Thomas Jarvis **20 October 2013**

Making Students Comfortable Thinking About Things
(or)
In Defense of Knowing Stuff

Many students are afraid to actually solve physics problems because that would mean committing to an answer that might be wrong.

Students often arrive at the end of a calculation lacking confidence that the result of their problem-solving process connects in any substantial way to a homework question – or to an even more remote problem in the real world. Perhaps they've found a number, but they don't have faith in the path they took to find it; they are fearful that there is only one way to get to a solution, and that solving their set problem means remembering how to keep nineteen complicated steps in order and perform them as an incantation, rather than understanding how to quantify the world and to interpret relationships between those quantities.

Central to my goal as an educator is teaching students to overcome that doubt in their intellectual work, and to believe that science – this process of describing and predicting – works for them just as well as it does for professional scientists. I want to convince students that scientific thinking is not the providence only of women and men in lab coats, but rather a way that they can think more rigorously about any problem that provokes their curiosity – and I believe that if I succeed, far more problems will seem curious. I want to help prepare students who choose to pursue science careers, but I also want to show more broadly all my students that they are more capable of understanding the world than they may otherwise imagine.

Scientific thinking lets us rationalize and order the world. Sometimes this ability can be cultivated in uncertain students by – for example – developing their familiarity with back-of-the-envelope calculations that encourage them to approach the world quantitatively. I often use exercises like Fermi problems – where students use best-guess estimates and dimensional analysis to approximate the answers to difficult questions[1] – to establish their familiarity with the scales of physical phenomena. Fermi problems build students' confidence that they can solve problems that exist in a universe more complicated than a freshman physics course's sterile frictionless planes and massless pulleys.

Solving Fermi problems, of course, depends on actually knowing something. Not on knowing how many piano tuners live in Chicago, but on a set of landmark or guidestar facts that allow students to interpolate moderately accurate guesses for unknown quantities. It's not the least bit important that my students know the

---

[1] Enrico Fermi's canonical question for students was "*How many piano tuners are there in the city of Chicago?"* If that seems trivial or foolish, Fermi used the same problem-solving technique to estimate the yield of the Trinity nuclear test at Alamogordo by observing how far the blast wave scattered scraps of paper – his declassified personal account of the observation of the explosion is found in the U.S. National Archives, Record Group 227, OSRD-S1 Committee, Box 82 folder 6, "Trinity." He immediately got a guess within a factor of two, while the more precise measurement took weeks and substantial computing resources to assess.

2010 census counted 2,695,598 Chicagoans, but it's very useful that they know a typical large American city's population is on the order of 10^6, and that a very large one approaches 10^7. Anyone who has attended a good physics class would not be surprised to hear a physicist say that she thinks it's a good idea to know the population of Chicago, the speed of a commercial jet, the mass of a Helium nucleus, or the weight of an average brown dog. Understanding the relative scales of things and events in the universe is inseparably tied to understanding what they mean and how they work.

Yet many educated people are increasingly hostile to the idea that there is usefulness in knowing such facts. Many assert that recalling memorized data is of little value, and that synthesis and analysis are the skills higher education ought to teach. They argue that it's foolish to know that the proton mass is about 2×10^3 times that of the electron[2], and that bothering to learn this is a waste – as though learning were a zero sum game, and knowing that number prevents a student from learning how to do something useful with it[3]. Indeed, it seems likely that the opposite is true, and that knowing how to access information without internalizing it is very different from knowing that information itself – consider J. Kassier's work showing that instant access to compiled or derivative data may negatively impact medical education.

It is often argued that one can rely on ubiquitous information technology to find that number to essentially arbitrary precision almost instantaneously. But a student who knows that a proton is about two thousand times more massive than an electron intuitively understands the Born-Oppenheimer Approximation separating nuclear and electronic motion in molecules. She has already learned that an anonymous heavy mass sliding around on a freshman physics lab's frictionless surface is deflected very little in collisions with a far lighter object, and she will naturally connect that concept to the proton/electron mass ratio. A student's ability to synthesize new ideas after finishing school will depend on knowing the concepts she's putting together – perhaps not knowing a particular number, but knowing about a relationship, or knowing to look for some very particular information. The notion that a student need only learn to synthesize or analyze some short, bullet-pointed list of data is rather absurd outside of a very didactic formal education.

Students frequently complain that being asked to solve a problem with no resources other than a pencil and paper is absurd, that in the proverbial real world that is so often featured in so many student complaints they could simply Google the problem to find its solution. These students are already confident in their real proficiency – navigating a noisy stream of search results to find a solution to some problem, learning the bare minimum necessary to implement it,

---

[2] It was a Russian physicist who told me it ought to be easy for me, a quasi-Texan, to remember that ratio to four significant figures because 1836 was also the year of the Battle of the Alamo, a date that he was sure I would know.

[3] Indeed, it seems increasingly likely that the opposite is true, and that knowing how to access information without internalizing it is very different from actually knowing that information – cf. N. Doidge's *The Brain that Changes Itself*, a popular book on neuroplasticity intended for a lay audience.

then moving on to something else. It's a valuable skill to have if a person can turn it on and off, but it would be useless for solving any question that wasn't easily posed, commonplace, and already completely solved. The kinds of questions that the best science education prepares a student to answer are those that he or she would not otherwise even know how to ask. Cultivating an ability to solve trivial problems ought not to be the goal of higher education.

Too frequently, the response to the *Just Google It* contingent is to make vague, eschatological threats about what will happen the day that Google unexpectedly isn't there anymore. It's an absurd counter-argument – it's unlikely that one needs to know subatomic rest masses to ensure survival in a Mad Max, postdiluvian world[4]. Ted Gray and Jerry Glynn wrote in their guide to Mathematica that worrying that your kid faces certain death after the power goes out because she can't remember the trick for factoring polynomials is absurd if you haven't also made sure she knows how to catch, kill, clean, and cook a wild rabbit.

But there is something valuable about knowing that number, and it has little to do with surviving a meteor strike. It's about reducing a kind of mental friction that occurs when working to create something. I can retrieve that ratio or nearly any other tabulated physical constant datum awfully quickly with the phone in my back pocket. But anyone who has worked at a chalkboard with a colleague and felt the hair start to stand up on the back of her neck as intuition alerts her that she is on the edge of a genuinely new insight knows the tenuousness of that moment. That liminal, creative problem-solving state breaks apart tragically quickly when she reaches for her phone.

If we can stomach another questionable analogy, we could consider facts as vocabulary and the ability to manipulate them according to certain rules as a grammar. Both are needed to speak the language – it's true you can always check a dictionary for a word you need, but it makes you a dreadful conversationalist. In math and science, that fluency is the ability not to divagate from a derivation or proof by losing momentum in the high friction sections[5] that often derail a student's continuous, present tense understanding of a lecture. When a student falls off a lecture's pace, he or she starts to try to record and its content in a step-wise, rather than continuous process, translating symbols and concepts one at a time, line-by-line in his note. Fluency – obviating the need to consult some dictionary or look-up table, whether mental or actual – keeps a student present in the lecture as conventional fluency would in a conversation. Without scientific and mathematical fluency, that lecture may otherwise deteriorate into an expensive and inelegant way for a student to reproduce the instructor's notes to pray to comprehend later. David Foster Wallace wrote in a

---

[4] This is the rhetorical device known as understatement.

[5] Again, without any expertise in cognitive science and pedagogy, we're forced to rely on analogy to describe these familiar but difficult to name aspects of scientific education.

pamphlet (as he insisted on calling it) about Cantor and transfinite numbers[6] that a novice student often feels as though the wall of intimidating mathematical symbols on a page or chalkboard is a barrier erected to prevent him from understanding what must surely be quite simple in the absence of this artificial obstacle. But upon developing what I have here called fluency a student comes to prefer this symbology because it abbreviates what would otherwise slow down her digestion of the mathematical content, and mitigates the friction that would eventually drag her to a halt[7]. Knowing what is meant by an outer product glyph permits a student to avoid laboring through a high friction passage of subscript heavy algebra because he already understands the concept it stands for, and will help him to stay in the mental frame necessary to continue to understand what he reads.

Perhaps this hostility to knowing things arises because those who object mistakenly believe that we argue for knowing only because it obviates the need to look up some particular piece of information. And there is certainly value in removing this drag force, but this objection is still misguided. It is made by people who have confused knowing with memorizing – and knowing a fact seems to me very different from memorizing one.

The very first trick I learned teaching physics is to ask students who come to office hours with a problem they say is unsolvable to write it out on a blank chalkboard for us to consider – without looking at their notes. There is no reason whatsoever to memorize a physics exercise, of course, and asking any student to do so would be an inane waste of time. Rather, what I want to see is that they have fought with the problem hard enough to develop expertise in its parts. This happens spontaneously, naturally, and it is a miniature version of the kind of transformation that a physics education can effect on a person studying the subject. As he or she tries to understand it, the problem embeds in the student's memory, not in the way that one memorizes a phone number by rote, but in the way that one can describe how she gets to work in the morning. I don't expect my students to recall a particular differential equation. Instead, I want to develop their fluency until they think *there's a stretchy rubber band tied to this wooden block*, and that makes them think *restoring force*, and then that makes them think *linear for small perturbations*. I want to hear them explain the problem to me, saying "something like a term proportional to $-a(x-x_0)$, I don't remember the coefficient, but it doesn't matter."

Brad Leithauser writes that his mentor Joseph Brodsky – a poet persecuted, imprisoned, and exiled from the Soviet Union, who would later be named the US Poet Laureate and win a Nobel Prize in literature – set his students about a thousand lines of poetry to commit to memory each semester, against the

---

[6] Intended for a lay audience, more or less. I largely agree with Rudy Rucker's review (*Science,* 16 January 2004: Vol. 303 no. 5656 (313-314) – it starts off with a pleasant and awfully likable authorial voice but starts to feel panicked and desperate as DFW approaches the crux of his topic.

[7] Howard Moss's poem "Einstein's Bathrobe" scrapes around the edges of how strange this phenomenon of abstraction is, especially explicitly with "From signs Phoenicians scratched into the sand\With sticks he drew the contraries of space."

possibility that they might need some particular verse later in their lives[8]. After Brodsky was released from the gulag – as a young man he was tried in secret for social parasitism and sentenced to a labor camp in the Russian arctic[9] – his friends said that he had never been as happy as he was above the Arctic Circle, where he learned poems for his only entertainment. There is something superstitious about the way these poets write about learning poems – Leithauser fancifully borrows the language but not the rigor of anatomical science, writing that there is a process of internalization whereby a reader commits poems into her or his body itself *(well)*, into the brain chemistry *(quite severely abusing medical science now)*, and even into the blood *(certainly not)*. But these are poets; theirs is a fantastical way of thinking, and it is not at all inappropriate for poets to entertain such notions.

As scientific educators we are interested in something less mystical and a little bit more smudged chalkboard-centric, and we don't entertain any such notions about altering human blood chemistry with poems. I've spent a substantial amount of time removing the iron bearing heme groups from hemoglobin and replacing them with chlorophyllin – changing the chemical information that blood could carry, if you will – and it's not a terribly poetic line of work. But there is a transformation in the way we think that occurs during our scientific education. I can clearly remember the very first time I realized that my brain was starting to work differently, when I had developed sufficient fluency to speak in a mathematical language – I was standing outside Phillips Hall on the campus of the University of North Carolina, discussing a quiz on vector calculus with a fellow student, and I began writing in the air with my finger as though we were standing at a blackboard. It took no extra mental effort to do so. Certainly neither of us could look at the empty spaces in the air where my fingers had been a few moments before and see what information they ostensibly contained, but this is exactly what we did, and both of us were able to point to any of those empty spaces and imply manipulation of terms that no one had actually written on a blackboard that didn't exist. I'm not going to offer a poetic soliloquy about physically internalizing that mathematical fluency, or (further) wave my hands in some fantastical way while ascribing a mystic quality to the process, but there is nonetheless this clear and real change in how the mind manipulates mathematical and scientific ideas that occurs with enough – sometimes grueling – practice.

That change is never so noticeable as in those fragile moments when one is worried about interrupting the process of creating a new idea – it's the opposite of the undergraduate's fear of his answer and his disbelief in the reality of his results; the trained scientist believes in the rigor of her creative process, and is terrified of any interruption that will disrupt that lucid instant of invention. There is a sense of the discovery of a previously unanticipated connection between unrelated ideas that is lost to people who believe that they can interrupt or avert

---

[8] Brad Leithauser, "Why We Should Memorize," The New Yorker, January 25, 2013.

[9] Robert D. McFadden, "Joseph Brodsky, Exiled Poet Who Won Nobel, Dies at 55," New York Times, January 29, 1996

that mental process to look elsewhere – to Google – for the next step, rather than relying on the honed edge of their own understanding. The ability to maintain that precarious mental state and reliably find the next few unknown steps depends upon the cognitive changes that the best scientific education produces.

A professor who had an enormous impact on me during my graduate education spent a lot of time in his lectures and seminars, and indeed, quite a lot of time during other people's seminars as well, reminding graduate students – rather energetically – that we already knew enough to create new things. He never hectored students when teaching, but he would mutter to them (paradoxically, at some incredible volume) something like 'You already know how this works,' and could suggest with an abbreviated chalk scribble how the physics of some optical process was no different than the precession of a spinning top.

That professor had built a high resolution Raman spectrometer to analyze Deuterium and Tritium sources his research group was using in a experimentally heroic attempt to measure the neutrino rest mass, but while I was at the University of Texas he found a number of new, radically different problems to solve with this device. Working with a small group of colleagues he built a cheap, miniaturized version of this spectrometer, and set about showing how a device built as a laboratory tool to check isotopic purity of his samples could be used to detect certain kinds of cancer or infant lactose intolerance by analyzing gases exhaled in our breath, to understand oxygen dead zones in the Gulf of Mexico, and even perhaps to predict earthquakes based on undersea plumes of dissolved Carbon Dioxide. None of these applications of a new scientific apparatus would have occurred without that moment of connection between some odd facts or concepts rattling around in his memory.

There are awfully good reasons to know things – to really know them. I once drove from a very small town to another very small town four states away with a memorized set of directions listing something like twenty turns I had to make, and it made for such an awful afternoon that I'm still talking about it now, years later. If I had actually known how to get where I wanted, instead of memorizing those directions – this was in the 1990's, before we had paper or pens – I would have gotten to the same place but in an inarguably better way. The goal of any scientific educator ought to be to be able to ask her students a question they've never heard before, and have them realize that they have already learned how to get to an answer.