Bridging the Engineering/Architecture Divide: The UVA Solar Decathlon Team

The Solar Decathlon was sponsored by the U.S. Department of Energy to inspire research in energy-efficient housing and demonstrate the current practicality of solar energy. The University of Virginia entered this contest with a team of students, faculty and community representatives drawn from a broad range of backgrounds and organizations. The collaboration of the School of Engineering and Applied Sciences and the School of Architecture required team members to bridge a cultural divide that included disparate skills, language, and perceptions. The award-winning result was both deemed as "high design" architecturally and as an advanced engineering solution. The success of the UVA team and of the other top teams in the competition depended upon attaining a successful collaboration among engineering, architecture, and construction. Teams in which one or the other disciplines elected to undertake the project alone did not fare as well. Similarly, the educational value of the experience for the students was significantly enhanced by the multidisciplinary orientation of the team. The project integrated many of the ABET requirements of Criteria 3 and 4, demonstrating both the value of these criteria and a vehicle for achieving them. This student-built home will serve as a lab and community resource for studying solar energy and sustainable design in residential applications.

"engineering schools ...are increasingly out of touch with the practice of engineering... many of the students who make it to graduation enter the workforce ill-equipped for the complex interactions across many disciplines of real-world engineered systems...What's needed is a major shift in engineering education's center of gravity, which has moved not at all since the last shift, some 50 years ago, to the so-called 'engineering science' model...Engineering is creativity constrained by nature, by cost, by concerns of safety, environmental impact, ergonomics, reliability, manufacturability, maintainability...To be sure the realities of nature is one of the constraint sets we work under, but it is far from the only one, it is seldom the hardest one, and almost never the limiting one."

William A. Wulf and George M. C. Fisher, Issues in Science and Technology, spring 2002.

INTRODUCTION

Design requires the synthesis of many competing factors in order to develop the best solution given the perceived problem. The Solar Decathlon project at the University of Virginia (UVA) attempted to teach students how to design and build a solar-powered house. In the process the potential and problems of engineering design education were exposed. There is a traditional triad in building design and construction made up of engineering, architecture and construction. The mismatch in cultures and goals between the three is profound and can lead to misunderstandings and even a degree of animosity. Yet when managed well, the process of assimilating different perspectives can both produce a superior building and enrich and expand the vision and skills of the participants. The Solar Decathlon project allowed largely inexperienced students from engineering and architecture, and advisors from all three disciplines, to breach the traditional barriers and to appreciate the contributions of the others—a maturing process that will serve them well. However, this was not accomplished without some difficulty.

Learning engineering design is challenging in today's academic environment due to the emphasis on research and specialization. Design requires both a breadth and depth of understanding. Engineering, as a field, has excelled in pursuing depth of understanding but at the expense of learning how to relate to other disciplines. In the Decathlon project, this narrow vision confronted the broad goal of improving the overall design of a building. The architecture students, in contrast, came to the project with a broad overview of building design, but with little appreciation for analyzing the underlying physical principles.

THE CULTURES OF ENGINEERING, ARCHITECTURE, AND CONSTRUCTION

Engineering is currently taught on the 'engineering science' model, i.e. largely as a series of loosely connected lecture courses dealing with various technical subjects germane to the respective engineering disciplines. Graduates and employers frequently discover that this academic background has not equipped students with the skills needed for the interdisciplinary, collaborative and cost-driven environment of the professional engineer. Even practiced engineers have a fragmented and specialized understanding of how their work relates to the larger enterprise, especially in terms of the key project management issues that require tradeoffs with other disciplines. Engineers often lack an appreciation for the organizational and political contexts in which technological development occurs, and seem unaware of the profound implications of engineering upon the society it is intended to serve. Conveying this breadth of understanding within an academic setting can be accomplished through large-scale engineering design/build projects that require teams of individuals with different backgrounds.

As observed by the three engineers authoring this paper, architecture education, in contrast with engineering education, encourages the broad view of a design that is yielded through projects and design studios. It is fundamentally a design curriculum, and much could be adopted for use by engineering educators. Architecture students are encouraged to continually visualize and internalize the end product of their designs and are ingrained with the need to document and be prepared to present the intent of a design. The young architect is being trained to provide the unifying force amongst different experts in a building design effort. The architect's tools are highly visual and emotive. Drafting, computer graphics and drawing are used to convey ideas in a format that is intended to provide a common understanding. Whereas engineering is taught as a science, architecture is taught as an art. Architecture students are guided through a sequence of activities that require them to explore the sensory experiences of various design alternatives before diving into a particular solution. They are taught to develop a vision and to defend that vision as something sacred, against mere utilitarian compromises. The architect considers herself to be the spiritual and aesthetic director of a building project. Modern materials and tightly-packaged comfort system equipment have allowed the aesthetic layout of a building to proceed independently from the physical limits of natural effects or structural considerations. The typical architect sees the engineering required to enable his aesthetic vision as a subsidiary effort akin to the construction required to realize the vision. This can result in a design with aesthetic integrity but that is functionally inefficient, e.g. a number of the Frank Lloyd Wright buildings with leaky roofs, or the current propensity for large, energy intensive office buildings that require cooling even in winter. For engineering students, the architect's sense of missionary zeal for their visions can be both foreign and intimidating. Yet, alongside these abstractions, there is an element of architecture education that is more practical than that of the engineer, specifically in the emphasis on detailed drawings and documentation of a project.

The third component of the building project triad is construction. The Solar Decathlon project offered a rare opportunity in modern education: the opportunity to reconcile the abstract knowledge of the scientific approach with the "real world" limitations of existing materials, products, and services. We found that the local community construction specialists were eager to participate in our project and were generous with their time and knowledge. However, even in the "real world," the trend toward specialization discourages the type of broad knowledge that is required for a good engineering design. Tradespeople are highly trained in one system or even one product line, and though they develop an awareness of the practicalities of its function, they are not encouraged to consider how that system might impact other aspects of the design. Government officials have responded to the need for safe practices and reliable products/services by enacting regulations that further enforce specialization. In the state of Virginia there are 35 different license classifications, 12 of which require the licensee to pass a specialized exam [Commonwealth of Virginia]. Thus, even the general contractor has several impediments to overcome before a broad level of detail can be assimilated for the overall building design. A given system expert is typically called in cold to design and perform an “installation.” As a result, innovation in the building trades at every level from the manufacturer to the installer has been restricted to refining appliances, HVAC equipment, refrigeration, water supply, and waste removal as if each system was isolated. The chief aim on the part of each building contractor is to provide a system that is sufficiently large and reliable to satisfy the customer in any circumstances—even if it is inefficient or adversely impacts the overall design.

TEACHING ENGINEERING DESIGN

The point of departure of any design is the definition of the problem, which is intimately tied to one’s perspective. The best designs will be resolved only after several different perspectives have been explored. This process of broadening one’s perspective is the opposite of typical closed-ended engineering homework assignments for which the problem is already defined, all the information deemed relevant to obtain the correct solution is provided, and innovative solutions that depend on problem redefinition are often discouraged.

Teaching design requires the instructor to convey a broad overview of the context in which the specific solution is sought. However, the engineering academic world discourages broad expertise. Engineering is broken into disciplines, sub-disciplines and specialties so that each individual faculty member is an expert on some narrow range of skills and techniques. Tenure, publication, and status all depend on leading-edge research, which is most readily accomplished by focusing all of one’s efforts on one specific aspect of a narrowly-defined problem or process. The goal of the engineering academician is to become the leading expert on a specific topic. Graduate level engineering education, viewed primarily as training to do research, is closely aligned with the advising professor’s own research and will therefore remain similarly focused. Unfortunately, this focus extends to the undergraduate level, as each engineering subject is presented by a specialist. Engineering design courses can be viewed by faculty as cumbersome distractions, as they require preparation that is outside the faculty’s area of interest and require a great deal of time and effort to guide the students and grade projects. There are few professional rewards or established funding venues to sponsor the effort required to integrate disparate fields of engineering.

The Accreditation Board for Engineering and Technology (ABET), working with major employers of engineering graduates, has launched a major effort to broaden the education of engineering undergraduates. Promulgated as Engineering Criteria 2000 (EC2000), ABET's new criteria for accreditation of undergraduate engineering programs require that engineering graduates be able to communicate effectively, function on multidisciplinary teams, demonstrate a knowledge of contemporary issues, an understanding of professional and ethical responsibility, and “the broad education necessary to understand the impact of engineering solutions in a global and societal context.” [ABET, Criterion 3, p. 29]

The new criteria place increased emphasis on engineering design, a creative process distinct from the study of the underlying science that dominates most curricula. They require that graduates have an ability to design a system, component, or process to meet desired needs. "Students must be prepared for engineering practice through the curriculum and culminating in a major design experience based on the knowledge and skills acquired in earlier coursework and incorporating engineering standards and realistic constraints that incorporate most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political." [ABET, Criterion 4, p. 30.]

This is a tall order for engineering faculty schooled in the engineering science model, and whose career advancement depends upon state-of-the-art research in a narrow area of expertise. Unlike the faculty of other professional educational programs (e.g. law, medicine, and architecture), engineering faculty are by and large not practitioners of the discipline they teach, or if they are, they practice a fragment of the discipline of engineering that is not typical of the careers their undergraduate students will enter. How then can we engineering educators best prepare our students for the broad demands of engineering practice? One way to broaden the mindset of engineering students is to engage them in design and development projects with students of other disciplines. This was the approach taken in UVA's Solar Decathlon project.

The Solar Decathlon project at the University of Virginia allowed, even forced, the students to be responsible for all aspects of design and construction. The students had to resolve their understanding of a wide spectrum of topics both within their specific discipline and beyond as the project went from conceptual to detailed design and finally to actual construction. The engineering students, begrudgingly at first, broadened their perspective and contributions to the project out of necessity. Firstly, they were forced to address adjacent engineering systems (if only to determine what was or was not their responsibility). Secondly, in order to define parameters of their specific system the larger design considerations had to be assimilated—even if that meant coping with non-engineering issues. Lastly, as the students were required to provide the organizational leadership and the funds required to realize the project, the broader social context of the effort became intensely relevant.

PROJECT ORGANIZATION

The Solar Decathlon is an intercollegiate design/build competition, sponsored by the Department of Energy, challenging student teams to demonstrate the feasibility of solar energy and energy efficiency in the residential sector. The first Solar Decathlon was held in fall 2002 with 14 schools competing; the second is being planned for 2005.

The formal organization of the UVA team began in fall 2000 when three engineering seniors enrolled in a special topics course in solar house design. They explored various options for fulfilling the criteria that were being developed simultaneously by the Solar Decathlon sponsors. This was a realistic experience where the design criteria were not given as aspects of the "assignment" but rather represented a moving target. The pace picked up in spring 2001 when the three engineering students were functionally integrated into an architecture fourth-year studio to perform the conceptual design of the house. The engineers worked with the 12 architecture students as they developed concepts and made the tradeoffs required to resolve engineering and architectural goals. The architecture students began by exploring individual designs then teamed to develop four, then two, then a single design, each succeeding design drawing on its predecessors and becoming increasingly well articulated. The engineers played a supporting role. As the process progressed, the engineers participated in astonishment in architectural design reviews where there was much talk about the "poetry of the design" and relatively little talk about how the details could be implemented. Yet, it was the architects' insistence on the developing the one surviving concept with detailed drawings and specifications that drove the process towards realization.

In fall 2001 the engineering and architecture advisors offered a combined class on solar house design and detailing, in which we pushed the participants to work with the conceptual design that had been developed the previous spring to reach final design decisions. Unfortunately, all of the architecture students who had developed the conceptual design had graduated, and most of the members of the class were new to the project. Many of the design principles required to produce an efficient *engineering* design had been ignored so that the students, and even some of the advisors, struggled with how to advance the design given the constraints. Much of the semester was spent justifying and providing an understanding of the systems and design that were being proposed. Not surprisingly then, this class was the venue for some of the most spirited debate between the engineering and architectural views of the design.

The philosophical discussions that often dominated the combined class, while interesting, were regarded by some of the students to have impaired progress towards our goal, so the ensuing spring 2002 semester we reverted to more fragmented sub-team meetings, focused on finalizing design decisions for an early start to construction. While this isolation of groups, within the engineering team as well as between engineering and architecture, may have sped the development of subsystem designs, it also lead to a number of misunderstandings that complicated the construction process when it finally began in April 2002.

The role of the advisors was also affected by the clash of cultures. While it was agreed that the project was for the benefit of the students, the advisors too had agendas and perspectives of which aspects of the project were most important. The engineering advisors tended to encourage an advance in the science of the systems while the architecture advisor required that aesthetic design be similarly leading-edge. The engineering students required a much more participatory form of guidance where the engineering advisor gave detailed direction on which design concepts to pursue and how to perform the detailed calculations. Often the engineering advisors presented both the broader issues that were of concern to engineering and how they were manifested in particular details of the design. In architecture, such interference is considered as an attempt to "control" the individual expressions. At times the architecture advisor actively downplayed the advice of one of the engineering advisors—particularly whenever there was an overlap in guidance required by engineering and architecture. This placed the third advisor (also an engineering advisor) in the uncomfortable position of having to choose sides. In many instances, the architectural view prevailed if simply to promote harmony between the two teams. Unfortunately, many engineering systems suffered and this added to the engineering students' sense that their views were not highly valued.

THE DESIGN PROCESS

The details of the design process evolved as the rules were developed by the Department of Energy. The DOE announced the Solar Decathlon in the late summer of 2000 with a simple brochure. The Decathlon was interpreted by UVA to be a contest between students, featuring student-designed, solar-powered houses.

During the fall of 2000, the DOE had not even issued the first set of rules so initial research was limited to concepts: heating and cooling systems, environmentally-friendly building materials, solar water heating and power production, and ideas of how to make solar living easy and comfortable. The team was ambitious and the possibilities seemed boundless. The following spring, the DOE issued the first set of rules, and the formal design of the building began. The rules declared that the house exceed neither 18 feet in height nor a footprint of 800 square feet, and that the house had to be complete with the appropriate rooms and appliances. [DOE]

As the project evolved, each group attempted to learn the language of the other but the first attempts resulted in some odd contributions such as engineers offering critical aesthetic observations of architectural "poetry" and architects passing on tidbits like "insulating paint" and "eco-friendly adhesives" that were non-functional. At first, each team was convinced that their own suggestions were valid but were not amused by the others. The engineers had few drawing skills and the architects were daunted by the analytical effort required to carry out an engineering calculation. Each group kept asking the other to finalize their contribution so as to have more certainty in pursuing their own. The architects wanted model numbers and drawings for the engineering systems—and questioned the need for all that "wasted" space. The engineers resisted investing the time in calculations until the design was finalized and instead gave qualitative descriptions of their systems along with requests to change the underlying architecture to allow more flexibility. The engineering students didn't have any experience with "Design," where the problems must be solved repeatedly with a coarse level understanding first, and the architects didn't appreciate how large the effort was to provide a separate analysis for each of the proposed alternatives. Many of the engineering groups were often at an impasse waiting for information from other groups, rather than making educated guesses and working with them to further the design. They wanted to solve the "one final problem" and had a great deal of difficulty moving beyond the concepts to final construction drawings. The engineers didn't want to perform calculations with data that was not finalized. The iterative approach to design seemed like a waste of time as if the knowledge gained "wouldn't be on the exam." In some cases, the architecture team opted to take over aspects of the design rather than invest the effort to understand the difficulties facing the engineers.

The engineers were focused on the efficiency of each system, because a purely solar-powered house has a finite amount of energy available. Their approach was to explore the various possibilities on a conceptual level because none of their training included selecting equipment from catalogues. A major energy consumer in many houses is the active heating, ventilation and cooling, or HVAC system. Hence, the primary HVAC methods adopted for the UVA house were to be passive: the house is heated as the sun's rays shine through the south-facing windows, and the house is cooled through ventilation and shading [McGowan]. The architects embraced the idea of passive solar heating, and responded with a design that was nearly entirely windows, which they viewed as making the small house appear larger and would allow an "ultra-modern" design. The total proportion of glazing to floor area at one point in the design process was in excess of 200%. The engineers objected and offered evidence that the optimum proportion for a passively heated design with fixed overhangs and standard double pain windows was widely documented as being 20%. The architects however, were taught to push the limits of accepted design and so did not take this evidence as damning. The engineers were dismayed that the number and size of the windows changed in the early design iterations depending on which individuals were present during the design process (typically reducing when the engineers were present then increasing dramatically if they were absent for more than a few days). The architects were aware that glazing *could* cause too much unwanted heat gain during the day and too much heat loss at night but asked the engineers to solve these problems. Various materials and techniques were explored as the function and limitations of windows versus walls were better comprehended by all members. The engineers and an increasing number of the architecture students lobbied to eliminate most of the windows on the north side of the building and a large percentage of the proposed skylights (that would not provide much positive heat gain during the winter) while retaining enough to provide a high level of daylighting. While more windows remained than the engineers preferred, the assumed properties of these windows were greatly improved after an extensive search for actual products. Krypton-filled triple-pane windows, active shading, and a retractable curtain of Thinsulate would combine to provide an R-value of 15, which is comparable to a traditional opaque wall yet also allowed passive solar gain. It also retained the visual connection with the exterior and the expansive glass surfaces that the architects desired.

Beyond the passive effects, one of the first major engineering questions was how the house would be *actively* heated and cooled to meet the strict temperature and humidity range imposed by the contest rules. A typical new house today (including most of the other schools' Decathlon houses) is built with a forced-air system, which moves air from a centralized heat pump out to the house through ductwork. The team determined that this was neither the most efficient nor most comfortable way to control temperature or humidity and opted instead for a hydronic radiant floor system that ran warm water (solar-heated when that is available) through tubing embedded in the floor. This easily won over the architecture students, as it promised an even, comfortable heating throughout the home without having to worry about placing (or hiding) the ductwork and vents. However, while radiant floor heating has gained popularity recently, radiant floor cooling has not because of issues in controlling humidity [McGowan].

For cooling and dehumidification, a naturally convecting valance cooling system was proposed that would not require ducting or fans. This appealed to both teams on a functional level but the architects objected to the visual interruption caused by the physically large valance units, which were to take up about 60 cubic feet of the interior space. The debate over placement of the valance went on from fall 2001 until the final moments of the project, as both sides learned the function of the units and attempted to make them smaller and better integrated into the building. Several solutions were proposed that interfered with major structural components. Other solutions would not allow the proper natural convection or could not incorporate a condensate line (at one point a senior member of the architecture team asked why the condensate couldn't simply be allowed to evaporate back into the room). In the end, after months of discussions with the manufacturer regarding custom sizing and configuration of the components, the company ran into scheduling problems and sent stock components that had been available all summer. The standard units were installed with hopes to modify them in the future. This practical exercise, though not completed to everyone's satisfaction, clearly demonstrated the limits of real design.

Another real factor in the construction was the availability of labor. While there were few budgetary restrictions for materials and systems, as most of these were donated by the manufacturers, there was a shortage of funds to retain skilled labor. Furthermore, there was a great disparity between what the architecture students were willing to accept as pay while completing a project that was directly in line with their career ambitions versus what the engineers could command from traditional employers that were unlikely to see even an award-winning construction project as warranting career advancement in say, electrical engineering. Thus, many of the architecture students were willing to delay the traditional pursuit of their careers while accepting a subsistence wage during the summer after graduation while most of the engineers opted instead for high paying permanent or summer positions. Thus, the project faced a shortage of engineers during its final months.

While construction united the team in a common experience, the ambiguities of scheduling construction and the preponderance of architects in the workforce skewed the project even further away from the engineering tasks. Scheduling is a difficult task under any circumstances but is nearly impossible when the managers and the labor force are all inexperienced, young, optimistic, and volunteers. The students were eager to participate in building tasks, which were both intriguing and offered a mental break from their studies. Out of necessity, the detailed engineering work was "temporarily" delayed in favor of making progress on the physical framework. This was not considered a problem because many of the engineering efforts were viewed as comprising systems that could be merely installed at the last minute whereas the imposing volume of construction tasks warranted as much manual labor as could be mustered. Those engineers that arrived on weekends and on breaks from full time jobs were anxious to participate in the hands-on building with the rest of the team rather than to work out engineering problems in isolation. Only as the date of the competition began to loom, and more engineering students returned from summer jobs, did the engineers begin to pull away from the manually intensive tasks and regroup for the final design of the engineering systems. Perhaps if there had been more engineers and a common place to gather and work that was attractive to the predominately young people, the engineering tasks might have been perceived as being more fun.

For much of the project, most of the engineers let the architects make most of the decisions. With a few exceptions, the engineers avoided responsibility and were hesitant to put forth requests that required a change in the architecture. There was a good deal of grumbling to be sure, but only late in the project, after the engineers became more confident of the design, did they invest the effort to put forward coherent arguments complete with data to reinforce their requests. A typical example of such discussions concerned the skylights. The initial design included a row of skylights installed in about 90 square feet of the roof. The engineers repeatedly objected that too much heat would be lost through the skylights, yet the architects prevailed with the aesthetic argument that the skylight's purpose was to emphasize the east-west line of the building and provide a uniform source of natural light. Only when one of the engineers presented calculations of the heat loss and another showed that a sufficient amount of uniform light could be provided even if half of the skylights were removed did the architects finally consent [Miller]. Ironically, the architects too were making progress towards engineering and made a similar argument. One aspect of the skylight compromise included movable insulation over the remaining glazing in order to bring the insulation value up to the same R-15 level that had been established on the windows. However, when the units were installed during construction, an architect surprised the engineers by calculating that the extra insulation would have a negligible affect on the building's thermal performance [MacNelly]. No additional insulation was installed and some of the engineers remained skeptical, but at least the two teams were learning to communicate with a common set of standards.

Another area of significant innovation that was created by collaboration of the two teams was the house's integrated shading system. Early engineering presentations about passive solar design stressed the need for a fixed overhang over the south windows. This overhang would shade them from the hot summer sun but allow the sun to penetrate during the winter, when the sun is lower in the sky. This presented a problem for the architects because the overhangs would take up too much of the allocated 800 square feet. Additionally, the Virginia weather during fall and spring varies widely from a need for cooling to a need for heating, so a fixed overhang would rarely be performing in the most efficient way. Working together, the team came up with the idea of an exterior louver system in front of the south-facing windows. By moving the louver system outside (as opposed to installing blinds inside), unwanted solar energy would be absorbed and dissipated as heat outside of the building's envelope. By automating the louvers the building can react to short term variations in the weather rather than simply depending on a fixed seasonal variation. Furthermore, the control system allows the louvers to be adjusted by the occupant to react to their own preferences—such as a particularly nice view. This is perhaps the single most significant innovation of the UVA Solar Decathlon house [Dorrier].

CONSTRUCTION—THE INTEGRATING EXPERIENCE

Construction was the process that forged the engineers and architects into a unified team and offers some tantalizing insights into what motivated the students we were trying to inspire. Whereas the design phase of the project encouraged an aspiration towards the ideals of each feature of the house, the construction phase imposed the exterior pressures of available materials and services as well as the intrinsic limits of the students involved. The engineers, in particular, had suffered in the conflict of opposing vision and goals that dominated the abstract design phase because they tended to work alone or in small isolated groups with little communication amongst them. The architects, on the other hand, worked during the non-construction phases of the design in a common "studio" area that allowed and encouraged communication and comradeship. This is a wise aspect of the architectural education infrastructure that fostered common aesthetic vision for the project and made the architects aware of and protective of the contributions of each other. Often the team would resolve a dispute with a vote, which greatly favored the unified group. The result was that the engineers started the construction phase disenfranchised to some extent whereas the architects felt empowered. However, the construction site offered a similar common work area, provided a shared experience of physical effort, and presented an unambiguous "visual aide" for discussing common obstacles and confounding details. The idealism faded as the practicalities dominated and their dependence on the talents of each other became palpable.

Neither student group had much experience with power tools or in taking their studies to full-scale fruition but all were enthusiastic about the prospects. This was the first opportunity for most of the students to exercise their newly-learned skills and they were well aware of the uniqueness of the opportunity. It was no longer possible to be satisfied with partial credit for a half-resolved problem. The process of building finalized decisions and forced the students to communicate the essential issues. As construction began, the architecture students felt confident of their broad view of the building project but were also acutely aware of their limited detailed functional understanding of the systems. Meanwhile, the engineering students each had a variety of specialized skills but were aware that they had little or no training in design or how to integrate their efforts amongst themselves or communicate them to non-specialists. Indeed, many of the engineers had no desire to involve themselves in aspects of the project outside of their original expertise—but were learning to broaden their perspective.

And lastly, the students had a wide variety of community advisors that each had a detailed but narrowly focused practical expertise that the students had to assimilate and apply. Throughout much of the design phase of the project the engineering science model of engineering education continued to hamper the students. The engineering students persisted in seeking that "one correct answer;" they were dismayed by the fluid nature of the design and were frustrated that the experts in the field offered conflicting advice and sometimes detailed but irrelevant information. Fortunately, as construction progressed, the design became less fluid and the "one correct answer" approach became more relevant as the practicalities of construction and the tight schedule restricted the options. Moreover, the applied experience crystallized the abstract knowledge that the students had learned in their class work and made them more confident of their understanding. This was observable in how they interacted with the experts. They stopped expecting enlightenment but became more appreciative of good advice and more discerning of its applicability. The maturing process was profound.

CONCLUSIONS

The UVA Solar Decathlon project engaged over thirty students from a variety of engineering disciplines with approximately twice as many architecture students, in designing and building a solar house. The resulting design placed first in "Architecture" and second overall in a national competition that involved 14 schools. While the outcome was encouraging, the process exposed many opportunities for improving the way engineering education is taught.

In contrast with most aspects of an engineering student's education, this was a messy, open-ended, ill-defined challenge that was further complicated by the vastly different cultures of the engineering school and the architecture school. The "engineering science" model of engineering education did not prepare the engineering students to embark on an iterative coarse level exploration of a . The students struggled, with varying degrees of success, to understand their roles and responsibilities in a design where every system interacted with and depended upon several other systems. As this was the first time such a project has been undertaken, the advisors and instructors were as inexperienced as the students in managing such a complex task. Project management was ad hoc and piecemeal. The architectural education system provided many insights into how engineering design could be improved. The architecture students tended to have a clearer vision of the design process and to be more expressive and assertive than the engineering students. This disparity in preparation for a design project left some of the engineering students feeling shut out of the process and alienated. Some responded by trivializing their own contribution to a level that demanded little interaction with the rest of the project. These students contributed little and learned little. Others persisted in grappling with the issues and how to integrate with the other team members; it was this group of students who emerged with enhanced design skills, a clearer vision of the design process, and experience with the compromises and collaboration required for success in a large multidisciplinary team project. They learned that initiative and persistence are essential to success.

A major improvement in engineering education could be to provide a more wholistic approach to project design. Engineers are taught the methods for generating one correct answer to a well defined problem, but this project demonstrated that the successful integration of multiple concepts and systems may well require the acceptance of solutions that are less than perfect. Other aspects of a large project that are not typically taught in engineering were also brought to the front as politics, economics, and availability dictated many decisions independent of the engineering fundamentals. On a sheerly practical level, familiarity influenced construction decisions as the students attempted to find experts and salespeople who could explain the systems being considered and understand the requirements.

The role of the advisors too was explored in the context of a large project with a potential clash of cultures. While much care was exercised in promoting harmony, sometimes this required compromises in the pursuit of some principles of engineering or architecture. The engineers in particular were ill-prepared to cope with such setbacks.

In addition to being taught to optimize the whole-design problem, engineers should be taught how to communicate their concerns and conclusions to other participants, especially non-engineers. They must also be taught to defend their work and to expect questions and challenges to their conclusions, though at the same time be willing to acknowledge a better solution if one is discovered. Only with a very broad perspective of the engineering and social pressures on a project can the engineer understand how and why compromises must be drawn.

It is not enough to teach engineers how to grind out problems.

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