

LESSONS FROM DAVID BILLINGTON

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ABSTRACT

Princeton Professor David Billington died on March 25, 2018 at the age of 90. David was a structural engineer, scholar, and a master teacher. He taught two courses at Princeton University. By Princeton standards these were very large courses, impacting as many as 20% of all students graduating from Princeton from the mid-1990's until he retired in 2010. One course was "Structures in the Urban Environment" and it focused on structural artists – engineers who designed efficient, economical, and elegant structures. The other course was "Engineering in the Modern World" and it focused on the history of engineering from the time of the American Revolution to the present day. Both courses are still being taught by his colleagues, Prof. Maria Garlock and Prof. Michael Littman. This article is about David's approach to educating the general public and engineers as described by Michael Littman, who co-taught the "Engineering in the Modern World" course with him for over 20 years.

Keywords: engineering education, history of engineering, teaching to a diverse audience, David Billington

1. INTRODUCTION

I worked closely with Prof. David Billington for over 20 years. He was an inspirational colleague and a close friend. I first heard him lecture about his then-new course, "Engineering in the Modern World" in the early 1990's and I was hooked. In those early days, I offered to help him teach it by running a once-a-week 'precept' – Princeton's 'precepts' are like classes at many other Universities – this allows students to meet in small groups (typically no more than 15 students) with a precept instructor, who preferably is a member of the faculty. The course has two lectures per week – these are given in a large lecture hall – and there is a weekly meeting with small groups of students in a classroom.

I am an experimentalist with a physics background and I teamed up with David to develop a set of laboratory experiments to help students understand many design formulas and concepts associated with the course – that way liberal arts students could use the course to get a general-education lab-science credit. We also had a research and writing version of the course where engineering and liberal arts students could receive general-education historical analysis credit – students in this version would read

additional historical documents and then discuss them in precept. Students in the historical analysis version would write a term paper about an engineering innovation and innovator of their choosing. Students in the laboratory version of the course would write lab reports of the historically-inspired or historically-relevant experiments that they performed.

In the mid to late 1990's, I began sharing the lectures with David. At that time, I developed several demonstration devices to help explain some of the technical ideas during lecture. David retired in 2010 but continued for a couple of years as a guest lecturer. I greatly enjoyed working with him and his teaching methods have had a lasting impact on me. Besides teaching David's course, I now use some of his ideas in another general education course, "The Art and Science of Motorcycle Design" [1], and in my work on STEM education [2].

2. A TEACHING MODEL AND FORMULA

The picture in Figure 1 is of David in our teaching laboratory. He is pointing to a model bridge that is instrumented with sensors. This was the first laboratory experiment that we developed. This

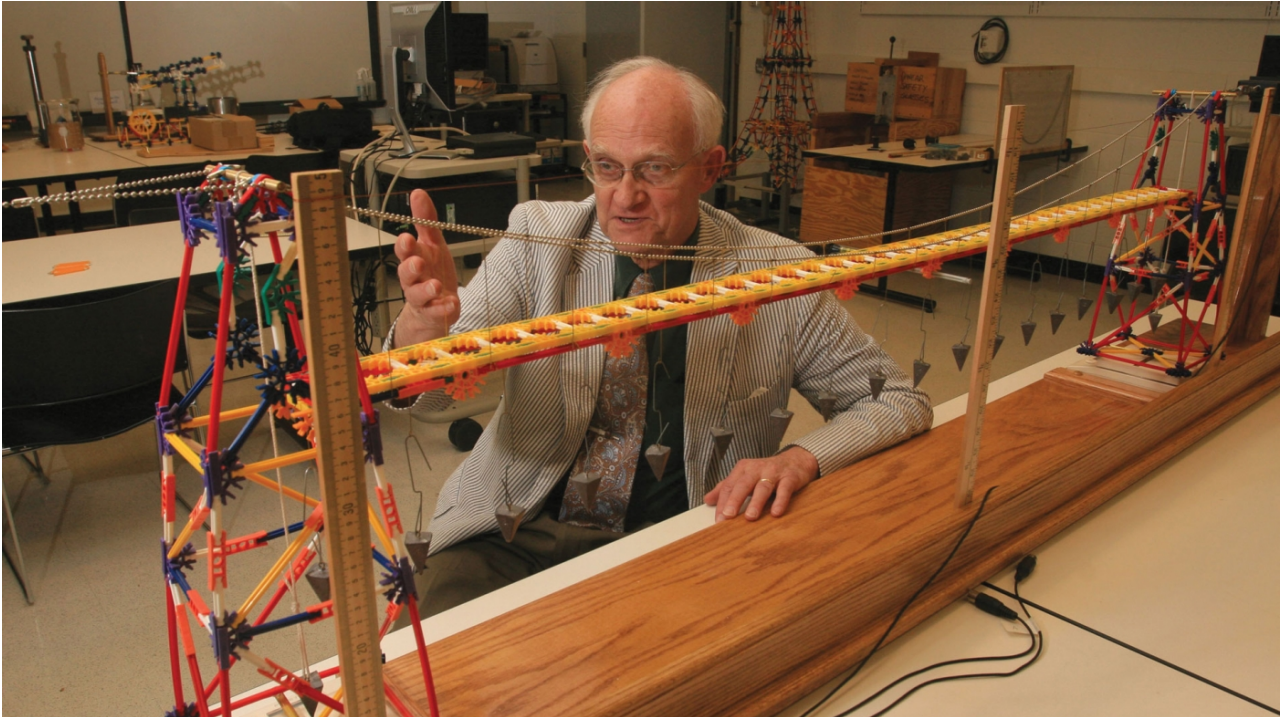


Figure 1: Prof. David Billington with the scale-model Menai Strait Bridge experiment in the Princeton University teaching laboratory

experiment allows students to understand the design formula $H = (1/8) \cdot (qL) \cdot (L/d)$, where H is the chain tension at mid-span, q is the deck load per unit length of the span, L is the bridge span, d is the chain sag. The bridge model is a scaled-down version of the Menai Strait Suspension Bridge designed by Thomas Telford - completed in 1826. At the time of its construction it was the longest spanning chain suspension bridge in the world. Load cells measure the horizontal component of the chain tension and ordinary postal scales measure the vertical tower compressive force, $V = qL / 2$. The bridge has an L/d that is about 13.5, so the horizontal reaction force is much greater than the vertical reaction force. Discrete weights (fishing sinkers) are distributed evenly along the deck to simulate the dead load of the deck. Students also add additional weights to simulate live loads and they record the changes in horizontal and vertical forces and note the deflections of the flexible deck as a result of the uneven loading.

3. SYLLABUS

Two versions of “Engineering in the Modern World” appear in the Princeton University Course Offerings with the common header:

“Lectures and readings focus on bridges, railroads, power plants, steamboats, telegraph, highways, automobiles, aircraft, computers, and the microchip. We study some of the most important engineering innovations since the Industrial Revolution.”

For the Historical Analysis version of the course, the following is added:

“Historical analysis provides a basis for studying societal impact by focusing on scientific, political, ethical, and aesthetic aspects in the evolution of engineering over the past two and a half centuries. The precepts and the papers will focus historically on engineering ideas including the social and political issues raised by these innovations and how they were shaped by society as well as how they helped shape culture.”

For the Laboratory version of the course, the following is added:

“The laboratory centers on technical analysis that is the foundation for design of these major innovations. The experiments are modeled after those carried out by the innovators themselves, whose ideas are explored in the light of the social environment within which they worked.”

Two text books written by David are used in the course. The second text is co-authored with his eldest son, a historian and independent scholar, David Billington, Jr.

- D. P. Billington, *The Innovators* [3]
- D. P. Billington and D.P. Billington Jr, *Power, Speed and Form* [4]

4. IDEAS AND METHODS

I list below some of David Billington's ideas and methods for teaching this kind of a course:

Ask 'big picture' type questions. What was the impact of engineering innovation on society? This question often leads to exploration of what David refers to as "radical innovations." Radical innovations are revolutionary rather than evolutionary and some have a major impact on economics (creating great personal or public wealth, or creating many jobs), politics (creating new laws or regulations), or the workings of society (changing the pace of society [Telegraph] or providing easy access to new regions [Railroad]). One example of a radical innovation is the telephone – it was not invented to solve a problem of the day and it was radically different from the telegraph. The turbojet was radically different from the piston-type internal combustion engine. One book that David especially liked about these ideas was "What Engineers Know and How They Know It" by Walter Vincenti [5].

Engineering viewed from a broad perspective. David used three perspectives to understand the significance and impact of engineering works – scientific, social, symbolic – these three perspectives cover all of the subjects in a University – natural sciences, social sciences, and the humanities – also he liked alliteration and would group ideas in individual lecture slides to a maximum of three – often grouped as a scientific idea, a social idea, and a symbolic idea. David's use of alliteration surfaced most regularly with his discussion of the structural art of bridges, starting with Thomas Telford in the early 19th century – the measures of which are efficiency (minimum materials - science), economy (minimum cost - social), and elegance (maximum expression - symbolic).

'Art History'-type lectures. David attended Art History classes taught by Princeton Prof. John Wilmerding where two slide projectors were used to alternate images on a screen. At all times there were two images visible side-by-side. This technique was

especially useful for critical comparative analysis, and it allowed any text slide to be left up long enough for students to write down the content while the lecture progressed. He adopted this style for the course. When David began in 1985, 35mm slides were used and all slides were put in sequential order on a tiered light box – all the even-numbered slides (1,3,5,...) were placed in one Kodak Carousel and all the odd-numbered ones (2,4,6,...) were in the other Kodak Carousel – the projector operator would advance first the left projector and then the right one and so on – sometime around the year 2000 we switched to PowerPoint Presentations based using the same approach of two images on a screen at all times with only one changing at a time.

The Tower and The Bridge. Like the art-history style of lecturing, David would often borrow good ideas from colleagues, friends, and even his brother. One of David's most celebrated books, written in 1983, was "The Tower and The Bridge" [6]. Tower as in Eiffel Tower and Bridge as in Brooklyn Bridge. The title is suggestively close to his historian brother James's 1966 book on Russian culture, "The Icon and The Axe" [7]. James used the axe and the icon (religious figures) as symbols to help one understand Russian culture. James's scholarship precedes David's in its heavy use of symbolism. Indeed James, the former Librarian of Congress, advised David with his book especially with the early chapters. Inspired by these titles and use of symbolism, I titled my lecture on the Panama Canal, "The Canal and The Bridge." The Panama Canal symbolically and literally connects the Atlantic and Pacific Oceans, and the Bridge of the Americas that was constructed as a land route over the Canal connects North and South America.

Art and literature used to explore the meaning of engineering innovations. For example, what does a railroad do to society? Joseph Turner, a pre-impressionist British painter, helps us understand the railroad's influence. Turner's painting, "Rain, Steam, and Speed" has a firefly-class locomotive frightening a hare (rabbit) and causing it to jump off the Maidenhead Bridge – the railroad is symbolically replacing the hare as the symbol of speed - this analysis, incidentally, is due to Turner himself [8]. Mark Twain's comments in his book "Life on the Mississippi" helps students to understand the beauty and the danger of rivers and steamboats [9]. Mark Twain himself was a riverboat pilot. Adding works of art and literature to the discussion of engineering objects captures the attention of many hard-to-reach

students and it broadens the topic, often making it much more memorable. One of the most memorable comments that David and I received from a student evaluation was, “The art spoke to me.”

How innovations happen. Understanding what was going on in society when the innovation developed builds an appreciation of how innovations are motivated and how they happen – perhaps it was Napoleon terrorizing Europe with a detrimental effect on shipping goods across the Atlantic (this led to the Embargo Act of 1807) or perhaps it was the Civil War that encouraged railroad development (east-west) over steamboats (north-south) – One consequence of the Civil War was competition for population between the cities of St. Louis and Chicago. St. Louis, a steamboat terminus, before the Civil War was more populous than Chicago – a situation that reversed after the Civil War [10]. Understanding context also helps to explain why it sometimes takes a long time before some innovations are adopted – for example, the telephone was the revolutionary work of Alexander Graham Bell who at the time was pursuing an evolutionary advance to telegraph transmission. The need for a telephone was not obvious then as it is today and as a result the telephone was slow to develop. Electrification is another example – electrification was common in cities but not in rural areas because it was expensive to build infrastructure – FDR’s New Deal and the shift in the Tennessee Valley Authority’s mission to providing electric power as its focus brought electricity and modernization to the economically depressed region.

Who did what? and What factors influence the growth of each innovation? Who are the innovators and what did they do? In some cases there are partnerships between entrepreneurs and inventors – such as Mathew Boulton and James Watt, or Robert Livingston and Robert Fulton; the important role of the entrepreneur emerges as a common idea in this kind of analysis, as neither entrepreneur nor inventor would have likely been so influential alone. In some cases, individuals acted as both inventor and entrepreneur (Thomas Telford or Thomas Edison, for example). In some cases, patents help an innovation (Watt’s atmospheric steam engine patent extension 1775, Bell’s Harmonic Telegraph patent 1876). In other cases, patents impeded an innovation (the Wright Brothers’ ‘Wing Warp’ patent of 1906 interfered with the development of the US aircraft industry prior to WWI).

Co-teaching. David attended all of the lectures that I gave in the course, and I attended all of his lectures. Sometimes when a course is equally shared it is viewed as a half teaching load – in this case it was a full teaching load for each of us. David felt very strongly about sharing the course in this way – he reasoned that if the course was to be truly integrated then both instructors must attend each other’s lectures and they should work together on all aspects of the course. I think his approach is right but it is “expensive” - I suspect that most Department chairs would not be happy to have two faculty members assigned to a single course.

Tell a good story. David was a master at telling interesting stories about the innovators featured in the course. He would provide enough detail so that students could relate to the people discussed in the course. Whenever a picture or portrait was shown of an innovator, it was an image of them when they were young and productive. David felt strongly about the importance of contributions of individuals. He also paid more attention to those who advanced an innovation dramatically rather than those who first invented an engineering object or system. For example, Henry Ford gets featured in the course for his role in growing the automobile industry as opposed to Frank and Charles Duryea who designed the first American gasoline automobile.

Discipline and Play. David’s method of storytelling was masterful. He would often present images in lecture with some twist or backstory. One of his favorites that he used in the “Structures in the Urban Environment” course was a photograph of the bridge designer Robert Maillart smoking a cigar shown in Figure 3. David would note that what Maillart was doing in the photograph was participating in a game where one holds perfectly still to form the longest possible ash pillar before it falls off. He would do this to tell you something about Maillart’s whimsies and then he would immediately transition to the concept of ‘discipline and play’ with regards to Maillart’s design of concrete bridges. Here, Maillart’s discipline becomes his attention to engineering principles, testing, and practice, and play is his masterful experimenting with new ideas in design.

Design formulas. David used formulas to explain both transformation and relationships – for example $H = (1/8)(qL)(L/d)$ is a formula that can help one understand design trade-offs in suspension bridges. As far as ‘transformation,’ a chain or cable



Figure 3: Robert Maillart and his cigar, circa 1926.
(Source: Madame M.-C. Blumer-Maillart – Image from ref. 15) [see ref. 15 for copyright detail and permission]

supporting a bridge deck transforms a vertical gravity load to a horizontal reaction force at the anchorage. As far as ‘relationships’ – H is a scientific factor; qL the weight of the deck that determines the cost of the deck, an economic factor; L/d expresses how flat the bridge is, an artistic factor. Therefore, one design formula relates science, economics, and art. If one increases the sag, the bridge is less flat and H decreases so the chain or cable becomes less costly and thinner. However, the towers need to be taller, so they become more massive and expensive.

Use scholarly sources. David felt that each lecture should be good enough to be published as a review of the topic. We were both careful to use historical peer-reviewed sources as well as first person accounts – for example, in our lectures we would incorporate primary sources such as the Wright Brothers article about their own work [11], or Thomas Telford’s autobiographical description of his structures [12]. Or, David would use peer-

reviewed secondary sources such as historian Thomas Hughes’s “Networks of Power” about electrification of America which won the Dexter Prize of the Society of History of Technology” [13]. (David also received the Dexter Prize for his book on Robert Maillart’s Bridges in 1979 [14].)

Use irony and symbolism. One of David’s favorite uses of irony was his description of the Eiffel Tower in contrast to the Washington Monument. He would say, the Eiffel Tower is a modern structure – the newest of forms – a light-weight metal cantilever – that is the symbol of an old city with a rich history – Paris. The Washington Monument, on the other hand, is the oldest of structures – an obelisk – and it is the symbol of a new city that was created from farmland and has no history. He would go on to observe that the Washington monument was actually made of individual stones and therefore consistent with the motto, “E Pluribus Unum” (out of many, one). He would then point out that there was a visible line in the exterior of the Monument between the original lower portion of heavy stone and the newer upper portion of light-weight stone completed by the Army Corps of Engineers. That line, he would say, represents the transformation from a craft society to one based on engineering.

Use critical comparative analysis. Whenever possible David would use the analysis of the original designers or the analysis of top designers in the field. For example, Thomas Telford’s comparison of his efficient flat arch bridge designs with Abraham Darby’s Iron Bridge (the first iron bridge constructed in 1779) is used to discuss the merits of metal bridge design. It is not David’s analysis that is presented to students; rather it is the analysis of the original innovator. This allows one to better understand what the innovator was trying to accomplish. Sometimes the analysis presented would be the result of studies by teams of engineers, such as his use of the study of the collapse of Leon Moisseiff’s Tacoma Narrows Bridge by Othmar Ammann, Theodore von Karman, and Glenn Woodruff.

Describe engineering through examples rather than by definition. Engineering is described by David as falling into four basic categories: Structures, Machines, Networks, and Processes. Definitions present a ‘theory’ and can be prone to overstatement or lack of precision. It is sometimes debatable as to what engineering is and how it differs from other disciplines. The use of examples is more straightforward. It is left to the individual student to

tease out the boundaries between, for example, engineering and craft.

Meet with teaching assistants weekly. David would run weekly meetings with graduate teaching assistants. The weekly meetings were like a separate graduate course on teaching. In David's view the teaching assistants are members of the 'board of directors of the course' – but, of course, the faculty retains 51% control. Both Maria Garlock and I have continued this practice. It builds a sense of comradery among the teaching staff.

Dissemination. David would tell others about his ideas through workshops, publications, and by training future faculty members (our teaching assistants) in the methods used in this course – David would run summer workshops about the style of teaching in this course and two other ones, "Structures in the Urban Environment" and "Rivers in the Regional Environment." He would run workshops to encourage others to adopt these methods. David managed to get funding for several workshops from various foundations including the Sloan and Mellon Foundations. But the best form of dissemination was through the many excellent graduate teaching assistants and civil engineering undergrads associated with the course who have become faculty at other Universities including MIT (John Ochsendorf, Gordana Herning), Tufts (Eric Hines), Syracuse University (Sinéad Mac Namara), Johns Hopkins University (James Guest), University of Notre Dame (Ashley Thrall), University of North Carolina (Nicole Leo Braxtan), Abby Liel (University of Colorado at Boulder), Powell Draper (Cooper Union), and Ted Segal (Hofstra).

5. CONCLUSION

I finish with mention of the one person that David felt was most important - his devoted, talented, and beautiful wife, Phyllis Bergquist Billington. Phyllis died two years before him. David loved to tell the story of how he won Phyllis's affection while they were both Fulbright Scholars studying in Europe in 1950. Phyllis majored in philosophy at Northwestern. She studied the piano and harpsichord in Belgium. She also modeled. As a young college student, Phyllis appeared on the cover of a number of national magazines including *Look*, *Collier's*, and *McCall's*. She was on the December 1949 cover of *McCall's* with a group of cover girls

along with the First Lady, Eleanor Roosevelt. Phyllis was the featured cover girl for the March 1950 issue of *McCall's*. David would explain that the very attractive and talented Phyllis captured the attention of many of the other Fulbright fellows in the Program. She initially rejected the advances of the lone skinny, tall, and awkward engineer. But he was persistent, and eventually won her over. David was all about persistence. In 1951 they married and would raise six children together.

I know David as a renaissance-type person with broad interests including engineering, literature, music, and the arts. There is no question that Phyllis's influence helped broaden his interests, and he helped broaden hers. Phyllis would lecture in Princeton and New York City about individual musical composers and their works. One lecture – one composer. She would accompany these lectures in their home with musical phrases and passages that she played on her grand piano. Her lectures about a musical master and their compositions paralleled David's lectures on engineering innovators and their works – David and Phyllis's lectures were a mixture of biography, history, and specific examples of creative genius.

Their life together was a whirlwind of engineering, music, and the arts, and they truly adored one other. With fond memory, I recall frequently working with David in the upstairs study of their home in Princeton, and in the background, I would hear Phyllis practicing a piece by Chopin or Mozart. We would often all end the evening together with a glass of sherry.

Phyllis was tireless at protecting David. In his later years, she would constantly push for him to take it easy and retire. Not David. He was driven to pursue his scholarship, his writing, and his teaching. David was also committed to increasing diversity of the engineering profession, especially encouraging future women engineers. He often commented to me on how he was proud to have supported so many women engineers, and he was distinctly proud that his daughter, Sarah, chose a career in engineering. Sarah is a Professor of Civil Engineering at Stanford.

David is missed but not forgotten. He left an indelible mark on the engineering profession and upon many who admired and learned so much from him. So long, my old friend.

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