What We Didn't Know

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One of the things that surprises you as you get older is the realization that, at various times in your life, something interesting was happening, and that at the time you were completely oblivious to its importance. This is about one such occurrence in my life.

Preamble

It's very clear from time to time that certain events are epochal. For my parents' generation, the Depression and World War II were certainly in this category, and Tom Brokaw has chronicled their feelings and accomplishments in The Greatest Generation. There is usually little doubt that an event such as the bombing of Pearl Harbor is one of those turning points in history, and one is awed when they occur -- usually with no little sense of dread, as the path ahead appears at that moment to be full of risk and uncertainty. Most of us abhor change, and these moments certainly signal major changes to come in our lives.

For my generation, there have been some events of this sort as well. Born in 1945, I experienced the civil rights marches, the Kennedys and King assassinations, the Cuban missile crisis, and several Viet Nam epiphanies. Each of these was in its own way a defining moment, and each of these was unmistakable as a turning point. They all had different weight and different import depending on your particular place, time, and orientation, but no one breezed by any of them.

In this article I want to focus on not a moment but an interval. So this is about a period or window of time, and as such, the impact and changes are not as obvious as any of the cataclysmic events called out above. It is about a small group of people, relatively speaking, and how their education changed a whole generation. It is a classic example of leverage. And for those of you reading from outside the United States, please note
that I take a strictly American perspective here.

What is new here is the notion that, at the time, and perhaps even today, we were not and are not aware of what is special about this group of people in this time period. Hence the title, "What we didn't know."

The Precipitator

On Oct. 4, 1957, the Soviet Union put into orbit a satellite called "Sputnik." It was reputedly only about the size of a basketball, weighed 184 pounds, and emitted beeps that could be monitored by shortwave radio. The world was shocked, and America's pre-eminence in the world of science and engineering took a huge public relations hit. And, to make matters worse, on Nov. 3 the Soviets launched the 1,121-pound Sputnik II, which contained a dog named Laika.¹ This occurred before Sputnik I spiraled to Earth and disintegrated, and its effect was profound. Just as the Nagasaki bomb detonating so shortly after Hiroshima, Laika showed that the Russians had the capability to do this regularly, and that it was not a one-shot deal. Even if the timing was calculated precisely to have this effect, the psychological perception transcended objective reality. We were at the height of the Cold War, and Russians had trumped us badly. For, if they could put a dog in space, was a monkey far behind? And, once a monkey was up there, well, you could figure it out. Nuclear missiles launched from space were now practically a reality. In military terms, the Russians had captured the ultimate "high ground," and our scientific, military, and political leadership figuratively and literally "went ballistic" over it.

At the time, I was twelve years old and in the seventh grade.

Actually, the seventh-and-a-half grade. Because of a special program in effect in the New York City public schools at the time, I would do the ninth grade the following year. Ninth grade was effectively the freshman year of high school. So Sputnik went up in my last year of elementary school.

Now Sputnik certainly was a barnburner, but it was also an event that triggered other things that turned out to be much more important for the country. Its legacy for John Kennedy included using the "missile gap" to help win the presidential election of 1960, and his subsequent engagement of the entire country in the space race of the 1960s, which culminated in our putting a man on the moon in 1969. In twelve short years we caught up and surpassed the Russians, much to the awe of the rest of the world. It was a great example of American "can do" spirit.

Of course, the physics required dated back to Newton, and the rocketry was, oddly enough, managed by veterans of Germany's V-2 days, at least if the popular myths are to be believed. But Sputnik changed a whole generation because of something more subtle -- it challenged our educational system to its roots.

Basically, what came out of Sputnik was that we Americans were behind because the Russians had a better educational system and funneled more of their "best and brightest" into science and engineering. While the
Americans were kings of mass producing consumer goods and raising the middle class's standard of living, the Russians were solving the really hard problems and getting ahead of us where it really mattered. Regardless of the reality of the situation, this perception was widely disseminated and accepted as the gospel truth. For a while, it seemed the whole country was in a dither over this. Something had to be done.

The Answer

In America, there is a time-honored solution to every new crisis. For those of you who are unclear on the concept, it is called "throwing money at the problem." That is, one can short-circuit a lot of dickering and consensus-building in a democratic society by using the free-enterprise system of rewards to influence behavior. While this method is not always the most efficient, and is almost always not pretty, it can be effective. It may attract a lot of the wrong kind of people -- those interested in making a fast buck, not solving the problem -- but it will also redirect a lot of the "right" kind of people.

Now, the people who needed influencing were NOT the young people who were my age. Sure, some of us would get caught up in the glamour, mystery, and intensity of science for the right reasons. Some of us might get interested out of some patriotic streak. But by and large, hormones dictated that for most of us -- I'm speaking for the adolescent males here --- the main "problematic" issues for the next few years revolved around the opposite sex. For the geeks among us, this loomed much larger and more daunting than getting to the moon. Seeing those attractive young girls hanging off athletes' shoulders was a motivator at least as powerful as atomic energy, believe me. Sputnik didn't change that.

No, the people who needed to be influenced were our parents. Because, in the late fifties and early sixties, there were the last vestigial remains of listening to your parents. The timing was perfect; within ten years, the rebelliousness of the sixties' generation would make parental influence de minimus. So the first bit of fortuitous timing was that we were literally the last generation who paid any attention when our parents spoke. It is hard to imagine the teenagers of the seventies and eighties being anything like those of the late fifties and early sixties. Think Father Knows Best, and a middle-class culture in which marijuana was something only jazz musicians smoked to get high.

Of course, we had no idea it could be any other way.

Why It Worked

So the great public relations campaign began. The unofficial message to the parents of America's youth ran something like this: "Science and engineering are a priority for the country." It was especially important for the campaign not to leave out the engineering part. This had (and still has) to do with the popular culture's beliefs about science and engineering. Science is hard; engineering is routine. Science is glamourous; engineering is grungy. Science is done by aristocratic philosopher kings; engineers are closer to blue-collar people. Only brilliant
people can aspire to science, whereas, with enough application, almost anyone can become an engineer. Stereotypes, each and every one. But think about it. If you were the nation's internal PR machine, trying to recruit the largest technological pool of young people you could, what would you do? Pitch just to the scientists? No, to catch as many fish as possible, you cast the net as widely as possible and point out that scientists and engineers are both needed. That way, if a potential scientist washes out along the way, you perhaps recapture an engineer. And for every parent who worries that perhaps his son is not quite M.D. material, the notion that dentistry is an honorable (and lucrative) profession is a great source of comfort.

Now, the people who were being pitched had lived through the Great Depression of the 1930s. Because of the subsequent intervention of WWII, and the fact that at this point in time (1957) they had school-aged children, we can infer that they had not gotten a lot of education themselves. (They couldn't go to college because of the Depression, they got taken out of action for the five war years in the early to mid-forties, and then got married and had kids as soon as the war was over. Many of them never got to benefit from their G.I. Bill of Rights.) So now they were lower middle class blue-collar workers, and their kids were getting ready for high school, and they were struggling economically. The pitch was brilliant: Get your kid to be a scientist or and engineer, and he will be set for life. "Economically, this is the ticket. Don't miss the boat. Make sure your kid doesn't wind up in the same bind you're in!"

The masculine pronoun is used advisedly. We hadn't yet figured out that women could be scientists and engineers. That would take ten more years and another revolution.

The rest of the pitch was even more persuasive: "We are going to make it easy on you. We are going to pump an incredible amount of money into educating these kids for free. Scholarships and fellowships will be abundant. Don't worry about the costs. If your kid has talent, the country will educate him, and he'll never have to worry about anything again."

Let me tell you, this was a great campaign, and it worked.

What was the reality? Well, as usual, good news and bad news. The country did pour a lot of money into many science and engineering programs. There was a lot of pump priming. I came out of the other end of this process in 1972 (oh yeah, it takes a long time if you get serious about it) with a Ph.D. in physics. My entire undergraduate and graduate studies were financed through a combination of summer and weekend earnings, scholarships, and fellowships. Aside from the opportunity cost of foregone wages during that time, I can honestly say that my entire education did not cost me (or my parents) a dime. I entered the job market entirely debt-free: Look ma, no student loans to pay off!

The bad news is that the lifetime meal ticket, as is true of all lifetime meal tickets, was an illusion at best. It may be hard to imagine that anyone could believe getting a bachelor's degree in engineering would secure economic well-being for a lifetime. But at the time, it seemed much more plausible and practical than any of the alternatives, and a lot of young
men (and later, young women) were pushed in this direction. And in one sense, it worked. For example, by the early seventies, we had physicists coming out of our ears, and a legitimate job crisis because supply had outstripped demand (at least in academia.) We forgot to stop priming the pump; as usual when the government is involved, fine-tuning is not remotely close to possible.

Of course, circa 1960 we had no clue that this could possibly happen. It was as improbable as putting a man on the moon.

**Why Was this Generation of Engineers Special?**

After this rather long prelude, I want to talk about ten years of engineering students, those from roughly 1960 to 1970. I entered engineering school (The Cooper Union) in 1962 and graduated with a Bachelor's Degree in Chemical Engineering in 1966, so I consider myself representative of this group. After lots of high school preparation, I entered college almost exactly five years after Sputnik went up. I was going to be an engineer.

I also want to talk about engineers, not scientists. I did my graduate work in physics and got my doctorate in experimental high-energy particle physics in 1972, so I can claim and consider myself both an engineer and a physicist. But while the physics and other sciences saw relatively little change during this decade, the engineering profession and engineering schools saw a lot of radical change.

We were on the cusp. We were the last generation to undergo some of the classical disciplines of engineering. This may have varied from school to school (Cooper was on the conservative side) but before 1960 things were one way, and after 1970 they were another way. During the sixties, it was a mix, and depending on which school you attended, you got a slightly different mix.

For example, my freshman class was one of the last classes to get formal training in engineering drafting and projective geometry. Drafting meant using dividers, compasses, and straightedges to do professional quality engineering drawings. Today you might know one subclass of these as blueprints. We had to understand top view, side view, and how to generate views at any arbitrary angle given these two. And my own special hell: We couldn't pass the course until we had done at least one India ink drawing on vellum paper. This was all part of the tradition of the engineer being just down the hall from the machine shop. You needed to be able to do drawings that communicated something meaningful to a machinist. It was the part of engineering that was "sleeves rolled up, loosen your tie." To be part of the team, you had to understand and be able to do engineering drawings, even though you wore a white shirt and tie and the machinist wore a blue-collar shirt and apron. In some sense,
you were going to be peers (at least for awhile), and learning to draw was part of the apprenticeship. The idea that you could become an engineer without being able to do "mechanical drawing" was a non-starter.

They laugh when I tell these stories today. But it was dead serious stuff back then. Imagine being able to ace calculus because you can do integration by parts to beat the band, but are in mortal fear of flunking out because that damn ink always runs underneath the straightedge before you can finish the bloody drawing.

**Computation**

But by far the biggest "cusp" experience had to do with computation. We were the generation that bridged the slide rule and the computer. Let me explain.

In the sixties, the pocket calculator was still Flash Gordon stuff. The HP-35, the first real pocket calculator for engineers, appeared on the scene in 1972. (What a coincidence -- just as I was finishing my Ph.D. Timing is everything!) The slide rule was instantly and irrevocably dead. But up until that point, slide rules were an engineering staple. Simply put, you did calculations on your slide rule. Using a computer to get everyday answers was simply not practical back then. Computers were batch-oriented, and to get answers, you had to write programs. In FORTRAN. It was just too much overhead for one-off work. Whereas today you might fire up Excel, back then you whipped out your slide rule.

Aside: the slide rule was sometimes called a "slip stick." We joked that we did our calculations with a "sly drool." We were very geeky.

You started to learn how to use the slide rule as a freshman in college, if not sooner. It was not just a matter of learning how to do it. You had to learn how to do it reliably, accurately, and fast. You used your slide rule to get answers on fifty-minute physics, chemistry, and engineering examinations. If you couldn't use this as a real tool, if you couldn't compute, fast, you would fall off by the side of the road. It was as bad as having the ink blot under the straightedge.

The instructors didn't cut you too much slack, either. Sometimes we would get some partial credit if we showed we understood the computation but screwed up the result; but ultimately we found that you didn't get enough credit for good grades if you didn't get the right answer. What a novel concept -- lots of credit for the right answer, not much for the wrong one. But, as one of our crusty old professors once remarked, "Engineers get paid for getting the right answers." By the way, did I mention that speed was important?

So, we practiced. Herman Bilenko, an upper-division electrical engineering student, ran a slide rule remediation club. We met at lunch, and he would give us problems and we would race to see who could get the right answer the fastest. As Dave Barry would say, I am not making this up.

**Getting to Know the Numbers by their First Names**
Now, for those of you who have never used a slide rule, I will point out that in most cases you are doing a computation with four or more factors in the numerator, divided by four or more factors in the denominator. The "answer" the slide rule gives you is something like "123." The decimal point location and the exponent (the "ten to the sixth power," for example) are up to you. This is a crucial point. To get a correct answer, you have to do two things right. First, you have to figure out where the decimal point goes in the final three-digit result based on the eight or more factors. Second, you have to be able to figure out, using rules of scientific notation, what the exponent of the final answer is going to be based on the exponents of all the factors. It was absurdly easy in these calculations to be "off by one" in either the exponent or the placement of the decimal point. So that for a correct answer of 1.23, it was almost always possible, through carelessness or misjudgment, to come up with an answer of 0.123 or 12.3. This is called in the profession "off by a factor of ten."

Consider this. A factor of ten is enormous. Apply it either way to your salary and see what I mean. Yet it is very, very easy, using a slide rule, to be off by a factor of ten. What this means is that for every calculation you did, you had to have some idea of what the answer should be BEFORE you did the calculation. You had to "know" that the answer should be around "one," so that if you "computed" that it was 0.123 or 12.3, you would know that you had made a mistake and go back and find it. This meant that you had to estimate the result beforehand. This was a survival skill. The people who never mastered it flunked out of engineering school, because it was just too easy to make a mistake. If you couldn't smell out a bad result, you were in big trouble.

Of course, this knowledge led to other interesting acquired behaviors. Most computations were multistaged, requiring that you plug an intermediate answer into another formula to get a secondary result, and then plug that in, and so on. So mistakes made early propagated, and if you got a completely absurd result at the end, it was a bear to backtrack all the way to the beginning. So we developed the habit of maniacally testing all of our intermediate results for reasonableness before going on. We became our own computational QA inspectors, not letting a computation proceed unless we were sure we were still in the ballpark. This was a great instinct to develop early in our careers.

Needless to say, as a by-product, we also got to be pretty good at computing things in our heads. None of us was equal to the legendary Feynman, but we all got to be pretty good. It was sometimes enough to make a liberal arts student's head spin. For us, it was just another acquired survival trait.

By the way, we often got asked about doing computations to only three significant digits -- the "123" mentioned above. Was that "good enough"? Well, it's one part in a thousand, roughly. Most experimental physical data is lucky to be within plus or minus one percent, or roughly ten times less accurate. So if you had three or four factors in the numerator and three or four factors in the denominator, each with at best one percent error, it was illusory to think that the calculated answer could be good to one part
in a thousand. Ergo, slide rules could be used for most calculations with few problems.

Of course, when computers came in, it all changed. Then calculations were done "numerically" by numerically iterating the equations -- replacing derivatives by finite differences, as it were. Then, because the result was obtained by cycling through thousands of steps, errors could accumulate insidiously. That's why computers have to have so much higher precision; you need lots of precision at each step to guard against accumulated error.

But in the end, the result can NEVER be MORE accurate than the input data. Many people have either never understood that, or lost sight of it over the years.

**So How About Those Computers?**

It is safe to assume that I think we lost a lot in terms of skills when we went from slide rules to pocket calculators. Years later I was amazed at how students would punch in numbers to their pocket calculators, come up with a patently ridiculous answer, and defend the answer based on the idea that "That's what the calculator says." The notion of an input mistake was somehow not part of the equation, nor was the idea of trying in some way to judge whether the answer made sense or not. How sad.

But, you say, no matter. Computers fixed all that.

Well, the hell they did. But let's not get off on that rant. What is more interesting is to talk about is how the last generation of slide rulers became the first generation of computer jocks. For during that ten years before the pocket calculator replaced the slide rule, computers arrived on campus, and those of us who could see the future knew there was a computer in it.

So we learned FORTRAN on an IBM 1620 class machine. I won't bore you with war stories. But we learned a lot about how to translate computations done by hand into computations done on a machine. And because the process was onerous to say the least, we reserved writing programs for something that really merited it, like a computation you had to do over and over again.

Even for those of us who took to "programming" like a fish takes to water, using "the computer" was a big pain in the butt. We discovered that these machines were notoriously picky about misplaced punctuation marks and inadvertent intrusions into column six. (Anything punched in column six on a FORTRAN statement card meant, "Tack this statement onto the previous one." It was the "continuation" field. Naturally, if you did this by accident, the FORTRAN compiler would burp unpleasantly.) It seemed to us that most of the time our programs were rejected for the most silly of reasons.

The reality was that we were being inconvenienced by batch processing. A single error would halt the entire process, and we had to fix these serially, one at a time. If you didn't get multiple "passes" at the machine per day,
debugging took a long, long time. So we learned to be precise, because, like it or not, the machine was unforgiving. We also learned to put in lots of diagnostic print statements, so that when things "went off into the weeds" we could detect when, where, and, hopefully, why. Above all, we became the original "defensive programmers." Once interactive terminals came, followed by personal computers, this style diminished in use. Not in importance, mind you, but in use.

We also made a discovery that would be remade over and over again for the next forty years. And that is that most college-level problems are "toy" problems, so your computer programs don't have to be very long or very good. And, ironically, we didn't write much code to handle errors on data input. After all, the computer was a tool to be used by professionals, meaning engineers. The idea that "civilians" would use a computer and need error checking on input was as improbable to us as a man walking on the moon.

Were we better computer users for having been slide rule jockeys? You bet we were. We were trained to suspect the result of every calculation, whether performed by man or beast (the computer was considered a beast). So there was no hypnotic trance induced by seeing results neatly printed out in rows on forms paper that had tractor hole punches on both sides.

No GIGO for us. We knew that the answer was probably wrong. Only after a lot of scrutiny were we willing to accept that the computer hadn't screwed it up this time. Like their pocket calculator brethren, we marveled at how many people would blindly accept a result just because "a computer" had printed it out. We knew that a person had written a program to obtain that result, and we all knew how easy it was to make a mistake writing a program. We had written enough of them ourselves to be painfully aware.

**Summary**

I will always remember my senior engineering thesis project. A team of us had to design an entire petrochemical refinery from scratch. We had a few weeks to do it, working day and night. Did we use a computer? No way. Not enough time to screw around with that. We slip-sticked that puppy until we were blue in the face, working the last thirty six hours straight and handing it in, bloody but unbowed, ten minutes under the deadline (this was back when there were deadlines, as in, "Not accepted for any reason after 10 a.m. on June 6.") And believe it or not, we all graduated, although interestingly enough, all of the team members did not get the same grade on the project. And nobody complained, either.

In the sixties there was a generation of engineers trained in both slide rules and computers. Those who went before never really adopted computers, and those who went after never really learned how to compute
by hand. But this group of young engineers got their most intensive engineering education working with both the tools of the previous generation and the tools of the next, at a time when the tools couldn't have been more different.

This, in turn, cultivated an entire behavioral culture toward engineering results. Among the tenets were the following:

1. Accept no answer just because you had computed it. Question everything. By the time we had gotten to computers, this principle had morphed its way to "trust no input data."

2. Break complex computations into reasonably-sized chunks, and check every intermediate result to avoid error propagation.

3. For both manual and computer calculations, figure out a way to debug your computation so that when you do generate a patently ridiculous result, you have a built-in way to sort it out.

These ideas were not abstractions; they were keys to survival. And from a pragmatic point of view, they became instincts that enabled survival in a cold, ruthless world of problem solving.

My theory is that this golden generation of engineers became the leaders of today's Silicon Valley colossus, and that we are now at risk as this generation approaches retirement age. We have bigger, faster, more powerful computers, and magnificent software running on them. But who is going to tell us when the answers are wrong?

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1 Male Soviet cosmonauts to this day have a tradition: The last act they perform before climbing into the ship is to "relieve themselves" on the wheel of the transport vehicle that brought them there. Apparently Laika was the one who inaugurated this tradition. If this story is not true, it ought to be.

2 *Father Knows Best* was an American television situation comedy of the day that presented a "typical American family," in which everyone was perfect and all problems were resolved in thirty minutes, less time out for commercial announcements.

3 The careful reader will note that this reinforces the abovementioned stereotypes. However, it was more common for physics students, for example, to migrate into engineering than the other way around. As you will see below, I was a curious exception to this general rule.

4 Strictly speaking, vellum is not paper. It is not parchment either; it is made from calfskin. But if I didn't say "vellum paper" no one would know what I was talking about.

5 Another antiquated American reference. Flash Gordon was what we had long before we had Luke Skywalker. In an interesting twist, his villainous arch-nemesis was Ming the Merciless instead of Darth Vader. Things were much less politically correct back then.

6 Also a graduate of Far Rockaway High School.