What could design learning look like?

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At the Center for Engineering Learning and Teaching we are conducting a study of engineering design expertise in which experts engage in the same tasks as students from a series of previous studies. One study goal is to create a continuum of engineering design expertise across a subset of dimensions (e.g., cognitive, process, affective) to describe learners' growth toward acquiring expertise. We envision this continuum as a tool for researchers to identify research opportunities or compare across studies, and for educators as a way of using research to inform teaching decisions. In developing the continuum our work has been guided by two questions: (1) how can we describe the shape of learning trajectories on the continuum and (2) what are important dimensions or road markers we can use to characterize the acquisition of expertise along these trajectories? This continuum will be populated by existing research and findings from our expert study. At this time, we are stepping back and exploring rich knowledge sources outside of the design research community such as the learning sciences. In this paper we present four windows into learning to motivate a discussion on possible trajectories and dimensions of acquiring engineering design expertise: learning viewed through within-subjects empirical data on student design processes, learning as adaptive expertise, learning as a complex dynamic system, and learning as discourse. As an exploration, we anticipate this discussion will promote dialogue on the dimensions and shapes of design learning as well as other research implications.

As a community we are generating a wealth of knowledge on how designers design and are working towards synthesizing this knowledge to create pictures of design learning (e.g., Eastman, McCracken & Newstetter, 2001; Cross, Christiaans & Dorset, 1996). One strategy for synthesizing the accumulated knowledge is to summarize design research contributions in terms of methodological approaches, disciplinary perspectives, and common themes from findings. For example, Cross (2001) synthesized studies on design cognition from protocol and other empirical studies of design activity. Research themes summarized include problem formulation, solution generation, the role of sketching and creativity in design, and design process strategies.

Another strategy is characterizing design behaviors across levels of expertise. We call this a *design expertise continuum*. As part of a funded research project, we are aiming to develop this continuum across a subset of dimensions (e.g., cognitive, process, affective) as a way of describing learners' growth toward acquiring expertise. The goal is to populate the continuum with specific findings from existing research including our own studies. Critical elements underlying this strategy include (1) anchoring synthesis themes in empirical research on design knowing and learning,

(2) organizing expert-intermediate-novice differences across research themes, and (3) representing synthesis efforts in ways that inform research and teaching practice. By presenting research in a language and organization that is accessible to researchers and educators, the continuum may serve as a tool for researchers to identify research trends or opportunities and for educators to inform teaching decisions.

In this paper we describe elements of a design expertise continuum and our work on developing a continuum. Central to this description is an exploration of four research efforts into the form and content of a design expertise continuum that sheds light into our question "what could design learning look like?" For each exploration we identify implications for candidate dimensions of design learning, shapes of design learning trajectories, and other issues that can support the development of the continuum.

1. The Design Expertise Continuum

As shown in Figure 1, we envision a design expertise continuum as an interpretation model for documenting learners' progression towards design expertise in terms of (1) learning *dimensions* and (2) *shapes* of learning trajectories.

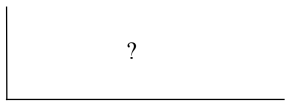
Candidate Learning **Dimension**	Potential **Shape** of the Learning Trajectory
X_1	 Novice ………………. Expert
X_2	 Novice ………………. Expert
…	…
X_n	 Novice ………………. Expert

Figure 1. Illustrating the Design Expertise Continuum

Ericcson et al (1980) provide a useful example for considering important features regarding candidate dimensions and shapes for a design expertise continuum. In this study subjects were asked to remember a string of digits. Study findings were used to create a plot comparing days of practice against the number of digits remembered. The plot illustrates a general positive progression in one "dimension" - the number of digits remembered - marked by plateaus and instances of first getting worse before getting better. These dips and plateaus were described as illustrating changes in chunking patterns of numbers. Although the task here is limited in complexity it does illustrate that the "shape" of learning is complex. These complexities can be numerous: learning is more than the gradual accumulation of knowledge, the transfer of knowledge to new contexts is neither direct nor immediate, and misconceptions can impede deeper learning.

As illustrated here, candidate continuum dimensions should represent important knowledge structures identified by rigorous research. Dimensions also need to be capable of being measured and tracked over time. Some dimensions may be relevant over the lifespan of design learning. Others may be relevant only during certain time intervals. For our continuum, each dimension also needs to be linked to the broader set of dimensions represented in the continuum (see Figure 1).

The example also illustrates features regarding potential shapes of learning trajectories towards design expertise. Potential shapes should characterize one or more dimensions of design learning when plotted over a change parameter such as time. They also need to highlight anticipated learning challenges or capture situations when a critical event changes the shape of a learning trajectory. Potential two-dimensional shapes may capture monotonic growth or temporary degradation of performance. Potential three-dimensional shapes may be spirals of two dimensions interacting over time.

2. Four Windows into Learning

The process of developing a prototype expertise continuum has been challenging. At this time, we are stepping back to think more broadly about the shape and dimensions for a prototype continuum of design expertise. In particular, insights into the question of "what could design learning look like?" may lie outside of the design research community. What other perspectives could we draw from to consider ways for representing gradual or radical changes in learners' knowledge and critical learning transitions? At what points in time or contexts do we see more novice designers radically challenge their pre-existing views or design processes and transform these into qualitatively different approaches?

In this paper we utilize four perspectives on learning from a variety of research efforts to explore the form and content of a design expertise continuum. Each perspective provides a window for envisioning potential continuum dimensions and shapes:

A *Design Process Window* which illustrates within-subjects data of engineering student design processes

An *Adaptive Expertise Window* which illustrates multiple pathways to expertise

A *Systems Window* which illustrates how human learning can be represented as a complex dynamic system

A *Writing as Design Window* which illustrates learning as discourse

Windows were selected based not on a goal of comprehensiveness but rather a goal of representing different scales in the leap between imagining specific and general features of design learning.

In the following sections we explore each window to identify implications for developing a design expertise continuum in four areas:

- *Dimensions*: What are the dimensions (or road markers) we can use to characterize the learning of engineering design and the acquisition of design expertise?
- *Shapes*: How can we describe the shape of learning trajectories in the continuum?
- *Additional Insights*: What additional insights are important in order to develop a design expertise continuum?
- *Implications*: What are the implications for additional research?

2.1 A Design Process Window – Learning Within Subjects

The first window is based on published empirical studies of engineering student design behaviors (Adams, Turns & Atman, 2001; Atman et al, in press, Turns et al, 2002;). Through these studies we have been gathering observations suggestive of design learning. For example, in one study aspects of design iteration were described as external markers of learning where learners are reconstructing their understanding of a specific task and to some extent their general design knowledge (Adams, 2002; Adams, 2001). These activities were described as transformative iterative processes in which designers simultaneously build a representation of the problem through levels of abstraction while articulating a more concrete representation of a solution. A design process window serves as one of many possible departure points for asking: in what ways do student design behaviors change over time (dimensions), how can we relate the variety of changes to characteristics of design learning, and what might be potential design learning trajectories (shapes)?

We have completed a number of large-scale empirical studies on engineering student design behavior. Most of these studies have used verbal protocol analysis, in which subjects talk aloud while solving an experimental task, to understand how engineering students solve different types of open-ended design problems (see Atman & Turns, 2001). One of these datasets consists of 32 freshmen in their first semester and 61 seniors solving three problems: designing a ping pong ball launcher (homework style task), designing a solution to safely cross a familiar street on campus (familiar context task), and listing the factors considered for designing a flood retaining wall for an area that consistently floods (breadth of problem scoping task). The dataset also includes 18 sets of within-subject data in which 18 of the 61 seniors were among the initial 32 freshmen. A particular focus for this dataset has been characterizing "change" in individual students' behaviors.

This data has been analyzed through three lenses (as illustrated in Figures 2 and 3). Two of these lenses – *process* and *breadth* – are based on previous work and are summarized in Table 1 in terms of (1) study goal,

(2) study codes, (3) study measures, and (4) significant differences across freshmen and senior engineering students. The third lens – *change* – is unique to the within-subjects data and is based on comparing individual students at two points in time (first semester and graduating semester). The last column in Table 1 provides codes for categorizing change across process and breadth measures known to be significant in the larger dataset (Turns et al, 2002; Rhone et al, 2001).

Table 1. Three lenses (process, breadth, and change) for comparing differences in engineering student design behaviors.

	Study Goal	Codes	Measures	Significant Differences	**CHANGE LENS**
PROCESS LENS	Design process activities for various tasks	- Problem definition (PD) - Information gathering (Gath) - Generating alternatives (Gen) - Modeling (Mod) - Feasibility (Feas) - Evaluation (Eval) - Decision (Dec) - Communication (Com) (see Moore & Atman, 1995)	- Time spent in coded activities - Number of transitions across coded activities - Progression to later stages of the design process	- Number and rate of transitions - Total time spent - Time spent in decision and problem scoping activities - Progression (see Atman et al, in press).	**CHANGE CODES FOR PROCESS:** - *More of the same*: the kinds of coded activities and number of transitions did not change, yet the amount of time spent in coded activities increased - *Change* = increase in the kinds of coded activities, time spent in coded activities, and the number of transitions - *Simplification* = the kinds of coded activities and time spent did not substantially change, and the number of transitions decreased - *No change* = no change in the kinds of coded activities, time spent in coded activities, and the number of transitions
BREADTH LENS	Breadth of considerations for designing a retaining wall system for a river	- Knowledge considered (technical, logistic, social, natural) - Scope of system considered (at the wall, in the water, at the bank, beyond the shore) (see Bogusch et al, 2000; Rhone et al, 2001)	- Number and types of knowledge - Number and types of system scope - Portion of problem definition space covered (number of nodes in a 4x4 problem space)	- Types of knowledge considered - Scope of system considered - Number of nodes covered in the 4x4 problem space covered (see Adams, Turns & Atman, 2001; Bogusch et al, 2000; Rhone et al, 2001).	**CHANGE CODES FOR BREADTH:** - *Expansion* = increase in the number of issues considered, number of issues for each code, and the number of nodes covered - *Shift* = no substantial change in the number of issues considered and the number of nodes covered, yet the type of nodes covered changed (e.g., from technical to social) - *No change* = no substantial change in the number of issues considered, number of issues for each code, and the number of nodes covered

Figures 2 and 3 illustrate examples of within-subjects change through all three lenses. Representations are for each of the tasks subjects completed: designing a ping pong ball launcher, designing a solution to safely cross a familiar street, and listing the factors considered for designing a flood retaining wall. Representations on the left are for that subject as an entering college freshman; those on the right are as a graduating senior. Data representations for the ping pong and street crossing problems are design process timelines where the tickmarks represent time in a particular coded design activity (on the left hand side of the timeline). As stated earlier, the coded design activities are: PD (problem definition), Gath (gathering information), Gen (generating ideas), Mod (modeling), Feas (analyzing feasibility), Eval (evaluation), Dec (making decisions), and Com (communicating the final design). The number of transitions is a measure of the number of times a subject moved from one design activity to another such as moving from problem definition to modeling or evaluation to generating ideas. The representation for the retaining wall problem is a 4x4 grid across knowledge and system dimensions. The codes for knowledge are on the left hand side of the grid (technical, logistic, social, natural); the codes for system are on the bottom of the grid (wall, water, bank, shore). The crosshatches on the grids represent each coded statement and each crosshatch is located at a particular knowledge / system interface (e.g., technical / wall).

As shown in Figure 2, the design processes of Subject GR across both problems were coded as "more of the same". As a senior, this subject engaged in the same kinds of design activities, progressed to a similar level in the design process, and transitioned across similar design activities. Although the process was relatively unchanged, the amount of time spent in the various design activities substantially changed. Comparing across the freshmen and senior timelines for both problems it appears that the timelines were "stretched" in time. Subject GR's design processes did not become more complex or simpler but rather quantitatively increased. As a senior, Subject GR spent more time solving the problem (from 11.16 minutes to 13.67 minutes), transitioned more across design activities (from 15 transitions to 23 transitions), and received a higher quality score (from 1.88 to 3.267). In addition, the design processes across the two tasks are qualitatively similar – with little or no deviation in the kinds of process activities.

The change for Subject GR in the breadth of design issues considered for the retaining wall problem was coded as "shift". As shown in Figure 2, nodes on the freshman grid do not appear on the senior grid and nodes on the senior grid do not appear on the freshman grid. Rather, the emphasis shifted from a predominantly technical focus at the wall and water interfaces to a broader system focus. As a senior, three nodes were dropped and four nodes were added for a total increase of one node. Similarly, the number of statements coded did not substantially change (from 40 to 44). As such, there was little quantitative change but rather a substantial qualitative change as illustrated in the shift to include broader system issues.

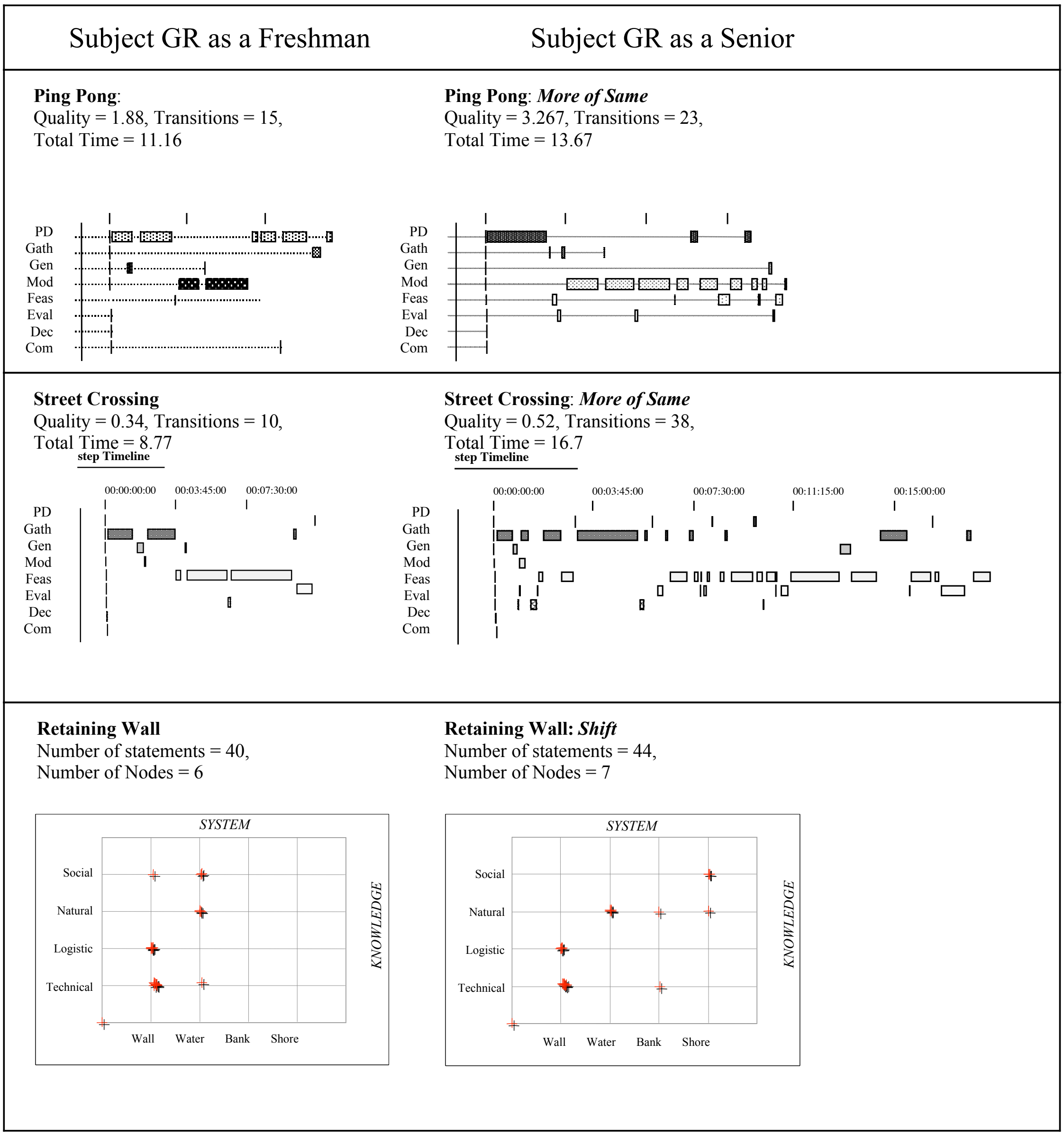


Figure 2. Within-subjects "change" for subject GR across potential measures of design learning.

As shown in Figure 3, the design processes of Subject GM were coded as "more of the same" for the ping pong problem and "change" for the street crossing problem. For the ping pong problem, as a senior this subject received a slightly higher quality score, transitioned more between essentially the same design activities (e.g., transitioning between problem definition and modeling), and spent somewhat more time solving the problem. However, both transition diagrams show a similar level of progression through the design process. Overall, the process is qualitatively the same, yet differs in the quantitative amount across some of the study measures (e.g., number of transitions, time spent in each activity and overall).

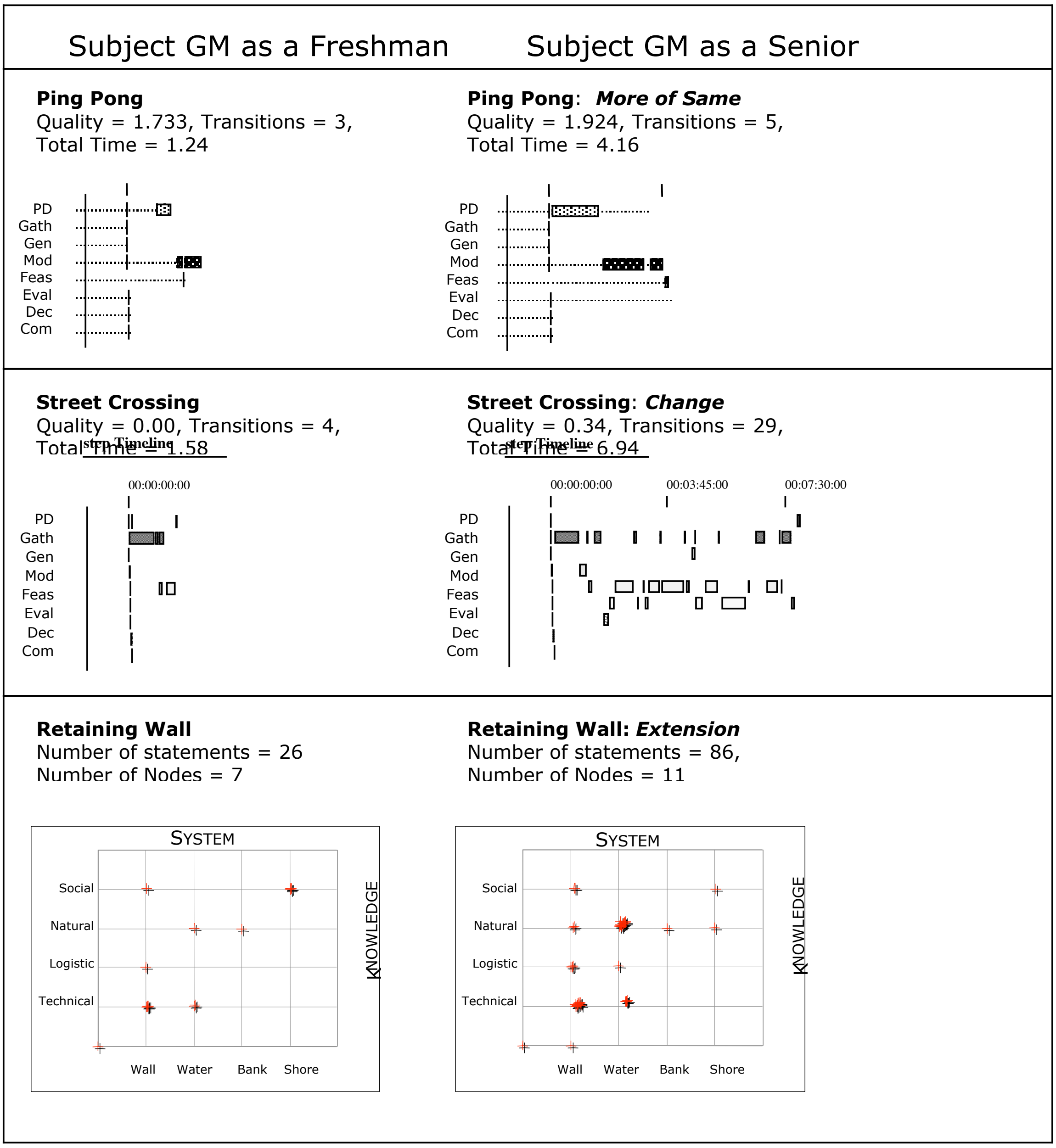


Figure 3. Within-subjects "change" for subject GM across potential measures of design learning.

For the street crossing problem, as a senior this subject received a significantly higher quality score, increased the number of transitions between design steps seven-fold, spent more time overall, and progressed much farther into the design process. Comparing the change in design processes across the two problems, it is clear that the design process for the street crossing problem qualitatively and quantitatively changed. Unlike Subject GR, the change in design processes of Subject GM was notably different across the two tasks suggesting that Subject GR approached the two problems in different ways. One explanation may be that the ping pong task was seen as trivial whereas the street crossing problem was more complex and required a more complex design strategy.

The change for Subject GM in the breadth of design issues considered for the retaining wall problem was coded as "extension". As shown in Figure 3, the number of coded statements increased substantially as well as the number of nodes covered in the problem space grid. As a senior, this subject considered new issues at the natural / wall, logistics / water, natural / water, and logistic / wall interfaces. All of these are broad issues that go beyond the engineering science or technical issues embedded in the problem. In addition the number of unique design issues at each knowledge / system node increased considerably across technical and logistic issues as well as water and shore issues.

Table 2 summarizes change codes across all the within-subjects data. As illustrated in the examples above, subjects were more likely to exhibit different change patterns across the different tasks. In particular, subjects were more likely to display a "more of the same" change for the ping pong problem and a "change" behavior for the street crossing problem. It is also important to note that some subjects already had sophisticated design processes as freshmen and as such there tended to be little difference in their design processes as seniors. For the retaining wall problem, subjects were more likely to exhibit a "no change" pattern. One explanation is that the criteria across the different categories for this problem were derived empirically and may have been too stringent. For example, problem space grids had to be significantly different across a set of parameters to be coded other than "no change".

Table 2. Summary of "change" across within-subjects (N=18).

Subject	Ping Pong	Street Crossing	Retaining Wall
SB	C	NC	NC
RB	NC	NC	NC
JD	M	M	NC
GR	M	M	SH
MM	M	C	E
GM	M	C	E
JV	M	C	NC
MK	NC	C	E
DD	C	C	NC
JW	C	C	E
VM	S	M	NC
RS	M	C	NC
ER	M	C	E
JS	NC	NC	NC
TW	C	C	E
GS	NC	NC	SH
JC	C	C	SH
AG	M	C	N/A
Totals	C = 5	C = 11	E = 6
	M = 8	M = 3	SH = 3
	NC = 4	NC = 4	NC = 8
	S = 1	S = 0	N/A = 1

NOTE: For Ping Pong and Street Crossing problems: C = change, M = more of the same, S = simplification, NC = no change. For the Retaining Wall problem: E = expansion, SH = shift, NC = No change, N/A = not available.

2.1.1 Implications

When revisiting our guiding questions, this window provides insight into possible shapes and dimensions of design learning. Clearly, the study measures are candidate continuum dimensions in that they are capable of capturing differences in design behaviors over time. Example candidate dimensions include the number of transitions, time spent in various design activities, and progression into the latter stages of design.

This window also suggests two kinds of shape changes – one that is qualitative in nature and one that is more quantitative in nature. Qualitative changes suggest that old strategies are transformed into new strategies; quantitative changes suggest that strategies gradually improve over time but remain essentially the same. Qualitative changes observed in our data include a change in the sophistication of design processes (e.g., transitioning more frequently) and a change in the breadth of issues considered. Quantitative changes observed were more a function of engaging in the same kinds of activities yet spending more time or considering more kinds of a particular issue. An unexpected finding was that the nature of the change often varied across tasks suggesting that the nature of the task provoked different kinds of design behaviors. This finding illustrates that the nature of change is quite complex, individualized, and context-specific.

This window also raises important questions. In this window, change is viewed over a very large time scale with little insight into the underlying nature (or nonexistence) of change. It is not clear if the change process occurs gradually as a result of small adjustments, as a result of responses to critical events, or a combination of learning events. One lingering question is how to anchor a particular kind of change within an individual context – are the changes exhibited in this window stable or fleeting, and where are they located in time relative to a complex set of educational experiences?

2.2 An Adaptive Expertise Window – Multiple Pathways to Expertise

Holyoak (1991) surveyed the research on expertise and found that characteristics of expert performance are quite diverse. One constant appears to be that the most apt general characterization of expert performance is someone capable of doing the right thing at the right time. Although a somewhat simplistic statement, this recognition serves as a useful departure for considering multiple forms of expertise – that experts do not approach every problem in the same way but rather adapt to the inherent constraints of the task. For example, Holyoak notes:

> if the task can be done most efficiently by a forward search, then the expert will search forward; if backward is better, the expert will search backward. If certain patterns of cues are crucial to performing the task well, the expert will likely perceive and remember them; if patterns are not so important, the expert will not selectively process them (Holyoak, 1991, pg. 309).

A perspective on learning that accounts for multiple forms of expertise broadens the field for considering diverse learning and acquisition processes. A particularly relevant perspective is what Hatano and Inagaki (1986) distinguish as routine and adaptive expertise. Theories of adaptive expertise focus on (1) procedural conceptual knowledge – decision rules and execution strategies along with the associated necessary skills and (2) how expertise is acquired and enriched over time enabling an ability to solve increasingly more complex problems. Distinctions between routine and adaptive expertise are most evident in situations where little or no declarative rules exist. As such, adaptive expertise is believed to be culturally specific because declarative rules are often culturally derived and generated. This focus on the development of culturally specific procedural conceptual knowledge is one pathway for relating ideas of adaptive expertise to the nature of acquiring design expertise. For example, procedural knowledge is considered a key aspect of design expertise and there are multiple models prescribing approaches to design activity that represent particular philosophies of design (e.g., Suh, 1990; Pahl & Bietz, 1984).

Two studies on routine and adaptive expertise are summarized here. The first is a study of mathematical reasoning in everyday life (Hatano, 1990; Hatano & Inagaki, 1986) and the second is a study on reasoning of historical evidence (Wineburg, 1998). Hatano (1988) conducted a cross-cultural study on mathematical calculation skills with a focus on understanding the acquisition and use of everyday scientific reasoning. Here everyday scientific reasoning relates to the application of procedural conceptual knowledge in daily life (which tends to promote flexible use) rather than school situations (which tends to promote mechanistic use). In this study, the use of the abacus in Asian cultures was compared to the use of "street math" of Brazilian children working as street vendors (see Carraher, Carraher & Schliemann, 1985). The use of the abacus, which involved a solitary skill of speed and accuracy, was not readily generalized to debugging pencil-and-paper arithmetic procedures and impoverished in social meaning. In contrast, the use of street math in selling merchandise, which involved a social enterprise that was transparent to the customer and that was more crucial than the speed of transactions, could be easily generalized to solve novel problems both on the street and in the classroom.

Based on a series of studies, Hatano (1988) later summarized characteristics of adaptive expertise as: inventing new procedures derived from expert knowledge to solve novel problems, a tolerance for ambiguity, fluidly adapting to new situations, performing minor variations in procedural skills and examining their effectiveness in a new context, engaging willingly in active experimentation and exploration, and being sensitive to internally generated feedback such as a surprise at a predictive failure or being perplexed by alternative explanations of a phenomenon. In contrast, characteristics of routine expertise include: technical competence in solving familiar problems quickly and accurately yet only modest competency in solving novel problems, tendency to solve problems based on past solutions, highly standardized procedural skills, unwillingness to risk varying the skills, and having a preference for strategies that ensure quicker solutions over strategies that promote seeking alternative solutions.

Wineburg (1998) studied how two university-based historians, one with detailed and one with limited background knowledge, interpreted a series of primary source historical documents on Abraham Lincoln's views on race. It was found that the historian who had limited content knowledge of the documents worked through confusion, resisted an urge to simplify, recognized a lack of knowledge of the situation and reoriented to the problem at hand, and revisited earlier assumptions. By the end of the task this historian regained his intellectual footing, created an interpretive contextual structure to make sense of the issues at hand, and ended the task where his more knowledgeable colleague began. Insights into how this historian kept learning in a situation where he had limited knowledge was described as a dialectic process between questions he asked and the textual materials provided which led to a search strategy that provoked and altered his knowledge base. Characteristics of adaptive expertise that map to the Hatano study include: an ability to adapt and stretch knowledge so that it addresses new situations (often in which key knowledge is lacking), showing restraint and self-awareness in the face of first solutions for resolving contradictions, a tolerance for ambiguity, and a dependence on professional training over using past solutions.

2.2.1 Implications

In comparison to the design process window, the adaptive expertise window moves the focus from process behaviors themselves to knowledge and values about process behaviors. From this window, potential dimensions to include in a prototype continuum should involve behaviors that illustrate the role of procedural knowledge (which may be culturally derived). Examples of these behaviors include: a tolerance for ambiguity and a willingness to actively engage in experimentation and exploration, showing restraint on using past solutions and instead relying on professional training to resolve contradictions, inventing new procedures derived from expert knowledge to solve novel problems, an ability to fluidly adapt to new situations in which key knowledge is often lacking, and being sensitive to internally generated feedback. Many of these categories resonate with design research findings. For example, creative design experts tend to design from first principles rather than use existing solutions, flexibly adapt their existing knowledge to new situations in which key knowledge is lacking (e.g., surrogate expertise), and actively experiment and explore assumptions (Cross & Clayburn Cross, 1998; Candy & Edmonds, 1996).

Reflections on adaptive expertise suggest that the shape of learning may have no upward bound – that a key to expertise is focusing on the path rather than some goal state. Lingering questions become what critical events or educational experiences promote different forms of expertise and in what ways may characteristics of routine expertise be representative of how adaptive expertise degrades over time?

2.3 A Systems Window – Learning as a Dynamic System

Learning is clearly complex. Embracing this complexity provides opportunities to approach the acquisition of expertise from a systems perspective. As one example, Hakkarainen (2001) illustrated a model of networked expertise in which cognitive, socio-cognitive, and knowledge-creation perspectives interact through the learning experiences of one expert (Pekka) in the communications technology industry. In the context of design, as a community we have developed a rich knowledge base in systems theory. In systems theory, not only is the design process critical but also the networked interaction between broad design issues such as technical, contextual, and socio-environmental considerations. When approaching learning from a systems perspective, important considerations include what elements drive the system, how the system responds to internal and external disturbances, and how the system stabilizes and evolves over time.

One perspective on learning, situated in catastrophe theory, is currently being used to study human learning as a complex dynamic system. The history of catastrophe theory began with Zeeman (1976) and was later revised by van der Maas and Molenaar (1996). Catastrophe theory draws on mathematical principles to simulate how a system responds to a disturbance. In situations of stability, the effect of the disturbance dies out; in situations of instability, the disturbance drives the system to a new morphology or state.

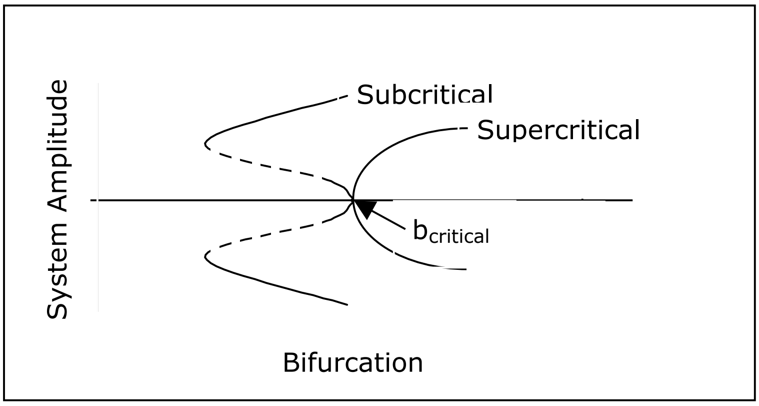


Figure 4. Bifurcation modes in a weakly nonlinear dynamic system.

As an example from the physical sciences, the effect of small disturbances to the solid-liquid interface in the laser melting of thin silicon wafers can be analyzed to determine the conditions that drive the onset of instability and the resultant morphology at the interface (Adams, 1996). These simulations can then be compared to visual observations of the real system. In this study two kinds of bifurcations were observed: a subcritical bifurcation in which the system experienced a hysteretic effect and a supercritical bifurcation in which the system moved to a new stable state (see Figure 4). The hysteresis effect illustrated in the subcritical trajectory is a situation in which the system approximates a return to an original state and then evolves into a radical new stable state.

The connection between catastrophe theory and human development is an effort to explain the dynamic reconfiguration of elements in a social or psychological system. Therefore, much of this research is situated within a conceptual change framework (see also e.g., Chi, Feltovich & Glaser, 1981; diSessa, 2002). Dynamic systems theory as applied to human learning explains how roles and behavior patterns in a relationship become established through repeated interactions that reinforce and complement each other both cognitively and emotionally, and become more stable over time. The process of change begins with perturbations that destabilize the learners' existing knowledge structure, which leads to questioning of the learners' current "mind-to-world" fit and related efforts to account for these perturbations. The outcome of this process may be the spontaneous emergence of coherent and higher order conceptual frameworks. Ultimately, this may lead to a massive reorganization (radical restructuring) where foundational conceptions of a domain must be changed. However, positive radical change – when a superior conceptual framework is evaluated and adopted over an inferior conceptual framework – is not always the case. Flawed radical change can also occur. One example is when a practice such as adopting a Darwinian view of evolution deteriorates over time or is replaced by an inferior practice such as a Lamarckian view of evolution.

Research in the area of human learning as a complex dynamic system is relatively new and more theoretical in nature than empirical. Ferrari and Elik (2003) provide one example of applying a dynamic systems approach to human learning from one perspective of conceptual change. The authors propose a model of intentional conceptual change to explore if conceptual stability is intentional. Intentional conceptual change is a specific case of conceptual change that focuses on the learners' intentions (beliefs, epistemologies, thoughts, desires) and the learners' deliberate desire to change his/her view about an issue and to listen to and value challenges to this view. Interest in intentional conceptual change research is based in findings that suggest deeper learning is more likely to be a case of intentional conceptual change rather than conceptual change motivated by external inputs such as educators (e.g., Guzzetti & Hynd,1998).

Figure 5 illustrates the mechanics of a complex dynamic system as applied to intentional conceptual change by Ferrari and Elik (2003). Here, the x-axis represents the *available resources* such as existing knowledge or tools. The y-axis represents the capability to use resources and as such represents an individual's level of cognitive or *conceptual development*. The z-axis represents the *probability of conceptual change* which occurs as the interaction between available resources and conceptual development. Ferrari and Elik propose that the surface curves represent types of conceptual change: radical and weak. For the case of radical conceptual change there is a change in ontology or essence in the concepts themselves. The resultant conceptualization is a radical reorganization of a learner's knowledge. This is illustrated in Figure 5 as a small discontinuous jump similar to the subcritical bifurcation shown in Figure 4. Because there is always a probability of returning to old conceptualizations, the radical restructuring trajectory curve also exhibits a hysteresis effect. For the case of weak conceptual change the new conceptualization is a mere articulation of an existing framework such as changing the relationships between concepts in a mental model. This is illustrated in Figure 4 as a continuous line where the learners' knowledge structure evolves through small steps.

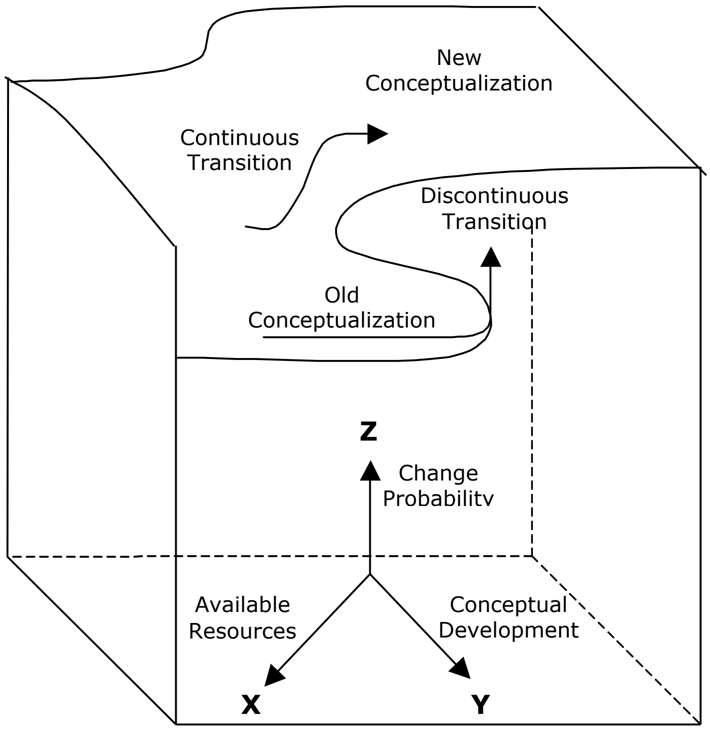


Figure 5. Intentional conceptual change as catastrophe theory (revised from van der Maas & Molenaar, 1996).

Using this model, the authors summarize possible mediators and moderators of intentional conceptual change. Mediators serve to frame one's entire approach to a particular concept and as such include cultural frameworks (norms and language), social frameworks (people), and ontological frameworks (how a concept is classified in one's conceptual ecology). Moderators serve to influence how easily or thoroughly one will attempt to change existing conceptual knowledge and may either facilitate or impede change. These include belief-related moderators, affect-related moderators, and intention-related moderators (will power and quality of self-regulation). Features of a system that promotes intentional conceptual change were described as individual self-regulation, regulation in relation to others, hierarchical groups such as in classrooms, and collaborative groups such as in teams.

2.3.1 Implications

Insights into potential dimensions of design learning from this window highlight the role of intentions (e.g., beliefs, epistemologies, thoughts, desires) in the learning process as both mediators and moderators.

This window also leads to various considerations about shape. A complex dynamic system model of human learning clearly articulates a perspective on learning where many theories of learning interact. The model also distinguishes radical and weak forms of change. From the perspective of the design processes window, radical forms of change may be associated with qualitative differences (e.g., less and more complex design processes) in design behaviors whereas weak forms of change may be associated with more quantitative differences (e.g., more transitions but same design activities). This window also brings greater light to considering what situations provoke bifurcations into radical or weak changes. From the perspective of design, some researchers have already been studying critical transitions in design processes from both a team (Badke-Schaub & Frankenberger, 1999) and individual (Adams, 2001; Adams, Turns & Atman 2003) point of view.

A unique quality about shape not evident in the other windows is the hysteresis effect. In this context, when learning degrades it may not return to a prior state but rather to a version of a prior state. Similarly, when a learners' conceptual framework becomes more complex it may be difficult to relate this new conceptualization to previous ones if the learner experienced a discontinuous jump. Finally, this window highlights the role of scale and time in the evolution of learning. In particular, a snapshot of learning located at different points on a hysteresis curve may have radically different interpretations. For example, a snapshot located at the onset of stability or at the negative slope of the hysteresis curve may be interpreted as two opposing views of conceptual change.

2.4 A Writing as Design Window – Learning as Discourse

Whereas the previous windows apply models of learning from the natural sciences, this window draws from a history of research on the acquisition of literacy expertise. Making connections between the process of writing and the process of design is straightforward. Since the 1960's engineering programs have utilized design as an approach for overcoming some of the learning problems engineers and scientists experience in their technical writing. Souther and White (1984) describe technical writing as a goal-oriented, logically ordered, and recursive activity in which no two communication problems are exactly alike and as such no formula can solve each of these problems satisfactorily.

In addition, findings from research on literacy and writing share commonalities with findings from research on design. For example, researchers have focused on the process of writing (e.g., Hayes & Flower, 1980), the factors writers consider when writing, and discourse communities (e.g., Zappen, 1989; Freed & Broadhead, 1987). Research on literacy emphasizes aspects of expertise typical of practice in the real world that can be hidden in other expert-novice research. In domains such as writing and design, the outcome is likely to achieve a novel or superior result. Features of expertise in these domains can differ dramatically from expertise in domains such as physics problem solving. For example, as experts writers get "better" they take more wrong turns, make more revisions, invest more time when constructing a problem representation, spend more time agonizing over the task, engage in more planning, and recall more problems (Scardamalia & Bereiter, 1981). Many of these characteristics resonate with features of design expertise.

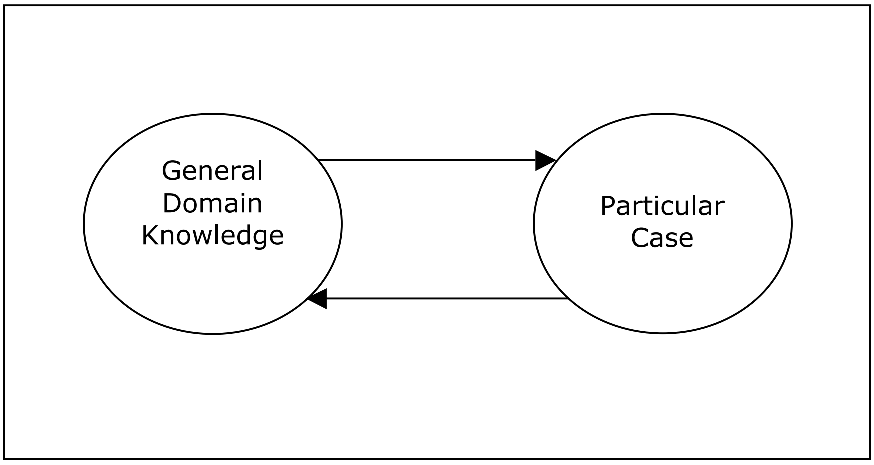


Figure 6. A generalized model of dialectic processes in the acquisition of expertise (from Scardamalia and Bereiter, 1981).

Finally, much of the research on writing and literacy has served as a point of departure for research on learning in other domains - including design. One example of literacy research that provides insight into shapes for describing the acquisition of expertise is a foundational piece of research by Scardamalia and Bereiter (1981). The authors propose that literate expertise is a dialectical process that serves to advance domain knowledge. Their model illustrates how domain-specific knowledge competencies interact in the advancement of expertise (see Figure 6) and how solving a problem and building a defense of a solution advance hand in hand in a goal-directed way (pg. 179). As shown in Figure 6 there are two elements in the model: (1) general domain knowledge is the learner's knowledge as it is brought to bear on some particular event, act, or need and (2) a particular case is the representation of a particular problem. This is a dialectical process of two-way influence: domain knowledge is used to interpret a particular case, the particular case yields new information that may be used to modify domain knowledge, and this in turn leads to different ideas about how to respond to the particular case, and so forth.

Situations in which non-experts can fall short in this dialectic process include (1) failures of a general–to–particular process (not having adequate knowledge to apply to the case or not having knowledge structured in a functional way), (2) failures of a particular–to–general process (solving a problem yet failing to learn or integrating generalizable knowledge into their existing knowledge structures), and (3) failures at an execution level (lack of knowledge checking procedures to determine if a solution makes sense). Failures at an executive level are a function of self-regulatory rules and are a characteristic that is most likely to be associated with non-experts.

The authors claim that the dialectic process illustrated in Figure 6 is an important part of what it means to be an expert and is most associated with more adaptive forms of expertise. Building on this process view of expertise, the authors summarized behaviors that facilitate expertise: reinvesting in learning by practicing and keeping up to date with current information, seeking out problems at the edge of what they know to develop new knowledge or apply old knowledge in new ways, actively taking risks to extend their own knowledge, and increasing rather than decreasing the complexity of representations of recurrent problems (Bereiter and Scardamalia, 1993).

Scardamalia and Bereiter (1981) describe literacy expertise as engaging in a high level of repetitive cycles between the general and the particular and continually enhancing competence through repeated encounters with particular cases. In comparison, non-expert behavior is characterized by attenuated or unidirectional passages of information. The authors have also drawn from this model to consider how experts became experts – emphasizing the transformation of knowledge already in the mind over the acquisition of knowledge. Knowledge transforming modes are most associated with experts and involve simultaneously enhancing subject matter understanding and enhanced problem solving. The authors relate this back and forth dialectic process as accounting for the greater quantities of mental activity in experts' thinking-aloud protocols as compared with inexpert writers. The shape of this process is described as a spiral of increasing competence in both general and particular knowledge.

Bryson et al (1991) applied a version of the model in Figure 6 to study writing as a complex problem solving process. The authors described the writing process as a dialectic interaction between content and rhetorical goals in which the representation of the problem evolves recursively as cognitive operators bridge the gap between initial and final states. They found that the experts in the study engaged in significantly more revisions and that these were of a more substantive and higher quality. They also found that the experts interpreted the significance of the writing topic on a more abstract level and worked to transform it so that it could be placed in a more meaningful epistemological perspective.

The results of this study (and the underlying model) have clear connections to research in design. For example, researchers have found that dialectic or coevolving problem and solution processes lead to more novel designs (e.g., Dorst & Cross, 2001). Observed features of iteration in the student design processes have also been described as a dialectic across problem and solution representations (Adams, 2001; Adams, Turns & Atman, 2003). In this study, seniors were significantly more likely to engage in coupled iterative processes and these processes were associated with higher quality final products. The authors proposed that these transformational dialectic processes might be external markers of learning.

2.4.1 Implications

A writing-as-design window into the dimensions and shape of design learning extends some of the ideas of the previous windows. Considerations for dimensions include iteration, the process of abstraction as the interaction of general and particular knowledge, and the process of coevolving problem and solution representations. Failure modes where the dialectic process breaks down also provide insight into situations in which learning may degrade or return to an initial conceptualization that may not be appropriate for a given context.

In regards to possible shapes, this window provides insights into learning as a dialectic process that illustrates possible cyclical and coevolutional aspects of learning trajectories. Scardamalia and Bereiter (1981) see this trajectory as a spiral of ever transforming knowledge where learning is contextualized via particular cases over large spans of time. One extension of this dialectic model to design could be the interaction between design knowledge and the particular design problem.

3. Four Windows – A Discussion

In this paper we situated an exploration into developing a design expertise continuum within four windows on learning. Other windows clearly exist such as brain research or implicit learning. There are also many perspectives on conceptual change processes. Throughout this exploration we have endeavored to broaden our perspectives for addressing four questions: what are dimensions for describing design expertise, what are possible shapes or trajectories for describing design learning and the acquisition of design expertise on these dimensions, what other issues are important in characterizing a design expertise continuum, and what are the research implications of having explored these issues. In this section, we revisit and summarize our responses to these questions.

Dimensions for Characterizing Design Expertise

To be useful, candidate dimensions for a continuum should encompass attributes of what would be changing as learners acquire design expertise. Some of these may be situated at specific points along a continuum and as such may not be evident at all points in time. Some of dimensions may be moderators or mediators with other dimensions and as such comprise a system for change. Categories highlighted across the four windows that resonate with existing design research include knowledge structures, procedural knowledge, and process measures. Other categories include conceptual knowledge, the role of epistemologies and intentions, the alignment between epistemologies and the application of knowledge, and features of adaptive expertise.

Shapes of Trajectories for Characterizing Design Learning

Possible shapes of learning trajectories should provide ways to track or anticipate changes across continuum dimensions. Some of these trajectories may be continuous, some may be slightly discontinuous, and some may exhibit both qualities over spans of time. In the context of the design processes window continuous and discontinuous trajectories may be described as quantitative and qualitative differences across process measures. Shapes observed through our four windows include gradual and radical transitions, dialectic spirals, conceptual ecologies, and learning plateaus.

Other Issues in the Design of a Design Expertise Continuum

Through this exploration other considerations of potential dimensions and shapes for a design expertise continuum have emerged. One consideration is the role of time or scale. If the timescale of a learning trajectory is too small, some features of learning may be artificially overemphasized; if it is too large, some may be underemphasized. Similarly, if snapshots of learning are not referenced within a longer event scale interpretations of what that learning trajectory represents may lead to erroneous conclusions. The scale of these trajectories should also be able to capture critical events and their impact on learning.

Another consideration is the recognition of individual differences – that learning trajectories may be individualized. Guzzetti and Hynd (1998) synthesized across multiple perspectives of conceptual change and found that learners experience the conceptual change process in qualitatively different ways depending on the interactions between knowledge of the content of a particular domain, strategy use, and motivation. This is also evident in the design process window where codes for change behaviors differed across problem task for individual subjects.

Implications for Future Research

As illustrated above, each of these windows has provided insight into possible dimensions and shapes of a design expertise continuum. A proposition best captured in the complex dynamic systems window is that no single window captures all the intricacies of learning. As such, this leaves open a wide door for integrating multiple perspectives. As Rumelart and Norman note (1978):

> Learning takes place whenever learners modify their knowledge base –and no single theoretical description will account for the multitude of ways by which learning might occur (pg. 50).

The process of envisioning design learning through each of these windows has also identified considerations for future research. Given the complexity of learning and the impact of timescales, the design research community clearly needs studies that follow in greater detail all the twists and turns of design learning.

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