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# Design Cognition:
# Optimizing knowledge transfer in digital design pedagogy

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## Abstract

Digital design as a medium for design research, praxis, and education has fundamentally disrupted the structuring of analog pedagogical contexts through an increased diversity of ontological, phenomenological, and existential design conditions. In an educational discipline noted for its exceptionally inefficient degree of knowledge transfer, how can traditional architectural pedagogy bear the burden of rapidly increasing educational content without exacerbating its instructional inefficiencies? Furthermore, how can cognitive overload for novice learners in this context be mitigated?

The purpose of this paper is to frame, expose, and explore how knowledge transfer in regard to the novice learner may be impacted by digital design as an architectural medium. The design education literature in both analog and digital environments as well as cognitive theories of learning will be explored to construct a theoretical lens through which the learning affordances and challenges of digital design can be addressed. Research conducted by Ausubel, R. Oxman, Schön, Sweller, and others will be used to expose the cognitive logics associated with introductory digital design and digital skill thinking. Cognitive issues including meaningful learning, cognitive processing efficiency, and automative thinking will be considered.

Pedagogical strategies supported by the educational literature related to schema development and cognitive loading will be suggested for educating novice learners in digital design. Design cognition as a subject for future research holds seminal importance in modern design education. It cannot be assumed that the pedagogical methods that provided the cornerstones of architectural education in an analogue environment remain relevant in digital contexts.

*Thus, the primary challenge of digital design education for novice learners is not simply the operational knowledge of digital tools nor the cognitive load resulting from "domain-general creative cognition (i.e. divergent thinking)" ...but rather the simultaneity of the aforementioned, differentiated cognitive processes.*

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# 1. Introduction

The transformation of design fields due to the digital revolution in academia and praxis has yielded a novel field for cognitive studies in design education (Oxman, 2008). Acknowledging that digital design includes its own unique technical and theoretical bodies of knowledge, its experienced-based learning processes elicit both challenges and opportunities for design education (Oxman, 2006; Oxman, 2008). The integration of digital design in the architectural studio has induced an ever-increasing breadth of design applications and processes which require learners to develop technological proficiencies while simultaneously developing design expertise. These cognitive demands for the learner also create critical pedagogical challenges for educators as they consider how to most effectively incorporate novel digital design media, modes, and methodologies into an educational discipline already burdened by an exceptionally inefficient degree of knowledge transfer (i.e. learning) (Akin, 2002; Kirschner, Sweller, and Clark, 2006).

Due in part to the infusion of digital design education into the pedagogical agendas at various institutions by leading figures in the design profession, singularly-focused agendas are often explored that result in specific areas of expertise rather than a more encompassing agenda that focuses on widely applicable learning outcomes in digital design (Oxman, 2008). Although a plethora of practice-driven educational agendas has introduced new landscapes to architectural education, it has only been since the late 1990's and early 2000's that there has been a more concerted effort to establish a theoretical foundation for digital design education. The result has been an increasingly voluminous amount of research focusing on the emergence of digital architecture in design pedagogy, restructuring of academic curricula, performative design technologies, and the design processes associated with Rapid Prototyping (RP), Digital Design Fabrication (DDF), and other uses of CAD-CAM technologies.

Although significant scholarly attention has been paid to the aforementioned areas of educational research in architecture, the intensified cognitive challenges for novice learners in a digital era have yet to be explicitly addressed in architectural literature. As educators consider how advanced, diversified software and tooling technologies impact the pedagogy of the design studio, cognitive theories of learning relevant to the novice learner provide the anchor for innovations in instructional design.

The purpose of this paper is to identify and exploit the aforementioned gap in the literature by addressing the cognitive and pedagogical factors that may inhibit or amplify efficient knowledge transfer for the novice learner in digital design. This will be accomplished by first differentiating analogue design in a traditional studio environment from digital design in order to expose both the learning opportunities afforded by digital technology and the cognitive challenges it creates for the novice learner. In response to these exposed learning challenges and pedagogical implications, the educational literature particular to the cognitive architecture of the novice learner will be addressed. Finally, in response to the links that will be established between the challenges faced by novice learners in digital design and the relevant cognitive literature, a fundamental and critical impediment to efficient knowledge transfer in introductory digital design education will be identified and strategies that may mitigate its negative learning consequences will be discussed. Although these pedagogical strategies are suggested for digital design in architectural education, they are applicable to a variety of design disciplines in which novice learners encounter both the cognitive trials and opportunities that are engendered by the use of digital tools.

# 2. Framework for Pre-Digital Design

### 2.1 Learning in pre-digital contexts

Analog design development processes in architecture are grounded in the cognitive development research initiated by Donald Schön and his collaborators (Schön, 1983; Schön and Wiggins, 1992). In the early 1980's, Schön published research that helped establish a cognitive theory of design that was designer-centered, a shift away from prior design research that was directed towards the study of domain knowledge and design thinking (Oxman, 2008). Schön and Wiggins' research exposed the “reflective 'conversation' with the materials of a design situation” (Schön and Wiggins, 1992, p.135) that occurs within the mind of the designer. This research observation is now commonly known as 'reflection in action' and has become widely accepted by academicians, serving as a primary underpinning of modern design education (Schön, 1984). Perhaps most importantly, Schön subdivides this visual-tactile learning process into three operations that iteratively repeat to facilitate the design proposition's development: reception, reflection, reaction. As Oxman (2008, p.101) noted, this “paradigm of design, strongly predicated on visual reasoning has provided a strong influence upon design research and pedagogy for the last two decades” and “the general characterization of design as a reflection supported by representational processes has had an almost universal influence on architectural design education.” In addition to the work by Schön and his collaborators, researchers such as Akin (2002), Eastman (1969), Oxman (1999), and others have also provided important contributions to research on the cognitive aspects of design pedagogy and design thinking. Despite the breadth of research focusing on design cognition over the past three decades, the interrelation between visual reasoning and conceptual processes explicated by Schön is still the cornerstone of studies of cognition in design-focused disciplines (Oxman, 1999).

Prior to the introduction of digital design media into studio-based design environments, the associations between designer and material representational medium were relatively direct, a unique aspect of analogue design that has served as a basis for educational theories of design cognition and a challenge for theories of design cognition in an era of digital design. As Schön and Wiggins (1992, p.135) have described in relation to analogue design, “the designer sees what is 'there' in some representation of a site, draws in relation to it, and sees what has been drawn, thereby informing further designing. In all this 'seeing', the designer not only visually registers information but also constructs its meaning.” In other words, an exploitation of knowledge processes and knowledge structures allow designers to translate or re-represent conceptual schema onto a representational medium. In turn, designers re-encode a post-analysis conceptual description into their conceptual schema, allowing meaning to be developed and learning to occur via schemata enhancement. In her theory of representation-redescription, Karmiloff-Smith (1995) explicitly defines learning as a successive process of representations which become increasingly amenable, allowing conscious access to schema. Therefore, the process of learning can be described as the exploitation of previously stored schema through re-describing its representations. In architectural design, for example, the student may first represent the typological concept of a 'courtyard'. After building a physical model of the 'courtyard' type building, they may then describe the building as a 'wind-blocking' type of building, thereby illustrating an increased cognitive development by having added the characteristics of the courtyard type, such as having a central space that receives shadow and wind protection, to the pre-construction notion of a 'courtyard' type, or a building mass that exhibits some variation of a central void. This example not only illustrates Karmiloff-Smith's theory of representation-redescription, but it also demonstrates the direct designer-to-material characteristic of analogue design.

### 2.2. Limiting characteristics of analog design

Unlike the digital design environment, the analogue design environment can be understood as primarily compositional and formal in nature and defined by material-based developmental processes and allowances. Extensive analysis of these properties of analogue design has been well documented by researchers; however, it is worth briefly summarizing two aspects that are particularly relevant to this prospective paper regarding the novice learner in a digital design environment. The physical characteristics, or affordances of design materials, have had a fundamental impact on the representational and formal nature of analogue design. From introductory to experienced stages in design education, the understanding of representational materials through physical, formal traits and geometrical transformations that are applied during the design development process has served as a limiting framework for conceptual and pedagogical exploration. As was previously presented, visual reasoning is fundamental to design studies, yet visual discovery is primarily through formal referencing, modification, or reinterpretation. This limited 'matter and material' approach has been described as the 'antithesis' of digital design and as lacking the diverse ontologies present in digital design (Oxman, 2008).

The second limiting aspect of analogue design is its encompassing typological definition and the self-referential nature of the typological critique, a foundational concept of modern architectural pedagogy (Oxman, 2008). Affordances of materials utilized in the design process and a history of typologically similar precedents assist in the persistence of conceptually related design typologies. As a system in which conveyance of meaning is predicated on the recollection of precedent typological attributes, design pedagogy in architecture faces a vast array of challenges as digital design mediums move the discipline beyond its typological structuring.

## 3. Digital Design in Analog Pedagogical Contexts

### 3.1 Theoretical foundation for digital design

Digital design as a medium for design education challenges the structuring of analog pedagogical contexts through an increased diversity of ontological, phenomenological, and existential design conditions. New technologies promulgate novel design possibilities which, in turn, engender novel theory and critique. As new conceptualizations now exist between matter and form, functional and formal knowledge, temporality, solidity, and the structuring of generative logics in design, digital design pedagogy requires the conceptualization of a cognitive framework that can encompass the aforementioned enhanced knowledge base of design. Although the implications of digital design for design pedagogy are vast, educators and researchers have already done much to establish a foundational underpinning to digital design and its dissemination in educational environments. The extensive body of scholarly work by Oxman (1994; 1996; 2004; 2006; Oxman and Oxman, 2014) could well become foundational material in the studies of digital design as it frames various approaches to design education and pedagogy, reviews changes in design media, and presents the evolutions in architectural knowledge bases, processes, theories, and designer-to-material relationships derived from the emergence of digital design.

### 3.2 Disciplinary diversification for digital design: praxis as catalyst

As researchers and educators attempt to frame and structure the emerging architectural knowledge base of digital design skill and digital design models, practitioners continue to play a central role in the expansion of design methodologies and conceptual content derived from the affordances of digital technology. In addition to the foundational texts regarding paradigmatic shifts in architecture spurred by the digital revolution (Kipnis, 1993 cited in Lynn, 1998; Lynn, 1998), the expanding range of conceptual foci such as topological form or hyper-continuity

(Kubo and Ferré, 2003), tectonics (Reiser and Umemoto, 2006), parametricism (Schumacher, 2009), materialization (Kieran and Timberlake, 2003), evolutionary form (Hensel and Menges, 2004), and emergent form (Kolarevic, 2003) also includes design paradigms that adapt historic technique into novel conceptual content (Cohen, 2001). The degree of individual control in design - arguably the most integral component of cognitive educational theory in design and a critical, paradigmatic element of digital design theory - has also recently garnered attention in architectural publications via its historical (Wu, 2014) and procedural (Meredith, 2013) abstraction. The diversity of conceptual foci as well as the continued emergence of conceptual paradigms in architectural praxis exemplify the vast array of challenges faced by educators and learners in the first digital age.

### 3.3 Are existing knowledge bases of design applicable in digital contexts?

Despite the aforementioned theoretical foundation for digital design, a lack of scholarly work exists that specifically focuses on the cognitive aspects of introductory digital design education. As questioned by Oxman (2008, p.100), “[h]ow can designerly ways of knowing, a concept so strongly derived from a paper-based culture of design, be adapted to the new situations of digital models and mediated design processes?” Oxman furthers the question by asking, “[a]re we encountering the same cognitive phenomena of known processes of design in the new digital media? Or are we encountering new forms of knowledge, new scientific foundations, and new models of design?” Questions such as these by leading figures in the field of design studies underscore the importance of research that theorizes and structures the role of cognition in digital design education. The literature clearly establishes that we are indeed encountering new forms of knowledge in digital design and that digital design is a methodologically unique form of design (Oxman, 2006; Oxman, 2008). Thus, it is important to reiterate that existing theories of cognition in design were developed in an age of analog design, or via paper-based representational re-descriptions, and note that the consideration of digital design cognition enters upon novel ground as cognition in a digital age has yet to be thoroughly theorized. Although the cognitive logic of 'visual reasoning' as defined by Schön and others that underlies analog design is still applicable to digital design, the diversity of 'challenges' or facets associated with digital design relegates the usefulness of this methodology to only a small segment of digital design studies.

### 3.4 Challenges of digital design pedagogy

The literature related to the traditional design studio environment and its cognitive underpinnings has been reviewed as well as the literature concerning the emergence of digital design in academia and its differentiation from analogue design. Building upon this cognition-focused foundation of digital design education, the following challenges of digital design pedagogy relative to the novice learner can now be addressed: 1) increased exposure of novice learners to advanced digital design media and materialization technologies; 2) vast array of digital technologies and associative specializations; 3) required specialization or 'elitism'; and 4) relative lack of pedagogical strategies anchored on cognitive theories of learning.

*3.4.1 Misuse of advanced technology*

Regardless of disciplinary thresholds, introductory education is characterized by the calculated-structuring of foundational schema, both paradigmatic and skill-based. While limited exposure to higher-order knowledge in introductory education can enhance learning (Kalyuga, Ayres, Chandler, and Sweller, 2003), the misuse of advanced technology is a common plague in introductory digital design education as affordances of advanced technology are exploited. For example, the user-defined associative compositions or frameworks that control parametric operations offer opportunities for explicit knowledge transfer and formative assessment in digital design education, but such affordances are also two-faced with opportunities for enhanced knowledge-transfer being abused for quick results via ease of transference and formal complexities that mask a lack of intellectual rigor. Thus, a significant challenge for educators in introductory digital design education is determining how to introduce, develop, implement, and control higher-order generative frameworks for effective knowledge transfer while still providing enough flexibility for student exploration of the new media.

*3.4.2 Expanding digital design specializations*

Highly sophisticated digital media has spurred a plethora of digital sub-specialties including the designer's role as tool-builder. This seminal differentiation from historical roles of the architectural designer poses exceptional challenges to architectural pedagogy. If digital design thinking is a necessary skill for praxis, how can design pedagogy possibly accommodate the diversity of advanced specializations and emerging professional roles? Should alternative curricula be developed for the 'digital design specialist'? The development of adaptable and easily-deployable knowledge structures may be essential to this inquiry, and such development begins at the introductory level.

*3.4.3 Diversity of interactions in digitally mediated design*

Digital design positions the designer in novel relationships with design media, a key characteristic of this field of design. Although the designer continues to occupy a central role in design schema, the nature of interactivity and the type of control make this form of mediated design unique. In digital design, the designer faces an increased range of roles regarding the condition of interaction with design media as compared to the analogue designer. The digital designers control generative and performative processes, structures and designs the material of information or data, and thus have their role symbolically represented via the link created between designer and sub-processes.

One such designer-to-material relationship in digital design is that of bi-directional information transfer, a complex interaction not encountered in analogue design. This complexity presents challenges to the design educator relative to the learner's cognitive capacity and the specific type of modeling processes employed. Unlike the early a posteriori Computer-Aided Design (CAD) models that exhibited a minimal differentiation from conventional design models, current digital models' efficient integration with material logics and the materialization processes of DDF and RP afford designers increased opportunities for information transfer. Physical designs can be scanned into a digital medium, manipulated, and printed back into physical form. The method by which digital ideational representations are developed is highly diversified compared to the analog era. Digital models are hierarchically organized by complexity – formation models, generative models, performance models, and integrated compound models – each differentiating the manner in which designers interact with design representational descriptions within the design process. Parametricism, BIM, shape grammers, evolutionary models, and dynamic design including animate form and morphogenetic models are included under the topic of bi-directional transfer in digital design (Oxman, 2006). Because BIM modeling in particular is rapidly expanding in breadth and complexity, it is also particularly apt for explicit knowledge evaluation (Eastman, Eastman, Teicholz, and Sacks, 2011).

*3.4.4 Digital 'Elitism'*

Digital 'elitism' is a term used to describe the specialist skills required to utilize advanced digital technology (Oxman, 2006). Considering that digital design media often requires knowledge of multiple software packages and advanced technical knowledge for operations such as scripting, parametric framework development, and managing of complex data models (Oxman, 2006), the requisite knowledge structures necessary for such advanced processes demand extensive development. How can design educators enhance development of digital media's technical skills or 'digital skill thinking' without over allocating curricular focus on this one learning outcome? In introductory architectural education this is especially important as digital design skill and knowledge of emerging theoretical frameworks for digital design are added to an already bulging curriculum. If trends in praxis continue, digitally 'elite' graduates may be increasingly prioritized, suggesting that higher-level technical and theoretical knowledge of digital design will be prioritized at increasingly earlier stages of design education.

*3.4.5 Dearth of cognition-based pedagogy*

Deliberate and well-researched pedagogical strategies to elicit efficiency in learning are increasingly important in the digital design environment. Yet, the rich body of research related to cognitive load, schema development, and knowledge transfer remains relatively untapped in design education. Anchoring digital design pedagogy in cognitive theories of learning appears to be especially promising due to the following two factors: 1) the increased importance of effective knowledge transfer to accommodate digital design's expanding knowledge base and 2) the un-tapped, intrinsic affordances between digital tooling processes and schema development. The following sections discuss aspects of cognition supported by educational research and affordances of digital technology that are especially relevant to the novice learner in digital design contexts. Affordances for the novice learner's cognitive development related to digital technology will be considered through the exploration of two relevant cognitive theories of learning, recognizing that other significant theories of learning may also apply to digital design education.

## 4. Cognition in Introductory Digital Design Education

As previously suggested, the beginning digital design student's intellectual development can be enhanced via the construction of higher-order, adaptable knowledge structures or schema capable of flexible re-appropriation in a variety of academic and professional environments. However, the development of schema in novice learners is particularly challenging due to pronounced learning curves for both 'digital design thinking' and 'digital skill thinking'.

As Akin (2002) suggests, students who are developing design skills typically must grope (i.e. problem domain) for a needle (i.e. knowledge) in a haystack (i.e. solution domain), a cumbersome cognitive task due the student's lack of knowledge concerning their own process and the 'happenstance' or 'loose' pedagogical context within which they are immersed. In addition to these design-related struggles, students in digital design contexts must also grapple with the technical challenges of digital tooling methods and related representational media. Students must rapidly shift their cognitive capacity between the knowledge induction methods of didactic cognition (i.e. the development of technical software knowledge) and design thinking (i.e. methods related to Finke, Ward, and Smith's (1992) theory of Creative Cognition). This bi-modal learning process can quickly overload cognitive capacity, thereby inhibiting effective knowledge transfer.

Thus, the primary challenge of digital design education for novice learners is not simply the operational knowledge of digital tools nor the cognitive load resulting from “domain-general creative cognition (i.e. divergent thinking)” (Beaty, Silvia, Nusbaum, Jauk, and Benedek, 2014, p.1186), but rather the simultaneity of the aforementioned, differentiated cognitive processes. Based upon research from the fields of educational theory and digital design, an effectual educational strategy for teaching novice learners in digital design may be a combination of pedagogical techniques that enhance schema development and knowledge transfer efficiency through cognitive load mitigation. Thus, the structuring of digital design pedagogy based on the general principles of schema development and cognitive load theory (CLT) may be particularly beneficial for novice learners (Ausubel, 1968; Dansereau, 1995; Van Merrienboer and Sweller, 2005).

### 4.1 Schema Development

Considering the continual stream of new or upgraded software packages necessary for higher-level digital processes, the 'novice' learner in digital design is an inherently abstract categorization. Novice learners are assumed to be those students lacking necessary technical, creative, and combinatory schema to facilitate effective digital design production. For the purpose of clarification, this discussion is also based on an assumption that 'near transfer' (Perkins and Salomon, 1992) likely occurs between analogue and digital design media, suggesting that the design knowledge (i.e. schema) formalized, represented, and re-transcribed (Oxman, 2000) via representational re-descriptive processes (Karmiloff-Smith, 1995) is not media specific. This assumption is reasonable due to the wide-spread ability of students to transfer established design knowledge from analogue to digital environments as well as the lack of understanding regarding the cognitive foundation for creative thought (Beaty et al., 2014).

A schema, also known as a mental configuration or cognitive framework, is the structure comprised by the learner's organized knowledge in a particular subject (Ausubel, 1963). Considering a schema's function as the “Velcro of the mind to which new information sticks” (Cross and Steadman, 1996, p.41), the organizational efficiency - particular to the individual learner - behind its underlying associations of related concepts is critical to the subsumptive process (Ausubel, 1963). The acknowledgement by design educators of factors affecting the subsumptive process is the first step to developing curriculum that supports effective meaningful learning and retention. One such factor particularly relevant to digital design is that of the hierarchically organized cognitive structure. Ausubel describes the epitome knowledge structure as one of highly inclusive “conceptual traces under which are subsumed traces of less-inclusive subconcepts as well as traces of specific informational data” (Ausubel, 1963, p.217). This organizational logic of “progressive differentiation” (Ausubel, 1963, p.217) is in essence a network of malleable, top-down cataloging, thus supporting the position that 'explicit pedagogical frameworks' (Mcalpine, 2004) for well-defined problem/solution spaces are beneficial as they enhance conceptual clarity and encourage deep processing strategies in students (Muis and Franco, 2009).

Although schema development in learning is but one of the many foci of cognitive studies in digital design education, it is the fundamental goal when teaching novice learners (Sweller, 1988). For the purpose of facilitating meaningful learning, rather than rote learning, goal-specific pedagogy with well-defined problem and solution spaces may be extremely beneficial (Eastman, 1969). Alternative techniques, such as those based on the theories of situated cognition (Lave and Wenger, 1991 cited in Mcalpine, 2004) including scaffolding, direct feedback, and supported trials (Mcalpine, 2004) are also particularly relevant for schema development.

**4.2 Cognitive load theory in digital design education**

The well-researched field of cognitive loading offers a foundational framework for introductory digital design pedagogy as teaching strategies based on the implementation of its core principles can reduce cognitive burden, increase clarity, and thereby enhance knowledge transfer efficiency for novice learners. The simultaneity of creative cognition and operational knowledge of digital tools makes cognitive load theory especially pertinent to digital design studies.

The primary presupposition of CLT is that learners, particularly those that are novices, have a limited capacity working memory when exposed to unfamiliar information (Sweller, Van Merriënboer, and Paas, 1998 cited in Artino, 2008). Learners also have “an effectively unlimited long-term memory holding cognitive schemas that vary in their degree of complexity and automation” (Van Merriënboer and Ayres, 2005, p.6). As such, a core objective of CLT has been the development of instructional methodologies that reduce “unnecessary cognitive burden on working memory” (Artino, 2008, p.146) so as to prevent a learner's limited working memory from being overwhelmed, thereby hindering learning (Artino, 2008).

*4.2.1 Expedited schema development via cognitive load reduction*

One important aspect of CLT for design educators is that a student's expertise is not based on their processing efficiency of information located outside long-term memory but rather the quality of, and accessibility to, knowledge contained in schemata. Consequently, the construction of expertise - a process involving the conscious combination of simple ideas into those with greater complexity (Van Merrienboer and Sweller, 2005) – can exploit the affordances of digital technology for enhanced schema development. For example, the seminal cognitive process in design of 'reflection in action' can be expedited due to the swift materialization capabilities of rapid prototyping (RP). With effective curriculum structuring and well-designed instruction (Van Merrienboer, 2002 cited in Van Merrienboer and Sweller, 2005), students can more quickly carry out their exploration of the design problem's conceptual and solution spaces via representational formalisms such as ICF (Issue-Concept-Form) (Oxman, 1994) and other knowledge acquisition processes via the use of RP. With digital technology, amount, diversity and complexity are no longer limiting factors in artifact production (Sass and Oxman, 2006).

*4.2.2 Prioritizing early automation*

Design knowledge is acquired as solution spaces and the development processes responsible for their emergence are reflected upon and transferred into long-term memory. As student's tap solution-space knowledge stored in long-term memory, limited working memory is freed for further application. Additionally, highly complex schemata can become automated through repetition, a natural cognitive load mitigative process uniquely applicable to machine operation and software applications (Van Merrienboer and Sweller, 2005). This cognitive affordance supports a pedagogical strategy in design that prioritizes the development of student's automative processes for software usage early in their education so as to curb superfluous computational cognitive load in future, higher-level design courses. The relevance of this perspective is amplified due to the design learner's near-complete incapacity to automate solution space knowledge of ill-defined problems, the type of problems comprising design-studio courses.

4.2.3 Intelligent precedent libraries

Novice learners in design are particularly prone to quandary or “stuckness” (Sachs, 1999), a state resulting from numerous contextual factors (Lewin, 1966 cited in Sachs, 1999). However, cognitive overload induced by the inductive reasoning processes associated with ill-defined problems is arguably a major contributor. Novice learners, by definition, lack advanced schema in the particular area of concentration, thus knowledge is not available to structure information. Information must then be organized randomly prior to being tested for effectiveness (Van Merrienboer and Sweller, 2005). It is processed linearly while the possible combinations of linear elements erupt exponentially, a cognitive complication particularly relevant to the ill-defined problems of design.

The existing literature indicates that enhanced schema development by means of intelligent, digital precedent libraries may help alleviate the severity of 'stuckness' – 'intelligent' meaning planned or algorithmically controlled precedent libraries that provide design information as well as offer related design solutions based on the queried topic. Even though design education utilizes precedent study to build concept and solution space schema – a seminal aspect of meaningful learning in design (Akin, 2002; Oxman, 2004) – precedent knowledge is particularly apt for near transfer in design problems and digital technologies can amplify this affordance. Logics of the associative and controlled-attention theories of creative thought each support the prior statement as well, given the assumption that constructing greater depth to, and a wider range of, creative thought can assist in 'stuckness' mitigation. On one hand, the associative theory (Mednick, 1962 cited in Beaty, et al., 2014, p.1186) suggests that flat associative hierarchies in semantic memory enable creative thought. The controlled-attention theory, however, hypothesizes that creative thought results from differences in the goal-directed, top-down, balanced control of attention and cognition (Beaty, et al., 2014). Research in both theoretical areas indicates that more encompassing precedent exposure in creative disciplines can induce expanded process and solution space schema, thereby supplying the learner with greater cognitive resources to tap into as they attempt to move beyond their quandary. 'Intelligent' precedent libraries can help supply knowledge concerning both how to design and knowledge of existing designs.

## 5. Discussion and Limitations

The aforementioned pedagogical strategies should be considered initial explorations of cognitive research applied to digital design education, especially in terms of the novice learner. The simultaneity of digital skill thinking and creative cognition warrant further development of this line of inquiry so that instruction can be designed to maximize schema development and enhance knowledge transfer. The dynamic nature of digital design and the rapidly evolving cognitive developmental sciences collectively indicate that there is ample opportunity for future research in this area of instructional design. What toolset of digital design knowledge is most appropriate for the architectural learner in the contemporary professional context? Structuring curricula and designing instruction around knowledge-transfer optimization strategies and compiling related, empirical results could be a valuable next step to further development of this line of inquiry.

## 6. Conclusions

The fundamental disruption in analog pedagogical environments resulting from the digital revolution in architecture suggests that the pedagogical methods which have provided the cornerstone of architectural education in an analogue environment must be re-conceptualized and restructured relative to the expanded knowledge base of digital design. This paper attempts to begin such reconceptualization by differentiating between analog and digital learning environments and identifying the unique challenges and affordances associated with digital design. The primary challenge for novice learners in digital design may be the simultaneity of operational knowledge of digital tools and the cognitive load resulting from domain-general creative cognition. As such, relevant learning theories including schema development and cognitive loading are proposed as they hold substantial promise for addressing the teaching and learning complexities associated with the simultaneous cognitive processes inherent in digital design.

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