Is a traditional engineering education useful in other fields?

Anindya Chatterjee
Mechanical Engineering
IIT Kanpur
Email: anindya100@gmail.com

November 3, 2018

Introduction

A very large number of young Indians today want to study engineering. These people are not usually interested in being engineers. They simply believe that after an engineering education they have a better chance at getting decent jobs. A bit disquietingly for engineering professors, most of those jobs are not in engineering. I admit that some of those jobs do use skills developed in the study of subjects like computer science. But, closer to my own academic home, why are mechanical engineers hired regularly for such jobs?

Cynics (including some friends) may say that hiring companies like the "brand value" of IIT students which lets them charge higher fees from clients; or that the pool of engineering students is so large that finding a few smart ones in there is statistically unavoidable; or that these jobs are inherently so easy that almost anybody could do them; or, perhaps, that all that these jobs require beyond minimal presentability[1] is an ability to follow simple instructions, well inculcated in an engineering education. But this depressing view surely cannot be all there is. Surely there are *some* students who are doing well, and *some* companies who are coming back to hire because their experience with our graduates was genuinely rewarding?

In this article I discuss why, at least in the best possible case, traditional engineering students might be valued even in non-engineering roles; and what that might imply for education in general. I think such ideas should enter our thinking, and perhaps affect our teaching of all kinds of subjects, as we train students for a post-internet, crowded, resource-constrained India.

Initial observations

Let me begin with some seemingly unrelated observations. I believe they can be connected up, and will try to do so in the remainder of the article.

A generation of Indian IT workers found jobs in the internet era by displacing westerners. The tasks that carried our big IT companies to success were originally carried out by graduates of our higher tier colleges, and then by graduates of less famous colleges. Salaries for these jobs have not gone up much[2]. There seems to be an endless supply of young Indians willing to work harder for less money. Some companies are trying to get rid of aging employees, presumably to induct cheaper, quicker, and younger employees[3]. Some IT-related tasks are also now being taken over by computers, which are the hardest-working and lowest-paid workers of all.

The next generation may need a new paradigm. For example, India[4] has more than 650 million people below age 25. This plain number predicts hard times ahead for those entering the workforce today. New opportunities we cannot foresee now will surely emerge over time, and the students of today will profit from them if they have the right skills. Which skills might those be?

---

[1] Brushing teeth, tying shoelaces, combing hair, etc.
[2] https://timesofindia.indiatimes.com/business/india-business/it-companies-formed-cartel-to-keep-entry-level-salary-low-former-infosys-boss/articleshow/62267791.cms
[3] https://timesofindia.indiatimes.com/city/bengaluru/techms-retirement-age-lowered-to-55/articleshow/66036267.cms
[4] https://en.wikipedia.org/wiki/Demographics_of_India as on October 3, 2018.

Today, as mentioned above, many undergraduates from IITs take up jobs outside traditional or core engineering (outside steel, cars, turbines, oil and gas, power, etc.; and inside business consulting, data sciences, or other areas). I discuss two aspects of the story here.

One, there are not enough core companies coming to hire from IITs, perhaps because

a) They offer jobs that students of less-reputed colleges do quite well for less money, and
b) There simply are not enough decent core engineering jobs to go around[5]. For example, a student from a college in Odisha tells me that the IT services company Accenture hired 160 students from her college this year while the metal company Hindalco, located close to her college, typically hires 2 or 3 per year.

Two, many undergraduate students of the IITs are hired by companies that seem to ignore their college grades, and set greater faith in JEE success. But these students are not hired directly after the JEE. Some may cynically think the JEE success shows they are smart to begin with, and four years of college (regardless of subject) provides a bit of maturity. Surely we must ask if there is something more? Could there be transferable skills from the IITs' engineering training that employers find useful?

When I was a teaching assistant in the US, many American students told me they had trouble with word problems, which I found a bit odd. It was their language, after all. I realized only later that trouble with word problems is widespread. For example, a Google search (October 3, 2018) for

(trouble OR difficulty) AND "word problems"

returned more than 2.3 million results. Many articles on the topic talk about teaching children how to deal with words that lead to desired calculations (subtraction, division, etc.). I think the matter goes beyond children's arithmetic. A bigger issue, cultural or psychological, seems involved.

I recall a conversation with a friend, a chemistry PhD, working with other PhDs, doing something scientific with mass spectrometers. She said (more or less), "You cannot expect all colleagues to be generally smart outside their specializations. The best you can hope for is that most of them understand their specific domain, know if something is wrong, and have some idea about how to begin troubleshooting." How is high competence within a specialization *not* linked with general smartness? Are specialization-based skills non-transferable?

A final story. When I was graduating from college, one of our teachers[6] told us, "With a bit of mechanical and a bit of electrical engineering, you will do well." I first thought this was a matter of being interdisciplinary, or maybe that knowing *two* things as opposed to *one* thing gives you an advantage at work. But there may be a wider and more subtle implication.

Perhaps it is a matter of crossing bridges between distinct worlds, back and forth, repeatedly and at will. This article is about such crossings.

Mathematics and physics as intertwined parallel worlds

The remarkable connection between mathematics and physics has been widely noted earlier[7]. I will not try to discuss here the fundamental truths of nature. Let us just say that simplified physics and applied mathematics play important roles in engineering.

[5] Wikipedia says there are presently 23 IITs and 31 NITs. There are many other good engineering colleges as well.
[6] The much liked Prof. P. K. Mishra, builder and modifier of interesting machines and devices.
[7] The reader might begin with E.P. Wigner, "The unreasonable effectiveness of mathematics in the natural sciences," *Communications on Pure and Applied Mathematics*, Vol. XIII, pp. 001-14, 1960.

Many of us have heard or even said the following: (1) mathematics is a *tool*, and our goal is to understand the physics, and (2) when we do mathematics, we should keep track of the *physical interpretation* of our calculations.

I suggest otherwise. I now think that mathematics and physics can be viewed usefully, if abstractly, as intertwined but distinct worlds with occasional bridges or connecting passages. A cartoon is sketched below (figure 1). Think of red as the physical world, and blue as mathematics. Some bridges have been found, and we can mentally cross over from red to blue and back, e.g., between points A and B, and between C and D.

I now introduce the idea of a physical construct. Consider the following:

A uniform straight perfectly elastic rod of circular cross section.

Engineers find such lines familiar. The key point here is that no such rod exists. The rod is not an object. It is an *idea*. This rod is an example of a physical construct. We can say many precise and true things about this rod. Several but perhaps not all of those things will hold accurately for a *real*, fairly straight, and close to uniform steel rod that might be lying in your lab.

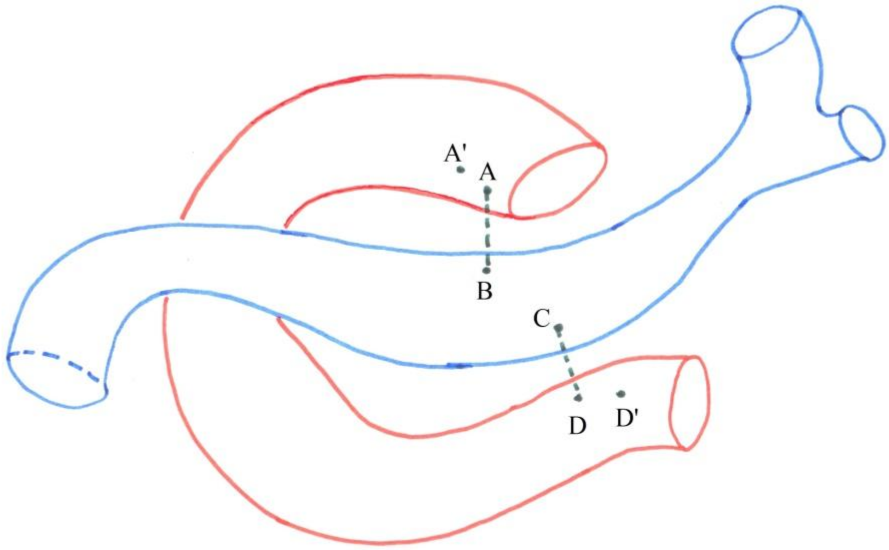

Figure 1. Distinct, intertwined worlds, with some known crossing points.

The above construct is useful because there do exist many *nonideal* rods that resemble it. The behavior of the construct, deduced using thought experiments or equations, may closely match the behaviors of those nonideal rods. The construct also ignores attributes which are irrelevant in the present context, like the weight of the rod, its color, and so on.

Many such constructs are familiar. An elastic sphere. A perfect conductor. An opaque thin sheet. An incompressible fluid. A rigid body. An inextensible string. Some constructs are more subtle, like a curved rod wherein, upon further bending, plane cross sections remain plane[8].

There are interconnected hierarchies of constructs in engineering, whose aim is to help in system modeling, whose aim in turn is simple approximation for practical results. Simplifying constructs appear in other subjects too, but they pervade engineering.

[8] In fact, plane sections do not remain plane. They bend and warp slightly. The next level up, treating the curved rod as perfectly elastic but allowing plane sections to bend and warp, one computes tiny corrections to the simpler theory. Yet another level up, one allows small bits of inelastic yielding. And so on, never quite reaching the truth.

The relationship between models and constructs is admittedly a bit fuzzy. There is overlap between them. A system model includes an assembly of constructs. We assemble constructs in ways we like to develop new models for new systems. An ability to think using constructs helps in good physical system modeling. A good system model that finds wide usage becomes a useful construct in its own right. A model has a practical goal, tied to a system. The goal of a construct is precise mapping between useful places in the mathematical and physical worlds. Some constructs are useful models, and vice versa. Models can be good or bad, depending on whether we can use their predictions to do useful things in the physical world. Constructs are precise, and can be more useful or less useful in modeling, but are not inherently good or bad.

The *precision* of the construct's mapping between the physical and mathematical worlds does not mean the two ends of the bridge are identical. For example, in class, I might hold my arms up and turn my wrists as I ask a student, "If I bend the rod into a semicircle first and then twist it out of plane, thus, which way will the midpoint move?" And the student retreats into an attempted physical thought experiment, perhaps looks into the middle distance and moves his or her own arms and wrists, thinks for a while, and proposes an answer (which could be right or wrong, but it surely did not emerge from solving equations). Even while a construct is amenable to precise mathematical investigation, it somehow still remains in the physical world. Perhaps a good way to say it is that constructs and their governing equations are processed differently within our brains.

Returning to figure 1, as engineers, we may need to go from A' to D'.

Perhaps the corresponding task is to find ways to convert candidate building materials into finished houses. The journey, if tried purely in the physical world, may be hard or impossible[9]. But with approximations, treating the real A' as close to some construct A, and the real D' as close to come construct D; and with bridges AB and CD; and going from B to C within mathematics, we may easily find a good design. This would be a mundane application of engineering.

But let us note key points in the sequence above. A and D are physical constructs. The bridges AB and CD are well defined. From A to B, we write equations that govern construct A. Solving those equations gives us results C that are precisely relevant to D. Finally, and here mathematics can help no more, only if our models are good will the *inaccessible and fuzzy truth* about D' be close to the *precisely knowable truth* about D.

The above abstract outline of an engineering activity demonstrates three things.

First, through approximations we nudge our actual physical problems towards useful physical constructs. In figure 1, a useful construct is a place where we know a bridge that leads somewhere useful, namely a good model. *Lack of approximation* is not a goal of engineering the way it is in, say, physics. Proposing, testing, making allowances for approximations, and going back from time to time to check for continuing relevance of our models, are all key parts of what engineers do. Purposeful approximation and simple representation with sensitivity to consequences may be a transferable skill that non-engineering employers like.

Second, going back and forth is worthwhile only if distances in the other world are shorter[10]. In the best case within figure 1, the distance between B and C would be *zero*. My favorite example to students of such a convergence is the Laplace equation, which governs among other things the shapes of nearly flat soap films *and* purely in-plane heat conduction in thin sheets. The two physical problems seem to have nothing in common. But, to one who knows the bridges, *they do.* One can in principle use a wire loop and soapy water to calculate temperatures in a plate. To thrive on this interconnectedness of things in a more general setting, one must have emotional comfort with the correct bridges, and with crossings back and forth. Such comfort is a useful trait, perhaps, to a non-engineering employer.

Third, in order to get better at exploiting this analogy (figure 1) for approximate analyses, for unexpected insights, and for labor saving shortcuts, the designer-analyst must grow in two distinct directions. (a) One is in

---

[9] Many experiments, much trial and error, many failures, time and money lost, injuries sustained, …

[10] Occasionally, I manage to use physical reasoning to shorten a mathematical calculation. This pleases my students, if I point out what just happened. Usually, though, we go from physics over to mathematics to save time and effort.

knowing many useful constructs and being confident about building new ones. (b) The other is in knowing many useful bridges and being confident about building new ones. These two, in my opinion, are truly useful transferable skills, and a good engineering education does a fair job of developing them.

Some people say engineers are good at modeling, and perhaps they are. I close this section by suggesting that comfort and practice with working with physical constructs is a separate useful skill, one that engages different parts of the brain.

Words and pictures

Musing further on figure 1, it seems that an engineering education offers other chances to cross back and forth between psychologically distinct worlds, or engaging different parts of the brain. I turn now to word descriptions versus sketches.

Often, a sketch *really* helps to understand a problem, points to a solution strategy, or presents the solution itself. In my exam-setting experience, typical students find it harder to solve problems presented without accompanying sketches. People tutoring struggling students often say, “Make a sketch”.

Engineering students get much practice in this arena.

“Consider a counter-flow heat exchanger,” says one professor, and sketches two pipes, adds arrows, marks in hot and cold and in and out and so on, and the student gets some practice.

“A simply supported beam has a point load at $0.6L$,” says another professor, and draws a longish narrow rectangle, adds roller or pin supports, and an arrow for the load a little to the right of center.

And so it goes on. A dam wall, a fan with three twisted blades, flow in a bent pipe. A car moving on a circular track with a child throwing an orange out of a window. An airplane coming out of a dive. A graph showing speed against time, or pressure against depth, or current density against radius.

Signal flow graphs, showing inputs to a system, its response coming out along one arrow, some information being fed back along another arrow to modify the input.

An imaginary box drawn with dashed lines inside a fluid flow domain, to start analysis of what goes in and what comes out. An imaginary plane that cuts through a stressed body, passing through some internal point of interest, with arrows to show forces from one part of the body on the other.

It is not the *subject* of the sketch, but the *comfort with making sketches* for many different things, that is the key transferable skill. I imagine it is like knowing two languages from very different cultures, with an enrichment in thinking that is hard to explain to one who does not know such disparate things.

A more general view of worlds and crossings

I now tentatively propose a more loosely defined picture of two parallel worlds that a usefully-educated person in the modern world may need to negotiate.

One is the world we live in and the words we use to describe it. The other world is a medium of alternative depiction, which I think of as paper. On this paper we write or draw symbols which we manipulate and from which we extract insights, understanding, or results. The symbols could be pictures, or sketches, or simplifying constructs, or flow diagrams, or mathematical formulas and equations, or numbers, or computing algorithms.

One useful skill for a person in modern workplaces is a high comfort level with passing back and forth between these two worlds. Most people are not, in fact, naturally very good at such crossings. Skill with such crossings can probably be developed with purposeful practice. And finally, a broad and core engineering education, perhaps *unintentionally*, offers excellent and frequent practice in such crossings.

And this may be why, though teachers in the IIT system may wonder what the point is of their technical subjects when students just go off to do non-engineering jobs, those same students thrive in such non-engineering jobs.

I suggest that at its best, engineering offers such indirect training better than many other fields. Students of the arts and humanities do not learn much about manipulating equations. Mathematicians study equations but rarely aim to connect with the outside world. Economists come a little close in that they study idealized models of behavior and draw mathematical conclusions therefrom, but they do not enjoy the engineer's luxury of simple experiments with many systems whose properties remain invariant across such experimentation. Computer scientists may develop great skill in computational or data based treatment of complex models, but the models often come from other fields. Physicists study deep truths about nature, but not many different approximations of mundane things. Chemists have a specialized way of looking at even common things, like water: a chemist's view of water lies in atoms and bonds and energies, and does not usually intersect with key aspects of living with water like transparency, coolness, floating, pumping, heating, splashing … all of which an engineer *does* think about due to various applications.

Freedom from constraints

By freedom from constraints, I do not mean the state of not having constraints. I mean a situation where *having* constraints frees up one's creative mind in some unexpected way. A look on the web shows several people discussing the issue. The idea is not novel. I merely suggest that it may have a role in traditional engineering education as well. I begin with general examples below, and then discuss engineering.

Imagine a professor like me visiting a high school and talking to the students. A plain invitation to "talk to the students" may leave me unsure of how to begin or where to go. But an invitation to talk about mechanical engineering in the modern world, or the role of calculus in daily life, or why grades matter, or how to prepare for a job interview, or any such *constrained* invitation would free me up.

I recall from my school days a class in English, where we were invited to write a short story. Many of us did not know where to begin, and our efforts were boring even to us. On another day, we were asked to write a story that began with the line, "Suddenly, the door opened, and a man ran out." Some interesting stories emerged. The constraint was liberating.

More recently, a friend's college-going daughter was asked to compose a piece of electronic music that was *inspired by a painting*. At first glance, this assignment employs both crossing between worlds and the gains from constraints in creative work; and that is surely a good thing. However, compared to engineering problems, I think there is notably little clarity in this assignment on what makes a correct answer. Perhaps correct and incorrect are less meaningful in the liberal arts than in the more mundane pursuits of engineering?

In comparison, typical engineering projects and contests can leave reasonable room for creative thinking within various constraints, with clearer criteria for judging what is correct or which entry is best. For example, contests for building model cars or airplanes may specify size, weight, fuel type, engine size, and payload; and require highest possible speed, or mileage, or maneuverability.

An old civil engineer I once met had run a small design firm for many years. A creative person, he won many design contests for low cost bridges over challenging locations (e.g., over gorges) or for somewhat offbeat use (pedestrian traffic near remote tourist locations, etc.). He told me that the location, loads, and materials were known (constraints). Anyone in the business merely had to glance at a competitor's drawings once, and could then steal the key idea; and so secrecy was a part of the job as well. It strikes me now that he was working in quite a constrained environment, and yet with room for creative design.

On routine engineering jobs, too, there are constraints. An automotive engineer working on noise issues is not given an unconstrained task, as in “go find me a quiet car”. The task is more constrained, e.g., “make *this car* quieter, and don’t change too many things”.

I am not aware of a similarly wide range of constrained design tasks in mathematics, economics, the sciences, or other subjects. Obviously these subjects can and do have great challenges of their own. It is merely a specific flavor of constrained design challenge that I am commenting on. Perhaps an undercurrent in engineering classroom discussions, at least in some courses, does reflect such constraints. I think there are gains from such thinking being a part of one’s worldview.

Implications for the classroom

Gainful employment cannot be the direct aim of all education. The world has too many college graduates anyway, with not enough jobs needing those specific college educations. However, if college graduates are able to transfer useful skills to other areas of work, then they may find better livelihoods.

Here I am interested in two specific transferable skills.

The first skill is one of using simplifying constructs, finding bridges, and generally being comfortable crossing back and forth between the world of words and the world of symbols and calculations.

The second skill is an emotional willingness to repeatedly engage in design activities, or solution seeking, under fairly arbitrary external constraints. I refer not to specific design specializations, but rather a sort of default state of mind.

Let us consider the first skill, namely crossing between worlds.

I tried an experiment with a 12 year old girl. I said, “A glass walled water tank is four feet long, one foot wide, one and a half feet tall, and two-thirds full. A ball is floating on the water. Sketch this system. Take two minutes.” She thought briefly, and made a sketch. I asked her if she liked the exercise. She said she found it interesting to take the facts coming in one by one, adding them sequentially to a picture forming in her head, modifying the picture as necessary, forming the final object in her imagination, thinking about the angle of view, and then executing the sketch. From my own school education, I remember no such exercises.

I now imagine a class where one child is given a picture[11] that the rest of the class does not see, and she writes a description of it; and the students in the class, based on that description, make individual sketches. And finally, in a friendly group setting moderated by the teacher, feedback is given to individual sketchers (“you missed this part of the description”) and to the writer of the description (“you missed this part of the picture”). A symmetrical exercise would be one where a picture was shown to the entire class, and every child would be asked to write a description of it with the intention that the description could be used by someone to make a sketch that resembles the original picture.

In technical colleges, when a subject is first introduced, sketches can be used to speed things up and aid understanding. But later, the instructor may explain the difficulty faced by students in drawing sketches based on descriptions, and give relatively simpler problems without accompanying diagrams, for skill building. The aim is not to solve small problems. The aim is to break the mental barriers between reading and sketching.

Let us now, more briefly, consider my second proposed transferable skill of design under fairly arbitrary constraints.

[11] For example, a view through a door into a room, with a table and two chairs in there, and a potted plant in the far corner. Or six cups on a table, lined up such that the nearest one obstructs half of the next one, and that one obstructs half of the next one, and so on. The verbal and artistic challenges should be balanced, since the goal is to develop comfort with crossing between domains.

While I think some sense of the idea may be communicated during usual coursework, perhaps courses in design need to be studied by engineering professors and schoolteachers alike to see what can be brought into regular classrooms so that many students of varied subjects can learn to think in such ways. Surely our usual mode of passing on information in a fixed sequence does not help much in this direction.

For high school students, I tentatively suggest a group design game format with random selections of components and constraints from a large set. For example, one random realization of such a game might be to use at least four from “string, battery, fan, water, magnet, wheel” in a device with application to “the household, children’s education, or sustainability”. The teacher’s role would be to moderate discussions as students evolve ways of thinking about such loosely constrained problems, and to develop value systems for assessing the relative creative merits of different solutions.

For engineering students, more applied design challenges are easier to imagine. For example, given an available engine and its characteristics, students might be asked to assess how they might try to package the same engine within a smaller space, without compromising performance. Or to assess how much power might be expected from an engine half the size. Or, perhaps, to consider how and where new probes for temperature, or pressure, or flow rate, etc., can be installed without affecting performance. As an engineering professor, the problem here will not lie in finding such questions, but in getting students engaged and in assigning grades that seem meaningful to both students and instructors.

Such efforts are not part of the curriculum in typical schools and colleges, to the best of my knowledge.

Counterpoints

Some friends who read an earlier version of this article have kindly indicated that I could be completely wrong. To reiterate their skeptical views, perhaps non-engineering employers merely hire engineers from the IITs because the JEE ensures they are fairly smart or because their JEE tag brings a snob value with it; perhaps these students have very little of the transferable skills I write about; and perhaps those skills are not needed on the job anyway. Perhaps our students just learn on the job, performing well enough that the employers return to hire again.

If the above is all there is, it makes a depressing worldview. I prefer to retain some hope and idealism, and assume that some engineering students are indeed valuable in some non-engineering professions, in ways that we should think about. I hope this article will still serve, if not as a statement of what engineering education is, then instead a statement of what it can be. I do believe that the best possible version of a good engineering education must inculcate such skills in our students.

Let me offer an analogy. Few will protest if I say, “Physicists uncover the fundamental truths that govern the universe.” But, on reflection, one might admit that only a tiny percentage of physics students actually ever uncover such fundamental truths. The majority of them study, hopefully understand, and sometimes even teach those truths. Physicists doing applied work may take a sliver of those truths to use for practical aims.

In the same way, perhaps very few engineers may develop the above transferable skills to truly high levels. The remainder would at least have some exposure to a way of thinking wherein such skills may be fostered.

In closing, I offer a final caveat. I suspect that engineers might perhaps be overly confident that *all* things are amenable to simplification, quantification, and fruitful numerical analysis. Perhaps an important possible addendum to engineering courses is discussion of how and where seemingly sensible models have failed. Examples of unanticipated hazards, nonstationary behavior, nonrepeatable experiments, and being fooled by biased statistics come to mind, and my colleagues may think of others.

Acknowledgements

I thank Anjan Ray, GK Ananthasuresh, DD Ganguly, JM Papadopoulos, and Milind Sohoni for useful comments.