Expert and novice conceptions of the design process: Developmental differences with implications for educators

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Abstract
If educators want students to learn to think like experts, then we need to learn how experts think. Addressing this issue, we asked what is "the wisdom" of biodesign (i.e., what are the key concepts)? How do people at different points of professional development define biodesign? Both questions were intended to inform our efforts to establish experiences that support students' understanding of the design process and professional development. The method we used to answer these questions was concept mapping. A concept map is a spatial representation of ideas and their relationships. To identify key concepts and processes associated with biodesign, we asked 15 experts to construct a map reflecting their definition of the biomedical engineering design process. Findings from this work were used to establish a biodesign taxonomy and benchmarks of expertise. Our taxonomy contained six broad categories: the design process, motivation for the design, interpersonal skills, technical skills, societal concerns, and marketing. We then applied our benchmarks to the maps of 32 undergraduates enrolled in a two-semester senior biodesign course. Students constructed maps at three time points: the first week of the first semester, the end of the first semester, and the end of the second semester. Despite considerable within-group differences, analyses showed areas of stability and change in students' conceptual understanding. Over time, the expert-novice gap closed in two areas: the design process and motivation for the design. Students made consistently fewer references to ethics and marketing than did experts, but did not differ from experts in the areas of interpersonal skills and technical skills. In addition to their implications for design educators, these findings offer an important avenue for understanding the nature of expertise. That is, they suggest that experts have a more developed understanding of the social context in which a design and designers function.

Introduction

Design is a core competence in engineering; however, we have a limited understanding of how expert designers think. To learn more about this, we asked experts in academia and industry, and students enrolled in a biomedical engineering design course to define the biomedical engineering design process. Our purpose was to capture "the wisdom" of design (i.e., key concepts and processes), and reveal how conceptions of the design process may differ according to people's level of experience and professional development. We had two overarching goals. One goal was to enhance theoretical understanding of the nature of expertise and the design process. Another goal was to enhance engineering educators' efforts to establish experiences that support students' understanding of design and professional development.

The method we used to explore expert-novice conceptions of the design process was concept mapping. Concept mapping was invented by Joseph Novak and his colleagues in the 1970s [1]. The technique emerged from a need to summarize extensive interview data about K-12 students' understandings of scientific phenomena, such as physics. Concept maps are spatial representations of ideas and their relationships. A concept map contains three elements: concepts, directed lines connecting concepts and linking words describing the connection. These three elements create a fundamental unit of meaning or a proposition. For example, "engineering leads to experimentation" is a proposition. Figures 1 and 2 represent two different concept maps structures. Figure 1 is a hierarchical structure with a superordinate concept and tiers of increasingly subordinate ideas and examples [2]. This map is read "top-down." Figure 2 is a non-hierarchical array. The former superordinate concept "concept maps" is directly linked to multiple concepts simultaneously.

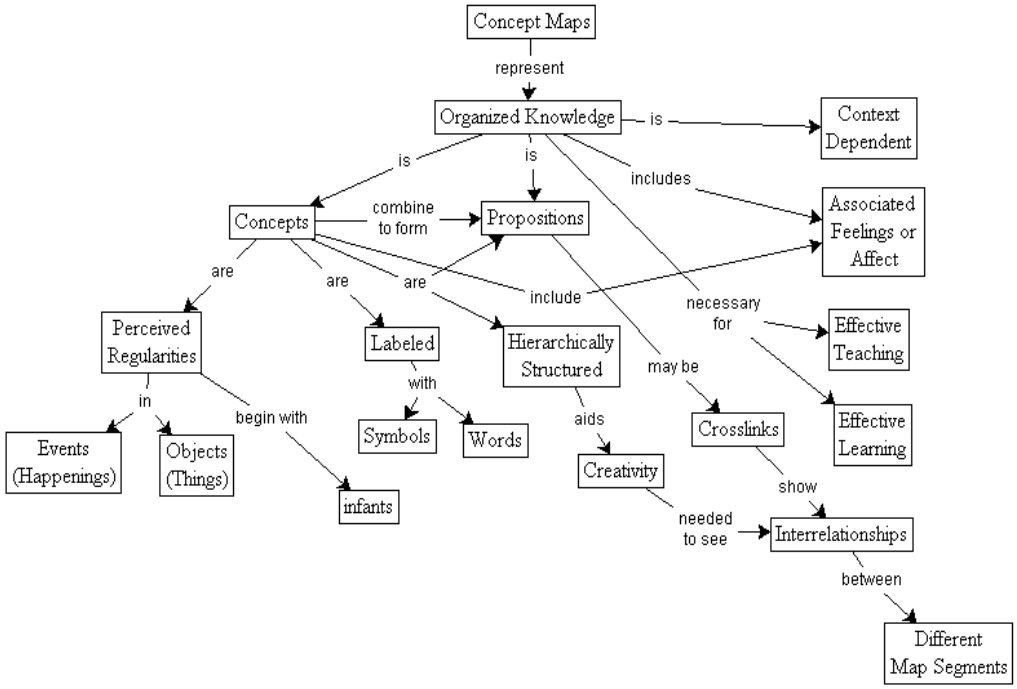

Figure 1. Example of hierarchical concept map [2].

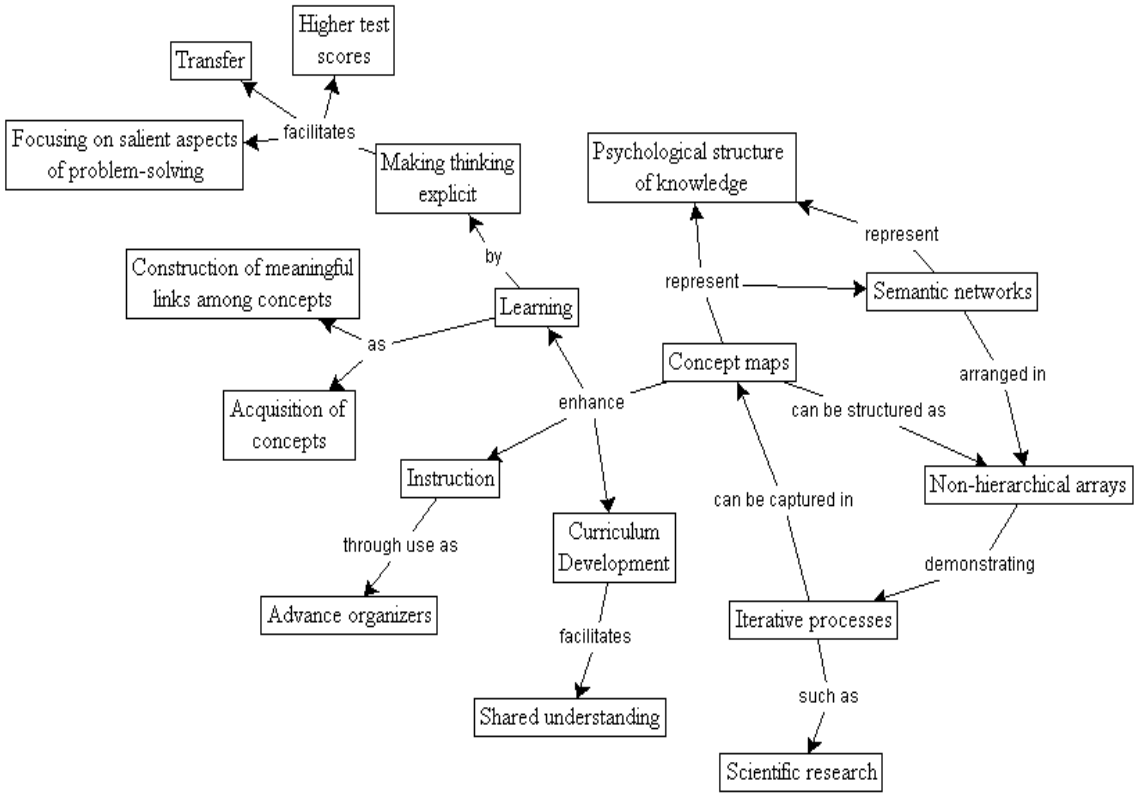

Figure 2. Example of non-hierarchical concept map.

Regardless of their structure, map elements identify key concepts and define the nature of their relationships (i.e., direction and quality). Clear map segments suggest knowledge differentiation while crosslinks among segments suggest knowledge integration. Because the technique is a useful way of making thinking explicit, it has been used as a teaching tool, an assessment tool, and a tool for curriculum development [3-8]. In this study, we used concept mapping to identify expert and student conceptions of the biomedical engineering design process, and as a tool for supporting students' awareness of their developing conceptions of design.

Cognitive psychologists' have argued that people's theories about a phenomenon manifest themselves in propositional representations [9] and that networked propositions are the bases for human reasoning [10]. Empirical work with concept maps supports these arguments. Research in a variety of fields has found that relative to novices, experts tend to construct dense, accurate networks which are coherently organized [3, 7]. These elaborate but efficient structures are thought to support experts' superior problem-solving abilities [11, 12]. By contrast, novices' limited knowledge and experiences can lead them to have incorrect, inconsistent or incompatible misconceptions [13]. In our own work in the field of biomedical engineering, we have noted that the structure and content of student maps change over time [7]. Consistent with constructivist learning theory [14, 14], this work suggests that learning involves not only acquiring new knowledge but also reconciling new knowledge with existing knowledge.

Within the field of engineering design, there is evidence that novices think in ways that may interfere with their ability to effectively enter the professional design community [16, 17]. For instance, when asked to define the design process novices often highlight the role of creativity while diminishing the importance of evaluation and revision. Further, when solving design problems, novices tend to seek less information and decompose problems into parts rather than focusing on the conceptual whole. They also tend to generate fewer hypotheses and reason less with conceptual models. Because they do little exploration and elaboration of the design space, it appears that novices tend to think of design as a linear process from ideation to product rather than as an iterative process. Finally, novices have a tendency to design for themselves rather than considering the constraints of the user.

These findings were obtained through a variety of methods including, problem-solving activities in which students "think aloud," observation of design teams, critiques of design solutions, and pictorial concept maps. In this study, we focused on concept maps because we wanted to not only assess students' conceptions relative to experts, but also to support educators' efforts in the classroom. Educational research has shown that helping students become aware of and criticize their tacit frameworks or assumptions promotes learning [18]. We capitalized on the power of concept maps as a tool for reflection by archiving students' representations over time, and then asking them to comment on the similarities and differences between their initial and final maps.

In sum, we posed three questions: (1) What are key concepts in the biomedical engineering design process? (2) Are there developmental differences in people's conceptions of the design process? (3) If so, then what do these differences mean for bioengineering education? We expected experts' maps to provide a meaningful framework for understanding the development of expertise. Specifically, we expected that, relative to students, expert maps would have more content, more accurate propositions, and have more densely networked concept across a wider breadth of categories. Over time, we expected student maps to increase in content and complexity.

Methods

Because expertise has not been systematically defined in this area, our first task was to determine how experts define the design process. Our second task was to examine students' definitions relative to an expert benchmark. The following sections reflect these objectives. We describe our work with experts as Study 1. Under the heading of Study 2, we describe our work with students and how expert data were used as a benchmark to evaluate student development during a two-semester biomedical engineering design course.

Study 1

Expert participants

We began by soliciting expert participants from a pool of experts in academia and industry; the second author and fourth authors invited approximately 60 design colleagues to participate via electronic mail. From this pool, 15 experts consented to participate. Ten participants had doctoral degrees, 3 had graduate degrees and 2 had

completed undergraduate programs in various engineering disciplines. Fields of specialization included BME (n = 8), mechanical engineering (n = 2), and the remaining five had various training (e.g., computer science, industrial engineering). Participants had an average of 9 years experience in academia, 11 years in industry and 10 years in teaching or supervising design. Nine of the participants had industrial and academic experience.

Procedures for experts

Because our experts were located across the globe, orientation procedures and data collection was conducted electronically. Specifically, participants were sent an electronic letter that explained the study, described the concept mapping procedure (see Appendix A), and provided a web link to a tutorial on how to build a concept map. Experts were asked to respond to the focus question, "What is your current conceptual understanding of what is involved in the BME design process?" Once constructed, maps were sent electronically to the first author. Participants also provided basic demographic information and a brief description of how their map reflected their professional history and understanding of the biodesign process.

Data analyses and results for experts

All maps were analyzed by the second and fourth authors. Blind to the identity of the map authors, these raters counted the number of concepts and lines in each map. Because network density has been associated with expert knowledge structures, a line:concept ratio was calculated by dividing the number of lines by the number of concepts. To evaluate the accuracy of map propositions we used a modified version of a relational scoring method [19] in which the validity of each map's proposition is evaluated based on the correctness of the linking word. We awarded no points for an invalid or misconceived link; 1/2 point for a partially valid, general or imprecise link; and 1 point for a valid, precise, and clearly stated link. A validity ratio was calculated by dividing the sum of these points by the total number of propositions. Inter-rater reliability on these metrics was acceptable (r = .80, range = 0 to 1). Expert maps contained an average of 26 concepts (M = 26.23, SD = 15.37), 33 lines (M = 32.97, SD = 17.78), and 1 line per concept (M = 1.31, SD = .25). Variability in these structural elements was considerable (concept, range = 13-60; line, range = 15-75, density, range = 1.04-1.86). The validity of map propositions was high (M= .83, SD = .22, range = 0 to 1).

Given the variability in our sample, we identified a subset of maps for more intensive analyses. Eight maps were selected on the basis of their relatively high validity scores (M = .93, SD = .03; range = .88-.97) and general coherence. These maps contained an average of 29 concepts (M = 29.19, SD = 14.06, range = 16-52), 37 lines (M = 37.06, SD = 14.49, range = 24-61) and 1 line per node (line:node, M = 1.35, SD = .27, range = 1.04-1.86). Of these eight experts, 6 had doctoral degrees; the 7th had a graduate degree, the 8th a bachelor's degree. Degree disciplines included biomedical engineering (n = 5) and 3 others (e.g., engineering science, mechanical engineering, computer science). This group had an average of 11 years experience in academia, 15 years in industry and 7 years teaching or supervising biodesign. Figure 3 is an example of one expert's map.

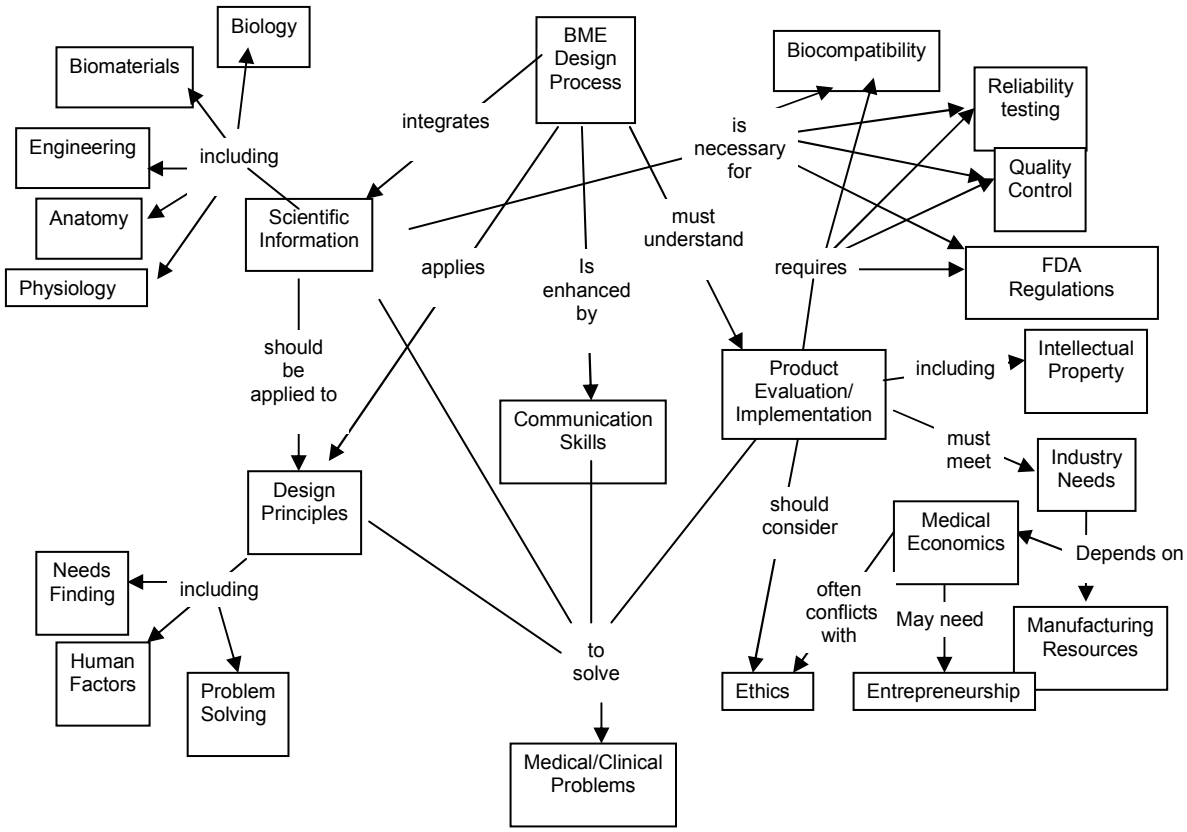

Figure 3. One expert's map of the biomedical engineering design process.

Content analyses of expert maps

To understand what these 8 maps contained, we wrote each concept on an index card; identically worded concepts were not counted. This yielded a set of 78 concepts. The first and second authors then sorted these cards based on their conceptual similarity. From this process, 6 categories emerged: the design process (e.g., product definition, prototyping), interpersonal skills, technical background, motivation for the design, marketing and overriding societal concerns (i.e., ethics, regulation). The first and second authors then reviewed each concept card with an eye toward eliminating conceptually similar ideas within these categories. For example, 'personal skills' and 'communication skills' were collapsed into the single term 'communication skills.' This process yielded a reduced list of 42 concepts. Iteration between specific concepts and concept categories continued until the full list of concepts was reduced to a set of 27 unique biodesign concepts (see Appendix B). We view this set of concepts and categories as a biodesign taxonomy.

Theoretically, densely networked concepts are more well-defined concepts [21]. Using this premise to validate our selection of key concepts, the first author identified the most densely networked concepts in each of the 8 maps. Concepts with 4 or more lines directed toward or away from them were identified. Across maps, the most densely networked ideas related to the design process itself. For instance, concepts such as "product definition" and "prototyping" were connected to other concepts by an average of 6 lines. Other densely networked ideas pertained to three surrounding issues: scientific

knowledge and skills, understanding of regulatory requirements, and core competencies such as teamwork. In general, this analysis supports our concept categories.

Finally, we turned our taxonomy "on itself" by examining the extent to which our 8 expert maps represented its ideas. Specifically, the second author and an industry expert examined the maps for references to the 27 identified concepts. Semantic similarity, not exact terminology was required. For instance, if both technical skills (e.g., "computer programming skills") and technical knowledge (e.g., "biology") were mentioned, then the map received a 100% coverage rating. If only one of these concepts was represented then a 50% coverage rating was given. Table 1 summarizes descriptive statistics across the six categories. Inter-rater reliability was acceptable (r = .85, range = 0-1).

Table 1. Means, standard deviations and ranges for percentage of concept coverage among 8 expert mappings (possible range = 0-1).

	Design process	Interpersonal skills	Technical background	Motivation for design	Marketing	Ethics
M	.40	.29	.44	.42	.35	.46
SD	.19	.33	.40	.22	.30	.29
Actual range	.10-.66	0-.84	0-1	0-.67	0-.67	0-.84

In sum, we asked a group of 15 experts in academia and industry to represent their thinking about the biodesign process in concept map form. We then extracted ideas from their representations to create a taxonomy of biodesign and benchmarks of expertise. Consistent with research in engineering design [16, 17], we found that experts tended to view the design process an iterative cycle (e.g., frequently used concepts such as product definition, prototyping) intended to meet a user's needs (e.g., noted client needs, scientific needs). Our findings also showed that experts tended to situate the design process in a social context, often mentioning issues related to ethics, marketing and interpersonal skills required for success in the workplace.

Study 2

Student participants

As part of their course requirements, 51 students enrolled in a capstone design course at Vanderbilt University were asked to construct concept maps. Students were given the same focus question that was presented to experts (i.e., "What is your current conceptual understanding of what is involved in the BME design process?"). Maps were given as homework assignments at three time points across two semesters. Complete data (i.e., maps for all three time points) was obtained for 32 students (participation rate = 63%). These students had spent an average of one summer in industry (M = 1.41, SD = .67) or laboratory settings (M = 1.28, SD = .67), and summer school (M = 1.30, SD = .66).

Procedures for students

During the second week of the first semester, the first author visited the class and gave students a brief orientation to concept mapping. Students were given a chance to ask any

clarifying questions about the technique and directed to the same web-based tutorial provided to experts. Once the orientation was concluded, students received their first homework assignment: Construct a concept map responding the question, "What is your current conceptual understanding of what is involved in the BME design process?"

Shortly before the final exam at the end of the fall semester, students constructed a second map focused on this same question. Students were allowed, and encouraged, to use this map as a study guide and final exam "cheat sheet." The exam marked the end of regular classroom instruction. During the spring semester, instead of attending class, students meet regularly in design teams, and with the course instructor and an advisor to develop a design project. Students completed a third map focused on the same question at the end of the spring semester, a time coinciding with their presentation of their design project and the composition of a final paper. At this time, we asked students to reflect on and summarize, in writing, how their final map compared to their initial map.

Data analyses and results for students

Analyses are identical to those described for expert mappings. Two raters counted the number of concepts and lines, and calculated a density ratio (i.e., number of lines per node). Raters were blind to the identity of the map author and the time point at which the map was constructed. Inter-rater reliability on these metrics was acceptable (r = .83, range = 0-1). Table 2 summarizes descriptive statistics for these dimensions of student maps over time.

Table 2. Means, standard deviations and ranges for the number of concepts and lines, density of network, and proposition validity of student mappings.

	Time 1		Time 2		Time 3	
	M	SD	M	SD	M	SD
Concept	16.47	4.62	34.19	12.34	20.92	9.40
range	*11-34*		*13-54*		*8-54*	
Line	19.58	6.16	39.38	13.99	24.91	11.44
range	*13-39*		*17.5-70*		*8-57*	
Density	1.20	.22	1.18	.20	1.21	.23
range	*.93-2.11*		*.94-1.63*		*.92-1.97*	
Validity	.93	.14	.88	.19	.88	.22
range	*.49-1.00*		*.24-1.00*		*.25-1.00*	

To determine trends for time in these map elements, we conducted one-way repeated measures analyses of variance (ANOVA). These analyses showed significant linear and quadratic trends for the number of concepts and lines (concepts: linear, $F [1, 31] = 8.20$, $p < .01$; quadratic, $F [1, 31] = 74.58$; lines: linear, $F [1, 31] = 8.05$, $p < .01$; quadratic, $F [1, 31] = 67.19$, $p < .01$). No significant trends were found for density and validity. The average line:concept ratio or network density was consistently low while the average validity of map propositions was high.

These data partially confirmed our expectations. Significant increases in the number of concepts and lines suggested that students gained conceptual knowledge about the design process during the first semester. However, stability in the validity of map propositions suggested that students did not necessarily develop a deeper understanding of associations among concepts. This may, however, be due to a ceiling effect or little room for scores to increase. Further, while we expected a steady increase in these map elements, we found significant quadratic trends. We suspect the increases observed at Time 2 stem from the fact that students constructed their maps more carefully. That is, Time 2 maps were constructed as a study aid for the final exam.

We also analyzed the content of student maps using the design taxonomy generated in our work with experts. Our two raters examined student maps for the presence and absence of the 27 key concepts. Consistent with our analyses of expert maps, the percentage of semantically similar concepts represented in the student map or "coverage" of the domain taxonomy was calculated. Because we are still in the process of obtaining inter-rater reliability on student maps, it should be noted that the analyses reported here are based solely on the ratings of the second author. Findings should be interpreted with this in mind.

One-way repeated measures ANOVAS showed significant within-subjects trends for time. These are summarized in Table 3. Suggesting growth in student understanding over the two-semester course, there were linear trends for the categories of the design process, interpersonal skills, motivation for the design, and ethics. A quadratic trend was also found for the design process and for ethics. Again, these quadratic trends may reflect greater student investment in the construction of Time 2 maps. We now turn our attention to comparison of expert and student maps.

Table 3. Results of one-way repeated measures ANOVA testing trends for time in categorical content of student mappings.

	F linear	F quadratic
Design process	7.05*	16.13***
Interpersonal skills	5.74*	ns
Technical background	ns	ns
Motivation for design	4.77*	ns
Marketing	ns	ns
Ethics	16.1***	33.39***

* = $p < .05$; ** = $p < .01$; *** = $p < .001$

Comparing experts and students

How did experts and students compare? With regard to structural elements, t-tests assuming unequal variance showed that at Time 1 expert maps had significantly more concepts and lines than did students (node, $t[7]= 2.52$, $p < .05$; lines, $t[8]=3.34$, $p < .05$); however, experts and students did not differ in density or validity. There were no

statistically significant expert-student differences on any of these dimensions at Time 2. Results for Time 3 were similar to Time 1, t-tests assuming equal variance showed that experts had significantly more lines and concepts (lines, $t[38]=2.60$, $p < .05$; concepts, $t[38]= 2.01$, $p < .05$), but did not differ from students in density or validity.

Table 4 summarizes the percentage of content coverage across the 6 categories for experts and for students; it also summarizes t-tests and p values regarding student-expert comparisons. At the beginning of the design course, students and experts placed equal emphasis on two areas: interpersonal skills and technical skills. Students differed from experts in four areas: the design process, motivation for the design, marketing and ethics. The biggest difference pertained to motivation for the design process. At the end of the first semester (Time 2), students closed the expert-novice gap in five of the six areas. The only difference pertained to marketing. These findings suggest growth in student understanding of the design process and its underlying motivational factors (i.e., client need, scientific need). At the end of their design experience (Time 3), students continued to differ from experts in two areas: marketing and ethics.

Table 4. Average percentage and t-tests comparing percentage of content coverage in expert and student and maps across the 6 identified categories.

	Design process	Interpersonal Skills	Technical Background	Motivation for design	Marketing	Ethics
Expert	.40	.29	.44	.42	.35	.46
Student						
Time 1						
M	.24	.16	.27	.16	.13	.10
t	2.30*	--	--	3.17*	2.21*	3.32**
Time 2						
M	.33	.36	.41	.38	.15	.60
t	--	--	--	--	2.09*	--
Time 3						
M	.30	.28	.40	.34	.11	.22
t	--	--	--	--	2.20^{+}	2.60*

-- = not significant, * = $p < .05$; ** = $p < .01$; $^{+}$ = approached significance ($p < .06$)

Student reflections on their initial and final maps

Because we were committed to using a research tool that also offered students a window into their own thinking, at the end of the course we asked students to identify and reflect on differences in their initial and final maps. Some student comments reflected initial skepticism about the value of the concept mapping task (e.g., "*I really didn't think that I would see big changes. But I can now understand").* Consistent with our previous work [7], many students commented that the design project offered them the opportunity to experience the culture of practice associated with design (e.g., *"I found myself relating my ideas with the textbook knowledge and applying that to my actual project. It surprised*

me that I didn't put much attention on certain topics when I constructed the first concept map").

Another student articulated the difference between his first and final maps in this way: *"The final concept map illustrates a more interactive, dynamic and complex relationship between the various concepts."* For this student, communication was the critical component in the design process (e.g., *"Although the ultimate goal is related to product or system, without effective communications the product or system could not be achieved"*). Examples of this student's work at the beginning and end of the course are presented in Figures 4 and 5.

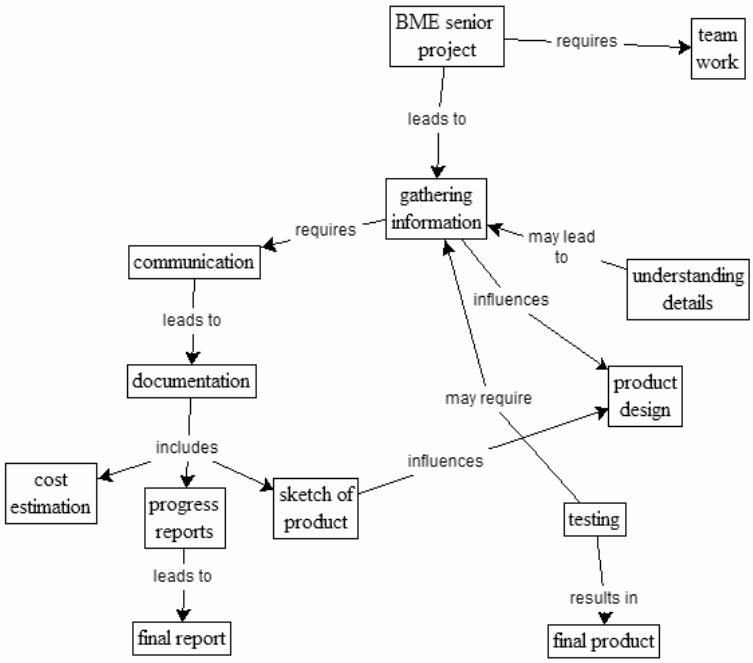

Figure 4. One student's map at the beginning of the design course.

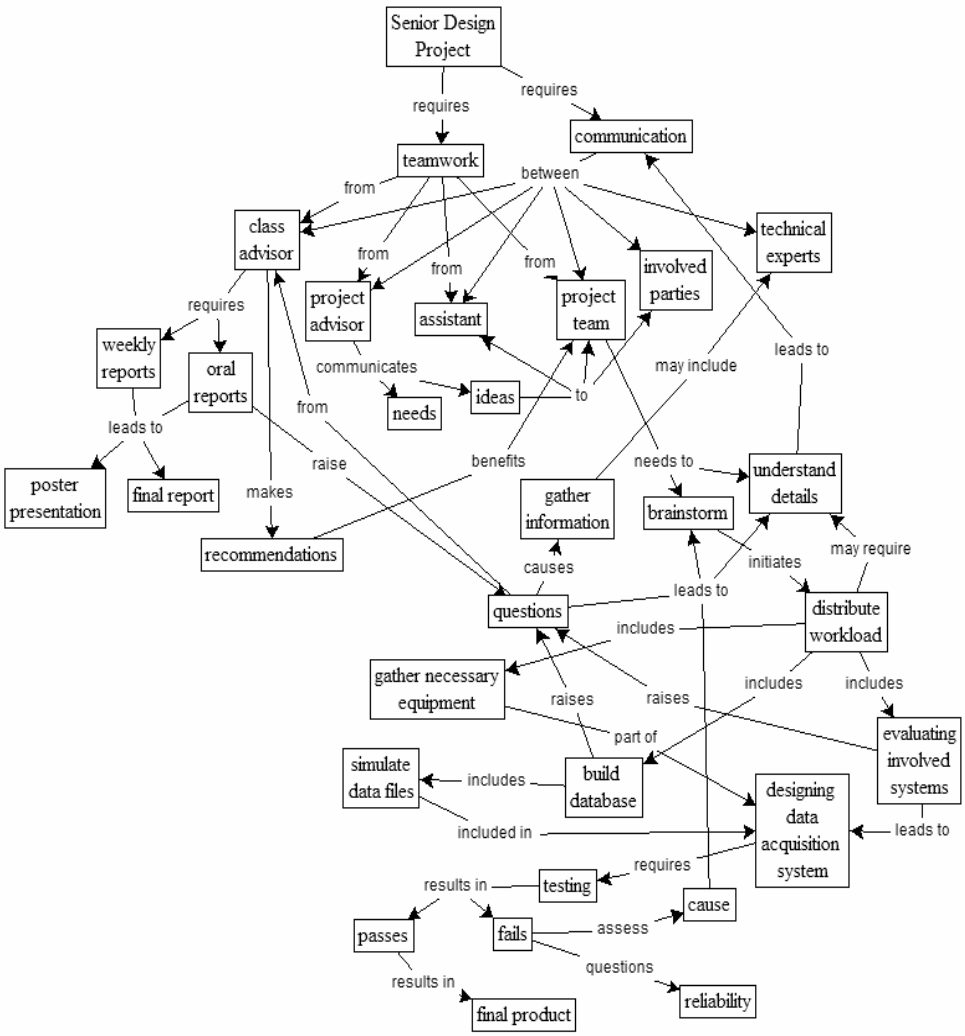

Figure 5. The same student's mapping at the end of the design course, approximately 7 months later.

In sum, quantitative analyses showed that students increased their knowledge of the design process; however, they did not appear to have greater knowledge integration (i.e., density did not change) or accuracy (i.e., validity did not change). Content analyses revealed similarities and differences between experts and students. These trends offer insight into the development of expertise in design. In the next section, we discuss the study's implications for psychological understanding of expertise and for educators' efforts to enhance students' conceptual and professional development.

Discussion

This study used concept maps to identify key concepts in the biomedical engineering design process and reveal developmental differences between expert and student conceptions. Despite considerable within-group differences, experts consistently

demonstrated a more comprehensive and differentiated understanding of the design process than did students. For instance, in addition to focusing on the design process itself, experts attended to issues in the surrounding social context, including understanding the need for the design, ethics, interpersonal skills (e.g., teamwork, management) and marketing. These findings offer an important avenue for understanding the nature of expertise. That is, they suggest that experts have a more developed understanding of the social context in which a design and designers function.

Findings also suggest areas in which biomedical engineering design educators might focus their attention to students' professional development. Over time, student conceptions of the design process became more expert-like in some areas and remained unchanged in others. Specifically, students were similar to experts in their references to interpersonal skills and technical skills and knowledge. Over the year, the gap between experts and students closed in two areas: the design process, and motivation for the design. Students made consistently fewer references to issues of ethics and marketing.

Essentially, our study shows that students moved from 'this to that.' What we want to know more about is the processes underlying these changes. How do you "build an expert?" Is expertise a mode of reasoning that can be readily acquired or does it require substantial amounts of domain knowledge and years of experience to master? Put another way, even if we know the "wisdom" of design, can we translate it into educational experiences that accelerate student development?

Our current hypothesis is that the expert-novice gap is closed when students increase their domain knowledge *and* bring that knowledge to bear on an authentic medical problem in a realistic way (i.e., work in teams, consult with experts in multiple disciplines, think through the design process from ideation to implementation). Thus, we view students' initial maps as their assumptions about the design process. Their second maps reflect an abstracted knowledge grounded in course readings and lectures. Their final maps are the most expert-like. We believe these representations differ from initial maps because they reflect the voice of experience and an internalized knowledge of what it means to design something.

We are currently extending our work in several ways. For instance, students are being asked to create a concept map of their senior design project and relate it to other technologies that visually represent design problems. To explicitly tap students' design competence, we are evaluating student responses to design scenarios. Further, students are evaluating former design projects (projects are pre-selected and represent excellent and average designs). We think this task will help students understand the requirements for their own project and, by providing contrasting cases, offer an opportunity to reflect on and articulate hallmarks of good design. Finally, given that students' conceptions of design develop through experience, we are developing "virtual" experiences that simulate issues pertinent to design and professional development (add wisdom cite here).

With regard to the use of concept maps as a form of assessment, the development of our taxonomy yielded an ability to assess map contents. This is a significant development.

However, given concerns about concept mapping as a form of assessment [21, 22], we are testing the validity of our taxonomy by comparing our findings to results derived from rubrics used by other design educators. Given that our current assessment of proposition validity does not appear to discriminate novice and student conceptions, we are also developing a means of assessing the quality of map propositions. This may require rescaling our existing assessment or establishing categories of appropriate and less appropriate linking words.

We are also seeking a way to express the more holistic nature of people's thinking about design (i.e., does it appear to be a linear or iterative process?). For example, we are characterizing maps in terms of the extent to which they describe the design process (i.e., is it to the design level, prototype level?). Further, analyses of student maps reflected some misunderstanding of basic issues such as human factors. Thus we are developing instruction and assessment methods that address such misconceptions. We are also developing instruction that helps students identify with the multiple perspectives associated with a design team (e.g., engineering, marketing). These are just two examples of how concept maps can be effective as research tools and as diagnostics for educators.

Finally, grounded in studies of *in vivo* problem-solving and collaborative cognition [23, 24], we are also comparing what people say about the design process with what they actually do when designing something. Specifically, we are studying how three student design teams form, and how they select and attempt to solve a real medical problem. Among the questions we are pursuing are: What does effective and less effective individual and team performance look like? What kinds of cognitive processes do teams engage in and how are they supported or frustrated by peer interaction? Further, because developing the project involves regular interactions with the course instructor and a project advisor, the study offers a window into the narrative of apprenticeship or how experts represent their wisdom to students and how students, in turn, act upon that information.

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Appendix A

How to build a concept map

1. Think about the focus question you have been given, and identify 10 to 20 of the most pertinent concepts (single words or three words at most). List these concepts on a piece of paper, and then write each one on a separate post-it note.

2. There are two options for arranging your post-it notes.
    - Your map can be structured hierarchically by placing the most inclusive, most general concept(s) at the top and less important concepts at the bottom (see Figure 1).
    - Your map may also be constructed as a non-hierarchical network. In this case, there is no superordinate concept; the map is structured like a web (see Figure 2).

3. Now begin arranging your post-it notes.
    - If your map is hierarchical, place less important concepts under the more general concepts. In other words, if someone else read the map they would move "top down" from the most to the least important ideas.
    - If your map is non-hierarchical, array the concepts according to their degree of relatedness. The map would read in a non-linear fashion.

Note: Sometimes people change their minds about the map's overall structure as they begin arranging the concepts. Whatever structure you prefer is fine. There are not right or wrong constructions.

4. Flip over the piece of paper on which you wrote your list of concepts and draw your array of post-it notes on it.

5. Think about which concepts are related. Connect related concepts with lines.

6. Label the lines with one or a few linking words. Linking words should define the relationship between the two concepts. For example, "involves" and "leads to" are linking words.

7. Each pair of linked concepts should read like a sentence. For example, the concepts "engineering" and "experimentation" could be linked by the words "leads to." This creates the statement "engineering leads to experimentation."

8. Add arrowheads to the lines between the concepts to indicate the direction of the relationship. Depending on the nature of the concepts' relationship, lines can have single or double arrowheads. For example, the proposition "engineering leads to experimentation" would have a single-headed connecting arrow between engineering and experimentation. Other concepts may be mutually influential (bi-directional). Use double-headed arrows to depict this relationship.

Appendix B

Concepts Extracted from Expert Maps

Design process
process
protocols
innovation and originality
useability analysis
project schedule
prototype
design review
hazard analysis
validation and verification
product
literature review
trials
manufacturing

Technical background
technical knowledge
technical skills

Motivation for design
medical/clinical problem
customer needs
scientific needs

Interpersonal skills
communication skills
teamwork
management skills

Market constraints & opportunities
market analysis
return on investment
industry needs

Overriding societal concerns
regulatory requirements
regulatory agencies
bioethics

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