INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN

ICED 95

PRAHA, August 22-24, 1995

HOW STUDENTS CONNECT ENGINEERING FUNDAMENTALS TO HARDWARE DESIGN: Observations and Implications for the Design of Curriculum and Assessment Methods

Margot Brereton, Sheri Sheppard and Larry Leifer

ABSTRACT: This paper explores how engineering students use fundamental concepts studied in analysis classes as they undertake experiences in hardware design and dissection. Examples are drawn from videotape studies and in situ observations of students. We observed that students learn by reflecting on their experiences and by linking and contextualizing theoretical and practical knowledge. Curriculum design and assessment methods that help foster these skills are discussed.

INHALTSANGABE: In dieser Studie wird untersucht wie Studenten die prinzipiellen Konzepte, welche sie in Kursen der Analysis erlernt haben, zu Erfahrungen in Hardware Design in Beziehung setzen.

1. INTRODUCTION

Fundamental concepts (such as torque, moment, friction) are part of the everyday language of engineering designers. They enable us to describe experiences with hardware and furthermore enhance our abilities to generalize and make predictions about hardware. Since the half life of the fundamentals of a field is a lot longer than the half life of today's technology, it is worth investing in learning and using fundamentals [1, 2]. However a large body of research in physics learning shows that students have difficulty connecting abstract concepts to their experiential understandings [3]. And yet in daily work of designing, troubleshooting, modeling and discussing, engineers use various levels of abstraction to help them relate to real artifacts and experiences (and vice versa) as illustrated in Figure 1. This paper explores how students relate fundamental concepts they have learned in analysis classes to experiences with hardware.

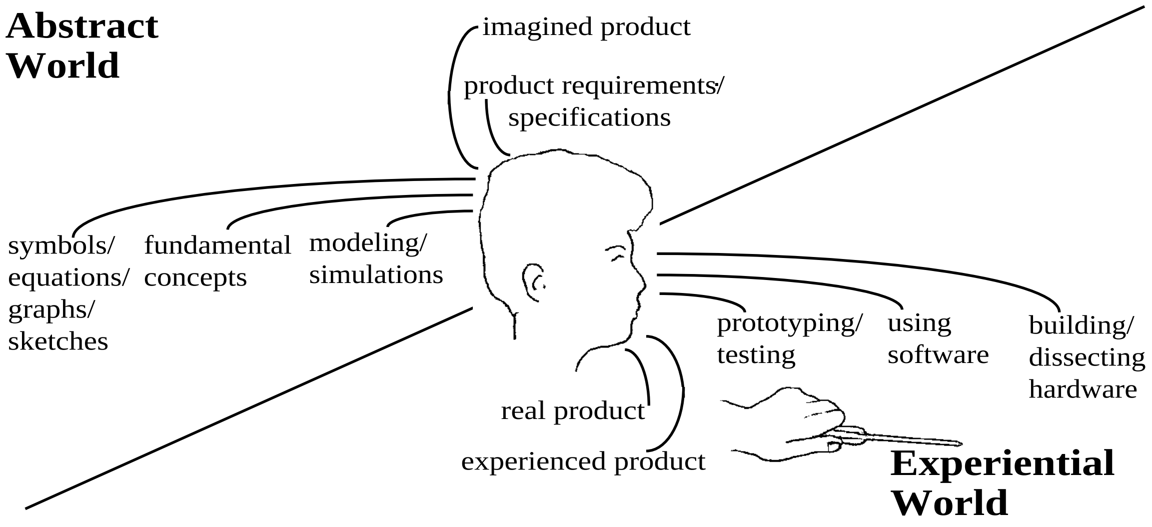

Figure 1: Learning engineering design requires us to develop rich links between our experiential and abstract understandings.

2. HOW AND WHY WE OBSERVED

We videotaped third and fourth year engineering students in classes and observed them in situ in their laboratories and dormitories as they worked in groups on design and dissection projects. These video studies and in situ ethnography[†] [4] revealed the ways in which students *actually* use the concepts they have studied, when faced with practical tasks. We assert that *we should pay attention to understanding these reasoning practices*, since these are the reasoning practices they will take with them to the engineering workplace, whether we like it or not. We have selected representative examples of how students work with concepts for this paper. In analyzing video, we used the Video Interaction Analysis method described by Jordan and Henderson in [5].

3. RELATED WORK

Recently many educators have reported on design as a core subject, transcending disciplines and integrated into all years of the curriculum [6,7,8,9]. These curricula are likely to help students relate to engineering fundamentals more readily, since they get more opportunity to apply them as they learn them. Peterson has paid attention to developing more open ended problems in analysis courses [10]. Brereton and collaborators have explored how students make sense of concepts learned in analysis courses in the context of hardware activities [11,12,13]. This paper probes deeper into how the concepts are applied during design and considers how we might provide better support for the student learning process.

4. EXPLORING CONCEPTS IN THE CONTEXT OF HARDWARE

In the first example that we discuss, two students try to relate the concept of torque to the experience of drilling. The experience took place in the Mechanical Dissection class developed by Sheppard [14] at Stanford University and an assessment of it was reported by Linde et al [15]. Students were asked to drill a hole and drive a screw into a block of wood using a two speed cordless drill. They were asked to identify features they would want in a drill and to explore how four of those features are implemented in hardware by taking the drill apart.

EXAMPLE 1: Both students have drilled a hole in a wooden block. Student A then tries to drive a screw into the block, without drilling a pilot hole. He applies a significant portion of his body weight down to keep the driver bit in the screw head slot, and succeeds in driving the screw in part way, but has difficulty preventing the driver bit from slipping out of and stripping the screw head slot. He says "That's called torque; the drill has too much torque." The students then decide to explore the features of "variable speed, weight, reversible direction and torque." In the conversation that follows we notice how the students make sense of torque by linking it to the experience and their existing knowledge:

1. B: So do you want to start with torque?
2. A: But it doesn't have adjustable torque though.
3. B: Well just the amount of torque it provides, well then pick another characteristic.
4. A: So I don't really know what torque is very much.
5. B: Well why did you suggest it then (laughs)
6. A: It's kind of like...
7. B: I think it's force times distance. It's the amount of force you apply over a distance.
8. A: yeah, but what it comes down to in English. Like does this stop at a certain point rather than keep going? you know what I mean? Like less torque means when you are screwing in and it hits the end? Then it will stop rather than just demolish the screw.
9. B: I thought torque was the amount of power it has to apply a force.
10. A: It's the amount of power it's given, yeah. If it's giving it too much power, sometimes you don't want to do that.
11. B: So you're talking about like variable force?
12. A: yeah, lots of them have variable force
13. B: Does this one have variable force?

[†] Fetterman provides a good introduction to ethnography, the art and science of observing and describing a group or culture [4].

14. A: Cause if you’re like screwing in the screw, you don’t want to give it as much power or else it’s just going to demolish the screw.
15. B: OK
16. A: Whereas if you are drilling you want it to have a lot more power, you know what I mean? Like did you notice how when we were drilling it drills really slowly, but when we were screwing, it screws far too fast. ?
17. B: mm, hmm
18. A: like it’s not just a speed thing it’s a torque thing.
19. B: so this doesn’t have (inaudible)
20. A: it doesn’t have an adjustment, it has an in-between one, it has one torque that is in-between what you want, you know what I mean.
21. B: Well, how about another feature?

We have observed that the students try to make sense of torque by making several connections:
a) to the immediate experience of drilling holes and driving screws,
b) to knowledge about different kinds of drills,
c) to terminology used to describe different kinds of drills,
c) to prior knowledge about torque and speed,
d) to the context of the problem, how to drive a screw into wood.

They draw upon a very rich, diverse base of knowledge and experience. This is quite a contrast to the clean restricted context in which most students learn about torque in analytical classes or even routine laboratory experiments. In fact the students above seem to have difficulty linking the definition of torque as the “force times the distance.” However their explorations begin to find a firm footing when they pose questions relevant to the context of drilling. They clearly show some understanding of torque in this context. In (8) student A says “less torque means when you are screwing it in and it hits the end it will stop.” When the drill does not stop and the driver bit slips out of the screw head, the student concludes “the drill has too much torque.” In (20), student A concludes that it has a torque that is in-between what you want for drilling and screwing. Student A also seems to notice torque and speed are related somehow in (18).

The example demonstrates that student A does not feel satisfied with his understanding of torque until he can connect it to his own experiences. It supports the constructivist view that meaningful learning relies upon interpreting observations, experience, or "objective knowledge" such as definitions and theories and relating them to prior experience and knowledge. Matthews comments on the history and philosophy of constructivism in [16].

The experiences, tasks and teammates act as resources that help the student explore his question about torque. But the students control the exploration process. They pose questions relevant to the context of drilling. Reflecting on their experience, they point out relevant features and patterns of the drill behavior, they link in knowledge about other kinds of drills and conceptual knowledge about torque and power, and they draw conclusions. The students ability to actively *ask the questions, make the observations and link the knowledge* transforms the raw experience into a learning experience. A challenge engineering educators face is to foster and better support this kind of inquiry through paying attention to the learning process and through design of experiences and resources (e.g. multimedia software).

5. SORTING OUT THEORIES IN DISCUSSIONS ABOUT HARDWARE

The following example is taken from a course “Exploring Engineering Intuition,” that encourages students to link concepts from analysis classes to the class design projects and rewards this learning through the assessment (grading) system.

EXAMPLE 2: An exercise to transport a weight as quickly as possible up a ramp and a vertical stretch, using two motorized systems, provokes a debate about whether or not “work” is path dependent. Confusion arises because the students have not distinguished between work done on the weight or work done by the motor. Six students take part in the debate, which lasts about twenty minutes. The key arguments were extracted and are presented verbatim below. We have italicized definitions and common technical phrases and discuss how students make sense of them below:

A1. So do we minimize power or work?
A2. The work is the same no matter what.
A3. No. It's energy that's path independent, but work is dependent on path. (Draws Carnot Cycle on board)
A4. If you did less work going up an inclined plane, there'd be inclined planes everywhere.
A5. I mean you can go all over the place on a curvy path exerting your force, and it all adds up so you do more work. But your *potential energy is m g h* [mass times gravity times height] regardless of path.
A6. The *extra work goes into friction*.
A7. The work is *the force times the distance moved in the direction of the force*. So if you have a curvy path it's still the same amount of work.
A8. The thing is, you've also got to look at what is your system.
A9. So the discrepancy here is *work done on the object or work performed by the object* and how the surroundings interact with it.
A10. I think that's why when my Prof. talked about the Carnot cycle he would always say '*work done on the piston*.'

The students readily recall definitions such as "potential energy is m g h" and the work is "the force times the distance moved in the direction of the force." It is interesting how these familiar definitions stick. They have been referred to as "physics slogans," because they seem to be readily recalled and repeated. The students seem to use them as resources to get a discussion going. But they then have to do the work of linking them to the problem at hand. In A8 a student makes sense of the discrepancies in the discussion of work by realizing they have to define the system. As soon as this link is made another student describes the discrepancy with the familiar phrase "work done on the object *or* work performed by the object" in A9. In A10, a third student literally states that he is attaching meaning to a familiar phrase that his professor used, saying "that's why he would always say work done on the piston." The discussion about work in the context of a hardware design problem gives the students reason to link some of the definitions that they readily recall to real tasks.

We noticed that students rarely begin with stating their assumptions. First, they need to get involved in the context of the problem. Definitions help them begin linking theory. Then, *if they persist in exploring a topic*, they begin to clarify assumptions such as "what is your system." We observe that students need to actively connect theory to real tasks so that they learn to sort out key parameters and assumptions from the problem context. Discussions help students do this.

6. GROUNDED KNOWLEDGE

We might ask what well-connected and what we call "grounded knowledge" looks like. By "grounded", we mean that conceptual knowledge is well connected to hardware experiences.

EXAMPLE 3: In the class "Elements of Machine Design" taken by third or fourth year students, three students are designing a model motorized vehicle to cross a stretch of gravel and climb a carpeted ramp. They are discussing how the vehicle could detect when it is on the ramp.

1. B: We might need to shift gears to go up the ramp. It could need more torque.
2. B: Could it sense it's wheels don't work? You know when the torque is...(doesn't complete sentence)
3. C: You mean at stall speed. [The team looks impressed]
4. A: You listen in class.
5. C: At stall it sucks up a whole amount of current. It could blow a fuse.

The students have attended a lecture on motor characteristics and seen torque speed curves. It is Student C who is clearly able to relate "stall torque" on a graph to what is happening in the hardware. She links the problem of wheels not working to the concept of stall torque and the knowledge that a stalled motor draws more current. She then relates the knowledge that it will "suck current" at stall and links that to a possible solution for detecting stall, blowing a fuse. These multiple connections to knowledge about "sucking current" and "wheels not working" imply the concept of stall torque is "grounded" for Student C because it is linked to hardware experience.

How does grounding occur? Whenever knowledge is being connected, learning occurs -- however if the links are sparse or linear or entirely in one domain, such as the theory domain, the connections are likely to be fragile and quickly forgotten. Instruction techniques and assessment design can encourage students to process their experiences and link knowledge. Instructors can lead by example and can provide frameworks for reflection, such as Kolb's [17]. Students derive great satisfaction when they make links. The team in Example 3 discovered that they needed to gear down the motor to reduce the speed and increase the torque to the wheels so that the vehicle would move. Student C built a two stage gear reduction using Lego TM gears. On spinning the motor shaft and *observing* the gear on the wheel axle, she exclaimed: "wow, when I turn this one, that goes really slowly. I guess that *would* be gearing down."

7. MISSED CONNECTIONS:

Students often have difficulty making connections or simply miss making them. For example:
1) Difficulties relating variables: Examples 1 and 2 showed that students had difficulty working with relationships between variables. In Example 2 line 1 the student asks "so do we minimize power or work?" In design projects, students often had difficulty working with relationships between variables like power, torque, force, work and speed. We observed two causes. First, physical world realities like friction, uneven surfaces and irregular objects cast doubt on the nature of relationships between variables. Second, students seemed to have little experience in qualitative reasoning about what should vary and what should not. In typical analysis problem sets they are used to being told what the independent variable is.

When project performance was emphasized over understanding, students often abandoned reference to concepts and used simple reasoning like *try bigger wheels* or *use a bigger motor*. Often they got their projects to work in this way. But although they gain confidence about design through doing, they may not learn to leverage their theoretical knowledge effectively. We assert that educators should nurture and reward both *learning design through experiences* and *learning to apply and link fundamental concepts and laws to hardware experiences*.

2) Experience as the first and only source of reasoning: An Example reported by Brereton et al illustrates how students use experience as their first source of reasoning rather than conceptual knowledge [11]. Six groups of students from two universities took part in an exercise to dissect bathroom scales and explain how they work. All students had taken Statics and Strength of Materials. In particular they were asked to explain why, if you place bathroom scales on a soft carpet, do the scales register an inaccurate weight. They were given soft carpet and scales to experiment with. In all six groups, at least one student offered the theory that the carpet absorbs some of the load. Three groups realized this contradicted Newton's Law of equal and opposite action and reaction and set about investigating what might be happening in the scale.[†] But, three groups simply settled on the absorption explanation without further probing. We often observed students stop questioning once they found an experiential explanation that seemed to matched the observable phenomena. The research study "Private Universe" [18] drew similar conclusions--many students hold on to their preconceptions more readily than to formally taught knowledge.

3) Questions leading away from the task: Example 4 below illustrates some of the reasons why students do not follow up their questions:
EXAMPLE 4: The group in Example 3 is concerned about whether the gear driving the rear axle should be mounted in the middle of the axle, or whether it could be offset to the side:

1. A: Can we drive the back axle just from one side of motor. Would it be out of balance?
2. C: [shakes her head]

[†] When on the carpet, the base of the scale deflects under loading, the four points supporting the weighing mechanism shift and then the scale reads incorrectly.Why does the deflecting scale tend to read lighter rather than heavier than the actual weight? Charlotte Linde offers the theory that in the social practice of weighing, one shifts around until the reading is minimized.

3. C: I think it doesn’t matter where it is on the shaft. It’s just spinning it.
4. B: What about torque one end to the other.
5. C: I don’t think so. It might, we could ask.
6. B: You’re putting it onto one side so... (doesn’t finish)
7. C: In a car, is just one wheel driven? I don’t think they’re connected. When your stuck just one spins. [Student looks confused].
8. A: If I have kids I’m giving them Lego^{TM}.
9. B: So we’ll just do offset.

Here we see two interesting questions that arise. First, is the torque to the wheels at either end of the axle the same when the driven gear is not mounted in the axle center? The students suspect there is no difference but are unsure. Student C then recalls an experience that when a car is stuck, just one wheel spins. This causes her to wonder about the driven axle configuration in cars. She infers that just one wheel is driven and the axle does not connect the wheels directly, but seems to doubt what she has reasoned. Student C is able to begin probing the axle question from experience because she has made an observation outside the classroom about spinning tires. This is a timely opportunity to learn about differential gears. Hopefully the student will follow up the question by asking a friend, exploring a car manual, looking under the car, or will link the observation when she does learn of differentials. In Vygotsky’s terms, learning about differentials is clearly within student C’s “zone of proximal development” [19]. The students do not follow up on their questions for the following reasons:

a) The resources needed to answer them are not immediately at hand.
b) They do not know which questions are within their ability to figure out and which are not and they lack incentive or confidence to probe.
c) Answering the questions is not crucial to designing or assumes a lower priority than meeting the design deadline. They can proceed with building and see if problems arise.

8. CONCLUSIONS:

This study raises many issues. Three of our main conclusions are:

Assessment drives learning: Even when students are motivated to learn for their own reasons, if the assessment method suggests that a more expedient process will get a better grade, students will take that route. It is extremely important that the assessment method be compatible with the kind of learning that the class strives to achieve and the motivations of the student [12,15,20]. Design performance, as an assessment driver, encourages students to learn necessary strategies for meeting performance requirements and deadlines, but we should also explicitly reward the learning processes that will also serve students in the workplace.

Developing students’ abilities to question, observe, and actively use and link theoretical knowledge to hardware experience should be a central goal of education to be pursued with particular care rather than taken for granted: These process skills are most likely to produce effective lifelong learners able to leverage the fragile understandings hard won in analysis classes. In the words of Salomon and Perkins [21]:

> Understanding is not something that comes free with data banks and thorough practice; it is something won by the struggles of the organism to learn- to conjecture, probe, puzzle out forecast and so on. Likewise ready recall of information and smooth execution of procedures do not guarantee active use of knowledge and skills as the learner later in life strives to cope creatively with new situations. On the contrary, there is considerable risk that a drill and practice regimen may yield knowledge and skills more contextually welded to very particular circumstances, less labile, less easily transferred. In Summary, understanding and active use become central goals of instruction to be pursued with particular care rather than taken for granted.

Developing an active learning community and supportive classroom culture requires new roles for teachers and students: Based on our research, we designed a class called “Exploring Engineering Intuition” to explore how to help ourselves and our students (a) become better observers of the world around us; (b) challenge assumptions through what-if questions about hardware; (c) motivate interest in learning theoretical concepts by relating them to hardware. Our goal was to develop a class environment and culture that promotes questioning, motivation to explore and link and confidence to act. We legitimized basic student questions and fostered discussion about them by showing videotape of typical questions asked in small group learning. The class method espoused was to predict, design and reflect. The coaches and the instructor took on roles as active learners rather than authority figures. Students were encouraged to relate questions from other classes that they were taking concurrently, such as Introduction to Physics, Introductory to Electronics, Strength of Materials. The class was designed around hardware design and dissection projects, but emphasis was placed on developing understanding. We paid particular attention to designing an assessment method that promoted meaningful learning and exploration, assessing students based on:

(i) reflective explorations in their log books that linked group projects, fundamental concepts and observations outside the classroom;
(ii) participation in discussions and
(iii) an individual project that explored a concept in the context of hardware.

Evaluation of videotape material from this class is still in progress, but preliminary findings are that students paid more attention to linking knowledge, asking and reaching meaningful resolution on their questions than in classes with conventional reward structures [22].

ACKNOWLEDGMENTS

We sincerely thank Steve Vassallo and David Cannon for helpful discussions on student learning and all the students who graciously took part in videotape studies and were willing to be followed by an ethnographer. In addition we thank all collaborating members of the NSF Synthesis Coalition and NSF for providing funding for this work in engineering education.

REFERENCES

[1] Healy, Tim, “Educating students for times of rapid change”, pp52-55, FIE 24th Annual Conference, November 2 - 6, 1994 San Jose, California.
[2] Kuhn, Thomas “The Structure of Scientific Revolutions,” University of Chicago Press, Chicago, IL 1962.
[3] diSessa, Andrea A., “Toward an Epistemology of Physics,” Cognition & Instruction, 10(2 & 3), 1993.
[4] Fetterman, D, "Ethnography: Step by Step," SAGE Publications, Inc. CA, 1989.
[5] Jordan, B. and Henderson, A. Interaction Analysis: Foundations and Practice. Palo Alto, CA: Institute for Research on Learning. 1992. Accepted for publication in The Journal of the Learning Sciences.
[6] “Integrating Design Throughout the Curriculum”, Engineering Education Special Issue, July/August 1990.
[7] Hamilton, P.H., Smith D.G., Gilchrist I., “Transcending Disciplines by Design - A Proven Approach” Proceedings of ICED ’93, The Hague, August 17-19, 1993.
[8] Leedham VE and Fieldhouse JD, “The Education of Mechanical Engineers using Design as the Core Subject”, Proceedings of ICED ’93, The Hague, August 17-19, 1993.
[9] Wallace, K.M. “Engineering Design Teaching in the New Four Year Course at Cambridge University”, Proceedings of ICED ’93, The Hague, August 17-19, 1993.
[10] Peterson, Carl R., "The Desegregation of Design", Engineering Education, pp530-532, July, 1990.
[11] Brereton, M.F., J.Greeno, J.Lewis, C.Linde, L.Leifer, "An Exploration of Engineering Learning, " Proc. of the 5th Int Conf on Design Theory and Methodology, ASME, Albuquerque, NM, Sept 19-22, 1993.
[12] Brereton, M.F., J.Greeno, L.J.Leifer, J. Lewis, C.Linde, Innovative Assessment of Innovative Curricula: Video Interaction Analysis of Synthesis Exercises, ASEE Annual Conference Proceedings, 1993.
[13] Greeno, J., Linde, C., Roschelle, J., Brereton, M., Lewis, J. and Stevens, R. . (1994) “Explanations in Discourse,” Proceedings of the American Educational Research Association Annual Conference, April, 1994.
[14] S.D. Sheppard, “Mechanical Dissection: An experience in how things work,” *Proceedings of the Engineering Education: Curriculum Innovation & Integration*, Jan. 6–10, 1992, Santa Barbara, CA .
[15] Linde, C., Roschelle, J and R.Stevens, “Innovative Assessment for Innovative Engineering Education: Video-Based Interaction Analysis: A Method for Assessment and Improvement of Synthesis Curriculum,” Report to the NSF Synthesis Coalition, Institute for Research on Learning, Palo Alto, CA 1994.
[16] Matthews, M. R., “Science Teaching: The Role of History and Philosophy of Science,” Routledge, 1994.
[17] Kolb, David A. “Experiential Learning” Englewood Cliffs, N.J. Prentice-Hall, 1984
[18] Schneps M./ 1989 “A Private universe” Santa Monica, CA : Pyramid Film & Video, c1989.
[19] Moll, Luis C., “Vygotsky and Education,” Cambridge University Press, 1990.
[20] Hall, R., Knudsen, J., & Greeno, J. Practice and technology in the participatory design of assessment systems. Palo Alto, CA: Institute for Research on Learning. 1992.
[21] Salomon, G and Perkins, D.N. (1989). “Rocky roads to transfer,” Educational Psychologist, 24(2), 113-142.
[22] Brereton, M.F. Ph.D. Thesis, forthcoming, Stanford University, 1995.

The authors can all be contacted at the Center for Design Research, Bldg 560, Panama St., Stanford University, Stanford, CA 94305-2232 USA. brereton@cdr.stanford.edu