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A Hierarchical Model of Design Knowledge

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Abstract. Despite the central role of knowledge in design, there is a dearth of research on the typology, intrinsic structure and composition of design knowledge. This results in an indeterminate epistemological picture of design outcomes. To address the need for effective conceptualizations, in this article I propose a hierarchical model of design knowledge, which stratifies the different bodies of knowledge into ranked levels. I illustrate some of the benefits of the model, and compare it with existing hierarchical models of knowledge in non-design fields of inquiry.

Keywords: Design · Design research · Knowledge · Bodies of design knowledge · Hierarchical models of knowledge · Epistemology of design

1 Introduction

The activity of design, or the activity of devising blueprints for future states, is characterized by a number of different *bodies* as well as *types* of knowledge. For example, specific bodies of knowledge commonly encountered in design include the set of design *requirements*[1] or the set of design *principles*[2] to be followed by a designer. Design artifacts themselves can be understood as *embodied knowledge*,[3] or objects that *contain knowledge of what the product should be*.[4]

Because contemporary design practice is imbued with various knowledge-related constructs, it follows that designers must nowadays master a range of knowledge-related skills and competencies. Such skills may include knowledge *transfer* (communication, instruction, coaching), knowledge *encoding* (modeling, sketching, writing, digital content

1. Donna P Duerk, *Architectural Programming: Information Management for Design* (Wiley, 1993); Klaus Pohl, "The three dimensions of requirements engineering," in *Seminal Contributions to Information Systems Engineering* (Springer, 2013), 63–80.

2. Max Wertheimer, "Gestalt Theory," 1938, Wolfgang Metzger et al., *Laws of seeing.* (Mit Press, 2006); Jakob Nielsen, *10 Usability Heuristics for User Interface Design*, http://www.nngroup.com/articles/ten-usability-heuristics/, Accessed on Jan 30, 2015, 1995; Brittany N. Smith, Anbang Xu, and Brian P. Bailey, "Improving Interaction Models for Generating and Managing Alternative Ideas During Early Design Work," in *Proceedings of Graphics Interface 2010*, GI '10 (Ottawa, Ontario, Canada: Canadian Information Processing Society, 2010), 121–128, http://dl.acm.org/citation.cfm?id=1839214.1839236; Dieter Rams, *Dieter Rams: Ten Principles for Good Design*, technical report (Retrieved 27/2/2016 from https://www.vitsoe.com/gb/about/good-design, 1980); Bertrand Meyer, "On to components," *Computer*, no. 1 (1999): 139–140; John Vlissides et al., "Design patterns: Elements of reusable object-oriented software," *Reading: Addison-Wesley* 49, no. 120 (1995): 11.

3. Nigel Cross, "Designerly ways of knowing: Design discipline versus design science," *Design issues* 17, no. 3 (2001): 49–55; Erik Stolterman and Mikael Wiberg, "Concept-driven interaction design research," *Human–Computer Interaction* 25, no. 2 (2010): 95–118.

4. Nigel Cross, "Design research: A disciplined conversation," *Design issues* 15, no. 2 (1999): 5–10.

creation), as well as knowledge *acquisition* and *synthesis* (learning, reasoning, problem framing). Moreover, since it is rarely economically feasible to develop new products and services entirely anew, contemporary design practices call for easy *reuse* of pre-existing design knowledge.

Yet despite the evident importance of knowledge in many aspects of design practice, there is a dearth of research on the typology, inner structure, and composition of design knowledge. Accordingly, this raises a number of pertinent questions, for instance: What is the best way to conceptualize knowledge generated in design? What are the typical bodies of design knowledge produced in a design project, and what are their mutual relationships? In particular, is there a way to arrange such bodies of design knowledge into an overarching organizing structure? And finally, how are bodies of design knowledge generated, acquired, and validated?

To address these questions, in this article I position design as an activity that is focused on generating knowledge, which Cross characterized as "peculiar to the awareness and ability of a designer".[5] To develop the overall argument, I first present an overview of related work in Section 2. I then present the hierarchical model of design knowledge in Section 3 along with the description of some of the bodies of design knowledge commonly found at each level of the model, as well as the methods used to synthesize them. In Section 4, I conclude the article by describing some common uses and benefits of our model, and comparing it with existing hierarchical models of knowledge as found in non-design disciplines.

2 Related Work

In general terms, and as first described by Plato in *Theaetetus*,[6] *knowledge* can be defined as any cognitive content that a person *believes* in, and is at the same time *true* and *justified*; in other words, as *justified true belief*. A number of different typologies and taxonomies of knowledge have been reported in the literature. For example, one well-known classification juxtaposes *know-that* (conceptual, factual) with *know-how* (procedural, algorithmic) kinds of knowledge. The former can be thought of as a network linking discrete concepts,[7] and the latter is a series of steps or actions that may lead to the fulfillment of some goal.[8]

Another example is the distinction between *representable* or expressible knowledge versus *tacit* knowledge[9] that cannot be easily encoded by means of external representations. An important variant of tacit knowledge is called *knowing-in-action*[10] knowledge, which is typically gained through informal learning and is best thought of as the practical and intuitive "professional artistry" that practitioners exhibit in unique, uncertain, and conflicted situations of design and practice.[11]

5. Cross, "Design research: A disciplined conversation."
6. John M Cooper and DS Hutchinson, *Plato Complete Works: Meno, Phaedo, and Theaetetus* (Hackett Publishing Company, 1997).
7. James Hiebert, *Conceptual and procedural knowledge: The case of mathematics* (Routledge, 2013).
8. Gilbert Ryle, *Concept of mind* (University of Chicago Press, 1949).
9. Michael Polanyi, *The tacit dimension* (Doubleday & Co, 1966).
10. Donald A Schön, "Knowing-in-action: The new scholarship requires a new epistemology," *Change: The Magazine of Higher Learning* 27, no. 6 (1995): 27–34.
11. Donald A Schön, *Educating the reflective practitioner: Toward a new design for teaching and learning in the professions* (Jossey-Bass, 1987).

2.1 Hierarchical Models of Knowledge

In non-design-based fields of inquiry, such as sciences and philosophy, knowledge has traditionally been organized into various "bodies" of diverse scope, including scientific *laws*, formal *models*, *theories*, research *paradigms*[12] and research *programs*.[13] Once acquired, such bodies of knowledge may then be further ranked into strata that retain their relative ordering, thus resulting in various *hierarchical* models of knowledge.

The typical hierarchical model of knowledge is depicted as a pyramidal, triangular sequence of layers or *levels*. The choice of this particular shape, characterized by its wide base and a narrow peak, visually indicates that the knowledge placed near the bottom is foundational, plentiful, and relatively easy to gather, while the knowledge placed towards the top of the pyramid is of an increasingly more refined, derivative as well as abstracted nature, and therefore progressively harder to obtain, compile, or synthesize.

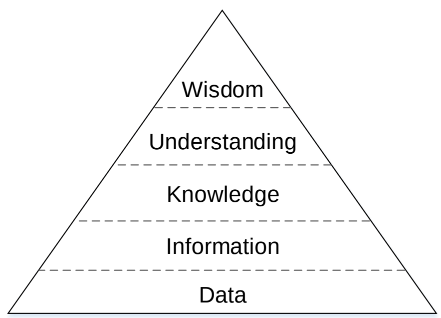


Figure 1: Ackoff's "Data-Information-Knowledge-Understanding-Wisdom" (DIKUW) model.

Figure 1 shows one exemplary hierarchical model of knowledge, Ackoff's influential data-information-knowledge-understanding-wisdom model[14] (DIKUW), which stratifies knowledge into the following five levels:

1. The base *data* level contains raw facts (i.e. numbers or symbols) obtained through perceiving, observing, and measuring some phenomena.
2. The *information* level contains processed data that can provide answers to *what*, *where*, and *when* questions.
3. The *knowledge* level contains processed information that can provide answers to *how* questions.
4. The *understanding* level contains processed knowledge that can provide answers to *why* questions.
5. Finally, the *wisdom* level contains processed understanding that facilitates correct *value judgements* about the observed phenomena.

Most notably in hierarchical models of knowledge, higher levels emerge from lower ones—that is, a level serves as the raw input into its immediately superior level.

12. Thomas S Kuhn, *The structure of scientific revolutions* (University of Chicago Press, 2012).
13. Imre Lakatos, *Mathematics, Science and Epistemology: Volume 2, Philosophical Papers*, vol. 2 (Cambridge University Press, 1980).
14. Russell L Ackoff, "From data to wisdom: Presidential address to ISGSR, June 1988," *Journal of applied systems analysis* 16, no. 1 (1989): 3–9.

Knowledge found at one level is transformed into the upper knowledge level through a number of associated cognitive processes and activities, such as decision making, comprehension, perception, evaluation, reasoning, memory storage, memory retrieval, and learning.

While Ackoff's model is perhaps the most renowned, other similar hierarchical models of both "know-that" and "know-how" knowledge have been reported in various disciplines, for instance in artificial intelligence,[15] network-based formalisms,[16] text mining,[17] and educational psychology.[18] Yet, despite the availability of various hierarchical models of knowledge in these diverse fields of inquiry, little equivalent work that describes the hierarchical rank, structure, mutual influence, or lineage of various bodies of design knowledge exists in design-related research literature.

2.2 Approaches to Knowledge in Design Research

Regarding approaches to design knowledge, Frayling[19] writes about the iterative development of design artifacts which can serve as "stepping stones" to further artifacts and *theories*, yet while providing little elaboration of the relationships among such design artifacts, theories, and other types of knowledge generated in design. Zimmerman *et al*[20] enumerate some common bodies of design knowledge such as *needs*, *process models*, and *design guidelines*; however, they neglect the order of generation and the structural and causal relationships among bodies of knowledge. Similarly, Stolterman and Wiberg[21] posit that design artifacts should be understood as features of *"embodied knowledge"* but forego discussion of how such artifacts might relate to other types of knowledge typically generated in design practice and design-based research. Visser[22] presents an approach for the "construction of design representations"which focuses narrowly on external manifestations or representations of design knowledge. Friedman[23] writes about theory construction in design research, while placing all bodies of design knowledge under the overarching term of "design theories", without discussing other kinds of design knowledge such as contextual design knowledge or design artifacts when understood as carriers of knowledge.

15. Allen Newell, "The knowledge level," *Artificial intelligence* 18, no. 1 (1982): 87–127.

16. Ronald Jay Brachman, "On the epistemological status of semantic networks," *Associative networks: Representation and use of knowledge by computers*, 1979, 3–50.

17. Hsinchun Chen, *Knowledge management systems: a text mining perspective* (Knowledge Computing Corporation, 2001).

18. Benjamin S Bloom et al., "Handbook I: cognitive domain," *Taxonomy of Educational Obiectives: The Classification of Education Goals. New York: Longman*, 1956, Lorin W Anderson, David R Krathwohl, and Benjamin Samuel Bloom, *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives* (Allyn & Bacon, 2001).

19. Christopher Frayling, *Research in art and design* (Royal College of Art London, 1993).

20. John Zimmerman, Shelley Evenson, and Jodi Forlizzi, "Discovering and Extracting Knowledge in the Design Project," in *Proceedings of Future Ground* (Design Research Society, 2004).

21. Stolterman and Wiberg, "Concept-driven interaction design research."

22. Willemien Visser, *The cognitive artifacts of designing* (2006).

23. Ken Friedman, "Theory construction in design research: criteria: approaches, and methods," *Design studies* 24, no. 6 (2003): 507–522.

3 A Hierarchical Model of Design Knowledge

Drawing upon existing hierarchical models of knowledge and the review of related literature, presented in Section 2, as well as my own design-based research experiences,[24] I introduce a *hierarchical* model of design knowledge. According to this model, all design knowledge typically generated and utilized within any given design project is first (a) grouped into specific bodies of design knowledge, and then (b) ranked into several hierarchical levels and associated sub-levels, in the order of their derivation, transformation, and progressive refinement.

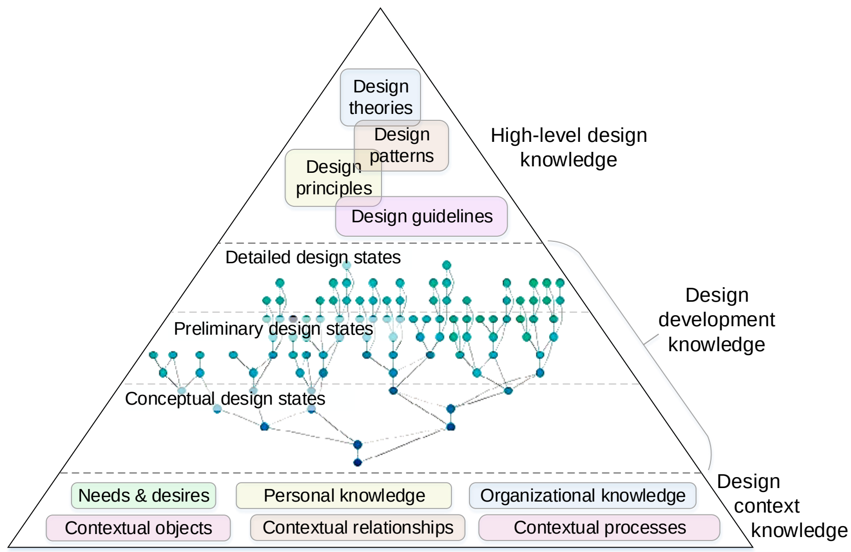


Figure 2: The hierarchical model of design knowledge.

I show the proposed model in Figure 2. Starting from the base of the pyramid, the principal levels of the model include:

1. *Design context knowledge.* Knowledge about the *design context*, or the part of the general environment that directly influences the design problem under consideration. This knowledge is further divided into *raw* observations of the design context, as well as *processed* and *understood* design context observations.

2. *Design development knowledge.* Building upon design context knowledge, this level contains knowledge about *design states* developed during the design project and includes information about (a) conceptual design states, (b) preliminary design states, and (c) detailed design states.

3. *High-level design knowledge.* This level builds upon design development knowledge and includes any post-design development knowledge, such as recommendations and guidelines; principles and rules; patterns; and design theories.

Like the existing hierarchical models, in the hierarchical model of design knowledge, each level emerges from the preceding one, transformed by a number of cognitive

24. Siniša Kolarić, "Interacting with Design Alternatives" (PhD diss., Simon Fraser University, 2016).

processes related to design practice or design research. In the following, I describe the various levels of the model in greater detail.

3.1 Foundational Level: Design Context Knowledge

The base level of the model contains *contextual design knowledge*. The term *design context* (or simply *context*) denotes the subset of the general environment that is related to, and influences the design problem at hand. Some of the typical bodies of design knowledge found at the design context level include:

- *Knowledge on needs, wants, and desires.* Design projects are initiated by an unsatisfactory condition requiring relief, or by a desire to use or own a certain artifact. Needs can be both personal and/or organizational.
- *Personal knowledge and expertise.* The context of any design project is further characterized by the participation and collaboration of many individuals who have some vested interests in the design project. Stakeholders possess personal knowledge or expertise, including the *know-what* knowledge about various aspects of the design problem, as well as personal *know-how* knowledge on design processes, methods, and techniques,[25] individual tacit *knowing-in-action* knowledge,[26] as well as personal *theories of action*.[27]
- *Organizational knowledge.* In many cases, especially in more complex design projects, design activities are frequently conducted by a number of collaborating individuals, which gives rise to organizations and other groups or design teams ranked at different scales. Important factors that comprise and influence the design context include communication among organizational and design team members, knowledge sharing, organizational learning, organizational culture, team roles, and workplace conditions.
- *Knowledge on contextual entities in general.* Generally speaking, many *contextual entities* (both natural as well as man-made) exist within the design context, thus influencing subsequent problem-solving activities. In most general terms, these include (a) contextual *objects*, (b) *relations* linking such objects, and (c) *contextual processes* through which both the objects and their relations undergo certain temporal changes (see Figure 3).

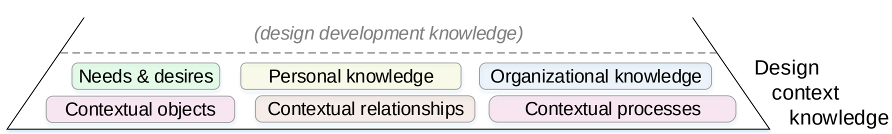


Figure 3: Design context knowledge.

Synthesizing contextual design knowledge. At the outset of a design project, the design context is generally *unknown* (or implicit, undiscovered) to the designer. As the

25. Cross, "Design research: A disciplined conversation."
26. Schön, "Knowing-in-action: The new scholarship requires a new epistemology."
27. Chris Argyris and Donald A Schön, *Theory in practice: Increasing professional effectiveness.* (Jossey-Bass, 1974).

design project unfolds however, the design context will become increasingly familiar and *known* to the designer. This implies the existence of cognitive activities of (a) *observing* the design context (which covers a range of methods, from casual observation to highly elaborate focus group and ethnographic approaches), (b) *analyzing* and *understanding* raw contextual facts, thus generating answers to the *what*, *where*, and *when* questions, as well as how these contextual facts might influence the design under consideration.

Not all *known* design context knowledge will be *relevant* for the design problem at hand. In fact, much contextual design knowledge might be irrelevant or have little bearing on the final design. Thus, the only contextual knowledge that directly influences the next, hierarchical level up (the design development level) is the *relevant* contextual design knowledge.

3.2 Middle Level: Design Development Knowledge

Building upon the relevant contextual design knowledge, the *design development* of *design states* can proceed. From the knowledge-centric viewpoint of design, this level can be understood as *embodied knowledge*,[28] *the thinking embodied in an artifact*,[29] or objects that *contain knowledge of what the product should be*.[30]

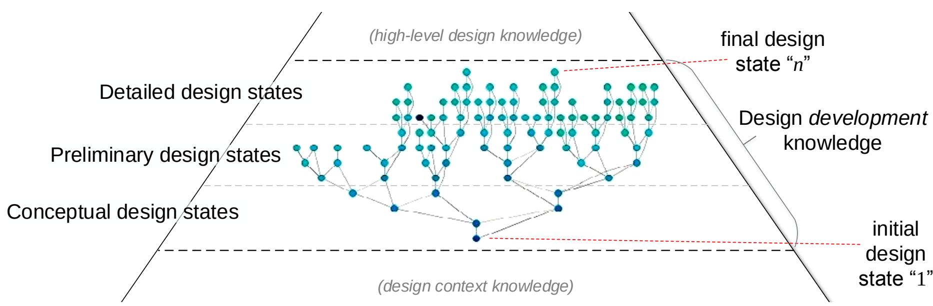


Figure 4: Mid-level design knowledge ("design history" view).

Figure 4 depicts the "design history" view of design development knowledge in an intuitive manner, with the *directed acyclic graph* (DAG) of history expanding from the bottom up. The existence of numerous branches in a design history DAG reflects the pragmatic, contingent nature of design as well as the multitude of potential design decisions that can be made during each design iteration. Figure 4 also illustrates the common division of all design activities into conceptual, preliminary, and detailed design as well as the corresponding, induced classification of all design development knowledge into three sub-levels: conceptual, preliminary, and detailed design development knowledge.

As a second, alternative and complementary perspective of the synthesis and acquisition of design development knowledge, it can sometimes help to further classify all design development knowledge into two subsets: (a) the *design requirements* that stipulate *conditions* or *capabilities* of the final design, and (b) the design *"solution"* artifacts or the relevant knowledge that satisfies the design requirements.

28. Cross, "Designerly ways of knowing: Design discipline versus design science"; Stolterman and Wiberg, "Concept-driven interaction design research."

29. Frayling, *Research in art and design*.

30. Cross, "Design research: A disciplined conversation."

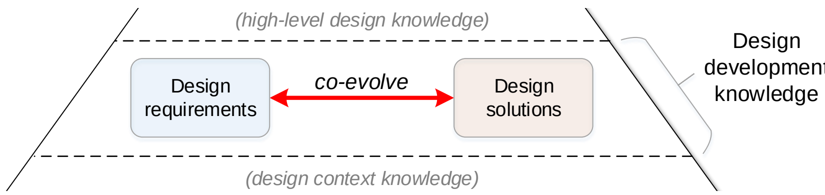


Figure 5: An alternative view of the mid-level, design development knowledge (the "co-evolving design ensemble" view).

Figure 5 illustrates this perspective of the design development knowledge, complementary to the "design history" view depicted in Figure 4. Within this view, the activity of design can be regarded as a cognitive activity *co-evolving* both halves of this ensemble,[31] as indicated by the two-way arrow in the center of the figure. In the arrow's left-to-right direction, design requirements influence design solution development directly, and in the opposite direction, the development of design solutions enables the designer to further elicit, discover, and modify design requirements. Progressive co-evolution of both subsets of knowledge will then ultimately converge to the final design.

3.2.1 A Deeper View into the Design Ensemble: The Double-Pyramid Model

Building further on the design ensemble co-evolution model shown in Figure 5, the middle level can be detailed further, whereby both the set of design requirements and the associated set of design solutions are represented by their own respective hierarchies of increasingly elaborate and refined (sub-)levels of knowledge.

Design Requirements If we begin with design requirements, this body of design knowledge is first sparked by a general "statement of needs", which can then decomposed into a number of hierarchical layers.

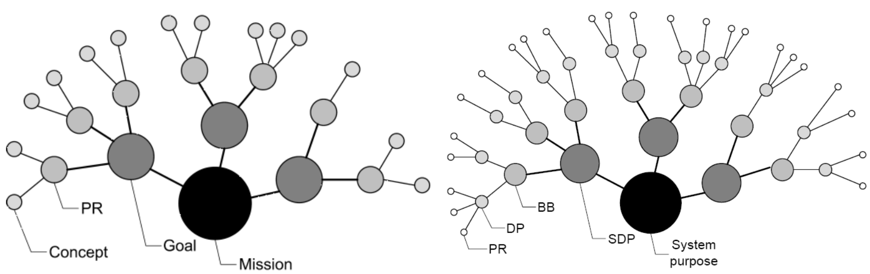
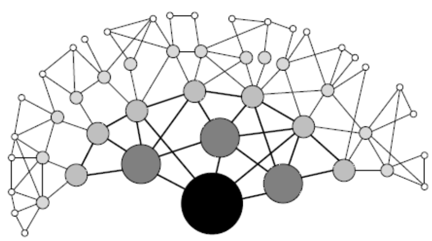


Figure 6: Examples of decomposing design requirements in two different fields of design: in architectural design, and in system design.

31. David G Ullman, Thomas G Dietterich, and Larry A Stauffer, "A model of the mechanical design process based on empirical data," *AI EDAM* 2, no. 1 (1988): 33–52; Mary Lou Maher and Josiah Poon, "Modeling Design Exploration as Co-Evolution," *Computer-Aided Civil and Infrastructure Engineering* 11, no. 3 (1996): 195–209; Kees Dorst and Nigel Cross, "Creativity in the design process: co-evolution of problem–solution," *Design studies* 22, no. 5 (2001): 425–437; Rongrong Yu et al., "Empirical support for problem–solution co-evolution in a parametric design environment," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2014, 1–12.

For instance, in architectural design, the activity of managing design requirements usually falls under the term of *architectural programming*. As one possible decomposition,[32] each architectural program begins with the highest-level *mission*, which is then progressively decomposed into *goals*, these in turn into *performance requirements* (PRs), and these into *concepts* (Figure 6, left).

In a similar fashion, in software engineering design, the initial *system purpose* can be decomposed[33] into *system design principles*, *blackbox behaviour* (BB), *design representations* (DRs), and *physical representations* (PRs), as depicted in Figure 6 (right).



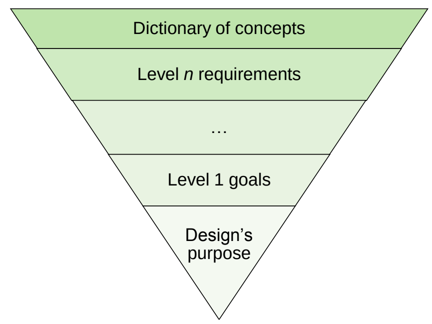


Figure 7: Left: a realistic (strongly inter-connected) model of design requirements. Right: the (inverted) sub-hierarchy of design requirements.

In general then, the statement of needs is distilled into purpose (or mission statement), purpose into goals,[34] and so on. In fact, since multiple requirements as a rule link to multiple requirements, the resulting underlying structure actually underlies a general set-theoretical *graph*, or an *heterarchy*.[35] I show this more realistic model in Figure 7 (left), together with the inverted sub-hierarchy of increasingly more elaborate types of design requirements in Figure 7 (right).

Design Solutions As per definition, any design solution can be defined as a representation instance that satisfies the design problem's set of design requirements. Again, the design development phase is characterized by the intensive use of many "designerly" types of representations, which includes but is not limited to notes, drawings, sketches, computer records, accepted design proposals, constraints, and strategies.[36] Similar to the "abstraction continuum" proposed by Fish and Scrivener,[37] in the following I order design representations by the following two criteria:

1. By their decreasing degree of *abstractness*, *vagueness*, as well as

32. Duerk, *Architectural Programming: Information Management for Design*.

33. Nancy G Leveson, "Intent specifications: An approach to building human-centered specifications," in *Requirements Engineering, 1998. Proceedings. 1998 Third International Conference on* (IEEE, 1998), 204–213.

34. Anne Dardenne, Axel Van Lamsweerde, and Stephen Fickas, "Goal-directed requirements acquisition," *Science of computer programming* 20, no. 1 (1993): 3–50.

35. Elizabeth Hull, Ken Jackson, and Jeremy Dick, *Requirements engineering* (Springer Science & Business Media, 2010).

36. David G Ullman, Stephen Wood, and David Craig, "The importance of drawing in the mechanical design process," *Computers & graphics* 14, no. 2 (1990): 263–274.

37. Jonathan Fish and Stephen Scrivener, "Amplifying the mind's eye: sketching and visual cognition," *Leonardo*, 1990, 117–126.

2. By their increasing degree of *exactness*, *consolidation* and *elaborateness* of said representation types.

1. *Mental images*	7. *Sketches*
2. *Signs, words*	8. *Illustrations*
3. *Grouped symbols, words*	9. *Models, prototypes*
4. *Verbal descriptions*	10. *Photographs*
5. *Diagrams, trees & tables*	11. *Full instantiations*
6. *Higraphs, maps*	

Figure 8: Typical representation types at the "design development" knowledge level.

Figure 8 shows a list of design representations, ordered by the aforementioned two criteria. All these representations can be arranged into their own pyramid or sub-hierarchy, as shown in Figure 9.

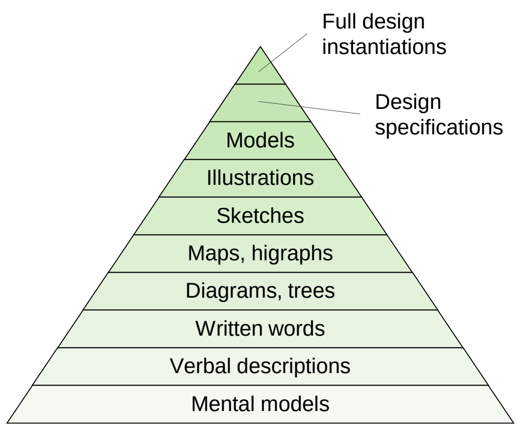


Figure 9: The sub-hierarchy of designerly representations for design solutions.

The "Double-Pyramid" View of Design Development Knowledge Finally, to provide an integrated picture, Figure 10 shows the two sub-hierarchies (pyramids) of design development knowledge embedded into the wider hierarchy of design knowledge. As per figure, in the upward direction, both the design requirements as well as design solutions exhibit increased levels of detail, elaboration, and completeness. And vice versa, following the downward direction, both sub-sets of design development knowledge exhibit increasing levels of generalization, abstraction, and ambiguity. Red arrows indicate that any level of design requirements knowledge can influence any level of design solution knowledge and vice versa, thus contributing to the co-evolution of the design ensemble.

Synthesizing design development knowledge. Generally speaking, design development knowledge is generated, synthesized and acquired through the application of "design methods"[38] which can be defined as a procedure or sequence of steps that one should

38. Cross, "Designerly ways of knowing: Design discipline versus design science."

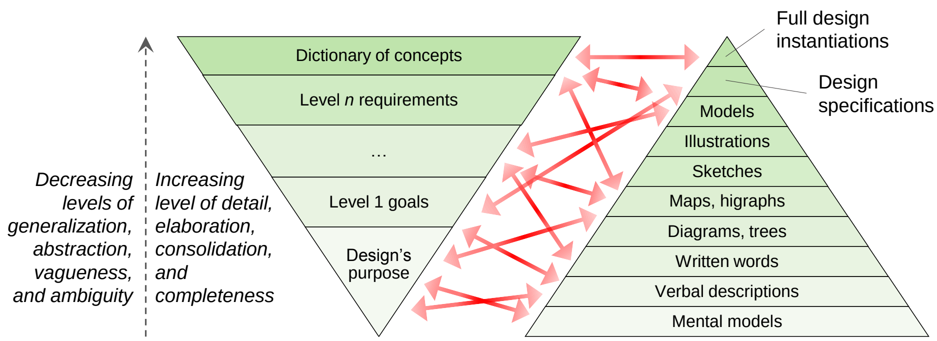


Figure 10: The "double-pyramid" model of the design development knowledge, showing two embedded, co-evolving sub-hierarchies of (a) design requirements, and (b) design solutions.

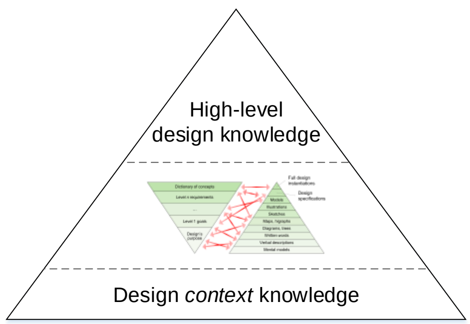


Figure 11: The "double-pyramid" model of the middle (design development) knowledge layer, as situated within the wider hierarchy of design knowledge.

follow in order to develop a design state. Nowadays, design "methods" range from relatively simple procedures followed by a single designer to complex, collaborative, and multi-disciplinary workflows involving numerous collaborating design professionals and a large number of contextual factors. A full treatise of the historical development of design methods and their gradual complexification is beyond the scope of this article; for additional details the reader may refer e.g. to the paper by N. Bayazit.[39]

3.3 High-Level Design Knowledge

Following the completion of design development activities, and depending on the demands of the project, the designer or design researcher may optionally proceed with the generation of high-level design knowledge.

As I show in Figure 12, the high-level bodies of design knowledge are situated at the pinnacle of the model, thus indicating their highly derivative, refined and generalized nature. Typical high-level bodies of design knowledge include:

1. *Knowledge on design guidelines.* Design guidelines are relatively low-level recommendations or suggestions that help designers frame and conceptualize any given

39. Nigan Bayazit, "Investigating design: A review of forty years of design research," *Design issues* 20, no. 1 (2004): 16–29.

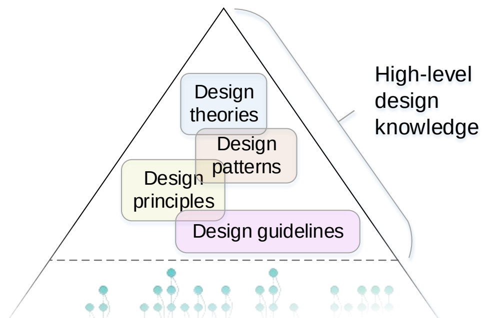


Figure 12: The pinnacle of the pyramid: High-level design knowledge.

design problem as well as heuristically evaluate design solutions for a design problem. Examples include design guidelines in architectural and urban design,[40] interior design,[41] interaction design,[42] product design,[43] and structural engineering design.[44]

2. *Knowledge on design principles.* Compared to design guidelines, design *principles* are of a more general, universal, and abstract nature since they tend to be *"more fundamental, widely applicable, and enduring"*.[45] Examples of design principles can be found e.g. in graphic design,[46] interaction design,[47] product design,[48] and software design.[49]

3. *Knowledge on design patterns.* A design "pattern" is a general or "templatized" design solution that can be used to solve an instance of *reccurring* design problems. Examples of design patterns can be found in architectural and urban design,[50] prod-

40. Oscar Newman, "Design guidelines for creating defensible space.," 1976, Clare Cooper Marcus et al., *Housing as if people mattered: Site design guidelines for medium-density family housing*, vol. 4 (University of California Press Berkeley, CA, 1986).

41. Sam Kubba, "Space planning for commercial and residential interiors," 2003, Mark Karlen, *Space planning basics* (John Wiley & Sons, 2009).

42. Scott Henninger, "A methodology and tools for applying context-specific usability guidelines to interface design," *Interacting with computers* 12, no. 3 (2000): 225–243; Ben Shneiderman and Catherine Plaisant, *Designing the User Interface: Strategies for Effective Human-Computer Interaction, 5th Edition* (Prentice Hall, 2010).

43. Geoffrey Boothroyd, "Product design for manufacture and assembly," *Computer-Aided Design* 26, no. 7 (1994): 505–520; William Green and Patrick W Jordan, *Human factors in product design: current practice and future trends* (CRC Press, 1999).

44. Trevor E Kelly, "Base isolation of structures: design guidelines," *Holmes Consulting Group Ltd, New Zealand*, 2001, D Schnerch et al., "Proposed design guidelines for strengthening of steel bridges with FRP materials," *Construction and building materials* 21, no. 5 (2007): 1001–1010.

45. Shneiderman and Plaisant, *Designing the User Interface: Strategies for Effective Human-Computer Interaction, 5th Edition*, p. 62.

46. Wertheimer, "Gestalt Theory"; Metzger et al., *Laws of seeing.*

47. Nielsen, *10 Usability Heuristics for User Interface Design*; Smith, Xu, and Bailey, "Improving Interaction Models for Generating and Managing Alternative Ideas During Early Design Work."

48. Rams, *Dieter Rams: Ten Principles for Good Design*.

49. Meyer, "On to components"; Vlissides et al., "Design patterns: Elements of reusable object-oriented software."

50. Christopher Alexander, S Ishikawa, and M Silverstein, "Pattern languages," *Center for Environmental Structure* 2 (1977).

uct design,[51] and object-oriented software design.[52]

4. *Knowledge on design theories.* A design theory is a coherent and comprehensive body of knowledge that prescribes, predicts, or explains observations or facts related to some aspect of the design problem (or class of design problems) at hand. Examples include design theories in architectural and urban design,[53] interaction design,[54] as well as *cross-disciplinary* design theories, such as those straddling the intersection of architectural design and philosophy.[55]

The four principal types of high-level design knowledge shown in Figure 12 may contain other sub-types of high-level design knowledge. For instance, design guidelines might contain or subsume relatively low-level design *recommendations*.[56] Likewise, design theories might subsume *laws* or small theories that underwent extensive, repeated confirmation, such as Fitts' law in interaction design.[57]

Synthesizing high-level design knowledge. I first note that, by developing various design states at the lower (design development) level, the designer will gain significant *personal expertise* with regard to the class of design problems at hand. For instance, by developing many designs of a specific building type, an architect acquires a deeper understanding of what makes an element of design sound (or unsound) and subsequently the discernment and expertise needed to reflect on and synthesize a set of design guidelines and other high-level forms of design knowledge related to that particular class of building designs.

The main method for synthesizing high-level bodies of design knowledge is the *reflective method*, which is based on accumulated experience, reflection, contemplation, and introspection. To illustrate, design guidelines in interaction design are commonly derived through "experimental results, experience with existing interfaces, and knowledgeable guesswork".[58] Sedlmair *et al*[59] likewise state that *reflection* is the main method to confirm, refine, reject, and propose design guidelines. Frayling[60] furthermore classifies design guidelines, design patterns, and design principles as outputs of *research-for-*

51. Mohammad Razzaghi, Mariano Ramirez, and Robert Zehner, "Cultural patterns in product design ideas: comparisons between Australian and Iranian student concepts," *Design Studies* 30, no. 4 (2009): 438–461; Dan Lockton, David Harrison, and Neville A Stanton, "The Design with Intent Method: A design tool for influencing user behaviour," *Applied ergonomics* 41, no. 3 (2010): 382–392.

52. Vlissides et al., "Design patterns: Elements of reusable object-oriented software"; Christopher Fox, *Introduction to Software Engineering Design: Processes, Principles and Patterns with UML2* (Addison-Wesley Longman Publishing Co., Inc., 2006).

53. Christopher Alexander, *A new theory of urban design*, vol. 6 (Oxford University Press, USA, 1987); Henri Lefebvre, *The production of space*, vol. 142 (Oxford Blackwell, 1991).

54. Donald A Norman and Stephen W Draper, "User centered system design," *New Perspectives on Human-Computer Interaction, L. Erlbaum Associates Inc., Hillsdale, NJ*, 1986, John M Carroll, *HCI models, theories, and frameworks: Toward a multidisciplinary science* (Morgan Kaufmann, 2003).

55. Gaston Bachelard and Maria Jolas, *The poetics of space*, vol. 330 (Beacon Press, 1994); Gilles Deleuze, *Desert Islands: and Other Texts, 1953–1974* (Semiotext(e) / Foreign Agents, 2004).

56. Céline Mariage, Jean Vanderdonckt, and Costin Pribeanu, "State of the art of web usability guidelines," *The handbook of human factors in web design*, 2005, 688–700.

57. Paul M Fitts, "The information capacity of the human motor system in controlling the amplitude of movement.," *Journal of experimental psychology* 47, no. 6 (1954): 381.

58. Shneiderman and Plaisant, *Designing the User Interface: Strategies for Effective Human-Computer Interaction, 5th Edition*, p. 40.

59. Michael Sedlmair, Miriah Meyer, and Tamara Munzner, "Design study methodology: Reflections from the trenches and the stacks," *Visualization and Computer Graphics, IEEE Transactions on* 18, no. 12 (2012): 2431–2440.

60. Frayling, *Research in art and design*.

design (RfD) activities that help other designers to approach, frame, and solve instances of a particular class of design problems. Frayling also asserts that design theories can be considered as the outputs of *research-about-design* (RaD) activities based on the empirical (scientific) method, and whose aim is to discover how humans carry out the activity of design.

4 Discussion

In the hierarchical model of design knowledge, similar to existing hierarchical models of knowledge, a level (or sub-level) emerges from the level (or sub-level) immediately preceding it. In other words, one level feeds into the level immediately above it and is transformed into its successor level through a number of associated cognitive activities common to design. Such cognitive activities include, among others, learning, decision making, comprehension, perception, evaluation, and various types of reasoning such as deductive, inductive, and abductive reasoning.

To illustrate this transformative process taking place in the model, contextual design knowledge is learnt, comprehended, evaluated, reflected upon, reasoned about, and then incorporated into the next (design development) level. *Conceptual* design development knowledge is likewise transformed into its immediate upper sub-level, that is, the level containing *preliminary* design development knowledge, and so on for other levels.

4.1 Uses and Benefits of the Model

I argue that the hierarchical model of design knowledge may contribute to the activities of *understanding*, *explaining*, and *predicting* of the outcomes of design practice and research, as viewed from a knowledge-centric vantage.

Better Understanding of Design First, the model may lead to a better understanding of outcomes of design, and thus of the phenomenon of design itself. Design problems can be "messy"[61] or "wicked",[62] and solving them is hard. As one particular aspect of their intractability, design problems utilize knowledge from many sources that cannot be determined in advance.[63] The model provides an intuitive, compact, and extensible cognitive map[64] of such sources of design knowledge, including their relative rank, ordering, and overall arrangement, thus contributing to a better understanding of the outcomes of design.

Explaining Pre-Existing Outcomes of Design Second, the model can also help elucidate and explain the genesis of any pre-existing body of design knowledge. As one example, if one views the well-known set[65] of patterns in architectural and urban design through the lens of the hierarchical model of design knowledge, the authors

61. Donald A Schön, *The reflective practitioner: How professionals think in action*, vol. 5126 (Basic books, 1983).

62. Horst WJ Rittel and Melvin M Webber, "Dilemmas in a general theory of planning," *Policy sciences* 4, no. 2 (1973): 155–169.

63. Raymonde Guindon, "Knowledge exploited by experts during software system design," *International Journal of Man-Machine Studies* 33, no. 3 (1990): 279–304.

64. Edward C Tolman, "Cognitive maps in rats and men," *Psychological review* 55, no. 4 (1948): 189.

65. Alexander, Ishikawa, and Silverstein, "Pattern languages."

first (a) observed, analyzed, and comprehended a variety of different contexts in architectural and urban design, and then (b) developed a number of architectural and urban designs corresponding to those contexts, thus achieving a deeper understanding of said designs. This personal understanding, in turn, resulted in the authors' ability to synthesize the aforementioned widely known and influential collection of design patterns.

Providing a Roadmap for Desired Outcomes of Design Third, the model likewise provides a convenient roadmap for generating a desired, target body (or target set of bodies) of design knowledge. For instance, if a designer's or a design team's goal is to develop a set of suitable design principles for a certain class of design problems, they may begin by synthesizing or acquiring contextual design knowledge and proceed with design development at the middle level (thus gaining necessary design development knowledge) and finally, reflect on and synthesize the target set of design principles.

4.2 Levels of Design Knowledge

Comparing the model to other hierarchical models of knowledge, a similarity appears in the way raw data in the Ackoff's model is "sensed" and the way facts about the design context are observed in the model. However, while Ackoff's initial level is uniform, containing just raw facts or data, in the hierarchical model of design knowledge the initial level is a composite consisting of *observed (detected) unknowns* and *understood unknowns*, which are then further triaged into *relevant* and *irrelevant* contextual design knowledge. Thus, the design context level implies and contains a hierarchy of progressively processed sub-levels of contextual design knowledge. As for ways to synthesize and acquire design context knowledge, there is agreement between *observe* and *understand* activities and, for example, the *define* and *discover* phases of design,[66] *discover* phase in the "double-diamond" model of design,[67] as well as with *learn*, *winnow*, *cast*, and *discover* design activities.[68]

In contrast to other hierarchical models, the design development knowledge level is characterized by the intensive employment of *abductive* reasoning, as detailed in papers by Kolko,[69] Dorst[70] and Cross.[71] Abductive reasoning, like deductive reasoning, seeks the best and most likely explanation for an action, proposition, or observed fact. However, while deduction reaches a *certain* conclusion from a set of premises, abductive reasoning leads to an *informed guess* which does not follow formally but as a "matter of course".[72] At the design development level of the model, an agreement thus exists with the *construct*

66. John Zimmerman, Shelley Evenson, and Jodi Forlizzi, "Discovering and extracting knowledge in the design project," 2005,

67. British Design Council, *Eleven lessons: Managing design in eleven global brands*, `http://www.designcouncil.org.uk/resources/report/11-lessons-managing-design-global-brands`, Accessed: 2016-12-17.

68. Sedlmair, Meyer, and Munzner, "Design study methodology: Reflections from the trenches and the stacks."

69. Jon Kolko, "Abductive thinking and sensemaking: The drivers of design synthesis," *Design Issues* 26, no. 1 (2010): 15–28.

70. Kees Dorst, "The core of 'design thinking' and its application," *Design studies* 32, no. 6 (2011): 521–532.

71. Nigel Cross, *Designerly Ways of Knowing* (Birkhäuser Architecture, 2007).

72. Charles Sanders Peirce and Patricia Ann Turrisi, *Pragmatism as a principle and method of right thinking: The 1903 Harvard lectures on pragmatism* (SUNY Press, 1997).

and *refine* phases of design,[73] the *define* and *develop* phases,[74] as well as with *design*, *implement* and *deploy* design activities.[75]

At the third level of the model, there is strong agreement between the high-level design knowledge and the *understanding* and *wisdom* layers in the Ackoff's model, with the *reflect* phase of design,[76] as well as with the activity of externalizing such knowledge through the *write* activity.[77] The designer, through many instances of design development, acquires an equivalent of *understanding* which results in the ability to synthesize design guidelines as well as in the *wisdom* or a *"grasp of the overall situation"*,[78] which enables the synthesis of higher-level design principles, design patterns, and design theories. Gaining wisdom in order to generate high-level design knowledge thus corresponds to Bloom's taxonomy[79] at the "evaluation" (level 6) with an individual's ability to exert value judgements, as well as to the ability to engage in Bateson's *third-order*[80] learning activities.

5 Conclusions and Future Work

I have presented a hierarchical model of design knowledge, whereby such knowledge is classified into three principal levels: (a) design context knowledge, (b) design development knowledge, and (c) high-level design knowledge. In addition, each level is characterized by associated sub-levels that refine the model further.

I believe that this model can assist design practitioners and design researchers in better situating and understanding various bodies of knowledge created in both design practice and design-based research, as well as in informing future research related to the epistemological and methodological foundations of design and design-based research.

Future work includes further elaboration of the methods for generating and justifying bodies of design knowledge, augmentation of the hierarchical model of design knowledge by additional bodies of knowledge typically produced in design practice or design-based research, as well as refinement of the model in terms of how bodies of design knowledge relate to each other.

73. Zimmerman, Evenson, and Forlizzi, "Discovering and extracting knowledge in the design project."
74. British Design Council, *Eleven lessons: Managing design in eleven global brands*.
75. Sedlmair, Meyer, and Munzner, "Design study methodology: Reflections from the trenches and the stacks."
76. Zimmerman, Evenson, and Forlizzi, "Discovering and extracting knowledge in the design project."
77. Sedlmair, Meyer, and Munzner, "Design study methodology: Reflections from the trenches and the stacks."
78. Irtaza Barlas, Antonio Ginart, and Jordan L Dorrity, "Self-evolution in knowledge bases," in *Autotestcon, 2005. IEEE* (IEEE, 2005), 325–331.
79. Bloom et al., "Handbook I: cognitive domain."
80. Gregory Bateson, *Steps to an ecology of mind: Collected essays in anthropology, psychiatry, evolution, and epistemology* (University of Chicago Press, 1972).