Expert and Student Conceptions of the Design Process: Developmental Differences with Implications for Educators*

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These studies identified key concepts and developmental differences in people's conceptions of the engineering design process. The method of assessment was concept mapping. Key concepts were derived from the concept maps of 15 experts and organized into six broad categories. Expert data served as benchmarks for assessing the conceptual development of 32 undergraduates who constructed individual maps at the beginning and end of a year-long design course. In general, students' conceptions tended to be more narrow, with consistently fewer references to larger societal issues such as ethics and marketing. Over time the expert–student gap closed regarding knowledge of the design process and the motivations underlying a design (e.g. customer need, scientific need). Findings suggest that an important difference between experts and students is that experts are more likely to situate the design process in a sociocultural context.

INTRODUCTION

IF EDUCATORS want students to learn to think like experts then we need to learn how experts think. Research across a variety of fields has suggested that experts differ from novices in several important ways. For example, Chi and her colleagues found that novices organized physics problems based on how they looked (e.g. involved inclined planes) whereas experts organized problems according to major principles (e.g. conservation of energy) [1]. Chase and Simon found that both chess masters and novices failed to recall random configurations of pieces on a board; however, when they were assembled in meaningful arrays experts were much more likely to remember them [2]. This work suggests that experts not only differ from novices in terms of how much they know, but also in how they organize and use their knowledge. Evidence that experts tend to organize their knowledge in 'chunks', often around abstract relational dimensions, is also consistent with psychological theories arguing that knowledge is structured as sets of linked ideas or propositions [3] which, in turn, are the bases for human reasoning [4].

Another important feature of expertise is that it is domain-specific. Expertise in one area does not necessarily guarantee expert performance in another [5, 6]. The set of studies described here focus on expertise in the domain of bioengineering design. A variety of methods have been used to explore how people reason about engineering design including asking people to 'think aloud' as they engage in design activities, critiquing the solutions of others, and observing people as they solve design problems *in situ* [7–9]. This work has identified patterns in students' thinking, some of which may interfere with their ability to enter the professional design community. For instance, expert designers tend to take a top-down, breadth-first approach in which varied approaches are considered [10, 11]. By contrast, less-experienced students tend to do little exploration and elaboration of the design space, often 'getting stuck' modeling a single alternative solution rather than considering many alternatives [8]. More advanced students advance to later stages of the design process (e.g. decision-making and project realization) without spending significantly more time in the earlier stages of problem definition [8]. Further, when asked to define the design process, students often emphasize the role of creativity more than iterative processes such as evaluation and revision; they also appear to design for themselves rather than considering the needs and constraints of the user [7].

While this work has been invaluable in identifying the cognitive processes of experts and students, we have a limited understanding of the nature of design expertise and how it develops. As part of a larger research program dedicated to enhancing undergraduate engineering education we sought to establish a method for identifying what experts regard as key design concepts and how they organize those concepts. In turn, we applied experts' performance as benchmarks in assessing the level of expertise attained by undergraduates during a year-long senior design course. Our overarching goal is to articulate a model of design cognition, which can then be used to inform

educational practice (e.g. determine areas of strength and weakness in student understanding).

A significant challenge to researchers interested in the novice-expert shift is establishing valid and reliable ways of capturing and representing what people know, how they apply their skills, and how their performance varies over time and with experience [12–14]. In this study, we used a method that would allow us to assess the breadth and organization of experts' and students' knowledge about design *and* support student learning. That method is concept mapping. Concept maps are useful for capturing the contents and organization of someone's knowledge because they 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 unit of meaning or a proposition. For example, 'engineering involves experimentation' is a proposition. Invented by Joseph Novak and his colleagues in the 1970s [15], concept mapping emerged from the need to summarize extensive interview data about K-12 students' understandings of science concepts.

There is evidence that the nature of concept mapping tasks and response formats tap different aspects of cognitive structures [16]. For instance, results vary depending on whether students construct their own networks or 'fill-in-the-blanks' of pre-structured networks [17]. Thus, assessment of knowledge structures should be consistent with how we assume knowledge is organized. Figures 1 and 2 represent two different concept map structures. Figure 1 is a hierarchical structure with a superordinate concept and tiers of increasingly subordinate ideas and examples [18]. This map is read largely in a 'top-down' fashion and assumes that new information is subsumed under more general concepts. Figure 2 is a non-hierarchical array. The former superordinate concept 'concept maps' is directly linked to multiple concepts simultaneously and in different directions.

Regardless of their structure, map segments suggest knowledge differentiation while links among segments suggest knowledge integration. These features of concept maps are especially important because they are consistent with constructivist perspectives [19, 20, 21], which argue that learning is not only acquiring new knowledge but also restructuring existing knowledge to accommodate new information. For instance, research in numerous fields has shown that as students gain knowledge, their concept maps tend to become more densely networked, accurate (i.e., contain more precise vocabulary), and coherently organized [22–26].

Elsewhere, we have described our initial investigations of concept maps as a tool for assessing [26]:

- expert–student differences in the field of biomedical engineering;
- the development of students' thinking about the design process.

Conducted with a small sample of students and faculty at Vanderbilt University, this work focused on quantifying the amount of information in people's maps (i.e. number of concepts and links) and comparing the extent to which their ideas were integrated (i.e. density of network or link/concept ratio). While suggesting important novice-expert differences, this work did not inform our understanding of the *quality* of the ideas contained in student and expert maps. Further, because students constructed maps in pairs, we were unable to evaluate changes within individual students' understanding.
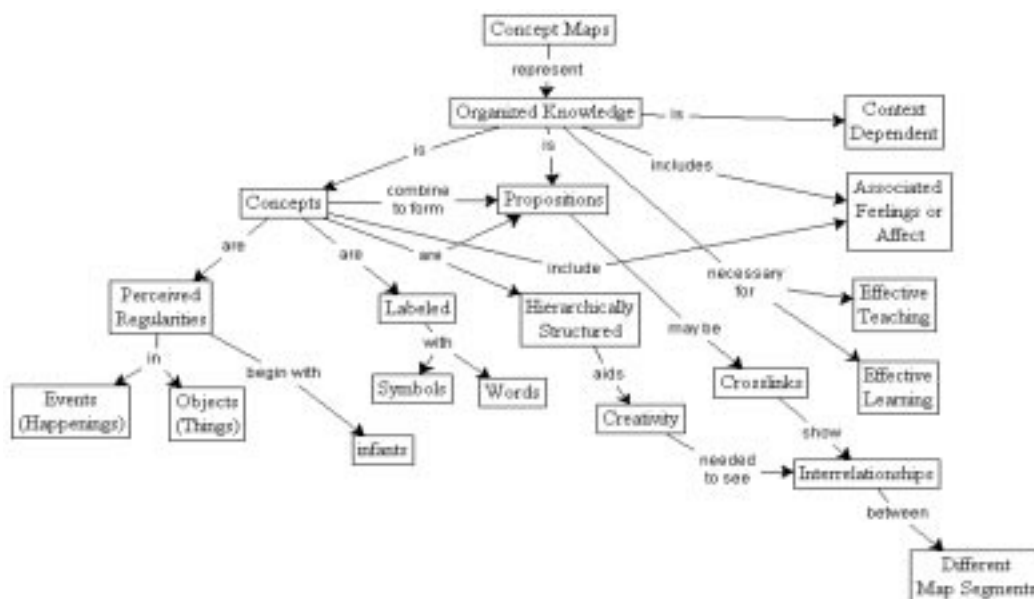

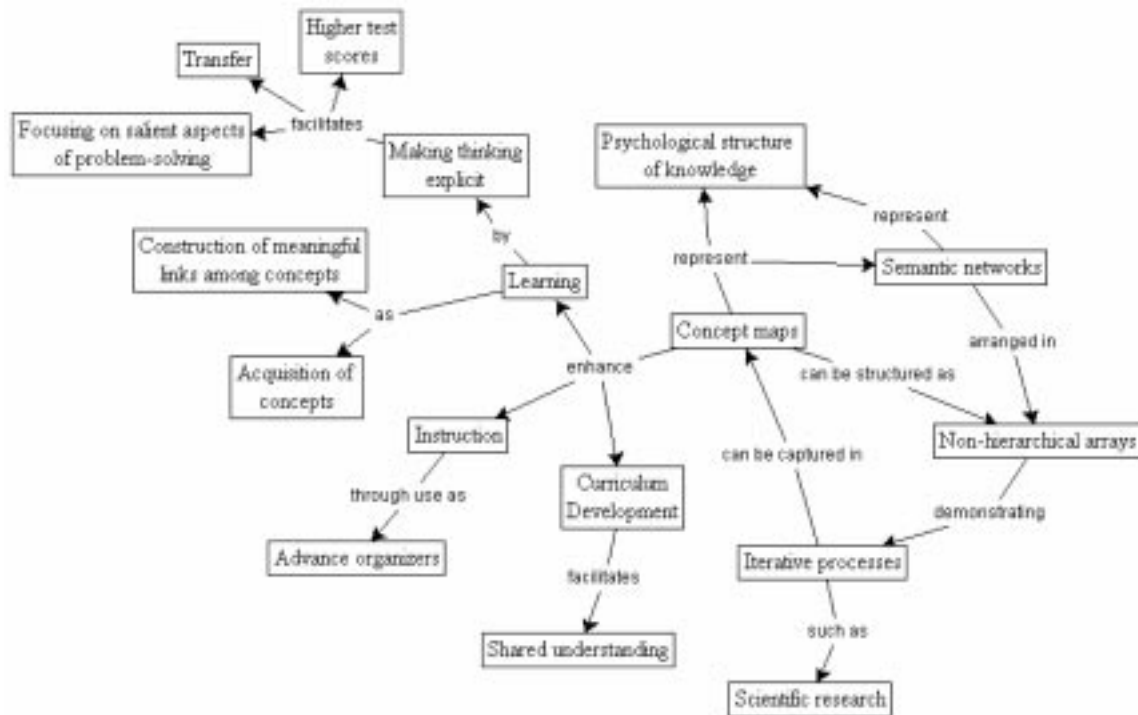Fig. 1. Example of hierarchical concept map [2].

Fig. 2. Example of non-hierarchical concept map.

We address these limitations in several ways. First, we replicated our original study with a larger sample of experts and students, and all maps were constructed by individuals, not pairs. Second, to identify the 'wisdom' of design, we established a method for identifying and categorizing concepts. Finally, given that raising students' awareness of their tacit frameworks for thinking is an important means to enhanced learning [27, 28], we leveraged the power of concept maps as a tool for student reflection. Specifically, we archived students' representations over time, and then asked them to comment on the similarities and differences between their initial and final maps. Although our primary goal was articulating the breadth of people's design knowledge, we also wanted to use a method of assessment that was meaningful to students and could be embedded easily into the existing class structure.

In sum, we posed two questions:

1. What are key concepts in the engineering design process?
2. Are there developmental differences in people's conceptions of this process?

Both questions were designed to inform theoretical understanding of design expertise and design education. Based on the literature, we expected that relative to the maps of students, experts' maps would contain a greater breadth of ideas arrayed in more accurate and densely networked propositions. Over time, we expected student maps to increase in breadth, accuracy and complexity.

We describe our work with experts as Study 1. Under the heading of Study 2, we describe our work with students. We conclude with a comparison of the two groups.

STUDY 1: EXPERT PARTICIPANTS

We began by soliciting participants from academe and industry; the third and fourth authors invited approximately 60 colleagues to participate via electronic mail. From this pool, 15 experts consented to participate. Ten participants had doctoral degrees, three had graduate degrees and two had completed undergraduate programs in various engineering disciplines. Fields of specialization included biomedical engineering (n = 8), mechanical engineering (n = 2); the remaining five had various training (e.g. computer science, industrial engineering). Participants had an average of 8 years experience in academe (range = 0–20), 11 years in industry (range = 0–28), and 10 years in teaching or supervising design (range = 0–21). Seven participants had industrial and academic experience. One participant was female.

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 biomedical engineering 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 third and fourth authors. Blinded to the identity of the map authors, these raters counted the number of concepts and links in each map. Because network density has been associated with expert knowledge structures, a link/concept ratio was calculated by dividing the number of links by the number of concepts. Expert maps contained an average of 26 concepts $(M = 26.23,\ SD = 15.37)$, 33 links $(M = 32.97,\ SD = 17.78)$, and one link per concept $(M = 1.31,\ SD = 0.25)$. Variability in these structural elements was considerable (concept, range = 13–60; link, range = 15–75; link/concept ratio, range = 1.04–1.86). Inter-rater reliability was acceptable (node, $r = 0.99$; link, $r = 0.99$; link/concept ratio, $r = 0.96$; range = 0 to 1). Figure 3 is an example of one expert's map. Eight of the 15 maps were structured as hierarchies; one resembled a flow chart and the remaining five were structured as networks.

To evaluate the accuracy of map propositions, we used a modified version of a relational scoring method [29] where the validity of each proposition is evaluated based on the correctness of the linking word. We awarded no points for an invalid or misconceived link; ½ 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. The average validity ratio of map propositions was high $(M = 0.83,\ SD = 0.22,\ \text{range} = 0\ \text{to}\ 1)$; our two raters had acceptable agreement $(r = 0.80,\ \text{range} = 0\ \text{to}\ 1)$.

The variability in our sample was consistent with the idea that expertise is in itself quite variable [30]. For this reason, we focused on identifying a subset of expert maps with relatively high density, validity, and holistic ratings. We also used demographic information in the selection process, focusing on identifying participants with higher levels of education and experience. Upon review, we selected a subset of eight maps for more intensive analysis. One of these experts was female, six had doctoral degrees; the 7th had a graduate degree, the 8th a bachelor's degree. Degree disciplines included biomedical engineering $(n = 5)$ and three others (e.g. engineering science, mechanical engineering, computer science). This group had an average of 10 years experience in academia (range = 0–29), 14 years in industry (range = 0–28), and seven years teaching or supervising design (range = 2–13). Five of the selected maps were structured as hierarchies; three were networks. Table 1 summarizes descriptive statistics and inter-rater reliability coefficients for the subset of expert maps.

Content analyses of expert maps

To identify key concepts, we wrote each concept contained in each of the eight experts' maps on a separate index card. This yielded a set of 78
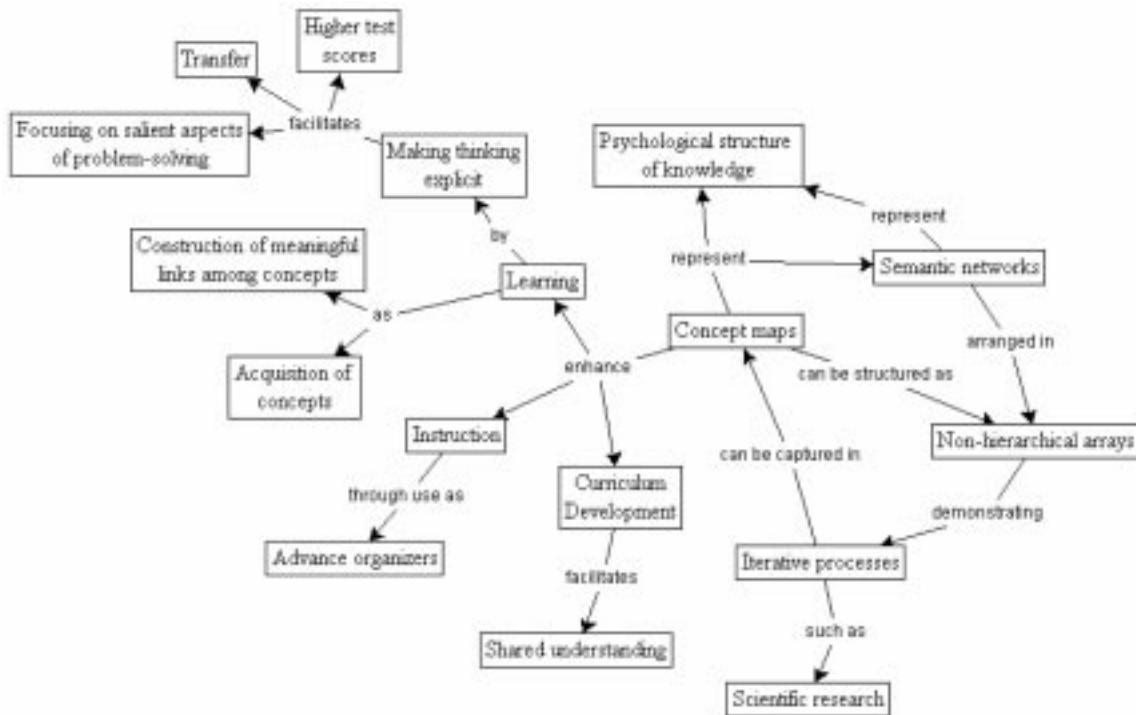

Fig. 3. One expert's map of the biomedical engineering design process.

Table 1. Descriptive statistics and reliability coefficients for concepts, links, network density and proposition validity for selected expert maps and student mappings at each time point

	Concepts		Links		Density		Validity ratio	
	M	SD	M	SD	M	SD	M	SD
Expert	29.19	14.06	37.06	14.49	1.35	0.27	0.93	0.03
Range	16–52		24–61		1.04–1.86		0.88–0.97	
Reliability	0.99		0.99		0.96		0.80	
Student, Pre	16.47	4.62	19.58	6.16	1.20	0.22	0.93	0.14
Range	11–34		13–39		0.93–2.11		0.49–1.00	
Reliability	0.94		0.95		0.63		0.20	
Student, Post	20.92	9.4	24.91	11.44	1.21	0.23	0.88	0.22
Range	8–54		8–57		0.92–1.97		0.25–1.00	
Reliability	0.99		0.99		0.91		0.95	

concepts; identically worded concepts were not counted. The first and third authors then sorted these cards based on their conceptual similarity. From this process, six categories emerged: the generic design process (e.g. product definition, prototyping), interpersonal skills, technical background, motivation for the design, marketing, and overriding societal concerns (i.e. ethics, regulation). These same authors then reviewed each concept card with an eye toward eliminating conceptually similar ideas within 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). The majority of concepts pertained to phases of the design process whereas the remaining concepts pertained to issues surrounding the design process

and designers. Recognizing that no one individual's map is a complete representation of the field, we view this pooled set of concepts and categories as an 'ideal' expert map or relatively complete biodesign taxonomy. Our taxonomy is not a time-dependent or phase model of design process activities but rather pieces of a design plan or essential concepts.

Theoretically, being knowledgeable in a domain requires a highly integrated structure among densely networked concepts [31]. Grounded in this premise, the first author identified the most densely networked concepts in each of the eight selected maps. Concepts with four or more links directed toward or away from them were then organized according to their conceptual similarity. Table 2 summarizes the most densely networked concepts, the number of links per concept, and the average number of links per identified category. In general, these analyses supported the validity of our identified categories. Across maps, the most

Table 2. Frequency and means of most densely networked concepts according to four design categories as they appeared in selected expert maps

Technical background		Frequency	Design process	Frequency
Scientific information		9	Product definition	12
Knowledge of math, biology, physics		7	Product design/manufacturing	12
Design principles		6	Product implementation	10
Engineering principles		6	Medical/life application	8
Technical knowledge		5	Customer input	8
Technical skills		4	Define product	7
Computer skills		4	Working unit	7
Subject matter knowledge		4	Research and development	7
	Average	4.8	Prototypes	7
Interpersonal skills			Design requirements	6
Personal skills		6	Financial management	6
Multi-disciplinary teamwork		5	Manufacturing phase	6
Project schedule		4	Clinical studies	6
Project management		4	Functional requirements	6
'Soft' skills		4	Finished product	6
	Average	4.0	Design outputs	6
			Product performance	5
Overriding societal concerns			Prototypes	4
Law/regulatory knowledge		8	Testing	4
Regulatory requirements		7	Analysis	4
The law		5	Hazard analysis	4
FDA		5	Prototype development	4
Regulatory requirements		4	Protocol	4
	Average	5.3	Average	6.5

Table 3. Means, standard deviations, ranges and reliability coefficients for percentage of concept coverage among selected expert mappings and students at each time point

Experts	Design process	Interpersonal skills	Technical background	Motivation for design	Marketing	Societal concerns
M	0.40	0.29	0.44	0.42	0.35	0.46
SD	0.19	0.33	0.40	0.22	0.30	0.29
Range	*0.10–0.66*	*0–0.84*	*0–1*	*0–0.67*	*0–0.67*	*0–0.84*
Reliability	*0.87*	*0.80*	*0.85*	*0.78*	*0.95*	*0.87*
Students, Pre						
M	0.24	0.16	0.27	0.16	0.13	0.10
SD	0.10	0.19	0.18	0.12	0.25	0.17
Range	*0–0.84*	*0–0.50*	*0–0.33*	*0–0.67*	*0–0.42*	*0–0.45*
Reliability	*0.34*	*0.59*	*0*	*0*	*0.56*	*0.48*
Students, Post						
M	0.30	0.28	0.40	0.34	0.11	0.22
SD	0.11	0.29	0.32	0.25	0.20	0.22
Range	*0–0.89*	*0–0.67*	*0–0.89*	*0–1.00*	*0–0.50*	*0–1.25*
Reliability	*0.36*	*0.71*	*0.27*	*0.24*	*0.51*	*0.79*

densely networked ideas related to the design process, knowledge and skills, legal and regulatory requirements, and interpersonal skills. Two categories from our taxonomy, marketing and motivation for the design, were not densely networked; however, these ideas may have been subsumed in the design process category (e.g. design requirements, medical application).

Our two raters established benchmarks of expertise in each of the six areas by examining 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 background knowledge (e.g. 'biology') were mentioned, then the map received a 100% coverage rating for the category of technical background. If only one of these concepts was represented then a 50% coverage rating was given. Table 3 summarizes descriptive statistics and reliability coefficients across the six categories.

Finally, we examined what experts said about their representations. Comments suggested that experts not only articulated the technical and procedural demands of the design process, but also situated the design process in a social context with ethical and financial constraints and opportunities. For instance, one expert noted that his map was 'greatly influenced by industry experience in product development,' and that it was 'based on practical, relevant, important issues and concepts crucial for successful medical device design and successful career paths. It is not based on theory and includes not only technical but related economic and regulatory concepts.' Another wrote, 'Most people in our industry define design as industrial design or artistic rendering or computer aided design. That is NOT what I mapped. I mapped the design and development process of converting an idea to a commercialized medical product.' A third offered that his map demonstrated that 'industry considers how the design process interfaces with other organizational components and the skills to successfully manage

the design process.' Thus, his map was 'broader' than a 'focus on the technical knowledge and skills required to design the device itself.'

In sum, we asked a group of 15 experts in academe and industry to represent their thinking about the biodesign process in concept map form. We then extracted ideas from their representations to identify key design concepts and benchmarks of expertise. No single knowledge structure emerged (i.e. maps were not predominantly structured as hierarchies or networks). However, experts consistently described design as an activity requiring varied skills and knowledge *and* awareness of contextual factors such as ethics, marketing. Thus, while design instruction might stress checklists [32], mathematical optimization [33] or a generalized approach [34, 35], our sample of experts described design as an activity that encompasses areas outside of the generic design process. This is an important finding for educators because it suggests that experts not only have extensive domain knowledge, they also situate that knowledge in a social and cultural context (i.e. they understand when and how to use what they know) [21, 36].

STUDY 2: STUDENT PARTICIPANTS

Study 2 involved the collection and analysis of data from students in a senior level biomedical engineering design sequence at Vanderbilt University. The course structure is composed of the following elements:

1. A senior seminar [37], worth one credit hour, wherein students in Mechanical, Electrical, Computer, and Biomedical Engineering were exposed to lectures on design subjects common to the disciplines. The seminar was also to serve as a vehicle for the formation of interdisciplinary design teams. This seminar was offered in the Fall term.
2. The Biomedical Engineering students also

attended a two credit hour design class for their major. Lectures in this class were primarily from a textbook [35] written by authors 3 and 4, this text also served as a reference for the seminar class. This textbook was derived primarily from lecture notes originally derived from an NSF workshop based upon the work by Pahl and Beitz, reviews of the literature [38] and revisions of a design textbook written for industry by author 4 [39]. By early November, formal design lectures in this class were terminated and students were free to work on projects that they had selected from a fairly comprehensive list solicited from industrial and campus project sponsors.

3. The Spring design class was a continuation of the work begun in the Fall, and was worth three credit hours. Students completed the year with a formal poster presentation of their projects (with accompanying designs and prototypes) and with a final term paper. Students gave monthly oral reports to the course instructor and a small peer group. The reports were intended to give students feedback and served as 'dress rehearsals' for their final presentation.

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 given to experts. Maps were constructed as homework assignments at the beginning of the first semester and at the end of the second semester. Complete data was obtained for 32 students (participation rate = 63%; 14 females, 18 males). These students had spent an average of one summer in industry or laboratory settings, or summer school.

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 were asked to construct a concept map responding to the question, 'What is your current conceptual understanding of what is involved in the biomedical engineering design process?' Students were asked to complete their second map at a time coinciding with the completion of their design project. Instead of attending class during the spring semester, students meet regularly in design teams and with the course instructor and an advisor to develop a design project. At this time we also asked students to reflect on and summarize, in writing, similarities and differences between their initial and final maps.

Data analyses and results for students

Analyses are identical to those described for experts. Two raters, blinded to the identity of the map author and the time point at which the map was constructed, counted the number of concepts and links, and calculated a density ratio. Table 1 summarizes descriptive statistics and reliability coefficients for these map dimensions at each time point. Fourteen of the initial maps were structured as networks; 18 were structured hierarchically. Of the final maps, 19 were structured as hierarchies and the remaining 13 were structured as networks. Paired samples t-tests showed significant gains in the number of concepts and links (concepts, t[31] = 2.83, p < 0.01; links, t[31] = 2.70, p < 0.05). The average link/concept ratio or network density was consistently low (i.e. almost 1:1) and the average validity of map propositions was consistently high. Our two raters also examined student maps for the presence and absence of the 27 key concepts identified in our work with experts. Analyses were identical to those for experts; the percentage of concepts represented or 'coverage' of the domain taxonomy was calculated; however, inter-rater reliability was not established for all concept categories (see Table 3). Where agreement was not above .50, the results reported here are based on the ratings of the third author. Findings should be interpreted with this in mind.

Student reflections

Because we were committed to using a research tool that offered students a window into their own thinking, at the end of the course we asked students to identify and reflect on any differences between their first 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 [24], 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 Figs 4 and 5.

COMPARING EXPERTS AND STUDENTS

How did students and experts compare? With regard to structural elements, t-tests assuming
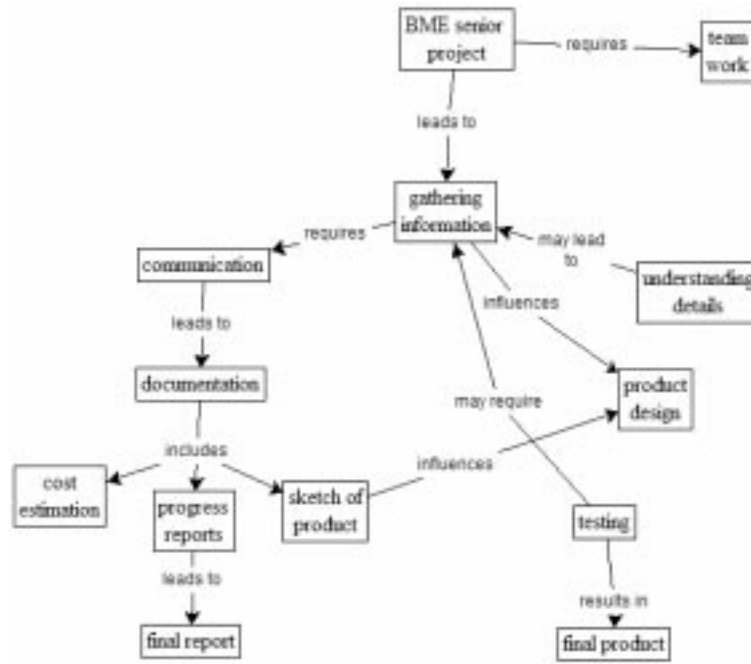
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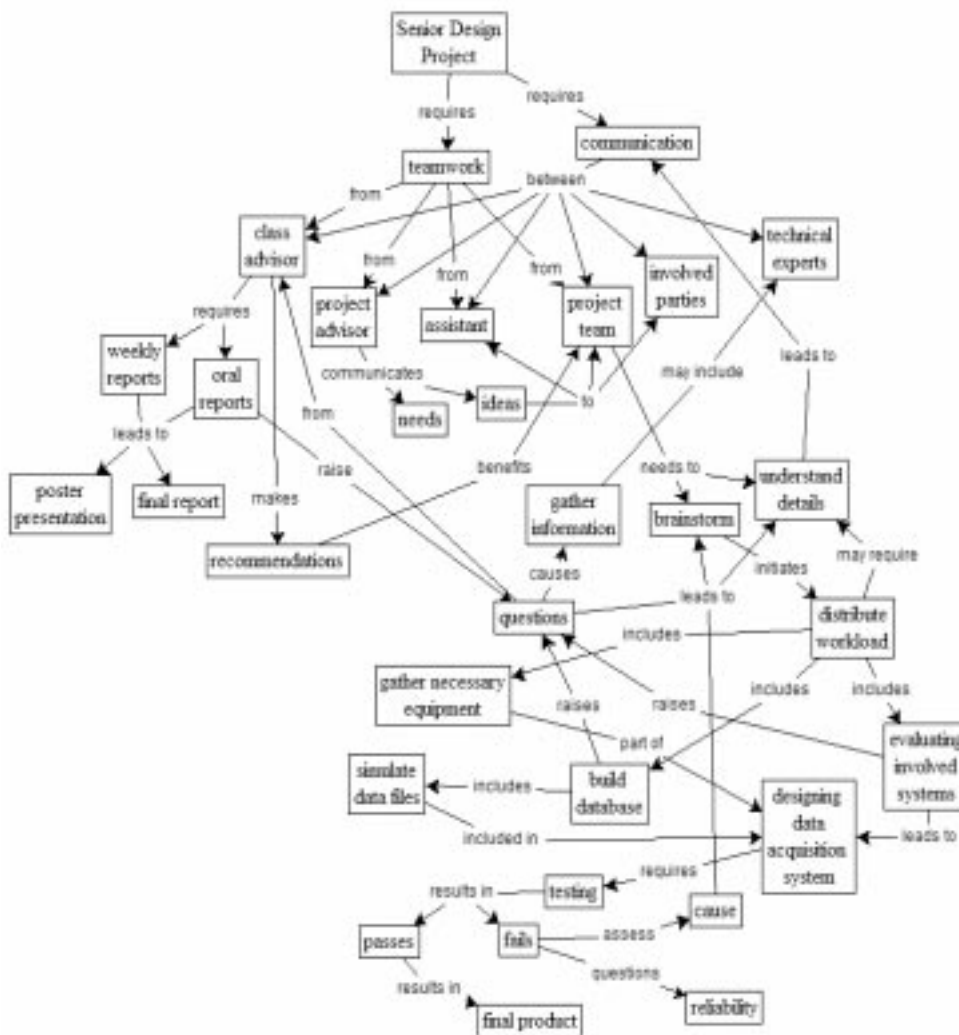Fig. 4. One student's map at the beginning of the design course.

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

unequal variance showed that students' initial maps had significantly fewer concepts and links than did experts (concept, t[7] = 2.52, p < 0.05; links, t[8] = 3.34, p < 0.05); there were no group differences in density or validity. Similar results were found for the final maps; student mappings had significantly fewer links and concepts (links, t[38] = 2.60, p < 0.05; concepts, t[38] = 2.01, p < 0.05), but did not differ from experts in density or validity. Descriptive statistics are presented in Table 1.

Regarding comparison of map contents, at the beginning of the design course students and experts placed similar emphasis on two areas: interpersonal skills and technical background. Students initially differed from experts in four areas: the design process, motivation for the design, marketing and societal concerns. At the end of the course, students differed from experts in only two areas: marketing and societal concerns. Table 4 summarizes t-tests and p values regarding student-expert comparisons.

In sum, over the year-long course students increased their knowledge of the design process; however, their knowledge did not appear to become more integrated (i.e. density did not change) or accurate (i.e. validity did not change). Content analyses suggested that experts had a more comprehensive conception of design than did students.

DISCUSSION

This set of studies used concept maps to identify key concepts in the engineering design process and explore expert–student differences. Despite considerable within-group variability, expert maps consistently demonstrated a comprehensive and differentiated understanding of the design process focused on six major areas. In addition to focusing on the design process, and the technical skills and knowledge required for design, experts attended to surrounding contextual issues, including the need to understand the motivation for the design, ethics and regulatory requirements, and marketing. These findings offer an important avenue for understanding the nature of expertise. That is, they suggest that experts consider the social context in which a design and designers function.

By contrast, students appeared to have a more constricted view of the design process, making few references to ethical concerns and the marketplace. Over time, however, the expert–student gap closed in two areas: the design process and motivation for the design. These patterns suggest areas in which design educators might focus instruction. For instance, given that students do not appear to consider non-technical facets of the design process, we are developing instruction that helps students identify with the multiple perspectives associated with a design team (e.g. engineering, marketing).

Contrary to our expectations, experts and students did not differ in terms of knowledge integration (i.e. density of network) or validity. Thus, while group and within-subjects differences are often visually striking, quantifying the nature of those differences in reliable, valid ways is an enduring challenge. Finally, analyses did not suggest a preferred method for organizing declarative knowledge (i.e. as networks or hierarchies).

We are establishing the validity of our taxonomy in two ways. Our first approach involves a card sorting task in which experts sort the initial full list of concepts derived from our expert maps. We then note which categories emerge. In another approach, we have asked our set of 15 experts to construct maps using the set of 27 identified concepts. We are currently examining these maps to identify concept clusters, matching propositions, and inclusion of any additional concepts. Both approaches may help establish a 'thesaurus' of design terms and propositions. Such an accomplishment, along with automated scoring of map contents, may reduce the amount of time required for map evaluation by instructors and thus facilitate the use of concept maps as an assessment tool.

Another concern is our current evaluation of proposition validity, which does not appear to discriminate experts from students. Addressing this issue may require rescaling our existing measure or establishing categories of appropriate and less appropriate linking words. We are also retrospectively applying a holistic scoring method recently described by Besterfield-Sacre and her colleagues in which maps are rated for their accuracy [40]. We think this holistic system will also allow us to further evaluate the organization of people's thinking about design (i.e., do they represent it as a linear or iterative process?) and the completeness of their representations (i.e., do they describe the design process to the design level, prototype level or product level?).

Essentially, our study shows that students

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

	Design process	Interpersonal skills	Technical background	Motivation for design	Marketing	Societal concerns
Pre *t*	2.30*	–	–	3.17*	2.21*	3.32**
Post *t*	–	–	–	–	2.20+	2.60*

– = not significant, * = p < 0.05; ** = p < 0.01; + = approached significance (p < 0.06).

moved from 'this to that'. We view students' initial maps as their assumptions about the design process. Their final maps are more expert-like and reflect the voice of experience and an internalized knowledge of what it means to design something. 'Unpacking' what underlies the differences between students' initial and final maps is essential to articulating the trajectory of students' transformation from novice to expert, an underdeveloped area in research on expertise [41]. To learn about this, we have developed and used several other assessments, including design scenarios that ask students to outline their problem-solving approach under various constraints. We have also asked students to evaluate fictitious and real design solutions (e.g., excellent and average former design projects). Providing students with contrasting cases offers students an opportunity to reflect on and articulate otherwise tacit features of good design [42]. To help students recognize the value of modeling the design process in various representational forms, we are also asking students to model their design project in concept map form and then compare that representation to other technologies that can visually represent design issues [37].

What we want to know more about is the processes underlying these changes. How do you 'build an expert?' Is expertise in design 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).

Finally, grounded in studies of collaborative cognition [43, 44], we are comparing what students say about the design process with what they actually do when designing something. Specifically, we are studying how design teams form, and how they select and attempt to solve a real medical problem. This work allows us to observe how students apply their knowledge and skills as they participate in organized, cumulative activities that may hold greater meaning for them than homework tasks.

In sum, our findings support the idea that experts' knowledge cannot be reduced to a set of isolated facts because their knowledge is linked to contexts and conditions for its use [36]. If this is the case, then design educators should place considerable emphasis on the conditions for applying the facts and procedures associated with the design process. In turn, assessment of student competence should focus not only on students' ability to recall facts, but also on whether students know when, where, and how to use their knowledge.

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APPENDIX A

How to build a concept map

1. Think about the focus question you have been given, and identify at least 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 super-ordinate 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. Now draw your array of post-it notes on a separate piece of paper.
5. Think about which concepts are related. Connect related concepts with links.
6. Label the links 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. 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.'
7. Add arrowheads to the links between the concepts to indicate the direction of the relationship. Depending on the nature of the concepts' relationship, links can have single or double arrowheads. For example, the proposition 'engineering involves 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
- usability analysis
- project schedule
- prototype
- design review
- hazard analysis
- validation and verification product
- literature review
- trials
- manufacturing

Technical background:
- technical knowledge
- technical skills

Motivation for the design:
- medical/clinical problem
- customer needs
- scientific needs

Interpersonal skills:
- communication skills
- teamwork
- management skills

Market constraints and opportunities:
- market analysis
- return on investment
- industry needs

Overriding societal concerns
- regulatory requirements
- regulatory agencies
- bioethics

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