UNDERSTANDING CREATIVITY

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Professor David Billington is engineering's greatest storyteller. Emphasizing the human character of engineering, his scholarship on great engineers and their work has transformed antiquarian subjects into relevant and surprising lessons on “the grand tradition of modern engineering.” Where complex mathematics were thought fundamental to engineering success, Professor Billington demonstrated that many great works of engineering were based on astoundingly simple calculations. Where engineers were assumed to be driven toward one best solution, he demonstrated that engineers have always made choices between many possible solutions. These solutions grew from the imagination and courage of individual engineers working within specific social, economic and historical contexts. Where the industrial revolution was assumed to have severed the relationship between thinking and feeling, he demonstrated that the greatest works of structural engineering often resulted from conscious aesthetic choices by their designers.

Many of Professor Billington’s stories explain how engineering’s human character has remained consistent in our modern era, notwithstanding our technological progress. To study the human character of engineering through great works is to learn about engineering creativity. Beginning in the tradition of Professor Billington, with the stories of two bridges, this essay aims to address the concept of creativity directly. In doing so, I wish to claim the word “creativity” for engineering.

Three interrelated questions drive this discussion: What does it mean to engineer well? How do we use this knowledge to enrich our own lives and the lives of our children? And how do we inspire and educate our children to become great engineers? These three questions are related, and they suggest the importance of discussing this subject on three levels: the world historical level, which defines quality and sets the standard by which we measure all other work; the professional level, which holds the tension between our ideals and the reality of a given context; and the educational level, which engages the nature of fundamental understanding as it seeks to help young people develop judgment and distinguish fundamental principles from mere facts.

I will begin this discussion by introducing two ideas that can be seen clearly in the work of two great 20th century structural designers: Robert Maillart (1872-1940) and Jörg Schlaich (b. 1934). The examples I have selected are short span bridges, lesser known for their finished condition, but exemplary for the insight they provide into process. Robert Maillart’s calculations for the 1925 Valtschielbach bridge exemplify the idea of conceptual transparency—a phrase that I use to describe fundamental understanding in its simplest possible form. Jörg Schlaich’s sketches for the Ingolstadt bridge exemplify the idea of drawing as a language, or as Karl Culmann (1821-1881) described it, “the language of the engineers.”

Following this glimpse into the processes of great structural designers, I will attempt to describe the discipline of creativity, i.e. the part of creativity that can be taught. The creative process consists not only in imagining ideas, but also in expressing them through language and in judging their fitness. These actions of imagining, expressing and judging ideas require human engagement across an entire spectrum from intuition and openness to detailed analytical critique and judgment. Some scholars might call this the spectrum between divergent and convergent thinking, however I prefer to use the words imagination, expression and judgment because these words feel more alive to me. Central to this understanding is the idea of language as our means of expressing ideas. We tend to understand language as words, however drawings and mathematics also form languages that are essential to expressing what we imagine as engineers.

In order to provide more detailed insight into a specific creative process, I will discuss my own work on the structural design of the Wind Technology Testing Center (WTTC) in Charlestown, Massachusetts. Talking about this process at the level of a practicing professional allows me to draw attention to key moments that are perhaps more subtle and ordinary than those we know from works of world historical significance. This discussion will help
to bring the details of process down to earth. It will also help to establish continuity on a spectrum ranging from student work to the great works. In my experience, the nature of process itself is relatively consistent on this spectrum. In the context of my own work, I will also argue the possibility for an engineer to be conscious of the ideals of structural art: efficiency, economy and elegance, not only in a masterpiece, but in all designs. This argument may also explain my attraction to lesser works by the great designers. These works may not be considered masterpieces, but they nevertheless demonstrate important details related to process that are less visible in the history of more famous work.

In the interest of achieving some level of generality in these ideas, I will then discuss the education of university students in engineering design. I will focus on the idea of drawing as a language in the context of a steel design course in the third year of the Tufts undergraduate curriculum. Two examples drawn from my own practice will illustrate the ability for drawing to function as a language which can be abstract and analytical or literal and visual. In the first case, drawing takes the place of mathematical analyses for variations on the theme of a cantilever with one or more backspans. In these examples, an expert sees one fundamental behavior at work, whereas students typically believe that they see as many kinds of behavior as there are examples. In the second case, hand sketches completed during a coordination meeting with multiple participants illustrate the potential for working effectively in real time with collaborators through the language of drawing. The ability to draw an idea and its corresponding details during a meeting saved weeks of coordination effort that would have been required had basic decisions been deferred to further, independent study.

**Conceptual Transparency**

While the following calculations and sketches were instrumental in the creation of sophisticated structures, they are themselves quite clear and simple. In a world enamored of complexity and computational power, where high-tech is often equated with intellectual merit, they demonstrate a higher level of thinking—one that radically distinguishes the essential characteristics of a system from the trivial—conceptual transparency. This power of abstraction serves a vital role in the design of large-scale structures, where failures are catastrophic and experimental prototypes are prohibitively expensive. Civil engineers typically have one chance to get it right. Overlay this warning with the imperative of economy and the desire for beauty, and it becomes clear that conceptual transparency addresses equally the need to assume responsibility and the opportunity to work creatively.

We value Robert Maillart’s work as much for its clear expression of engineering process as for its inherent quality as structural art. Robert Maillart was educated in the early 1890s under Wilhelm Ritter (1847-1906) at the Swiss Federal Technical Institute, or Eidgenössische Technische Hochschule (ETH), in Zurich. As successor to Karl Culmann, Ritter fulfilled Culmann’s ambition to express analytical concepts graphically, and brought structural design education at the ETH to its high point in the 19th century. Ritter not only emphasized fundamental understanding of structural behavior but also discussed structural systems and details both in terms of their constructability and their appearance. Maillart spent his early career as a designer and builder, developing a series of bridges that defined the structural, constructive and visual potential of reinforced concrete. During this time, Maillart worked closely with Ritter on the full scale evaluation of completed structures, such as his 1901 Zuoz bridge.

From Professor Billington’s scholarship on the life and work of Robert Maillart we not only learn about the designer himself, but also about his process. For instance, Maillart was exposed to the notion of deck-stiffening as a student of Wilhelm Ritter. He internalized the idea of bending compatibility between arch and deck based on observations of cracks in his 1912 Aare River bridge. And before arriving at his simple calculations for the Valtshielbach deck-stiffening he had developed more complex calculations for the 1923 Flienglibach bridge. The relatively small scale of Maillart’s structures makes them accessible to most...
engineers. Maillart sublimated work that otherwise would not have merited distinction. He made it clear that in the hands of a structural artist, the same bridge could achieve a level of quality far beyond mere usefulness.

We value Jörg Schlaich's work because it provides contemporary examples of structural art at its finest. Whereas most structural artists designed independently and constructed their own work, Schlaich has demonstrated that it is possible to create structural art as an engineering consultant in collaboration with architects. For this reason, Schlaich's work offers insight into process that is consistent with contemporary culture. Schlaich was educated in the strongest tradition of structural engineering to emerge from Post World War II Germany. In his thirties he led the design of the 1972 Munich Olympic Stadium for the firm of his mentor Fritz Leonhardt (1909-1999). Shortly thereafter in 1974, Schlaich assumed Leonhardt's professorship at the University of Stuttgart, and in 1980 he founded the office of Schlaich, Bergermann and Partners in Stuttgart with the team of engineers and staff who had worked together to build the Munich Stadium. The core of
this team continued to work together for the rest of their careers. Schlaich’s major contributions include not only design innovations such as the cable net wall and the glazed grid shell, but also the development of steel castings and cable structures, the legitimation of the pedestrian bridge, the development of strut and tie methods for reinforced concrete, and the development of renewable energy resources from solar chimneys to parabolic mirrors. Schlaich defined what it means to be engaged as a structural engineer in the late 20th and early 21st centuries—a designer motivated by social conscience, who uses the best tools of research and analysis to push the limits of structure and realize new forms.

Robert Maillart’s Valschielbach Bridge

For me, Robert Maillart’s most compelling calculations stand behind his 1925 Valschielbach Bridge in Donath, Switzerland, shown in Figure 1. At their core is a simple algebraic equation, derived according to static equilibrium. There is nothing special about the mathematics. Yet the assumptions behind Maillart’s mathematics and the resulting design conclusion represent the highest level of engineering thinking. These calculations demonstrate that our chief concern as engineers is the quality and significance of our assumptions for a particular case, not the generality of our analytical tools. In Professor Billington’s words:

Robert Maillart, the Swiss bridge designer, developed in 1923 a limited theory for one of his arched bridge types which violated in principle the general mathematical theory of structures and thereby infuriated many Swiss academics between the wars. But Maillart’s limited theory worked well for that special type of form. Within that category of type, Maillart’s theory was useful and had the virtue of great simplicity; he developed the theory to suit the form, not the form to suit the theory. In the United States, by contrast, some of our best engineers understood the general theory well, but not understanding Maillart’s specific ideas, they failed to see how new designs could arise. They were trapped in a view of an engineering analysis which was so complex that it obscured new design possibilities. Adherence to a general theory in this case is tantamount to the blind application of equations so often observed in the work of engineering students. Maillart’s much simpler approach, however, with its emphasis on new possibilities for arched bridge forms, represents the heart of creative engineering thinking—creativity not only with respect to the appearance of form, but also with respect to its engineering substance. Even Maillart’s calculations were creative. In other words, Maillart recognized that there was more than one way to approximate the structural behavior of his deck-stiffened arch systems, and he chose an approximation that exhibited a high degree of conceptual transparency. In the appropriate context, Maillart’s calculations were entirely correct. That was precisely what angered Maillart’s academic peers, and distinguished Maillart’s engineering thinking. Maillart’s calculations for the deck-stiffened Valschielbach bridge total 3 ½ pages. The calculations representing Maillart’s conceptual leap filled the last half page, and are shown in Figure 2.
Seldom has the point been made more clearly that the engineering genius of the work rests on the assumption supporting this half page, and not on the calculations themselves. Based on the full scale behavior of his previous bridges, Maillart assumed that the deck and the arch deform together, and would thus carry bending moments in proportion to their flexural stiffnesses. Maillart designed the deck to be significantly stiffer than the arch and thus to carry most of the bending in the system. Such a conceptual leap reflects the same level of intellectual quality as the creation of any general theory, and far surpasses the technical exercise of applying such a theory. From a human point of view, Maillart's conceptual leap exceeded the generalized theory in value, because it led to more economical bridges that have become artistic icons. Many of these bridges are still in service.

The essence of Maillart’s engineering calculation in Figure 2 for the Valschiellbach bridge is represented by the equation

$$M = \frac{pL^2}{2 \cdot 8 \cdot 4} = \frac{(0.9 \text{ t/m})(40 \text{ m})^2}{64}$$

In order to understand this calculation, it is helpful to discuss the Valschiellbach bridge with respect to two other structural forms: a simple beam and an American arch of similar vintage. Comparison with a simple beam places the potential efficiency of the arch form in perspective. Maillart designed the arch in its funicular form under dead + live load uniformly distributed along the span. The resulting static equilibrium is shown in the upper left image of Figure 3. Under this load case of approximately 6.77 t/m, he proportioned the arch to be 3.4 m wide and 23 cm deep at the crown, resulting in an axial stress at the crown of 35 kg/cm² (500 psi).

By contrast, these loads on a simple beam would induce bending moments on the order of 1350 tm, as shown in the upper right image in Figure 3. The moment demands on Maillart’s arch, however, were 60 times smaller for two reasons. First, only the unbalanced live loads were expected to produce bending moments in the arch. These live loads were 0.9 t/m, and hence very small in comparison with the total loads. Second, the bending moments in a three-hinged arch under unbalanced live loads can be estimated to be $pL^2/64$ as opposed to $pL^2/8$ for the uniformly loaded simple span. Combining the effects of lighter loads with the reduced bending moment results in a drastic reduction of
bending demands on the arch:

\[
\frac{M_{arch}}{M_{beam}} = \frac{P_{live} \cdot M_{arch}}{P_{total} \cdot M_{beam}} = \frac{0.9 \text{ t/m}}{6.77 \text{ t/m}} \cdot \frac{1}{8} = 0.1125
\]

The lower images in Figure 3 depict the same arch and simple beam under uniform live loads on half the span. Under unbalanced live loads only, the bending moments in the arch are still 22% of what they would be in the simple beam. This can be explained by the fact that the deformed shape of the arch experiences a point of inflection at the crown. This deformed shape has an appearance similar to the moment diagram drawn in the lower left image of Figure 3. Since half of the arch bends upward, the maximum moments are lower than in the beam which bends down along its entire span. Another way to understand this behavior is to consider the effects of the horizontal forces in the arch. Bending moments in the arch resulting from vertical forces alone are identical to the moments in the simple beam. The horizontal forces at the abutments subject the arch to bending moments that oppose those induced by the vertical forces, effectively reducing these moments to their final values in the arch.

While comparing an arch to a simple beam says much about the potential efficiency of an arch system, it does not explain what distinguished Maillart’s Valtschielbach bridge from other arch bridges of the time. In order to understand this, it is more helpful to compare the Valtschielbach bridge to an American arch bridge of similar span, rise and vintage.

For this purpose, I would like to reference a 1930 textbook entitled *Elastic Arch Bridges* written by McCullough and Thayer. Conde McCullough was the Assistant Chief Engineer of the Oregon State Highway Department, and Edward Thayer had been the Senior Bridge Engineer of the San Francisco-Oakland Bay Bridge. Since these two men were accomplished bridge engineers, their book gives special insight into the cultural pull of analysis on 1920s American engineering.

Figure 4 shows two of the arches featured in McCullough and Thayer’s book. Unfortunately, the authors did not give dimensions for these arches. Their images, however, convey the basic form of American arch designs, and their captions are informative. The bridge on the left is described as “A rather plain yet pleasing example of rib arch design,” while the bridge on the right is described in the following way: “Curved approach gird-
ers, a dentil and bracket treatment, and the employment of bush hammered panels relieve the monotony of this open spandrel arrangement." The bridges are not considered as unified designs either analytically or aesthetically. McCullough and Thayer's book focuses on the theory of arch design and contains only sparse reference to actual designs. When designs are referenced, they are not presented as designs, but as opportunities to illustrate the theory at hand. The authors themselves seem to convey that visually an arch is no more interesting than a beam, and the rest of the bridge requires various "treatments" in order to break the monotony wrought by such a structure.

In a table with arch rib dimensions of several American bridges, McCullough and Thayer listed seven bridges ranging from 128 ft to 132 ft in span—similar to the Valschielbach bridge. Of these seven, one bridge is listed with a rise of 15 ft, also similar to the Valschielbach. The roadway width for this bridge is listed as 24 ft, and the bridge is described as an open spandrel design with two ribs. Since the Valschielbach bridge is approximately half as wide as the American bridge, it is not unreasonable to compare the Valschielbach arch to one of the American bridge's ribs. Figure 5 compares the thicknesses of the Valschielbach and the American arches, each drawn at the same scale. The 9 ft – 0 in. wide American arch rib has a crown depth of 2 ft – 3 in. (69 cm) and a spring point depth of 3 ft – 9 in (114 cm), whereas the 3.4 m wide Valschielbach arch has a crown depth of 23 cm and a spring point depth of 28 cm. The three primary differences between these two designs are the fact that the American arch was probably designed to take fixed end bending moments at the spring points, take all of the bending without cracking, and gather up the arch structure into a rib rather than spread it out as a slab. Gathering the material into deeper ribs makes sense if a designer wants to provide the ribs with sufficient depth to resist bending stresses without cracking. While this particular American arch rib is relatively wide, McCullough and Thayer listed other bridges of similar span with ribs up to 6 ft thick and 3 ft – 6 in. wide at the spring points. American arches of the time were designed according to elastic theory, which often assumed an uncracked section for the sake of linearity. Similar to McCullough and Thayer, Hardy Cross emphasized the importance of this simplifying assumption and its design implications in the face of relatively complicated elastic theory calculations.7 Ultimately, this approach led to arches designed as curved beams.
Danube River bridge in Ingolstadt. (a) Elevation. (b) System concept sketches.
In spite of the importance these engineers attached to simplifying assumptions, the cultural pull toward complicated theory was too strong to resist. Perhaps this resulted as much from a misunderstanding of the creative process as from a fascination with elastic theory. As Professor Billington discussed in Chapter 9 of Robert Maillart's Bridges, the American emphasis on analysis and elastic models prevented academics and designers alike from seeing the potential for elegant structural forms. Conversely, Maillart's close observations of his completed bridges, his focus on system behavior, and his design-oriented education under Wilhelm Ritter led to the assumption that the arch and the deck bend together. For this reason, as the deck was stiffened with respect to the arch, it would assume more bending until the arch experienced negligible bending demands.

Jörg and Michael Schlaich's Ingolstadt Bridge

Figure 6(a) shows the third bridge over the Danube River in Ingolstadt, Germany, which won a design competition in 1993 and was completed in 1998. Jörg and Michael Schlaich generously allowed us to photocopy many sketches from their collaborative design process for this bridge with Architects Kurt and Peter Ackermann. These sketches and several interviews formed the basis for our story of this design process and the design competition published in 1998. In the discussion of conceptual transparency, these sketches complement the simplicity of Maillart's Valtenschielbach calculations by demonstrating the power of drawing as a language.

One of the important early system sketches is pictured in Figure 6(b). While simple, this sketch captures the essential ideas of the proposed system: a slender deck, supported as an inverted suspension span, and longitudinally prestressed by the arching action between two raked piers. The separation between the road and the pedestrian can be seen in the section at midspan. The second elevation below shows a representation of massing with vertical supports between the cables and deck. The sketches are executed quickly in the company of collaborators. They are the standard means of communicating between designers. Yet, it is rare that we consider closely and discuss such sketches that represent the creative process. They are often considered either to stand alone as a flash of genius or to be mundane in their multitude. Representing hundreds of sketches developed during a design process, the sketches in Figure 6(b) and in Figure 7 show the kind of communication that is essential to the creative development of an idea in structural engineering.

Figure 7 shows this communication in further detail. It is not enough simply to sketch a system. The system relies on its details, and conceptual transparency is largely concerned with the interaction between a system and its details. Figure 7(a) shows the supports between the cables and the deck, along with the horizontal ties between these cables and the pedestrian walkway. Figure 7(b) shows sketches of these details that were developed in close proximity to the sketches in Figure 6(b). Figure 7(c) shows the skewed support, which evolved to retain a high degree of plasticity from a very simple decision to skew the supports by 20 degrees. Figure 7(d) shows the early conceptualization of this support as a plastic element.

The examples set by Figure 6(b) and Figure 7 imply that the creative work of engineers involves intense communication between ideas for a system and ideas for its details. This communication poses a challenge, because it is easier to fall into a habit of focusing only on the big picture or only on the details. The sketches in a design process need to be effortless because they need to be disposable. The value of any given sketch resides in its relation to all the other sketches and to the design process as a whole—not in its quality as an independent work of art. The disposable nature of these sketches gives them their value—they record fleeting thoughts and ideas, set down quickly for the purpose of critical evaluation and discussion. To produce them fluently is to speak the language of the engineer. Leonardo Da Vinci's sketch books are compelling precisely because they exhibit his artistic talent not for its own sake but as eloquence in the language of drawing. Often these sketches are accompanied by simple calculations and
text. Their value lies in their ability to represent clearly and accurately a dynamic process that is invisible to most students in its human character—composed of sketching, simple calculations, discussion, debate and an iterative approach to the development of an idea. I tell my students that if our imaginations were perfect, we would not need to concern ourselves with the discipline of creativity. Our ideas would come fully formed out of our imaginations. In the real world, however, most of us harness the power of our ideas by communicating about them. We communicate with ourselves, with our colleagues, and with our critics. In this communication, we learn more about our ideas and develop them further. While it may not be possible to teach creativity per se, it is certainly possible to teach the discipline required for creative work to flourish.

**THE CREATIVE PROCESS**

Engineers ought to understand their work as creative because it requires choices. If there is more than one way to do something, creativity comes into play. The creative process can be understood to consist of three stages:

1. An idea is *imagined* and exists in the imagination only.
2. It is *expressed* in language: drawings, words, mathematics.
3. Only then can it be *judged* through thought, feeling, and discussion.

The imagination, expression and judgment of many ideas proceed iteratively and in parallel. Modes of expression may change over the life of an idea, people may alter their judgments, and the idea

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Figure 7

Ingolstadt details and concept sketches. (a) deck support on cables with bracing to pedestrian walkway; (b) concept sketches for connections between deck support cables and pedestrian walkway; (c) skewed pier with deck and pedestrian walkway; (d) pier sketch.
itself may evolve. The creative process becomes an artistic process when expression is intended to evoke an emotional response. Understood in this way, Engineering, Mathematics, the Arts, the Humanities and the Sciences need not vie for superiority. They are all creative endeavors, each with distinct intentions.

Understanding creativity as a process of choice-making brings it down to earth without corrupting its essence. Creativity does not belong to inventors and artists alone. Common themes between the lives of creative individuals are the courage and effort with which they engage the creative process. If the creative process is misunderstood as consisting of its first two stages only, imagination and expression, the result is a fundamental lack of rigor. When engineers recognize that the rigors of judgment are as essential to creativity as the openness of imagination, they can learn to withhold judgment of an idea until it has been appropriately expressed. Inability to recognize the place of rigor within a larger process leads many engineering students to short circuit this process. They believe that ideas come into being fully formed. Therefore, they must solve each problem correctly on the first try. This prejudice robs students of their courage.

A student once asked me where ideas come from. I replied that I do not know, and that I think of ideas as gifts. I also related, however, my experience that ideas come richer and in greater number when I am engaged in a process. I told her that where I begin my process often doesn't seem to matter, so much as that I try to focus on what I want and then try to stay open to new ideas as they come. In the process of expressing and judging my initial ideas, I learn quickly. Soon enough, new ideas come, often unexpectedly, and rarely when I am sitting at my desk. I reserve my time at my desk for expression and judgment. When it comes to my imagination, I simply try not to get in my own way.

In my conversation with my student, this description of my experience ended with the advice that she ought not to worry about her ideas. They would come, but only on the condition that she was fully engaged in the work of imagining, expressing and judging. In addition to relating my own experience, I discussed the process behind Maillart's Valtschielbach bridge (described earlier in this essay). The moment at which Maillart developed his calculations was less important than his process of preparing for that moment. This process spanned decades: from his time as a student under Wilhelm Ritter, to his construction of the 1912 Aare River bridge, to the early 1920s.

I have continued to appreciate my student's honest question, and I felt a sense of satisfaction as I watched her own ideas develop in the midst of her process and the process of her design team. One of the most compelling conclusions drawn by her and her teammates three months later was that originality was less important than they had first thought. In their final presentation, they told a wonderful story about how their desire to produce good work eventually overshadowed their concerns about where their ideas came from and who they came to. At this point, not only did they begin to feel more creative as individuals, but also they began to enjoy their work together. There was no question that regardless of where various ideas had come from, the created work belonged to them. For me, this realization is important because it challenges the harmful cliché of some genius imagining great thoughts a priori. Once my students gave themselves permission to engage a creative process (even though they were not feeling particularly like geniuses), and once they believed that the good ideas would eventually arrive (so long as they committed themselves to their process), their motivation to see the process through sustained itself.

Parts of the creative process can be taught, and parts of it cannot. The unteachable parts may be understood in terms of inspiration, talent and wisdom. The teachable parts may be understood as the discipline of creativity:

1. **Imagination**: it may not be possible to teach inspiration, but it is possible to share the development of one's own ideas honestly and transparently. It is possible to tell the stories of real engineers and artists. Educators who are present for their
students can create environments and share techniques that encourage them to think in new ways.

2. **Expression**: it may not be possible to endow talent, but educators can teach the use and meaning of fundamental languages such as drawings, words and mathematics. Educators can share examples of expression and discuss their effectiveness in the creative process.

3. **Judgment**: it may not be possible to teach wisdom, but it is possible to demonstrate it. Students can learn to think critically. They can learn how to understand their own feelings and the feelings of others. Students can learn the nature of responsibility by assuming responsibility.

The discipline of creativity accepts the necessity for iteration, and so requires engagement of the creative process with speed and courage. In this context “speed” is necessary to ensure that the expression of ideas is uninhibited and that judgments are disciplined. “Courage” is necessary to temper one’s fears of expressing a bad idea or facing a tough decision. Since most engineering projects are the work of more than one person, individuals need to be aware of interpersonal interactions that can either fuel or inhibit the creative process. We should not shy away from the potential discomfort these interactions present. In doing so, we miss opportunities. Understanding the principles of the creative process provides strength to see the process through.

### DRAWING, THE LANGUAGE OF THE ENGINEERS

The concept of drawing as a language was expressed by Karl Culmann in the mid 19th century as he developed graphic statistics. In Culmann’s words, “Drawing is the language of the Engineers, because the geometric way of thinking is a view of the thing itself and is therefore the most natural way; while with an analytic method, as elegant as that may also be, the subject hides itself behind unfamiliar symbols.” For this discussion, however, I would like to consider drawing even more broadly—as a language requiring multiple levels of abstraction, similar to words and mathematics.

Expression of thought through language is an essential stage in the creative process, and engineering requires the command of three primary languages:

1. **Words** communicate action and express ideas that cannot be seen.
2. **Mathematics** express quantity.
3. **Drawings** express substance or abstractions thereof—real objects and behaviors that are best understood by their appearance.

Contemporary American university culture clearly recognizes the value of words and mathematics as forms of communication. The act of acquiring a liberal education involves the extensive use of these languages. Drawing, on the other hand, has often been misunderstood as either artistic talent or a mere technical discipline. Understood as a language however, drawing is similar to writing, speaking and mathematics: it requires skill, but it also requires intellectual engagement.

Similar to written and oral communication, the audience matters. For presentation to an owner, realistic appearance is helpful. For communication with architects, realistic appearance is valuable, but can be tempered with abstraction and style in a manner that facilitates a collaborative process. For contractors developing an estimate, drawings should depict quantities and the general level of complexity. For contract documents sufficient detail to construct the work is required. Even with the most powerful computer modeling systems, experience and thoughtfulness are required to develop contract drawings that are clearly expressed and well coordinated. Providing information that is incorrect can be more harmful than not providing any information. In order to provide contract information in a manner that is consistent and easily understood by an expert, engineers have developed several abstractions such as weld symbols, elevation marks, tolerance...
numbers and typical details. These abstractions, while often communicated in the form of drawings, are generally not comprehensible to a person who does not speak this language.

Among engineers, drawings form the heart of a process by which we come to understand the behavior of structural systems. In the next section, I will attempt to demonstrate some essential moments in a creative process from my own work. Drawings figure heavily in this process, and tell most of the story. The words in the following section are necessary only to describe the design team’s actions, feelings and judgments about different ideas that were expressed in the language of drawing.

**The Creative Process and the WTTC Trussed Frames**

The recently completed Wind Technology Testing Center (WTTC), in Charlestown, Massachusetts provides an example from my own work where I can explain in greater detail the process by which the structure was conceived. This laboratory for testing off-shore wind turbine blades required an enclosure approximately 300 ft long, 140 ft wide, and 80 ft high. Blades would be anchored to one of three posttensioned concrete test stands, shown in Figure 8, and tested as cantilevers either horizontally, vertically or biaxially. The dimensions and expected deformations of a 90 m blade determined the enclosure requirements. The laboratory also required two 50-ton cranes for handling the blades and mounting them to the test stands. The length of the lab being twice the width, plus the desire for potential future expansion in the east-west direction made three-dimensional framing or length-wise framing unattractive for this building. Early in the process designers and owners agreed that a modular, planar system made the most sense for supporting the enclosure.

Several early schemes for the enclosure responded to the fact that the blades would be anchored to the test stands at angles of up to fourteen degrees. If the roof of the facility were sloped upward...
from the test stands towards the blade tips, it would be possible to reduce the enclosure volume and surface area significantly. This would conserve cladding material, reduce the heated volume and provide some opportunity for expression in the otherwise simple exterior form of the building. Such a system would, however, limit the use of cranes in the facility, would necessitate two sets of runway beams for a high crane and a low crane, and would inhibit future vertical expansion of the test stands. Such a form would also require each bay of framing to be unique in its total elevation. While varying elevations would not necessarily pose a problem for solid elements, it would complicate attempts to develop truss columns with regular panel points.

Figures 9 through 11 show early concept sketches for the facility. All concept sketches were developed at similar scale and with reference to the required crane clearance envelope. The architect experienced some frustration with the brute fact that a simple box best suited the crane requirements. This frustration, coupled with the owner’s desire to save money early in the project led to removing the cranes from the design altogether for approximately 3 months. Eventually, however, it was concluded that bridge cranes were an essential part of the facility. During this time, the conceptual studies in Figures 9 through 11 represented collaborative work by the architects and engineers to develop a regular system with a strong form. One form favored by the architects was the swoosh shown in Figure 10(a). As we developed this system to suite the span, we attempted to lighten the form by supporting the main span with a kingpost, as shown in Figure 10(e). Figure 11(a) shows an attempt to stabilize the structure by lateral bracing instead of the frame action depicted in Figure 10(d).

Once the system was to be stabilized laterally by braced columns, it became possible to lighten the connection between the roof truss and the column as shown in Figure 11(b). This scheme
maintained the exterior expressive quality of the swoosh, while behaving structurally similar to its symmetric counterpart in Figure 11(c). These roof schemes offered the potential for dynamic and interesting details, such as the one shown in Figure 11(d).

In a final attempt to draw plastic expression out of the otherwise rigid program, each individual frame was rotated slightly about its south foot, resulting in a warped roof surface. Furthermore, it was possible to integrate the transverse and longitudinal column bracing on the north side by shifting the columns off their transverse axes. Both of these moves are shown in Figure 11(e). This figure also shows the crane columns as an independent structure inside the building.

It hardly needs to be observed that by this point the roof scheme had overwhelmed the structure and stolen focus from the main purpose of the enclosure—which was to give ample room to test blades, support bridge cranes with maximum flexibility, and allow the lab to be lengthened eastward in the future. Furthermore, the spreading column supports on the north side would result in significant additional foundation expenses, since this site required piles or shafts 160 ft down to bedrock.

During this process, the owner made clear that future flexibility of the lab was important to the facility. The largest blades in the world were currently on the order of 60 m. No 90 m blades were even under design at this point, let alone in production. While the wind industry could not imagine blade lengths exceeding 90 m, recent history had shown that blade lengths had grown exponentially over the past 20 years, in spite of continued expectations that blade lengths would eventually plateau. In light of this history, even 90 m could not be considered an absolute limit. While most of the schemes in Figures 9 through 11 were judged to be unrealistic for the lab, the general idea of a self-stabilizing, planar system allowed future east-west expansion by obviating the need
for bracing on the east and west ends of the structure.

For initial pricing, the design team carried forward two designs: conventional 6 ft deep bar joists at 10 ft on center supported on girders and wide flange columns at 20 ft on center; and a series of trussed frames supported at 30 ft on center. The result of initial studies was that the two system costs were estimated within a few percent of each other. Some estimates even implied that the trussed frames would cost less than the joist system. The premium for fabrication at exacting tolerances would be offset by material savings and simplified erection due to a reduced number of pieces. Heavy grade beams, whose designs were dictated by laboratory testing requirements, offered stiff foundations to which the bases of the trusses could be fixed. This fixity helped to stiffen the frames while maintaining their slender 7 ft truss depth.

Figure 12 and Figure 13 show some of the studies undertaken on the form of the trussed frames once the system had been chosen.
We decided to make the frames three dimensional for stability against lateral torsional buckling. This eliminated all out of plane bracing and achieved an elegant simplicity both in the erection and in the appearance of the trusses. It further allowed for free space between the trusses to remain open for future blade testing. The three dimensional truss forms would require special joints at the frame corners. We decided early in the project to design and price these joints as steel castings. With eleven frames, some economy of scale could be achieved in the castings, which would ensure a higher level of quality control than welded joints. The castings would also make it possible to transfer approximately 440 kips of vertical force and 330 kips of horizontal force from the roof truss nose pipe to the column truss nose pipe without any visual disturbance to the frames. By allowing these critical joints to disappear, the steel castings helped to create a pure and refined form.

Figure 12 shows schemes for different panel point dimensions.
We set the panel points in an attempt to harmonize the overall form with its diagonal members. Details in Figures 12(b) and (c) represent multiple studies of the truss panel points to ensure that the diagonals would not intersect. This was important not only for visual reasons, but would also avoid the expense of analyzing, fabricating and welding overlapping diagonals. The object of the panel spacing studies was to reach a height of approximately 80 ft with 7 ft deep trusses and ensure a high degree of regularity in the panels. Figure 12(a) shows a concept for an 8 ft deep roof truss on 7 ft deep column trusses—which resulted in a jarring visual transition between roof and columns. Figure 12(b) shows an attempt to lengthen the panels and emphasize the slenderness of the 4 in. diagonal members in contrast with the more robust chords. Although the transition at the frame corners was not symmetric, it did express some dynamism in the relationship between the diagonals and the chords. The resulting longer diagonal and chord spans would have necessitated larger sizes in the most heavily loaded members, however. Among these studies, it had already been concluded that all diagonal shear members could be used instead of the combination of vertical and diagonal shear members shown in Figure 9(a). The final panel layout settled on ten-14 ft panels for the roof and five-14 ft-10 in. panels for each column. This satisfied dimensional requirements for the building, maintained structurally workable member sizes, preserved harmony between the roof and column trusses, and maintained a smooth transition at the frame corners. For drainage, the roof was required to slope up 1/4 in. per foot toward center span. In order to preserve the continuity of the frame, the bottom chord was kept straight and only the top chord was raked (Figure 12(d)).

The resulting 8 ft-6 in. depth at the roof truss midspan proved critical for both strength and stiffness under the final analysis. The gradual transition between roof truss depth from the columns to the center span also avoided the heavy-handed appearance of schemes similar to Figure 12(a).

Figure 13(a) shows a study for the frame corners as represented in Figure 12(a) through Figure 12(c). While this scheme had generated interest in profile because of its emphasis on turning the corner and its consistency with architectural proposals to literally curve the corners of the building, it resulted in 10 intersecting members, and seemed to complicate the overall frame. Figure 13(d) shows an attempt to reduce the number of members converging at the nose pipe joint to seven. This scheme also represents an attempt to shape the trusses further in three dimen-
Consideration of construction and appearance, however, led to the judgment that this form was overwrought. Figure 13(b) shows another study of the corner joint with the intention of generating a more radical appearance. The idea behind this form was to follow the moment diagram of the structure under lateral loading. This form resulted in approximately 50% loss of stiffness, however, and again felt unrefined. The final corner scheme is shown in Figure 13(c) as it was communicated to the foundry who had offered to help price the castings. Figure 13(c) shows the two primary cast joints in context along with approximate weights for pricing.

Figure 13(c) also shows the decision to accentuate the corner diagonals by making them the same size as the tail pipes. While these diagonals were required to support higher forces due to joint shear, they could have been made smaller. Similarly, the first two pairs of compression diagonals in the roof span were heavily loaded and required double extra strong sections. Our decision to maintain the larger pipes in the joint region and smaller pipes with thicker walls in the truss span reflected our judgment regarding both the formal and the plastic qualities of the frames. The heavier joint diagonals connect the nose pipe and tail pipe chords visually, while the lighter diagonals inside the spans create a sense of rhythm. The generation of multiple readings from such a simple system was one of the happy results of prioritizing refinement over novelty. This result also speaks to the need for judgment in context regarding structural design impulses such as forming the structure to the moment diagram, seeking maximum three dimensional plasticity, or proportioning all members exactly to their structural demands. Each of these impulses has the potential to lead to elegant results—but not when they are in conflict with larger design drivers. In this case the larger design drivers were the desire for a high degree of lateral stiffness to stabilize the crane, economy of construction, and the pursuit of harmony between the overall system and its parts.

When I encourage my students to draw, I often emphasize that I wish them to draw clearly. Whether they draw well is in many ways beyond the scope of our work together. It is the intellectual part of drawing that matters for the creative process. Here I am referring to drawing in its most general, abstract sense. The hand sketches are drawings, the CADD file in Figure 12 is a drawing, the three dimensional extrusions in Figure 13 are drawings. With the exception of the final CADD drawing, these drawings were
created quickly during a creative process. They were required to be clear enough to facilitate judgments regarding a specific idea. In the act of judging, we were unconcerned with how these drawings came into being. In the act of expressing, our priorities were often speed and clarity. If some drawings were beautiful, this beauty probably resulted from the joy experienced during their creation, or from a deliberate intention to express something beautiful. If some drawings were not beautiful, their inherent beauty may not have been a necessary condition for good judgment. Still, perhaps if other drawings could have been made more beautiful, they might have led to an improved design. These things are difficult to know. The purpose of this discussion, however, is to argue that quality of draftsmanship can and ought to be evaluated separately from the usefulness of drawings in the creative process. The creative process stalls when engineers and students hesitate to draw.

Similar to drawing, a purposeful approach to calculation can enhance the creative process of structural design. Figure 14 shows the results of some analyses engaged during the conceptual design of the braced frames. The final analysis of the frames included models of the entire system with over 128 load cases and consideration of material and geometric nonlinearities. Two separate teams developed independent models and we checked them against one another until we achieved convergence on the most important results. This part of the process is too compli-
cated to represent here. Furthermore, it would add little to this discussion—which is about expressing specific ideas with a level of clarity that allows for sound, defensible judgments. The more complicated part of the process would not be successful had 90% of the important decisions not been made during the conceptual phase discussed here. Note that the conceptual phase emphasized both systems and details.

The images in Figure 14 show another dimension to drawing as the language of the engineer. In these figures, the drawings are rendered to yield analytical insight. Their appearance is in many ways similar to the drawings in previous figures, but the focal points are new. These drawings help to envision deformations and forces. They highlight numerical points of interest and place these key points in context. Again, they are a mixture of hand drawings, calculations and computer output annotated by hand. The mixture of expression by hand and by computer validates the principle discussed earlier—drawings must communicate appropriately. The speed with which they are created, the clarity with which they communicate, and the refinement of their results must be appropriate to the process. For these reasons, they develop organically in an effort to support the imagination and judgment of ideas. As our first introduction to the frames, we produced the analyses in Figure 14(a). These analyses fit onto a single page and became the touchstone by which we evaluated later computer results.
Figure 14(b) and Figure 14(c) represent a series of studies engaged by changing the boundary conditions at the bases of the frames. Rather than print up a new image for each study, the key results were recorded in a color corresponding to that particular study. The colors were kept consistent so they could be recognized at a glance during further discussion. Figure 14(d) shows a three dimensional study of the truss columns’ susceptibility to torsional loads. With the exception of the end frames, the trussed frames were allowed to remain torsionally flexible. Removing the diagonals between the tail pipe chords directed visual focus to the diagonals between the nose pipe and tail pipe chords. This was acceptable structurally in all but the end bays, which were required to transfer longitudinal wind loads into the system. Figure 14(d) helped us study the effects of adding diagonals between the tailpipe chords, which ultimately reduced torsional deformations in the end trusses by a factor of six. Because these diagonals were only required in the two end trusses, we were able to construct them symmetrically using cast steel x-joints. The incremental cost of these castings was marginal because there were 42 of them and they constituted a small portion of the total castings order. The consistent principle animating all of the images in Figure 14 is the importance of communication. The communications are made as compact as possible with an aim toward understanding them at a glance. In this way, they can be revisited, shared with colleagues, critiqued and checked.

Perhaps the greatest disappointment resulting from our current use of the computer stems from the reams of data that are printed and submitted as calculations. Without an engineer to make sense out of the data, and to refine this sense into legitimate communication, the analyses themselves are worth little. The virtue of hand calculations in our current age, therefore, is their contribution to sense-making. While I do not wish to state this absolutely, I notice a general correlation between the quality of an engineer’s thinking and the balance they maintain between computer results, hand calculations, drawings, notes, tables and figures. Foolish
consistency in this regard can have detrimental effects, but as a rule of thumb, consistent integration between human activity and computer activity seems to benefit the creative process.

Figure 15 shows the nose pipe joint in five different contexts, ranging from a physical model (a), to a finite element model (c), to construction documents (d), to an image of the completed joint (e). This figure shows again the range of purposes that can drive communication about this joint. The figure does not include representations of the multiple iterations required to develop the joint’s interior, to carry loads, or to refine the appearance of the fillets. Understood in general terms these five images are five different drawings of the joint. In other words, they are not expressed in the languages of words or mathematics. I prefer to call them drawings in order to maintain consistency with Culmann’s assertion that “drawing is the language of the engineers.” The drawing in Figure 15(b) was sent to the fabricator during a value engineering exercise with the object of redesigning the cast steel joints as weldments. Once the fabricators understood the demands on these joints, they recommended to the general contractor not to pursue this further. This communication was as much a part of the creative process as any other. An idea was imagined by the contractor to redesign the joints. The loads on the joints were expressed, and a judgment was made not to pursue a redesign based on these loads. Interestingly, during this value engineering process, it was critical that the castings survive based on their technical and economic merit alone. Had the engineers expressed any preference for their appearance, they would have categorically been perceived as too expensive. While this experience presents a sad commentary on contemporary American aesthetic culture, it is not inconsistent with the tradition that structural artists often assume full responsibility for the construction of their work. When the structural artist is also the builder, she needn’t be concerned with the politics of “value engineering”—a process that typically offers little value and even less engineering.
Figure 16 provides a compelling synthesis of the aesthetic choices discussed in this section. Additional members would have obscured the structural form and detracted from its visual power. The three dimensionality of the trusses makes it possible to experience them as objects as well as spaces. Although the view shown in Figure 16 is not accessible to every laboratory visitor, it is possible to experience similar views from inside the trusses on the laboratory floor. In order to save money on the foundations, laboratory offices were designed inside the north trusses, so it is also possible to experience the trusses and castings on a human scale as well as the scale of the laboratory. The trusses are simple enough that they give way to the laboratory space when they are not the focus, but they are able reappear as interest dictates. As Figure 8 shows, their lightness makes the bridge cranes appear to float above the lab floor. To have ignored the bridge cranes visually would have been to misunderstand the form of the lab. To have competed with them would have distracted from the unity of the space. Even inside this relatively simple system, there were countless choices we were required to make. Some of these choices were judgments based on analysis, but some of them were also judgments based on a conscious desire to express an aesthetic emotion. In such cases, the bases for these judgments were subjective thoughts and feelings. It is possible to have made other choices at multiple levels in the design. While many elements of the design were refined through careful analysis, the design is not an optimum, it is the conscious and unconscious result of an intensive creative process born out of the engineering imagination.
DRAWING AND THE EDUCATION OF STRUCTURAL ENGINEERS

In order to provide further context for the characteristics of drawing as a language, I will discuss two recent lobby renovations in Boston and their role in my teaching the third year steel design course at Tufts University. Figure 17 shows before and after photos of a lobby renovation completed with CBT Architects at 100 High Street in Boston in the spring of 2009. The former entrance to the building in Figure 17 was located at 150 Federal Street. The lobby renovation consisted of removing three bays of slab framing from the second story in order to create a new 2-story high lobby with a structural glass façade by W&W Glass/Pilkington Planar. Figure 18 shows the framed area before and after the slab was removed. Since the new glass wall was to be hung from the cantilevered third floor framing, reinforcement of the columns prior to demolition of the slabs required not only considerations of column stability under 28 stories, but also of column flexural deflections and their effect on cantilevered slab deflections.

Figure 19(a) shows original sketches and calculations developed during concept design of this slab removal. While it may seem natural that sketches, calculations and words occupy the same page of work (as do also graphs and tables often times), it is important to note that many students are not educated to communi-
cate in this kind of hybrid language. At the top of Figure 19(a) is a sketch of the plan, which gives context and which will become the primary form of communication in later contract documents. Also listed are the assumed loads. These loads are deliberately simple, and their importance lies in the fact that they allow this communication to stand alone, without reference to other documents. This makes the work easier to check and to discuss with colleagues. For columns supporting a fully-occupied 28-story building, it became important to check both the relevant assumptions and calculations many times, with many different colleagues. The intellectual merit of the problem lay in distilling the problem down to its essence—to make it so simple that the unconscious could continue to consider the problem at all hours—so simple that one could wake up in the middle of the night and check the work at bedtime. The analysis on the lower portion of Figure 19(a) is a simple, single degree of freedom moment distribution, which was carried out on half a page. A sketch of the physical system with moment diagrams helped to facilitate this level of conceptual transparency.

Figure 19(b) shows a series of homework exercises based on a parametric investigation that followed the calculations in Figure 19(a). The object of the investigation was to determine the stiffening effects due to a range of possible reinforcement schemes for the cantilever and its beam and column back-spans. I learned from assigning this series of problems that there was a significant
The difference between how I saw these simple sketches and how my students and teaching assistants saw them. I saw several variations on one theme—a cantilever with a backspan. The variations entailed different types of backspans resulting in different levels of rotational stiffness at the root of the cantilever. My students, however, saw eight different problems, with little or no conceptual thread running through them.

When I solved these problems in Figure 19(b), the moment diagrams and axial force diagrams yielded significant insight into system behavior—even before I calculated any numbers. From the principle of virtual work, more area under these diagrams implied more system flexibility. To a novice, the diagrams appear more simple than they actually are. This speaks to the subtlety and effectiveness of their abstraction. Only an expert can see all they have to offer. And to an expert, they facilitate a powerful understanding. A similar observation was treated extensively by the National Research Council in *How People Learn*.
Experts’ abilities to reason and solve problems depend on well-organized knowledge that affects what they notice and how they represent problems… The fact that experts are more likely than novices to recognize meaningful patterns of information applies in all domains, whether chess, electronics, mathematics, or classroom teaching… Because of their ability to see patterns of meaningful information, experts begin problem solving at “a higher place.”

Figure 20 shows a sketch for another structural lobby renovation at 225 Franklin Street in Boston. I developed this sketch during a coordination meeting with the architect, the glass installer and the general contractor. During the meeting, the sketch helped our team to align our interests with regard to developing an slender steel header that could be attached to the glass system. Both the system and the details were important to all parties involved, and the actual engineered header system ended up resembling this concept sketch closely.

Figure 21 shows an elevation of the 225 Franklin Street entrance, which was conceived as a glass box, protruding from the intensely textured 1963 façade. This façade is supported by floor slabs cantilevered 17 ft from the building columns. The box is transparent, but also ordered in its proportions and arrangement of insulated glass lites. Accentuating this order, the lites have a horizontal orientation, the joints between the lites are filled with black silicone, and the portals assume the exact space of two lites. From outside, the repose of the glass box intensifies the dynamics of the Paonazzo marble wall which presides over the lobby’s interior. Once inside, the lobby’s horizontal orientation heightens the excitement of approaching the rare marble wall to study its golden and rust colored limonite markings.

AN ABUNDANCE OF MEANS

In our current age of advanced technology, why should we even consider executing our calculations and drawings by hand? Current questions regarding the relationship between the computer and hand calculations are reminiscent of the tension between machine production and handicrafts that began over a century and a half ago. Gottfried Semper, who was a colleague of Karl Culmannis, visited the 1851 Crystal Palace Exhibition in London and wrote a famous essay on this tension. Semper wished to remain optimistic about machines that “encroach deeply into the field of human art, putting to shame every human skill,” and asserted that “there is no abundance of means but only an inability to master them.” By the early 20th century, the question of machine production had come to dominate modern architectural discourse.
Our current use of computers has developed all the more rapidly in light of our hindsight regarding the history of machine production. What seems to be missing, however, is the intensive cultural discussion that flourished from the 1850s to the 1920s, on the merits and weaknesses of the new tools. I can't help but feel that we are missing a cultural opportunity, and perhaps also an economic opportunity, in our reluctance to discuss what it means to have mastered our tools.

The changes are occurring rapidly. Within a span of thirty years, we have transitioned from hand calculations, punch cards, drafting boards and blueprints; to CADD, structural analysis software, and laser printers; to BIM, structural design software, professional outsourcing and electronic files. At the same time, codes have changed nearly every three years and have multiplied in size and number. Our present tools are powerful. They have the potential to make our work more efficient, more accurate, and more comprehensible to owners. So why do we need engineers? What does it mean to have mastered our tools? Since before Semper’s time, machines have successfully replaced human labor—even skilled labor. Still, it remains important to sit with these questions. They may be uncomfortable, but to engage them thoughtfully is to chart the future of engineering. I don’t intend to answer these questions so much as to offer a personal response to them.

Since the industrial revolution of the 18th century, we have created unprecedented wealth by systematizing, dividing and refining our approach to labor and production. In the service of this grand project, engineering has developed a reputation for acting instrumentally, for rationalizing and optimizing. This reputation, however, misrepresents most of the stories behind the engineering that supports our modern world. What needs to be made transparent is that even design in the everyday professional sense requires a human way of thinking—drawing on experience, analogies, associations and feelings. The interaction of the human and the technical is the life blood of our modern world, but this interaction is hard to understand and discuss. For this very reason, we ought to value this discussion as one of our most cherished and important intellectual disciplines.

While our trade journals are filled with articles wishing to advertise an ability to keep pace with our latest tools, a few simple observations seem to escape discussion. For instance, building professionals have grown more uncomfortable with drawing by hand. This makes it harder to express and discuss new ideas at meetings. Necessity no longer requires younger engineers to calculate by hand. This has removed the old safeguard that proficiency not attained in school would be acquired in practice.

For the first time in history, it is possible to practice for ten years and not advance beyond fundamental understanding attained as a student. Prior to the widespread use of computers, engineers spent thousands of hours calculating by hand. The imperative to calculate by hand continually challenged engineers to rethink
problems, to simplify them, and to understand them fundamentally. With justified excitement and satisfaction, our profession has embraced its liberation from arduous calculations. We have not come to terms, however, with the loss of mental discipline that naturally accompanied them. At its height, the fundamental understanding and mental discipline that made hand calculations possible also supported the calculations behind the Valschielbach bridge discussed earlier.

Robert Maillart’s design of the Valschielbach bridge teaches us that human judgment, in the service of clear understanding, exceeds in power and majesty even the most complex computations. This is a different way of thinking than either accepting the drudgery of complicated hand calculations or accepting uncritically a computer’s “answer” as the truth. I do not disagree with Semper. There is no abundance of means, only an inability to master them. Maillart and the other great structural designers teach us, however, that we master our tools not by learning every new tool that comes along, but by making sense out of their use.

The current abundance of means forces me to ask myself the question: “Is it moral for me not to understand what I am doing as an engineer?” Phrased in this way, most people I have asked would answer the question, “No.” But consider how this is complicated. Perhaps Maillart’s academic colleagues sensed something immoral about his use of simple calculations. Perhaps Maillart sensed something immoral in his academic colleagues’ insistence on added complexity. From a distance, we may conclude that Maillart won the debate because the Valschielbach bridge is still standing. Nevertheless, analytical complexity continues to seduce scientific research as practice in our modern universities.

Furthermore, what if the Valschielbach is simply standing by accident? Plenty of buildings are currently standing whose designers do not fully understand their behavior. Fortunately, however, Maillart did understand his bridge. We can see this understanding ourselves, because it is not hidden inside reams of data. Maillart’s Valschielbach calculations provide a compelling critique of misplaced analytical complexity, whether by hand or by machine. Our escape from drudgery ought to provide us with more time for understanding. But for many engineers it has simply created a new drudgery even more insipid than lengthy calculations. At least in the midst of the old calculations, engineers were compelled to understand their work if they wanted any answer at all.

Superior computational power has reduced the apparent need to think long and hard about how best to model structures. This has promoted a literal approach to modeling which is highly inefficient and often incorrect. It has also indulged a culture where professionals and students alike are unable to explain their results. In response to questions regarding structural behavior, I have heard the phrase, “Would you like to see my spreadsheet?” No! I would not like to see your spreadsheet. I would like for you explain to me what is going on. Habitual work on the computer
has diminished both a sense of scale and the means of expression available to engineers working on paper. This need not be the case. It is possible to use computers appropriately, but this requires conscious deliberation and judgment. In the absence of necessity, we are left alone to discipline our thinking. This requires a strong professional culture, whose values are clearly understood and expressed.

When I calculate, my pages are filled with sketches, notes, tables, equations, numbers and graphs—each is a means of expression appropriate to its purpose. On a daily basis, our office receives calculations for review that are as empty of thought and clear expression as they are voluminous in size. These calculations not only contain mistakes, but the mistakes can be very hard to find. Taking Karl Culmann at his word, I often develop my force diagrams directly on top of a picture of the structure or detail. Drawing, calculation and understanding are connected. It is not enough to understand the concepts internally. An engineer must convey the same understanding to someone else.

An understanding of the creative process allows me to explain my choices of tools. As a practitioner no explanation is required. As an educator, however, my job is to help students make sense of the world, so I struggle to understand why I practice the way I do. Teaching keeps me honest. For each situation, I judge the value of my tools based on three criteria:

1. How quickly and directly can I express the idea?
2. How much does this expression facilitate judgments and inspire further ideas?
3. How well may I expect this expression to communicate?

These criteria are especially helpful in determining appropriate use of the computer. While I belong to a generation of engineers who are proficient with all types of software, I find that many problems can be solved more quickly by hand—especially if I model them in an efficient way. Other problems are solved more quickly by the computer, but their solution offers less fundamental insight. This poverty of insight has a tendency to obstruct both my imagination and my judgment. Still other problems, however, are solved elegantly and quickly on the computer. The best tool for a given situation is not a foregone conclusion. I am responsible to judge which tool best suits my present purpose. To judge well is to have mastered my tools.

**The Role of Design in University Engineering Education**

The role of design in university engineering education is to motivate and challenge students’ fundamental understanding of the physical world. Design is relevant in the university, not because it prepares students for the working world, but because it motivates and challenges students’ understanding of the fundamentals in the best possible way. Design requires a personal way of directing creative thinking toward the solution of an actual problem. It has little use for rote application of equations that a student may or may not understand. Design requires a philosophical approach rooted strongly in the fundamentals of a discipline. Fundamentals are not just theory, but how theory is applied in a context. To separate theory from practice is to ignore context—and hence to forsake what is most human and most wonderful in engineering.

Architecture and the fine arts have developed superior creative processes to engineering. Lacking a self-conscious creative process, engineering has misunderstood its own human principles and has misrepresented itself to the public. The most common example of this is the canonical structural engineering design course—steel design. While the word “design” is captivating, the course itself often consists of learning how to select pre-formed member sizes from a manual based on force calculations. This is not design. This is member selection.

About three years ago I reached a turning point in my teaching. I had become disillusioned, wondering if I was ever going to produce work that could be expressed in textbook problems. Every
real problem, no matter how simple, needed some context in order to make sense. Most designs that could be used to illustrate an analytical point could be improved if I was willing to change the analysis. Eventually, I realized that my professional work would remain problematic to the textbook format for the rest of my career. Reality is messy. I decided that it wasn’t my work that was flawed so much as it was the textbooks. Textbooks deliver example problems in step-by-step format—and teach students to look for the steps as opposed to thinking for themselves. Textbook problems are nicely typed and give the impression that whoever solved them was a stone cold genius. My point here is that I had to gather up some courage in order to take reality seriously—and it has greatly benefited my teaching.

The question of what an engineer learns in school and what an engineer learns at work is very interesting. Clearly, work exposes people to hundreds of problems. The question is whether these hundreds of problems get integrated into a conceptual framework that sees them as hundreds of variations on a few important themes. When the framework is not intact, it is more likely that these experiences continue literally to appear as hundreds of problems. My professional colleagues’ ability to understand diverse problems in terms of a powerful and efficient conceptual structure appears to have been influenced by their educational experience—particularly their professors and their mentors. The frequency with which my senior colleagues relate stories about their own undergraduate years emphasizes the persistent power and meaning of their education. We know from Professor Billington’s scholarship, that Wilhelm Ritter’s influence on both of his students, Robert Maillart and Othmar Ammann, played a significant role in these designers’ careers.

The purpose of design in the university is not to expose students to all the problems they will see in practice. Rather, it is to expose them to a few carefully selected problems that will allow them to see relationships between fundamental understanding and the design of real structures. These relationships are so strong that they cannot be separated into theory and practice without doing violence to reality—which itself is a unity. Not all real-world problems are appropriate for educational purposes. And simple examples which illustrate a theory as well as they reflect reality are rare indeed. It is a wonder, therefore, that the development of high quality examples for teaching is not an intellectual discipline in its own right.

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