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FROM SLIDE RULE TO COMPUTER: FORGETTING HOW IT USED TO BE DONE

Twenty-five years ago, the undisputed symbol of engineering was the slide rule. Engineering students, who at the time were almost all males, carried the "slip sticks" in scabbard-like cases hanging from their belts, and older engineers wore small working models as tie clips that in a pinch could be used for calculations. When I became an engineering student myself, one of my most important decisions was which slide rule to purchase. Not only was $20 a big investment in 1959, but also I was choosing an instrument that I was told I would use for the rest of my professional life; I was advised along with all the other freshmen to get right at the start a good slide rule with all the scales I would ever need. After much comparative shopping, I chose a popular Keuffel & Esser model known as the Log Log Duplex Decitrig, and for a long time it was my most prized possession. Many of my fellow students also chose K & E rules, and the company was selling them at the rate of twenty thousand per month in the 1950s.

A slide rule was indispensible for doing homework and taking tests, for all our teachers assumed that every engineering student had a slide rule and knew how to use it. If we had not learned in high school, then we quickly studied the manual folded into the box. What our engineering instructors were interested in teaching us was not all the grand things that our various models of rules could do, but their common limitations. They told us about significant digits, for most engineering instruments then had analog dials and scales from which one had to estimate numbers between the finest divisions in much the same way we have to estimate sixteenths of an inch on a yard stick or tenths of a millimeter on a meter stick. The scales on the slide rule have the same limitations, and we were expected to know that we could only report answers accurate to three significant digits from our rules, unless we were on the extreme left of the scale where finer subdivisions existed.

We often had these things inculcated in us by trial and error. If the answer to a test question required us to multiply, say, 0.346 by 0.16892 and we reported the result as 0.05844632 we would be marked for an error in significant digits, for the result of a calculation could not have a greater accuracy than the least accurately known input number. (When older engineers write 0.346, it is implied to be known only to three digits after the decimal point, otherwise it would have been written as 0.3460 or 0.34600 or to whatever decimal place the number is known.) Since no one could ever read as many digits as those in 0.05844632 from his slide rule, the closest he would be expected to get would be 0.0585. (The extra digits were a dead giveaway that the student had forgotten his slide rule and had done the multiplication longhand on some scrap of paper and, worse yet, had forgotten the significance of significant digits.) We also learned how to estimate the order of magnitude of our answers, for the slide rule could not supply the decimal point to the product of 0.346 and 0.16892, and we had to develop a feel for the fact that the answer was about 0.06 rather than 0.6 or 0.006. These requirements on our judgment made us realize two important things about engineering: first, answers are approximations and should only be reported as accurately as the input is known, and, second, magnitudes come from a feel for the problem and do not come automatically from machines or calculating contrivances.

As I progressed through engineering school with my slide rule in the early 1960s, electronic technology was being developed that was to change engineering teaching and practice. But it was not then widely known, and as late as 1967 Keuffel & Esser commissioned a study of the future that resulted in predictions of domed cities and three-dimensional television in the year 2067—but that did not predict the demise of the slide rule within five years.

In 1968, an article entitled "An Electronic Digital Slide Rule" appeared in *The Electronic Engineer*. It could dare to prophesy, "If this hand-size calculator ever becomes commercial, the conventional slide rule will become a museum piece." In the article the authors, two General Electric engineers, described a prototype that they had built with some off-the-shelf digital integrated circuits. Their "feasibility model" looked like an electric blanket control and, at 1½ × 5 × 7 inches, it resembled a novel in size. Yet their marvel could give four-digit answers to any four-digit multiplicands, and it could also divide and calculate square roots, exponentials, and logarithms. It had, however, one shortcoming, and the engineers made the concession that, "Since it has no decimal points, you must figure out your decimals as with a regular slide rule." As far as cost was concerned, that of course would depend upon the cost of the components, but there remained one big obstacle in 1968: "Only the digital readout still poses a problem, since at present there are no low-cost miniature devices available. But there is no question that this last barrier will soon be overcome."

They were right, of course, and within a few years Texas Instruments had developed the first truly compact, handheld, pocket-sized calculator using an electronic chip. Texas Instruments started manufacturing pocket calculators in 1972, but they were still expensive in 1973, costing about ten times as much as a top-of-the-line slide rule. However, price breakthroughs came the next year, and Commodore was advertising its model SR-1400, a "37-key advanced math, true scientific calculator" that could do everything my Log Log Duplex Decitrig could do—and more. If one knew input to ten significant digits, then this calculator could handle it.

I was teaching at the University of Texas at Austin at the time of this great calculator revolution, and there were some engineering students whose daddies did not have to wait for the pocket calculator to become competitive in price with the slide rule. We faculty were thus faced with the question of whether students with electronic slide rules had an unfair advantage on quizzes and examinations over those with the traditional slip sticks, for the modern electronic device was a lot quicker and could add and subtract—something a slide rule could only do with logarithms. The faculty members generally were unfamiliar with all the features of the calculators that were still priced out of their reach, and there seemed to be many pros and cons and endless discussions over the issue of whether an electronic slide rule was equivalent to a wooden one. The question soon became moot, however, as prices plunged and just about anyone who could afford a conventional slide rule could afford an electronic model. By 1976 Keuffel & Esser was selling calculators made by Texas Instruments faster than traditional slide rules, which by then made up only five percent of K & E's sales, and the company consigned to the Smithsonian Institution the machine it once used to carve the scales into its wooden slide rules.

By the mid-1970s calculator manufacturers were making fifty million units a year, and soon just about everyone, including engineers who went through school in the old days, had a calculator. But no older engineer that I know discarded or consigned his slide rule to any museum. At most the old slip stick was put in the desk drawer, ready for use during power failures or other emergencies. A study conducted by the Futures Group in the early 1980s found that most engineers in senior management positions continued to keep slide rules close at hand and still used them "because they are more comfortable." But the always-growing younger generations naturally feel just the opposite. In 1981 I asked a class of sophomore engineering students how many used a slide rule, and I got the expected answer—none. (Some did own slide rules, perhaps because their engineer fathers bought one for the freshman to take away to engineering school. And K & E was selling out its remaining stock of 2,300 at the rate of only two hundred per month in 1981.) I did not ask my class how many used a calculator, for that would be like asking how many use a telephone. And I did not ask how many used a computer, for that was by then a requirement in the engineering curriculum. The trend is clearly that eventually no engineer will own or use a traditional slide rule, but that practicing engineers of all generations will use—and misuse—computers.

Engineering faculty members, like just about everyone else, got so distracted by the new electronic technology during the 1970s that more substantial issues than price, convenience, and speed of computation did not come to the fore. The vast majority of faculty members did not ask where all those digits the calculators could display were going to come from or go to; they did not ask if the students were going to continue to appreciate the approximate nature of engineering answers, and they did not ask whether students would lose their feel for the decimal point if the calculator handled it all the time. Now, a decade after the calculator displaced the slide rule, we are beginning to ask these questions, but we are asking them not about the calculator but about the personal computer. And the reason these questions are being asked is that the assimilation of the calculator and the computer is virtually complete with the newer generations of engineers now leaving school, and the bad effects are beginning to surface. Some structural failures have been attributed to the use and misuse of the computer, and not only by recent graduates, and there is a real concern that its growing power and use will lead to other failures.

The computer enables engineers to make more calculations more quickly than was conceivable with either the slide rule or the calculator, hence the computer can be programmed to attack problems in structural analysis that would never have been attempted in the pre-computer days. If one wished to design a complicated structure of many parts, for example, one might first have made educated guesses about the sizes of the various members and then calculated the stresses in them. If these stresses were too high, then the design had to be beefed up where it was overstressed; if some calculated stresses were too low, then those understressed parts of the structure could be made smaller, thus saving weight and money. However, each revision of one part of the structure could affect the stresses in every other part. If that were the case, the entire stress analysis would have to be repeated. Clearly, in the days of manual calculation with a slide rule—wooden or electronic—such a process would be limited by the sheer time it would consume, and structures would be generally overdesigned from the start and built that way. Furthermore, excessively complex structures were eschewed by designers because the original sizing of members might be too difficult to even guess at, and calculations required to assure the safety of the structure were simply not reasonable to perform. Hence engineers generally stuck with designing structures that they understood well enough from the very start of the design process.

Now, the computer not only can perform millions of simple, repetitive calculations automatically in reasonable amounts of time but also can be used to analyze structures that engineers of the slide rule era found too complex. The computer can be used to analyze these structures through special software packages, claimed to be quite versatile by their developers, and the computer can be instructed to calculate the sizes of the various components of the structure so that it has minimum weight since the maximum stresses are acting in every part of it. That is called optimization. But should there be an oversimplification or an outright error in translating the designer's structural concept to the numerical model that will be analyzed through the automatic and unthinking calculations of the computer, then the results of the computer analysis might have very little relation to reality. And since the engineer himself presumably has no feel for the structure he is designing, he is not likely to notice anything suspicious about any numbers the computer produces for the design.

The electronic brain is sometimes promoted from computer or clerk at least to assistant engineer in the design office. Computer-aided design (known by its curiously uncomplimentary acronym CAD) is touted by many a computer manufacturer and many a computer scientist-engineer as the way of the future. But thus far the computer has been as much an agent of unsafe design as it has been a super brain that can tackle problems heretofore too complicated for the pencil-and-paper calculations of a human engineer. The illusion of its power over complexity has led to more and more of a dependence on the computer to solve problems eschewed by engineers with a more realistic sense of their own limitations than the computer can have of its own.

What is commonly overlooked in using the computer is the fact that the central goal of design is still to obviate failure, and thus it is critical to identify exactly *how* a structure may fail. The computer cannot do this by itself, although there are attempts to incorporate artificial intelligence into the machine to make it an "expert system," and one might dream that the ultimate in CAD is to have the computer learn from the experience contained in files of failures (stored in computers). However, until such a far-fetched notion becomes reality, the engineer who employs the computer in design must still ask the crucial questions: Will this improperly welded pipe break if an earthquake hits the nuclear reactor plant? Will this automobile body crumple in this manner when it strikes a wall at ten miles per hour? Will any one of the tens of thousands of metal rods supporting this roof break under heavy snow and cause it to fall into the crowded arena?

One *can* ask of the computer model questions such as these. Whether or not they *are* asked can depend on the same human judgment that dismissed the question of fatigue in the Comets and that apparently did not check the effects of the design change on the Hyatt Regency walkways. Even if one thinks of the critical questions and can phrase them so that the computer model is capable of producing answers to them, there may have to be a human decision made as to how exhaustive one can be in one's interrogation of the computer. While the computer works very quickly as a file clerk, it cannot work very quickly when it is asked to analyze certain engineering problems. One of the most important problems in design is the behavior of metal under loads that deform structural components permanently. While it takes only seconds to put a bar of ductile steel in a testing machine and pull the bar until it stretches out and breaks like a piece of taffy, simulating such an elementary physical test on the largest computer can take hours.

There can be miles of pipes in a typical nuclear reactor plant, and it could take some of the largest and fastest computers a full day of nonstop calculation to determine how wide and how long a crack in one ten-foot segment of the piping would grow under the force of escaping water and steam. The results of such a calculation are important not only to establish how large a leak might develop in the pipe but also to determine whether or not the pipe might break completely under the conditions postulated (by the human engineer). Since it could take years of nonstop computing and millions of dollars to examine every conceivable location, size, and type of crack in every conceivable piece of pipe, the human engineer must make a judgment just as in the old days as to which is the most likely situation to occur and which is the most likely way in which the pipe can fail. The computer does not work with ideas but with numbers, and it can only solve a single problem at a time. The pipe it looks at must have a specified diameter, a specified crack, a specified strength, and a specified load applied to it. Furthermore, the computer model of the cracked pipe must have a specified idea as to how a crack grows as the postulated accident progresses. All these specifications are made by human beings, and thus the results of the computer are only as conclusive about the safety of the system as the questions asked are the critical ones.

The computer is both blessing and curse for it makes possible calculations once beyond the reach of human endurance while at the same time also making them virtually beyond the hope of human verification. Contemporaneous explanations of what was going on during the accident at Three Mile Island were as changeable as weather forecasts, and even as the accident was in progress, computer models of the plant were being examined to try to figure it out.

Unfortunately, nuclear plants and other complex structures cannot be designed without the aid of computers and the complex programs that work the problems assigned them. This leads to not a little confusion when an error is discovered, usually by serendipity, in a program that had long since been used to establish the safety of a plant operating at full power. The analysis of the many piping systems in nuclear plants seems to be especially prone to gremlins, and one computer program used for calculating the stresses in pipes was reportedly using the wrong value for pi, the ratio of the circumference to the diameter of a circle that even a high school geometry student like my daughter will proudly recite to more decimal places than the computer stores. Another incident with a piping program occurred several years ago when an incorrect sign was discovered in one of the instructions to the computer. Stresses that should have been added were subtracted by the computer, thus leading it to report values that were lower than they would have been during an earthquake. Since the computer results had been employed to declare several nuclear plants earthquake-proof, all those plants had to be rechecked with the corrected computer program. This took months to do and several of the plants were threatened with being shut down by the Nuclear Regulatory Commission if they could not demonstrate their safety within a reasonable amount of time.

Even if a computer program is not in error, it can be improperly employed. The two and a half acres of roof covering the Hartford Civic Center collapsed under snow and ice in January 1978, only hours after several thousand fans had filed out following a basketball game. The roof was of a space-frame design, which means that it was supported by a three-dimensional arrangement of metal rods interconnected into a regular pattern of triangles and squares. Most of the rods were thirty feet long, and as many as eight rods had to be connected together at their ends. The lengthy calculations required to ensure that no single rod would have to carry more load than it could handle might have kept earlier engineers from attempting such a structure or, if they were to have designed it, they might have beefed it up to the point where it was overly safe or to where its own weight made it prohibitively expensive to build. The computer can be used to calculate virtually all the possibilities, which, so long as calculations are not made for rods that stretch or bend permanently, is not nearly so time consuming as the calculation for a cracked pipe, and engineers can gain an unwarranted confidence in the validity of the resulting numbers. But the numbers actually represent the solution to the problem of the space-frame model in the computer and not that of the actual one under ice and snow. In particular, the computer model could have understated the weight on the roof or oversimplified the means by which the rods are interconnected. The means of connection is a detail of the design that is much more difficult to incorporate into a computer model than the lengths and strengths of the rods, yet it is precisely the detail that can transmit critical forces to the physical rods and cause them to bend out of shape.

In reanalyzing the Hartford Civic Center's structure after the collapse, investigators found that the principal cause of failure was inadequate bracing in the thirty-foot-long bars comprising the top of the space truss. These bars were being bent, and the one most severely bent relative to its strength folded under the exceptional load of snow and ice. When one bar bent, it could no longer function as it was designed to, and its share of the roof load was shifted to adjacent bars. Thus a chain reaction was set up and the entire frame quickly collapsed. The computer provided the answer to the question of how the accident happened because it was asked the right question explicitly and was provided with a model that could answer that question. Apparently, the original designers were so confident of their own oversimplified computer model (and that they had asked of it the proper questions) that when workmen questioned the large sag noticed in the new roof they were assured that it was behaving as it was supposed to.

Because the computer can make so many calculations so quickly, there is a tendency now to use it to design structures in which *every* part is of minimum weight and strength, thereby producing the most economical structure. This degree of optimization was not practical to expect when hand calculations were the norm, and designers generally settled for an admittedly overdesigned and thus a somewhat extravagant, if probably extra-safe, structure. However, by making every part as light and as highly stressed as possible, within applicable building code and factor of safety requirements, there is little room for error—in the computer's calculations, in the parts manufacturers' products, or in the construction workers' execution of the design. Thus computer-optimized structures may be marginally or least-safe designs, as the Hartford Civic Center roof proved to be.

The Electric Power Research Institute has been sponsoring a program to test the ability of structural analysis computer software to predict the behavior of large transmission towers, whose design poses problems not unlike a three-dimensional space-frame roof. A full-size giant tower has been constructed at the Transmission Line Mechanical Research Facility in Haslet, Texas, and the actual structure can be subjected to carefully controlled loads as the reaction of its various members is recorded. The results of such real-world tests were compared with computer predictions of the tower's behavior, and the computer software did not fare too well.

Computer predictions of structural behavior were within only sixty percent of the actual measured values only ninety-five percent of the time, while designers using the software generally expect an accuracy of at least twenty percent ninety-five percent of the time. Clearly, a tower designed with such uncertain software could be as unpredictable as the Hartford Civic Center roof. It is only the factor of safety that is applied to transmission towers that appears to have prevented any number of them from collapsing across the countryside.

In the absence of these disturbing tests, the success of towers designed by computer might have been used to argue that the factor of safety should be lowered. Conservative opposition to lowering a factor of safety would be hard to maintain for structures that had been experiencing no failures, and time, if nothing else, would wear down the opponents. But a lower factor of safety would invariably lead to a failure, which in turn would lead to the realization that the computer software was not analyzing the structure as accurately as was thought. But it would have been learning a lesson the hard way.

Thus, while the computer can be an almost indispensable partner in the design process, it can also be a source of overconfidence on the part of its human bosses. When used to crunch numbers for large but not especially innovative designs, the computer is not likely to mislead the experienced designer because he knows, from his and others' experience with similar structures, what questions to ask. If such structures have failed he will be particularly alert to the possibility of similar modes of failure in his structure. However, when the computer is relied upon for the design of innovative structures for which there is little experience of success, let alone failure, then it is as likely, perhaps more likely, for the computer to be mistaken as it was for a human engineer in the days of the slide rule. And as more complex structures are designed *because* it is believed that the computer can do what man cannot, then there is indeed an increased likelihood that structures will fail, for the further we stray from experience the less likely we are to think of all the right questions.

It is not only large computers that are cause for concern, and some critics have expressed the fear that a greater danger lies in the growing use of microcomputers. Since these machines and a plethora of software for them are so readily available and so inexpensive, there is concern that engineers will take on jobs that are at best on the fringes of their expertise. And being inexperienced in an area, they are less likely to be critical of a computer-generated design that would make no sense to an older engineer who would have developed a feel for the structure through the many calculations he had performed on his slide rule.

In his keynote address on the structural design process before the Twelfth Congress of the International Association for Bridge and Structural Engineering held in Vancouver in 1984, James G. MacGregor, chairman of the Canadian Concrete Code Committee, expressed concern about the role of computers in structural design practice because "changes have occurred so rapidly that the profession has yet to assess and allow for the implications of these changes." He went on to discuss the creation of the software that will be used for design:

> Because structural analysis and detailing programs are complex, the profession as a whole will use programs written by a few. These few will come from the ranks of the structural "analysts" . . . and not from the structural "designers." Generally speaking, their design and construction-site experience and background will tend to be limited. It is difficult to envision a mechanism for ensuring that the products of such a person will display the experience and intuition of a competent designer.
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> In the design office the reduction in computation time will free the engineer to spend more time in creative thought—*or* it will allow him to complete more work with less creative

> thought than today. Because the computer analysis is available it will be used. Because the answers are so precise there is a tendency to believe them implicitly. The increased volume of numerical work can become a substitute for assessing the true structural action of the building as a whole. Thus, the use of computers in design must be policed by knowledgeable and experienced designers who can rapidly evaluate the value of an answer and the practicality of a detail. More than ever before, the challenge to the profession and to educators is to develop designers who will be able to stand up to and reject or modify the results of a computer aided analysis and design.

The American Society of Civil Engineers considered the problem of "computer-extended expertise" such an important issue that it made it the subject of its 1984 Mead Prize competition for the best paper on the topic "Should the Computer be Registered?" The title is an allusion to the requirement that engineers be registered by state boards before they can be in charge of the design of structures whose failure could endanger life. Professional engineering licenses come only after a minimum period of engineering work with lesser responsibility and after passing a comprehensive examination in the area of one's expertise. Computers, while really no more than elaborate electronic slide rules and computation pads, enable anyone, professional engineer or not, to come up with a design for anything from a building to a sewer system that looks mighty impressive to the untrained eye. The announcement for the Mead Prize summarized the issue succinctly:

> Civil engineers have turned to the computer for increased speed, accuracy and productivity. However, do engineers run the risk of compromising the safety and welfare of the public? Many have predicted that the engineering failures of the future will be attributed to the use or misuse of comput-

> ers. Is it becoming easy to take on design work outside of the engineer's area of expertise simply because a software package is available? How can civil engineers guarantee the accuracy of the computer program and that the engineer is qualified to use it properly?

By throwing such questions out to its Associate Members, those generally young in experience if not in age and the only ones eligible to compete for the Mead Prize, the ASCE at the same time acknowledged and called to the attention of future professional engineers one of the most significant developments in the history of structural engineering.