno patented his "endless conveyor or elevator," George H. Wheeler obtained a patent for an "elevator" that was similar. The Wheeler design did not have the early popularity of Reno's product, but it proved to be a basis for sound development. Instead of a steeply sloped plane, the passenger was confronted with familiar steps moving up the incline (fig. 13.25). Some were startled: "The sight of all those stairs gravely walking upstairs for ever and ever is calculated to seriously shock a man of nervous temperament, and is a thing to be avoided by one of uncertain or unsteady vision."[67] Each step was in itself a small cart carried on four wheels, the wheels at the front of the step riding on one pair of tracks and the wheels at the back riding on separate tracks. By altering the relationship of these tracks the steps could be positioned as a customary stairway or could transform the treads of the steps into a continuous plane. By this means the boarding passenger could step onto a flat moving surface, which would gradually become a stair and then return to a flat surface. The principal flaw of the Wheeler design lay at the beginning and end of the escalator trip, where the steps were flattened to be even with the floor surface and then rolled down into or rose out of the floor. A large gap was necessary between the floor and the steps, a gap that had to be filled to "prevent the toes of the party from becoming wedged fast at the floor line," as Wheeler wrote in his patent. A barrier (or "shunt," as it was often called) covered the gap and, by its angled or curved shape, assured that passengers left the escalator by stepping off to the side and approached it from the side. The Wheeler patent was sold in 1898 to Charles D. Seeberger, an experimenter in escalators, who the following year joined forces with the Otis Elevator Company.



It was the Paris Exposition of 1900 that most dramatically brought attention to the advantages of the moving ramps, just then becoming known as escalators. A feature of the Exposition was an elevated moving platform that carried visitors along a circuit of about two miles, paralleling and crossing avenues. At two of the system's nine stations, escalators were used to lift passengers from the pavement to the level of the moving platform. In addition, planners of the Exposition, fearful that visitors would not bother to climb stairs to upper levels of some exhibition halls, installed 28 escalators within buildings, all required to be from French manufacturers. Over half were constructed after the Hallé system, a stiff belt supported on rollers every two feet. The LeBlanc system, which also provided escalators for the Exposition, employed bars between two sprocket chains that were supported on rollers. There was little fundamental difference between these two escalator systems and that of

Reno, five of whose machines were supplied to the Exposition through the company's French agent.[68]

Within the U.S. display in the Palace of Thread, Fabrics, and Clothing, Otis installed an escalator in addition to those selected by the authorities of the Exposition. A British engineering magazine made clear the way that it differed from others: "This device . . . is really a staircase, and is not a traveling band, such as was employed in places to carry passengers to the higher levels. It has treads and risers, and when at rest can be ascended and descended just as any other stair."[69]

The principal problem that remained in the stepped escalator was that of leaving it. At the Exposition of 1900 the single Otis escalator had been provided with the company's usual solution to this problem. At the top of the run, treads of the steps continued even with the floor for about five feet beyond the end of the incline. In this area a low V-shaped barricade was placed to shunt passengers to either side and off the moving surface (fig. 13.26). This awkward maneuver was eliminated shortly after the Exposition, when the treads of escalator steps began to be made of strips of wood or metal, which meshed with a comb plate such as that used in the early Reno machines. With this improvement shunts were no longer needed.

13.26 Escalators developed from the Wheeler patent required a barrier that covered the dangerous gap into which the steps disappeared. (*Cassier's Magazine*, March 1904.)

The logic of escalators demanded a heavy, even flow of passengers. From Reno's first installations at the stations of New York's elevated railways to present-day terminals, the escalator has always provided a means of moving crowds without delay. Early installations usually provided only upward transportation, an adjacent stair being provided for downward travel or for those who were reluctant to use the escalator. Eight escalators placed in a six-story Massachusetts textile mill in 1905 to speed the movement of its 6,000 workers were the first to be reversible. When workers arrived in the morning or returned from lunch, the escalators lifted them to the level on which they worked; going to lunch or leaving at the end of the day, the escalators were switched to the descending direction. Although such industrial uses were rare, it was reported to have been the careful decision of the mill's owners, based on such economic factors as the conservation of employees' energy and attracting the pick of available workers.

At stations of the New York elevated railway, escalators became extremely popular. When it was necessary to shut down the escalator at 23rd Street and 6th Avenue for a period, the station lost almost 65,000 fares. Early in this century, major railroad terminals began to install escalators to take passengers from the level at which trains arrived to the main concourse and waiting rooms. At the Gare du Quai d'Orsay in Paris in 1908, the decision to use a stepped escalator, rather than an inclined belt, was greatly influenced by the feeling that it was necessary that "the traveller's foot can rest on a plane that is absolutely horizontal" and that there be a place to rest hand luggage as one moved upward.[70] A few years later a similar escalator was installed in New York's Pennsylvania Station, but by that time stepped escalators had almost completely supplanted belt escalators, and the Reno patents had been sold to the Otis Elevator Company.

With improved city transportation, residents of metropolitan centers could take advantage of large department stores that sold a wide variety of articles at predetermined and clearly marked prices that were low in order to insure rapid sale. Any observer of the "restless activity and untiring energy of modern shoppers" realized that speeding them on their way about the sales areas increased sales, and escalators became an attractive solution to the problem. In the 1890s Reno escalators were installed in two New York department stores, Greenhut-Siegel-Cooper and Bloomingdale's. Similar escalators were also added at Harrod's in London and the Magasin du Louvre in Paris.

After the Paris Exposition of 1900 the enthusiasm of department stores for escalators blossomed. The escalator Otis had displayed at the Exposition was returned and installed in Gimbel's department store in Philadelphia. A few years later Gimbel's archcompetitor in New York, R. H. Macy and Company, connected all of its store's five floors with escalators. A measure of the escalators' value was found shortly before Christmas 1906, when the number of customers coming up to each floor by stair, escalator, or elevator was counted. At the third floor arrivals by escalator were double those by elevator; at the fourth the count was almost equal; and at the fifth arrivals by elevator were half again the number by escalator.[71] Store owners discovered that systems combining elevators and escalators drew buyers to upper floors, and as they traveled they saw the merchandise displayed on each floor. Escalators and elevators were also technological symbols of luxury. Because Berlin housewives were somewhat embarrassed to seek bargains, a major department store there was decked out with marble walls, glittering chandeliers, fountains, three escalators, and 83 elevators.[72]

Used in combination, elevators and escalators—like sidewalks and streets—made possible the increase of urban density and brought to realization the century-old characterization of vertical transportation within buildings as upended streets. Heavy-duty electric motors, the latest method of powering vertical transportation, had been developed for streetcars, and the controls needed for safely stopping and starting streetcars were not greatly different from those needed for elevators. Like horizontal transportation systems, elevators systems in skyscrapers were designed for peak hours of coming and going, and by zoning the heights to which different elevators provided service the system worked rather like a routing of streetcar lines. In fact, many of the tallest buildings have established mid-height lobbies in which travelers must transfer from one elevator to another that is routed to serve the uppermost floors, just as one waits on a street corner to transfer to another bus.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OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

14

Fire Protection

1680	Nicholas Barbon establishes the earliest company to offer insurance against fire loss
1793	London committee of architects compares materials to control the spread of fire
1844	Chemical fire extinguishers introduced
1871–72	Chicago and Boston fires test the durability of buildings
1875	Automatic sprinklers offered for sale by Henry S. Parmalee
1880s	Introduction of methods for protection of the metal frameworks of skyscrapers
	“Slow-burning” construction encouraged by Edward Atkinson

14.1 An engraving by William Hogarth, intended as a satire of the British government's war policies in the middle of the eighteenth century, shows the ways of fighting a fire at that time. While hand-held squirts are aimed from windows of a building, an insurance company's fire engine is pumped and men carry leather buckets of water to keep it filled. (William Hogarth, *The Times* 1762.)

Ancient cities were always in risk of fire, whether started by carelessness within the city walls or by invading armies. Conquerors customarily set fire to the shrines and temples of a vanquished city, a practice so common that at the end of the Persian invasion in 479 B.C. the citizens of Attica pledged to eschew rebuilding their burned sanctuaries and leave the ruins "as memorials of the impiety of the barbarians."[1] In cities largely built of masonry walls and tile roofs it seems surprising that fire could quickly spread, but the explanation lies in the density of buildings within the cities. Around 480 A.D., radical regulations in Constantinople demanded that streets be at least 12 feet wide and balconies be no closer than 10 feet from the wall opposite.[2] Since the walls of most buildings were set at the edge of their owners' property and most rooms opened on small courtyards in the center of the buildings, it is reasonable to picture such a city as consisting of large districts of continuous building, with fire delayed by streets little more than it would be slowed by a hallway.

In medieval London, regulations enacted by subdivisions of the city included requirements that fireplaces be built with space left between them and wooden members of construction, that large houses have ladders present for fighting fires, and that during the months of June and July barrels of water be kept beside their doors.[3] Such controls were common in the densely populated and highly combustible warrens of medieval cities. Curfew (from *covrefeu*, or literally, "cover your fire") was usually imposed, and at night city patrols were alert for sparks rising from chimneys. Fire prevention regulations were based on both humane and economic factors, for James I in his Proclamation of 1620 observed:

> In the time of King Richard the first, Henry Fitz-Ailwyn, then Mayor, for the prevention of casualties of fire, caused provision to be made, that Buildings in the sayd Citie [London] should be of Stone, which for many yeeres after was observed; But the neglect thereof in succeeding times, especially in the present, the great confluence of Our sayd Citie, pestering of the Streets with Jutties, Stalles, and other annoyances, scarcitie of Timber, and many other occurrents, have turned the policie of those ancient times from conveniencie to necessitie.[4]

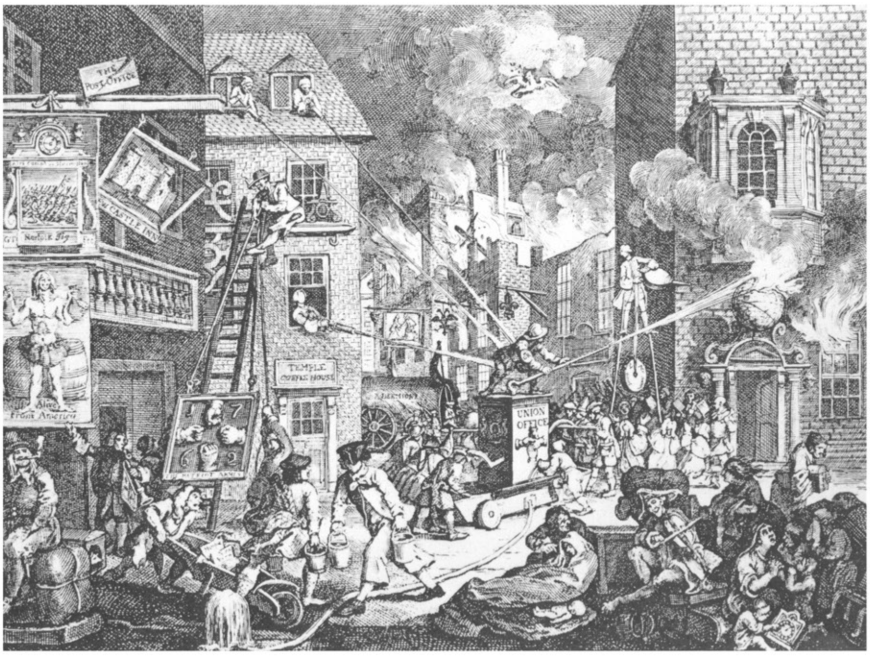
Efforts to curtail fire risks in London centered on controlling the use of flammable building materials, and it appears that this was also true in provincial towns. From 1650 to 1850 the major fires in four counties of southern England diminished to a startling degree, the first three decades of that period having 36 major fires and the last three decades only one. The improvement of fire-fighting equipment and methods was the principal factor in this reduction, though improvements made while rebuilding also made a significant contribution. The hand-pumped fire engine was introduced into England from Germany during the seventeenth century, and from the Dutch later came the use of flexible hoses by which water could be directed toward the heart of a fire (fig. 14.1). More common were hand-held "squirts," syringes by which a small jet of water could be forced a short distance.

Winchester, a major market town, in 1656 required new kinds of roofing: "For ye avoyding of the greate inconveniences w^{ch} are found by experience to grow by thatcht Houses within that citty, both in respect of the danger it occasions by Fire and the unseemliness thereof in soe auncient and famous a citty . . . all such Houses that are already thatched, [are] to be covered with Tyle or Slatt within One yeare next ensuing, upon the like payne of Tenn Pounds."[5] In general, the process of replacing timber and thatch with brick and slate reduced the flammability of each building that was rebuilt and deterred the spread of flames from the thatched roofs that remained.

In New England, the governor of Massachusetts Bay Colony in 1630 ordered that in Boston "noe man shall build his chimney with wood, nor cover his house with thatch," but this regulation was not enforced.[6] A series of fires that followed brought further restrictions, each fire frightening the townspeople into short-lived concern. After the 1653 fire, Boston householders were required to have ladders on their premises and the city government purchased "good strong Iron crooks" for pulling down burning buildings. The fire of 1676 led to restrictions on the spacing of houses, and three years later another and larger blaze caused the Boston General Court to demand rebuilding in brick and tile, a requirement that was soon set aside because of the expense it entailed.

The Great Fire of London started early on Sunday morning, 1 September 1666, and continued until it had laid waste to 395 acres of the city and demolished 13,000 houses. Unlike previous attempts to legislate fire-retardant construction, the Rebuilding Act of the following year had two vital characteristics: detailed requirements and a sound system of enforcement. New brick plants were soon set up in the outskirts of London to feed the feverish activity of reconstruction under the new regulations. The continued use of timbers for floor construction was somewhat offset by an increased popularity of plaster ceilings. In this Act and subsequent legislation, attention was repeatedly given to the thickness of brick party walls and separations between chimneys and the wooden members supporting floors, the first a restraint on the spread of fires and the second serving to lessen the risk of fires starting.

New York adopted its first building regulations in 1625; those simple requirements were succeeded by more detailed limitations meant to discourage the start of fires. Early in the eighteenth century, New Yorkers



were forbidden to distill rum or burn oyster shells for lime within a half mile of City Hall. Later the outdoor stacking of hay was prohibited, and regulations were imposed on the storage of pitch, tar, and turpentine. Expansion and construction continued apace, and around 1840 the New York *Mirror* longed for "the day when some portion of New York may be considered finished for a few years."[7] Such activity demanded further protection from fire, and soon New York regulations designated boundaries south of which wooden construction was outlawed. Because of the linear nature of New York's growth, the limits were simple to define: in 1860 at 52nd Street, in 1866 at 86th Street, and at the end of the century 149th Street on the east side and 190th Street on the west side of Manhattan. The flaw in this early determination of a fire zone was the law's being limited to the *construction* of wood buildings. Existing frame structures could still be shifted from lot to lot within the southern part of the city, and buildings erected in the northern fringes of settlement could be moved southward across the established line.[8]

After the Great Fire of London a young doctor, Nicholas Barbon, established the first system of fire insurance. Barbon was the son of Praise-God Barebone, leather merchant, member of Parliament supporting Cromwell, and lay preacher of the Anabaptist faith. Barbon was trained in Holland for the practice of medicine, but before the fire he had begun speculating in the construction of houses in the London area. Not the first to undertake the residential development of sizable tracts of land, Barbon advanced the system by laying out streets and squares, pricing lots by the lineal foot of frontage, and constructing houses that were—though narrow in plan and meager in form—attractive to naive buyers. Known for his showy clothing and love of food, Barbon considered building to be "the most proper and visible Distinction of Riches and Greatness, because the Expences are too Great for Mean Persons to follow."[9]

A year after the disaster, while the city was busily rebuilding, Barbon began offering fire insurance on real estate. In the beginning Barbon conducted his insurance business alone, but in 1680 he combined with other investors to establish a company called the Fire Office. In the six years following 1686, the company provided coverage for 5,650 houses with premiums set twice as high for timber construction as for brick. The company's monopoly was ended with the founding of the Friendly Society for Insuring Houses from Fire, and the later competition of The Amicable Contributorship for the Assurance of Houses and Goods from Fire. (The latter company, with good reason, soon changed its name to Hand-in-Hand Fire and Life Insurance Society.) In 1710 the Sun Fire Office opened, and it came to dominate the English fire insurance activity along with the Phoenix Assurance Company and the Royal Exchange Assurance.[10]

Nicholas Barbon hired a corps of men to fight fires at properties on which his company had written policies. Other companies formed their own fire brigades, and soon each insurer installed cast lead insignia to mark the buildings on which it held insurance. Being privately funded, a fire brigade only fought fires on buildings insured by its company, and it withdrew if the unfortunate householder's insignia proved to be that of another underwriter. When there was no insignia, all fire brigades that might be present watched as flames consumed the structure, thereby clearly demonstrating the wisdom of a householder's contracting for insurance.[11]

In the United States a fire in Philadelphia during the spring of 1730 razed a number of shops and some residences. After this fire, city officials purchased additional fire-fighting equipment and instituted new regulations, including one that forbade smoking on the streets.[12] In addition, citizens organized the Union Fire Company, a volunteer group of fire fighters, self-equipped and limited to 30 in number, which included Benjamin Franklin. This organization was the springboard from which came the first stable fire insurance company in the United States. (A previous company had been established in Charleston, South Carolina, but it had failed after the 1741 fire in that city.) Begun as a simple compact among men who each contributed to the group's funds for investment, within two years the Philadelphia company adopted the name Philadelphia Contributionship for the Insurance of Houses from Loss by Fire, and it began selling policies to nonmembers. For the next 32 years the Contributionship was the sole fire insurance company in the United States. Unlike English insurance firms of the time, the Contributionship inspected each building before issuing a policy on it, and rates were determined individually for each building rather than being set for broad categories of function and construction. The rate determinations of the Philadelphia Contributionship sometimes included requirements that alterations or improvements be made to the property considered for insurance. One of the most controversial of these measures was the company's decision in 1781 that it would not insure buildings with trees nearby, a declaration that led to the formation of a competing insurance company more generous toward the Philadelphia landscape.

As the actuarial determination of fire insurance rates developed, competition quickened. In 1810 there were few companies in the United States, but their number gradually increased. New York had a rate-fixing agreement among all of its companies in 1821, but within a few years 17 new companies were formed and open competition was restored. In 1826 another agreement on rates was reached, but the New York fire of 1835 ruined many companies and rates soared, to be followed once more by a flurry of new companies and the concomitant rate cutting. This cycle was repeated before and after the New York fire of 1845. Between 1849 and 1865 there were at least 70 new fire insurance companies started in New York. Throughout the United States competition and rate fixing alternated until conditions were stabilized by the formation in 1866 of the National Board of Fire Underwriters.

Attempts were made to limit the likelihood of fires starting or spreading. In the 1770s at the edge of London on Putney Heath the Lord Mayor attended a demonstration arranged by David Hartley, a member of Parliament and diplomat who later signed the treaty ending the American Revolution. A fire roared in the lower room of a house, while the inventor and trusting friends waited confidently in the upper room. Hartley's fireproofing method, which was patented in 1773, consisted of thin plates of iron fastened beneath, above or on both surfaces of wooden floor construction. Spaces between the plates and wood were filled with sand or other noncombustible granules. The results of the test on Putney Heath were so impressive that the Lord Mayor marked the event by constructing a commemorative obelisk nearby, and in 1777 Parliament extended Hartley's patent for 31 years.[13]

14.2 The Chicago fire burned more than 2,024 acres and 17,450 buildings, consuming property valued at $200,000,000. Many insurance companies collapsed, but those surviving poured over $40,000,000 into Chicago's reconstruction. (*The Conquest of Fire*, 1914.)

14.3 A cartoon after the Chicago fire showed insurance agents bemoaning their situation. Insurance adjusters were viewed with suspicion, a sentiment encouraged by the fact that almost two-thirds of the city's losses were held by insurers outside Illinois and almost all companies within that state were forced to suspend operations. (*Fighting Fire*, 1873).

14.4 The 1872 Boston fire razed 776 buildings in an area of 65 acres, and these were largely masonry buildings of size and pretension. Rebuilding was completed in several years, despite the world-wide depression that began about six months after the fire. (*The Conquest of Fire*, 1914.)

The Royal Society of Arts in 1778 heard a paper presenting the method of fireproofing floors that had been devised by the young Lord Mahon, later the third Earl Stanhope, who long combined scientific investigations with his political career. Mahon's fireproofing relied on the fire resistance of plaster covered with a grout made by boiling together pine tar, chalk, and sand.[14] Wood laths were nailed about 1½ inches below the top edge of floor beams, and the stucco was applied to both upper and lower sides of the laths, filling the space almost to the top level of the wooden beams. Wood flooring was added above this and a ceiling of plaster was fastened to the bottoms of beams. Lord Mahon provided another dramatic display, sitting with friends in the upper room of a test structure, while a fire blazed beneath with enough heat to melt the glass in the windows.

In 1792, an organization of the most prominent London architects, originally intended only for social purposes, launched a search for means of preventing the spread of fire within buildings. Henry Holland, a foremost architect, son of a builder, and known for the sturdy construction of his buildings, led the investigation, perhaps because of his outspoken conviction that the current building regulations in London were "insufficient, unintelligible and the source of perpetual contention."[15] Two houses in Hans Place were obtained for tests much like the dramatic demonstrations that had been staged more than a decade before. Wood shavings and tar barrels were set afire in rooms protected by various fireproofing measures, principally those of Hartley and Stanhope. The fires blazed for one or two hours and both methods proved successful, limiting the spread of fire although wood was charred and plasterwork damaged. Another test proved the effectiveness of "Wood's liquid," a paint whose formula we do not know today, but which probably paralleled the alum solution that had been used on wooden beams by ancient Greeks and had served to fireproof the fabric of Montgolfier's balloon.

Holland and his committee reached conclusions that were published in 1793 as *Resolutions of the Associated Architects with the Report of a Committee by them appointed to consider the Causes of the frequent Fires and the best Means of preventing the like in the Future.* The primary causes of fires were declared to be the unwise location of fireplaces and furnaces; flames rising through stairways and behind paneling; and the liberal payments of fire insurance companies. Only in England did fire underwriters pay the amount of a policy or replace a building, even though the burned structure might have been old and ramshackle. Only in England did a fire underwriter accept the owner's claims on a building's burned contents without requiring corroboration or a prior listing. Apparently the sharp competition among insurance companies had led to terms that encouraged and even rewarded arson.

A remarkable effort to develop fireproof construction for dwellings was accomplished around 1800 when Sir Robert Peel, cotton manufacturer and father of a prime minister, built fireproof row houses for workers in his Staffordshire mill. One must assume that Peel had sound and humane reasons for taking such extraordinary precautions in the construction. Decreasing the possible damage from fire protected a landlord's investment, and the quality of housing often affected the quality of workers available. The system employed in the houses at Peel's Fazeley mill used brick vaults with concrete filled between the vaults and the roof or floor.[16] Over the lower rooms the transverse semielliptical vaults were little more than customary basement construction of the period. Above the upper story there was a longitudinal semicircular vault with a wrought-iron tie rod holding the exterior walls against the vault's outward thrust. Roof tiles rested directly on the concrete above this vault.

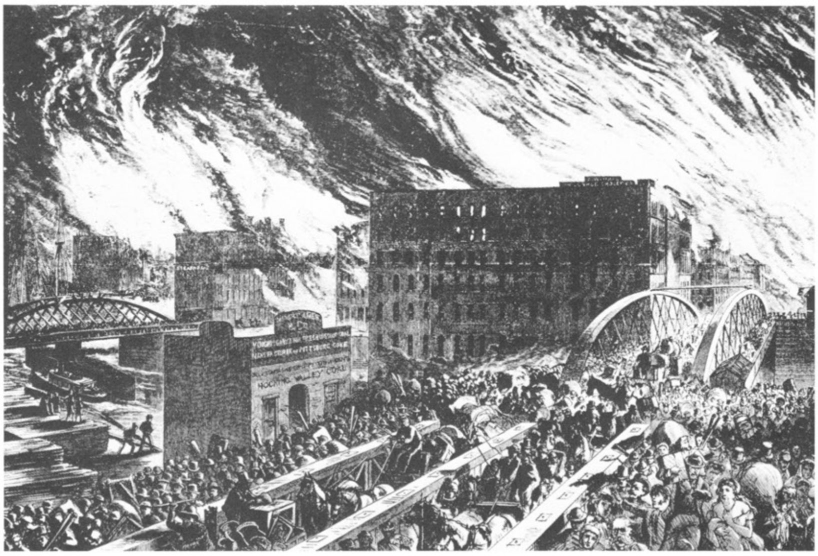
* * *

In November 1872, thirteen months after Chicago burned to the ground, Boston suffered a disastrous fire (figs. 14.2, 14.3, 14.4). The Chicago fire had been spread by strong winds, but the night of the Boston fire was calm. Panicked crowds in Chicago had handicapped all efforts to halt the flames, but Bostonians remained remarkably calm. Men had to drag fire-fighting equipment through the streets of Boston because the fire department's horses still suffered from "horse distemper," an epidemic from which most of Boston's draft animals had recovered.

A full year before, a letter published in a Boston newspaper had predicted catastrophe:

> When that dozen lumber-yards on the roof is once well on fire, it will be taken, not by little sparks only, but by cords, into and upon every building within half a mile! Every window on the line of the gale will be broken into by the fiery brands, every place where there is wood for fire to catch upon, and fires will soon be rushing from fifty of those windows or roaring from the exposed wood. . . . Then would come the story, so lately told of Chicago: "Awful conflagration! Boston in ruins! Thousands of houses and the business portion of the city in ashes!"[17]

This warning was not heeded, but it proved to be horribly accurate. In a meeting held in Faneuil Hall three days after the Boston fire, a resolution condemning mansard roofs was passed



by a large majority. One calmer participant pointed out that roof shapes were not at fault, that instead blame lay in building them of wood even when a building's walls were of masonry. Fire insurance companies then declared war on mansard roofs, forcing construction of noncombustible materials if not the abandonment of the style.

Blame was also placed on open elevator shafts and the height of some Boston buildings, beyond the reach of water from volunteer firemen's hoses. This did not cause limitations to be placed immediately on the height of buildings in Boston, but it strongly encouraged later efforts in that direction. Combined, the tragedies of Chicago and Boston led to the inception of municipal fire departments in the United States. Volunteer organizations, often more attentive to social and political interests than fire-fighting skills, were soon supplanted by municipal employees, and their equipment was modernized. In 1866 only 15 cities in the United States had steam fire engines, but ten years later the number had grown to 275.[18]

On the day following the Boston fire, Henry Ward Beecher, one of the most popular speakers in an age that admired oratory, addressed a hall of mournful Bostonians. In his opening remarks he declared:

> There is no other city that could have offered such buildings to destruction. Granite—it is a child of fire, and would seem to be able to defy the flame; but it sparkled and cracked and was destroyed as if it were but chalk. . . .
>
> Was it wise to lay the foundations of [buildings] solid, to carry up the first story fire-proof, the second story fire-proof—the third, the fourth, the fifth story all fire-proof—and then put a Mansard roof on the top of all, to take fire and scatter sparks around the neighborhood? Those great buildings were admirable for business purposes, and now, as it proves, although not intended by the architect, admirable for fire.[19]

Not only granite, the hardest stone commonly used in building construction, but other sorts of stone were found seldom to survive the concentrated heat of a building fire, especially when suddenly drenched by cold water from firemen's hoses. (It had long been a practice of New England farmers to crumble granite boulders in their fields by building a fire around a stone and then throwing water on it.) From sandstone to granite, the durability of building stones under normal conditions did not necessarily relate to their resistance to the intense heat to which they were subjected when entire business districts burned. However, it was observed that brick had performed well in both the Chicago and Boston fires.

At that time a topic of discussion among architects and engineers was the problems that arose from the expansion of material under the fierce temperatures of a conflagration. When buildings had been built of masonry and wood, the wood trusses and joists burned and fell, while heat merely caused overall expansion of the masonry. With iron beams supporting the floors, there was a real danger of the metal's expanding and thrusting outward against the surrounding walls of masonry. For a complete iron framework, with columns adjacent to or embedded in the exterior walls, expansion became even more threatening.

Cast-iron storefronts, which had been introduced at the middle of the nineteenth century, presented particular dangers. In the heat of fire, their metal cracked or melted; long before that, fire was often transmitted from building to building through the voids left between the cast-iron panels and masonry walls behind them. Those spaces should have been filled with masonry and mortar, but in practice they rarely were.

The characteristics of wrought iron were quite different. It would not crack in a fire and seldom melted, but instead it expanded, warped, bent, and twisted.

Most of Boston's mansard roofs had been built of quick-burning light wood framing, and once fire reached the roof of a building it leaped to the next. Many of the buildings that perished in Boston were reported to have burned from the top down. At all levels of the blazing buildings, window glass broke in the glare of heat and firebrands entered the openings, often setting the structure afire at all levels from sidewalk to mansard.

* * *

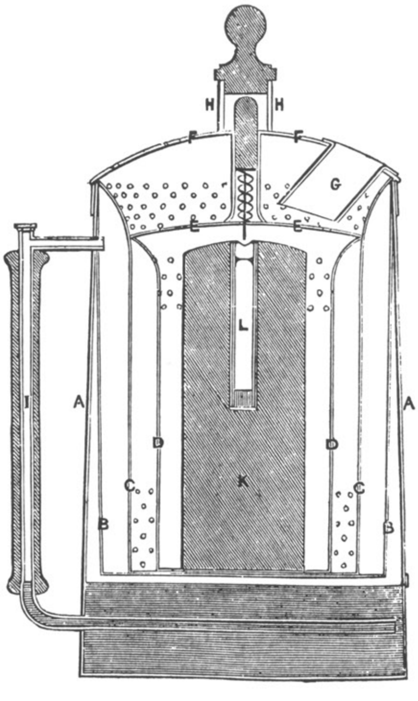
On an April day in 1723 the Lord Chancellor, Sir Hans Sloane, physician and scientist, and several other gentlemen of note gathered in Belsize Park, north of London. There a three-story wood house, filled with oil and kindling, was set afire. Once the flames ran high, Ambrose Godfrey's fire extinguisher was rolled into the fire, and with a loud explosion the fire was suppressed. Another demonstration was conducted about two months later and it is recorded that this fire was extinguished in three minutes. Godfrey's fire extinguisher consisted of a small wooden keg filled with water, in the center of which was set a pewter sphere containing gunpowder.[20] From the sphere to the top of the barrel a metal tube held a fuse by which the powder could be ignited before the barrel was rolled to the center of a fire.

There is no evidence that Godfrey's extinguisher was often used in the 20 years following those tests, but interest was revived by the inventor's son in the 1760s, when he persuaded the Royal Society of Arts to test the device. A three-room, three-story structure of brick was built in a field outside London. With the Duke of York, Prince William, Prince Henry, and distinguished scientists attending, the lower two rooms were set afire and the flames were quickly suppressed when three extinguisher kegs were rolled into the building. The experiment was repeated with fire in the second story, and again in the topmost room. All these tests were successful, but there is no evidence that such extreme measures were particularly popular.

In 1844 a fire extinguisher better suited to stopping flames before they became a conflagration and without broad damage to the surroundings was patented by an Englishman, H. Phillips (fig. 14.5). He patented an improvement on the device five years later, and soon the chemical extinguisher was accepted in its home country and the United States. A "portable machine for domestic use," Phillip's design consisted of a metal cylinder whose diameter was about half its length. Its action was activated by pushing a spike that broke open a small vial of sulphuric acid.[21] This acid flowed into a bottle of chlorate of potassium and sugar, which caused combustion, the products of which fell on a surrounding block formed of a mixture of charcoal, potassium, and a bit of gypsum. This in turn produced intense heat and a violent expansion of the gases in the vessel, which was filled with water. The steam produced by these chemical reactions issued from a hose attached to the extinguisher.

Carbon dioxide extinguishers were brought into use during the 1860s. One of the first was patented in France by Carlier and Vignon, but all were similar. In them a container of sulphuric acid was poured into a solution of water and bicarbonate of soda, either by inverting the entire extinguisher or by pulling a plunger that opened the bottle of acid. The soda and acid combined to produce quantities of carbon dioxide gas about 300 times the original volume of water, and the formation of this gas produced sufficient pressure to shoot gas and water out of the extinguisher with considerable force. A large version of this device was built for the fire department of New York City, and in its trials the stream of gas and water was driven as far as 250 feet through the hose and 50 feet beyond the nozzle of the hose.[22]

For two sound reasons the owners of textile mills often led in investigating ways of preventing and extinguishing fire: the mills were veritable tinderboxes, and capital investments in buildings and machines were sufficiently large to justify expenditures for preventive measures. An atmosphere filled with floating particles of lint, lighted by oil lanterns, gas burners, or electric arc lamps, made fire a constant threat. Heating was customarily provided by pipes containing exhaust steam from the factory's engines, and valves in that system could be opened to release hissing jets of steam into any portion of the mill in which fire was detected. Where floor areas were relatively small, this precaution was sufficient, but in larger mill buildings it appears to have been of little value.[23] An obvious improvement, encouraged by underwriters, was the English manner of installing parallel runs of perforated water pipe at the ceiling level. By turning a valve, water from a tank atop the mill's hoist tower could be sprayed over a given area of the mill. By 1859 perforated pipe sprinklers were required in Lowell, Massachusetts, for any part of a mill having particular susceptibility to fire, but in other locales they were usually installed only in the highly flammable picker buildings, where bales of cotton were broken open and debris was blown out of the cotton with air jets.



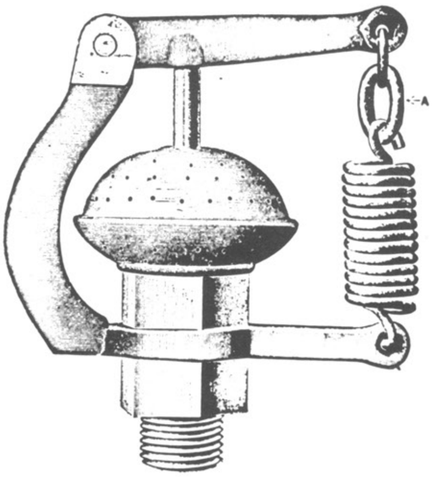
14.5 Phillip's Fire Annihilator had a handle on the side, from which issued the hot gases generated by chemicals and the steam from a water-filled jacket. (*Illustrated London News*, 8 September 1849.)

14.6 The first automatic sprinkler installed in the Parmalee piano factory was activated by heat melting a metal ring (*A*). Once the lever at the top was no longer held by the spring, water pressure in the valve raised the lever and filled the perforated sprinkler. (G. Dana, *Automatic Sprinkler Protection*, 1914.)

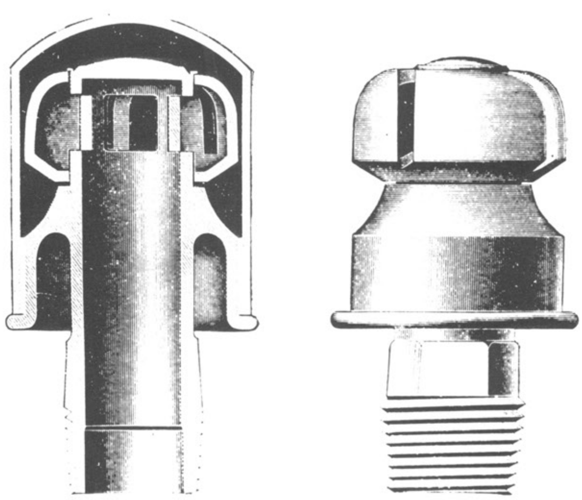
14.7 In one of the most popular sprinklers around 1880 a brass cap was soldered over the slotted spinner. A disadvantage of this design was the tendency of the water inside the cap to conduct heat away and thus delay the solder's melting. (G. Dana, *Automatic Sprinkler Protection*, 1914.)

14.8 A sprinkler introduced early in the 1880s replaced the perforated head with a jet of water that was directed against a deflector above it. The valve was kept shut by two levers held together by a clip of fusible material. (G. Dana, *Automatic Sprinkler Protection*, 1914.)

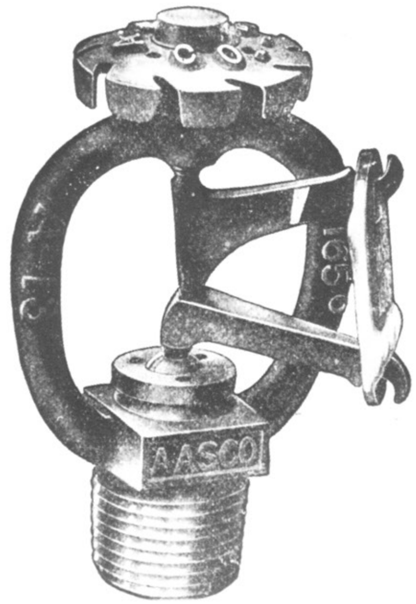
A system of automatic sprinklers was offered for sale in 1875 by Henry S. Parmalee, a piano manufacturer in New Haven, Connecticut. Overhead piping was laid out in the same manner used for perforated pipe sprinklers: a water pipe crossing the factory space in the center of each structural bay, fed from a main along one side wall of the building. The automatic sprinkler, as it developed through several years, consisted of an outlet from the pipe, capped with a small grooved button that whirled as water passed, showering a fine spray over an area of about 100 square feet (fig. 14.7). Over this was soldered a brass cover. When the temperature reached about 160° F the solder melted and water pressure blew the cap away, letting the spray soak the fire area. It took some time to heat the brass cover to the temperature required, but there was no danger that a forgetful or frightened worker might fail to open a valve.



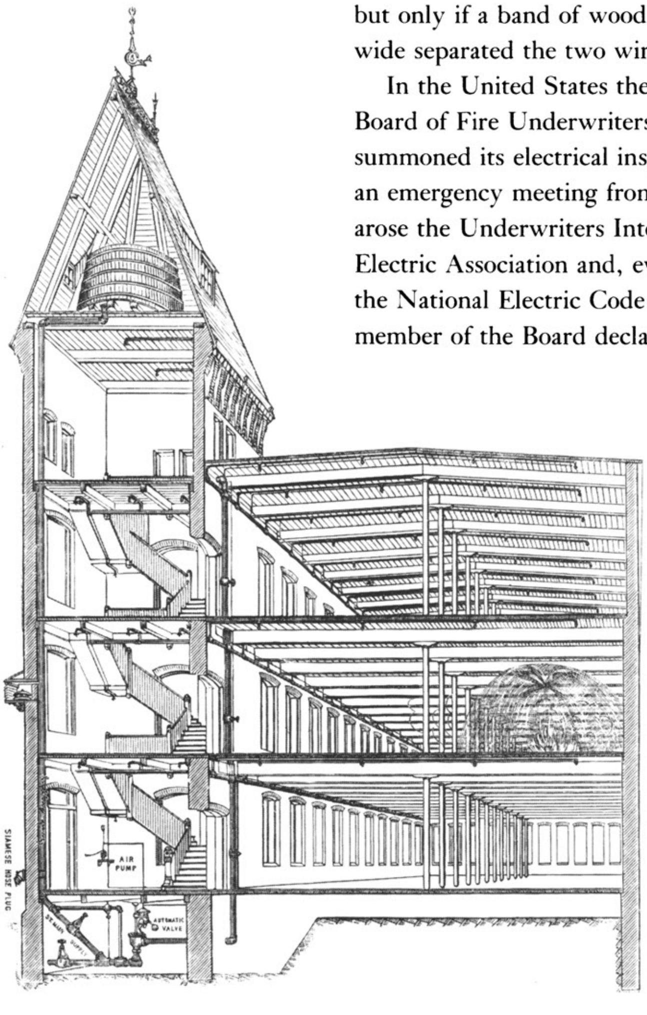
Within five years of Parmalee's introduction of his automatic sprinkler there were 18 other types on the market (fig. 14.8). Fire insurance authorities soon discovered that of almost 1,000 mill fires, about 80 percent occurred in mills without automatic sprinklers, and the average loss in those instances was about 16 times the average for mills equipped with automatic sprinklers.



The convenience of illumination has always been accompanied by a threat of fire. Whale oil lamps might overturn, and later illuminants, such as camphene, coal oils, and kerosene, were so volatile that explosions were frequent. Gas lighting too had obvious dangers. By the turn of the century, Buffalo, New York, required at least 3 feet between a ceiling and any gas burner, 18 inches when a protective shield was provided. The New York Charter required globes or other glass surrounds for all gas burners in "theaters and other places of public amusement, manufactories, stores, hotels, lodging-houses, and in show-windows."[24]



The introduction of electric lighting did not entirely eliminate the danger of fire being caused by an illuminating system. When textile mills began to install them in the 1870s, arc lamps led to 23 fires within half a year. Fluctuations in current supplied to arc lamps could cause bits of the lamps' carbons to fly off, and imperfections in the quality and consistency of the carbons could cause



14.9 This 1889 catalog shows a sprinkler system installed in a typical textile mill building. Although the work space of the mill maintains the flat-roofed form of slow-burning construction, a romantic tower holds a water tank that feeds the sprinklers. The spray of one sprinkler is shown at right. (Insurers' Automatic Fire Extinguisher Company, *Automatic Sprinklers for Extinguishing Fires*, 1889.)

them to break or scatter sparks. The Brush Electric Company placed asbestos trays at the bottom of the glass globes around their arc lamps, and other manufacturers employed an assortment of guards to prevent sparks and flaming shards of carbon coming near flammable materials.

Less risk came from incandescent lighting, and it must be remembered that electricity, unlike gas and kerosene, does not add fuel to the flames it might cause. At first, caution was the rule. According to the regulations published in 1882 by the Phoenix Assurance Company, an English fire insurance firm, wires for lighting were required to be insulated and installed with no less than 2½ inches between the two wires serving a fixture. In "non-hazardous" buildings, wires could be covered by a wood molding, but only if a band of wood 1 inch wide separated the two wires.[25]

In the United States the National Board of Fire Underwriters in 1892 summoned its electrical inspectors to an emergency meeting from which arose the Underwriters International Electric Association and, eventually, the National Electric Code. One member of the Board declared:

> We cannot assume that the most reputable merchants have all at once become criminals. We find that our better class of risks is burning in a greater ratio than ever before, and that there are mysterious causes at work. . . . That mysterious element I believe to be electricity. . . . When we consider the appalling increase in fires during the last eighteen months we may well be startled. We are standing, I repeat, in the presence of a mysterious element which no one is at present able to fathom.[26]

Such anxiety was understandable, for, according to an insurance journal, between 1890 and 1900 the number of electrical fires per year grew six times as great, and the financial losses rose to almost 6½ million dollars. By 1900 U.S. fire underwriters had mounted a powerful campaign for adoption of the National Electrical Code. In 1893 a laboratory had been established in Chicago to advise on the dangers that might be involved with the electrical lighting installed for the Columbian Exposition, the first large public gathering to be lighted with electricity. This pioneer effort became the basis for the National Underwriters Laboratory.

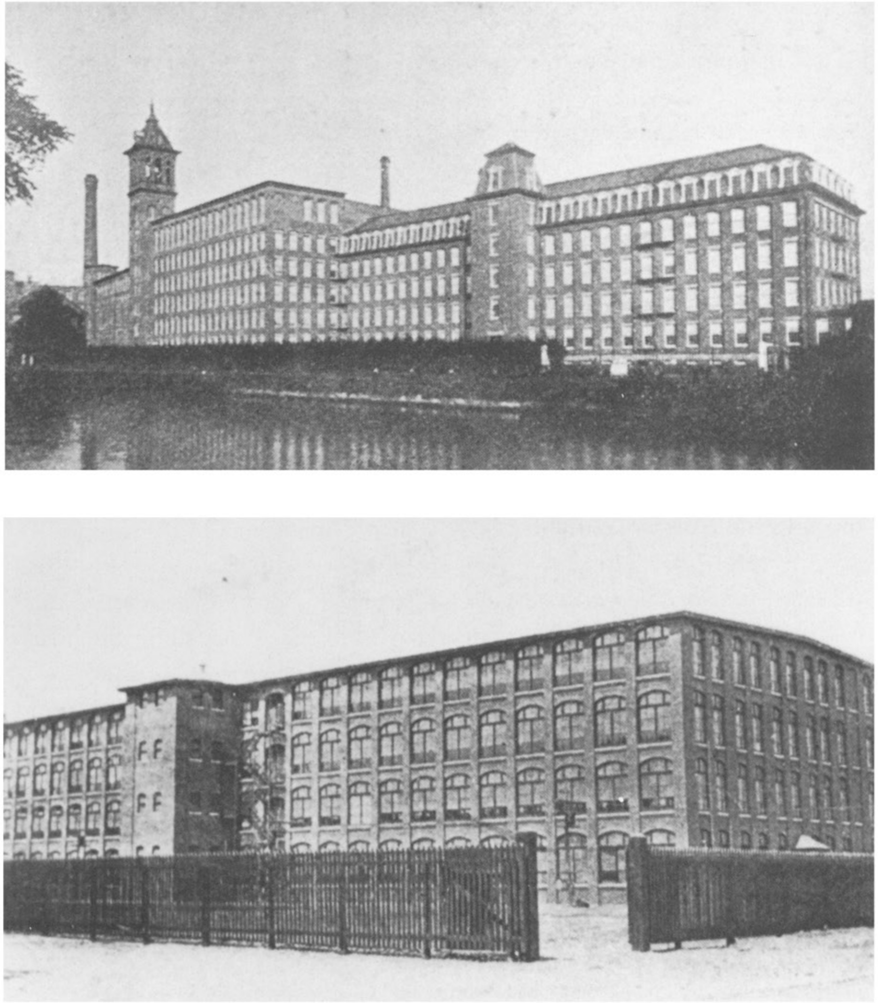
* * *

New England owners of textile mills found early in the nineteenth century that their own efforts to make their mills less combustible did not bring corresponding reductions of insurance rates. Resentment led to the formation in 1835 of the first factory mutual fire insurance company in the United States. Under a mutual company, fire losses were recompensed by payment from funds contributed by all members or, in extreme cases, by assessments made on all member companies; therefore, mutual companies were more strongly motivated than proprietary companies to discover methods of fire prevention and to provide favorable rates to their members who employed those methods. Edward Atkinson, who had been an official of several textile companies, became a leader in the development of factory architecture while president of the Boston Manufacturers' Mutual Fire Insurance Company, a position to which he was elected in 1878. A large man, characterized as "positive often to the point of obstinacy," Atkinson campaigned to improve the construction of factory buildings, although his manner of presenting his opinions alienated many architects and drew biting rejoinders from his opponents.

Basically, Atkinson attacked a method of building developed "after the pestilent invention of the buzzsaw," a method that consisted principally of "destructible granite, exposed iron and light wood."[27] Ample evidence was cited to show that the intense heat of a fire caused stone to crumble, melted or twisted iron, and fed upon the multitude of small wooden members. It was found in one period that the majority of mill fires were being caused by overheated oils on machinery, and research to determine standards for lubricants was thereupon funded at the new Massachusetts Institute of Technology. When kerosene began to replace other oils for lighting, Atkinson sent out a warning that all kerosene should be tested and a flash point of 124° F or higher should be required. Many factories had installed iron fire doors that twisted and sometimes melted during a fire. New metal-clad doors of heavy wood were strongly recommended by Atkinson, who invented a device by which they closed automatically when heat melted a soldered connection. He also strongly favored the use of automatic sprinkler systems. With the authority of the insurance rate schedule, Atkinson was able to press for conformity among the owners of factory buildings that his organization insured; others he lectured, chided, and reprimanded with unrelenting passion.

Though economical and strong, the American system of wood frame construction had faults, as John Wellborn Root pointed out: "The bonfire thus carefully prepared has the peculiar merit of having each stick of wood provided with its own flue and draft."[28] Edward Atkinson's principal prescription for industrial buildings was "slow-burning" construction, now more commonly known as mill construction. For this system of building, cast-iron columns and masonry piers were replaced by heavy timber columns; iron beams and light wood joists were supplanted by large wood beams; and floors were made of thick wood planking. In the construction of mills, stylish roofs of turrets, mansards, and gables gave way to flat roofs, also built of heavy wood planks (figs. 14.10, 14.11). The advantages of this system of factory and warehouse design lay in the fact that heavy timber construction burned slowly and remained capable of supporting its load even after a considerable amount of the wood had been charred by a fire. Even with mill construction, subsequent decisions could negate those advantages, and in 1891 Atkinson wrote:

> Architects who are not conversant with all the rules of safety prescribed by the mill engineers have adopted the heavy timbers set wide apart and the thick plank floors covered in by a solid and suitable roof; but they have then converted these primary elements of slow combustion into very quickly combustible buildings, first, by connecting floor with floor by open stair-



14.10 **With the introduction of slow-burning mill construction, the complex silhouettes of mansard roofs and towers (top) were succeeded by a more severe outline and roofs that were nearly flat (bottom). (E. V. French, *1860—Fifty Years—1910*, 1910.)**

14.11 **A drawing of typical slow-burning construction shows heavy rafters (10 by 12 inches) and floor beams (10 by 14 inches). Echoing the principles of skyscraper construction, Atkinson insisted that "the mill should hold up the walls, rather than that the walls should support the mill." (*Engineering Magazine*, November 1891).**

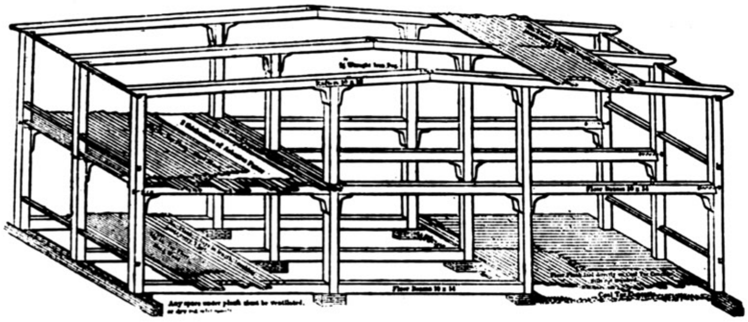
14.12 **Twenty years of tests on the relationship of heat and the strength of iron and steel were summed up in a graph published by the British Institution of Civil Engineers in 1890. (*Minutes of Proceedings, Institution of Civil Engineers*, 1890–1891.)**

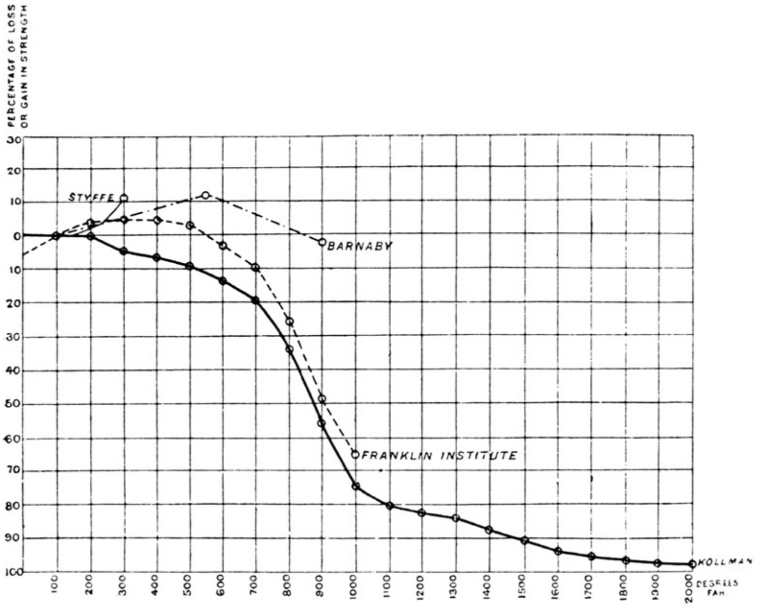
> ways or stairways sheathed with wood; second, by sheathing the walls of the lower stories and sometimes the whole building with wood; third, by setting up partitions containing many cords of light wood; and lastly, making the most fatal mistake of all in finishing the woodwork with ordinary varnish, over which a fire runs with the rapidity of a race-horse.[29]

Steel construction too had dangerous reactions to fire. William Fairbairn, a Scottish engineer, was one of the first to study the behavior of iron and steel when subjected to changes of temperature, although his tests were narrow in scope. For instance, plate iron had been found to suffer little change in strength until it was raised to a red heat, whereupon its strength rapidly decreased. Studies made by the Franklin Institute in the 1880s supported previous findings that upon reaching a temperature around 400° F iron bars began to lose strength quickly, only a third of the strength remaining once the temperature had reached 1,000° F.[30] With the advent of iron construction it soon became evident that, although the material was incombustible, iron structures were not to be relied on at high temperatures (fig. 14.12). Since the advantages of iron and steel construction were obvious, it was necessary to find ways by which structural members could be protected.

In England the prevalent method of protecting columns was to form concrete around them, using a wire mesh to reinforce it. After its introduction around 1889, expanded metal lath was employed as reinforcement for concrete fireproofing and as a base for plastering on the underside of floor construction. In the United States the protection of structural frameworks was long dominated by the use of hollow terra-cotta tiles, shaped to fit around the steel members (fig. 14.13).

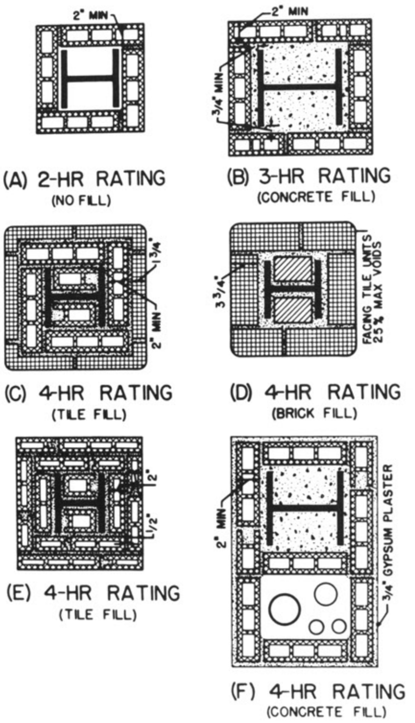
Expert opinion on fireproof construction at the end of the nineteenth century was summarized in the pamphlet *How to Build 'Fireproof'* by Francis C. Moore, an insurance official in the United States. Published in 1898 by the British Fire Prevention Committee, Moore's paper set about informing his British readers of practice in the United States, because "the general introduction into the Metropolis [London] of what are termed 'frame buildings' as used in America for warehouses and offices, cannot be far distant."[31] Moore was insistent about the need for covering structural metals: "All ironwork, columns and pillars, beams and girders, should be 'fire-proofed,' *i.e.*, covered with at least 4 ins. of incombustible material, terra-cotta or brick. . . . Brick-work is a good covering but porous terra-cotta, or even wire lath and plaster, may prove effective. Where wire lath and plaster is used, the column should first be wrapped with quarter-inch





14.13 A handbook of the 1960s illustrates typical column fireproofing methods and their fire-resistance ratings. The rating corresponds to the protection provided around metal columns in terms of the time during which adequate protection might be expected. (H. C. Plummer, *Brick and Tile Engineering*, 1962.)

14.14 This stack of typical terra-cotta fireproofing shapes includes pieces meant to protect round columns, several with recesses to fit around the flanges of I-beams, and skewed shapes for use in flat-arch floor systems. (*Insurance Engineering*, September 1907.)



(A) 2-HR RATING (NO FILL)

(B) 3-HR RATING (CONCRETE FILL)

(C) 4-HR RATING (TILE FILL)

(D) 4-HR RATING (BRICK FILL)

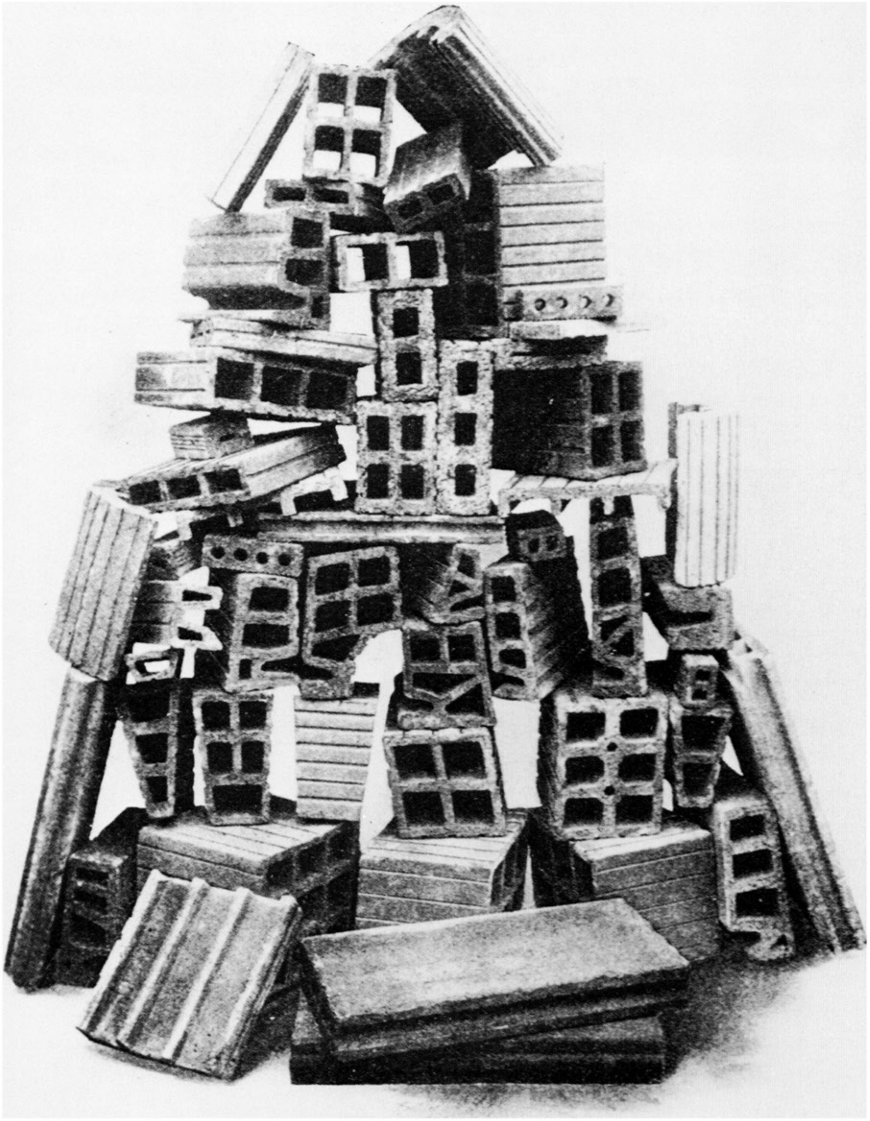
(E) 4-HR RATING (TILE FILL)

(F) 4-HR RATING (CONCRETE FILL)

asbestos, bound with wire. This would prove reliable and inexpensive."[32] Porous terra-cotta was made by mixing such materials as sawdust or hay with the clay from which hollow tiles were to be made (fig. 14.14). The high temperatures of the kiln burned away those materials, leaving a terra-cotta that was light and could be sawed and nailed. Hence, the product was sometimes referred to as "terra-cotta lumber." Terra-cotta's light weight led many to question its adequacy as fireproofing. Moore pointed out that when the ten-story Leonard Building in Detroit, Michigan, had burned in 1897, "as fast as the columns or wall girders were warped by the heat the tiling dropped out like loose bricks."[33] A similar report came from the ruins of the Pittsburgh fire in the same year, where expansion of the heated building frames had caused the bottom faces of terra-cotta floor arches to scale off. Although popular because of its low cost, wire lath and plaster was always considered questionable protection for structural metal. In 1896 a New York building in which wire lath and plaster had been used to reduce the area occupied by columns, thereby gaining the last bit of rentable floor area, was quoted an insurance rate 15 percent greater than that for buildings with columns surrounded by brick or terra-cotta.[34]

More costly than office building fires were those in department stores and multistory warehouse buildings, where both the structure and the merchandise were lost. A New York architect, F. H. Kimball, recommended that in buildings where merchandise was stored the first-floor columns should have a double jacket of fireproofing with a 2-inch air space between them. However, most experts opposed any hidden spaces—no matter how small—within which fire could rapidly extend itself. Warnings were given to provide blocking in the vertical shafts left for piping or wiring. Investigation of fires showed that protective walls and floors meant little if they were penetrated by even small openings.

Often the heat from a blazing building would crack windows across the street, but in the 1889 Thanksgiving fire in Boston the collapse of a nearby building blew in the large glass show windows in the front of the Ames Building, and the structure was quickly enveloped in fire. Flames in the lower floors of a building could leap out windows and enter the windows above. Around the turn of the century, New York required that any building over two stories high and not



more than 30 feet from another building should have metal shutters on all windows above the ground floor and that the shutters be closed each night.[35] Similar regulations were proposed for London, but they were not made part of the Building Act.

City regulations were often strengthened in response to fires in which large numbers of people were threatened. In 1847 the German theater in Budapest, one of the city's largest buildings, was razed by flames that started in its new heating system. This conflagration, luckily occurring when the theater was empty, came shortly after theater fires in Karlsruhe and Stuttgart, and German architects quickly responded by proposing legislation that would dictate the number, location, and size of exits from theater seating.

Lighting was essential to the theatricality of performances, and the introduction of gas illumination did little to make a stage area less dangerous. In England it was reported that the 69 theater fires of the 1850s were followed by 99 in the 1860s and 181 in the 1870s.[36] By the 1880s deaths in theater fires averaged 187 per year. Many of the larger British cities required fireproof curtains between the stage and the audience before a

14.15 Although terra-cotta blocks that fit around I-beams' flanges were widely used (top), the floor construction indicated in the lower drawing was often recommended. Deeper blocks reduced the concrete required, which reduced both weight and cost, and small reductions in floor thickness were advantageous when accumulated through 20 or more floors of office building construction. (*Engineering Magazine*, October 1892.)

theater was licensed to operate, although their building regulations contained no such requirement. With gas lighting, glass chimneys and protective gratings provided a degree of safety, but accidents were almost as inevitable on stages as they were in textile mills. The French world of ballet was shocked in 1862 when Emma Livry, the rising star of the Paris Opéra *corps de ballet*, was enveloped in flames as her tutu touched a backstage gas flame. Her lingering death only served to emphasize the dangers that lay behind the proscenium. Most theater fires could be attributed to faulty lighting. A backstage light started a fire in a theater in Vienna's Ring area during a performance of Offenbach's *Tales of Hoffman* and, although the proscenium of the theater was outfitted with an iron curtain, it was not lowered soon enough to prevent flames trapping those who were seated in the balconies.

Six years later the Opéra-Comique in Paris burned during the first act of *Mignon*. The official reports listed only 77 fatalities, but an additional number died after weeks of suffering. A public prosecutor claimed that the fire had been started when a poorly placed stage light with a damaged protective grating came in contact with cluttered pieces of scenery. The building engineer failed to lower the iron curtain and firemen panicked in the face of the flames. Exit in one direction was seriously limited by a revolving door the theater management had installed in response to patrons' complaints about drafts of cold night air.[37] More than a year later Paris authorities enacted new regulations for theaters requiring the use of electric lighting, incombustible materials, sprinkler systems, and improved emergency stairs, including external stairs. Several years before the fire in the Opéra-Comique, comparative studies had been made for the Paris Opéra, Charles Garnier's building of the 1860s. As a result of this investigation, 7,455 gaslights were eliminated in that building and were replaced by 18 arc lamps on the building's facades and 6,131 Edison incandescent lamps inside.[38] Nevertheless, a British committee reported the Opéra's stage to be one of the most dangerous in Europe, a height of 13 stories in which hoses were provided with water pressure of only 70 pounds.

The accounts of theater fires form a somber litany of accidents, neglect, and indifference. Disaster was usually required before stronger regulations were enacted and enforced. An investigation of London theaters by the Royal Society of Arts in 1883 showed that almost all of the city's theaters used scenery treated with some chemical preparation that might lessen the danger of fire, usually having a borate or silicate as its basis. Electric lighting was adopted rapidly by theaters, for it offered advantages in staging as well as safety.

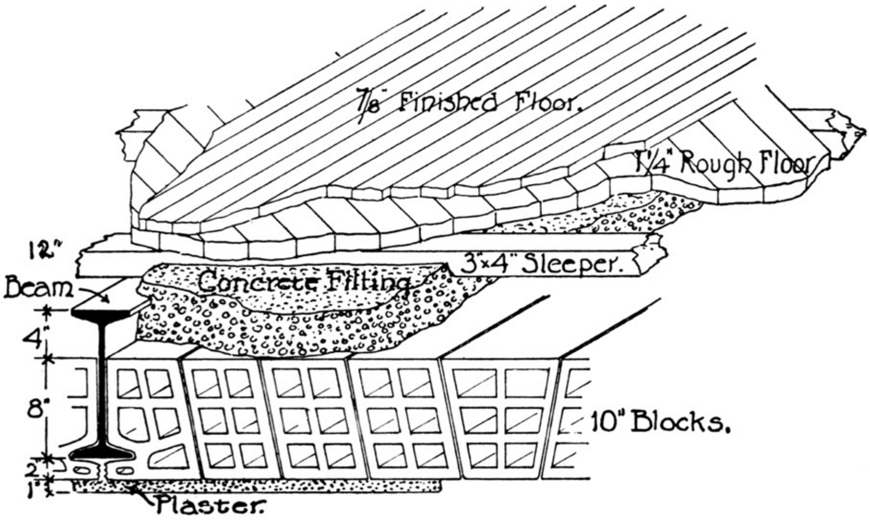
One of the most influential fires of the nineteenth century took place in the Iroquois Theater in Chicago during a matinee performance of *Mr. Bluebeard* during the Christmas season of 1903. The theater was new and soundly built, but sprinklers above the stage were not yet operable. At the end of the second act, when lights had been adjusted for the song "In the Pale Moonlight," sparks issued from an uncovered arc light. As the scenery caught fire, stagehands unsuccessfully used tubes of Kilfire, a powder extinguisher, which were hung about the stage area. The fireproof curtain was lowered but jammed before reaching the stage floor, and, as fleeing actors left by the only stage exit, the draft of outside air blew flames under the curtain into the auditorium. Ventilators above the stage were inoperable. While most of the audience seated at ground level escaped, those in the balconies and boxes were trapped. Over 570 died, and many others were trampled on stairs and in hallways.

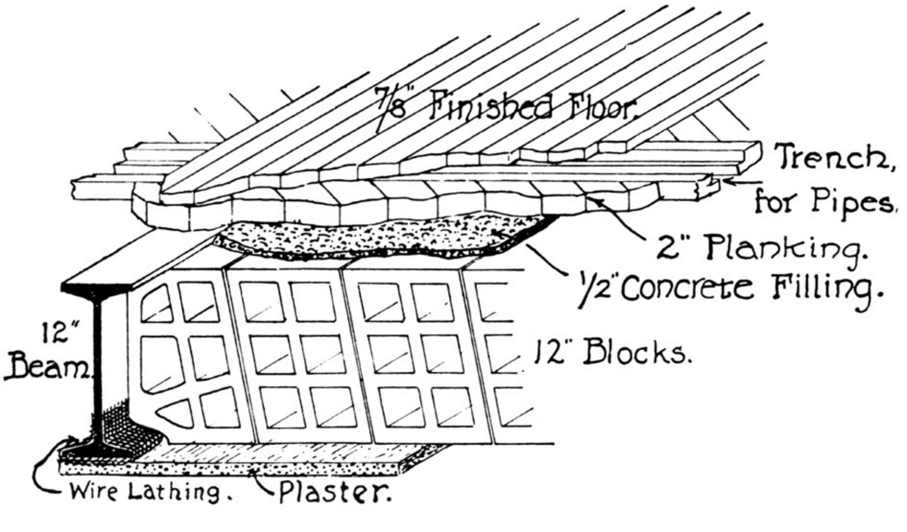
The horror of the Iroquois Theater fire moved officials in Chicago and elsewhere to look more closely at their regulations and inspection procedures. As in most theater fires, no single factor could be blamed. It was necessary to view all precautions as parts of an interrelated system, the failure of any one part capable of proving the others inadequate.

Fortunately, most theater fires occurred before and after performances, when audiences were not present but fewer actors and stagehands were present to notice flames in time to extinguish them. Electric lighting, sprinkler systems, and advancing regulations regarding exitways led to some amelioration of conditions, but theater fires in the 1870s were almost three times as many as in the 1850s.[39] It became evident that the principal precaution that could be taken was frequent inspection and stricter enforcement of the laws that were being enacted to control the design of theaters.

* * *

During the nineteenth century the professional press principally con-





14.16 Hotels, apartment buildings, and theaters were often touted as being "fireproof" because their principal materials were incombustible. Frequent fires in "fireproof" structures made such advertising another symbol of the greed and deceit attributed to real estate investors. (Bettmann Archive.)

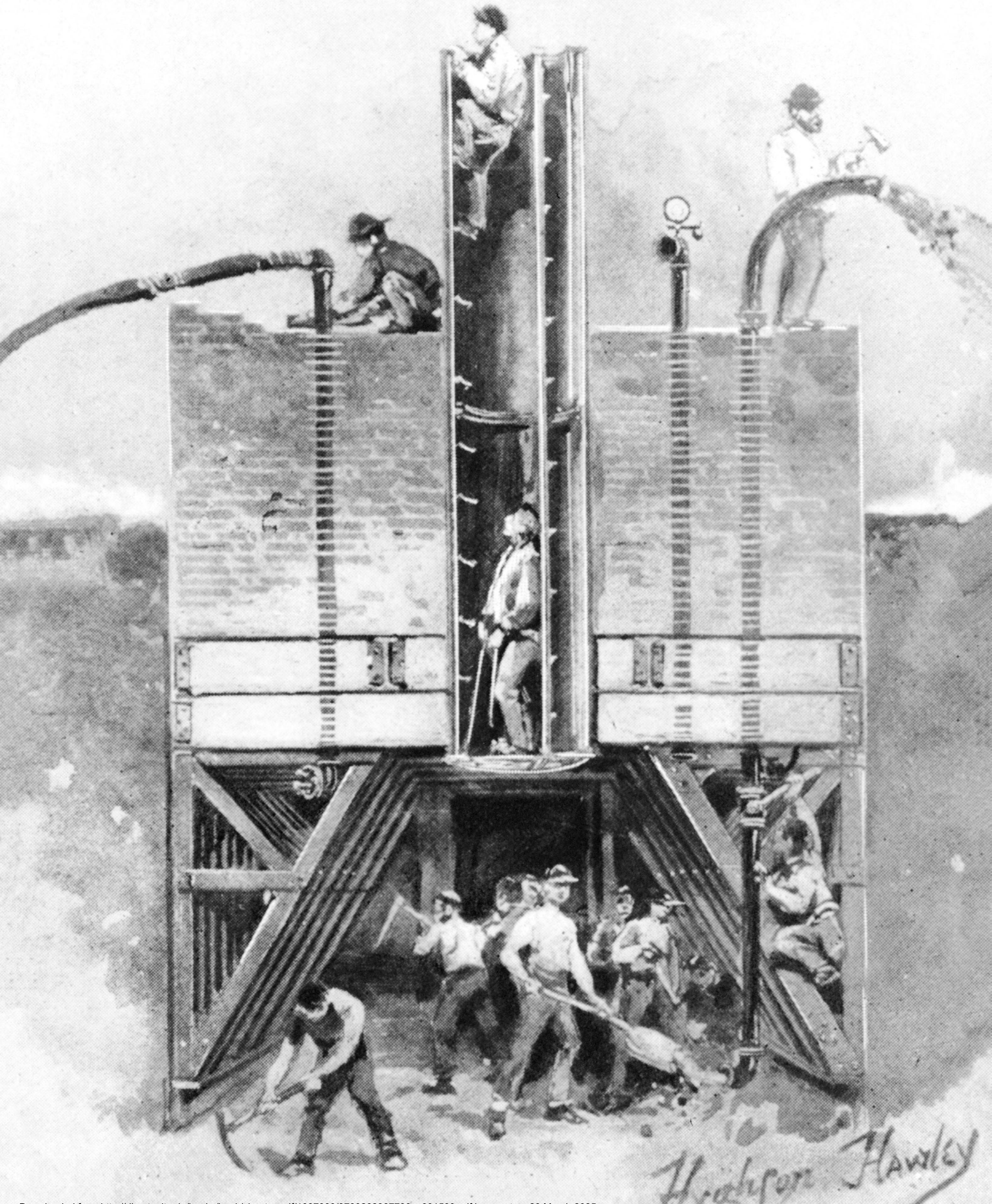
cerned itself with fireproofing buildings, in terms of reducing the way in which they might catch fire or be damaged by fire. Little attention was given the problem of insuring means of safe exit for the occupants of buildings. In this regard a speaker before the Royal Institute of British Architects pointed out early in the twentieth century that "experience in all countries had indicated that the remedial measures must in the first instance be indicated by the public authorities. Private enterprise in this matter has not been satisfactory."[40]

It was reported in 1898 that the Berlin Building Act required that any tenement or commercial building of four or more stories have two enclosed stairwells and that no part of the building be more than 100 feet from a stair.[41] In 1905, amendments to the London Building Acts allowed city authorities to require satisfactory means of escape in both old and new buildings, but there were so many offending structures that the requirements were not enforced.[42] Cities in the United States, according to an English insurer reporting on his tour of the eastern states in 1902, had found no consensus and presented a variety of regulations.[43] For purposes of fleeing a fire, buildings at that time often contained such provisions as ropes, canvas chutes, and wire ladders. The exterior iron fire escape, peculiarly American, included types having ladders from level to level, which merited the criticism that "only athletic and cool-headed men could be expected to descend such a contrivance."[44]

Installation of fire escapes with iron stairs was a common method of improving precautions in existing tenements and factory buildings. In some cities' codes the provision of fire escapes could do much to reduce the requirements for stairways within a building. Fire fighters considered external fire escapes to be a good form of exit and also a useful method for their gaining access to fires. At one time the Chicago building ordinances required that fire escapes be provided at each level with standpipes into which firemen could fit hoses. New York authorities in 1902 demanded that all new stores, factories, and hotels of 2,500 to 5,000 square feet of floor area should have two stairways. It was not required that these stairs be enclosed, but if they were enclosed exterior fire escapes might not be insisted on. No such requirement was imposed for office buildings, though they were on the whole taller. Chicago and other cities had ordinances that were similar. In searching through published plans of the major skyscrapers of the period, one finds that until World War I it was common for buildings as high as 25 stories to have only a single unenclosed central stairway. It was also common to have only ornamental grillwork closing elevator shafts from corridors on every floor.

At the beginning of skyscraper construction, enthusiasts spoke of such buildings as cities within themselves and elevators as thoroughfares turned on end. The simile unfortunately also applied to the dangers of fire. Crowded as a walled medieval town and almost as combustible, skyscrapers had few gates through which their inhabitants could escape, and the vertical thoroughfares could act as chimneys filled with flames and smoke. The assumption that buildings could be made fireproof was repeatedly disproved by events. But tall buildings were born from the urge to gain maximum profit from a restricted area of land, and confidence in fireproofing may well have been encouraged by economic considerations. Probably the most realistic attitude is

that of a civil engineer writing in 1890 on the subject of "Fire-proof Construction": "It is intended that the word 'fire-proof' shall apply to any materials or combination of materials which have been designed to resist the action of fire; whether successfully or not is immaterial. A comparison between various structures or materials can thus be instituted, and one can be described as being more, or less fireproof than another."[45]


Hughson Hawley

Technics and Architecture

The Development of Materials and Systems for Building

OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

15

Structural Engineering

1586	Fundamentals of graphic statics published by Simon Stevinus
1638	Galileo Galilei presents his explanation of beam action
1678	Robert Hooke publishes theory of elasticity
1757	Publication of the first of Leonhard Euler's papers on the buckling of columns
1775	The engineering program of the Ecole des Ponts et Chausées is reorganized
1776	Charles Augustin Coulomb states the conditions governing strength of beams
1857	Theorem for continuous beams published by B. P. E. Clapeyron
1865	David Kirkaldy's testing establishment opens
1882	Grillage foundations constructed for the Montauk Building, Chicago
1893	Pneumatic caissons used in constructing foundations for the Manhattan Life Building, New York
1932	Moment distribution introduced for the design of building frameworks

15.1 The skill of medieval architects was such that they could propose artful conceits, as shown in the handbook prepared by Villard de Honnecourt in the thirteenth century. In the pair of arches, joints of the stones in both are aligned toward a point on the center support. Hence, the stones act as a single arch and would remain stable after removal of the wood column. (Drawn from the *Album of Villard de Honnecourt*, circa 1235.)

Structural design must balance the realities of construction practices and the discipline of structural engineering. The former is largely empirical, based on experience gained in building and the skills of the building crafts. The latter, usually expressed in mathematical terms, is founded on theoretical knowledge, experience, and the profession's responsibility for public safety. To clarify the nature of structural design, let us consider a simple formula that is used to determine the size of an evenly loaded beam needed to support a floor area:

$$\frac{(L + D)\,l}{8} = fS$$

where:

L = live load of the supported area, the estimated maximum weight of fixtures and occupants, as set in regulations;
D = dead load of the supported area, the calculated weight of building materials;
l = distance spanned by the beam;
f = allowed stress for the material according to regulations, as determined by tests and adjusted by a factor of safety;
S = section modulus, a function of the cross-sectional shape of the beam.

The left side of the equation describes the conditions imposed on the beam, and the right side determines the resistance of the beam. On both sides there are factors that can be determined with considerable accuracy (D, l, and S). On both sides there are factors arising from the theoretical understanding of the conditions imposed on the beam and the manner in which a beam responds (S and the number 8). In addition, on both sides there are factors that are adjusted by the wisdom of the engineer and decisions of official agencies in the interests of safety (L and f). This simple case demonstrates the manner in which structural engineering, as an "empirical technology," combines theoretical investigation, data, and social responsibility in its designs.

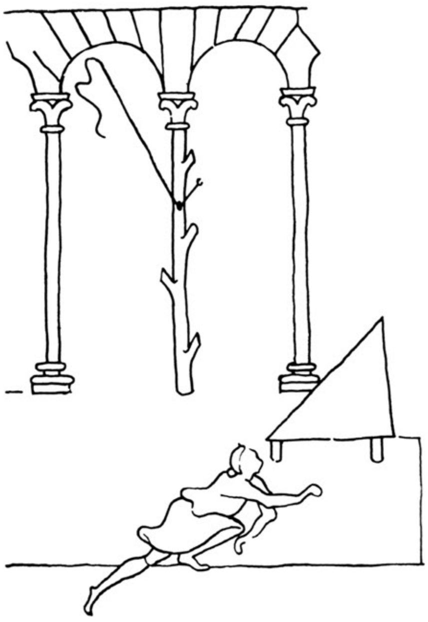
* * *

No such complexity is to be found in ancient times, when the empirical knowledge of building crafts, taught by master to apprentices, provided the tradition and theory on which structural design was based. The Roman architect Vitruvius in his *Ten Books of Architecture* compared the qualities of stone taken from various quarries and the wood of different trees. Referring to the four elements as they were understood at that time, Vitruvius characterized fir as having "a great deal of air and fire with very little [of] moisture and the earthy," because of which it is "naturally stiff, it does not easily bend under the load, and keeps its straightness when used in the framework." In contrast he viewed oak as "having enough and to spare of the earthy among its elements, and containing but little moisture, air and fire," which caused it to warp.[1] Although Vitruvius wrote at length about the traditional proportions of columns and the spaces between them, little was said of structural considerations, except for a declaration that in one style of temple (araeostyle) columns were spaced "farther apart than they ought to be" and, hence, wooden beams were required, rather than stone.[2]

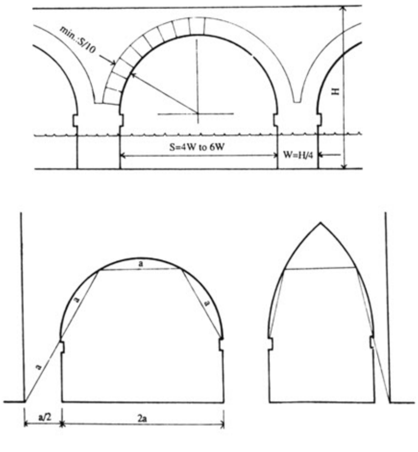
Medieval masons during their apprenticeships were introduced to the involved geometric techniques required to lay out plans and prepare the templates and models from which stonework would be cut. The traditional methods and "rules of thumb" of their craft were imparted to them as part of the mysteries of the mason's lodge, and all guild members were sworn to secrecy. The Ordinance of the German Lodge Masons (1459) required that "no craftsman, whether master or warden or fellow shall teach by means of any extract how to set up from the ground-plan to anyone whomsoever who is not of our handicraft, who has not employed his days on stone masonry."[3]

The transformation of the massive stonework of Romanesque architecture into the delicate tracery of the Gothic presents clear evidence of the powerful logic of the trial and error methods employed by medieval master builders. Without mathematical theories or predictive methods, but with great geometrical skill, Gothic builders learned to fashion stone—a material limited to receiving compressive forces and requiring careful fitting—into ribs and vaults that display a profound understanding of the action of forces within the structure (fig. 15.1). Little has been discovered to indicate medieval knowledge of elementary engineering as it is known today, and it is evident that builders of that period did not employ any form of structural analysis (if analysis is taken to mean assigning numerical values to the events taking place within a structure and the assumption of basic physical characteristics). But through experience with the actual performance of a relatively small group of structural elements (arches, vaults, ribs, buttresses, and counterweights being foremost) an impressive empirical wisdom was achieved. Still, a degree of prediction was furnished by the building process. When famine, plague, or warfare halted construction of a cathedral, the tops of walls and vaults were protected with thatch, and the stonework settled through the years it waited for work to be resumed. The appearance of cracks or the spalling of stone indicated incipient dangers, and corrections were made when work resumed.[4]

While craft traditions had sufficed for the remarkable traceries of Gothic construction, theoretical explanations were sought in the Renaissance, and at the heart of the earliest discoveries was the study of mechanics and statics. Mechanics describes the ways in which forces, gravitational and others, act on objects; and statics—as opposed to dynamics—is that branch of mechanics that considers those actions that result in equilibrium. Archimedes, who was inclined to rely more on experimental evidence than the many-layered theoretical explanations of other Greek writers on science, had arrived at the principle of the lever, although the nature of nongravitational forces is not clearly stated in his works. Despite suggestions of the subject that are to be found in writings of the scholastic period, the fundamentals of statics were not known until the Renaissance.



By the fifteenth century, knowledge of construction had escaped from the secrecy of masons' lodges and came to be published in books on architecture. Most often the controlling proportions for construction were described as the extreme conditions at which failure threatened—probably with the numbers altered to provide additional precaution (fig. 15.2). For instance, Leon Battista Alberti stipulated the dimensions of arches for a bridge: "And there should not be a single Stone in the Arch but what is in Thickness at least one tenth Part of the Chord of that Arch; nor should the Chord itself be longer than six times the Thickness of the Pier, nor shorter than four times."[5] Renaissance writers on structure did not know exactly what path the pressure within a vault took as it made its way down to a support. Indeed, engineers since that time have pursued this problem with differing assumptions leading them to a variety of conclusions. In Leonardo da Vinci's notebooks is found a drawing of a pointed arch that is loaded only at its top point, a problem simpler than the usual loading. Leonardo contended that a straight line drawn between the top and bottom ends of the outer curve of the stones of the arch should not meet the inner curve.[6] Almost two hundred years later, François Blondel proposed a method in which three equal chords were inscribed in the curve of an arch and one chord was extended an equal length to determine the required thickness of the pier that would adequately support the arch (fig. 15.2). For semicircular arches Blondel's method results in a pier whose width is one-fourth of the span of the arch, the narrowest pier that had been permitted by Alberti.



15.2 Top: Alberti's recommendations on bridge building required that the footings be half and the pier width one-quarter of the vertical distance from the roadbed to the streambed. The arches' spans could range from a distance equal to that height to one-half again as great. Bottom: Blondel's system advised drawing three lines of equal length within an arch and extending one for the same distance to determine the required thickness for a pier. (Drawing by author.)

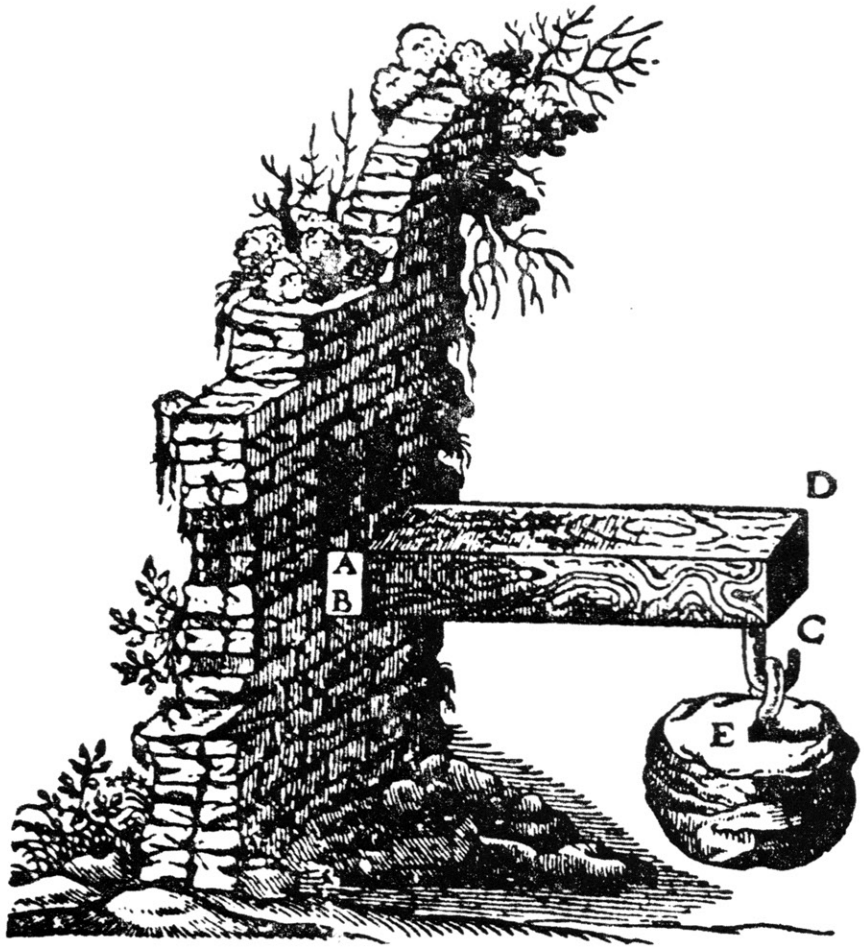
A lengthy study of structure commenced in the Renaissance, much of it focused on the construction of domes. Since they were the central and dominant architectural feature in many of the most important buildings of the sixteenth, seventeenth, and eighteenth centuries, the design of domes was an attractive and rewarding challenge to experts. Since ancient times, tie rings, superimposed masses, and buttressing to resist outward thrusts had been used to stabilize domes. Tie rings of bronze chains or linked oak timbers were the most popular method, probably because they were least likely to obscure or encumber the dramatic silhouette that architects sought when using a dome. In experiments, chains were draped to represent the curves that might be the inverted lines of thrusts, and intricate graphic solutions attempted to follow forces from stone to stone. The objective was, as with Leonardo's drawing of an arch, to make sure that the thrusts followed a path that remained within the thickness of the dome's shell. In a hemispherical dome of uniform thickness, outward thrusts begin at an angle 52° down from the vertical, but, with cupolas at the top and colonnades around the lower portion, there was significant variation of the level at which tension might be first encountered.

The notebooks of Leonardo include sketches that demonstrate his understanding of forces in terms of direction and magnitude, as they are described in modern mechanics. In his drawing of a weight suspended by two cords of unequal length, a superimposed rectangle is marked off in units that indicate the distribution of the load between the cords. In writing a prospective employer, Leonardo presented himself as an architect who knew "what is the nature of weight and of energy in force, and in what manner they should be combined and related to one another and what effect they will produce when combined."[7] However, Leonardo's studies of statics, mingled among his many ideas, are limited to speculative consideration of the topics, and apparently were neither tested nor communicated to others.

Long after Leonardo, in 1586, a Dutch army quartermaster published a book on statics; its translation into Latin in 1608 as *Mathematicorum Hypomnemata de Statica* made his knowledge of the subject accessible to scientists and mathematicians throughout Europe. Simon Stevinus acted as a tax collector before studying mathematics at the University of Leyden. His army responsibilities included superintending dikes and waterways, critical factors in Holland. Recognized as a founder of the science of hydrostatics, he also introduced the use of decimal fractions and devised methods of navigation. Stevinus was clearly aware of the principle of moments, which describes the action of levers, and of the force triangle, a fundamental means by which the resultant action of two or more forces may be determined in both direction and magnitude. By representing forces as lines drawn at slopes related to their directions and lengths proportional to their magnitudes, Stevinus provided the basis for nineteenth-century advances in graphic statics, which enables the solution of structural problems through drawings.

While the science of statics defines the nature and power of forces acting on parts of a structure, there remains the investigation of the means by which the parts or the entire structure resist external forces and maintain stability. This study, known as the strength of materials, focuses on the characteristics of the material of which the structure is built, the shape in which it is present, and the manner in which internal forces respond to forces that are imposed on the structural element.

As the dominant architectural material of early times, masonry had limited capabilities and so was relatively simple to understand. Although stone could to a degree sustain tensile stresses (those that pulled on it), there was always a lurking possibility that any stone had within it some undetected flaw, some weakening stratum created when the stone was first formed. Mortar caused one stone to adhere to another, but weathering and uneven settlement could cause hairline cracks to appear. Because of these vulnerabilities of masonry, it has usually been assumed that only compressive (pushing) forces can be effectively resisted by it, and since the time that they were developed by the Romans the spanning forms of arches, vaults, and domes have been the most common structural forms in which masonry has been used. (The outward thrusts could be counteracted by the addition of materials capable of withstanding tensile forces.) When stone was used as beams, the spans between the capitals of columns was small, in Greek temples ranging only from around 1½ to 2½ times the depth of the beam. As a precaution such stone beams were often made of three



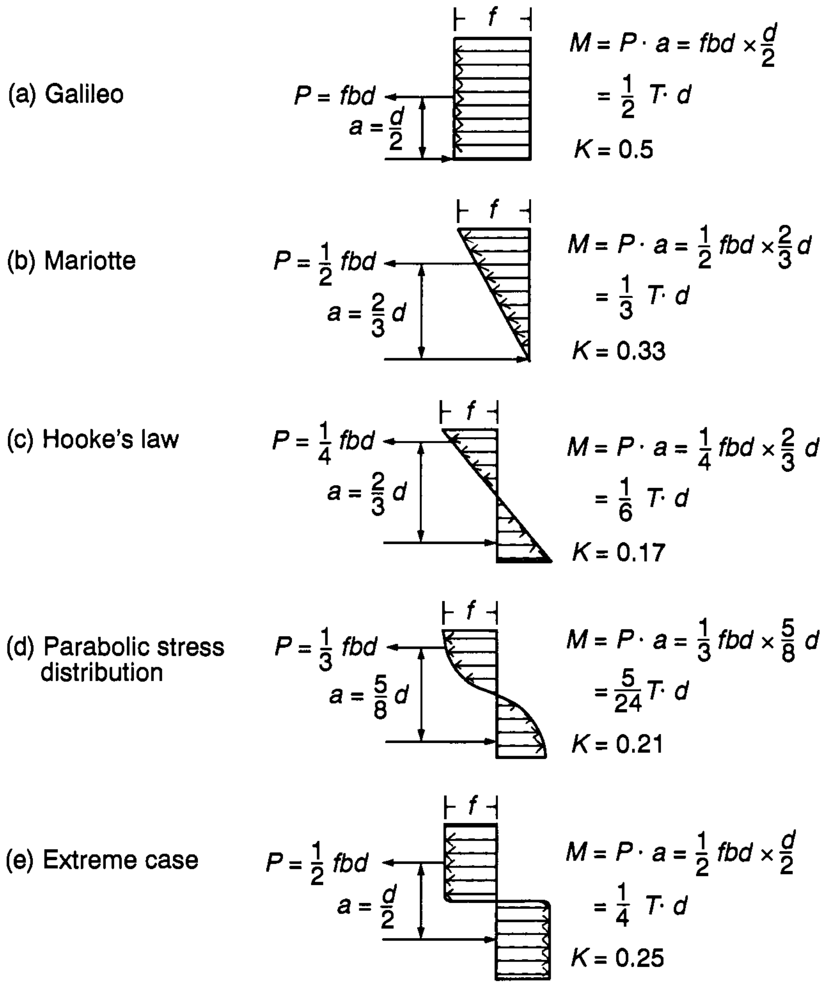
15.3 In this drawing from *Discorsi e dimostrazioni matematiche* (1638), Galileo posed the classic problem of the cantilever beam. He assumed that the beam's fibers acted around the point *B* with no variation in the intensity of their action. This results in the beam's strength being evaluated as three times that assigned by present-day theory. (Galileo, *Discorsi e dimostrazioni matematiche*, 1638.)

15.4 Arrows in these diagrams represent the relative strain on parts of a beam. Mariotte at first assumed that tensile action pivoted around the bottom of the beam, but later he recognized the significance of Hooke's Law of elasticity and designated the neutral axis at midheight of the beam's cross section. (Redrawn from *Proceedings, Institution of Civil Engineers*, 1952.)

pieces, placed side by side, so that if one should split the others would continue to support the load.

Understanding of the internal action of beams was advanced when Galileo Galilei published his book *Two New Sciences* (1638) in Holland, after he had been condemned by the Roman Inquisition for his espousal of the Copernican theory of the planetary system. The first two parts of Galileo's book present his findings regarding the strength of materials, and his explanation of a cantilevered beam reveals his insights and errors (fig. 15.3): "Fracture will occur at the point B where the edge of the mortise acts as a fulcrum for the lever BC, to which the force is applied; the thickness of the solid BA is the other arm of the lever along which is located the resistance. This resistance opposes the separation of the part BD, lying outside the wall, from that portion lying inside."[8] In other words, Galileo believed the cantilever beam was held fast solely by tensile resistance of its fibers and that they were equally stressed. These assumptions may now seem naive, but if one were confronted with a failed cantilever, all the fibers torn except the bottom slivers from which the beam dangles, this conclusion would seem more plausible.[9]

It was around 50 years later that Edme Mariotte, a French priest, physicist, and one of the founders of the French academy, concluded that fibers in the upper half of a cantilever beam would be in tension, pulling to hold up the beam, and fibers in the lower half would be in compression, pushing to support the beam. Unlike Gali-



M denotes moment of resistance under extreme fiber stress f in a beam of rectangular section

P denotes resultant longitudinal force in tension or compression

T denotes "absolute resistance" or ultimate tensile strength of the section of area $b \times d$

K denotes the ratio of M to $T \cdot d$

leo, Mariotte surmised that these two forces, tensile and compressive, acted about a level located at mid-height of the beam. He also reasoned that the strain on individual fibers would increase from zero at this axis to a maximum at the top and bottom of the beam. Mariotte's explanation of the cantilever beam initiated recognition of the fact that within a beam a distribution of tensile and compressive responses of the fibers must equal the action instigated by any load carried by the beam (fig. 15.4).[10] As Mariotte put it: "You may conceive that for half the thickness the parts are pressed together, those near the outside more than those near the middle and that for the other half of the thickness the parts are extended."[11] Mariotte's structural theories were developed from his experiments with rods of wood and glass, undertaken while he was in charge of designing a system that would bring water to the palace at Versailles. The validity of his theory of stress distribution depended largely on Hooke's Law, which was developed by experiments with springs: "It is very evident that the Rule or Law

15.5 In this 1921 graph comparing eight formulas for steel columns, the horizontal scale shows the degree of slenderness and the vertical scale shows the load allowed by a formula. Although there is some similarity among the graph lines, it should be noted that for a column with a slenderness ratio of 160 the uppermost line permits a load almost twice that shown by the lowest line. (*Machinery*, May 1921.)

of Nature in every springing body is, that the force of power thereof to restore itself to its natural position is always proportionate to the distance or space it is removed therefrom, whether it be by rarefaction, or the separation of its parts the one from the other, or by a Condensation, or crowding of those parts nearer together."[12] Therefore, for the loaded cantilever, which had become known as "Galileo's Problem," when the beam bowed under a load, its fibers were stretched (rarefaction, tension) on the convex side and were pressed (condensation, compression) on the concave side. And the same would be true for a simple beam spanning between two supports, where fibers would be in tension on the convex (lower) side of the beam and in compression on the concave (upper) side.

For almost a century, mathematicians and physicists debated the action of a beam's cross section. Some clung to Galileo's theory that the neutral axis (the horizontal about which forces within the beam rotated and where neither tension or compression are present) was located at the bottom of the beam; others were uncertain about the location of the neutral axis and furthermore attached no importance to its exact placement; and still other agreed with what became known as the Mariotte-Leibniz theory. Then Charles Augustin Coulomb, a French physicist and military engineer, in 1776 stipulated the basic conditions that govern the strength of beams: (1) The neutral axis of a rectangular cross section of a single material is at the middle of its height. (2) The total tensile force in beam fibers on one side of the neutral axis must equal the total compressive force on the other side of the neutral axis. (3) The resistance within the beam must equal the bending induced by the loads on the beam.

* * *

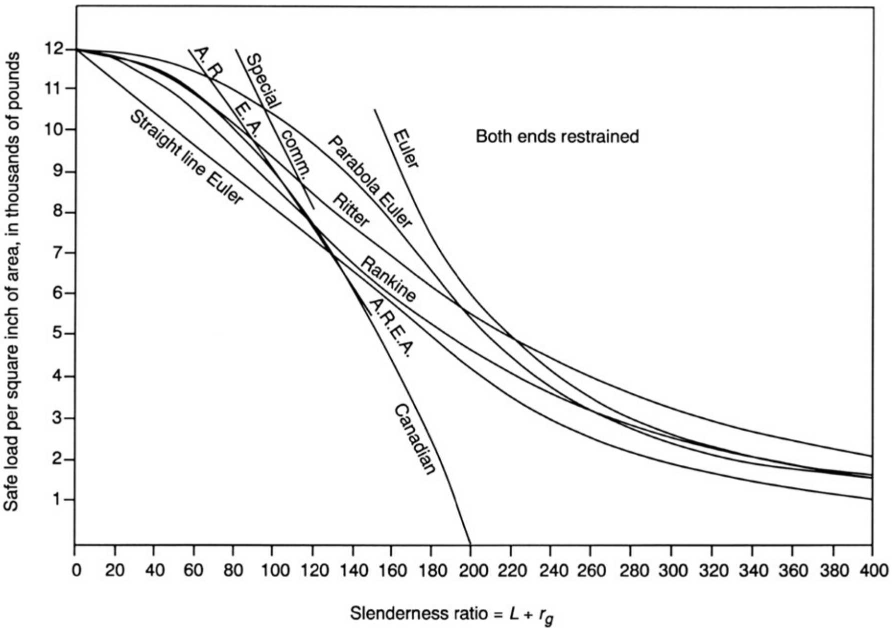
Among a multitude of other structural problems that required solution was the design of columns, a problem of greater complexity than that of beams. For centuries, columnar supports had taken the form of massive piers or cylinders of sufficient size to counteract the thrusts of arches and domes and to support the weight of massive stone construction. With the introduction of iron columns it became necessary to ascertain the characteristics of columns that were more slender. It was not the vertical pressure that was the problem, for, according to calculations using today's standards, a column of sandstone, if it could be braced in a vertical position, could be over a mile high before it would be crushed by its own weight.[13] The primary hazard for iron columns was buckling, bowing out to one side or another. Once a column begins to buckle, any load it bears has an increasingly strong effect. Therefore, theorists sought a means of describing the stiffness of columns and a way to determine the degree of stiffness required when a given load was imposed on a column.

The first influential theory of columns came from Leonhard Euler, a Swiss mathematician who spent much of his life at the Prussian and Russian academies under Frederick the Great and Catherine the Great. In 1757 Euler published a paper in which he presented his formula for determining the maximum load that could be applied to a given column before it would buckle. This formula combined the elasticity of the material from which the column is made, the shape and size of the column's cross section, and the height of the column. Euler's formula was corroborated by the results of tests and other mathematical studies of columns, but the limits generally accepted for its validity restricted it to very slender columns. As builders shifted from cast iron to wrought iron and steel, tests were made of each material using different methods of fastening the columns at top and bottom. In the century and a half that followed Euler's publication of his column formula, many additional formulas were developed, either based on the results of tests or on other theoretical studies.

In 1913 an engineer of the United States Bureau of Standards compared an array of 27 formulas for steel columns. Fifteen of these were used by American railway engineers; two were noted as being popular among English engineers; and two were favorites of German engineers.[14] A few years earlier the writer of a similar article comparing column formulas had said that "there is no better device for 'whipping the devil round the stump' than the invention or promotion of a new column formula. In times gone by it was a rather popular amusement; today it is out of fashion. Not that the utmost pitch of perfection has been attained; rather, a conviction of the fruitlessness of the diversion has impressed itself quite deeply into the current tradition of engineering."[15] In 1926 another article compared some 50 requirements for columns found in different United States municipal building codes. An editorial note observed: "There seems to be an almost unlimited array of column formulas which all seem to reach about the same result. If that is the case why not throw them all together and strike an average?"[16]

* * *

The complexity of most column formulas demonstrated that many engineers at the end of the nineteenth century had sound theoretical grounding in physics and mathematics. It was France that had set the pattern for training engineers. In 1671 the Académie Royale d'Architecture was founded, the first French school of higher education dealing with technical subjects, and its curriculum stressed engineering subjects fully as much as instruction in the fine arts. Five years later France's army corps



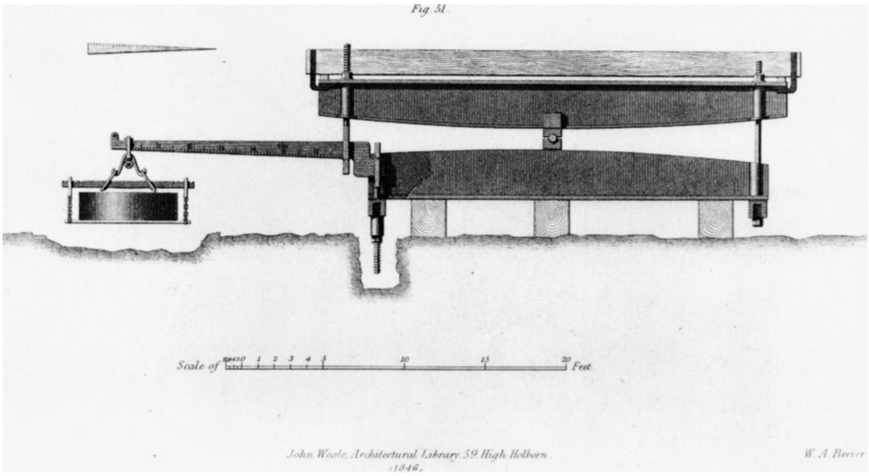
15.6 This machine was used by Eaton Hodgkinson around 1840 to test cast-iron beams of different shapes. By simple leverage, the weight at the left applies a greatly magnified force on the beam, causing the failure shown. (E. Hodgkinson, *Experimental Researches on the Strength and Other Properties of Cast Iron,* 1846.)

of military engineers was formed. In 1775 the Ecole des Ponts et Chaussées, where most French military engineers were trained, reorganized its program of instruction, which had been in operation for several decades. After the Revolution the Ecole des Ponts et Chaussées became one of the schools designated for advanced instruction, and before entering upon the advanced studies its students were expected to have completed study at the Ecole Polytechnique, which had been set up in 1794.[17] This system of technical education provided France with a succession of brilliant engineers, versed in actual construction as well as theory and mathematics.

Early in the nineteenth century, German polytechnical schools were established; unlike the French schools, they accorded as much attention to training engineers for industry as for the military.[18] Britain, the leader in mechanization, lagged behind the Continent in the education of engineers, and it was 1840 before its first engineering professorship was established at the University of Glasgow. Professional opinion in Britain was divided on the virtues of classroom training or apprenticeship. Thomas Telford, England's most accomplished civil engineer at that time, favored the latter means of preparing for the profession, but at the same time he believed a knowledge of the French language was essential in order to have access to the information in the manuals and handbooks used in the French engineering schools.[19] Technical education in the United States was not formalized until the last half of the nineteenth century. In 1862, during the Civil War, Congress appropriated land that states could sell in order to establish colleges whose curriculums should include instruction in the "mechanic arts." Before the land-grant colleges' engineering curriculums were well established, much of the construction in the United States depended on many immigrant engineers and on others who had received brief training during military service in the Civil War.

Each nation seems to have developed its own attitude toward structural design during the years that followed. Around 1920 the contrasts that had developed were spelled out in letters published in the *Engineering News-Record* and other journals.[20] It was contended that British engineers did not use books in their practices to the extent that they were used by engineers in the United States and that the British relied much more on experience. One party to the brief crossfire questioned why British writers on the design of structural steel preferred long and complex mathematical methods to simple graphic analysis. A British writer deplored American "profound faith in 'figures' and 'figureability,' " and American engineers were depicted as being "influenced by the German thirst for unnecessary detail."[21] Similarly and more recently, others have written of "German science and French daring."[22] However accurate such stereotyping may have been, these comparisons demonstrate that within the scope of structural engineering there can be sharp and clear distinctions between the operative points of view of individual engineers and engineering specializations (such as bridges and buildings), as well as among national groups.

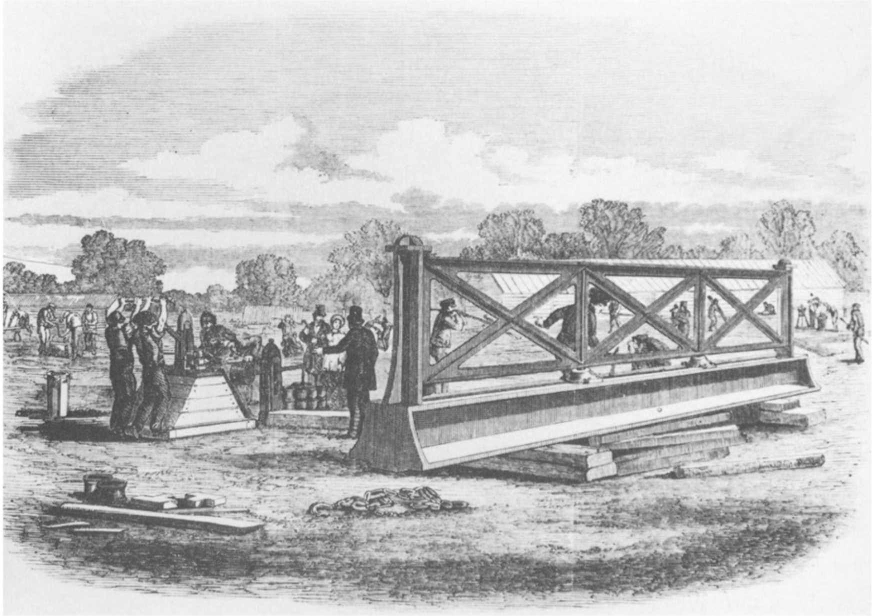
The validity of formulas could be judged by testing the actual structural members in place, loading parts of the building with bags of sand or bars of metal far beyond the load for which it had been designed; or members could be tested separately. Since all formulas included factors based on the nature of the material to be used, a



sample of the material could be tested to determine its characteristics. All of these possibilities, except the first, called for the services of testing machinery. Many formulas in use were developed from test data, and others were verified by tests that supported their theoretical predictions. By the middle of the eighteenth century several experimenters had constructed machines in which small samples of wood, iron, or stone could be tested to determine their strength in tension, compression, or bending. A series of tests made during construction of the French Panthéon (Ste.-Geneviève, Paris) attracted much attention and, as discussion continued, improvements made in the testing machines made their findings more accurate. Improvements continued through the next century. Efforts were made to lessen friction in the machines; loads were placed on the test samples with greater accuracy, and experiments were conducted to ascertain the sizes and shapes of samples that should be tested for the most accurate results.

Because several of the early English cast-iron bridges had failed by the 1840s, a Royal Commission on the Application of Iron to Railway Structures recommended extreme caution in the design of metal bridges. Isambard Kingdom Brunel, the most prominent of railway engineers, called it the "Commission for Stopping Further Improvement in Bridge Building."[23] Nevertheless, railway construction thrived and much of the engineering work in England and the United States related to the use of metal construction in railway work. In England, William Fairbairn and Eaton Hodgkinson conducted exhaustive tests of the material to be used in a railway bridge over the Menai Straits, a bridge in the form of a rectangular tube across an unprecedented span of 459 feet (fig. 15.6).

During the 1860s the testing laboratory of David Kirkaldy was set up in London, and many foreign companies sent samples there, often in an effort to check the accuracy of their own testing machines.[24] It was in Kirkaldy's laboratory that the tests were



15.7 In the construction of the Crystal Palace (1850), a hydraulic press was used to test the 214 cast-iron girders that were major elements of the structural system. The girders spanned 24 feet, and those supporting galleries were tested at 22 and 15 tons. This procedure was less newsworthy than the troops of running cadets that simulated the loads that might be induced by the public's footsteps (fig. 4.28). (*Illustrated London News*, 30 November 1850.)

conducted through which Thaddeus Hyatt discovered the principles of reinforced concrete construction. Kirkaldy's testing laboratory was one of the first established in Great Britain, where such work was usually carried out by private concerns. On the Continent most laboratories operated under government auspices. In Germany universities were the usual locale, permitting use of the equipment for research as well as for the investigation of samples presented by manufacturers.[25] In America, an organization of engineers petitioned the government for construction of a machine suitable for gaining data about American iron and steel. It took about four years to construct the "United Testing Machine," which was installed at a Massachusetts arsenal in 1879.

All of these machines were based on eighteenth-century models. Lever-fulcrum machines applied test loads by placing weights on a lever far from the fulcrum's knife-edge. Other designs applied loads by hydraulic pressure. Such simple principles required augmentation by a host of refinements that assured even application of the loads and accurate methods of measuring the stresses that caused materials to fail.

The testing of a completed building or its parts was the most definitive manner in which strength could be determined. However, loading a floor with sand or lead, as was sometimes required by city officials, merely indicated that the tested portion satisfied the minimum requirements of regulations. Testing every member before it was put in place—a process more suitable for wood, iron, or steel than for reinforced concrete—or testing randomly selected samples of members provided a limited reassurance for, as editors of the *Engineering News* wrote in 1906: "Few structures have such simple service; most structures are designed for (and actually exposed to) distributed loads and concentrated loads, quiescent and moving loads, shock, wear, corrosion, freezing, and other forces of attack, each of which may be destructive independently of the others."[26]

* * *

The variation probable in a material, the narrow set of circumstances considered in many design formulas, and the unpredictable loads inflicted on the structure all encouraged caution. For that purpose, engineers employed a factor of safety, which has also been realistically defined as a "factor of uncertainty" or even a "factor of ignorance."[27] Probably there was always a custom of exaggerating the magnitude of threatening conditions and underestimating the strength of structure, for only in the Gothic world does there seem to have been a sense of daring that made precautions relatively rare. A clear-cut determination of a factor of safety appears in the middle of the eighteenth century when three mathematicians, investigating cracking in the dome of St. Peter's basilica, doubled their calculation of the amount of steel that should be provided, or in other words halved the stress that was to be imposed on the steel.[28] Through the two centuries that followed, the problem of safety occupied the attention of many organizations and their committees on safety.

Engineers on the Continent tended in the early nineteenth century to relate the stress allowed for materials to the maximum lengthening of the material from which it would elastically return to its original length. English engineers, on the other hand, related allowable stress to the maximum stress, the loading conditions at which the material would fail. In 1849 a German engineer visiting the United States expressed his surprise that American engineers based their calculations on lower loads and higher allowable stresses for their materials than was European practice.[29] Late in the nineteenth century, W. J. M. Rankine in a standard reference book presented a more complex procedure for determining a factor of safety, which he defined as the ratio of the load causing failure to the load that might be safely utilized in calculations. Rankine recommended factors of safety that varied with the type of material and the engineer's judgment of whether the structure would have "perfect materials and workmanship" or "good ordinary metals and workmanship." The same sort of distinctions were made in the United States with different standards for buildings, bridges, and machines.[30]

In other approaches, factors of safety were applied to the assumed loading of members as well as to the strength of the materials of which they were fashioned. By 1962 the extenuating conditions were so carefully considered by an English committee that it recommended estimated loads be adjusted by a factor calculated by a formula having six factors: seriousness of the member's failure, quality of workmanship, loading conditions, importance of the member, estimated warning of incipient failure, and the manner in which members might collapse. From these subjective evaluations, a number was to be derived, and this would be used as the factor of safety for the particular member under consideration.[31] As with the design of columns, a choice might be made among available formulas for designing a structural member, but the variation of cost

15.8 **Different cities' building codes in the United States required that engineers' calculations assume 40 to 150 pounds per square foot as live load for office buildings. In 1905 a professor of engineering displayed photographs of his students standing in a box, 6 feet square, to demonstrate the conditions that produced loadings of 41.8, 100.0, and 154.2 pounds per square foot. (*Transactions, American Society of Civil Engineers,* June 1905.)**

associated with the choice of formula was usually much less than the cost imposed by the stipulation of a factor of safety or the assumption of a specific loading condition.

Rankine, a professor at the University of Glasgow, also introduced the distinction between dead loads, the actual weight of the fabric of the building, and live loads, the estimated maximum weight of furnishings and occupants. Dead loads were easily calculated with reasonable accuracy, but live loads were largely guesswork. In 1905 an American engineer compared the regulations of American cities and found that the prescribed live loads for apartment buildings and hotels ranged from 40 to 75 pounds per square foot; for office buildings from 60 to 150; for theaters from 80 to 150; and for schools from 75 to 150 (fig. 15.8).[32] Through most of the nineteenth century columns had been calculated as carrying all the required live load above them, but with the advent of the skyscraper some cities allowed reductions in live loads. Following the lead of New York, many requirements assumed that all floors would never be fully loaded at the same time, and the top floor was considered to have the entire prescribed live load, the next lower floor 95 percent, the next 90 percent, and so to a 50 percent load, which would be used for all remaining floors.

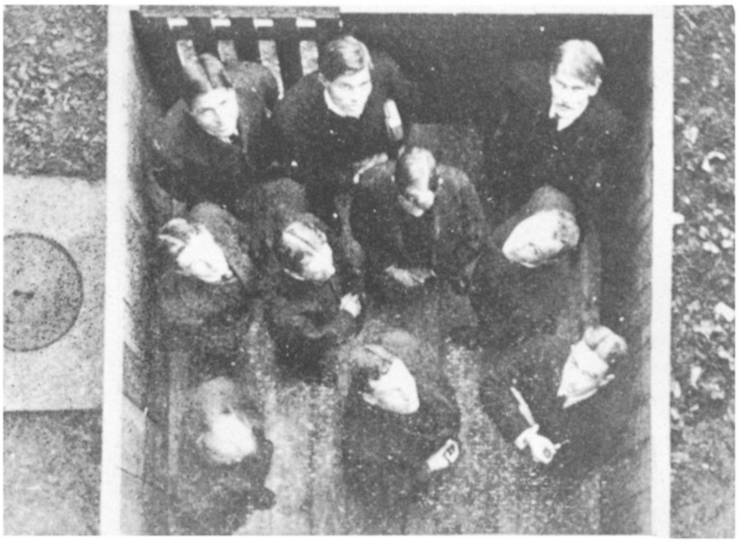
These arbitrarily reduced loads were critical in designing foundations. Even with live loads reduced, live loads and dead loads in tall buildings caused pressures on foundations much greater than had been encountered previously. As an engineer wrote in 1908:

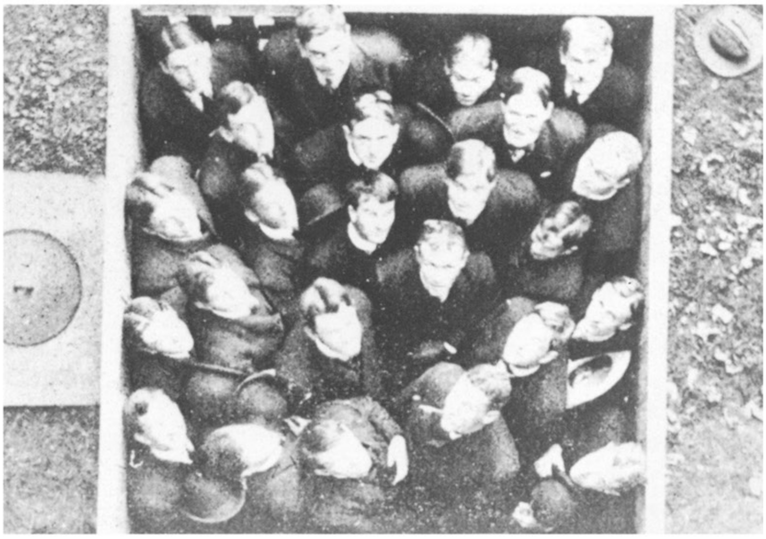
> In New York, there are two buildings over forty stories high. These [tall buildings] develop concentrated loads of 3,000,000 or 4,000,000 lb. in a single column and their heights, of from 200 to 500 ft., are so great that the slightest irregularity of settlement in the foundation produces a greatly magnified variation from the vertical in the superstructure and causes great injury or destruction to the delicate and accurate machinery installed, besides settlement, and cracks and displacement of the beautiful cut-stone walls and lintels which would be great blemishes and would inspire public distrust sufficient to seriously impair the value of the building. It is therefore necessary that the foundations should be more than safe; they must be absolutely immovable within the smallest fraction of an inch; or that, if displacement occurs, it must be perfectly regular and uniform.[33]

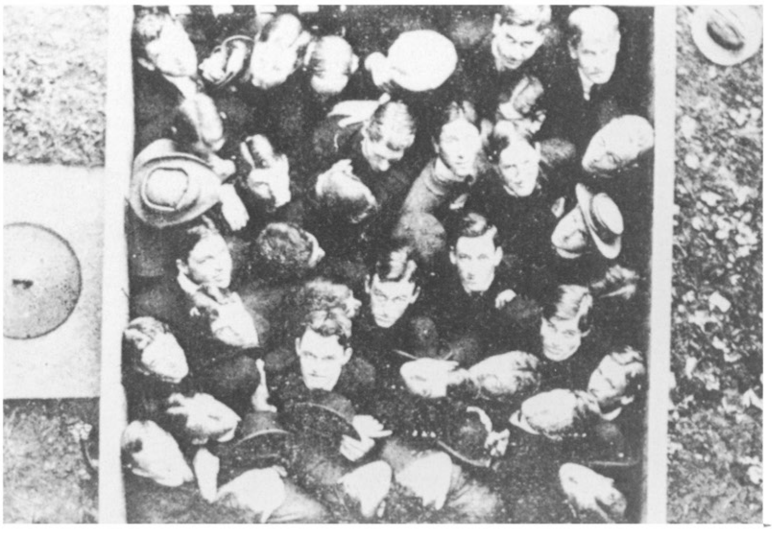
Traditionally, most walls and piers had been supported by extending stone to a level below the frost line, each course of stone widened to enlarge the area at the bottom. There were, of course, marshy sites that demanded other treatment, but in earlier times such places very seldom were selected as sites for buildings of significance. It was more likely that ancient buildings would be located in a healthful, well-drained site, perhaps with solid rock beneath them.

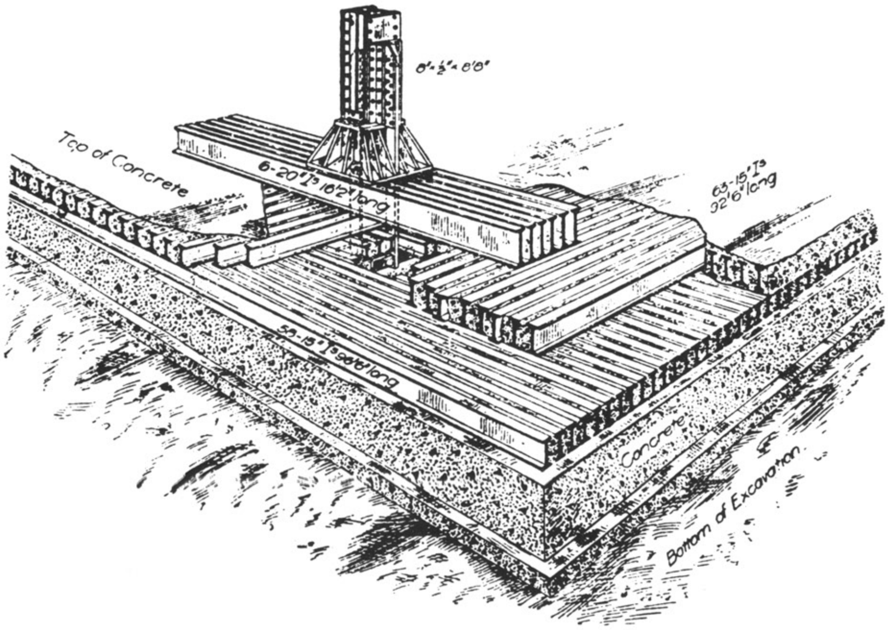
In Chicago, where construction of tall commercial buildings began, foundations were first made of rubble or trimmed dimension stone, a choice made on the basis of cost. However, Chicago's water level, roughly that of Lake Michigan, was about 15 feet below ground level and only 1 or 2 feet above a crust consisting of 3 or 4 feet of stiff clay. Beneath that crust, soft clays extended for about 45 feet, and firm stone was first encountered around 80 feet below water level.[34] In order to provide basement areas and rest foundations on the layer of stiff clay, it was often necessary that the stepped portion of foundations extend upward into the basement area, which was sorely needed for the building's equipment. Indeed, calculations of spread footings for the Montauk Building, Chicago (1882) showed that the slopes of footings would extend into the ground floor and leave insufficient space in the basement for placing dynamos. Therefore, the architect, John Wellborn Root, employed old steel railway rails, placed in layers at opposite directions.[35] The steel rested on a broad slab of concrete and was itself surrounded by concrete. This rail-grillage system saved weight, basement space, and time in its construction, and the same principle, using I-beams instead of rails, offered even greater advantages. This form of foundation could spread a load as much as 10 feet beyond the sides of a column, and required no more than 3 or 4 feet of depth. Steel grillage foundations were commonly used in many cities in the United States (fig. 15.9). As buildings grew to be taller, the grillages were often extended to cover the entire base of the building, but this method did not sufficiently recognize the large variations in the loads on different columns. Soon areas of grillage were separated, each being used for a single column or a group of three or four columns. In New York special care had to be exercised when pouring the concrete layer over quicksand.[36]

Simple spread footings were usually sized according to rules of thumb. In several parts of the United States the continuous footings beneath bearing walls were given a width equal to one foot for each story of the building.[37] An 1873 pamphlet by Chicago architect Frederick Baumann advised that each footing be of a size proportional to the amount of dead load resting on it and that it be made certain that the center of each footing coincide with the center of the loads resting on it. Furthermore, he recommended the use of allowable







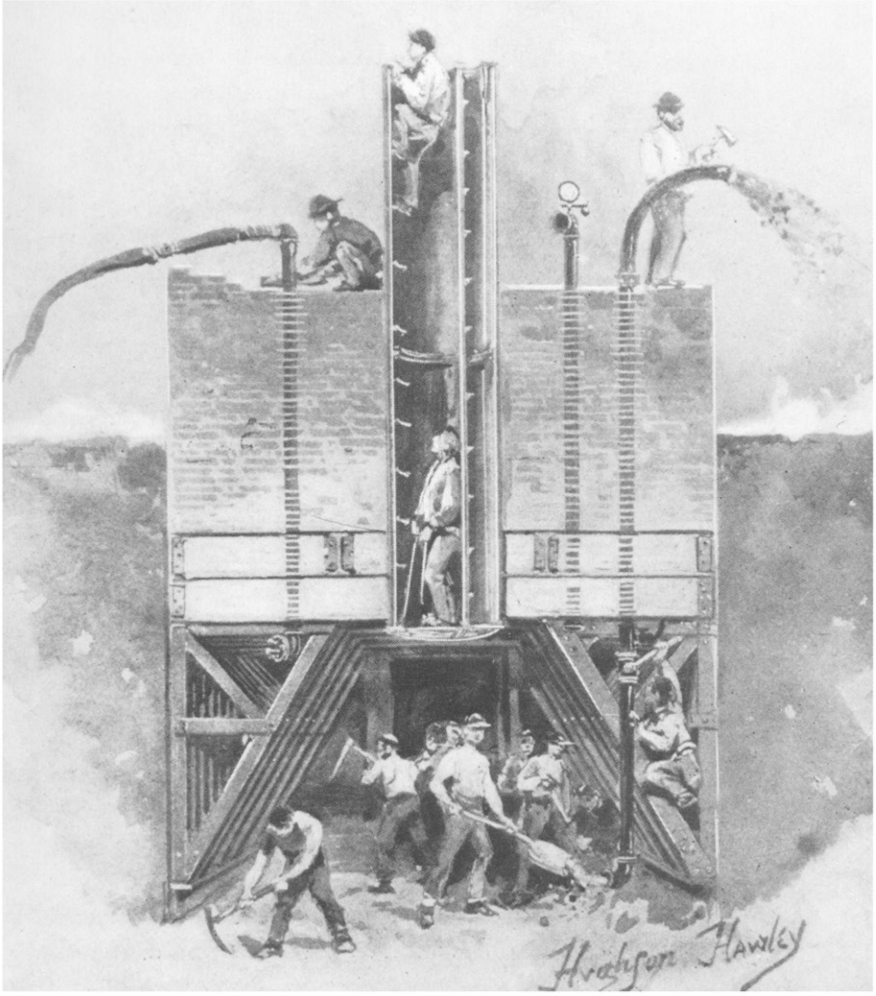


15.9 The Spreckels Building in San Francisco was 75 feet square in plan and 15 stories high. It rose from a grillage foundation, resting on a concrete slab 2 feet thick and 96 by 100 feet in area. Each column bore on a weight-distributing pad of six I-beams. The structure was sturdy enough to survive the San Francisco earthquake of 1906 and support the additional six stories of a 1938 remodeling. (*Engineering Record*, 4 April 1908.)

15.10 For this turn-of-the-century caisson, pressure was provided by a steam-powered air pump and regulated according to a gauge atop the pier. Earth was either hoisted out the airlock tube or, as shown here, blown out by the air pressure. As excavation progressed, masons continued building the pier, its weight forcing the caisson down. (*Engineering Magazine*, April 1897.)

bearing capacities that ran as low as 20 percent of those that had been commonly used in Chicago.[38] Baumann's principles came to be standard practice among many architects and engineers in the United States during the period in which spread footings and grillages were most often employed. Nevertheless, settlement continued to be a major building problem in Chicago. At the end of the nineteenth century it was accepted that a new building would settle, and they were built at a level that anticipated a settlement of 2 to 9 inches. The Masonic Temple building (1892), a skeleton construction and the first building to reach 21 stories, settled over 11 inches in the first five years it was occupied, and 4 inches more in the following ten years. By 1913 some portions of the building had sunk at least 6 inches more than other parts. Since a greater control of settlement would have required the considerable expense of going much deeper, owners considered settlements of this order acceptable. In New York few tall buildings settled more than a fraction of an inch, solid rock or "hardpan" usually providing a firm base of construction.[39]

With buildings taller and consequently heavier, piles were introduced, an ancient method of building in wet places such as for bridges and harbor works. In principle, piles may be viewed as columns, taking the weight of the building to a supporting stratum of rock and braced by the surrounding soil; and as supported by friction between their surfaces and the soil; and they may be used to compact the building area, converting loose soil into a denser material. For early skyscrapers the piles, if wooden, were cut off a short distance below the water level in order to avoid their rotting. Around and over the tops of wooden piles a concrete slab was poured, and



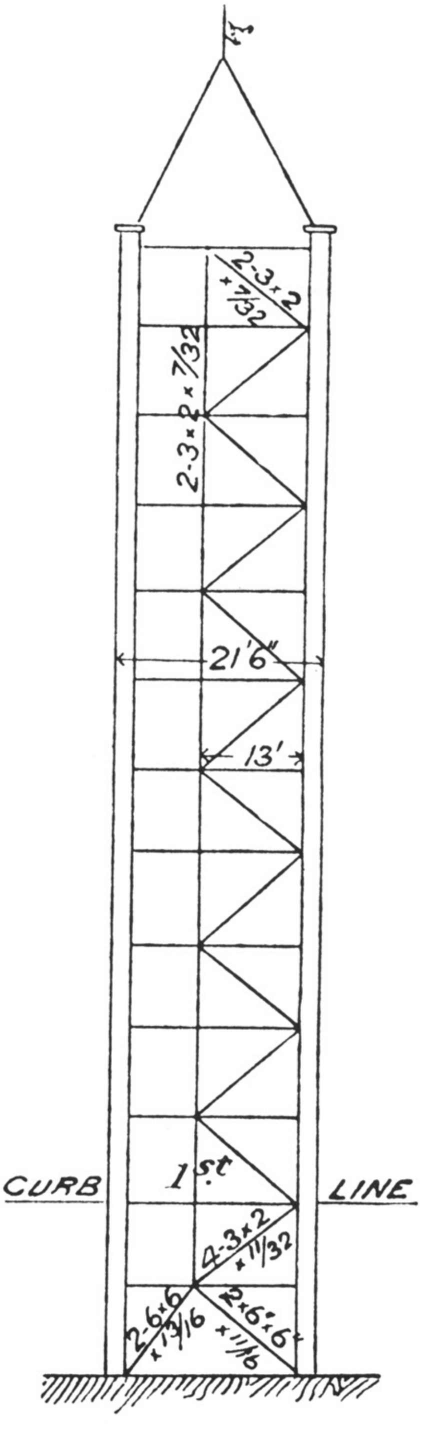
this was capped with spread footings or steel grillages.

Piles to compact the soil for the construction of the Park Row Building, New York, 30 stories high and the tallest building in the world when it was completed in 1898, were spruce trunks about 12 inches in diameter, and they were driven so close together that their cross sections filled over a fourth of the area on which the foundation bore.[40] For some New York projects for which piles were driven into dense, fine sand, they could not be forced down more than 10 or 12 feet. In Chicago, piles were driven much deeper, and piles for the Chicago Post Office were so closely spaced that driving the last ones caused others to rise several feet.[41] In cases where a constant level of ground water could not be safely assumed, steel tubes were driven into the soil, then removed, and the holes filled with concrete.

Excavation and pile driving for buildings could often require precautions to avoid disturbing the soil and foundations beneath existing adjacent buildings that rested on shallower foundations. At the end of the nineteenth century the building regulations of New York made the owner of a new building financially responsible for correcting damage done to any adjacent building with foundations 10 feet or farther beneath street level.[42] When the Manhattan Life Building in New York, 17 stories high, was being designed in the 1890s, the architects were forced to turn to a new system of support. There was not sufficient space on the site to drive the number of piles needed; grillages would have risked the soft soil being squeezed out sideways, and an open excavation 45

15.11 The Tower Building (New York, 1888) included an 11-story wing on a single lot 21½ feet wide, which provided an enviable Broadway address. To neutralize wind pressure on the side walls, diagonals were introduced at five points in the wings' depth of 108 feet, acting as upended trusses from the basement to the roof. (*Transactions, American Society of Civil Engineers*, September 1892.)

15.12 The Venetian Building (Chicago, 1891), a 12-story office building, employed portals (shop drawings shown here) as wind bracing for two ground-floor bays where shops were to be located. In the office floors above, diagonal rods (upper right and upper left) set in partitions provided bracing. (*Engineering News*, 26 December 1891.)

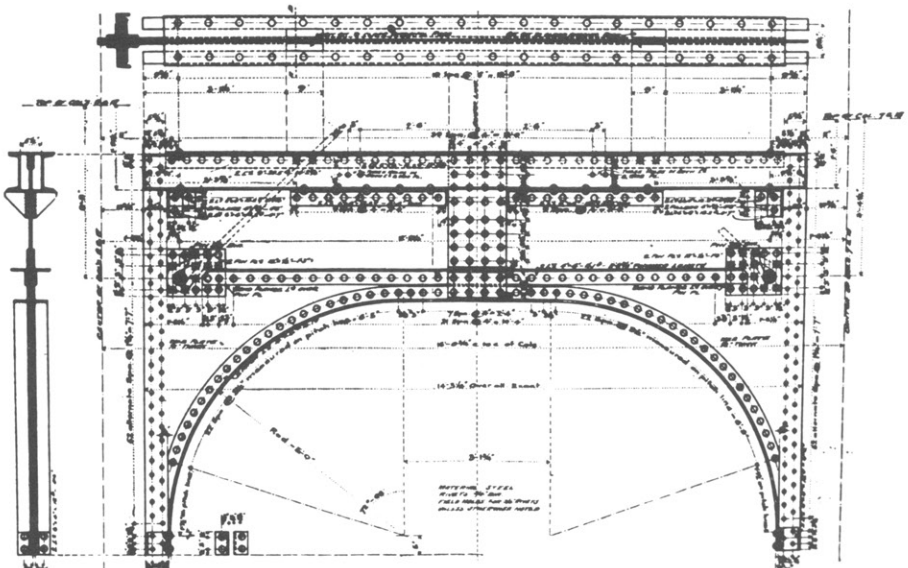


feet to rock would have endangered adjacent buildings.[43] The architects and engineers decided to use pneumatic caissons, a method that had been employed in the construction of many major bridges. A box of steel, the size of the required pier foundation, 7 or 8 feet high and its bottom open, was located on the site. From the center of this caisson a tube rose so that the soil removed by workers within the box could be taken away. On the top of the caisson, construction of a masonry pier was begun, and its increasing weight forced the box downward as workers dug. Air pressure within the caisson was increased as needed to keep water out. Using the pneumatic caisson, foundations of a typical large New York building at the end of the century took only two or three months to prepare, and engineers foresaw greater speed as more experience was gained (fig. 15.10).[44]

As skyscrapers grew to be much higher than the dimension of their bases, problems arising from wind pressure demanded attention. In 1895 a New York engineer pointed out that in the city "there are many instances of buildings varying from 23 to 25 feet in width and from 120 to 175 feet in height, with the uppermost 100 feet exposed to wind."[45] Although the depth of such buildings' sites might commonly be around 100 feet, it was the typical narrow lot in New York that often established the smaller dimension of a site, the dimension that would be needed to resist the overturning pressure of winds blowing against a side wall above any adjoining structures. Many failures occurred during construction, at a stage of incompletion when winds could blow into partially enclosed spaces but little of the building's weight was in place. It was assumed that the weight of walls and floors would counteract part of a wind's overturning force, a resistance estimated to be as much as 30 percent of the needed force in the case of one Chicago building.[46] Though economical, cast-iron columns were used less often than previously because that brittle metal could not satisfactorily withstand the bending forces produced by winds. Some architects believed that the partitions within a building could effectively resist wind forces, but most partitions were interrupted by door openings and were made of flimsy masonry materials.[47] The most effective methods of combating wind pressures were diagonal bracing and portals. Diagonals had been used in wind bracing for the towers of suspension bridges, but in most buildings the diagonals between the ends of columns, whether rods in two directions or stiffer members in only one, interfered with the placement of windows (fig. 15.11). Therefore, it became customary to arrange the diagonals as knee braces, members slanting from midheight of a column to a point near the middle of the beam above. When knee braces were provided for at least two corners of a bay, these corners were stiffened without disturbing the customary window locations. The portal was an archlike construction of sheet metal, squared on the outside to match the rectangle of the bay and arched inside the top to provide rigidity at the upper corners of the bay (fig. 15.12). By using either of these methods in vertical bands up a tall slender building, the framework was made to act as a truss, anchored to the ground at one end and cantilevered upward to resist the wind.

The general practice in wind bracing in 1915, as reflected in city building regulations in the United States, exempted buildings less than 100 feet in height "in which the height does not exceed four times the average width of the base."[48] New York regulations, which many other cities followed, permitted inclusion of the action of partitions and a 50 percent increase in the stress allowed in the framework. Both of these provisions were considered unwise by some prominent engineers. The wind pressure to be assumed in computations was at that time usually required to be around 30 pounds per square foot, although engineers often believed it wise to increase that number.

During a flurry of skyscraper construction in the 1930s, tests were made in smooth-flow aeronautical wind tunnels to determine wind con-



ditions more accurately. It was perhaps those findings that prompted adjusting the New York City code to ignore conditions below a height of 200 feet, to assume a pressure of 20 pounds per square foot, and to increase design stresses allowed for the steel by one-third. Since the 1930s the changes in the materials and methods of constructing tall buildings have introduced new considerations in problems of wind bracing. The strength of the materials used in construction has increased and the weight of buildings has decreased—from about 20 pounds per cubic foot to 10 pounds.[49] Taller buildings with lighter walls have made wind pressure a much more important factor in structural design.

* * *

Continuous beams and statically indeterminate systems were paramount problems in structural theory during the last half of the nineteenth century. When a beam rests on two supports, the condition is *statically determinate*, because the span can be considered in isolation, the action of external forces being entirely counteracted by the action of forces within the span; when a beam extends over three or more supports it is classified as *statically indeterminate*, in which case no span can be isolated because each is influenced by the action of external and internal forces of adjacent spans. This case is much more complex theoretically and mathematically. Attention was drawn to the subject of continuous spans at midcentury by the desire of railway engineers to construct metal framework bridges across several supports. Toward the end of the nineteenth century the metal frameworks of tall buildings came into consideration, for the rigid connections between beams and columns brought about complex interactions that transferred stresses among beams and columns throughout the entire framework. This structural problem is much more difficult to solve in theory and execute in application than are simple beams acting in relative isolation from the remainder of a structure.

Around 1850 B. P. E. Clapeyron, a French engineer working principally for railway companies, began using a new method of solving the problem of continuous beams, the theorem of three moments, in the design of bridges. In the next two decades the theorem was extended and study of the three-dimensional frame was advanced. A wide variety of approaches appeared, many of them related to the extensive study of railroad bridges. Much of this highly detailed work was done by Germans, who felt that the availability of iron in Britain made British engineers less concerned with theoretical principles than "the poor devils of the Continent."[50] In the 1870s, a period when the British were thought to be notably negligent in the mathematical education of their engineers, a German engineer wrote that "continuous beams are popular only in countries where engineers can calculate."[51]

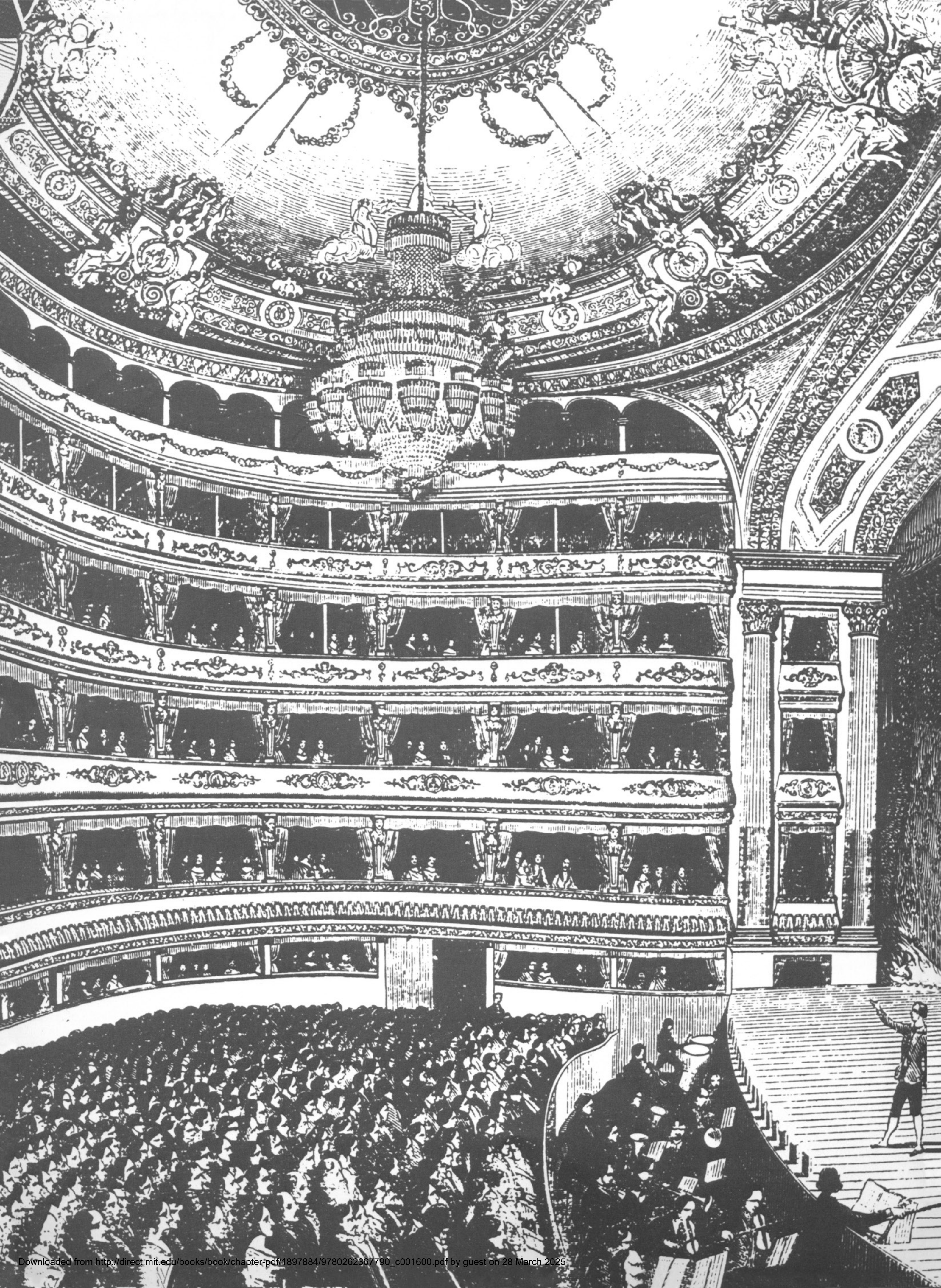
Many engineers had received little mathematical training or had been trained by years of experience as draftsmen, and both sorts were enthusiasts of systems of graphical analysis that could remove the mathematical mystery from problems and utilize graphics, a form of investigation with which they were more familiar. The simple depiction of forces as lines drawn at angles that indicated their direction, with a length that showed their magnitude, had been introduced by Stevinus at the end of the sixteenth century. By 1860 these principles were sufficiently advanced to be used in the complete analysis of simple trusses, and during the three decades that followed, graphical methods for studying continuous beams were developed.[52] Until the 1930s, whenever new formulas for column or floor girders appeared, there could be heard an outcry questioning the need for such mathematical intricacies and lauding the simplicity of graphical methods.

A succession of events made the study of three-dimensional structural frameworks even more complex: the use of welding in steel construction gave the building frame a greater rigidity; reinforced concrete construction demanded the investigation of composite construction in which two or more materials acted in combination; and new methods of lighting, temperature control, and ventilation permitted the use of different plan forms for tall commercial buildings, allowing a greater depth for workspaces, now less dependent on being near windows. Many methods for the analysis of frameworks were introduced. Some were based on assumptions about the "energy" or "work" involved in resisting loads, and found mathematical expressions for these factors. Others were derived from the small deflections (sagging and bending) that would result from loading a structure, and endeavored to trace the movements of the framework in its efforts to distribute these movements. Outstanding was the "moment distribution" method of 1932, by which the individual elements of a framework were initially considered in isolation, as statically determinate, and a method of mathematical approximation was used to bring these numbers into balance.

* * *

Always there has been a startling contrast, increasing as buildings' complexity increased, between the sophistication of the formulas and theories employed by engineers and the generalizations found in establishing factors of safety, loads, and the characteristics of materials. This is, it must be remembered, the inevitable expression of the different interests and capabilities of physicists and mathematicians, engineers, the construction industry, and those who regulate construction standards in the interest of the public.

The failure of a building does not necessarily mean its falling down. Undue settlement and the appearance of large cracks in an office building would probably result in its failure as a profitable investment for the owners. At the same time, the provision of every conceivable structural precaution would make construction of the building so expensive that financial failure might be inevitable. Through the nineteenth century the factors of safety required for wrought iron and steel by some British governmental agencies was around 4, and in the United States current codes for concrete construction require a factor of safety of 2.2 for concrete and 2.5 for reinforcing steel.[53] We have previously noted the variation of live load requirements, an irregularity that has diminished through the years, and the arbitrary assumption of a method for reducing the loads considered for the design of columns and foundations for tall buildings. No likely change of structural theory or the formulas employed in structural design would affect the cost and stability of buildings nearly so greatly as do the justifiable precautions that are fundamentally measures of the probability of failure.



Technics and Architecture

The Development of Materials and Systems for Building

OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

16

Acoustics

1820s	John Blackburn constructs a paraboloid sounding board behind his pulpit
1820–36	Attempts to correct the acoustical faults of the House of Representatives, U.S. Capitol, Washington
1832	Benjamin Henry Latrobe's principles of acoustics published in the American edition of the *Edinburgh Encyclopedia*
1847	The "isacoustic curve" presented by John Scott Russell in a lecture before the Royal Institute of British Architects
1886–91	Construction of the Auditorium Building and Schiller (Garrick) Theater, Chicago
1895	Wallace C. Sabine commences his study of the acoustical problems of the Fogg Museum, Harvard University
1900	Sabine publishes his acoustical principles
1927	Construction of Salle Pleyel, Paris, according to acoustical design of Gustave Lyon
1964	Initiation of experiments that lead to the electronic adjustment of the acoustics of the Royal Festival Hall, London

16.1 Dots in the plan indicate the location of acoustical vases in the vaulting of side aisles in the church of St. Victor, Marseilles. While the necks of the vases result in openings only 2 or 3 inches in diameter, depths vary from 7 to almost 27 inches. The variety of shapes employed and ridges on the interior surface of one vase suggest a planned acoustical treatment rather than a casual use of potters' discards. (*Archeologia*, May–June 1971.)

16.2 Geometric concentration of sound reflections is illustrated by this seventeenth-century drawing showing a speaker and listener at the foci of a semiellipse. Reflection and the "whispering gallery" phenomenon found in many buildings' domes drew the attention of early scientists. (A. Kircher, *Phonurgia Nova*, 1673.)

Vitruvius described the acoustical details of Roman amphitheaters in the fifth book of his *Ten Books of Architecture.* Like Aristotle, Vitruvius was aware that sound was the result of air waves, and in writing on theaters he clearly described the phenomena of reflection and reverberation. He mentioned an interesting acoustical device:

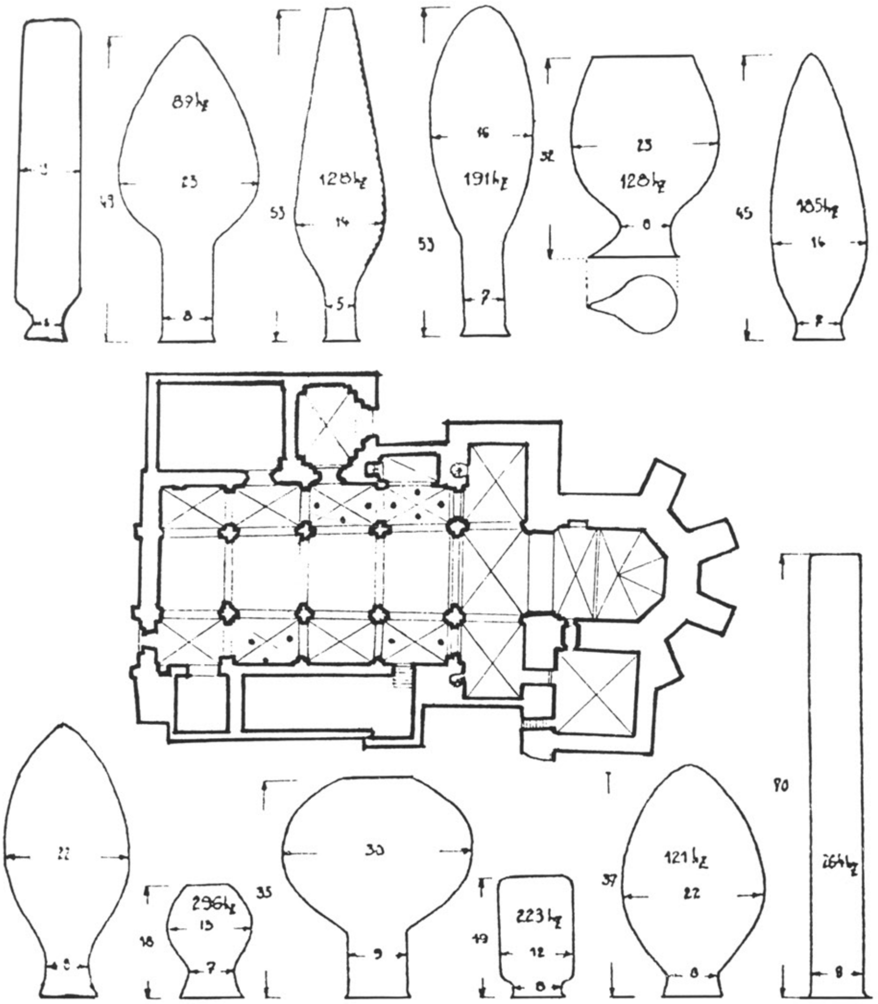
> Let bronze vessels be made, proportionate to the size of the theater, and let them be so fashioned that, when touched, they may produce with one another the notes of the fourth, the fifth, and so on up to the double octave. Then, having constructed niches in between the seats of the theater, let the vessels be arranged in them, in accordance with musical laws in such a way that they nowhere touch the wall, but have a clear space all round them and room over their tops. They should be set upside down, and be supported on the side facing the stage by wedges not less than half a foot high. Opposite each niche, apertures should be left in the surface of the seat next below, two feet long and a half a foot deep.[1]

For a small amphitheater Vitruvius recommended that 13 niches be provided in a tier of seats halfway up the slope of the seating. For a larger amphitheater he advised niches in three tiers.

Although Vitruvius stated that such vessels were not to be found in Rome at that time, he claimed that amphitheaters in some Italian provinces and Greek states used bronze vessels, or ceramic urns where cost was a significant factor. There was long no concrete evidence of such vessels in ancient amphitheaters, but archaeologists have discovered niches of the kind described by Vitruvius, niches that were used as ovens by modern generations of peasants. More recently, ceramic urns about 3 feet in diameter and 5 feet high have been found in the stage structure of an ancient Sardinian theater.[2] Although Vitruvius's prescriptions were perhaps more advanced than common practice in the first century B.C., it seems likely that Romans employed resonant vessels located in both the audience seating and stage, as well as megaphones built into the actors' masks. Since modern tests show typical ancient theaters to have excellent acoustics, bronze vessels may seldom have been needed.[3]

Medieval builders on occasion embedded clay pots in ceiling vaults of churches and chapels, and sometimes in walls or beneath floors, for what were obviously acoustical purposes. As early as 1824 earthenware vessels were discovered in the vaulting of St. Blaise, Arles, and other examples have since been found throughout much of Europe.[4] In the case of the small medieval church at St. Victor in Marseilles, each of the 12 clay pots discovered in its vaulting had a decidedly different shape (fig. 16.1). Modern tests suggest that the pots did not significantly amplify sound at the floor level, but they effectively absorbed sound, smoothing the frequencies and decreasing contrast.[5]

By the middle of the seventeenth century the geometry of sound reflection was familiar to many scientists, principally because of its assumed similarity to the behavior of light. Using a newly developed system for pumping air from a container, Athanasius Kircher proved that sound was not conducted by a vacuum, and in *Phonurgia Nova* he presented descriptions of the manner in which sound is reflected, dispersed, and concentrated by the shapes of interior spaces (fig. 16.2).[6] By this time the requirements of the speaking voice, delivering a lecture or sermon, had become as important as the needs of actors and choruses. Speakers insisted that the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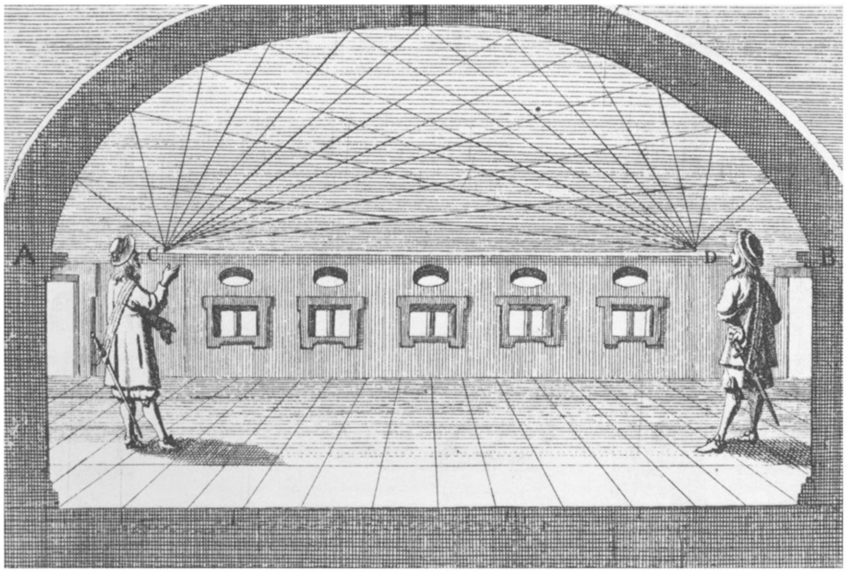
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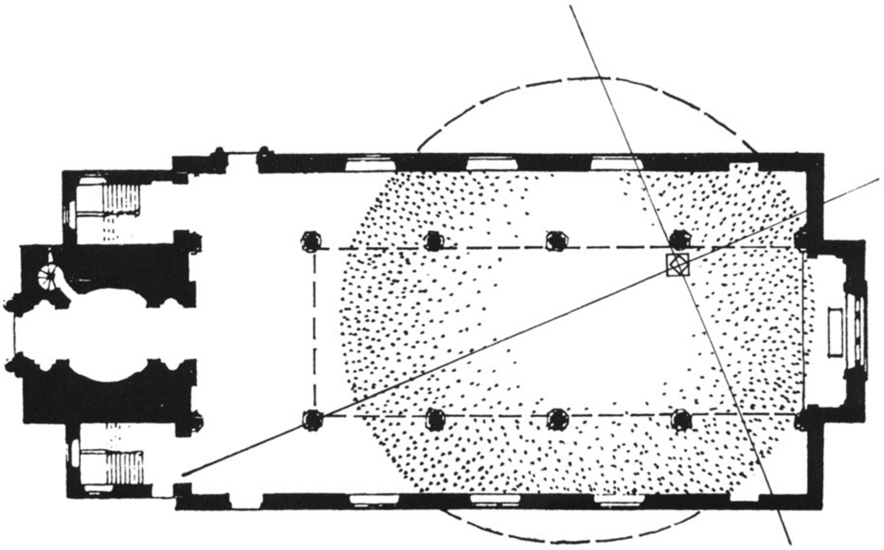
form of buildings assist in their efforts to be heard in every cranny of the lecture halls and churches in which they spoke.

Sir Christopher Wren, scientist and geometer as well as architect, was perforce concerned with the placement of pulpits in order to assure that sermons might be heard clearly in all the 51 London churches that he designed to replace those destroyed in the catastrophic fire of 1666 (fig. 16.3). Wren insisted that a church's nave should not exceed 90 feet in length and 60 feet in width, and in his designs for places of worship the pulpits were customarily placed well forward of the altar, near parishioners in the front pews. Wren's conclusions on church acoustics appear to have been principally based on his observation that "a moderate Voice may be heard 50 feet distant before the Preacher, 30 Feet on each Side, and twenty behind."[7] More than a century later Benjamin Wyatt, architect of Drury Lane Theater, in *Observations on the Principles of a Design for a Theater,* estimated a much larger scope of the human voice, 92 feet in front, 75 on the sides, and 30 to the rear.[8] The listening area described by Wyatt is roughly four times that established by Wren, but this difference may have resulted from Wyatt's considering the trained voices of actors rather than the intonations of vicars.[9]

Common professional knowledge of architectural acoustics in the United States is indicated by the explanations provided in 1804 for the congregation of St. Michael's Church, Charleston, by the young architect Robert Mills. Asked to prepare plans for an addition to the church (a project never completed), the native Charlestonian provided his clients with a proposal accompanied by explanations that included his "Doctrine of Sounds." Mills recommended removing the church's flat ceiling and installing a vault the length of the nave. In justifying his design, Mills spelled out the basic principles of acoustics as they were accepted at that time:

> 1. Sound has some of the properties of light. It is radiant, that is, it proceeds when excited from one centre, in every possible direction in which it meets with no obstruction.
>
> 2. It is reflected, and follows the general laws of reflection, its angle of *incidence* and *reflection* being equal. Its reflection is called *Echo.*



16.3 The range of the speaking voice, as stated by Sir Christopher Wren, is here superimposed on the plan of St. Bride's, one of his London churches. The nave of the church had dimensions very near those Wren considered to be the maximum for good hearing. With the pulpit brought well forward, Wren's conservative estimate of vocal range meant that almost all of the pews at the lower level and more than half those at the upper level could hear a sermon clearly. (Drawing by author.)

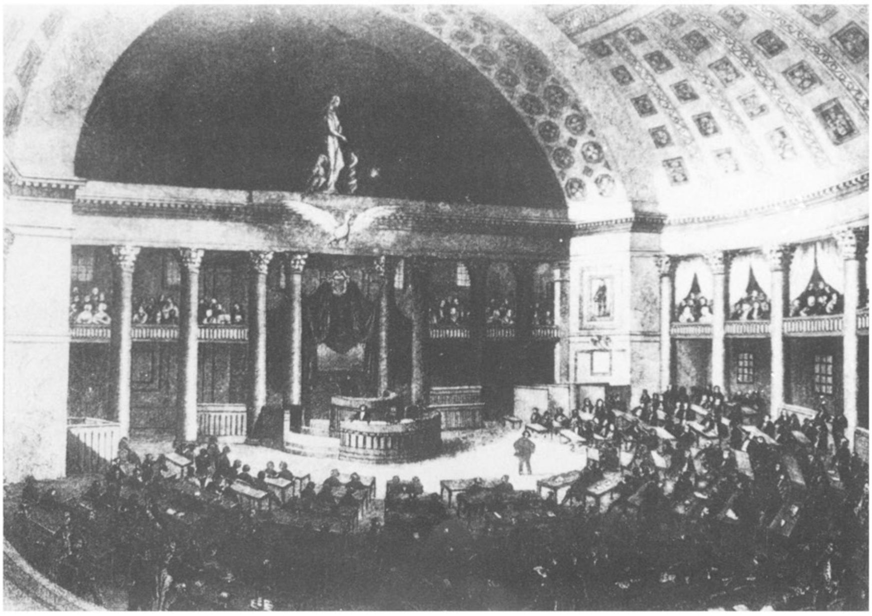
16.4 The chamber of the House of Representatives in the U.S. Capitol had the centers of the arch and half-dome at about the same level as the heads of the congressmen. This engraving shows draperies hung between the columns of the gallery, but such corrections were not sufficient to overcome the acoustical problem. (G. Brown, *History of the U.S. Capitol,* 1899–1900.)

> 3. It is probably also refracted. Its peculiar properties are not so well understood.[10]

Most of Robert Mills's technical knowledge came from his early association with Benjamin Henry Latrobe, who had endeavored to solve some of the acoustical problems of the U.S. Capitol before it was burned by the British during the War of 1812. When Latrobe contributed the article on "Acoustics" for the 1832 American edition of *The Edinburgh Encyclopedia*, he declared acoustical considerations to be particularly important in the United States, "a government in which public debate precedes every public measure."[11] Latrobe's explanation of room acoustics is firmly based on the geometric reflection of sound.

> The object then would be attained were the room so constructed that no secondary and subsequent echoes could reach the audience, or that they should be so weak as not to have any perceptible effect.
>
> The most effectual means, which could be adopted, would probably be, to prevent all echo excepting from the ceiling, by hanging the walls with drapery, or otherwise covering them so that they should not reverberate sound. Rooms, the walls of which are broken into sunk pannels enriched by relievos, or which are decorated with fluted pilasters, or otherwise so varied in their surface as to offer to the *rays* of sound, which in this respect resemble those of light, no regular mirror from which they can be uniformly reflected, are better calculated to render the voice distinctly audible, than those, the walls of which are unvaried in their surface. . . .
>
> I cannot help regretting that the abuse, attributed to the use of pictures and statuary in churches, has expelled them from most of the religious edifices of our country. Independently of the operation of sensible representations of the objects of our veneration or faith on our minds, pictures and statuary have a great effect in suppressing interfering echoes in churches.[12]

Latrobe provided no standards by which other architects might determine in advance the extent to which reflective and absorptive surfaces would be required. He discussed geometric principles at length, and the corrective functions of soft or diffusing treatments were emphasized, for these indefinite standards were the



16.5 In 1826 Robert Mills's recommendations for correction of the acoustics of the House of Representatives contrasted the existing conditions (upper drawing) with his proposal of a curved back wall (lower drawing). Six years later Mills proposed raising the floor and reversing the seating in the chamber. ("Alteration of Hall, House of Representatives," Rep. No. 495, 22d Congress, 30 June 1832. Courtesy of the Architect of the Capitol.)

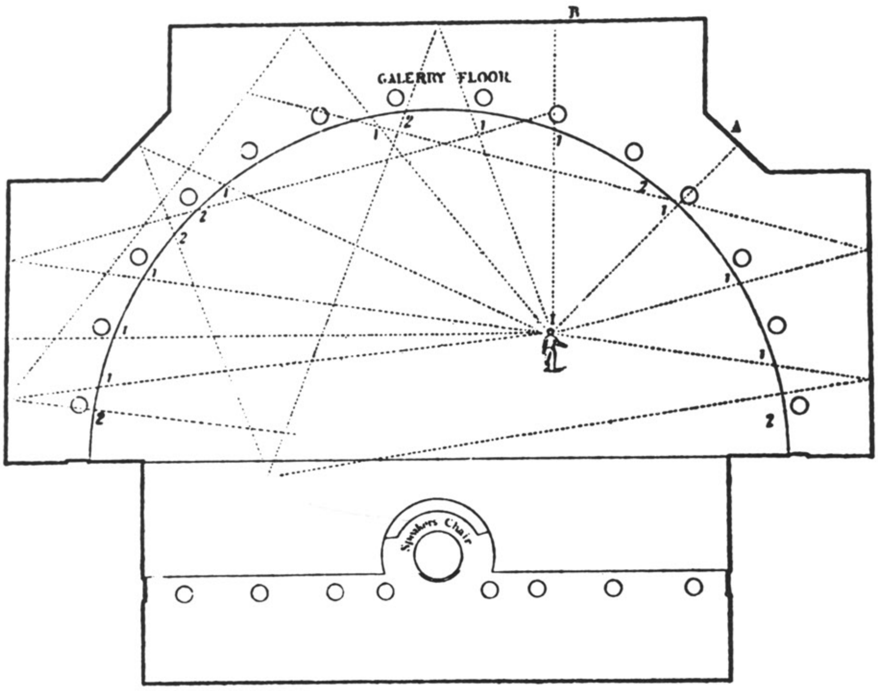
period's response to failures of acoustical design. While the most common practice of the time was the addition of absorptive materials, when that failed efforts were made to reshape rooms.

When the U.S. Capitol was rebuilt after the War of 1812, the Hall of Representatives suffered even more acoustical problems than its predecessor, which had received Latrobe's attention (fig. 16.4). Dr. William Thornton, designer of the original building, recommended hanging heavy curtains to absorb the sound, the same advice he had offered 12 years before for the previous hall. After the room had been occupied only a year, the bothersome conditions were attributed principally to dampness within the new construction, but draperies were hung between the columns and the gallery floor was covered with carpet. The following year complaints were renewed, and a congressional committee sought advice from a variety of sources. Charles Bulfinch, Capitol architect, in 1822 recommended that a flat ceiling of fabric be stretched beneath the dome, a solution said to have been taken from Saunders's book on theaters. This was done and was successful in ending echoes, but it drastically reduced the available light and absorbed so much sound that speakers could hardly be heard. After only a few days the fabric was removed. Wooden walls were built between the columns, but these too were soon removed.[13]

For more than 15 years there were complaints from the congressmen, recommendations from all sides, and no successful solution. Then Robert Mills executed a solution that had been proposed long before. He raised the floor a distance of about 4 feet, to the top of the pedestals upon which the columns stood. The center of the domical ceiling's curvature had been at almost the same height as speakers' heads, and therefore elevating the floor served to reduce the focusing of sound as it was reflected from the dome (fig. 16.5).[14] Mills also recommended reversing the arrangement of the representatives' seats so that the speaker's chair would be in the center of the semicircular colonnade, but this scheme was used for only one session. Complaints continued throughout the years that the House of Representatives met there and ended only when the space was converted to use as Statuary Hall.

Churches were often plagued by acoustical problems. The elaborate carvings we see directly above the pulpits of Baroque churches could fulfill little more than a decorative function, for they reflected little sound toward the pews. Later great faith was placed in the use of sounding boards, sound-reflecting surfaces set at speakers' positions to direct the sound of a voice toward its audience. Usually of light wood construction, sounding boards in churches were intended to bolster the preacher's voice so that it could be clearly heard in the pews at the rear of the nave. Speaking before the Royal Institute of British Architects in 1860, T. Roger Smith stated the common practice:

> It will be readily understood that a slanting reflector overhead, to beat downward and forward rays of sound that would otherwise escape towards the ceiling and be lost, is likely always to do good, and can in no case be so injurious as one behind the speaker; and it need scarcely, I think, be added that the only reflectors that *can* be of advantage are those that throw the sound forwards in the same direction as that in which the speaker is speaking. An echo reflected down from a high ceiling, or worst of all, back from an opposite wall, will always be disagreeable.[15]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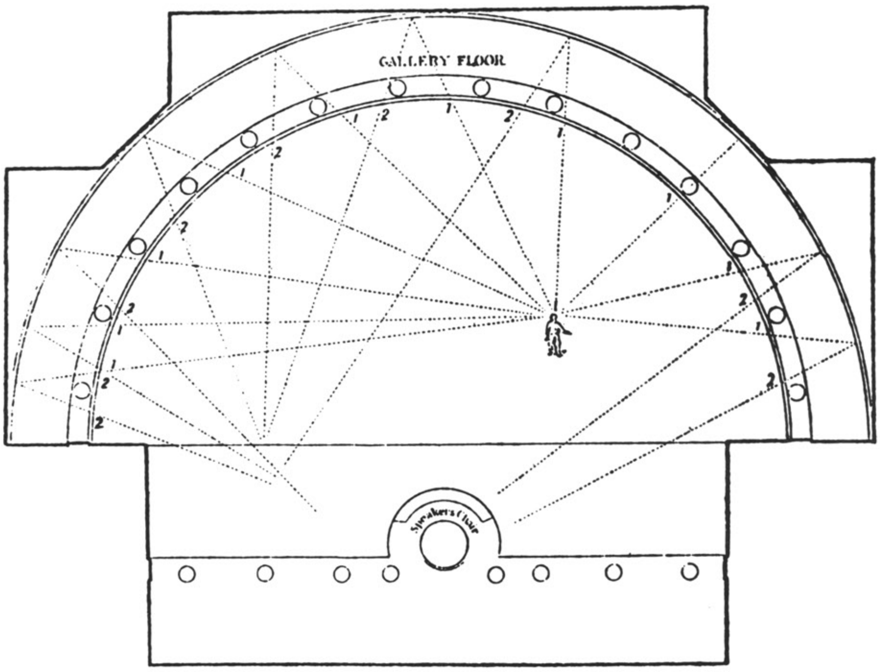
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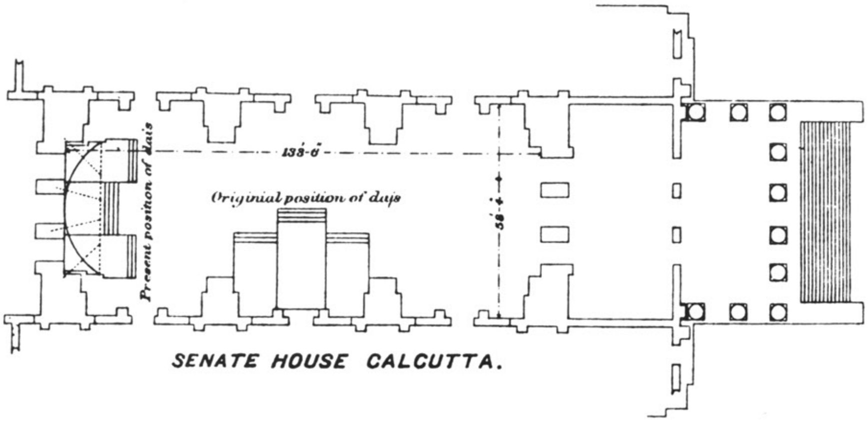
16.6 In the Hall of the Senate House, University of Calcutta, where graduation ceremonies were conducted, a trial reflector was made in 1896 of tin sheets mounted on a framework of iron angles. The final version attempted to gain resonance through a 2-inch space between its wooden front surface and a tin back surface. The shape is a truncation of a paraboloid with its focus 5½ feet above the floor of the dais and its axis directed toward the floor at the opposite end of the hall. (*Indian Engineering*, 21 March 1896).

Sometime before 1829 the Reverend John Blackburn, finding it difficult to make himself heard in his church, had erected behind the pulpit "a sounding board like a hood—parabolic in section, with his head in about the focus of the parabola."[16] The parabolic form was chosen because rays radiating from the focus would be reflected as parallel rays extending the length of the church. Apparently Blackburn's scheme fulfilled its purpose, for we are told by Smith, "The congregation were now able to hear the preacher, and the remote seats of the church became some of the best." Blackburn published his design in a small pamphlet that was circulated to scientific groups, and a model was presented to the Royal Society of Arts. The carpenter who had built Blackburn's reflector went on to construct at least 29 others. However, these sounding boards were spoken of as being "villainously ugly," and most were dismantled soon after they were built. Indeed, many clergymen found the parabolic reflectors to be more bothersome than beneficial. Not only did the preacher's head need to be kept at a relatively constant position within the sounding board, but the parabolic form received sound in the reverse of the manner in which it projected sound. One visiting clergyman who preached in a Cambridge church having such a reflector reported that he was startled by the clarity with which he heard "the whisperings of the charity children in the remotest part of the west gallery."[17]

A similar device was constructed in 1895 to correct the acoustics of a long rectangular room used for the annual graduation convocation at the University of Calcutta (fig. 16.6). A large, shallow paraboloid dish was constructed on an iron framework. The diameter of the reflector was about 37 feet and its concavity had a depth of about 10 feet. After a first trial model of this giant reflector had been constructed and found helpful during one graduation, a permanent reflector was built, its front surface covered with thin boards of teak and the back covered with sheets of metal. It was believed that this double surface and the air space between would provide a useful resonance.[18] In practice it was discovered that, as with Blackburn's reflectors, should a speaker shift his position appreciably, acoustic conditions were little better than before construction of the reflector.

Not all acoustical problems were those of an inadequate strength of the sound. When Thomas U. Walter in 1832 began construction of Girard College in Philadelphia, an institution for training "poor white male orphans, between the ages of six and ten years," his design was severely restricted by the stipulations of the will left by Stephen Girard, the leading American banker of the period. In extraordinary detail the college's benefactor spelled out the plan of the buildings that were to be built and the materials and methods that were to be used in their construction.[19] The architect had little choice but to follow those instructions, although problems of reverberation in the classrooms were evident early during construction. In his final report to the building committee Walter commented wryly: "As Mr. Girard left no discretionary power in reference to this part of the design, we were compelled to take the letter of the will as our guide, let the results be what they might."[20] The result was eight classrooms, each 50 feet square, 25 feet high, and having vaulted ceilings. When J. B. Upham, a Boston physician who wrote on architectural acoustics, visited the college in 1847 he found that the reverberation of a

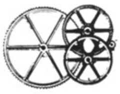


SENATE HOUSE CALCUTTA.

sound in these rooms lasted 6 seconds, a noisy condition that prevented the rooms being used for classes. The usual corrective procedure at that time would have been the introduction of carpets and curtains to absorb sound waves. Such furnishings were not, however, appropriate to the use of the rooms at the institution and other means were found. Upham described the results:

> In one room, which had been treated simply by papering upon the solid walls and extending festoons of cotton cloth from the apex of the dome to the corners and centre of the cornices on each side, the reverberation was reduced to four and a half seconds; and in others, in which a partition of cloth was stretched across the room horizontally, from the opposite cornices, thus completely shutting off the arched ceiling of stone, and substituting a level surface of yielding canvas, its duration was only half a second. By whose suggestion these simple contrivances were tried, we could not learn, but presume they originated with the skillful architect of the building.[21]

The solution was not unusual. It had been used about three decades before in one of the attempts to correct the foul acoustical conditions of the Hall of Representatives in the U.S. Capitol.



By the middle of the nineteenth century a general knowledge of architectural acoustics was established, partly theoretical and partly empirical, that permitted a designer to avoid disastrous acoustical conditions. Nevertheless, there was no method by which predictive study of conditions could be used to enhance the acoustical characteristics of a space. In fact, early in the nineteenth century it was said that when a friend told a prominent English jurist that he wished to build a room with splendid acoustics, the justice immediately warned, "Then be sure you don't tell your architect so!"[22]

Some believed that a semicircular hall, modeled after Greek and Roman amphitheaters, provided an ideal form, although this view may have resulted largely from an infatuation with classical examples or from the fact that an audience seated around a 180° sweep would be nearer to the speaker than in most rectangular arrangements. Others opposed circular or semicircular forms with equal fervor. Two major English architects at the start of the nineteenth century held contrary views:

> [Sir John] Soane.—Is it not probable that you will be more successful in having a good sound by having a circular end than by having square sides? Yes, you will find that in the Olympic theater at Vicenza there is a circular end; so had all

> the ancient theaters, both Greek and Roman. . . . [I have] concluded that shape to be peculiarly favorable to hearing.
>
> [Sir Robert] Smirke.—I think if the circular form were preserved . . . above the proposed seats, it would be a very inconvenient room for hearing; there would be in all probability such reverberation of the voice, that it would be scarcely possible to hear with distinctness.[23]

For rectangular rooms there was a strong belief that acoustical conditions were improved by having a simple ratio among the room's dimensions, a typical Renaissance recommendation for obtaining proportions that were visually harmonious. The ballroom at Buckingham Palace was considered excellent for musical performances, and this was attributed to the fact that its dimensions were about 110 feet by 60 feet by 45 feet, nearly a relationship of 8:4:3. Simpler ratios were commonly recommended , such as 2:3:5 or 2:3:4, just as they had once been preferred for esthetic reasons. In the discussion following Smith's paper at a 1860 meeting of the Royal Institute of British Architects, John Scott Russell made the proud announcement that a hall to be built at the University of Edinburgh—the dimensions determined by a professor of science—had been set at 96 feet in length, 48 in width, and 32 in height (6:3:2), "the three proportionate numbers of musical harmony."[24] Much later Wallace C. Sabine was to point out that in a great many halls it was impossible to determine if the measurements to be considered in calculating proportions should be taken at the front or rear of balconies and stage platforms.

There was even debate on the materials to be used in building a hall. Some, many musicians among them, swore that only wood could produce the desired resonance, and here the recurrent analogy of the violin is evidenced. Others accepted plaster and stone.

There was also an inexplicable belief that wire strung overhead across a hall would counteract undesirable acoustical conditions that were due to reverberation or would vibrate in sympathy with a speaker's voice, thus strengthening the sound. Wires were to be seen in many English churches at the turn of the century, and a troubled lecture room in H. H. Richardson's Sever Hall at Harvard University had a multitude of overhead wires. A British physicist later remembered that wires were one of the first remedies proposed by architects in the period before World War I.

Although the belief strangely persisted that wires could augment or clarify sounds in an auditorium, the most imaginative extension of this notion seems to have been proposed in England around 1880. Inspired by the examples of the sounding boards of stringed instruments and the vibrations of tuning forks, a man named Engert invented a complex acoustical contraption of wires and springs. A report on one demonstration described the hall: "One or more layers of steel wires were stretched along a [room] lengthwise, connected by cross wires and spiral springs, and properly tuned, so that the vibration may be absorbed and conveyed from one to another, and instantaneously spread over the whole building."[25] Another report described what is apparently a different system devised by Engert. In this case five boxes fronted with louvers were located at the back of the stage and two were placed in front of the orchestra. Each box contained five steel plates of different dimensions, placed about an inch apart and suspended by wire springs. These were claimed to resonate with different tones of the music, thereby reinforcing the sounds produced by orchestral instruments. Unfortunately observers attending Engert's demonstrations were unable to detect significant changes in the acoustical quality of the performances due to the devices provided by the inventor. In fact, the *Builder* complained that Engert's demonstrations were held in halls that had no apparent acoustical flaws. Soon mention of these intricate schemes, examples of both the wire theory and the musical instrument analogy, vanished from the architectural press.

Constant references were made to the resonance of musical instruments, particularly stringed instruments. A French consultant as late as 1933 compared concert halls and instruments, saying: "All enclosed space, of the size of a violin or that of a concert hall, in order to send out a pure sound wave or to resonate without echoes, must have the form of two cylinders."[26] He went on to compare that form with the violin, the Mormon Tabernacle in Salt Lake City, and the Salle Pleyel in Paris.

When Charles Garnier was designing the Paris Opera House in the 1860s, he grew concerned about the acoustical properties of the dome over the hall. His study of the problem was not easy:

> It is not my fault that acoustics and I can never come to an understanding. I gave myself great pains to master this bizarre science, but after fifteen years of labor, I found myself hardly in advance of where I stood on the first day. . . . I had read diligently in my books, and conferred industriously with philosophers—nowhere did I find a positive rule of action to guide me; on the contrary, nothing but contradictory statements. For long months, I studied, questioned everything, but after this travail, finally I made this discovery. A room to have good acoustics must be either long or broad, high or low, of wood or stone, round or square, and so forth.[27]

For advice he consulted Charles Joseph Sax, the famous Belgian instrument maker. Asked whether a metal dome would be less desirable than a traditional dome of stone, Sax stated categorically: "The nature of the material used for this dome should have no influence on the reverberation of the sound."[28] Indeed, in spite of Garnier's frustration with the mysteries of architectural acoustics, the dome appears to have contributed to the conditions that make the Paris Opéra one of the better halls of Europe.

There was great concern about the influence the movement and temperature of air might have on sound waves. Certainly, anyone who had shouted far across an open field knew that the sound carried farther with the wind than against it. As a result there were often proposals that air brought into auditoriums for purposes of heating or ventilation should originate in the vicinity of the stage and be withdrawn at the opposite end of the hall, carrying sound waves along as it traversed the length of the auditorium. A physicist at Johns Hopkins University in 1878 published results of an experiment that seemed to show that listeners, unaware of the change, detected distinct and unfavorable alterations in an orchestra's sound after the hall's fans had been reversed to no longer draw air from the stage.[29] At the end of the nineteenth century this logic was recommended by some for the new Boston Symphony Hall, designed by Charles McKim. Wallace C. Sabine, acoustical consultant to the architects, calculated the influence of air movement in such circumstances as being about the same as a forward tilt of the listener's head, and he curtly pointed out that "the problem of properly heating and ventilating a room is sufficiently difficult in itself."[30]

In addition, there were observed difficulties in sound waves crossing zones of very warm air. This appears to have been a genuine and frequent problem at a time when public spaces were often heated by stoves placed in the center of the floor. A member of the House of Commons complained to David Boswell Reid in 1835 that when the large stove beneath the middle of that chamber sent up a current of hot air through the floor grill, a speaker on the opposite side of the room became almost inaudible, though he had been clearly heard before the heater started. Another instance was reported to Sabine by William LeBaron Jenney, the Chicago architect who built the first skyscraper. Consulted regarding a courtroom in which observers could not hear judges, lawyers, or witnesses, Jenney diagnosed the problem as arising from the placement of a stove between the major areas of the courtroom and also between two doors, one on each side of the courtroom. A band of air moving through the doors and toward the heavy upward draft of the stove appeared to be the muffling obstacle, and Jenney recommended "that the stove be removed and that the warm air should be let into the room from steam coils below."[31] This phenomenon, which Sabine explained as resulting from both reflection and refraction of the sound waves as they experienced a radical alteration of air temperature, became a less significant problem during the late nineteenth century. In his advice about the courtroom Jenney had forecast the solution, for the development of improved methods of heating and ventilating replaced the use of central stoves and so eliminated such problems.

16.7 The isacoustic curve, as presented in John Scott Russell's lecture in 1847, recommended that the floor of a hall should be shaped so that rays representing sound would pass 18 inches above a head in the row in front of a listener. (*Edinburgh Philosophical Journal*, 1838.)

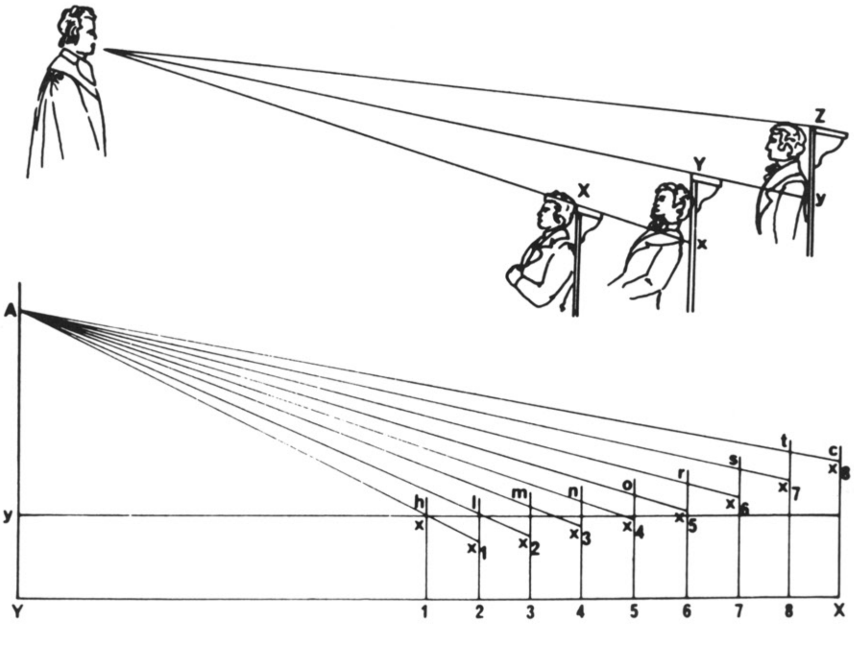
* * *

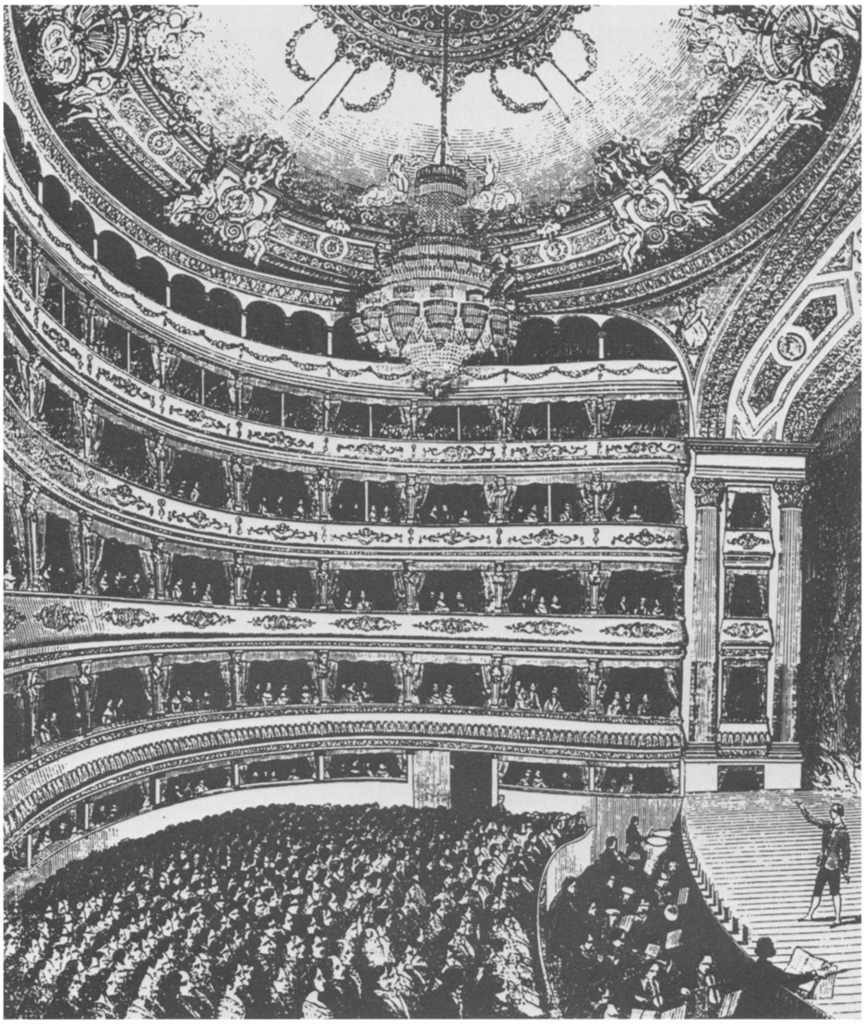
From the time of Newton's development of a value for the velocity of sound in air (*Principia*, 1687), the attention of physicists and mathematicians was directed toward the phenomena of sound and hearing. By the early nineteenth century, fairly reliable measurements had been made for the speed with which sound traveled through water and metals, as well as air and other gases. The production of sound was investigated by study of the basic tone-producing elements that were present in traditional musical instruments, vibrating strings, open and closed pipes of air, bars of metal, and taut membranes like drum heads. Fundamentals and harmonics were identified, and the relationship between pitch and frequency was established. This patient investigation was part of that period's exhaustive scientific study of all phenomena; and it may also have been influenced by the musical enthusiasms of some gentleman of science. At the same time, economic interests of trading nations encouraged the study of the ocean wave's action against ships and the sounds of warning bells in heavy fog.

When John Scott Russell, a young professor of natural philosophy and geometry at the University of Edinburgh, was approached around 1835 by businessmen to study the possibility of using steam power to move barges on the Edinburgh and Glasgow canal, he was assigned an unused section of canal in which to study the wave phenomena that often impeded the movement of barges when they were pulled too rapidly by horses. Russell had been born in the Vale of Clyde near the shipbuilding fringes of Glasgow; although studying to follow his father's life as a minister, his summers had been spent working in engineering shops, and his keen interest in science was not neglected. When he was 27 years old, Russell delivered his first paper on waves, and he also completed his first ship as the new manager of the Greenock shipworks near Glasgow. Several ships later, including work in collaboration with the foremost British engineer, Isambard Kingdom Brunel, Russell moved to London where he continued his study of ships' hulls and became a leader in shipbuilding.[32]

In 1847 Russell delivered an address, "On the Arrangement of Buildings with Reference to Sound," to the assembled membership of the Royal Institute of British Architects. In his book *Waves of Translation in the Oceans of Water, Air and Ether*, Russell treats sound waves in the "air ocean" in the same terms as waves in the sea. Little direct application is provided for architectural conditions, and one can only ponder the manner in which Russell may have developed the extremely specific recommendations he presented to architects. The lecture was not published at the time it was delivered, and therefore it had little immediate influence, but 11 years later it appeared in three issues of the *Building News*, as reconstructed from an editor's notes made during Russell's lecture.[33] This publication seems to have reached many eyes and to have become part of architects' working knowledge of room acoustics.

Russell's first principle was the isacoustic (equal hearing) curve, which he had first presented in the *Edinburgh New Philosophical Journal* for 1839 (fig. 16.7). Based on the same logic as that employed to determine lines of sight in theaters, the isacoustic curve derived the slope of an auditorium floor through the requirement that a line from the speaker's mouth to a listener's ear should pass 12 to 18 inches above the ear of a listener in the next row forward. (To avoid excessively steep floor slopes in large halls, the isacoustic curve was often laid out with much less clearance above the head of the person in front.) In addition, Russell stated that each row of seats should be arranged as a circular arc having its center at the speaker's position. This system was claimed to have the advantage of "simply taking the great body of sound and dividing it equally between all the hearers," although this could not actually be the case, due to the reflection of sound





16.8 Theaters or opera houses, such as Covent Garden, had their floors and walls covered with seats, boxes, balconies, and audience, leaving only the ceiling surface bare. This arrangement provided ample absorption of sound and brought the listeners near to the stage. (*Builder,* 10 April 1847.)

16.9 In the Chicago Auditorium (Adler and Sullivan, 1889), the successive surfaces of the proscenium arch extend almost to the midpoint of the seating area, including the balcony levels. In addition to helpful reflection of sound waves and providing a relatively low ceiling, this shape fulfilled Adler's dictum on "formation of a stage picture." (P. E. Sabine, *Acoustics and Architecture,* 1932.)

and the fact that the strength of the sound would necessarily diminish as the distance between the speaker and the listener increased.

The second principle stated by Russell had to do with room dimensions. As was common in that day, the length and breadth of a room were associated with musical tones ("thirty feet long gives out C natural") and dimensions that were arithmetically related were believed to make certain that the sound could be clearly heard throughout ("forty-eight feet long, twenty-four feet wide, and sixteen feet high . . . the room will be easily voiced").[34]

As a third principle, Russell stated the well-established fact that sound is reflected at an angle equal to that at which it strikes a surface. Like Latrobe, "he thought it desirable that the voice should be but once heard, and that echoes should be entirely got rid of."[35]

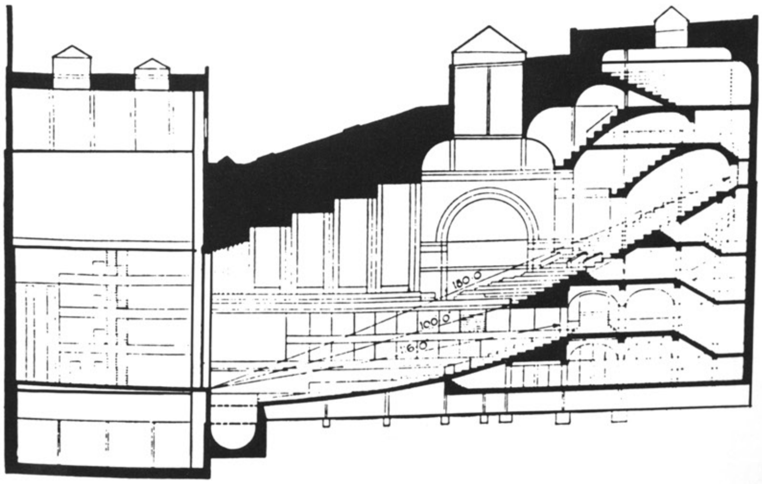
For curved spaces, the "following" action found in domes and their whispering galleries was explained by Russell's having observed that ripples of water approaching a wall at a small angle tend to follow the wall instead of being reflected. For the horseshoe-shaped plans of opera houses Russell recommended that the boxes around the back wall should be separated by partitions and drapery should be hung to prevent the reflection of sound waves from their back walls.

A somewhat different view of reflected sound had been stated in 1835 by David Boswell Reid, a British scientist better known for his study of ventilation: "In the most perfect form of building for the communication of sound, any reflected sound must be prevented from continuing so as to interrupt any new tone by being thrown upon a non-reflecting floor. So long as the reflected sound comes up in time to strengthen the primary impulse before any new sound is heard, it is to be taken advantage of; beyond that it is injurious."[36] Having measured reverberation times as long as 7 seconds in hard-surfaced rooms, Reid recommended auditoriums be built with low walls, high pitched ceilings, and floors covered to absorb sound. This viewpoint was later supported by Joseph Henry, director of the Smithsonian Institution, in describing his preparation for the construction of the Institution's lecture hall in Washington.[37] Through experiments made by clapping his hands before hard smooth walls, Henry concluded that a distance greater than 30 feet from the wall resulted in an identifiable echo, making one-sixteenth of a second the limiting interval between two sounds. Clarity of hearing, he said, depended on four factors: room size, strength of the sound, placement of reflecting surfaces, and the materials of these surfaces. These are in essence the variables found in much modern acoustical calculation.

* * *

Early theaters with several balconies and ceilings nearly flat had few echoes, because the audience was brought close to the stage and most of the surfaces were made absorptive by the vertical tiers of audience. For eighteenth-century theaters and concert halls, domed ceilings became popular. By the nineteenth century, theaters had fewer balconies, sometimes only one. These changes in theater design brought increased acoustical problems, both in the amount of sound reflected and the geometry of the hall.[38]

A notable application of Russell's isacoustic curve was the Auditorium in Chicago, where music had become a part of civic ambition. Opera started in Chicago in 1850 with a performance of Bellini's *La Somnambula*, and in the period before the Chicago fire English, Italian, and German troupes vied for the public's ear. Chicago's Central Music Hall was designed in 1879 by Dankmar Adler, a young architect who had just established his own practice. Another music hall had



been designed by Adler about seven years before, and it seems to have been his first venture into a building type for which he was to become justly famous. The Central Music Hall's acoustic qualities were widely admired and helped establish a local reputation for Adler in that architectural specialization. When a board of public-spirited citizens in 1884 began planning the first Chicago Grand Opera Festival, there was no hall available large enough to seat the audiences that were required if the performances were to be financially successful. An ingenious solution was found when the board engaged the architectural firm of Adler and Sullivan—for young Louis Henry Sullivan had become Adler's partner—to construct a hall of 6,000 seats entirely within the Interstate Industrial Exposition Building, located where the Art Institute now stands. Only five weeks and about $60,000 were available for construction of this temporary opera house. The festival was a cultural and financial success, in spite of the moderate prices charged for tickets. The following year Adler and Sullivan built similar facilities inside the Milwaukee Exposition Building, seating 10,000 and having a stage large enough to hold the massed choruses of the North American Sänger-Bund. This auditorium too was admired for its acoustics.

When Chicagoans, encouraged by their success in presenting opera, organized to build a suitable permanent hall for musical performances, Adler and Sullivan were the architects to whom they turned (fig. 16.9). The Chicago Auditorium was planned with offices, a hotel, and retail establishments, in addition to the performance hall that had originally suggested the project.

In a paper read at the annual convention of the American Institute of Architects in the year that his firm received the Auditorium commission, Adler stated the acoustic principles on which he worked:

> It should be said, in a general way, that in the construction of the banks of the seats, Scott Russell's isacoustic curve should be adhered to as far as practicable. That wherever possible resonant materials should be used in the construction and facing; that large, hard, smooth surfaces should be avoided; that walls and ceilings should be well broken; that the width and height of the house should be least at the stage, and that these dimensions should be increased with the distance from the stage, and that all our measures should tend toward the reduction to a minimum of the volume of air to be set in motion by the voices of speakers and singers. . . .
>
> I will add in this connection that a comparatively low proscenium . . . is desirable as one of the first conditions of this system of construction for acoustic effect. . . .
>
> A modification of Scott Russell's isacoustic curve should be used in laying out the banking of the seats. This modification . . . consists in shifting the level of the focus to which the curves are drawn from the level of a speaker's mouth to the floor-line at the front of the stage, and in substituting for a single focus to middle of the stage, foci tending toward the sides of the curtain opening for the respective sides of the house. . . . [39]

In this and other writings on theater design, Adler stressed the logic behind the features that identified the theaters of Adler and Sullivan: the deeply splayed proscenium arch reflecting sound to the audience; a ceiling springing from the top of that low arch, limiting the volume of the hall and directing sound toward the rear; and a floor sloped steeply enough to allow ample visual and auditory connection between performers and audience.[40]

When completed in 1889, the Auditorium proved the wisdom of these measures, but the transverse arches of the ceiling concentrated sound toward the center seats and the hall's size (4,237 seats) demanded that the orchestra sacrifice subtleties of interpretation to the production of volume. The Schiller (Garrick) Theater, completed about two years later, was more successful. This record of accomplishment led to Adler's being called as acoustical consultant on Andrew Carnegie's Music Hall in New York, for which the architect was William B. Tuthill, himself well versed in acoustics.

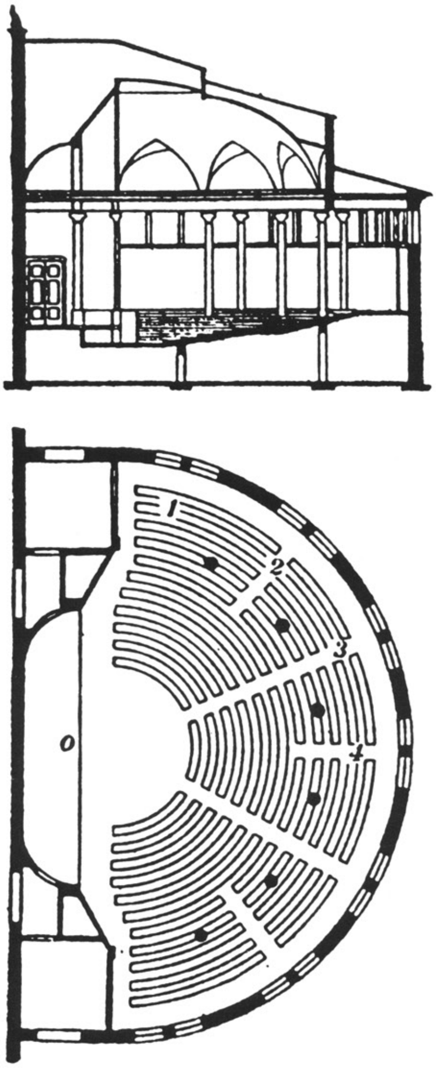
* * *

In 1891 the widow of William Hayes Fogg, a merchant, died in New York, leaving Harvard University funds to build and maintain a small museum to house the university's meager art collection. Designed by Richard Morris Hunt, the original Fogg Museum building (later assigned to other functions and renamed Hunt Hall after its architect) included gallery rooms and a semicircular lecture hall, which was to some extent modeled after the classical theater. It was to be a modest building placed among a polyglot group of architectural examples. For the Fogg Museum, Hunt chose a rather pure and refined classicism, stricter in style than the mansions he had built for the Astors and Vanderbilts and more restrained than his Administration Building at the Columbian Exposition in Chicago. No one has suggested that the design has particular merit among Hunt's works.

The lecture hall of the Fogg Museum had been included in the building program principally to provide space for the lectures on art history that were delivered by Charles Eliot Norton, then approaching retirement from his professorship at Harvard University. These lectures, described by his son as "Lectures on Modern Morals as Illustrated by the Art of the Ancients," were presented with a heady mixture of charm and sarcasm that attracted large numbers of students. To Professor Norton's dismay the lecture hall of Fogg Museum when completed was ill suited for lecturing because its acoustics were dreadful. Norton, who had long ridiculed the jumble of architectural styles built at Harvard during his decades there, did not hide his dissatisfaction with the lecture hall: "Had it been intended as an example of what such a building should not be, it could hardly be better fitted for the purpose." Declaring the building to be an indication of the "lack of civilization" in the United States, Professor Norton refused to lecture in the room.[41]

The president of Harvard University, Norton's cousin Charles Eliot, tolerated the controversy about the Fogg Museum, even when student pranksters painted "Norton's Pride" in red letters on the walls of the museum. Eliot had studied and taught mathematics and science, and it was not surprising that he should call upon the scientific resources of the university to relieve his embarrassment. He assigned the task to Wallace C. Sabine, a 27-year-old instructor in physics. The investigation that followed would establish the quantitative science of architectural acoustics, replacing rules of thumb that had been used through most of the nineteenth century.[42]

The lecture hall of Fogg Museum was semicircular in plan and most of its seating fell under a half-dome (fig. 16.10). The floor was gently sloped, and a semicircle of columns set off an



16.10 The acoustical shortcomings of the somewhat classical form of the lecture hall in the original Fogg Art Museum, Harvard University (Richard Morris Hunt, 1895), were the focus of investigations begun soon after the building was completed. Equipped with an organ pipe and almost 1,500 seat cushions from another hall, Wallace Sabine studied the hall's reflection and absorption of sound, working "every second or third night for two months." (*American Architect and Building News*, 21 April 1900.)

aisle around the back of the hall. Acoustical conditions within the lecture hall were such that when it was empty a word spoken in an average tone faded away only after a bit more than 5½ seconds, interfering with the intelligibility of several syllables that might follow. If a full audience were present, there was a slight improvement, but reverberation still made it almost impossible to endure a lecture.

Looking around for readily available absorptive materials, Sabine brought loose seat cushions, hair stuffing covered with fabric, from another Harvard auditorium and stored them in the vestibule of the lecture hall. In all there were about 1,500 cushions, enough to cover all the seats, aisles, speaker's platform, and the back wall of the room and allow some additional cushions to be hung from the ceiling in the final stages of experimentation. Working late at night so that the sounds of carriages in the streets would not interfere with his measurements, Sabine started by placing 27 lineal feet of cushions on the front row of seats and again timing the reverberation. Row by row, cushions were added to the lecture hall, and measurements of the reverberation were made as the room was gradually padded. The results were plotted as a graph, a hyperbolic curve that indicated the relationship between the number of cushions used and the reverberation of the museum lecture hall. To extend his data, Sabine removed the cushions and tested other materials. He draped chenille about the room, rolled out heavy Oriental rugs, hung pads of hair felt, and filled the seats with listeners, men and women in separate tests. For each change, measurements were obtained as they had been for the seat cushions. But since the characteristics of these materials could be mathematically related only to a number of cushions borrowed from another auditorium, a more appropriate unit of scientific measurement had to be found. This was accomplished by opening the windows of the lecture room. Assuming open windows to provide the ultimate level of absorption, the performance of cushions and other materials was mathematically related to them.

When measurements had begun on the Fogg Museum lecture hall, it was suggested that rough troweling or a sand-finish of plaster on the walls might solve its problems. Sabine showed that textural variation was useless when he scattered a layer of uniformly sized pebbles on the floor of a test room and found no appreciable change from the reverberation measured with the concrete floor bare. The young physicist experimented with other rooms and often repeated tests as his techniques and equipment improved. He was assigned a Harvard laboratory that had been originally constructed underground for experiments requiring a constant temperature, made possible by structurally isolating it from the remainder of the building. This made it possible for much of his testing to take place during the day, protected from outside noises.

By 1900 at least a dozen faulty spaces on the Harvard campus had been studied by Sabine, and his fund of data had greatly expanded. In less than five years he developed a formula for the prediction of reverberation time, analyzing the contributions of absorptive or reflective materials that might be present. By that time his tables of the absorptive qualities of materials had grown to include even houseplants and oil paintings.

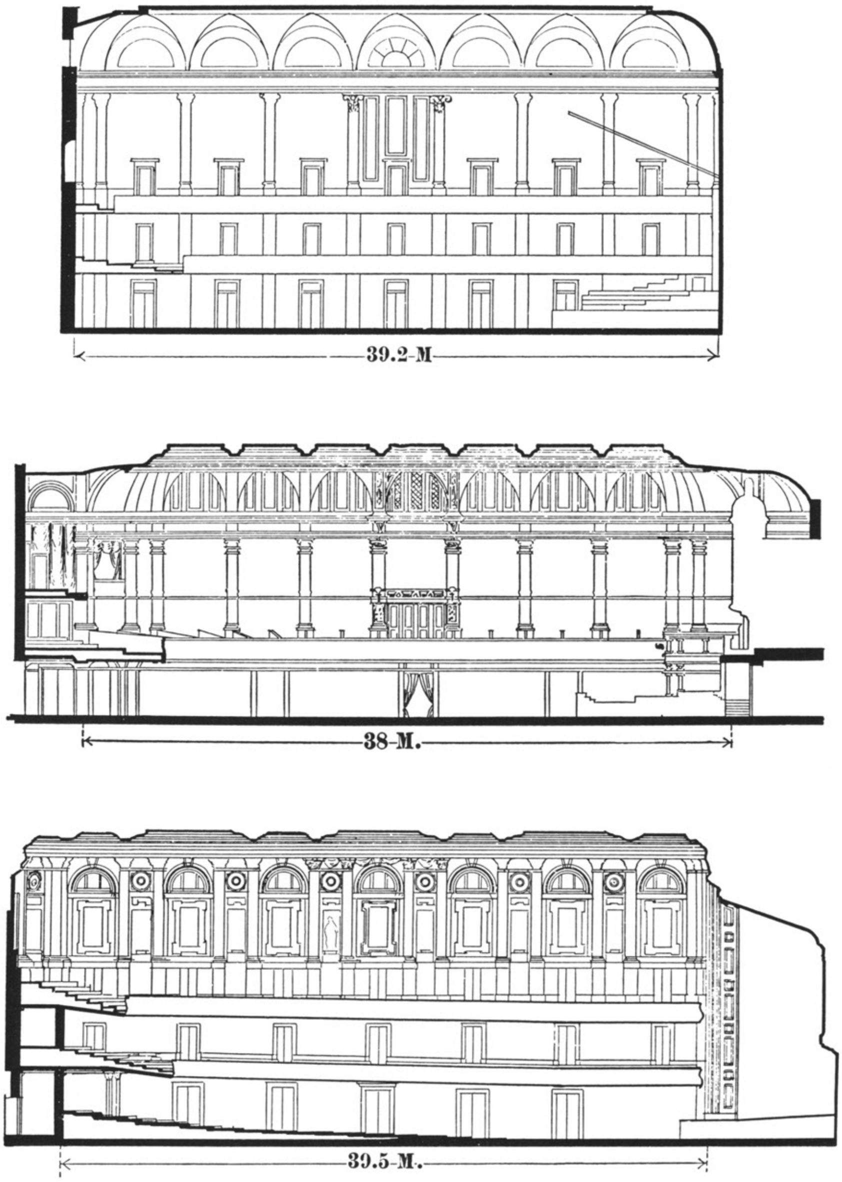
The remedy that Sabine applied to the lecture room in the Fogg Museum was rectangular panels of hair felt under thin sheets of asbestos paper, which were placed over rectangular sections of the upper walls and in the semicircular recesses of the ceiling. Although Sabine pronounced the results "entirely satisfactory," other corrective measures were made periodically until the building was demolished in 1973.

H. H. Richardson's Sever Hall, a neighbor of the Fogg Museum on the Harvard campus but built more than a decade earlier, was another subject for Sabine's diagnostic studies. It too had been a target for Professor Norton's scorn: "Its interior arrangement was sacrificed to its exterior appearance."[43] Sever Hall contained a large lecture room that was long and low-ceilinged, a shape that led to acoustical difficulties. When Sabine investigated the room, he found a profusion of wires stretched across the ceiling with lengths of cloth hanging from some of them. His diagnosis was that the wires had "the merit of being harmless," while the yards of fabric were "like bleeding a patient suffering from a chill."[44]

There was no shortage of acoustical problems in the Boston area. The Boston Public Library, completed by McKim, Mead and White a few years before the Fogg Museum, had a lecture hall that was an acoustical tragedy. Its hard surfaces sustained sound for almost 9 seconds. Sabine was called upon to remedy this condition. Sabine's work on this project, as well as Charles Eliot's recommendation, led to his being chosen as consultant on the design of Boston Symphony Hall, one of the world's greatest spaces for music.

Charles McKim had been approached to design a hall for the Boston Symphony in the fall of 1892, when he was deeply involved in completing designs for the Chicago Columbian Exposition. During the following summer McKim submitted drawings of three designs to Major Henry Lee Higginson, founder and perennial benefactor of the Boston orchestra. One design, much preferred by McKim, was laid out as a classical theater, semicircular in plan. Another was elliptical in form, and the third was a rectangular hall. Drawings of the classical scheme and a model of its interior were displayed

16.11 Top: old Music Hall, Boston (George Snell, 1863); center: Neue Gewandhaus, Leipzig (Martin Gropius and H. Schmieden, 1887); bottom: Symphony Hall, Boston (McKim, Mead and White, 1900). McKim's semicircular design for Symphony Hall, modeled after ancient amphitheaters, was abandoned; work on the project resumed after a delay of ten years. Although the committee wished to emulate Leipzig's new hall, some decisions were obviously influenced by the hall in which the Boston orchestra had performed for many years. (*American Architect and Building News*, 16 June 1900.)



in the Boston Public Library early in 1894, and it is reported that the design was favorably viewed by the public.

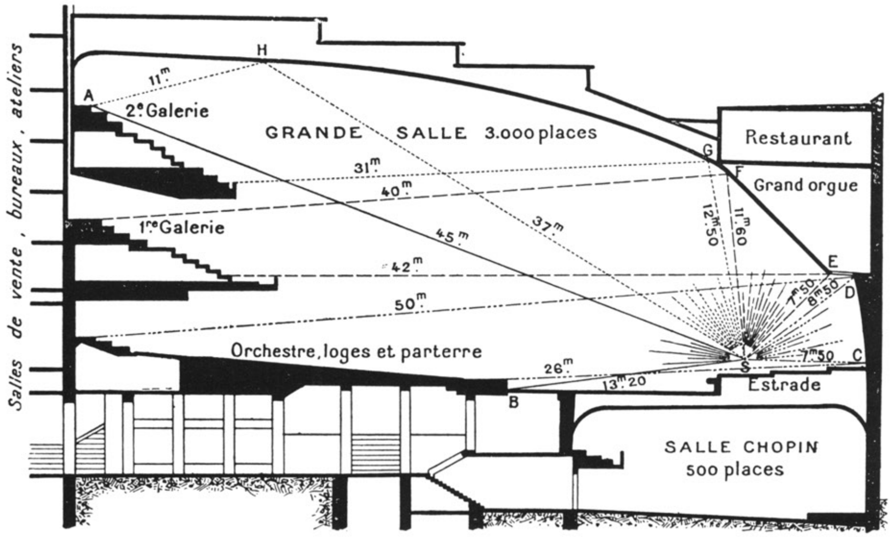
In the years before construction began, McKim visited Europe and had an opportunity to visit concert halls there. The celebrated Viennese conductor Hans Richter is said to have told him, "I don't know anything about acoustics, but my first violin tells me we always get the best results in a rectangular hall." Major Higginson and the directors of the Symphony resisted the semicircular scheme that McKim favored, perhaps because of their attachment to the rectangular shape of the old Music Hall in which the orchestra had been performing. Several years later a rectangular plan was chosen for Symphony Hall. That decision was strengthened by the acclaim given the Neues Gewandhaus in Leipzig (1887), said to be better for Bach and early Classical music than for Romantic works (fig. 16.11)

The Leipzig example was not closely followed in Boston. Symphony Hall seated an audience of 2,631, over a thousand more than were seated in the Neues Gewandhaus. The proportions of Symphony Hall were made much the same as those of the old Boston Music Hall, which was wider and lower-ceilinged than the Neues Gewandhaus. In describing the design of Symphony Hall, Sabine stressed the fact that the duplication of proportions cannot produce identical acoustical qualities. He pointed out: "Our increasing demands in regard to heat and ventilation, the restriction upon the dimensions enforced by location, the change in size imposed by the demands for seating capacity, have prevented, in different degree, copies from being copies, and models from successfully serving as models."[45] With all such differences of materials considered, particularly those required by new standards of fireproofing, Sabine adjusted the conditions in the new Symphony Hall to produce a reverberation time of 2.31 seconds according to his calculations, a figure almost the same as that for the Neues Gewandhaus.[46] (Sabine calculated the reverberation time of the Neues Gewandhaus from published plans; the reverberation time was, in fact, 1.9 seconds.)[47] Both models on which the Boston Symphony Hall was based had placed the orchestra platform within the hall, although the old Music Hall in Boston had a sloped reflective plane above the platform. In Symphony Hall the orchestra was placed in a shallow recess with splayed surfaces at the top and the sides reflecting sound toward the audience.

Sabine had begun in 1895 with the assigned task of searching for an escape from an embarrassing situation on the Harvard campus; only three years later he addressed the annual convention of the American Institute of Architects on his findings. From the many acoustical problems that were found on the campus, his work spread to include consultation with architects over a broad geographic area. More important, the articles he wrote for major American architectural journals (*American Architect and Building News*, 1900; *Brickbuilder*, 1914–1915) long served as texts for alert architects.

* * *

In the first half of the twentieth century few large concert halls were built and only one, Salle Pleyel, attracted attention. France's foremost manufacturer of pianos, the Pleyel company was directed by Gustave Lyon, an accomplished musician, graduate of



16.12 Although Gustave Lyon emphasized geometric acoustics, the Salle Pleyel, Paris (Auburtin, 1927), did not result in a hall of distinction. Similar forms were understandably fashionable among early functionalist architects. (*L'Illustration*, 10 September 1927.)

the Ecole Polytechnique, inventor of improvements in the piano, and ranking French expert on architectural acoustics.[48] Before his company undertook the construction of Salle Pleyel in 1927, Lyon had gained a reputation for imaginative solutions to acoustical problems. At the turn of the century he had been approached to organize annual series of symphonic concerts in the Trocadéro, a massive cylindrical building across the Seine from the Eiffel Tower. From the time it opened in 1878, the Trocadéro had been branded a failure as a hall for musical performances. Its acoustics were dreadful, there were not enough fire exits, and the toilets were totally inadequate.[49] Lyon wisely insisted that acoustical corrections be made before he assumed responsibility for scheduling concerts. Vaulting of stretched cloth had been installed above the stage organ, concave shapes that Lyon felt should be replaced by convex. After estimates revealed the prohibitive cost of merely erecting the scaffolding necessary for any change, Lyon found a startling alternative: "He had a cylindrical balloon made, almost ten feet long and thirty-two inches in diameter, along its length a rigid member made of aluminum. This balloon when inflated with hydrogen had an upward force strong enough to require a silk anchor cable. . . . The acoustics of the hall were found to be appreciably improved."[50] Lyon relied greatly on reinforcing sound by the reflective shaping of halls.

In Salle Pleyel the ceiling formed a giant parabola, curving upward from the rear of the stage platform to the ceiling of the second balcony (fig. 16.12). Side walls were canted to project additional sound toward the back seats. At the time, the French architect Le Corbusier was preparing his entry in the competition for the design of the Palace of Nations, the League of Nations' center to be built in Geneva. The plan and ceiling shape of the auditorium in his competition entry were those of Salle Pleyel, "conceived exactly after the principles of Mr. G. Lyon."[51] Incensed by the rejection of his design by a "dull-witted gang of architects affiliated with the Institute and some Academies," Le Corbusier wrote glowingly of Lyon's design for Salle Pleyel, citing it as an example of the new functionalist point of view: "Here today is the Salle Pleyel, it too is *the truth,* the truth of reality, the functioning truth, as opposed to the fake truth of the Institute; and the Institute is bent before this new irrefutable truth. There is the historical value of the Salle Pleyel: with neither ambiguity nor limitation, *it is true,* true as the aircraft that flies and the fish that swims."[52]

When the hall opened, the *New York Times* critic reported, "This immense auditorium possesses the most perfect acoustics that I have ever known. Never an echo, never an unpleasantly resonant sound."[53] But not all opinions have been so favorable. One American expert felt that the high ceiling caused a "slight interfering effect . . . during the very rapid movements."[54] Another said that sound waves returning from the back wall and balcony fronts produced echoes. It is interesting to note that drawings published by Le Corbusier in connection with the Palace of Nations competition showed a lower ceiling, while maintaining a generally parabolic form by using sections of four parabolas.[55] In analyzing the entries in the Palace of Nations competition, a Swiss expert wrote admiringly of the auditorium designed by Le Corbusier and Lyon, though he judged that the hall would have been too reverberant for its purpose since the ceiling and walls were proposed to be made of double layers of plate glass.[56]

* * *

After the ravages of World War II and the massive social and economic readjustments that immediately followed, the British proudly staged the Festival of Britain on the south bank of the Thames in 1951, the centenary of the Great Exhibition of Victoria's time. The focal point of this event and of the complex of cultural facilities that were built there later was the Royal Festival Hall, an auditorium seating around 3,400 for symphony concerts. From the first, external acoustical factors had to be considered along with internal conditions, for the site was near trains crossing Hungerford Bridge, and London's Underground ran directly below (figs. 16.13, 16.14). Hope Bagenal, the foremost British authority on architectural acoustics, advised the architects of the London County Council, and the hall was built as an independent shell, carefully insulated from the outer shell of the building. Interior shapes and materials were designed with the most advanced techniques, and prior to the first official performance four test concerts were held over a two-month period.[57] Among the usual audiences there were selected groups of listeners, including frequent concertgoers, professional music critics, and musicians. In response to these tests some minor changes were made in materials used in certain areas of the hall. Scientific measurements of the hall's acoustical characteristics were conducted before the test concerts, during the test period, and after the hall was formally opened. Similarly, subjective opinions continued to be sought after the opening, and the press was scanned for comments on the acoustics of the hall. When 18 acoustical experts, in London for an international conference, attended a concert, 13 evaluated the hall as "excellent to very good," but six wanted more "fullness," a view that was paralleled by many press comments during the first 18 months the hall was in use.[58]

After more than a decade, the reverberation time of the Royal Festival Hall was found to have slightly decreased, probably due to minor changes made in the building's ceiling. Subjective opinions of critics and musicians still tended to indicate that its sound was too "dry" and needed to be "warmer"—satisfactory, that is, for the quieter passages of Classical works, but not fully supporting the climaxes of Romantic symphonies. Officials of the Royal Festival Hall decided to test a new corrective procedure. Their acoustical consultants noted:

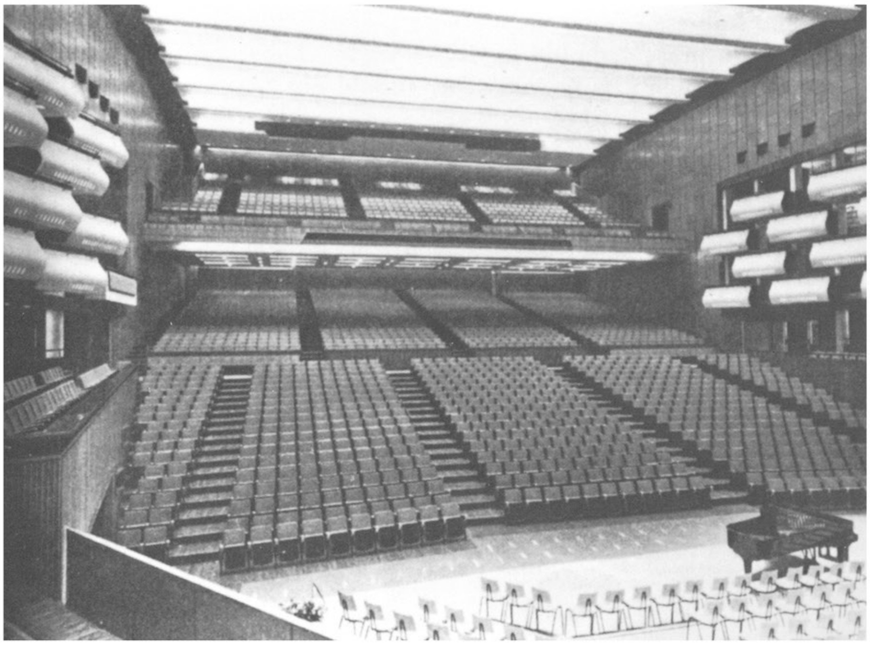
> Even if opinions had been unanimous that the Hall should be made acoustically warmer—which we assume means lengthening the r.t. [reverberation time]—there was nothing that could be done by conventional methods to get a substantial increase of the r.t., short of such impracticable measures as removing the ceiling, raising the roof, or reducing the audience capacity by, say, 25%.[59]

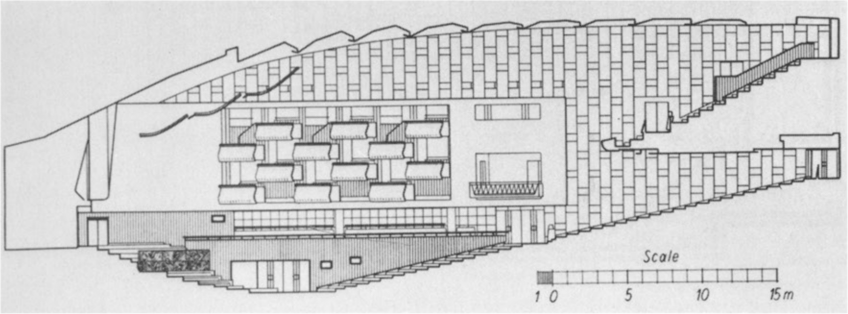
The essential device of the new method comprised a microphone, an amplifier, and a loudspeaker, all commonplace items in the 1960s. To test the procedure, 89 such units were installed, each serving to reproduce only one frequency. By putting the microphones toward the rear of the hall and locating loudspeakers toward the front, about 50 to 75 feet away, it was assured that the sound from the speakers (called "assisted resonance") would reach the listener after the sound heard directly from the orchestra.[60] The sound traveled farther before reaching the listener's ear, and the effect was much the same as if the roof and ceiling *had* been raised. Although the equipment was simple, the planning was understandably intricate.

The test of assisted resonance was begun quietly. Unannounced, the system was operated at a low level at first and was gradually advanced to its intended setting during a series of 29 concerts. Public announcement of the change was made only after eight con-

16.13 The Royal Festival Hall, London (Architects of London County Council, 1951), was built on a site where trains ran above and below ground level in the immediate vicinity. The problems of the surroundings were adequately solved, for the most frequent complaints after the hall's completion involved the interior, its lack of "fullness" or a "singing tone." (*Acustica*, 1953.)

16.14 A permanent system of "assisted resonance" was installed about 15 years after the first opening of the Royal Festival Hall. (*Acustica*, 1953.)





certs at full setting. Comments of critics, musicians, and acousticians, as well as concertgoers, were mostly favorable. Some heard faults in the orchestral sound, minor but troublesome to them, and some had misgivings about the propriety of what had been done. The music critic for the *New York Times* reflected on a concert:

> One was conscious of a smoothness, richness and instrumental fusion that definitely puts the Festival Hall into a superior class . . .
>
> The total result is an amazing improvement. Before last March the hall had a reverberation time of 1.35 seconds. Now it is 2.1, about ideal for a 3,000 seat hall.
>
> But in so doing, the sponsors of "assisted resonance" have raised many esthetic and even moral questions.[61]

By 1968 a full and permanent system had been installed in the Royal Festival Hall using 172 units, almost twice the number of microphones and loudspeakers used during the test period. Years later another music critic recalled: "It was too late for indignation: the musical merits of the system had been proved and approved. Festival Hall performers and audiences have long since stopped remembering that what they listen to is electronically 'fudged.' Is it a moral matter? I think not."[62]

Increasingly, systems of "electronic acoustics" have been used to attain the desired conditions for differing sorts of performances. Halls built for a broad range of presentations—concerts, plays, and popular music—have been equipped for instantaneous alteration to the acoustical characteristics most flattering to the evening's event. Technological systems have made it possible to "hear" a hall that has been electronically shaped, without the limitations imposed by the hard and heavy materials of which traditional architecture is made.

Technics and Architecture

The Development of Materials and Systems for Building

OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

Notes

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Technics and Architecture

The Development of Materials and Systems for Building

OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

Select Bibliography

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Technics and Architecture

The Development of Materials and Systems for Building

OA Funding Provided By:

Humanities/Andrew W. Mellon Foundation Humanities Open Book Program.

The title-level DOI for this work is:

doi:10.7551/mitpress/6674.001.0001

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