

From Intellectual Development to Expertise

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Introduction

Over the past five years we have conducted a longitudinal study of undergraduate engineering students based on the Perry scheme of intellectual development. [1,2] (For readers not familiar with the Perry scheme, a summary is provided in the Appendix of this paper.) One of the major goals of that study was to determine how our students were developing in their ability to undertake complex problem solving as indicated by their descriptions of the general strategies that they used in attacking ill-defined problems. We are now analyzing the transcripts of the student interviews to search for evidence of their development specifically related to complex problem solving along with the expert knowledge and skills required to support it. Our focus on solving complex problems is driven by the fact that we take this ability as *the* defining ability of an expert engineer. Thus, in this analysis of the Perry data, we are seeking an indication of the progression of our students towards expert status within their chosen engineering field.

The analysis presented in this paper is the beginning of the development of a refined interview protocol to elicit information on how students progress towards expertise and about their process for solving complex engineering problems. This work is motivated by the desire to answer questions such as the following:

- Can our educational processes be restructured to allow students to focus more effort on the development of higher levels of engineering expertise than most achieve in the current system?
- Given that the expertise literature suggests that the development of expert performance in any field requires roughly ten years, what are realistic expectations of student performance after a four-year undergraduate program?

A valid and reliable protocol related to engineering expertise must be developed, along with an appropriate experimental design, if questions such as these are to be answered. The work presented here is a small first step along this path. In developing the initial protocol for the work described here, literature on expertise, domain learning, and complex problem-solving was explored.

The literature on expertise in the U.S. has focused to a large extent on defining differences between experts and novices. The recent National Research Council book, “How People Learn,” [3] provides a good summary of the major findings, some of which are:

- *“Experts notice meaningful features and meaningful patterns of information that are not noticed by novices.*
- *Experts have acquired a great deal of content knowledge that is organized in ways that reflect a deep understanding of their subject matter.*
- *Experts knowledge is ‘conditionalized’ on a set of circumstances.”*

Thus, evidence of expertise would include the development of more sophisticated knowledge structures, problem-solving driven by underlying principles rather than surface features, and an understanding of when, where, and why a given method to solve a problem can be applied. Unfortunately, the expert-novice literature does not provide much insight into the process by which expertise is developed; however, other research has begun to address this process.

A model of domain learning proposed by Alexander addresses development through three phases: acclimation, competency, and proficiency/expertise [4,5]. Her model includes the role of interest, strategic processing of knowledge, and subject matter knowledge. Alexander distinguishes between situational interest, which is related to specific circumstances, and thus transitory, such as the desire to get a good grade, and individual interest, which is longer lasting because the learner is intrinsically interested in the domain and forms a personal association with it, e.g., a learner seeing herself as an electrical engineer rather than a student. In Alexander’s model situational interest is high during the acclimation stage and individual interest is low, with their importance switching as the learner moves toward expertise. Alexander breaks subject matter knowledge into two types: domain knowledge and topic knowledge. Domain knowledge encompasses the underlying concepts and principles of a field, whereas topic knowledge includes the depth of knowledge related to a domain specific concept. As an example, an expert engineer could have domain knowledge in thermodynamics, fluid mechanics and heat transfer, and topic knowledge in diesel and gasoline engines. The final dimension of Alexander’s model is strategic processing of knowledge that encompasses the procedural knowledge that a learner applies to maximize learning or performance, including general cognitive and meta-cognitive processes.

Alexander’s model is general in nature and must be supplemented with other work that provides more detailed descriptions of complex problem solving skills. Don Woods did substantial work on complex problem solving while developing the McMaster Problem Solving program. In a recent article [6], he describes a model process for problem solving that has six stages plus a transition stage. He points out that successful problem solvers do not apply the stages sequentially, rather they move back and forth (transition) among the stages as they proceed toward their solution. He describes the cognitive, meta-cognitive, and attitudinal skills that relate to each stage. Not surprisingly this set of skills align closely with those included in Alexander’s model for the development of expertise in a given domain.

While there has been much research done on complex problem solving and the development of expertise in a given domain, there has been little work done to directly link these studies to more general measures of intellectual development such as those based upon the Perry scheme. Woods et al. [7] included an instrument to measure Perry rating in their evaluation of the McMaster Problem Solving Skills program, but they used it as a measure of attitude and skills related to lifelong learning. Hence, one of the questions we wish to explore is the extent to

which Perry rating correlates with evidence of complex problem solving skills in the engineering domain.

Analysis of Interview Transcripts

Of the 27 students who completed senior interviews in our longitudinal Perry study, 24 were still in the College of Engineering. The transcripts of these 24 students were analyzed for evidence of complex problem solving skills in the engineering domain as well as the knowledge, skills, and motivation that support them. The coding of the transcripts was done using questions primarily based on the complex problem-solving literature and Alexander's model. Questions based on the complex problem solving literature were:

- Is the student's conception of the process linear or iterative?
- Does the student discuss the need to define the problem?
- Does the student recognize that multiple solutions exist? And the need to generate alternative solutions?
- Does the student discuss the need to make assumptions/approximations to proceed toward a solution?
- Does the student discuss the need to go beyond textbooks as part of their solution strategy?
- Does the student discuss trade-offs among conflicting goals for the project or design?
- Does the student consider cost/profit, time to completion, safety, environmental impact, and other factors that are not "purely" technical?
- Does the student discuss criteria for making a decision on the "best" solution?
- To what extent does the student rely on experts, such as their professors or managers, to help solve the problem or to decide on the "correctness" of the solution? (related to their view of authority *ala* Perry.)

Questions based on Alexander's model were included to provide a broader view of the students expertise:

- Is there evidence of situational interest?
- Is there evidence of individual interest?
- Is there evidence of topic knowledge?
- Is there evidence of domain knowledge?
- Is there evidence of strategic processing of knowledge such as attempts to organize knowledge around principles or to conditionalize knowledge?

An initial review of the transcripts showed that only a few of the students discussed complex problem solving in terms of design or engineering projects because of the general nature of the questions in the Perry interview protocol. However, nearly all of the students were asked about making decisions in "real world" situations where they did not have all of the information that they needed, and how they would decide that they made the "right" decision. Their responses to these questions were used to make an initial rating of their complex problem solving; the students were rated on a three level scale: low, intermediate, and advanced. After this review process, only eight of the transcripts were judged to have answers that permitted a rating to be given, and all of these were rated at the intermediate or advanced level. Finally these eight

transcripts were reviewed in their entirety to gather all the evidence available and then the students were assigned a final rating. When the interviews were reviewed the need for another level, called Intermediate-to-Advanced became evident.

The following excerpts from the student interviews indicate typical responses. (These are *verbatim* transcriptions of the oral interviews, so they contain occasional ramblings.)

Student A

I guess if I had to gather as much information as I personally could find whatever resources that I had available. I think then I'd go to the next person that I knew had knowledge on that topic or whatever it was. Go to them. Whoever I thought was the most well suited for that type of decision question. See what they had to say about it. I guess even just I think obviously if you put it in a work situation where you have a whole department of people and you kind of got assigned that task. Okay I don't really know what to do here. Got as much as I can but I still don't feel like I know what I'm doing. I think I'd ask get feedback from as many people as I could. See if they knew anything about the topic. Just keep going until hopefully I'd find someone and then I guess once I got to that point where I hopefully I would've found someone and they could kind of go that way. Go with that but if even after you know accessing all the other people that you know things like that and no one could really help you. I guess it's from whatever information I did have try to reason it down and go with the best guess kind of situation. I guess that's hopefully it will work out.

I guess depending on what it was. First thing you'd obviously know if you made the right decision. Thing broke, you didn't. Other ones if there was more of a judgment kind of ethical sort of thing where you know it's not going to break or not break. I think that's one of those kind of things where you have just like at the end did I do everything that I could. You'd use every possible resource that I have available. All the people that I have available and you know was I honest about everything and just chose what I felt was the best possible choice. If there is no person there to say oh that was wrong or that was right. Then I guess just with your gut feeling and in your conscious did you do everything you possibly could and I guess that's the best you could've done with what you had.

This student was judged to be at an intermediate level of development of his conception of complex problem solving. He describes the need to gather information personally, but emphasizes the need to seek input from others, hoping to find an expert to guide his choice. He indicates that failing to find an expert, he would “reason it down.” In discussing how he would judge whether his solution is “right,” he again looks for someone to tell him “that was wrong or that was right.” Failing that he indicates that he would “go with gut feelings.” His Perry rating was 3.67.

Student B

One of the things you could do is try to talk with the client about what they're trying to accomplish with whatever they want even if they don't really know what it is they want then usually the reason that they've hired you in the first place is because they have some sort of need or problem and they might not have any idea how to solve it or even what's available to solve it with, so that's why they hired you is because you're supposed to know that sort of thing. So I

think one of the things that you could do is try to understand the problem that the client has and see what it is that they're really trying to tell you even if they don't know how to tell you in the way that you would phrase it.

Right, one of the things that's good in that situation is to develop some sort of prototype and see something you can make rather quickly and then go to the client and say is this anything at all like what you had in mind. and a lot of times seeing something that not necessarily works in the way that the final system but suggest that it will work . A lot of times that will help the client to be more specific and they'll say yeah I like this but I don't like this and this needs to do something else that isn't in this at all. Or no that's way off in left field. That's not at all what we're looking for and you can ask them well why not. What's wrong about it. and that's sort of what-if's situation will often help to focus the project and to really figure out what it is that you're trying to accomplish.

Well I'd certainly have a discussion with the team and see why each person thinks the way they do and it's quite possible that other people on the team will be able to critique some of the ideas and show why they're good why they're not. But if there are a few that the team can't agree on which one is better then perhaps the guy might want to build a prototype of the things and see which one seems to be better or easier to build or just to sort of see what the qualities are so that the rest of team can look at something that's a little more concrete and again that's not something that I think should occupy too much time as a percentage of the overall project.

Right, but something like that can I think can help to make a better decision about what's the best way to proceed, but eventually it will come down to the team has to make a decision and sometimes that if you have a few things that are they may be relatively equal in merit but you just have to pick one and do it. Because you can't spend too much time trying to figure out what's the best way to go when the best thing really would've been to pick one of them back in the beginning and do it.

Well you made the right choice if the project is successful. That's certainly a way to know if you did the right thing. It's possible that you might never made an acceptable choice. It as the project finished on time and everything but if you had chosen another alternative . If you might have been able to do it in less time and [inaudible] less cost. So I don't know if it's ever possible to know if you made the best choice. Without actually trying all of the potential alternatives but it's possible to know if you made a good choice and one that's worth repeating. Again it's also possible to know if you made a bad choice if what you did didn't work out very well. And sometimes you realize that early on and then the development and other times you don't realize that until much later and at that point its' if you can't really start over from scratch, it's very hard to know what to do.

This student's process includes defining the "problem" by discussing it with the client, creating alternative solutions, and critiquing/evaluating them to decide which one to use. He recognizes that time factors and costs play a role and that you may never know if you made the "right" choice. Elsewhere in his interview he discussed the existence of "infinite number of solutions" to complex engineering problems and the need to sell your solution and convince others that it is

a good way to go. This student was judged to be high in his conceptualization of the complex problem solving process. His Perry rating was 5.0.

Table 1 presents the Perry ratings, complex problem solving (CPS) rating, and GPA; the Perry and CPS data are plotted in Figure 1. For purposes of plotting and data analysis the CPS ratings were simply coded as 1=low, 2=intermediate, and 3=advanced. The relationship of the decimal Perry ratings to Perry's nine positions is described in the Appendix. The students that received advanced or intermediate to advanced ratings were rated at 4 or above on the Perry scale, with one exception. The exception is the last student listed who had a Perry rating of 3.33 and an advanced CPS rating; he is represented by the circled data point in Figure 1. He also had the lowest GPA of all of the students. Interestingly, however, this student was the only one to give evidence of "topic knowledge" and "individual interest" as defined in Alexander's model; this evidence will be discussed in more detail below. Perhaps his high level of complex problem solving skills are a result of this individual efforts and experience, and not his formal education.

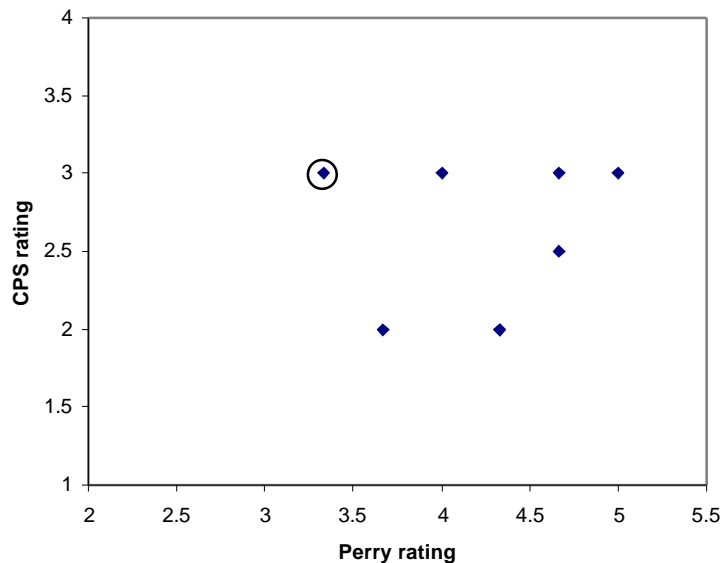
Table 1. Perry and CPS ratings

CPS Rating	CPS numerical coding for data analysis	Perry rating	GPA
Intermediate	2	3.67	3.5
Intermediate	2	4.33	2.99
Intermediate	2	4.33	3.92
Int. to Adv.	2.5	4.67	3.4
Advanced	3	4	3.86
Advanced	3	5	3.92
Advanced	3	4.67	3.78
Advanced	3	3.33	2.91

A linear regression was run between the CPS scores and the Perry scores. The regression coefficient was nearly zero. Even when the anomalous student was removed from the data, the regression showed that only 25% of the variance in the CPS ratings was explained by the Perry ratings. Thus, the correlation between the Perry rating and CPS rating is weak at best, in this limited data set. Regression analysis of CPS rating against GPA yielded very similar results.

Further analysis of the transcripts of the rated students was performed to seek evidence of the development of expertise using the questions based on Alexander's model. Due to the nature of the Perry protocol, relevant quotes tended to arise in general discussion of knowledge and learning, but sometimes they just arose spontaneously. Not many relevant quotes were found in some of the areas, such as topic knowledge and strategic processing of knowledge. The lack of evidence may be because the students had not yet reached sufficient levels of expertise to offer relevant quotes, but it may also be due to the general nature of the questions used in our Perry protocol. The following discussion presents some of the relevant quotes to illustrate the type of evidence that was found.

Figure 1. Scatter Plot of CPS score versus Perry rating; circled point is “outlier”



Alexander proposes that individual interest must be high if truly expert capabilities are to be developed. She also proposes that situational interest is likely to be high as a learner begins learning in a given domain. The Perry transcripts were reviewed for evidence of both types of interest. As expected the most common types of interest in the transcripts were situational, which is typical of learners in the acclimation stage. Typical comments included interest in getting good grades, not wanting to “let my boss down,” or wanting to impress others. Only one student indicated a high level of individual interest in a specific topic within his major field of electrical engineering, wireless communication. This student was the one with the low GPA and Perry rating, but an advanced CPS rating.

... something happened; I decided to keep getting more and more knowledge on the material. You know occasionally you get some free time and I'd jump on the web and start searching for certain things. Anything to further my knowledge in the wireless communications.

Alexander's model of domain learning includes two types of knowledge: domain and topic. The research on expertise indicates that expert's domain knowledge is more complex and conditionalized than that of novices. The Perry interview transcripts were searched for statements that indicated the students were attempting to build more complex knowledge structures beyond rote memory or that they were acquiring an understanding of when they could apply skills and knowledge most effectively. Also evidence of topic knowledge was sought in the transcripts. Little evidence in these areas was found in the interviews, perhaps as a result of our protocol, which was not directed in this way, rather than a lack of development of the students in this area. The student with the anomalous Perry/CPS ratings provided one of the few relevant quotes related to building more complex knowledge structures:

...I think most of it was because it was such a hands-on experience that you were constantly were doing. Not the same thing every day but you had to use the same principles that you know when I

had first started there I tried to learn what exactly is going on here. And every time you would do something new I would rely back on some of the knowledge or the information I had learned earlier in the co-op. ... Just continuously always being in the field you know just the vocabulary, constantly being around it I think it as with any job you just get experience . You just get you've been around it so much you start asking questions that, you know, it's not stuff that you can't remember. It's, you know, new stuff. How does that relate back to the stuff that you've already learned?

Another student in discussing learning gave evidence of “conditionalized” knowledge:

... And also you have to understand that that analysis may not apply to every situation. So maybe you can't use that equation or you can't use that theory or you can't use that grammatical structure. Doesn't work here. Doesn't' sound right. That's theoretically correct but in the real world that's not going to work.

The student with the anomalous Perry/CPS ratings also gave evidence of topic knowledge, in his case, in the area of wireless communication:

... So I've been working. It's called TDMA. Time division multiple access. Just the way they have of dividing up the spectrum. So I mean I definitely have a lot of experience doing that and there's two other types of technology out there that the wireless industry uses. GSM and CDMA. I have a little bit of knowledge of GSM and a little bit of CDMA. And the department I'll working for down in [inaudible] does CDMA and TDMA, and CDMA. ...

Although the analysis of the transcripts did not yield as much evidence related to Alexander's model of domain learning as we hoped, the evidence that was found was consistent with her model, and supports its use as a framework for assessing expertise. For example the most common type of “interest” represented in the students' comments was situational, as expected for learners in the acclimation stage. Also the evidence from the anomalous student appears to support Alexander's model as his individual interest in wireless communication seems to be driving his growth in expertise.

Summary

The results of the present analysis show at best a weak correlation between the Perry rating and the CPS rating. The one student who had the lowest Perry rating and lowest GPA, but an advanced CPS rating raises interesting questions about the development of expertise, its relationship to Perry ratings, and our educational processes. Clearly the present work cannot answer these questions, but it does point to the need for further study. The analysis of the transcripts based on Alexander's model of domain learning did produce some evidence of levels of expertise beyond acclimation, but not as much as might have been expected if the CPS ratings are valid. It is likely that the nature of the Perry interview protocol, which did not probe areas related to Alexander's model, is the culprit. A different protocol with questions to probe the five areas of Alexander's model would have elicited more evidence.

As we extend the work discussed in this paper, our goal will be to develop a refined protocol that will allow us to gather information on how students progress towards expertise based on Alexander's model and also descriptions of students' personal process for solving complex engineering problems. We will use the results of the analysis described in this paper to guide the process of developing this protocol. Ultimately, we hope to use the refined protocol to answer the questions mentioned in the introduction (repeated below) along with the two additional questions which derive from Alexander's work

- Can our educational processes be restructured to allow students to focus more effort on the development of higher levels of engineering expertise than most achieve in the current system?
- Given that the expertise literature suggests that the development of expert performance in any field requires roughly ten years, what are realistic expectations of student performance after a four year undergraduate program?
- Should we provide opportunities for students to discover areas of individual interest, as defined by Alexander, and allow them to pursue those areas to accelerate their growth in expertise?
- Might there be an optimum mix of “broad learning,” which is typical of most undergraduate engineering programs, and learning driven by “individual interest” that maximizes the development of expertise in undergraduate students?

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Appendix: The Perry Scheme of Intellectual Development

William Perry began asking undergraduates about their experiences at Harvard in the 1950s. Using an open-content interview method, Perry was able to collect a rich set of data. Common themes began to emerge, and he was able to identify what appeared to be a series of “positions” that characterize the students progress of intellectual development. The scheme begins with basic dualism (positions 1 and 2), proceeds through relativism (positions 3 through 5) and concludes with commitment within relativism (positions 6 through 9) [Table A-1.]

Table A-1. Major Positions on Perry Scheme

Position	Family	Label	Characteristics
1	Dualism	Basic Duality	Dualistic structure of the world unquestioned. Good/Bad, Us/Them, Right/Wrong
2	Dualism	Multiplicity Pre-Legitimate	Multiplicity is perceived, but not believed. Authority still holds answers.
3	Relativism	Multiplicity Subordinate	Multiplicity perceived, but trust in authority to eventually find answers is not shaken.
4	Relativism	Multiplicity Correlate or Relativism Subordinate	All opinions equally valid. Authority “wants us to think” that relativism exists.
5	Relativism	Relativism Correlate, Competing, or Diffuse	Relativism accepted intrinsically.
6	Relativism	Commitment Foreseen	Relativism accepted, commitment seen as necessary to operate in a relativistic world.
7	Commitment	Initial Commitment	
8	Commitment	Orientation in Implications of Commitment	
9	Commitment	Developing Commitment(s)	Commitments continue

While college students may typically begin their first year as intellectual dualists, believing, for example, that experts know the "truth", they are soon confronted with situations that test this basic faith. With each new dissonant experience, the student is compelled to resolve the

dissonance either by adapting his or her cognitive schema or rejecting the authenticity of the experience. Adaptation moves the student forward in the Perry scheme. Rejection represents actions that Perry termed as “escape” or “retreat” – a refusal to move forward. Such students may delay progress for a year, as they re-gather the energy they will need to change. Others may remove themselves from the situation that precipitated the conflict. For the most part, students who entered as dualists should tend to graduate with a more sophisticated view, recognizing the need to gather evidence from multiple sources and making their own judgments. This change is desirable for developing engineers who must solve complex engineering problems and who are responsible for their own continued learning in the world at large.

Although Perry postulated nine positions the ratings assigned by the expert rater who rated our students used somewhat finer distinctions. The scheme used in establishing the ratings listed in Table 1 of this paper follow the approach listed in Table A-2. The table shows the meaning of the ratings from 2.0 to 3.67 to illustrate the meaning of the numerical scores reported here.

Table 2. Perry ratings as assigned by expert rater

Rating	Dominant position	Trend	Numerical equivalent for data analysis
222	2	Stable	2.0
223	2	Opening to 3	2.33
233	3	Not fully developed	2.67
333	3	Stable	3.0
334	3	Opening to 4	3.33
344	4	Not fully developed	3.67

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