chapter 1

The Evolution of Design Process

The exact point in time when design professions’ embrace of green principles changed from a desirable commodity to a fully integrated design expectation is probably lost in history. The difference between both designer and client expectations now versus the 1990s is striking. Green design transcends mere descriptions of the techniques that may be employed in shaping a more sustainable existence on Earth. It must also incorporate the principles, processes, and cycles of nature in a way that leads to a deeper understanding of what makes a design successful. Ideally, a book in the first decade of the third millennium that addresses green design should form the foundation for exploration and discovery of new and innovative ways to minimize ecological footprints. But it must be even more than avoiding the negative. Now and from now on, designers must strive for an end product that mutually benefits the client, the public, and the environment.

It is only through creating a better understanding of the natural world that new strategies can emerge to replace the entrenched design mind-sets that have relied on traditional schemes steeped in an exploitation of nature. Designs of much of the past four centuries have assumed an almost inexhaustible supply of resources. We have ignored the basic thermodynamics.

Almost everything we do in some way affects the health of the planet, from showering and brushing our teeth in the morning to well after we are finally tucked in at the end of the day, and the small clock on our nightstand continues to demand energy from the grid. One of the great misconceptions of scientists and nonscientists alike is that environmental consciousness is not dictated by sound science. To the contrary, everything that we do to the environment can be completely explained scientifically. The good news is that by applying the laws of science, we can shape our environment and provide the products demanded by society both predictably and sustainably. That is, strategic use of the principles of physical science informs our designs and engineering decisions.
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Such thoughtfulness will moderate or even eliminate the slowly unraveling web of nature that has been accelerating at an alarming rate. Innovators such as Albert Einstein have noted that new and emerging problems demand new approaches and ways of thinking. “The significant problems we face cannot be solved at the same level of thinking we were at when we created them.”

Our hope is that this book is one of the building blocks of the next stage of green design. We advocate taking proactive steps toward evolving our thinking about solutions to the many complex environmental challenges we face at the beginning of the twenty-first century.

Since the industrial revolution of the nineteenth century, architects and engineers have been key players (culprits?) in the war against nature. Single-minded exploitation and subjugation of nature was the norm during much of the twentieth century and persists as a mainstay of design. Technology has hastened the process. Notably, “man-made weather” (i.e., air conditioning) is now a universal expectation of building design in the West, following the invention of an “apparatus for treating air” patented by Willis Carrier in 1906.

It is entrenched in the desire for conformation of the International Style of Architecture, which spanned much of the twentieth century. Many of us follow the remnants of this style, still seeking one universal building, regardless of climate and place. We take great comfort in our templates. What worked last time surely must work again this time.

Actually, green thinking is not new at all. In fact, our new way of thinking resembles an understanding of and respect for nature found in antiquity, as evidenced by the designs of cliff-dwelling native peoples. Reestablishing the link between built form and the environment will require a more complete understanding of the science that underpins successful sustainable design strategies, and incorporating this knowledge as architects and engineers engaged in shaping our world along with the construction community charged with realizing a new vision. In Cradle to Cradle, McDonough and Braungart note the challenge of this approach: “For the engineer that has always taken—indeed has been trained his or her entire life to take—a traditional, linear, cradle to grave approach, focusing on one-size-fits-all tools and systems, and who expects to use materials and chemicals and energy as he or she has always done, the shift to new models and more diverse input can be unsettling.”

A more complete understanding of the first principles of science and a re-examination of the “normal” process of conception and delivery in the design and construction communities puts the green designer in a position of strength. These principles provide the knowledge needed to challenge those who choose to “green wash” a product by presenting only a portion of the entire story of a product’s environmental impact. For example, a product may indeed be “phosphate free,” which means that it does not contain one of the nutrients that can lead to eutrophication of surface waters. However, this does not translate directly
into an ecologically friendly product, especially if its life cycle includes steps that are harmful, such as destruction of habitat in material extraction, use and release of toxic materials in manufacturing, and persistent chemical by-products that remain hazardous in storage, treatment, and disposal. For example, simply replacing the solvent with a water-based solution is often desirable, and can rightly be called “solvent free,” but under certain scenarios may make a product more dangerous, since many toxic substances, such as certain heavy metal compounds, are highly soluble in water (i.e., hydrophilic). Thus, our “improved” process has actually made it easier for any heavy metals contained in the solution to enter the ecosystem and possibly lead to human exposures.

The law of unintended consequences is ever ready to raise its ugly head in design. There are numerous examples of building design solutions touted as sustainable that fail to recognize and respond to the specifics of local climate. A building project that has applied sustainable principles with the mind-set that these principles are “universal” solutions will produce less than optimal results, if not total failure. For example, a wind system is renewable but is not necessarily efficient. Incorporating wind turbines without first understanding local climate and the physics of wind-generated energy could lead to poor design solutions by placing turbines in an area that does not generate sufficient wind speeds throughout the year.

The idea of a more “holistic” approach is required to arrive at complete, sustainable design strategies. The notion of life cycle in the design and construction community has too often been confined to a cost–benefit economic model of demonstrating the return on investment that can be expected over the life of a building. Although this approach to applying a financial model demonstrates the return on investment of sound design choices, the concept must also be applied beyond a comparison of the initial investment as a fraction of the total cost of operating and maintaining a building or system to an expanded definition beyond pure economics. For example, design decisions on how we shape our environment also include less tangible impacts on the individual, society, and ecology that may not fit neatly on a data spreadsheet.

**PROCESS: LINEAR AND CYCLICAL DESIGN**

The critical path from building conception to completion has changed very little over the thousands of years since humans began to shape the environment to create shelter from the elements. The first builders harvested locally available materials, and assemblies grew from trial and error and from observation of the structures found in nature. Trial and error created the feedback loop that guided the technical development of these structures. Marcus Vitruvius Pollio is believed to have authored *De Architectura* (*On Architecture*), written in the first
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century b.c. De Architectura provided one of the first sources of guidance for building, containing 10 chapters, or 10 “books.” Codifying existing practice on topics ranging from building materials to proportional relationships based on the human body, the text served for centuries as an influential reference. Vitruvius wrote of architecture as being an imitation of nature, and a central tenant of his writing was the suggestion that a structure must contain three essential qualities: “firmitas, utilitas, and venustas.” *Firmitas* is translated from Latin as firmness or strength, *utilitas* suggests commodity or usefulness, and *venustas* is a quality of delight or beauty. These remain as core design criteria. Engineers emphasize the first two, and architects give much attention to the second two.

Leonardo da Vinci, Michelangelo, Filippo Brunelleschi, and other key design figures of the Renaissance did not distinguish boundaries between the roles of artist, architect, and engineer (see Fig. 1.1). The Renaissance master builder represents the next step in the evolution of rationalizing the process with the introduction of science and engineering principles. The emergence of architectural treatises, increased physical challenges of larger spans, and a desire for an increasingly rich aesthetic expression all contributed to the growing complexity in navigating this pathway from conception to completion. The master builder of the Renaissance played the roles of architect, engineer, material scientist, and builder, simultaneously serving as the source of inspiration, technical resolution, and delivery. Florentine architect Brunelleschi (1377–1446) was a seminal figure.
in the Renaissance period who studied science and mathematics (see Fig. 1.2). He began as a painter and sculptor, and then became a master goldsmith, with most of his success in acquiring important architectural commissions attributed to his technical genius.

It was not until the industrial revolution that boundaries between professions began to become distinct, opening a path toward specialization. The twentieth century witnessed the acceleration of this migration toward specialization, as building systems became more complex and the number and diversity of building typologies grew. The industrial revolution brought the rise of transportation and manufacturing infrastructure, providing the ability to fabricate components off-site and assemble on-site. This increasing complexity begins a transition away from the model of master builder along with the emergence of discrete professional disciplines, and eventually, further fragmentation within these disciplines as the roles of design and technical expertise no longer reside in any one individual.

The single defining and unchanging characteristic of the building professions remains the act of designing. Merriam-Webster Collegiate Dictionary defines design as "to create, fashion, execute, or construct according to plan" and "to conceive and plan out in the mind." Research, analysis, optimization, constraint identification, prototyping, and many other facets of the design process remain common to all design professions. Depending on the design specialty or disciplines, the scientific and aesthetic principles are applied in differing measures to achieve the core objective of problem solving.

The actual view of the process of design, however, varies substantially both within the professions and between design disciplines. Some view the process as purely direct, sequential, and linear, following a prescribed set of activities that will lead to a final solution. This stepwise approach is often referred to as the waterfall model, drawing on the analogy of water flowing continuously through the phases of design. This approach has value, especially when the number of variables
are manageable and a limited universe of possible solutions are well behaved and predictable. An example of this approach would include a “prototype” design that is simply being adapted to a new condition. This process is often the most direct, conventional, and least costly when “first cost” is a primary consideration. For example, a reduction in the time required for design and delivery can mitigate the impact of price escalation due to inflation and other market variables. Most projects are planned around schedules that appear to be linear, but the actual activity within each phase tends to be somewhat nonlinear (e.g., feedback loops are needed when unexpected events occur).

Building Design Process

The process of design and delivery of buildings in particular, from conception to completion, has generally followed a linear or stepwise model in which distinct phases guide the design from definition of need or problem statement, followed by drawings through technical evolution, construction, and final completion. As illustrated in Figure 1.3, the path from project conception to completion follows a stepped progression with discrete phases for each stage of the project’s development. Much of the work and many of the insights are provided by the designer well into the process. Some technical input is sought early, but it is very limited. The builder typically does not provide input until midway through the process, but at the end is almost exclusively responsible for the project. This “hand-off” approach can lead to miscommunication and the lack of opportunity to leverage different perspectives. Even if the builder has good, green ideas from experience, the process may be too far along to incorporate them without substantial costs and need to retrofit.

The progression of the stepwise process from idea to realization is a sequence of events and involvement of specialized expertise. This process can be thought of...
as analogous to the conceiving of a new living organism. The process begins with the necessary definitions of the essential systems to support this new form of life. Next, performance characteristics are defined in precise detail to communicate assembly (embryonic growth). Finally, the concept is realized (born) by translating this vision from two-dimensional constructs into three-dimensional reality. Let us consider each step in a bit more detail, applying the analogy of the living organism to the design process.

**Program or Problem Statement**

Linear progression of the process would logically begin with a clear definition of the problem to be solved. In this case it is essential to pose questions of our client to determine in sufficient detail the goals for this new living organism, organizational form and systems, and how these will interact and influence each other in the functioning of the whole. It would also be helpful to understand and characterize the environment in which this organism will reside and the potential for symbiotic relationships within this ecosystem.

**Skeletal Form or Schematic**

Once the data are collected and understood, the logical next step in the design process would be to synthesize alternatives for weaving these forms together to create a skeletal framework or schematic for the new organism. This frame provides the basic support structure and places the forms identified in the first step in the most appropriate relationship with one another, seeking optimization of the design to meet the original goals and objectives most efficiently. At the end of this step, as a measure of design success, the original program or problem statement would be consulted and would serve as a checklist.

**Systems Development**

With the skeletal frame in place, the design proceeds forward. It moves in a linear fashion to the next rational step, of developing this design concept to incorporate the internal systems required to nourish the organism by transporting air and water, removing waste, and designing a central nervous system that provides the means for individual systems to communicate with one another. The heating, ventilation, air-conditioning, plumbing, and electrical systems for our organism are put in place. Our quality control/quality assurance measures at this point require that we confirm that we indeed have accounted for and incorporated all
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of the required systems and that they all fit within the skeletal frame developed in the schematics phase.

Technical Detailing and Documentation/Implementation

In the traditional linear model, the focus of the design team shifts from design conception and development to implementation. This transition in focus to the production of technical documents required to communicate the assembly of the design proposal coincides with a dramatic shift away from further synthesis and innovation. Computer-aided design and drafting (CADD), although a relatively new technology, has resulted in dramatic improvements in efficiency but has remained anchored in the processes and methods of the past. While design and drafting are given equal importance in the naming of the tool, the first several generations of this tool’s development provided essentially an electronic pencil for drafting, with great new features representing the integration of a number of previously separate and singularly purposed tools: scales for measuring, line and arc function commands replacing T-squares, parallel bars, and compass; and the delete key rendering the eraser obsolete and eradicating all past sins committed in ink.

A TRANSITIONAL MODEL

A linear model of the type we have described, which has remained relatively unchanged for decades, is now beginning to experience significant evolution. The means for ensuring sustainability has been achieved using accountability point systems, such as those in the Leadership in Energy and Environmental Design (LEED), BRE Environmental Assessment Method (BREEM), and Green Globes. Such documentation and recognition of “greenness” has emerged to encourage design and construction professionals to create projects with an eye toward environmental quality. They have often focused on uncovering options that will mitigate a proposed project’s environmental impacts. As such, these systems have profoundly changed the design process by moving up the technical input to the earlier phases of a project’s development.

In addition to “greening” proposals, designs now undergo a series of integration steps, which have been articulated by Mendler et al.:

1. Project description
2. Team building
3. Education and goal setting
4. Site evaluation
5. Baseline analysis
6. Design concept
7. Design optimization
8. Documentation and specifications
9. Building and construction
10. Post occupancy

Note that like the stepwise model, this model for the most part does one thing at a time. However, each step includes feedback to the preceding steps (see Figure 1.4). The design concept does not show up until the sixth step and is followed immediately by a comparison of design options. A key difference, however, is the extent of integration of goals into the design process. In fact, Mendler et al. identify global goals that must be part of a green design:

- Waste nothing (a “less is more” approach; reuse, avoiding specification of scarce materials).
- Adapt to the place (indigenous strategies; diversity, form fit to function).
- Use “free” resources (renewable energy, renewable materials, locally abundant resources).

![Figure 1.4](image-url)
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- Optimize rather than maximize (synergies, less reliance on active, mechanical systems).
- Create a livable environment (protect sensitive ecosystems, actively restore damaged habitats, look for pedestrian-friendly and mixed-use design options; avoid toxic materials).

The difference between the stepwise and transitional models is that the former is based on monetary costs, scheduling constraints, and quality; whereas the latter expands to integrate human health, safety, and comfort as well as ecological considerations. The transitional model still pays close attention to the stepwise model’s three attributes. In fact, the transitional model requires that even more scrutiny be given to costs, scheduling, and quality; so every step is reviewed in light of the preceding and subsequent steps. The dynamic nature of the model means that more variables are introduced with each step.

The LEED Green Building Rating System was conceived and implemented by the United States Green Building Council (USGBC) to define and measure the sustainability of “green buildings.” The USGBC, created in 1993, formed a diverse committee representing expertise in architecture, engineering, real estate, environment, and law focused on the creation of a benchmark for measuring building performance. According to the council, “This cross section of people added a richness and depth to the process and to the ultimate product.” Since the introduction of version 2.0 in March 2000, the LEED rating system has begun to transform building design and construction. One of the important by-products of the introduction of this system framework is the increased collaboration between design and construction professionals unified by common tools, principles, and the desire to achieve high-performance buildings (see Fig. 1.4). Benefits of the program now extend well beyond the building community, as both the public and private sectors recognize the benefits of sustainable design and now in many cases require the incorporation of these design principles, providing direct and indirect financial incentives and recognition. Another ancillary benefit of the rating system is that it has created markets for green materials. For example, points are given for reusing building materials, such as old ceiling tiles, which had previously found their way to landfills.

Sidebar: Applying the Synthovation/Regenerative Model: Green Buildings
The U.S. Green Building Council has established the Leadership in Energy and Environmental Design (LEED) rating system, which distinguishes “green buildings.” The greater the point total, the more sustainable the project. The rating system encourages design and construction practices that reduce the negative impact of buildings. Most of the points are gained using existing, proven technologies. Projects
are evaluated according to five separate categories: sustainable site planning, the safeguarding of water and water efficiency, energy efficiency and renewable energy, conservation of materials and resources, and indoor environmental quality. Applicants can earn points in 69 subcategories. An example of a scorecard is shown in Figure S.1.1. The U.S. Environmental Protection Agency (EPA) submitted this card for its Science and Technology Center in Kansas City, Kansas, hoping to earn a gold-level certification. LEED has four certification levels: LEED certified, 26 to 32 points; silver level, 33 to 38 points; gold level, 39 to 51 points; and platinum level, 52 to 69 points.

![Figure S.1.1](image.png)

**Figure S.1.1** LEED scorecard submitted for the Science and Technology Center in Kansas City, Kansas.


Laboratories present a particular design challenge. For example, air exchanges are needed to maintain air quality, especially when a laboratory contains hazardous chemicals. Most laboratories need to maintain positive pressure toward fume hoods, which pull air out of the lab space and vent it outdoors. This means
that warmed and cooled air also escapes. Thus, safety and green operations can be competing values. However, it does point the way to creativity and innovation. For example, how might heat-exchange systems be used to optimize safety and sustainable design?

More information is available at www.usgbc.org/LEED/LEED_main.asp.

THE HOME DEPOT SMART HOME AT DUKE UNIVERSITY

The Home Depot Smart Home at Duke University is a live-in laboratory dedicated to advancing the science of living smarter.

Green Roof

A green roof (also known as a vegetated roof) is an area of roof surface that is covered with living plant matter. In the case of the Home Depot Smart Home at Duke University, the green roof is populated with succulents that are low maintenance and drought resistant. Benefits of green roofs include:

- Preventing heat gain (also known as the urban heat island effect)
- Evaporation creates a cooling effect on the building
- Prefiltering rain water for later use
- Buffering rain water to prevent rapid site run-off
- Pleasing aesthetics
- Increasing the roof lifetime

Water Efficiency

The irrigation system for the Home Depot Smart Home at Duke University uses 100% captured rainwater. This guarantees that no public water will ever be used to water vegetation on the Home Depot Smart Home at Duke University site. The rainwater is collected from roof run-off and stored in two 1000-gallon storage tanks for later use (Fig. S.1.2). The Home Depot Smart Home at Duke University site is also populated with indigenous plant species which further reduce the demand on the rainwater system.

Energy and Atmosphere

At the Home Depot Smart Home at Duke University, there is an array of 18,160-W photovoltaic panels (see Fig. S.1.3), which creates a ~3-kW solar power station. The energy generated by the panels is connected to the public power grid and puts energy back onto the grid for use by the neighbors. It also reduces the total energy consumed by the Home Depot Smart Home at Duke University by approximately 30%.
Figure S.1.2  A 1000-gallon rainwater cistern at the Home Depot Smart Home at Duke University.

Figure S.1.3  Photovoltaic panels at the Home Depot Smart Home at Duke University.
Materials and Resources

All waste generated at the Home Depot Smart Home at Duke University site during construction was placed in a single bin for convenience. When the bin was collected, it was taken to a sorting facility where the waste was separated into disposables and recyclables. Using this process, more than half of the total waste was being diverted from landfills.

Indoor Environmental Quality

Research has shown that providing daylight views to building occupants increases productivity. Anecdotal evidence suggests that having access to daylight and views creates happier residents. In the Home Depot Smart Home at Duke University, greater than 90% of locations inside the building have direct daylight views.

Innovation and Design Process

The Home Depot Smart Home at Duke University is a resource for use by the university and local community for learning about sustainable building techniques. At the facility students can learn about sustainable construction techniques. Public tours are also available upon request.

The transitional model represents a significant break from the linear model and the virtual independence of each stage of development in the progression from concept to completion. Using software tools earlier in the design process to model energy consumption or the effectiveness of daylighting strategies, for example, allows specialized technical input earlier in the process, and the feedback gathered from this iterative cycle can then be used to refine the solution while the design is still malleable.

THE SYNTHOVATION/REGENERATIVE MODEL

Our view is that design is moving toward more sustainable solutions by increasing the role of teamwork to find synergies through synthesis and innovations. We call this *synthovation*: *synthesis* being the merging or integration of two or more elements, resulting in a new creation, and *innovation* being the introduction of
something new—an idea, method, or device. The opposite of synthesis is analysis. Environmental programs have, for good reasons been dominated by analytical thinking. Each step in a process has been viewed as a possible source of pollution. Monitoring is an act of analysis (breaking things apart to see what is wrong). However, the environmental community is calling for more synthesis, especially as technologies such as the best available control technologies called for by the Clean Air Act are gradually being supplanted by risk-reduction approaches. In other words, emphasis in the 1990s was on the application of control technologies, but the U.S. Congress wanted to be able to determine what risk remains even after these controls are put in place. Addressing such residual risks requires green thinking.

Thus, the call for innovative pollution control equipment in the twentieth century has moved to innovations in holistic design. Reducing risks in the first place harkens to the advice of business guru Peter Drucker, who has noted that innovation is “change that creates a new dimension of performance.”

This ethos is also being expounded by designers such as John Kao, who suggests that innovation is “the capability of continuously realizing a desired future state.”

Emerging collaboration software tools are creating the potential for powerful synthesis and integration across technical expertise that has historically remained segregated until much later in the life of a project’s development. This migration of technical input to earlier phases of the design process holds the opportunity not only for more complete synthesis but also the promise of innovation in the way we conceive and shape the built environment. As illustrated in Figure 1.5(a), the progression from concept to completion would draw from multiple expertise of the design team from the very early stages of development. The “spine” forms the path of project delivery in this case and is representative of the progress from concept to completion as the input from design, technical, and construction expertise is reflected in the growth of the concept as it evolves. The next generation of software will allow digital, rapid prototyping of alternative scenarios incorporating diverse inputs as the model grows with each successive iteration, building on the preceding cycle of input and providing a frame for continuous integration and performance improvement.

The nautilus shell [see Fig. 1.5(b)] and sunflower seed patterns provide useful analogies when describing this new model that bridges concept to completion, with multiple interlocking spirals representing the continuous iterative process and integration of multiple dimensions of technical expertise. The spiral pattern is repeated in nature in many variations, from the rotation of plant stalks to provide leaves with optimal exposure to sunlight by never occupying the same position twice, to the spiral growth pattern of a seashell, continuously expanding and maintaining optimal structural strength (see Fig. 1.6).
Figure 1.5  (a) Synthovation model adapted from the nautilus shell; (b) nautilus shell cross section.

Part (b) is a Wikipedia and Wikimedia Commons image and is from the user Chris 73 and is freely available at http://commons.wikimedia.org/wiki/Image:NautilusCutawayLogarithmicSpiral.jpg under the creative commons cc-by-sa 2.5 license.
Figure 1.6 Examples of spiral forms in nature.

The Home Depot Smart Home at Duke University: Energy Models, Feasibility Models, and Iterative Design

“One of the major missions of the Smart Home is the focus on energy efficiency and sustainable living.”
—Tim Gu, Undergraduate Student, Duke U. and Smart Home President

The Home Depot Smart Home at Duke University is a 6000-ft$^2$ residential dormitory and technology research laboratory operated by the Pratt School of Engineering, Duke University.

During the design development phase of the Home Depot Smart Home at Duke University, it was very important to the team to select an overall building design that was efficient to heat and cool. To achieve this end, three models were conceived of, each highlighting different design concepts attractive to the team (see Fig. SH1.1).

- **Model: Two Houses.** Designed to blend with the size of the other local houses but to provide the increased square footage needed by the program for a 10-student occupancy.
- **Model: Courtyard.** Designed around the idea of having a large amount of public outdoor space available for program use. The building was built around an open area in the center.
- **Model: Berm.** Designed around the idea of having a large, south-facing test platform for experimentation with various types of solar power and heating technologies.

After all the models were created, they were each evaluated for their theoretical heating and cooling loads over the course of a year (see Fig. SH1.2). The design elements with the best energy performance synthesized into three more designs, each superior to the others. Those designs were then built into
physical models and evaluated for feasibility (see Fig. SH1.3). The keyboard model was built around the idea of having different pods for each bedroom which would be added to, removed, or expanded. The bar model was built for simplicity. It had a great surface area/volume ratio and was easy to construct. The squirrel model was designed for experimentation with different types of sun exposure as well as providing interesting aesthetic contours.

A third design phase combined the best features of the energy and feasibility analyses and created a single design concept for what closely resembles the as-built Home Depot Smart Home at Duke University (see Fig. SH1.4).
The design process that follows this spiral approach is preferable to the current “loops,” which represent feedback. Half of the loop is retrograde. That is, the client can infer that the design is progressing, but in order to incorporate various viewpoints, it is losing ground (and costing more money and time). Often, however, a synergistic and innovative design never goes backward. In fact, better and, frequently, more cost-effective features are being integrated into the project continuously. This goes beyond the “pay now versus pay later” decision, although considerations of the entire life cycle will save time and money, not to mention preventing problems of safety and pollution that can lead to costs, dangers, and liabilities down the road, after completion (see Fig. 1.7).
Design software is becoming increasingly robust. We can now store parametric data that allow comparisons of various options across multiple dimensions. Design teams can rapidly develop prototype alternatives early in the process and continue to test development as solutions emerge and take form. And as we gather more data and test these models, our uncertainties will continue to decrease. Of course, we will never be completely certain about outcomes, in light of the myriad influences and variables. However, the integrated approach is much better than the brute force of a single design strategy, in which we can only hope that there will be no unpleasant surprises down the road (e.g., material and system incompatibilities, unexpected operational costs, change orders, retrofits).

Continuous improvement calls for sound science (see Fig. 1.8). New dimensions against which design alternatives will be able to be measured include the evaluation of technical inputs being proposed, as well as modeling performance against multiple variables such as climatic conditions. Returning to our living organism analogy, a design needs technical expertise to grow; thus such information is the design’s “nutrients.” Such technical nutrients cycle through the design process. For example, a more complete picture of energy consumption is gained by models able to look both upstream to manufacturing and transport to account for embodied energy, as well as downstream to test the digital prototype against a range of environmental conditions, not simply a static condition derived from the averages for a particular site. Consideration can also be given to the potential for regenerative design by accounting for and analysis of the technical and biological nutrients that a proposed design will consume and how easily these nutrients are able to find productive reuse in the next generation or cycle of use.
Daniel Pink in his book *A Whole New Mind* makes the argument that humankind is at the threshold of a new era that he has coined the *conceptual age*.\(^{10}\) Pink argues that success in this new era will necessitate seeking solutions that leverage the thought process of both the right and left hemispheres of the brain. He identifies six essential right-brain aptitudes necessary for the “whole new mind” that this new era will demand: (1) design, (2) story, (3) symphony, (4) empathy, (5) play, and (6) meaning.

Pink argues that these six senses will increasingly shape our world.\(^{11}\) We agree. Pink has identified the need for a “symphony aptitude,” which is at the heart of integrated design. This is the ability to put the pieces together, to synthesize, “seeing the big picture and, crossing boundaries, being able to combine disparate pieces into an arresting new whole.”\(^{12}\) Design and symphony aptitudes must be developed in order to create innovative solutions that reach beyond functional and aesthetic considerations to address environmental concerns.

This argument for discovery at the intersection of what have traditionally been compartmentalized and partitioned thought processes is counter to the twentieth century models of practice for architecture and engineering. Successful sustainable design strategies demand an integrated approach to practice in which both quantitative and qualitative considerations are valued, and provide leverage in conceiving the highest and best solutions to society’s challenges in the built environment.
Sidebar: Applying the Synthovation/Regenerative Model: The Symphony of Sustainability

Symphony is a musical term. It is also a metaphor for integration and synergy. Interestingly, music has played a prominent role in environmental awareness. The environmental movement is a relatively young one. Popular culture enhanced scientific awareness of the concept of Spaceship Earth: that our planet consists of a finite life support system and that our air, water, food, soil, and ecosystems are not infinitely elastic in their ability to absorb humanity’s willful disregard. The poetry and music of the 1960s expressed these fears and called for a new respect for the environment. The environmental movement was not a unique enterprise but was interwoven into growing protests about the war in Vietnam, civil rights, and general discomfort with the “establishment.” The petrochemical industry, the military, and capitalism were coming under increased scrutiny and skepticism. Following the tumultuous 1960s, the musical group Quicksilver Messenger Service summed up this malaise and dissatisfaction with unbridled commercialism and a seeming disregard for the environment in their 1970 song What About Me. The song laments that Earth’s “sweet water” has been poisoned, its forests clear-cut, and its air is not good to breathe. The songwriters also extended Rachel Carson’s fears that the food supply is being contaminated, linking diseases to food consumption (i.e., “the food you fed my children was the cause of their disease”).

These sentiments took hold, became less polarized (and eventually, politically bipartisan for the most part), and grew to be an accepted part of contemporary culture. For example, the mind-set of What About Me is quite similar to that of the words of the 1982 song Industrial Disease, written by Mark Knopfler of the band Dire Straits, but with the added health concerns and fears created by chemical spills, radioactive leaks, and toxic clouds produced by a growing litany of industrial accidents.

In poetic terms and lyrical form, Knopfler is characterizing the growing appreciation of occupational hazards, the perils of whistle-blowing, and the cognitive dissonance brought on by people torn between keeping their jobs and complaining about an unhealthy workplace (“Somebody blew the whistle and the walls came down…”). His words also appear to present a hypothesis about the connection between contaminant releases (known and unknown) and the onset of adverse effects in human populations (i.e., “Some come out in sympathy; some come out in spots; some blame the management, some the employees…”).

Such a connection is now evident, but in the early 1980s, the concept of risk-based environmental decision making was still open to debate. These
Sustainable Design

Concerns were the outgrowth of media attention given to environmental disasters, such as those in Seveso, Italy and Love Canal, New York (e.g., could Knopfler’s “some come out in spots” be a reference to the chloracne caused by dioxin exposure at Seveso and Times Beach, Missouri?), and the near-disaster at the Three Mile Island nuclear power plant in Pennsylvania. But Knopfler’s lyrics are particularly poignant, prescient, and portentous in light of the fact that he penned these words years before the most infamous accidents at Bhopal, India and Chernobyl, Ukraine, both causing death, disease, and misery still apparent decades after the actual incidents (“Sociologists invent words that mean industrial disease”).

Recently, musicians have embraced green and sustainable design principles. One of the most prominent advocates is singer/songwriter Jack Johnson. Beyond lyrics, Johnson has rethought his music enterprise, including redesigning his studio, specifying green materials such as bamboo flooring and utilizing the sun as a source of energy. The band Pearl Jam required that its 2003 tour be “carbon neutral,”† and in 2005 completely switched all tour buses to run on renewable biodiesel fuel. Johnson did the same and credits many of the ideas to the older “rockers,” including Neil Young and Bonnie Raitt. In our first class of first-year green engineering students at Duke, when asked about their reasons for taking the course, two mentioned that they want to combine science and engineering with music. This is further evidence of an emerging trend in whole-brain thinking of the next generation of designers.

This is also evidence that sustainable design is really not just about sustaining but about enhancing green ideas. The symphony is being played at the intersection of the two generations, and spanning once distinctly separate worlds of study.

†Carbon neutrality is the concept that no more carbon is released than is sequestered in a given process.

MODELS FROM NATURE OF INTEGRATED SYSTEMS DESIGN

Human subtlety will never devise an invention more beautiful, more simple or more direct than does Nature, because in her inventions, nothing is lacking and nothing is superfluous.

Leonardo da Vinci
(The Notebooks of Leonardo da Vinci, Jean Paul Richter, 1888)
Duke University is a leader in environmental and biomedical engineering research. Emulating nature is a prominent area of research, especially the research that is taking place in the Center for Biologically Inspired Materials and Material Systems. Nature has been extremely successful in design at a vast range of scales. The elegance of the simplicity of a virus, and the complexity of a blue whale or a giant redwood tree, testify to the efficiency and effectiveness of natural systems. So, then, what can we learn from a tree as a system that can be emulated in good design?

If we think about the tree as a design entity, it is a very efficient and effective “factory” that makes oxygen, sequesters carbon, fixes nitrogen, accretes solar energy, makes complex sugars and food, creates microclimates, and self-replicates. Beyond a single tree, the ecological association and community of trees makes use of what nature has to offer. It takes up chemical raw materials (nutrients) using two subsystems, roots and stomata. Thus, the community of trees makes use of two fluids, water and air, to obtain the chemicals needed to survive. Furthermore, a collective of trees is more than just a group. A stand of 100 trees is not the same as the product of 100 times a single tree. The collective system differs from the individual tree's system. Engineers and architects can learn much from biologists, especially the concept of symbiosis. There are synergies, tree-to-tree relationships, as well as relationships between the trees and the abiotic components (nonliving features, such as the sand and clay in soils and the nitrogen in the atmosphere and soil water). The tree system also depends on and is affected by other living things, that comprise the biotic environment, including microbes in the soil that transform chemical compounds, allowing trees to use them as nutrients, and insects that allow sexual reproduction via pollination. So what would it be like to design a building in a manner similar to how nature shapes a tree? What are the possibilities of designing a city that is like a forest? In Chapter 7 we discuss the tree as a design component.

Principles of Biomimicry

Living systems reflect the “new” design model. In her book Biomimicry, Janine Benyus argues that nature presents a workable model for innovation worthy of imitation. The biomimicry model looks to nature as a learning resource rather than merely as a natural resource commodity to be extracted from the Earth. Benyus writes that “nature would provide the models: solar cells copied from leaves, steel fibers woven spider-style, shatterproof ceramics drawn from mother-of-pearl, cancer cures complements of chimpanzees, perennial grains inspired by tallgrass, computers that signal like cells, and a closed-loop economy that takes its lessons from redwoods, coral reefs, and oak–hickory forests.”
Nature demonstrates beautifully how scientific principles such as optimization and the thermodynamic laws are evident and interwoven in nature’s community of diverse and cooperative systems. This is evidenced in Benyus’s *principles of biomimicry*:

- Nature runs on sunlight.
- Nature uses only the energy it needs.
- Nature fits form to function.
- Nature recycles everything.
- Nature rewards cooperation.
- Nature banks on diversity.
- Nature demands local expertise.
- Nature curbs excesses from within.
- Nature taps the power of limits.

Innovations in material science have accelerated over the past few years with new materials that are built from science and engineering discoveries. As discussed later in Benyus’s text, many innovations in material science draw inspiration from nature. For example, the study of lotus petals’ ability to repel rainwater is now finding applications in “biometric paint” and in surface treatment for concrete that absorbs pollution from the air. What can the orb-weaver spider teach today’s architects, engineers, and material scientists? The study of such organisms and a closer look at the chemistry underlying the transformation of flies and crickets into materials that are five times stronger per ounce than steel at room temperature could lead to a new way of conceiving and manufacturing materials and assembling them to create more sustainable environments.

**EMERGING TOOLS FOR COLLABORATION, SYNTHESIS, AND INNOVATION IN DESIGN**

New tools are emerging to facilitate creation of whole systems and integrated approaches through collaboration, synthesis, and innovation in the design process. In addition to supporting collaboration, new software tools are allowing designers to develop, digitally prototype, and test on demand, providing freedom to explore virtual models of alternatives quickly.
Open-Source Software

In *Massive Change*, Bruce Mau envisions a future in which we will build a *global mind*. This is made possible through the impact of emerging network protocols for distributed computing that provide for the linking of databases and the sharing of simulation and visualization tools available to anyone, anywhere. Mau notes that “to imagine that any one closed group could solve the problems we confront today is folly. The free and open software movements promise to overcome our territorial attitudes and take advantage of our collective potential.” Open-source software is counter to the traditional approach of source codes, which both technically and legally, protect the fundamental working structure of the software from the general public. Open-source software opens the operating system to anyone with the interest and technical ability to propose improvements or extend the capabilities of the software tool. The emergence of open-source software has led to the collaboration of a diverse collection of people bringing varied experiences and creativity to the development of these tools. *World Changing*, a collection of essays on meeting the great challenges of the twenty-first century, includes commentary on the importance of this emergence of open-source software in providing a critical design tool for collaboration. “Open-source software would, by itself, be an important tool, but the real revolution of open-source is the model itself. All around the world, people are putting the principles of open collaboration to work on all manner of projects, which transcend the world of software.”

ThinkCycle

At the Massachusetts Institute of Technology, a group of graduate students in the Media Lab set up an open, online structure to allow them to collaborate on design and engineering projects. This initial idea has evolved, and as the Media Lab website states, “ThinkCycle is an academic, non-profit initiative engaged in supporting distributed collaboration towards design challenges among underserved communities and the environment. ThinkCycle seeks to create a culture of open-source design innovation, with ongoing collaboration among individuals, communities and organizations around the world.” ThinkCycle–Open Collaborative Design provides an invitation for a diverse cross section of students and researchers to link together and synthesize solutions that build on the expertise of others participating through ongoing peer review, critique, or simply posting of ideas and suggestions. In a contribution to *World Changing*, Dawn Danby writes about ThinkCycle and notes that “we often lack the technological or contextual knowledge to effectively solve design challenges: by bringing together complementary knowledge bases, ThinkCycle created a brilliant, pragmatic model for
conducting reality checks on visionary concepts and designs.”

Danby also notes the connection between open-source software such as ThinkCycle to the work of Victor Papanek, the UNESCO designer who refused to patent any of his works but rather, focused on creating a “public domain of form and function.”

**BIM Tools**

Tools are now available to both architect and engineer to conceive and deliver design solutions in a more integrated manner. **Building information modeling (BIM)** uses computer technology to create a virtual multidimensional models of a building as an integrated part of the design process, not as an afterthought for use in marketing the design as a finished product (see Fig. 1.9).

This approach is revolutionary in the design professions. Most design software used in architectural/engineering offices since the introduction of computer-aided design systems has represented productivity gains through increased efficiency but really has not represented major advances beyond digitally representing primitive lines, arcs, and circles to define buildings.

Designers using BIM software can apply digitally bundled information called objects to represent building components such as windows and doors. These models are enriched by their ability to represent a much wider range of information on the physical characteristics of the building. The potential for these models to behave in an “intelligent” manner provides the opportunity for exploration and collaboration among design disciplines as well as with the construction community. The term **integrated practice** has been coined to describe this approach, which represents both an opportunity and a challenge for the architecture and engineering professions.

Better quality, greater speed, and lower cost by way of improved efficiency can be expected from the BIM approach. From a sustainable design perspective, the greatest potential is for increased collaboration and integration across design disciplines supporting the promise of a trend toward systems solutions similar to those found in nature. This allows the designer to envision positive and negative outcomes of various options. The BIM process is also a tool for moving beyond the stepwise model, in that it requires that issues which historically have been addressed exclusively during the development of construction documents be discussed during the design phases. Recently, Carl Galioto, FAIA, a partner at Skidmore, Owings & Merrill in New York, noted that “BIM will change the distribution of labor in the design phases. When done correctly, the labor is front loaded earlier in the design process, during schematic and design development phases, and less in construction documents.”

This shift in the labor distribution is consistent with Pink’s notion of value-added input occurring during the early phases of the conceptual development of design.
These information-rich models provide the ability to simulate and analyze alternative scenarios that incorporate project specifics such as local climate that are critical to finely tuned sustainable design strategies. This ability to test design via simulation provides the architect and engineer with a more complete understanding of the ramifications of their designs across multiple measures of performance. While the models provide the ability to advance beyond two-dimensional representation to create three-dimensional space models as found in other recent...
software programs, the BIM models also have the ability to introduce multiple new dimensions into the design process, including time, cost, procurement, and operations. By leveraging the additional information provided in these new dimensions, a more robust database and an adaptive expert system are available to the design team to explore and conduct more comprehensive life-cycle cost models.

INTEGRATION AND COLLABORATION

To be an architect, engineer, or designer is to be an agent of change, and by working collaboratively, we have the potential to become the alchemists of the future, transforming a collection of data and myriad inputs to derive designs that protect and shape our environment in a manner that benefits all. The amount of “lead” is increasing exponentially, but the opportunities for “gold” (innovation) are also rapidly growing. We may be tempted to take shortcuts, but we must remain steadfast in search of sound designs. The common thread is adherence to nature’s rules as codified in scientific principles. There is no substitute for sound science in green design. That is our focus in Chapter 2.

NOTES AND REFERENCES

1. Attributed to A. Einstein, this quote appears in numerous publications without a source of citation.
4. Of course, this is not correct to a chemist, since water is indeed a solvent.
6. Ibid.
12. Ibid, p. 66.
13. This paragraph is inspired by and is an annotation of words and ideas of William McDonough in lectures and the film The 11th Hour.