How to Teach Engineering: A Biased Literature Survey

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Much has been written about learning and epistemology. The goal of this document is not to provide a comprehensive survey of the varying viewpoints. Instead, I have compiled a selection of theories, quotations and anecdotes on learning which I find particularly interested, enlightening and (admittedly) preferentially in agreement with my own experiences and thoughts on engineering education. To summarize those thoughts briefly, I have found that I only truly master some body of knowledge when I want to create something (a computer game, or a robot, or a digital controller, etc.) or when I try to teach it to someone else. The key factors seem to be 1) a significantly higher motivation (i.e. trying to accomplish something, versus trying to attain a particular grade or “learning for its own sake”) and 2) the human ability to recall direct physical experiences more effectively than abstract ones.

Although I did not initially plan to focus so heavily on anecdotal evidence in this section, it is, upon reflection, both appropriate and telling that my natural inclination has led me in this direction: one common thread throughout this survey is the importance of real experiences, as compared with a recitation or lecturing of lists of facts, in creating intuitive (self-evident) understanding of a subject.

Piaget (and Papert)

I begin this survey with Jean Piaget, since his work is seminal to most of the other educational perspectives I will later discuss. Piaget was born just before the close of the 19th century and remained engaged and influential in research until his death in 1980. He moved to Zurich briefly to attend lectures on experimental psychology by Carl Jung (after WWI) and soon after studied with Theodore Simon and Alfred Binet (famous for their innovations in testing human intelligence). One of Piaget’s most influential theories is that children think differently than adults. It is an idea that Einstein famously described as “so simple only a genius could have thought of it.” A child’s mind processes information differently than a mature mind, and in fact observing the way her mind evolves\(^1\), according to Piaget, might, logically enough, hold the key to understanding human knowledge more generally. According to Seymour Papert, “his (Piaget’s) real interest was epistemology - the theory of knowledge... The core of Piaget is his belief that looking carefully at how knowledge develops in children will elucidate the nature of knowledge in general.” [10]

Seymour Papert, mentioned above, founded the Epistemology and Learning group (more commonly known as the “LEGO Lab” in the late 80’s and early 90’s) at MIT’s Media Lab. Papert worked with Jean Piaget in Switzerland in the late 1950’s and early 1960’s, which inspired his own interest in epistemology and the study of how children learn. Piaget’s work focuses on the (famously four [10]) stages of mental development in a child (i.e. how they think), while Papert is particularly interested in the dynamic processes by which children progress from one stage to the next (i.e. how they learn) [1, 10, 12]. Papert invented the “Logo” programming language, which is designed to be compatible with LEGO robot-building and

\(^1\) Piaget received his PhD in evolutionary biology
accessible to young children. Logo is designed to foster learning from the perspective that we learn best by doing and, more particularly, by making [10].

I have some experience with Logo. I assisted, with Fred Martin, and later taught classes in LEGO/Logo robot-building intermittently for a couple of years in the early 1990’s at Boston’s Museum of Science. The kids (various levels of elementary age, depending on the session) were always incredibly motivated and engaged, despite the fact that classes ran up to six hours a day, in two solid, 3-hour blocks. They could indeed pick up the Logo language rapidly, and LEGO blocks are a wonderful medium, allowing one to begin building simple structures and yet providing a well-planned flexibility that allows for surprisingly sophisticated or clever designs.

The educational philosophy behind Logo is essentially Piaget’s concept of “constructivism” or, more precisely, what Papert has coined “constructionism” [10, 1]. So what are constructivism and constructionism? And how do they relate to our discussion engineering education?

**Constructivism: To Learn by Doing**

Piaget describes constructivism as the “use of active methods” so that “every new truth to be learned be rediscovered or at least reconstructed by the student” [12]. A constructivist believes, in other words, that we naturally construct our own self-consistent frameworks (theories) to explain and to predict the world around us. Often, the intuitions we form are incomplete or simply flawed, but they work adequately (perhaps) to aid us in most day-to-day reasoning. Since specific fields of study (organic chemistry, for instance) are built upon the experimentation and observation of generations of researchers, students clearly require some level of intermediation to guide them toward mastery. This, Piaget argues, suggests two basic roles for the instructor. First, writes Piaget:

> The teacher as organizer remains indispensable in order to create the situations and construct the initial devices which present useful problems to the child. Secondly, he is needed to provide counter-examples that compel reflection and reconsideration of over-hasty solutions. ...his role should be that of a mentor stimulating initiative and research [12].

Piaget’s research focuses on childhood learning, but he and others [5, 14, 6, 4, 7, 9] postulate that further learning at the university level (and specifically scientific and engineering education) will be most effective if we customize our style of teaching to match the natural processes which orchestrated development of the logical structure of our minds (as humans) in the first place. In Piaget’s words:

> ...if there is any area in which active methods will probably become imperative in the full sense of the term, it is that in which experimental procedures are learned, for an experiment not carried out by the individual himself with all freedom of initiative is by definition not an experiment but mere drill with no educational value: the details of the successive steps are not adequately understood [12].

He states later:

> What is needed at both the university and secondary level are teachers who indeed know their subject but who approach it from a constantly interdisciplinary point of view... In other words, instructors should be sufficiently penetrated with the spirit of epistemology to be able to make their students constantly aware of the relations between their special province and the sciences as a whole. Such men are rare today [12].
All right: so from a Piagetian perspective, we should construct physical learning environments (e.g. laboratories or design projects) where students can and will experiment. But at the same time, we must take care that such an experience is not so overly structured or “canned” that it degrades into a mechanical drill. On one hand, an instructor must clearly design the experience with some sort of goals in mind, and yet (s)he needs to be able to react spontaneously to (and indeed even encourage) deviations from the “planned” path. It’s a sticky situation!

**Constructionism: To Learn by Making**

“There are two basic ideas of education,” Papert asserts. “One is instructionism; people who subscribe to that idea look for better ways to teach. The other is constructionism; we look for better things for children to do, and assume that they will learn by doing” [11].

Papert’s term “constructionism” is clearly a play on Piaget’s constructivism. The two philosophies are similar: Essentially, constructionism accepts the constructivist premise that we learn by building mental constructs, but it also places importance quite literally on the construction of artifacts. “The principle of getting things done,” Papert claims, “of making things - and of making them work - is important enough, and different enough from any prevalent ideas about education, that it really needs another name.” [10] Perhaps; at any rate, any subtle linguistic distinctions should not distract from his real point here. Design and creation are the ultimate goals in putting knowledge to use, and I think most people would agree that the acts of doing and building are both powerful methods for learning. We are motivated to learn by a desire to create things, and the process of creating in turn helps us learn.

Finally, Papert feels too much of education focuses on the concepts of right or wrong answers: it’s solutions that matter. “Discipline means commitment to the principle that once you start a project you sweat and slave to get it to work... Life is not about knowing the right answer’ - or at least it should not be - it is about getting things to work!” [10].

**Cautionary Advice to the Would-be Piagetian**

Many people try to reduce Piaget’s ideas to create a tidy approach to learning. For instance, an instructor may reason, “in the first lab, I will present a situation where the students discover Principle 1-A. The second lab will then be structured such that they discover Principle 1-B, and in the third, they will discover that two phenomena are really instances of the same general rule...” The problem lies in the meaning of “discovery”! How can you predict the activation energy (if you will) it will take for a student to truly discover something? (Particularly anything worth learning.) One may indeed create laboratories soundly based on the principles of interest, and one may in turn guarantee that, hell or high water, the students will hear about the relationship between the physical demonstrations and those “underlying principles”. But there is no guarantee either that they will fully comprehend at the level we expect or that they will have “discovered” something for themselves (which is the key to Piaget’s ideas).

As Seymour Papert noted at a symposium on computer in education at MIT in 2002, stating:

> The essence of Piaget was how much learning occurs without being planned or organized by teachers or schools. His whole point was that children develop intellectually without being taught! A Piagetian curriculum is a contradiction in terms! [15].

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2Or “rediscovery”, if you prefer.
Papert’s point is that many of Piaget’s observations and principles have been trivialized and reduced to a point where their meaning is completely lost. Certainly, he is not opposed to Piaget’s ideas. The following quotation (Papert writing on Logo three years earlier) illustrates this:

Choosing constructivism as a basis for teaching traditional subjects is a matter for professional educators to decide. I personally think that the evidence is very strongly in favor of it, but many teachers think otherwise and I respect their views. [10]

Figure 1: Piaget, Minsky and Papert. Starting at top left: Swiss philosopher and psychologist Jean Piaget [3], co-founder of the MIT AI Lab Marvin Minsky [8], and Seymour Paper, founder of the Epistemology and Learning Group at the MIT Media Lab [2].

Marvin Minsky on Education and Development

In his book “The Society of Mind”, Marvin Minsky provides an amusing anecdote which illustrates how the application of Piaget’s ideas about learning can go wrong [9]. Minsky is perhaps most famous as the co-founder (in 1959) of the MIT Artificial Intelligence Project (later known as “the AI Lab” at MIT, which merged several years ago with the Laboratory for Computer Science to form its current manifestation: “CSAIL”). Minsky emerged from the “golden age of mathematics at Princeton” [9](p. 323). His teachers included John Tukey (who later worked at Bell Labs and famously introduced the fast Fourier transform) and the incomparable John von Neumann, and his fellow students included John McCarthy (the other co-founder of the MIT AI Lab) and John Nash [9](p. 323). The study of machine learning (AI) is intricately entwined with that of human learning; each provides insights on the other. Thus, like Piaget and Papert, Minsky is also a keen theoretician on how humans (and particularly children) learn, and in fact Seymour Papert and Marvin Minsky have collaborated in the field of AI.

Let me introduce the anecdote with some key background on Piaget’s work. Piaget applied a scientific approach in studying how children think. He designed a variety of experiments to test whether a child had developed an understanding of concepts like mass or volume conservation. A famous Piaget test for an understanding of volume conservation, for instance, goes as follows: Present two identical (short, wide) jars of water to children and all will agree they hold the same amount of liquid. Now, have them watch as you pour the liquid from one of these jars into a taller, thinner jar. A typical 5-year-old will reply that the taller jar has more that the shorter one, but a 7-year-old is likely to reason each jar holds the same
amount. “These experiments have been repeated in many ways and in many countries - and always with the
same results: each normal child eventually acquires an adult view of quantity - and apparently without adult
help!” [9](p. 99).

Thanks to Piaget, we can identify specific stages or concepts in the development of learning, but it is
difficult to preempt (i.e. shortcut) the complete process by which such information is ultimately absorbed.
This is because we must, in the end, build our own hierarchical structures in the mind which help us interpret
the world around us - to solve (and indeed also to formulate) problems, for instance. The development of
such structures in our minds need not be conscious, but before such a hierarchy is fully developed, a child
(and I would argue any learner) is essentially treating the information as a set of “special rules, and so
many exceptions to them” [9](p. 106). Let me describe the dilemma (briefly) in a second way, before we
launch into Minsky’s story. Suppose one reasons: “If we know key benchmarks of the stages in the mental
development of a child, can’t we then focus on teaching each benchmark to accelerate learning?” Stated
in this way, perhaps it is easier to realize where this strategy may go wrong. We may be successful in
communicating a set of declarative facts to a child, but the connections that link these facts can only be
made in his own mind. This is why, as Minsky put it is:

...educational programs allegedly designed “according to Piaget” often appear to succeed from
one moment to the next, but the structures that result from this are so fragile and specialized that
children can apply them only to contexts almost exactly like those in which they were learned
[9](p. 106).

He continues:

All this reminds me of a visit to my home from my friend Gilbert Voyat, who was then a student
of Papert and Piaget and later became a distinguished child psychologist. On meeting our five-
year-old twins, his eyes sparkled, and he quickly improvised some experiments in the kitchen.
Gilbert engaged Julie first, planning to ask her about whether a potato would balance best on
one, two, three or four toothpicks. First, in order to assess her general development, he began
by performing the water jar experiment. The conversation went like this:

   Gilbert: “Is there more water in this jar or in that jar?”
   Julie: “It looks like there’s more in that one. But you should ask my brother, Henry.
   He has conservation already.”

Gilbert paled and fled. I always wondered what Henry would have said. In any case, this
anecdote illustrates how a young child may possess many of the ingredients of perception,
knowledge, and ability needed for this kind of judgment - yet still not have suitably organized
those components.

On Mentoring

Prof. Herbert Simon of the psychology department at CMU offers the anecdote below in an essay on
teaching and learning in universities. The story is about Bob Doherty, president of CMU around 1949, when
Simon came to CMU as a student. I feel this excerpt provides a perspective on higher level education and the
thought processes educators ultimately hope their students will develop, particularly through mentorship.
Doherty came from General Electric via Yale, and had been one of the bright young men who were taken under the wing of the famous engineer Stiglitz. Every Saturday, Stiglitz would hold a session with these talented young men whom General Electric had recruited and who were trying to learn more advanced engineering theory and problem-solving techniques. Typically, Bob Doherty would sometimes get really stuck while working on a problem. On those occasions, he would walk down the hall, knock on Stiglitz’s door, talk to him - and by golly, after a few minutes or maybe a quarter of an hour, the problem would be solved.

One morning Doherty, on his way to Stiglitz’s office, said to himself, “Now what do we really talk about? What’s the nature of our conversation?” And his next thought was, “Well Stiglitz never says anything; he just asks me questions. And I don’t know the answer to the problem or I wouldn’t be down there; and yet after fifteen minutes I know the answer.” So instead of continuing to Stiglitz’s office, he went to the nearest men’s room and sat down for a while and asked himself, “What questions would Stiglitz ask me about this?” And lo and behold, after ten minutes he had the answer to the problem and went down to Stiglitz’s office and proudly announced that he knew how to solve it.[14]

Prof. Simon’s premise is that “the emphasis in engineering education should not be placed on knowledge, but should focus attention on the learning processes solving processes of the students”[14].

“Design is a special kind of problem solving...we call ill-structured” [14], Simon says, because “the goals are never completely defined until the design is almost finished” [14]. Expert designers seem to rely heavily on intuition to sort through this cycle of defining and solving problems, and “Intuition is essentially synonymous with recognition.” [14] More precisely, it involves recognizing patterns, accessing related information (in your brain), and then making decisions about which information is most relevant and how it can be used. And the more efficient you get at doing this, the more effortless and subconscious (“intuitive”) the whole process becomes. Simon notes that this pattern recognition approach is essentially the process researchers in A.I. use in algorithms for expert system and chess-playing programs. I would make an analogy with many physical processes, like playing tennis or sight-reading piano music, where experts are able to respond efficiently to familiar (yet unique) situations because they have years of experience practicing.

“Learning has to occur in the students,” Simon finally warns, and whatever ideas you try to impart to your students, “doesn’t make a whit of difference unless it causes a change in [their] behavior” [14].“The beginning of the design of any educational procedure is dreaming up experiences for students” [14] to help them learn. Even so, providing students with relevant demonstrations and hands-on labs is not enough; ultimately the students have to do the work of learning.

In concluding this (biased) literature survey on “how to teach engineers”, I include some remarks from Prof. James Roberge, who notes: “Many designers mention one or two mentors...who had a major impact on their careers.” If this is so, then a good instructor in dynamic modeling can clearly have a much more global impact in a student’s education than simply building a strong foundation in dynamics alone. Roberge continues: “The abilities required for effective design, while hard to quantify, are common to all disciplines. I believe that a good analog circuit designer could also become a good designer of airplane wings or steam turbines after a relatively short internship in the new field. (It may be fortunate for frequent flyers that this hypothesis is infrequently tested.)” [13]

As educators and mentors, we have the opportunity to share how our own minds work in iteratively identifying and solving problems: at least half of good problem solving involves clearly defining exactly what “The Problem” actually is, after all! Our challenge is to provide good experiences and feedback to encourage (but always to challenge, as well) the problem-solving skills of our students.
References


