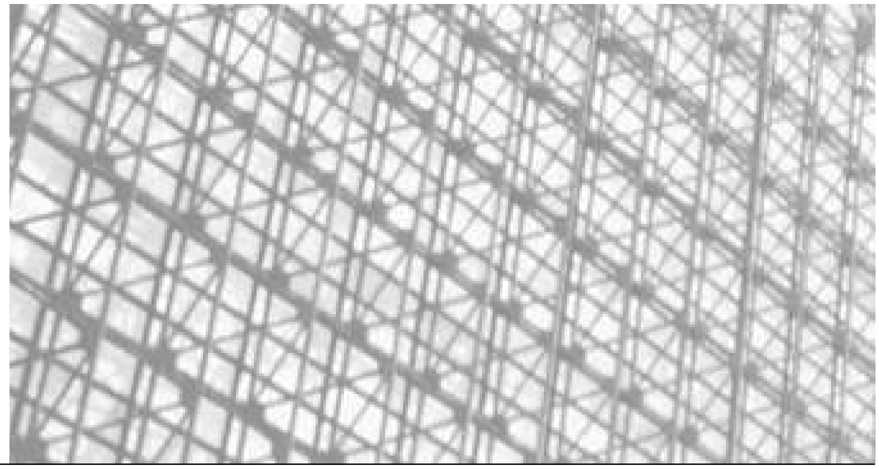
CHAPTER 3



Integrated Building Systems

CHAPTER 3 TOPICS

- Modes of Integration: Physical, Visual, and Performance
- Building Systems: Envelope, Structural, Mechanical, Interior, and Site
- Integration Potentials

This chapter proposes a framework for the integration of building systems by identifying different modes of integration and delineating a classification of major building systems. These taxonomies are supplemented in Chapter 4 with an overview and example of how integration thinking is included in design activity.

Integration can be described by its intended result as effecting physical, visual, or performance benefits. Frequently, any combination of these three methods is employed to achieve compound results. The classification is nonetheless helpful in understanding the various approaches and outcomes.

The major designations of building systems are site, structure, envelope, mechanical, and interior. Within each of these macrosystems are subsystems. A forced-air ductwork distribution is a subsystem of the mechanical system; doors are a subsystem of the envelope, and so forth. Integrations occur with equal ease between major systems, between subsystems within major systems, and between subsystems of different major systems.

Modes of Integration: Physical, Visual, and Performance

The most fundamental goal of integrated building systems design is the elimination of redundant resources, usually achieved through strategic combinations of the systems that are deployed in concert with their shared mandates of space, image, or function. It is important that integration measures provide these and sufficient other tangible benefits to justify the effort involved. Exposing structure or mechanical systems components, for example, is a popular and often highly visible aspect of integration. But exposure itself is not inherently good, no matter what level of integration is attained. Some design intention or programmatic goal must actually be served.

Physical Integration

Physical integration occurs wherever systems share architectural space by occupying a common area or volume. This is the most fundamental of integration activities and must be considered for practically all building components. For an air-conditioning duct to pass through a steel bar joist system, for example, the structural system and the mechanical system must be physically integrated. This can be accomplished by comparing the size of the duct to the space available in the web of the joist. If the optimal size and shape of the duct is greater than the available space in the optimal joist, then one of the systems will have to be modified if physical integration is to occur. This specific modification would more likely involve the duct system inasmuch as its dimensional characteristics are less critical than those of the structural supports. But because the air-conditioning duct has its own criteria of cross-sectional area for the volume and velocity of air it carries, the modification to achieve physical integration would be limited to shape.

An interesting application of computer-aided design (CAD) drawing is its use in identifying physical integration problems and opportunities. By its organizational nature, CAD separates different systems of a building into distinct layers of the drawing. Turning various layers of the drawing on and off allows the designer to examine the physical intersections of different systems and identify specific integration tasks. In the ductwork-to-structure example it may be found that the duct indeed does fit through the truss but will not pass under the solid steel beam located at the end of the structural bay. The same method can apply to lighting and air diffuser arrangements above furniture layouts, interference between lighting and ductwork, and so forth.

Physical integration is also accomplished by the meshing, layering, and folding together of space taken up by building systems. The aforementioned exercise of placing ductwork in the structural voids is only a crude example of meshed space. A more refined example can be seen in IKOY Architects' design of the interior street of the Wallace Building in Winnipeg (see case study #5). Here, the corridor is left wide enough to double as a gathering place for class discussions, social meetings, and geology displays. Collecting the building's four levels of circulation together in a central axis also forms an interior street that serves as the entryway from major parking lots to the central campus. Similar examples of physical integration of space are found at different scales in many buildings: Storage systems fold space into itself compactly; open rooms expand into one another, making small houses feel big; and so on.

Another mode of physical integration commonly occurs in every building wherever two systems or different materials connect; that is, in the details. The proper detailing of these connections assures permanence and security through the integrity of the joint as well as the intended finish condition of adjoining materials. Water- and air-tightness, water drainage, thermal expansion and contraction cycles, differential movement, structural deflection, dissimilar metal separation, and a host of other pragmatic factors have a part in the physical integration of the joint. These joints are most pronounced where two macrosystems intersect, such as where structure and envelope systems meet, but they occur as well at the level of subsystem or material interface. Detailing is also important to visual integration because it expresses design intentions, or at least an attitude about how a particular detail expresses the larger design concept.

Visual Integration

The expression of a system or combination of systems as a visual design element constitutes an act of visual integration. For systems to be visually integrated, they must be either exposed and ordered in some compositional way or concealed behind layers of finish materials. Compositional techniques used in visual integration include modifications of the color, size, shape, and placement of systems and their component pieces.

Exposure of commonly hidden structural or mechanical systems is an integration strategy that relies heavily on such visual modifications. This strategy of exposure can be traced to the precedent of Brutalism in the works of Le Corbusier or Alison and Peter Smithson. The concrete structure at Corbusier's Unité d'Habitation in Marseilles is left exposed and unfinished to express the wooden formwork of fabrication, for example. As a design method, the notion of exposure has opened the architectural palette of materials to include the visual potential of previously foreign and characteristically industrial elements. And as these elements are exposed, the essential nature of their function, materials, and detail connections necessarily become part of the architect's concern and enthusiastic attention.

Separation of systems by the layering of materials is also a method of visual integration. This strategy commonly employs a layer of finish material to cover and segregate unwanted systems from exterior or interior view. This is something of a negative approach to integration as compared with the gesture of exposure but is often an effective and economical way of solving the problems caused by the distribution of services and structural systems in a building. Finish layers are often helpful, if not particularly inventive means of dealing with the problems of dirt accumulation and noisy equipment. They also can perform critical functions: sound-absorbent ceiling tiles in offices, acoustically reflective panels in auditoriums, light-reflective surfaces for daylighting, and so forth.

Performance Integration

Whenever building systems share functional mandates, performance integration is accomplished. In the case of Louis Kahn's Kimbell Art Museum, the cycloidal vault of the concrete structure also forms the container of the building envelope and defines the interior space. Further, in concert with the narrow skylight and perforated reflector at the ceiling level, the vault becomes an integral part of the daylighting system by washing the galleries with diffused and comfortably graduated levels of light.

A second mode of performance integration deals with the adaptive response of buildings to fluctuating demands. The ability to adjust and regulate building response to changing conditions through intelligent use of design elements constitutes "dynamic integration." This sort of integrative and comprehensive design is what allows a building to respond appropriately to daily and seasonal changes in temperature, wind patterns, solar geometry and other environmental variations. Dynamic systems are integrative in the same multifunctional and shared mandate ways that hardware systems are integrative. Passive and sustainable buildings are generally good examples of integration through dynamic response. A basic example of dynamic integration is a roof overhang that allows sunlight to penetrate a window during underheated seasons of the year when the sun is low and then provides shade from high sun in overheated periods. The overhang shading device is bimodal in that it differentiates according to the thermal needs of the building, even though it has no moving parts.

Bimodal sorts of dynamic integration are typical of buildings where aerodynamic response is tuned to winter winds versus summer breezes, or day versus night thermal response is controlled by the heat capacity of structural mass. Designs for adaptation to summer versus winter, day versus night, empty versus occupied are all examples of bimodal response. Such responses can be associated with factors of the thermal environment or any other performance function based on changing conditions. Norman Foster's headquarters for Willis Faber Dumas in Ipswich, England, changes from dark glass, reflecting its historic surroundings by day, to an illuminated interior showcase at night (see case study #7). In this instance, the change in envelope mode is accomplished by employing the luminous properties of glass that make it reflective to the bright side and transparent from the dark side.

Automation technologies advance performance integration as well. Computerized control systems have transformed buildings into intelligent robots that not only respond to changes and schedules, but actually anticipate, measure and learn from them. Replacing resources with measured responses provides such benefits as improved comfort, operational economy, and reduced capacity of servicing equipment. In other words, automation replaces brute strength with intelligence.

The Example of Exposed Ductwork

Consider an example of exposed ductwork in a building interior. This common treatment can be used to illustrate the thinking associated with all three modes of systems integration. First, of course, the motivation for visually exposing ductwork to occupied interior spaces must be considered. Such motivations may relate to the architectural character of the design in general or may simply be dictated by physically restricted space as in a low floor-to ceiling height that makes a dropped ceiling undesirable. The results of these motivations become the initial benefits of the integration. Other consequences of the integration may provide additional positive results. In the final analysis, cumulative benefits will have to outweigh both the extra resources required and the negative trade-offs of the decision to expose the ductwork. In this example there are several compromises to consider, such as mechanical system noise and additional cleaning maintenance.

In terms of physical integration, exposed ductwork provides additional volume to the occupied space by eliminating the ceiling layer and meshing the structural void of the space between the ceiling and the floor or roof above. These are issues of shared space that define physical integration. Visual integration of the ducts is more complicated, as the design will be exposing a hardware component that is normally configured and installed to maximize performance and economy without regard to visual appeal. The designer may take care to arrange the horizontal duct routing in overhead patterns that reinforce the order of the space, perhaps following the circulation paths between workstations, without sacrificing the ability of the duct system to deliver air efficiently to where it is needed. Other compositional techniques may then be applied through the material and finish selections for the ductwork. Consideration can also be given as to how the ductwork is supported by the structure, its connection to air register devices, and all manner of detailing.

Performance integration of ductwork adds considerable sophistication to the idea. Ducts not only provide temperature relief and air motion in a space, they also play a role in the acoustical environment, specifically in the background noise level. Performance benefits may include energy savings by removing cooling air at 55°F from a nonconditioned attic at 140°F and thereby eliminating thermal duct losses. Acoustically, however, it may be necessary to use internally insulated ductwork with thicker wall construction to provide adequate noise isolation from air friction noise in the duct and low-frequency reflected fan rumble from the air handler.

When Louis Kahn decided to expose the mechanical systems at the Richards Medical Research Laboratory, he planned on weaving ducts and pipes into the open webbed concrete trusses of the floor-ceiling layer and maintaining a low 8 ft clear ceiling height below the trusses (see case study #1). Initially, this proved to be a problem of coordination with building trades, which failed to realize that the systems would be left exposed and so installed them in the usual messy but convenient functional arrangements. Much of the initial work had to be redone. Eventually, Kahn realized that the exposed ducts, conduits, and pipes merely provided excessive areas for dust to collect and would thus be impractical in a biological research setting. Kahn used this experience at the Richards laboratories by providing 7 ft deep interstitial attics for all the mechanical services above each of the three laboratory floors of the Salk Institute for Biological Studies (see case study #2). The interstitial spaces at Salk are connected to the lab spaces via stainless steel access slots. This ensures complete freedom and flexibility of services, in keeping with the requirements of laboratory spaces. After Richards Medical, Kahn never employed exposed ductwork again.

A positive example of ductwork integration is found in IKOY Architects' Wallace Earth Sciences Laboratory in Winnipeg (see case study #5). Ducts are painted in the color scheme of the interior street and provide scale and visual interest to the long corridor.

Integrated Systems

This section describes the component elements, performance mandates, and relationships of the five fundamental systems of a building. These systems are categorized as follows:

- Envelope — the separation of indoor and outdoor conditions
- Services — HVAC, electrical, plumbing, vertical transportation, and life safety systems
- Structural — elements providing static equilibrium against gravity and dynamic loads
- Interior — occupied space encompassing partitions, finishes, lighting, acoustics, furniture, and so forth
- Site — landscape and support systems for the building, including parking, drainage, vegetation, utilities, and the like

Any attempt to analyze or synthesize the integration potential of building systems must be based on a sound understanding of how each system and its subsystems satisfy their roles in the total design package. The following descriptions establish a very general and necessarily incomplete framework for the systems approach to integration. Encyclopedic knowledge of building systems is not the goal here, and much of this framework should be general knowledge to the readers of this text. There are a virtually infinite number of systems that can be combined in a possibly infinite number of ways, and no one text can do much more than graze the surface. Further, the particulars of each building design form a shifting picture in these times of what Forrest Wilson (1987) has called "relentless technological change." Moreover, each building design presents its own unique context for selecting building elements and methods of assembly. The ability to deal with this complexity and shifting variability in design requires considered reasoning more than it does practical knowledge. In other words, systems integration has a great deal more to do with the relationships between systems than with the particulars of any one technology.

An obvious subplot to the theme of integration involves the relationship between natural systems and building systems. Most building systems entail some level of environmental performance, so the pragmatic theme of natural systems is largely self-evident. Ethical concerns for the environment that confront the practice of modern architecture are equally compelling. From energy conservation to land conservation, from worker productivity to indoor air quality, and from construction waste management to sustainable design, the relationship between buildings and nature has become an integral part of the practice of architecture.

What follows, then, is a conceptual framework for facilitating the appropriate integration of systems and subsystems. A basic understanding of design and technology is assumed to be at hand or easily acquired from reference sources.

As an example of what is being addressed here, consider the case of a hypothetical passive cooling system that offsets all the heat transferred through the building envelope as well as from internal gains. This may, on the surface, seem to be a satisfactory replacement for mechanical cooling. In fact, mechanical systems provide far more than the sensible heat relief of passive cooling. Omitting a mechanical system would ignore other needs. The problem of humidity control, which most passive cooling systems cannot address, is only the most prominent oversight. This error in judgment also overlooks mechanically provided benefits of air motion, air filtration, and ventilation air—a package of requirements that passive cooling does not reliably deliver. So what at first appear to be redundant passive and active systems that the designer can choose between actually offer an opportunity to examine how the two might work together to satisfy building comfort requirements more comprehensively and elegantly. It is fundamental considerations of this sort that an outline for the integration of systems must address.

This review of the five major building systems, their elements, and functional mandates, is ordered by general familiarity with their integration issues. Different approaches are taken with each system to broaden the scope of how each component can be thought of in the context of the complete building. Envelope systems are discussed first because the envelope forms the most obvious part of any building as its outside skin and container of space. Structural systems follow, as the traditionally ennobled framework of form and space. The discussions of physical, visual, and performance integration of structural systems will be familiar to most readers. Mechanical services are third, with an emphasis on how extensively air-conditioning impacts today's highly serviced buildings. The ensuing discussion of interior systems focuses on functional, thermal, luminous, and acoustical zoning as both ordering concepts and integration opportunities. Finally, the site is presented in special terms of the architecture's microclimatic response and the ongoing interface with natural forces.

Envelope Systems

Building envelope systems separate the indoors from the outdoors—they provide the "skin" of architecture. For this reason, they become the fundamental interpretation between the interior and the site condition. This interpretation sets in motion a large number of modulating functions of the envelope system—thermal, solar, acoustic, aerodynamic, and other forces largely invisible to direct observation but highly significant to human occupation.

The envelope is also the most visible element of the building and must respond to our appreciation of image, form, and orientation to the building. These dual roles of invisible forces and visible mandates are repeated to a lesser degree in other major building systems, but the envelope is the most obvious point of their resolution.

Elements

- Walls
- Fenestration
- Roofs

Mandates

Separation/Connection. The distinction between indoors and outdoors is not always an exclusive one. There are often ambient conditions that benefit the interior environment and can be employed passively to condition occupied space. The dynamic relation of these indoor and outdoor conditions leads to an interactive definition of the envelope system. As discussed in the previous chapter, the ability of designers to respond to this interaction is one of the important trends in the systems view of architecture. Reynolds and Stein (2000) (after Christian Norberg-Schultz, 1965) describe this concept as "filters, barriers and switches" or as Stephen Groák says in discussing flows of matter and energy, "The building forms a system of barriers, filters, containers—sometimes condensers—for an enormous collection of materials and energies."

Control over levels of connection and separation to the outdoors plays a direct role in the comfort of occupants. Weather has to be excluded so that the indoor environment can be controlled. But rooms allowing visual contact with the natural environment are more restful than windowless rooms. Workers with a view, for example, are more productive, and hospital patients in windowed wards heal faster. On the other hand, people require various degrees of separation from the outdoors for privacy, security, and control of indoor conditions.

Because the envelope must satisfy both the barrier and the filter roles, switches have to be provided. Window blinds are a good example of switches; they allow the window glazing to be effectively turned off, along with view, light, and sun. Operable shading devices such as movable awnings, movable insulation like window shutters, and operable windows for ventilation are further examples.

Weathering. Upon the completion of a finished exterior envelope surface, there begins a continuous relationship with the elements of weather. Sun and wind, moisture and ice, dust and decay all tend to age the building, diminishing its pristine newness. Erosive elements like acid rain, ultraviolet radiation, and chemical interactions with building components accelerate this process. Either the building will require continual renovation to maintain its newness, or it will be, to some extent, reclaimed by the site. The former choice results in a building that has been "stained" by time and the elements; the later can produce a building that acquires a graceful "patina" (see Mostafavi and Leatherbarrow, 1993).

Structural Form. The structural possibilities of envelope systems range from Louis Kahn's cycloidal vaults of concrete at the Kimbel Art Museum in Fort Worth, Texas, to Philip Johnson's transparent space frame structure at the Crystal Cathedral in Garden Grove, California.

Thermal Form. The thermal form of a building refers to its level of exposure between inside and out. For heat transfer by temperature difference, this exposure is a product of the area of exterior skin and its thermal conductance. From a purely geometric view, an efficient form has a low surface-to-volume ratio, enclosing the maximum amount of interior space with the minimum of skin exposure, and will also have a low heat transfer conductance. An inefficient form, conversely, will has a high surface-to-volume ratio and high-conductance envelope assemblies.

In actual practice, of course, as compared with a purely geometric view, the envelope becomes more efficient if it is shaped to maximize good exposures. Although a sphere would be the most efficient thermal container of space, a long rectangle stretched from east to west offers better opportunity for collecting low winter sun and avoiding harsh summer solar impacts. For this reason, various ratios of length-to-width can be considered before determining an appropriate aspect ratio (see Olgyay, 1963).

Thermal form is a way of talking about the "leakiness" of the envelope. This encompasses not only heat transfer by temperature difference, it also includes the consideration of accidental air change by infiltration and exfiltration as well as the migration of moisture into and out of the building.

Solar Form. Solar impacts on a building are determined less by its overall shape as considered in thermal form than they are by the placement and distribution of glazing and the use of shading devices to protect them. So solar form results primarily from window size and orientation. Mitigating factors can also play a large role: appropriate use of external shading devices, both fixed and operable; the selection of glazings with differing ratios of visible light transmission versus total solar transmission; the slope of window glazings toward the sky or the ground. Even the configuration of the building envelope into self-shading forms such as courtyards and setback stories makes a significant difference.

Unlike thermal form, solar form is bimodal. In small surface-load-dominated buildings in particular, the need for solar gain in colder months will be replaced by a need for defensive shade in comfortable and warm seasons. Because every latitude has its own schedule of solar geometry and every building a particular set of sun-to-shade requirements, the interplay of these factors is one of the enduring truths to which a designer must respond.

Luminous Form. In terms of daylighting, the luminous form of an envelope is bound up in the solar form. Because most building spaces are occupied for daytime activity, daylight through the envelope is generally a desirable resource. In fact, the abundance of available natural light is usually much less of a resource problem than the difficulty of distributing daylight any distance away from a glazed aperture.

Separating natural light from the heat it eventually becomes is possible, to a limited extent, by admitting light in measured portions and avoiding the Promethean overheating that usually accompanies daylight saturation. Because daylight is generally useful year-round, it is not a bimodal condition as found in solar form, which confronts sun versus shade. But because available daylight levels vary with sky condition, time of day, and season of the year, it is no less a dynamic condition than solar geometry.

The envelope glazing is the lens of a daylighting system and functions just as the cover lens of an artificial lighting fixture does. Additional envelope components, such as reflectors and baffles, can also serve as artificial lighting fixture equivalents. These components bounce the light deeper into a room or modulate its penetration in other ways. When total control of natural light is important, such as in theaters and auditoriums, the envelope must function as a switch by means of daylight-control curtains or blinds, to close out the sky. Switchable glazing that employs laminated glass with an electrically excited diode layer of mylar to change from opaque to clear will be an option when the technology matures. Phototropic and thermotropic glass that darkens in response to high light levels and warmer temperatures (like darkening sunglasses), are technically proven but have not yet demonstrated economic practicality.

Aerodynamic Form. Wind is both a structural and a comfort factor in envelope design. The magnitude of uplift and surface wind loads are the important structural considerations. Cross-ventilation and buffering of cold winds are prime environmental concerns. The environmental aspects qualify as bimodal dynamics because of the changing seasonal patterns of prevailing winds and the alternating needs of a building for opening to ventilation versus closing for heating or cooling.

Computational fluid dynamics (CFD) is the science of predicting airflow in closed spaces and around freestanding obstructions. Recent advances in computing power have made CFD an important tool in studying the complexities of convective air currents. Three-dimensional modeling is accomplished in carefully constructed wind tunnel tests. Two-dimensional modeling can be performed on fluid mapping tables by standing a scale profile section of the building in a moving horizontal film of water.

Acoustical Form. The acoustical form of an exterior envelope is primarily related to site noise control. Self-sheltering forms include courtyard and atrium plans. Because mass is the primary source of noise attenuation, the solid, heavy elements of the envelope can be directed to reflect unwanted sounds away from occupied spaces.

Hydrological Form. The rainscreen functions of an envelope mandate the routing of precipitation away from the structure to the storm drainage system. In many cases this integrates the form of the roof into the topography of the site. Other factors, such as the need to provide a dry cover for entry to the building, may also be considered.

Structural Systems

Conceptually, structural systems comprise the following functional elements:

- Bearing—transfers loads to stable supporting grade, generally made up of foundations, footings, grade beams, piers
- Lifting—columns, load bearing walls, arches and other members providing vertical support
- Spanning—horizontal support of beams, girders, trusses, purlins, slabs, arches, vaults, coffers, domes, space frames, and the like; also includes roof structures of cable and membrane or pneumatically supported envelopes
- Bracing—diagonal bracing and diaphragm resistance to racking and lateral loads

Structure is fundamentally intended to provide static equilibrium, just as mechanical systems are meant to supply thermal equilibrium. Where heating, ventilating, and air-conditioning (HVAC) work to maintain a constant indoor temperature by equalizing heat losses and heat gains, structure works to transfer physical forces to supporting foundations and into supporting grade. There are some important conceptual differences of course—thermal loads are dynamic and heat flow changes direction with changes in the climate. HVAC systems use a constant source of energy to balance thermal loads and are controlled to operate in response to climatic change. Structural loads are generally static rather than dynamic; they result primarily from the uniform and unchanging force of gravity. Gravity loads consist of the dead load of the structure itself and uniformly distributed live loads imposed by the interior furnishing and occupants on the floors as well as snow loads on the roof.

There are some dynamic forces that influence structural design: wind and seismic lateral loads, for example, and imbalanced loads incurred during construction. From a systems perspective, it is interesting to note that structure must be designed for the worst set of loads that code can dictate and then left to operate at full load conditions forever, whereas HVAC capacity is designed for the 95 percent worst condition and operates at partial load in all but the worst of weather. Further, because building structure is permanent and difficult to modify, and because the structural loads are only estimates, structural systems must have large safety factors built into them. They must respond statically and continuously, even to dynamic events like hurricanes and earthquakes that may never occur. This precaution is based on the fact that failure in a structural system is potentially sudden, catastrophic, and disastrous. Failure in an HVAC system may be equally dangerous, such as involving an outbreak of Legionnaires' disease or other indoor air quality hazards, but air-conditioning disaster is usually prevented by proper maintenance. Ongoing HVAC failures are easily remedied by modifying or replacing the system. Not so with structure, which is never bimodal and seldom dynamic. Earthquake design has opened a few possibilities for dynamic dampening of seismic loads, but these are rare exceptions (study the John Hancock Building for an example of seismic dampening).

Another issue of physical integrity that structural systems must address is fire safety. Here, the selection of wood, masonry, concrete, or steel construction must be weighed against the presence of fire suppression sprinklers or the need to protect the structural members with another layer of noncombustible material. These decisions have significant first-cost impacts and thus can reduce the amount of resources available for other design features. They also, however, involve ongoing costs associated with insurance premiums. Sometimes a more expensive structural system pays for itself in the reduction of insurance costs.

Visual Integration

Structural systems selection, then, generally involves the choice of the lightest-weight members of the most economical-grade material, allowing the most efficient configuration that is appropriate to the anticipated loads. Taken in isolation, there is nothing architectural about this procedure; it is pure engineering. In concert with other systems, however, structure acts in visually expressive ways. It creates a grid and rhythm with the envelope system, for example, through modular repetition of horizontal and vertical supports. It creates an open frame or a closed shell for the envelope to infill. Exposed to the interior, it modulates space and orders the plan. Left clear, structure contains and organizes service elements such as ductwork and lighting.

In all, the visual expression of building structure and its intentional integration with other major systems is part of what Kenneth Frampton (1995) calls the "tectonic order." This ordering is primarily an ennoblement of how architects think about and through the construction of a building while fully considering the methods and materials to be employed. It arises from a long tradition of the challenge of structural problems before the advent of numerical method. Structure, as a means of architectural clarity, is also associated with the human sense of stability that comes from the everyday experiences of gravity: remaining upright on a top-heavy two-legged base and walking around by continually falling forward. This lifelong experience of gravity gives the structural expression of buildings an easy communication with our intuitive senses—if it looks as though it will stand up, it probably will. Comparing this to HVAC systems again, it is clear that we have no such intuitive sense about systems of thermal equilibrium. It is hard to intuitively judge the adequacy of a mechanical system by the physical size of its components.

Another visually accessible aspect of structural systems is the graphic depiction of loads, vectors, and the resultant forces in members. These diagrams take the familiar form of free-body moment and reaction, shear and funicular diagrams. At the scale of a building they become tributary load diagrams that can be used to generate the basic geometry of the structure. These graphic illustrations connect the visible geometry of structure to the invisible geometry of imposed forces. Because the illustrations are literal, they give the structure its necessary geometry. Antonio Gaudi (1865–1934) used graphic methods like these to work out the form of the huge dome over the Segrada Familia in Barcelona, Spain (begun in 1884 and still in progress). An upside-down, three-dimensional model of the dome was constructed to scale in his workshop. Small bags of lead weights were then attached to the load points to reveal the regular parabolic curves of the structure. Later, however, when Jorn Utzon proposed the irregularly curved form of roofs in his competition scheme for the Sydney Opera House (1957–1973), there was no similar empirical method for resolving the indeterminate loads. Ove Arup and his team of engineers in London, including Peter Rice, had to write massive computer programs to resolve the transfer of loads through irregular shapes. In the end, Utzon found it preferable to base all the shells at Sydney on a radius of 246 ft (75 m).

Because gravity is static, uniform, and constant, and because the dynamic forces acting on buildings are assumed to act uniformly on any surface with equal probability, certain consistencies are manifested in structural design. The first of these, hierarchical consistency, results from the cumulative transfer of loads from top to bottom of a building and from intermediate members to primary members. In terms of a tributary load diagram, horizontal structure grows larger from purlin to joist to beam. Vertical structure grows in size as loads from above accumulate in columns and load-bearing walls transferring loads to grade. The second result of the uniformity of loads is consistency of pattern. Uniform loads dictate uniform member size and uniform spacing. Uniform member size and spacing in turn creates patterns within the hierarchies: purlin spacing, joist spacing, beam grids, column modules, and so forth.

Physical Integration

From the perspective of physical integration, structure is often made to contain the service systems. At one scale, the interstitial space between floor and ceiling layers in a building normally carry the horizontal distribution of services: HVAC ducts, electrical wiring, and recessed lighting systems. Similar but usually smaller voids in walls can carry services as well. At another scale, hollow structural members are stronger in bending than solid members of the same diameter. This allows the voids in individual members to be used for the distribution of services. Shaped steel beams, box beams, tubular frames, and hollow-core slabs are all appropriate conduits for the distribution of service elements.

Performance Integration

Functionally, structure can often lend its massive materials or its void interstitial spaces to the mandates of other systems. Return or supply air plenums are easy examples. This is an elaboration of physically integrated ducts to the extent of structure's actually becoming a duct rather than just housing it. Such plenums are now frequently found in ceiling or floor voids and occasionally in wall cavities.

A more dynamic example of performance integration in structural systems is the use of structural mass as thermal heat capacity. Passive heating systems normally use floor slabs as thermal batteries to store absorbed solar energy and limit interior temperature swings. In hot, arid climates, external envelope building mass is used for its flywheel effect to effectively balance the impacts of hot days followed by cool nights. Night ventilation cooling is also used in both surface-load-dominated and internal-load-dominated buildings to provide a passive cooling heat sink for daytime heat gains. In some instances, internal thermal mass in a supply air plenum is cooled continuously by the HVAC system in order to lower the peak cooling load.

Mechanical Systems

Mechanical systems, for the purposes of this discussion of integration, are limited here to HVAC and related thermal comfort components. The other "mechanical" aspects of buildings such as lighting and plumbing are considered in the discussion of interior systems later in this chapter.

Mandates

There are eight fundamental requirements of mechanical air-conditioning, the last three of which are predominantly for public buildings:

- Temperature control by heating or cooling
- Humidity control by cooling air below its dew point for dehumidification, or by evaporatively adding moisture when humidification is required
- Air motion to occupants by forced air circulation
- Air filtration to remove some level of particulates
- Exhaust of polluted air from indoor sources of heat, odor, moisture, or chemical concentration, such as found in toilet rooms, laboratory vent hoods, and kitchens
- Air change for ventilation, economizer cooling, and nighttime flush cooling
- Air balance for positive indoor pressure to avoid infiltration of untreated outdoor air, dust, and moisture
- Smoke exhaust and fire safety control of indoor air pressure by compartmentalization

Elements

Conceptually, the mechanical systems of a building consist of the following functional components:

- Thermal plant where heating and cooling energy are generated
- Distribution of thermal energy to individual zones of the building
- Delivery of comfort to occupants by forced air or radiant temperatures
- Control of mechanical equipment to match HVAC operation to thermal loads
- Thermal energy storage (TES) as an optional HVAC operating scheme

The Thermal Plant

Every mechanical system has at its heart a mechanism whereby source energy is converted into comfort energy. This thermal plant can also be the connection between the building's indoor conditions and the environment serving as a source of thermal energy or a thermal "sink" for heat being rejected from the building. At the largest scale, a campus of buildings would have a central plant where boilers and chillers produce hot and cold water. This requires the use of utility-provided energy, normally in the form of electricity and natural gas. The hot and cold water is sent from the plant to individual buildings where fans blow room air across coils of circulating water, much like what occurs in the radiator of automobiles. Cooling towers in the central plant reject the space heat captured in chilled water return lines back to the environment by evaporation. This evaporative effect is used to cool the condensing side of the central plant chillers, thus moving the heat from occupied space back to the central plant and then into the environment. Besides using outside air to reject heat, cooling systems can be designed to use below-grade soil as geothermal heat sinks or to reject building heat to large bodies of water such as cooling ponds or even seawater.

The most common sort of thermal plant is the conventional split-system direct-expansion freon cycle machine, which works for one single individual thermal zone of the building. In this arrangement, the outdoor unit of compressor and condensing coil make up the cooling plant and a gas furnace or electrical resistance heat strip is located in the indoor half of the system to provide heating energy. The outdoor compressor and condensing coil are connected by refrigerant lines to the indoor evaporator coil. Heat collected at the evaporator coil is thus rejected to the environment by outdoor air blowing across the evaporator. Split-system heat pumps use a reversing valve to get double-duty cooling and heating from the outdoor unit. They employ a valve to reverse the flow of refrigerant between the indoor and outdoor coils. This allows the unit to either "pump" heat from indoors to out, or from outdoors to in; a feat conventional direct expansion systems can perform only in one direction.

At the smallest scale the thermal plant can be part of a compact package of equipment that contains all the elements of mechanical servicing. A wall unit heat pump, a package rooftop unit, or a window unit air conditioner are examples of systems that not only produce comfort energy by converting source electricity, but also deliver it directly to the occupants.

Integration concerns for incorporating thermal plants into design schemes, or simply in accommodating their functional requirements, entail several givens. The first is that utility services have to be routed to the central plant as a large portion of the building's power and energy requirements. Second, thermal energy has to be delivered from the plant to the zones in some form. Generally, there is also the necessity of dealing with exhaust flues from combustion equipment and similar functional requirements. Finally, in the vast majority of systems, there must be some outdoor component where heat is rejected to the environment (water source heat pumps are an important exception to this arrangement).

Distribution of Thermal Energy to Zones. In large heating and cooling systems, the distribution of energy from the plant to the fan/coil systems located in zones of a building is a distinct part of the system. These distribution systems are usually composed of all-water systems (also called hydronic systems) in which two, three, or four pipes are used to convey thermal energy from the plant to the individual thermal zones. In medium-sized systems, where direct expansion air-conditioning prevails, delivery from the plant is made by the freon loop between the condenser and evaporator coils.

Once thermal energy is delivered to a zone, there are a host of choices as to how the system will distribute comfort to individual areas of the zone or to separately controlled subzones. Aside from the common "single zone, single duct" system, there are variable air volume, multizone, and dual duct options.

Delivery of Comfort to Occupants. Delivery of comfort to the occupant of each space is generally accomplished by forcing supply air through a tapering network of insulated ducts. Air delivery registers then direct the air into rooms to promote complete circulation. A return-air system serves the complementary function of extracting the room's thermal load and excess humidity by recycling room air though ducts or open plenums and removing it. Air is returned to the distribution fan for filtering and reconditioning, and the cycle is repeated. Exhaust fans are located in kitchens and toilet rooms and other sources of air pollution and excess humidity. Outdoor air is provided in public buildings to mechanically replace the polluted air and keep buildings positively pressured relative to the outdoor environment. The prime components of the delivery system are ducts, registers, and grilles.

Aside from air delivery systems, the designer can use radiant systems to provide or ensure thermal comfort. The mean radiant temperature of surrounding surfaces is some 10 percent more important to comfort than air temperature at normal room and activity conditions. Controlling surface temperatures is sometimes accomplished by artificially heating an overhead "radiant panel" or a floor slab with hot water or electricity. Frank Lloyd Wright used hot water coils in the floor slab of the Solar Hemicycle Jacobs House (Madison, Wisconsin, 1944) to replace upright radiators hidden behind intricate wood grilles of his earlier Prairie Houses. This was one of many innovations that defined the course of his Usonian Houses.

Passive solar heating of the thermal mass of a floor, Trombe wall, or other interior room surface is another way of accomplishing the radiant effect. Passive systems are slower and rely on subtle temperature differences than does active radiant heating. Further, passive systems use greater mass and therefore have greater thermal inertia, resistance to temperature swings, and are more difficult to control as compared with the on/off of active heating. Recently "air walls" have been used to circulate return air from a room through a glass cavity exterior wall as part of the return air path. This eliminates the effects of cold window walls during cold weather. Richard Rogers and Partners' headquarters for Lloyd's of London is an early example of this comfort delivery strategy (see case study #24).

Control of Mechanical System to Match Thermal Load. Thermal loads in a building vary both in magnitude of heat transfer and in mode of operation between heating and cooling. The match between thermal loads and mechanical systems operation is intentionally controlled to maintain a fairly constant indoor condition. This is accomplished by modulating the heating and cooling energy expended to offset thermal loads. Better controls mean both lower energy consumption and superior comfort conditions, because controls replace indiscriminate energy use with some level of building intelligence. Each 1°F of error in a cooling thermostat, for example, results in about a 5 percent error in energy use.

This match between the operation of mechanical equipment and the opposing variations in environmental conditions amounts to what has been termed "using information to replace power" (Lyle, 1994). More exact information about needs and conditions always allows for better design and operation of systems. Basic control strategies can vary from on/off switching to one-way sensing like that found in a thermostat. More sophisticated systems include feedback loops of two-way sensing, whereby mechanical equipment can provide operating information back to the controls. At the extreme, computerized controls result in intelligent building systems that can anticipate indoor and outdoor environmental changes and learn to accommodate such things as the building's thermal response time.

Control strategies are often used in combination to fit the required degree of critical control to the appropriate sophistication of hardware. The most common of these are as follows:

- On/off switching—such as may be used on a ceiling fan
- Clock timer—providing a daily or weekly on/off equipment schedule
- Thermostat—sensing the dry-bulb temperature of the return air stream
- Humidistat—sensing the moisture content of the return air stream
- Setback thermostat—a programmable thermostat with a schedule of selectable temperature setpoints
- Occupant sensor—motion or infrared detection of the presence of room occupants
- Direct digital control—automated control of mechanical systems by computer program and potential integration of controls with lighting, security, fire safety, and other systems
- Intelligent buildings—robotic intelligence of building control decisions; sensing of outdoor, indoor, and mechanical systems conditions; may incorporate the ability to learn and anticipate changes; may integrate control of all building systems; can interface with building management personnel

For hardware controls to be most effective, it is essential that the thermal scheming that underlies the design of a building's mechanical system be integrated with the interior systems. These schematic strategies include the following:

- Zoning of interior into distinct areas of servicing, usually under the control of an individual thermostat; divisions are made according to exposure, orientation, occupancy type, and use schedule.
- Staging of successive levels of cooling capacity to accommodate different modes of occupancy (such as entertaining large crowds) or environmental loads (such as morning versus afternoon).
- Diversity of independent package units for individual zones versus economy of central plant, which can shift capacity from zone to zone.
- Modulation of cooling capacity in very large buildings or campus central plants by use of variable speed equipment.
- Thermal energy storage systems (TES).

Because most mechanical cooling systems are sized to the peak hourly load of a building, their full capacity is utilized only about 5 percent of the year. And because heating systems operate at a much higher temperature difference from room air than do cooling systems, the need for air circulation in heating is much less than that for cooling. Consequently, heating is generally sized to match the fan and delivery systems required for the cooling system. Heating systems usually use the same fan and ducts as the cooling system by operating less frequently and more intermittently than the cooling. At any rate, most of the heating and cooling capacity of a conventional system is greatly underutilized.

The economics of this oversizing does not end with the excessive capacity of the cooling equipment that must be installed and maintained to meet infrequent peak conditions. The real penalty comes in the way large buildings pay for electrical power to operate their cooling systems. Not only do they pay for energy in kilowatt hours (kWh), they also pay for their peak demand in watts, or in utility engineering language, in kilovolt-amperes (kva). This is where thermal energy storage can be beneficial.

TES systems use smaller cooling plants that run continuously under full load to produce the same amount of ton-hours of cooling that a peak-load-sized plant would produce running intermittently at part load, or on/off cycling, over the same period of time. Instead of providing cooling energy directly to the building load, however, TES systems produce chilled water or ice and store it for later use. The building then draws from the thermal storage as needed. The time period for equalizing the storage capacity and the fluctuating building load may be as short as a day, but the aim is frequently a one-week interval in order to save up cooling energy over the weekend when the building is used more sparingly. Thus, instead of operating a large cooling plant to relieve small off-peak cooling loads, TES systems use smaller plants to produce ice or chilled water for later use.

TES systems require less peak power (kva) at any one given time than conventional systems because they are significantly smaller in cooling capacity. They do use about the same amount of total energy (kWh) over the course of a month as conventional systems, as they ultimately produce the same amount of cooling. Because the constant power load of TES matches the way utility companies have to continuously produce power in case it is needed by a customer somewhere on their electrical grid, there are significant savings in avoiding the cost of having to construct new generating capacity. The utility companies can pass these savings on to the consumer in the form of lower demand charges as an incentive to control peak loads. Many utilities even rebate some portion of the initial cost of TES installations.

The designer should remember that TES requires a significant increase in equipment and physical storage area for ice or chilled water, as compared with conventional systems. The first costs of a conventional system and a thermal energy storage system are frequently about the same. The benefit of thermal energy storage results from the savings in peak load demand from the utility, measured as the highest power requirement at the building meter for any one time during a month.

Another consideration in favor of TES, more specifically for ice storage systems, is the ability to supply conditioned air at very low temperatures. Whereas conventional systems deliver cooling at about 55°F supply air temperature, ice storage systems can approach 35°F. This enables the use of much smaller, high-velocity duct systems for delivering the cooling energy to occupied spaces. The smaller ducts require less space and allow for lower floor-to-floor heights.

Mandates

- Basic controls—temperature, humidity, air motion, air filtration, ventilation.
- Size and placement—HVAC requirements range from 10 to 50% of a building's area, volume, and cost.
- First cost—capacity in installed tons and associated distribution, delivery, and control. There is also an associated cost in size of required electrical service.
- Energy and power—efficiency in Seasonal Energy Efficiency Ratio (SEER) and Coefficient of Performance (COP), energy use (kWh), and power demand (kva).
- Servicing—maintenance, replacement, and repair of equipment.

Interior Systems

Occupied space reflects a basic principle of architecture by serving the many aspects of human comfort and security. Beyond this overriding goal, interior spaces are usually individually arranged to facilitate a particular set of uses and are optimized accordingly. Flexibility is often an issue, as the use of the space and the people in it will change over time. In many cases, rapid technical advances change the way a space is used and the services needed. The advent of the desktop computer is a prime example. Architects frequently must anticipate future interior conditions as well as addressing current ones.

Elements

- Lighting—ambient and task lighting fixtures, as well as display, accent, and emergency light
- Acoustics—sound absorption, reflection, reverberation time control, room acoustics, noise control, and privacy
- Circulation—communication between spaces, emergency egress, security, signage
- Furniture—fixed and movable elements
- Finishes—floor and wall coverings, hardware and trim, paints and stains
- Specialties—equipment

Mandates

Zoning for Function. The grouping of building spaces together to best serve their various common needs is the act of zoning. Zoning provides for intelligent marshalling of resources, ease of control, and articulation of the inherent order of the building's character. Such groupings into separate zones are fundamental to organization of the building problem and are performed separately for different aspects of the design. Resolving the discrepancies between the various organizing forces requires work of informed inspiration.

Functional zoning is best recognized in the bubble diagrams of adjacency relationships common to conceptual design thinking. These clustering relationships may reveal the organization of a complete plan or suggest component modules that are repeated to fulfill the design. The number of potential zoning principles that should be overlaid on a plan varies from project to project according to the critical issues to be addressed. But even restricting these overlays to the most basic ones can create a complex organizing scheme. Arriving at an integrated scheme requires attention to each and the ability to synthesize the requirements of each into an overall plan.

Thermal Zoning. *Thermal zoning* is common parlance for the grouping of different rooms into distinct areas serviced by HVAC systems. Each distinct area is typically under the control of one thermostat. Common residential zoning strategy separates the day-use public spaces from the night-use bedroom spaces and places them on different HVAC systems. Note that this typically reflects the functional organization scheme of locating bedrooms upstairs or in a separate wing of the residence.

In order for thermal zoning to satisfy thermal loads and times of peak gain in all rooms in a zone with any degree of uniformity, the rooms must share five characteristics:

- Similar solar exposure and orientation: East-facing rooms and west-facing rooms will have vastly different schedules of thermal needs, just as rooms with large window areas will have different needs than rooms with smaller windows.
- Similar envelope exposure: Perimeter rooms with exposure to the outdoor environment through the exterior envelope will have different needs than rooms in the core of the building, which always need cooling because they have no means of heat loss.
- Similar occupancy type and density: Libraries and auditoriums should be grouped in different zones. Likewise, private offices and large classrooms should also not share a thermostat.
- Similar schedule: The weekday classrooms of a church school should not be in the same zone as the Sunday congregational assembly space. Weekend-use offices where cooling systems may be activated for the comfort of a few workers should not be zoned together with large lobby spaces.
- Shared incremental capacity: Where multiple modular HVAC systems are used, it is common engineering practice to select small package units and distribute them as needed across the different zones of the building. Retail buildings typically use rooftop units of about 8 to 10 tons cooling capacity and divide the retail floor area into zones of appropriate size.

Luminous Zoning. Luminous zoning is primarily determined by the availability of daylight and its depth of penetration into interior spaces. Typical approaches consider perimeter, interior, and core areas of a plan. Supplemental artificial lighting must be planned for each of these zones individually, to account for the amount of fill light required to reach desired illumination levels.

More recent and enlightened luminous zoning strategies reverse the typical uses of these zones—clerical areas are placed close to windows, where demanding visual tasks receive high-quality and abundant natural light. Executive offices and conference rooms in this scheme are placed to the interior of the plan, where fewer critical demands are made on illumination. Finally, core areas, elevators, stairs, and the like are positioned on east and west walls so that no windows are exposed to the worst solar orientations. Norman Foster's Hong Kong Bank, Leo Daly's Lockheed Building in Sunnyvale, California, and the Farmers Credit Bank Building in Spokane, Washington, are all examples of this luminous and solar zoning scheme (see case studies #25 and #9).

Acoustical Zoning for Noise Control and Privacy. Noise is unwanted sound. The discomfort it causes is of concern to designers of buildings. Privacy is a complementary concern, related to matters such as confidential conversation. Both of these issues require planning for sound separation between the sound source and the listener. Neglecting acoustical issues in the early stages of design may dictate very-high-performance walls and door separation (Transmission Loss, TL, or Sound Transmission Class, STC) between occupancies, as well as increased levels of background masking sound (Noise Criteria, NC, or Room Criteria, RC) in the final solution (see Stein and Reynolds, 2000).

In terms of basic acoustical zoning, spaces can be classified as noisy, quiet, silent, or buffer areas, depending on the noise level generated by activities they house. Rooms for mechanical equipment, copy machines, toilets, and so forth, are noisy. Conference rooms, study carrels, and sleeping rooms are examples of silent spaces. Good acoustical arrangement isolates noisy areas and separates them from silent rooms with buffer spaces such as storage rooms and closets.

Using just these four fundamental principles of functional, thermal, luminous, and acoustical zoning, it is easy to imagine the complexities encountered when all four are being considered simultaneously. Any multiuse building program will have areas with distinct thermal, luminous, and acoustic needs. Even a residence will require different thermal zones based on schedule, different luminous zones based on activity, and different acoustical zones based on noise and privacy. Consider how an overlay of these zoning considerations would affect the interior systems of a hotel, office, or school.

Circulation, Egress, and Life Safety. There are many systems of flow within building interiors. Air circulation, electrical power, daylight penetration and diffusion, paperwork and supplies, and so forth. The most important flow in a building, however, is the circulation of the occupants. Individuals and groups of people need easy access to each other, to the facilities of the building, and to its exitways. In the case of fire or other emergency these circulation flows become highly critical matters of life or death. Even in normal operation the flow rates and resulting density of people requiring open routes can be very high. Lunchtime at the Lloyd's of London building, for example, leads to increased usage of the escalators, elevators, and toilet room arrangements of the office building as 8000 people leave the market floor and surrounding offices, only to storm back in at the end of their break (see case study #24). Other buildings, such as airports and classroom buildings, have similar critical issues related to circulation.

Life safety codes dictate organizational design responses to circulation in all public buildings. The minimum number of exits and minimum width of corridors, as well as the maximum distances to exits, are just some of the basic form regulating design considerations. The construction assembly fire rating and the corresponding fire rating of doors and mechanical penetrations are also specified by code.

Aside from the convenience and safety factors, horizontal and vertical circulation strategies are also connective elements of space planning. To use the example of Lloyd's of London again, the market trading floor, or The Room, as it is called, is the focus of the building, much like the trading floor of the New York Stock Exchange. Richard Rogers and his team enhanced the level of face-to-face communication among the traders by folding five floor levels of The Room back onto themselves around an open atrium and connecting the vertically layered floors with open escalators. This greatly reduces the walking distance from the most remote desks as compared with the situation that would have been produced by a larger floor plate and fewer stories. It also reduces the distance to exitways and the required width of the circulation paths. Rogers then used the site area preserved by the smaller floor plate for towers containing the elevators, toilet rooms, and stairs and located them in six residual corners of the site. Norman Foster used a similar strategy at the much larger Hong Kong and Shanghai Bank (see case study #25) to organize the 43-floor bank into seven distinct vertical villages with interconnecting escalators but only one elevator stop per village.

Site Systems

Systems integration at the site level deals with issues of context: environmental, social, urban, cultural, and whatever special conditions are presented by the exact situation of the building project and its neighboring surroundings. Site systems are the first level of interface between the building solution and the site context.

Elements

- Topography—building set on, above, or into differing grade levels; retaining walls and modifications to natural grade
- Surrounding structures—shade, wind, and view determined by immediate surroundings
- Footprint—orientation, elongation, and massing of the building
- Perimeter—defining the boundaries of the site with fences, gates, walls, hedges, and/or landscaping
- Landscape—vegetation, bodies of water, and other natural features
- Paving—parking, access, driveways, pedestrian paths, terraces, patios
- Storm water—rainwater drainage, detention ponds, swales, gutters and downspouts, area drains, curbs, and gutters
- Utilities—service connections, transformers, meters, waste disposal
- Site lighting—general illumination, façade lighting, lighting for pathways, security, signage
- Appurtenances—gazebos, porte-cocheres, arbors, fences

Microclimates and Environmental Site Design

From the environmental perspective, the site forms microclimatic conditions by modifying the regional climate. Then the relationship of a building to its site begins as a series of formal responses: thermal, aerodynamic, solar, luminous, and so on. For example, a building on the north side of a hill is in a very different microclimate than a building on the south side of the same hill; a building surrounded by asphalt is in a very different condition than one surrounded by trees. To a large degree, these microclimatic modifications can be controlled by careful design and deployment of the site systems. This means that the site can be treated as an outer layer beyond the envelope and act to interpret environmental conditions favorably.

The integration of site systems should maximize the results of these modifications. Trees established for shade also affect wind patterns and views into and out of the building. Paving is used to drain storm water from parking and surrounding areas. Solar orientation and the placement of glazing impact the availability of lighting and the issues of view and privacy. Natural bodies of water and storm water detention ponds can work as cooling towers for the HVAC system. This list can be elaborated at length, as can be seen in the next section of this chapter, but bear in mind that potential benefits depend heavily on the particulars of the building program.

Architecture as an Armature for Nature

Ultimately, site design determines a building's place in nature. As soon as the building is completed, nature begins to reclaim it by acts of weathering, erosion, and chemical and biological change. High levels of maintenance will be required if the building and site elements are to resist nature's reclamation. Without continuing maintenance, nature will mark the building with its weathering processes. The architect has to design according to assumptions about ongoing maintenance over the building's lifetime to accommodate this aging. Durable materials that defy the weather are more expensive than those with shorter lives; exposed materials require more detailing than painted ones.

Mostafavi and Leatherbarrow (1993) have characterized two opposing perspectives in their book, *On Weathering.* They portray the maintenance of a building's original condition as resistance to *stain* and the planned aging of a building into its surroundings as a graceful *patina.* On another level, this opposition can be seen as a more philosophical distinction between the entropy of nature and the organizational work of industrial society. Nature works toward diffuse homogeneity as wet moves to dry, hot moves to cold, high pressure moves to low, mountains erode to fill the valleys. The laws of physics move our environment toward homogenous conditions, higher states of entropy. Any potential for movement, any difference in energy levels, drives the work of nature. In nature's pristine state, all of these motions are present. The works of an industrial society, on the other hand, are directed against natural entropic decay. In the pristine state of industry, everything is clean and gleaming. Civilization to date has been the history of this pioneering against entropy, moving instead toward organization, focus, and concentration. The pioneer mentality that generated the rise of industrial society was always aligned against the erosion of nature; stain was a symptom of failure to hold back its forces.

Accepting the inevitability of weathering embraces the opposite perspective: a graceful patina acquired as nature reclaims a built work and its setting. This attitude is more evident in Eastern civilization and in organic and naturalistic approaches to architecture. Certain aspects of it have crept into Western thinking as economic pressures make submission to entropy more practical than resistance: xeroscape and native landscapes, organic gardening, passive solar design, and the selection of natural materials, to mention a few.

Many attitudes about design are prone to regard the site as a resource for the building. The imposition of the architectural footprint on the land is given dominance over the condition of the site in terms of everything from orthogonal geometries to border plantings. The counterposition asks about the notion of buildings as systems that will gradually be reclaimed by nature anyway. It proposes that a building is, in fact, an armature for nature and so replaces industrial mechanics with natural ones wherever feasible:

- Paving blocks or stones replace concrete and asphalt paving
- Water gardens replace runoff and storm water retention ponds
- Hedgerows replace border plantings and fences
- Natural landscaping is used in favor of pesticides, fertilizers, watering, mowing and raking
- Earth-integrated buildings are designed in underground, earth-covered, or earth-bermed configurations instead of on graded sites
- Habitats for native species are incorporated in favor of exterminated lawns.

Conclusion: Integration Potentials

There are an infinite number of possible integrations between the five major building systems, between the subsystems of each, and among subsystems of different major systems. There can be no exhaustive list, and, more important, developing the correct list for each building project is a matter of careful decision making in design. It is quite possible, however, to generate a beginning list based on what has been defined here as shared mandates between the major systems. Examples of the integration potential of overlapping shared space, shared image, and shared function among the ten possible pairs of major building systems are outlined in Table 3.1.

TABLE 3.1 Some Integration Opportunities as Shared Mandates Between the Ten Possible Pairings of Five Major Systems

	Site	Structure	Envelope	Services
Interior	Indoor/out relationships	Exposed structure Integrated lighting	Daylighting	Exposed ducts Masking background Air-handling luminaries
Services	Cooling ponds Earth tube cooling	Duct routes Interstitial mechanical Plenums	Passive design Solar roofs Vented skin Double envelope	
Envelope	Earth shelter Natural habitat Noise barriers Storm water	Building shell Shading Light diffusing		
Structure	Underground Terraced			