she ji [ʃə: dʒi:]

The Evolution of "Co-evolution" (Part I): Problem Solving, Problem Finding, and Their Interaction in Design and Other Creative Practices

Nathan Crilly

Keywords
Design process
Design thinking
Creativity
Design history
Interdisciplinarity

Received
May 26, 2021
Accepted
July 1, 2021

NATHAN CRILLY
Department of Engineering, University of Cambridge, UK (corresponding author)
nc266@cam.ac.uk

Abstract
One of the most influential descriptions of design activity emphasizes how problems and solutions "co-evolve." This concept has somehow escaped critical review and cross-disciplinary comparison, resulting in a fragmented approach to the subject. Reviewing the published literature on design co-evolution reveals that the term is used to refer to a range of distinct concepts, and the study of co-evolution has generated a number of elaborations and alternatives. Reviewing the broader literature in design and other disciplines further reveals that discussions of design co-evolution are disconnected from the history of relevant concepts in design research, and disconnected from a range of relevant concepts in other disciplines that describe creative work. Here I examine what the different concepts of design co-evolution are, how they have been modified and what they are related to. This leads to questioning the distinction between problems and solutions, defining them in relative terms, and drawing a connection between design co-evolution and design fixation.

http://www.journals.elsevier.com/she-ji-the-journal-of-design-economics-and-innovation
https://doi.org/10.1016/j.sheji.2021.07.003

Introduction[1]

For the last thirty years, design creativity has often been described as a process of problem-solution "co-evolution." On this account, rather than just solving a problem, design involves developing both an understanding of the problem and the possible solutions until a good match is found. Ideas for solutions might drive a reinterpretation of the problem, which, in turn, prompts new ideas for solutions. These changes to the representation of problems and solutions might be relatively minor, such as a change in emphasis or a refinement. However, they can also be radical, opening up entirely new parts of the design space. Creativity can thus be seen not just in the solutions that are offered, but also in the problems that are posed, and in the dynamic interplay between these processes.

Descriptions of design as the co-evolution of problems and solutions have become influential in the study of a range of design disciplines and work contexts. However, such descriptions have not been collected and subjected to critical assessment. To thoroughly examine the idea of design co-evolution, I here review the origins of that idea, its later development, and its connection to other ideas in design and other disciplines. I then examine assumptions about the distinction between problems and solutions on which descriptions of co-evolution rest. This leads to the proposal that problem-solution distinctions should be seen as relative rather than absolute, which I use to draw a connection between accounts of co-evolution and accounts of fixation. This is all with the objective of encouraging, stimulating, and extending useful accounts of creative activity.

Conceptual Origins

The history of design co-evolution concepts is rather complicated, with many early publications contributing to that history. However, the origin of the idea is most often attributed to Mary Lou Maher's work in the 1990s, especially her 1994 conference paper focused on how computer systems could perform creative design work.[2] Compared to well-structured problems, Maher described design problems as presenting the additional challenge that "design requirements are neither consistent nor complete, they have to be considered as a dynamic set of knowledge that can be updated or revised."[3] Maher's proposal was to develop an algorithm that would permit design exploration through "the co-evolution of designs and design requirements."[4] This proposal was later illustrated with a diagrammatic representation of the co-evolution model, which has subsequently been widely reproduced and modified (Figure 1).[5]

This diagram represents a model of design exploration in two interacting spaces: the problem space (P) and the solution space (S). These spaces each evolve over time (the horizontal arrows), and time (t) proceeds from left to right (with increments of "+1"). Search processes between the two spaces can take two different forms: "Problem leads to Solution" (the downward arrows) or "Solution Refocuses the Problem" (the upward arrow). Explaining this, Maher and Josiah Poon say,

1 This is the first part of a two-part article. For Part II, see Nathan Crilly, "The Evolution of 'Co-evolution' (Part II): The Biological Analogy, Different Kinds of Co-evolution, and Proposals for Conceptual Expansion," *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 3 (2021): 333–55. DOI: https://doi.org/10.1016/j.sheji.2021.07.004.

2 Mary Lou Maher, "Creative Design Using a Genetic Algorithm," in *Proceedings of the First Annual Conference on Computing in Civil Engineering*, vol. 2, ed. Khalil Khozeimeh (Washington, DC: American Society of Civil Engineers (ASCE), 1994), 2014–21, available at https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0090304.

3 Maher, "Genetic Algorithm," 2018. Also see a similar argument in Leila Alem and Mary Lou Maher, "A Model of Creative Design Using a Genetic Metaphor," in *Artificial Intelligence and Creativity: An Interdisciplinary Approach*, ed. Terry Dartnall (Dordrecht, NL: Springer Netherlands, 1994), 288, 291, DOI: https://doi.org/10.1007/978-94-017-0793-0_20. This material was derived from Leila Alem and Mary Lou Maher, "A Model of Creative Design Using a Genetic Metaphor" (paper presented at the Symposium on AI Reasoning and Creativity, Queensland, Australia, August 1991), 1–4.

4 Maher, "Genetic Algorithm," 2014.

5 Mary Lou Maher and Josiah Poon, "Modeling Design Exploration as Co-evolution," *Microcomputers in Civil Engineering* 11, no. 3 (1996): 196, Figure 1, DOI: https://doi.org/10.1111/j.1467-8667.1996.tb00323.x. In other versions, the upward arrow is dashed. For example, see Mary Lou Maher, Josiah Poon, and Sylvie Boulanger, "Formalising Design Exploration as Co-evolution," in *Advances in Formal Design Methods for CAD: Proceedings of the IFIP WG5.2 Workshop on Formal Design Methods for Computer-Aided Design*, ed. John S. Gero and Fay Sudweeks (Dordrecht, NL: Springer-Science + Business Media BV, 1996), 7, DOI: https://doi.org/10.1007/978-0-387-34925-1_1.

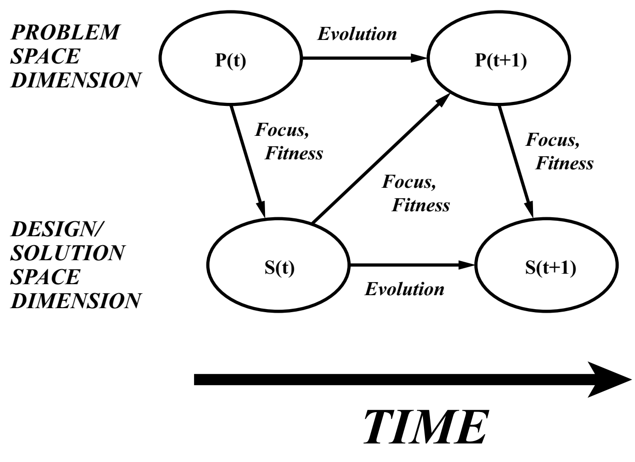

Figure 1
Maher and Poon's diagrammatic representation of the design co-evolution model. © 1996 *Microcomputers in Civil Engineering* (John Wiley & Sons). Reproduced with permission.

> "The problem space $P(t)$ is the design goal at time t and $S(t)$ is the solution space which defines the current search space for design solutions. The solution space $S(t)$ provides not only a state space where a design solution can be found but it also prompts new requirements for $P(t+1)$ that were not in the original problem space $P(t)$."[6]

Each of the two spaces represented in the diagram has a certain "population" at any point in time, a population of related problems and a population of related solutions, where "the evolution of each space is guided by the most recent population in the other space."[7] Maher and Poon call this model "co-evolution," explaining that it provides the basis for a computational model of design exploration. In later work, Maher and colleagues used this general computational model to describe a real professional design project,[8] and protocol studies of students and expert designers.[9]

The widespread influence of Maher's concept of co-evolution can partially be attributed to Kees Dorst and Nigel Cross's reproduction and modification of Maher and Poon's diagram.[10] In studying creativity in the design process, Dorst and Cross analyze a protocol study with experienced industrial designers working in response to a brief. They observe that the designers did not treat the design assignment as a fixed "design problem," but constantly manipulated it:

> "It seems that creative design is not a matter of first fixing the problem and then searching for a satisfactory solution concept. Creative design seems more to be a matter of developing and refining together both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis, and evaluation processes between the two notional design 'spaces'—problem space and solution space."[11]

Dorst and Cross connect this analysis to the co-evolution model from Maher and colleagues, which they then modify and annotate to represent the specific behavior observed in their own protocols. Over the next twenty years, Dorst and Cross's article became one of the most highly cited works

6 Maher and Poon, "Modeling Design Exploration," 197.
7 Ibid., 197.
8 Josiah Poon and Mary Lou Maher, "Co-evolution in Design: A Case Study of the Sydney Opera House," in *CAADRIA '97: Proceedings of the Second Conference on Computer-Aided Architectural Design Research*, ed. Y-T Liu, J-Y Tsou, and J-H Hou (Hsinchu: National Chioa Tung University, 1997), 439–48, available at http://papers.cumincad.org/data/works/att/4925.content.pdf.
9 Mary Lou Maher and Hsien-Hui Tang, "Co-evolution as a Computational and Cognitive Model of Design," *Research in Engineering Design* 14, no. 1 (2003): 47–64, DOI: https://doi.org/10.1007/s00163-002-0016-y. The work of Maher and colleagues, especially their use of the biological analogy, is further discussed in Part II of this article.
10 Kees Dorst and Nigel Cross, "Creativity in the Design Process: Co-evolution of Problem-Solution," *Design Studies* 22, no. 5 (2001): 425–37, DOI: https://doi.org/10.1016/S0142-694X(01)00009-6. Dorst and Cross cite a similar diagram presented by Maher et al., "Formalising Design Exploration as Co-evolution."
11 Dorst and Cross, "Creativity in the Design Process," 434.

in design research,[12] and co-evolution became one of the most theoretically developed concepts in the field.[13] Whereas Maher and colleagues' work in the 1990s had primarily described co-evolution as a means by which computers could perform creative design work,[14] Dorst and Cross provided a detailed description of human designers creatively engaging in problem-solution co-evolution, and it is this aspect of human creativity that I focus on in this article.

Conceptual Development

Since the publication of Dorst and Cross's article, co-evolutionary accounts of human design activities have become widespread, appearing in general accounts of design cognition and design behavior.[15] The concept of problem-solution co-evolution is used to describe observations based on a variety of research methods, including laboratory studies with students,[16] naturalistic studies of student projects,[17] interview studies with professionals,[18] and naturalistic studies of projects in industry.[19] Co-evolution is used to describe thinking processes in different design disciplines, including architecture,[20] industrial design,[21] engineering design,[22] software design,[23] and design thinking more generally.[24] It is also used to understand how designers behave in different work contexts, including design teams,[25] stimuli-rich environments,[26] and computer-supported design tools.[27]

Accounts of design co-evolution are often introduced with reference to the diagram presented by Maher and Poon. This diagram can be contrasted with many other diagrams of the design process which represent design proceeding in stages, typically from problems to solutions, even if some iteration is indicated.[28] The co-evolution diagram is different, and it is seemingly widely appealing to have a visual representation of problems and solutions developing through time, and reciprocally influencing each other during that development. Many researchers using this diagram have modified it to illustrate additional features of design work, such as analogizing and mental simulation,[29] methods and framing,[30] and analysis, synthesis, and evaluation.[31] The diagram has also been extended to illustrate specific sequences of events in real projects[32] and laboratory studies.[33] The need for these modifications and extensions is not surprising. The original diagram is a representation of how a computer might perform creative design tasks, rather than of how designers think. There may be similarities between the two,[34] but the original co-evolution diagram should be seen as a point of departure when describing human design activities, and so further modifications and extensions are to be encouraged.

As represented in Maher and Poon's diagram, the co-evolution of problems (P) and solutions (S) involves four kinds of change: problem-to-problem change (P-P); solution-to-solution change (S-S); problem-to-solution change (P-S); and solution-to-problem change (S-P). These changes or transitions are commonly used in the analysis of design activity, such as coding schemes where researchers categorize and measure behaviors relevant to co-evolution in design. For example, in Maher and Hsien-Hui Tang's coding of laboratory studies of human designers,

12 Bo T. Christensen and Linden J. Ball, "Building a Discipline: Indicators of Expansion, Integration and Consolidation in Design Research across Four Decades," *Design Studies* 65 (2019): 29, DOI: https://doi.org/10.1016/j.destud.2019.10.001.

13 Philip J. Cash, "Developing Theory-Driven Design Research," *Design Studies* 56 (May 2018): 91, DOI: https://doi.org/10.1016/j.destud.2018.03.002; Philip Cash, "Where Next for Design Research? Understanding Research Impact and Theory Building," *Design Studies* 68 (May 2020): 125, DOI: https://doi.org/10.1016/j.destud.2020.03.001.

14 Although see Poon and Maher, "A Case Study of the Sydney Opera House," 439–48.

15 Nigel Cross, *Designerly Ways of Knowing* (London: Springer, 2006); John S. Gero and Julie Milovanovic, "A Framework for Studying Design Thinking through Measuring Designers' Minds, Bodies and Brains," *Design Science* 6 (2020): e19, DOI: https://doi.org/10.1017/dsj.2020.15; Ricardo Sosa, "Accretion Theory of Ideation: Evaluation Regimes for Ideation Stages," *Design Science* 5 (2019): e23, DOI: https://doi.org/10.1017/dsj.2019.22; Willemien Visser, "Design: One, But in Different Forms," *Design Studies* 30, no. 3 (2009): 187–223, DOI: https://doi.org/10.1016/j.destud.2008.11.004.

16 Shanna R. Daly et al., "Innovative Solutions through Innovated Problems," *International Journal of Engineering Education* 34, no. 2(B) (2018): 695–707, available at https://www.ijee.ie/contents/c340218B.html.

17 Zoë Dankfort, Luuk Roos, and Milene Gonçalves, "Inspiring Co-evolution Moves and Creativity in Design Teams," in *ICDC 2018: Proceedings of The Fifth International Conference on Design Creativity*, ed. Elies Dekoninck et al. (Glasgow: The Design Society, 2018), 395–402, available at https://www.designsociety.org/publication/40743/.

18 Mieke van der Bijl-Brouwer, "Problem Framing Expertise in Public and Social Innovation," *She Ji: The Journal of Design, Economics, and Innovation* 5, no. 1 (2019): 29–43, https://doi.org/10.1016/j.sheji.2019.01.003.

19 Phil Cash and Milene Gonçalves, "Information-Triggered Co-evolution: A Combined Process Perspective," in *Analysing Design Thinking: Studies of Cross-Cultural Co-creation*, ed. Bo T. Christensen, Linden J Ball, and Kim Halskov (Boca Raton: CRC Press, 2017), 501–20, DOI: https://doi.org/10.1201/9781315208169-27; Stefan Wiltschnig, Bo T. Christensen, and Linden J. Ball, "Collaborative Problem-Solution

they represent the proportion of time spent in the problem and solution spaces and the transitions that are made between those spaces.[35] In a similar approach, although now with real-world data, Stefan Wiltschnig, Bo Christensen, and Linden Ball measured the proportion of S-P transitions compared to P-S transitions.[36] Beyond these notions of two co-evolving design spaces and four kinds of design transition, some studies have identified subspaces and additional categories of design transition (see Table 1).

Co-evolution research is seemingly unified by use of a common terminology, common family of diagrams and notations, and common references to early work.[37] However, this masks some underlying differences in how “co-evolution” is interpreted or how it is operationalized. Put simply, the term does not always refer to the same thing—within or between

Co-evolution in Creative Design,” *Design Studies* 34, no. 5 (2013): 515–42, DOI: https://doi.org/10.1016/j.destud.2013.01.002.

20 Maher and Tang, “Computational and Cognitive Model,” 47–64; Frido E. Smulders, Isabelle M. Reyman, and Kees Dorst, “Modelling Co-evolution in Design Practice,” in *Design Theory and Research Methodology*, Vol. 2 of *DS 58-2: Proceedings of ICED ’09: The 17th International Conference on Engineering Design*, ed. Margareta Norell Bergendahl et al. (Glasgow: The Design Society, 2009), 335–46, available at https://www.designsociety.org/publication/28597/.

Table 1 **Modifications to the “two-spaces-and-four-transitions” model of co-evolution.**

Authors	Modifiers	Spaces	Transitions
Maher & Poon, 1996[a]		Problem (P), solution (S)	P-P, S-S, P-S, S-P
Maher & Tang, 2003[b]	features (fea), behavior (be)	P-fea, P-be, S-fea, S-be	
Maher & Tang, 2003[c]	function (F), behavior (B), structure (S)	P(F), P(B), P(F), S(F), S(B), S(S); S(S) is also divided further	
Smulders, Reyman, & Dorst, 2009[d]	architect (a), client (c)	Pa, Pc, Sa, Sc	Pa-Pc, Pc-Pa, Sa-Sc, etc.
Yu, Gu, Ostwald, & Gero, 2015[e]	knowledge (K), rules (R)	P_K, P_R, S_K, S_R	
Chivukula & Gray, 2020[f]	interaction within (intra) and between (inter) designers		Intra P-P, Inter P-P, Intra S-S, etc.
Martinec, Škec, Perišić, & Štorga, 2020[g]	analysis (A), synthesis (S), evaluation (E)	PA, PS, PE, SA, SS, SE	

a. Mary Lou Maher and Josiah Poon, “Modeling Design Exploration as Co-evolution,” *Microcomputers in Civil Engineering* 11, no. 3 (1996): 196, DOI: https://doi.org/10.1111/j.1467-8667.1996.tb00323.x.

b. Mary Lou Maher and Hsien-Hui Tang, “Co-evolution as a Computational and Cognitive Model of Design,” *Research in Engineering Design* 14, no. 1 (2003): 47–64, DOI: https://doi.org/10.1007/s00163-002-0016-y.

c. Ibid.

d. Frido E. Smulders, Isabelle M. Reyman, and Kees Dorst, “Modelling Co-evolution in Design Practice,” in *Design Theory and Research Methodology*, Vol. 2 of *DS 58–2: Proceedings of ICED ’09: The 17th International Conference on Engineering Design*, ed. Margareta Norell Bergendahl et al. (Glasgow: The Design Society, 2009), 335–46, available at https://www.designsociety.org/publication/28597.

e. Rongrong Yu, Ning Gu, Michael Ostwald, and John S. Gero, “Empirical Support for Problem–Solution Coevolution in a Parametric Design Environment,” *AI EDAM* 29, no. 1 (2015): 39, DOI: https://doi.org/10.1017/S0890060414000316.

f. Sai Shruthi Chivukula and Colin Gray, “Co-evolving Towards Evil Design Outcomes: Mapping Problem and Solution Process Moves,” in *Proceedings of DRS 2020 International Conference: Synergy*, ed. Stella Boess, Ming Cheung, and Rebecca Cain (London: Design Research Society Digital Library, 2020), 1707–26, DOI: https://doi.org/10.21606/drs.2020.107.

g. Tomislav Martinec, Stanko Škec, Marija Majda Perišić, and Mario Štorga, “Revisiting Problem-Solution Co-evolution in the Context of Team Conceptual Design Activity,” *Applied Sciences* 10, no. 18 (2020): 1–29, DOI: https://doi.org/10.3390/app10186303z.

studies — or it is not always clear what it refers to. In some empirical studies of design behavior, "co-evolution" seemingly describes something close to Maher's original concept, with changing interpretations of problems and solutions reciprocally influencing each other.[38] However, in other studies, the term might simply describe how designers alternate their attention between problems and solutions, even if no changes are necessarily being made.[39] Still other studies describe co-evolution "episodes," for example where designers propose a new solution to a problem *or* a new problem for a solution, without requiring reciprocity in the definition of such episodes.[40] In this article, I remain at the stricter end of the spectrum of co-evolution concepts, using the term to refer to the process where changing interpretations of problems and solutions reciprocally influence each other. I consider this form of co-evolution not to be a fully developed theory with predictive power,[41] but simply a way of describing design activity, a form of description that might be developed into a theory through combination with other accounts.[42]

Other Origins

Although the work of Maher and colleagues is generally credited with introducing concepts of problem-solution co-evolution into the design literature, there are at least two other seemingly independent[43] streams of work relevant to the first usage of the term "co-evolution" in design. Between 1990 and 1993, Kumiyo Nakakoji and Gerhard Fischer published several works describing how software environments could assist with the co-evolution of problem setting and problem solving.[44] Of most interest here is their co-evolution diagram, showing that the "specification" (problem representation) and "construction" (solution representation) evolve through time but also reciprocally influence each other until a final "match" is realized.[45] Using a similar language, Raymond Yeh and his colleagues argue that problems and solutions should necessarily "co-evolve" in projects where the design problem cannot be defined in the absence of a solution.[46]

Yeh's work was an explicit response to two concepts which became prominent in the 1970s: Horst Rittel's description of wicked problems,[47] and Herbert Simon's description of ill-structured problems.[48] Nakakoji and Fischer were additionally building on work from the 1980s: William Swartout and Robert Balzer's arguments for the "inevitable intertwining of specification and implementation,"[49] Donald Schön's work on reflective practice,[50] and a number of early design research publications collected by Cross.[51] That early work must have informed Dorst and Cross's own study of co-evolution, but they also drew on more recent case studies of expert design practice.[52] In contrast, the description of co-evolution presented in the early publications from Maher and colleagues is primarily connected to formal descriptions of design that would enable computational approaches,[53] although some more philosophical work is also cited.[54] The relationship between these early publications is illustrated in Figure 2.

21 Kees Dorst, "Co-evolution and Emergence in Design," *Design Studies* 65 (November 2019): 60–77, DOI: https://doi.org/10.1016/j.destud.2019.10.005.
22 Jin Woo Lee et al., "Cognitive Strategies in Solution Mapping: How Engineering Designers Identify Problems for Technological Solutions," *Design Studies* 71 (November 2020): 100967, DOI: https://doi.org/10.1016/j.destud.2020.100967.
23 Antony Tang et al., "What Makes Software Design Effective?," *Design Studies* 31, no. 6 (2010): 614–40, DOI: https://doi.org/10.1016/j.destud.2010.09.004. Also see similar discussions that are independent of the Co-evolution literature discussed here. Theo D'Hondt et al., "Co-evolution of Object-Oriented Software Design and Implementation," in *Software Architectures and Component Technology*, ed. Mehmet Akşit (Boston: Springer US, 2002), 207–24, DOI: https://doi.org/10.1007/978-1-4615-0883-0_7; Antony Tang et al., "Traceability in the Co-evolution of Architectural Requirements and Design," in *Relating Software Requirements and Architectures*, ed. Paris Avgeriou et al. (Berlin: Springer Verlag Berlin Heidelberg, 2011), 35–60, DOI: https://doi.org/10.1007/978-3-642-21001-3_4.
24 Lucy Kimbell, "Rethinking Design Thinking: Part I," *Design and Culture* 3, no. 3 (2011): 285–306, DOI: https://doi.org/10.2752/175470811X13071166525216; Cara Wrigley, Genevieve Mosely, and Michael Mosely, "Defining Military Design Thinking: An Extensive, Critical Literature Review," *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 1 (2021): 104–43, DOI: https://doi.org/10.1016/j.sheji.2020.12.002.
25 Tomislav Martinec et al., "Revisiting Problem-Solution Co-evolution in the Context of Team Conceptual Design Activity," *Applied Sciences* 10, no. 18 (2020): 1–29, DOI: https://doi.org/10.3390/app10186303; Wiltschnig et al., "Collaborative Problem-Solution Co-evolution."
26 Dankfort et al., "Inspiring Co-evolution Moves," 395–402.
27 Sivam Krish, "A Practical Generative Design Method," *Computer-Aided Design* 43, no. 1 (2011): 88–100, DOI: https://doi.org/10.1016/j.cad.2010.09.009; Yi Teng Shih and Willy Sher, "Exploring the Role of CAD and Its Application in Design Education," *Computer-Aided Design and Applications* 18, no. 6 (2021): 1410–24, DOI: https://doi.org/10.14733/cadaps.2021.1410-1424.
28 For a review, see David C. Wynn and P. John Clarkson, "Process Models in Design and Development," *Research in Engineering Design* 29, no. 2 (2018): 161–202, DOI: https://doi.org/10.1007/s00163-017-0262-7.

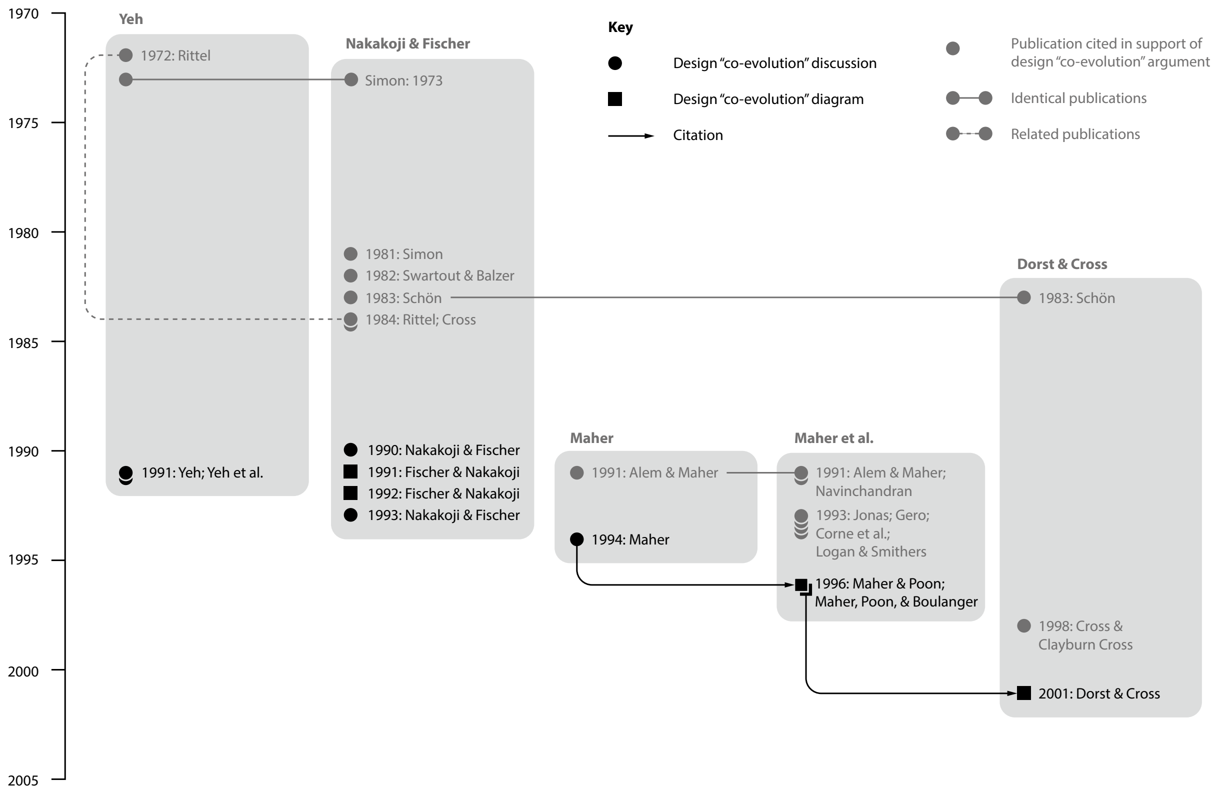

Figure 2
Simplified illustration of the early literature on design "co-evolution." Five strands of work are identified, defined by publications referring to "co-evolution" (at the bottom of each block) and the works cited in developing that position (above them, or connected by arrows). Later works by Maher and colleagues and by Dorst and Cross are discussed in this article and in Part II. © 2021 Nathan Crilly.

As emphasized above, although descriptions of design co-evolution seem to first appear in the early 1990s, there are many prior works that also emphasize the dynamic relationship between problems and solutions in design. Today, very few studies discussing design co-evolution make much mention of this early work; if they do, then it is most often with reference to Schön's book, *The Reflective Practitioner*:

> "In the designer's conversation with the materials of his design, he can never make a move which has only the effects intended for it. His materials are continually talking back to him, causing him to apprehend unanticipated problems and potentials. As he appreciates such new and unexpected phenomena, he also evaluates the moves that have created them."[55]

Schön's design-as-reflection perspective is often presented in contrast to Simon's design-as-search perspective.[56] However, Simon's work actually provides a strong foundation for considering design reflection and co-evolution. In the sixth chapter of his book *The Sciences of the Artificial* (a chapter added in the 1981 second edition), he explains that "a paradoxical, but perhaps realistic, view of design goals is that their function is to motivate activity which in turn will generate new goals."[57] Simon goes on to compare the activity of design to the activity of oil painting, saying, "The painting process is a process of cyclical interaction between painter and canvas in which

29 Wiltschnig et al., "Collaborative Problem-Solution Co-evolution."
30 Rosa Storm, Jeffrey van Maanen, and Milene Gonçalves, "Reframing the Design Process: Integrating Goals, Methods and Manifestation into the Co-evolution Model," in *Proceedings of the Design Society: International Conference on Engineering Design* 1, no. 1 (2019): 359–68, DOI: https://doi.org/10.1017/dsi.2019.39.
31 Martinec et al., "Revisiting Problem-Solution Co-evolution," 1–29.

current goals lead to new applications of paint, while the gradually changing pattern suggests new goals."[58] These ideas are explored in more detail in his work entitled, "Problem Forming, Problem Finding, and Problem Solving in Design."[59] There, in an extensive discussion of how goals emerge and change during design work, Simon explains that

> "The design problem is continually reformulated during the process of design. Design is a process of forming, finding, and solving problems. Nor does the forming and finding always come first, followed by the solving. All three sub-processes are thoroughly intermingled."[60]

Simon's arguments are reminiscent of the perspective promoted in Christopher Alexander's earlier book, *Notes on the Synthesis of Form*, where he discusses the essential work that designers do in changing the definition of the problem:

> "Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context.… Understanding the field of the context and inventing a form to fit it are really two aspects of the same process."[61]

So, long before any explicit discussion of co-evolution in design, three of the field's most influential theorists—in three of the field's most influential books—had argued for a description of design that included the emergence of new problem representations in response to new solution representations, and for the iterative process that develops them both.

Schön, Simon, and Alexander were not alone. The first of Horst Rittel and Melvin Webber's ten distinguishing properties of wicked planning (or design) problems is that there is no definitive formulation of a wicked problem:[62] "The information needed to *understand* the problem depends upon one's idea for *solving* it.… Problem understanding and problem resolution are concomitant to each other."[63] This is similar to Jane Darke's concept of a "primary generator" guiding the design process, where the development of design concepts precede complete definition of the requirements because those requirements only become "operational" in the context of a particular solution.[64] Defining concepts and defining requirements must therefore proceed in parallel, as Darke illustrates in a quotation from her interview with the architect Richard MacCormac: "Everything you do modifies your idea of what is possible … you can't start with a brief and (then) design, you have to start designing and briefing simultaneously, because these two activities are completely interrelated."[65] Darke's work was published in the inaugural issue of *Design Studies*, the same issue in which Bruce Archer also emphasizes the obscure nature of design problems and the role of design activities in understanding them, telling us that "The design activity is commutative, the designer's attention oscillating between the emerging requirement ideas and the developing provision ideas, as he illuminates obscurity on both sides and reduces misfit between them."[66]

32 Poon and Maher, "A Case Study of the Sydney Opera House," 446.

33 Dorst and Cross, "Creativity in the Design Process," 435.

34 Maher and Tang, "Computational and Cognitive Model," 62.

35 Ibid., 62. This is seemingly independent of Dorst and Cross's 2001 article on Co-evolution, which is not cited, although other works by both Dorst and Cross are.

36 Wiltschnig et al., "Collaborative Problem-Solution Co-evolution."

37 There are also some seemingly independent streams of work. For example, Daniel Brissaud, Olivier Garro, and Oscar Poveda offer a description (based on empirical studies of human designers) of problems and solutions progressing together through a design process, "feeding off one another" (p. 164). This is represented diagrammatically as problem spaces and solution spaces evolving, with moves between these spaces being made by "conjectures" for solutions (P to S) and "criteria" by which the solutions are assessed (S to P). Later work by Pierre Lonchampt, Guy Prudhomme, and Daniel Brissaud reframed this as a process of "co-evolution," citing Maher's work. Daniel Brissaud, Olivier Garro, and Oscar Poveda, "Design Process Rationale Capture and Support by Abstraction of Criteria," *Research in Engineering Design* 14, no. 3 (2003): 162–72, DOI: https://doi.org/10.1007/s00163-003-0038-0; Pierre Lonchampt, Guy Prudhomme, and Daniel Brissaud, "Engineering Design Problem in a Co-evolutionary Model of the Design Process," in *DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference* (Dubrovnik, Croatia, 2004), 361–66, available at https://www.design-society.org/publication/19776/.

38 Nathan Crilly and Roxana Moroşanu Firth, "Creativity and Fixation in the Real World: Three Case Studies of Invention, Design and Innovation," *Design Studies* 64 (September 2019): 202, DOI: https://doi.org/10.1016/j.destud.2019.07.003; Maher and Tang, "Computational and Cognitive Model," 62. A more permissive variant would state that problems and solutions both change during design, but not necessarily due to each other's influence.

39 Rongrong Yu et al., "Empirical Support for Problem–Solution Coevolution in a Parametric Design Environment," *AI EDAM* 29, no. 1 (2015): 39, DOI: https://doi.org/10.1017/S0890060414000316.

40 Martinec et al., "Revisiting Problem-Solution Co-evolution," 8; van der Bijl-Brouwer, "Problem Framing Expertise," 37; Wiltschnig et al., "Collaborative Problem-Solution Co-evolution," 525–27.

Other Disciplines

As we can see, design research has a long history of considering things like co-evolution, much of which would provide a strong and varied basis for ongoing research.[67] However, the rich seam of ideas that precede Dorst and Cross's article is absent from many contemporary accounts of design co-evolution.[68] In these accounts, Nakakoji, Fischer, and Yeh are not cited, and so their framing of co-evolution as an extension of ideas from researchers like Simon and Rittel has been lost.[69] One problem with overlooking these relevant discussions is that it directs attention away from the language they used. Searching the literature for "problem-solution co-evolution" (and similar terms) returns a body of work dominated by design research. However, other highly relevant work can be identified by searching for processes of "problem solving" combined (or alternating or iterating) with processes of "problem finding," "problem identification," "problem construction," "problem discovery," "problem posing," "problem framing," and "problem structuring."[70] Research that is reported using such terminology is diverse in terms of academic disciplines, theoretical foundations, research methods, and application domains, while still being descriptive of "design" in its broadest sense.

Beyond design research, a particularly relevant discussion of iterating between problem solving and problem finding is in the field of mathematics education, which offers a rare example of the term co-evolution being used. There, researchers are concerned with how to train mathematicians to engage in the unbounded task of problem posing or problem formulation, rather than just the more bounded task of problem solving. In this respect, mathematicians have long discussed the interaction between these processes. "What typically happens in a prolonged [mathematical] investigation is that problem formulation and problem solution go hand in hand, each eliciting the other as the investigation progresses."[71] In conducting empirical research into this phenomenon, Jinfa Cai and Victor Cifarelli characterized mathematical exploration as a recursive process in which mathematicians formulate problems, solve problems and reflect upon their solution activity to formulate new problems. They found that "problem posing and solving may co-evolve in the course of solution activity … each informing and serving as a catalyst for the other as solution activity progressed."[72] Such work emphasizes observation, experiment, discovery, and conjecture in mathematics education, focusing on different reasoning modes and the role of metacognition, all topics relevant to design.[73]

Perhaps closer to everyday understandings of a design process is business entrepreneurship, which is generally regarded as a creative practice,[74] and is understood to involve a combination of effect-driven and means-driven reasoning.[75] Especially relevant here are discussions of "pivoting," where nascent organizations retain some aspects of what they have learned so far while making a fundamental change in strategy in order to learn more.[76] Entrepreneurs can implement many different types of pivot, including the zoom-in pivot (refocusing the offering on what had previously just been one aspect of a larger offering), zoom-out pivot, customer segment pivot, customer need pivot, business architecture pivot, technology pivot, and so

41 Cash, "Theory-Driven Design Research," 84–119; Peter Hodges et al., "Four Criteria for Design Theories," *She Ji: The Journal of Design, Economics, and Innovation* 3, no. 1 (2017): 65–74, DOI: https://doi.org/10.1016/j.sheji.2017.02.003; John G. Wacker, "A Definition of Theory: Research Guidelines for Different Theory-Building Research Methods in Operations Management," *Journal of Operations Management* 16, no. 4 (1998): 361–85, DOI: https://doi.org/10.1016/S0272-6963(98)00019-9.

42 For example, see Milene Gonçalves and Philip Cash, "The Life Cycle of Creative Ideas: Towards a Dual-Process Theory of Ideation," *Design Studies* 72 (January 2021): 3, https://doi.org/10.1016/j.destud.2020.100988.

43 These three streams of work do not refer to each other and they refer to different foundational works. See Figure 2.

44 For example, see Kumiyo Nakakoji and Gerhard Fischer, "CATALOG EXPLORER: Exploiting the Synergy of Integrated Design Environments," in *Proceedings of Software Symposium '90* (Kyoto, Japan, June 7–8, 1990), 264–71, available at http://l3d.cs.colorado.edu/~gerhard/papers/Scanned/1990-Catalog-Explorer-10th-SoftSym90.pdf; Gerhard Fischer and Kumiyo Nakakoji, "Empowering Designers with Integrated Design Environments," in *Artificial Intelligence in Design '91*, ed. John S. Gero (Oxford: Butterworth-Heinemann, 1991), 191–209, https://doi.org/10.1016/B978-0-7506-1188-6.50014-4; Gerhard Fischer and Kumiyo Nakakoji, "Beyond the Macho Approach of Artificial Intelligence: Empower Human Designers — Do Not Replace Them," *Knowledge-Based Systems* 5, no. 1 (1992): 15–30, DOI: https://doi.org/10.1016/0950-7051(92)90021-7; Kumiyo Nakakoji and Gerhard Fischer, "Knowledge Delivery: Facilitating Human-Computer Collaboration in Integrated Design Environments," in *Human-Computer Collaboration: Reconciling Theory, Synthesizing Practice, Papers from the 1993 Fall Symposium, Technical Report FS-93-05*, ed. Loren Terveen (Menlo Park: The AAAI Press, 1993), 63–68, available at https://aaai.org/Papers/Symposia/Fall/1993/FS-93-05/FS93-05-012.pdf.

45 Fischer and Nakakoji, "Empowering Designers," 198.

46 Raymond T. Yeh, "System Development as a Wicked Problem," *International Journal of Software Engineering and Knowledge Engineering* 1, no. 2 (1991): 117–30, DOI: https://doi.org/10.1142/S0218194091000123; Raymond. T. Yeh et al., "A Commonsense Management Model," *IEEE Software* 8, no. 6 (1991): 23–33, DOI: https://doi.org/10.1109/52.103574.

on. Some of these strategic changes can be seen as a change to the problem being addressed, whilst others can be seen as a change to the solution being offered. For an evolving business venture to succeed, a series of pivots might be required until a good match is obtained between what the market wants and what the organization can offer. Such processes require entrepreneurs to balance flexibility with persistence as they demonstrate creativity and resist fixation in developing their business ideas.[77] Iterative pivoting of this kind can be seen in Nathan Crilly and Moroşanu Firth's accounts of design co-evolution among inventors, where what is seen to co-evolve is not just technical problems and technical solutions, but also ideas about customer segments and business models.[78]

Mathematics and entrepreneurship are just two examples where the interplay between problem finding and problem solving is recognized as an important aspect of creativity. Many if not all creative practices generate or encounter problems and sub-problems that require definition and re-definition during acts of discovery or creation. For example, in science the activities of problem solving and problem finding are considered creative,[79] and something like co-evolution is described as "dual space search," where scientists navigate both the hypothesis space and the experiment space, each of which interact with the other.[80] Viewing the negotiation process between two or more people as a creative activity, Katia Sycara describes negotiation as "an iterative search for appropriate changes in the goals and constraints of the participants in order to achieve resolutions that are members of a changing joint solution set."[81] Similarly, in studying the process of policy formation amongst groups, Sara Harvey and Chia-Yu Kou describe an "iterative" relationship between problem solving and problem framing, where problem frameworks are renegotiated to accommodate multiple solutions from across the group.[82]

The study of more expressive practices has also focused on iterative processes of problem solving and problem finding. In the visual arts, it is well understood that creative achievement requires artists to make changes to the structure and content of an existing problem in response to their exploration activities.[83] Music composition has been modelled as a creative problem solving process, one in which there is a recursive reframing of the "givens" (ideas and themes) and "goals" (the postulated end state).[84] Similarly, in essay composition, the rhetorical problem "is an elaborate construction which the writer creates in the act of composition," and good writers continue to develop their image of the reader, the situation, and their own goals during writing.[85] Here, the overlap with descriptions of design has not gone unnoticed, with Mike Sharples explicitly describing writing as a design process, and citing Brian Lawson's *How Designers Think*[86] to explain why writing goals change during the composition of the text, and how the writer must shape the text in response to those changing goals.[87]

In addition to these descriptions of specific creative practices, something like problem-solution co-evolution is described as a feature of general creative behavior. For example, writing at about the same time as the earliest works on design co-evolution, Stephen Grossman and Edward Wiseman were providing general advice for creativity training that sounds very

47 Horst W.J. Rittel, "On the Planning Crisis: Systems Analysis of the 'First and Second Generations,'" *Bedriftsøkonomen* 8 (1972): 390–96, DOI: https://doi.org/10.1007/978-94-009-7651-1_4.

48 Herbert A. Simon, "The Structure of Ill Structured Problems," *Artificial Intelligence* 4, no. 3-4 (1973): 181–201, DOI: https://doi.org/10.1016/0004-3702(73)90011-8.

49 William Swartout and Robert Balzer, "On the Inevitable Intertwining of Specification and Implementation," *Communications of the ACM* 25, no. 7 (1982): 438–40, DOI: https://doi.org/10.1145/358557.358572.

50 Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action* (London: Temple Smith, 1983).

51 Nigel Cross, ed., *Developments in Design Methodology* (Chichester: Wiley–Blackwell, 1984); Horst W.J. Rittel, "Second-Generation Design Methods," in *Developments in Design Methodology*, ed. Nigel Cross (Chichester: Wiley–Blackwell, 1984), 317–27.

52 Nigel Cross and Anita Clayburn Cross, "Expert Designers," in *Designers: The Key to Successful Product Development*, ed. Eckart Frankenberger, Petra Badke-Schaub, and Herbert Birkhofer (London: Springer, 1998), 71–84, DOI: https://doi.org/10.1007/978-1-4471-1268-6_7.

53 Dundee Navinchandra, *Exploration and Innovation in Design: Towards a Computational Model* (New York: Springer-Verlag, 1991), DOI: https://doi.org/10.1007/978-1-4612-3114-1; John S. Gero, "Towards a Model of Exploration in Computer-Aided Design," in *Proceedings of the IFIP TC5/WG5.2 Workshop on Formal Design Methods for CAD*, ed. John S. Gero and Enn Tyugu (New York: Elsevier Science Inc., 1994), 315–36, available at https://cs.gmu.edu/~jgero/publications/1994/94GeroIFIPFormalMethodsCAD.pdf; Brian Logan and Tim Smithers, "Creativity and Design as Exploration," in *Modelling Creativity and Knowledge-Based Creative Design*, ed. John S. Gero and Mary Lou Maher (Hillsdale: Lawrence Erlbaum Associates, 1993), 139–75, available at http://papers.cumincad.org/cgi-bin/works/paper/c9cf; Tim Smithers, Dave Corne, and Peter Ross, "On Computing Exploration and Solving Design Problems," in *Proceedings of the IFIP TC5/WG5.2 Workshop on Formal Design Methods for CAD*, ed. John S. Gero and Enn Tyugu (New York: Elsevier Science Inc., 1994), 293–313, available at https://www.academia.edu/30972621/.

54 Wolfgang Jonas, "Design as Problem-Solving? Or: Here Is the Solution — What Was the Problem?," *Design Studies* 14, no. 2 (1993): 157–70, DOI: https://doi.org/10.1016/0142-694X(93)80045-E.

much like what would later be called the solution-to-problem transition in co-evolution:

> "The new idea of breakthrough solution presents itself *before* the problem has been formally redefined. Thus the solution carries the redefinition within itself rather than the problem being explicitly redefined in a rigorous sequential process. In other words, the solution that presents itself carries within it the problem redefined in such a way as to bridge the gap between Present and Future State."[88]

More generally, in describing the creative problem-solving process, Donald Treffinger observes that separating problem finding from problem solving is often arbitrary, unnecessary, and inappropriate.[89] This recognition that problem solving and problem finding are interrelated reflects the work of the gestalt psychologists, such as Karl Duncker, Wolfgang Köhler, Kurt Koffka, Abraham Luchins, Norman Maier and Max Wertheimer.[90] They described problem solving largely as a matter of problem restructuring, insight and emergence: "Problems are situations with gaps between what one has and what one wants. To solve a problem is to subject the situation to successive restructurings until the gap has been closed."[91]

The observations of the Gestalt psychologists were primarily derived from experimental work focused on individuals undertaking set tasks under controlled conditions. Informed by this work,[92] but based on detailed case studies of the lives and work of exceptional individuals, Howard Gruber developed his "evolving systems" approach to the study of creativity:

> "Understanding creative work requires us to conceive of the creative person as an evolving system in an evolving milieu. Each such system is comprised of three subsystems—organizations of knowledge, purpose, and affect. Each of these subsystems has a dual aspect: In one sense it has a life of its own, in another it contributes to the internal milieu of the others."[93]

These different subsystems are said to "co-evolve" as the creative individual's objectives, projects, problems and achievements develop with each other through the course of their work.[94] So, co-evolution is relevant not just to how problems and solutions change during projects, but also how they change from one project to another when the creative person has control over the projects they engage in, or control over the overall "project" of their creative life.

From considering descriptions of many specific creative practices and broader descriptions of creative work, it is clear that the process of problem-solution co-evolution is not unique to the design disciplines—it is a general feature of creative activity.[95] Design research could thus benefit from drawing on broader accounts of how problem solving and problem finding interact, but to date such interactions have remained very limited .[96] Similarly, other research disciplines could benefit from the focused work that design research has done in this area, but such interactions have also been rare.[97]

55 Schön, *Reflective Practitioner*, 100.

56 For scholarly analysis of how Simon's work is mischaracterised by those only referring to the first edition of *Sciences*, see Jude Chua Soo Meng, "Donald Schön, Herbert Simon, and *The Sciences of the Artificial*," *Design Studies* 30, no. 1 (2009): 60–68, DOI: https://doi.org/10.1016/j.destud.2008.09.001; Jude Chua Soo Meng, "Design Without Final Goals: Getting Around Our Bounded Rationality," *Artifact* 3, no. 4 (2015): 2.1–2.7, DOI: https://doi.org/10.14434/artifact.v3i4.12787; Xinya You and David Hands, "A Reflection upon Herbert Simon's Vision of Design in *The Sciences of the Artificial*," *The Design Journal* 22, no. sup1 (2019): 1345–56, DOI: https://doi.org/10.1080/14606925.2019.1594961.

57 Herbert A. Simon, *The Sciences of the Artificial* (Cambridge, MA: MIT Press, 1996), 162.

58 Ibid., 163.

59 Herbert A. Simon, "Problem Forming, Problem Finding, and Problem Solving in Design" (paper presented at the 1987 International Congress of Planning and Design Theory, Boston, August 20, 1987); Herbert A. Simon, "Problem Forming, Problem Finding, and Problem Solving in Design," in *Design and Systems: General Applications of Methodology*, ed. Arne Collen and Wojciech W. Gasparski (Brunswick, NJ: Transaction Publishers, 1995), 245–57, available at http://digitalcollections.library.cmu.edu/awweb/awarchive?type=file&item=34208.

60 Simon, "Problem Forming, Problem Finding," 251–52.

61 Christopher Alexander, *Notes on the Synthesis of Form* (Cambridge, MA: Harvard University Press, 1964), 15–16, 21.

62 This property of wicked problems is explicitly what Yeh is responding to in his promotion of "Co-evolution." For a more recent connection to Co-evolution, see Pieter E. Vermaas and Udo Pesch, "Revisiting Rittel and Webber's Dilemmas: Designerly Thinking Against the Background of New Societal Distrust," *She Ji: The Journal of Design, Economics, and Innovation* 6, no. 4 (2020): 538, DOI: https://doi.org/10.1016/j.sheji.2020.11.001.

63 Horst W.J. Rittel and Melvin M. Webber, "Dilemmas in a General Theory of Planning," *Policy Sciences* 4, no. 2 (1973): 161, DOI: https://doi.org/10.1007/BF01405730; also see David L. Marples, "The Decisions of Engineering Design," *IRE Transactions on Engineering Management* EM-8, no. 2 (1961): 64, DOI: https://doi.org/10.1109/IRET-EM.1961.5007593.

Problems and Solutions

Whether considering discussions of design co-evolution specifically, or other concepts that are simply like co-evolution in design and other practices, a clear distinction is often drawn between problems and solutions. This separation conforms to many people's everyday understandings: a problem is a description of an unfavorable situation that should be improved; a solution is a description of the action or object that will deliver that improvement. However, despite the intuitive appeal of viewing problems and solutions as clearly different kinds of thing, there are many arguments and observations that contradict this distinction. For example, in studying co-evolution in the interactions between a client and architect, Frido Smulders, Isabelle Reyman, and Dorst struggled to separate problems from solutions when coding their data:

> "It was often not clear whether the actors talked about the problem or about a possible solution *per se*. This holds for the architect as well as the client.... These observations raise the question of whether it is possible at any time in a design project to make a strong separation between 'problem' and 'solution,' even if theoretically one might be able to distinguish them."[98]

Diagrammatically, this ambiguity is depicted in Dorst's later account of a commercial design project, framed in co-evolutionary terms. The process is represented in a modified co-evolution diagram, with some problems being represented as closer to the solutions than others, and vice versa. Dorst explains that

> "the line between the 'problem space' and 'solution space' has been intentionally blurred, to highlight the phenomenon that it is often unclear whether a propositional design step (that has implications for both problem definition and possible solutions) would belong to either one or the other."[99]

Dorst's diagram has some similarity to one of Maher and Tang's illustrations of a co-evolutionary design algorithm, where there is a continuum from "problem focus" to "solution focus," with computational activity moving along that continuum.[100]

The apparent difficulty in distinguishing problems from solutions with confidence can at least partly be explained by recognizing that a given statement or representation of a design situation can be either viewed as a problem or a solution.[101] For example, the idea of bridging a river can be seen as a solution to the problem of how to cross a river (a solution is a bridge across the river), but can also be seen as a problem that needs solving (the problem is how to bridge the river). If we are asking how an idea can be implemented then that idea is a problem, but if we are asking why an idea should be implemented then that same idea is a solution.[102] Referring back to the Gestalt psychologists, this situation is neatly summarized by Duncker:

> "The solution of a new problem typically takes place in successive phases which (with the exception of the first phase) have, in retrospect, the character of a solution and (with the exception of the last phase), in prospect, that of a problem."[103]

64 Jane Darke, "The Primary Generator and the Design Process," *Design Studies* 1, no. 1 (1979): 43, DOI: https://doi.org/10.1016/0142-694X(79)90027-9. For a recent analysis, see Michael Mose Biskjaer and Bo T. Christensen, "A Second Look at Primary Generators," *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 1 (2021): 7–23, https://doi.org/10.1016/j.sheji.2020.08.007.

65 Darke, "The Primary Generator," 42, quoted from R. MacCormac, "The Evolution of the Design," *Archer De* (October 1971): 617.

66 Bruce Archer, "Design as a Discipline," *Design Studies* 1, no. 1 (1979): 17, DOI: https://doi.org/10.1016/0142-694X(79)90023-1.

67 For a discussion of some of these early contributions and others, see Nigel Cross, "Research in Design Thinking," in *Research in Design Thinking*, ed. Nigel Cross, Kees Dorst, and Norbert F. M. Roozenburg (Delft: Delft University Press, 1992), 3–10, available at http://resolver.tudelft.nl/uuid:83a0d981-d053-4944-90af-3d165b9d079e; Norbert F.M. Roozenburg and Nigel. G. Cross, "Models of the Design Process: Integrating across the Disciplines," *Design Studies* 12, no. 4 (1991): 215–20, https://doi.org/10.1016/0142-694X(91)90034-T; Roger J. Volkema, "Problem Formulation in Planning and Design," *Management Science* 29, no. 6 (1983): 639–52, DOI: https://doi.org/10.1287/mnsc.29.6.639.

68 For an exception, see Per Liljenberg Halstrøm and Per Galle, "Design as Co-evolution of Problem, Solution, and Audience," *Artifact* 3, no. 4 (2015): 3, DOI: https://doi.org/10.14434/artifact.v3i4.12815.

69 For a more general discussion of the importance of connecting contemporary creativity research to its history, see Vlad Petre Glaveanu et al., "Advancing Creativity Theory and Research: A Socio-Cultural Manifesto," *The Journal of Creative Behavior* 54, no. 3 (2020): 744, DOI: https://doi.org/10.1002/jocb.395.

70 For reviews on problem construction or problem finding, see Roni Reiter-Palmon and Erika J. Robinson, "Problem Identification and Construction: What Do We Know, What Is the Future?," *Psychology of Aesthetics, Creativity, and the Arts* 3, no. 1 (2009): 43–47, DOI: https://doi.org/10.1037/a0014629; Ahmed M. Abdulla et al., "Problem Finding and Creativity: A Meta-Analytic Review," *Psychology of Aesthetics, Creativity, and the Arts* 14, no. 1 (2020): 3, DOI: https://doi.org/10.1037/aca0000194.

In other words, when we are not sure what to do, a promising idea might seem, at first, as though it is a solution, but as we explore it further it transforms into a new problem that leaves us again unsure what to do.

Another reason that problems can be difficult to distinguish from solutions is that designers might already know the "solution," in the form of a design or technology, but they are searching for "problems," in the form of possible applications or markets. This is common in solution-driven design (or technology-push innovation), as compared to problem-driven design (or market-pull innovation). [104] An example is illustrated in Crilly and Moroşanu Firth's analysis of a project in which a series of designs for a novel wheel with integrated suspension was initially intended to improve the performance of pushchairs, but then later of bicycles and finally of wheelchairs. They say, "we can see that with the basic suspended wheel concept in place, finding the wheelchair application is either an instance of finding a solution for the problem (the problem of identifying an application vehicle) or an instance of finding a problem for the solution (the solution of the suspended wheel). The distinction is arbitrary."[105]

The idea that problems and solutions are not neatly distinguishable motivates much of the discussion (from at least the 1960s onwards) about how problems and solutions are refined iteratively through design, or (from the 1990s onwards) how they co-evolve. In fact, Maher and Poon's description of their diagrammatic model is explicit on the point that problems and solutions swap places. They describe the upward arrow that points from the solution space (at t) to the problem space (at t+1) as "an inverse operation where $S(t)$ becomes the goal and a '*search*' is carried out in the problem space $P(t+1)$, for a '*solution*,'"[106] So, in one of the most influential descriptions of the design co-evolution concept, "solution" temporarily becomes a problem to be solved, and it will be solved by finding a suitable "problem," Clearly the problem-solution terminology is sometimes difficult, so it is curious that contemporary accounts of design co-evolution have generally reified the distinction between problems and solutions, rather than questioning it. Talking of problems and solutions as occupying separate "spaces" that co-evolve has seemingly marked them out as different kinds of thing, rather than different perspectives on the same kind of thing.

To develop a view of co-evolution that permits the problem-solution distinction to be relaxed, consider again the example of a bridge. It can be thought to occupy a position in a problem-solution hierarchy where it represents a solution to the overall problem of providing a river crossing, or where it represents a problem that is solved by different kinds of bridge (see Figure 3, left). Any item in the hierarchy is a solution to the items above it and a problem to the items below it.[107] Any item in that hierarchy can also be thought of as being not only a problem with multiple possible solutions, but also a solution with multiple possible problems. The bridge is a possible solution for the problem of providing a river crossing, but also a possible solution for the problem of providing a road crossing (see Figure 3, right).

Combining the two forms of diagram in Figure 3 results in the representation of a heterarchical design space where any single idea can be seen as a problem with multiple possible solutions (branching out below it) or

71 Philip J. Davis, "What Do I Know? A Study of Mathematical Self-Awareness," *The College Mathematics Journal* 16, no. 1 (1985): 23, DOI: https://doi.org/10.1080/07468342.1985.11972847.

72 Victor V. Cifarelli and Jinfa Cai, "The Evolution of Mathematical Explorations in Open-Ended Problem-Solving Situations," *The Journal of Mathematical Behavior* 24, no. 3-4 (2005): 305, 321, https://doi.org/10.1016/j.jmathb.2005.09.007, emphasis added. Also see Jinfa Cai and Victor V. Cifarelli, "Exploring Mathematical Exploration: How Two College Students Formulated and Solved Their Own Mathematical Problems?," *Focus on Learning Problems in Mathematics* 27, no. 3 (2005): 43–72, available at https://researchgate.net/publication/288351412.

73 As such, methods and findings from this research are especially relevant to researchers who want to promote the potential of Co-evolutionary perspectives in design education. For example, see Storm et al., "Reframing the Design Process," 336; Sai Shruthi Chivukula and Colin Gray, "Co-evolving Towards Evil Design Outcomes: Mapping Problem and Solution Process Moves," in *Proceedings of DRS 2020 International Conference: Synergy*, ed. Stella Boess, Ming Cheung, and Rebecca Cain (London: Design Research Society Digital Library, 2020), 1707–26, DOI: https://doi.org/10.21606/drs.2020.107.

74 Teresa M. Amabile, "Entrepreneurial Creativity through Motivational Synergy," *The Journal of Creative Behavior* 31, no. 1 (1997): 18–26, DOI: https://doi.org/10.1002/j.2162-6057.1997.tb00778.x; Thomas B. Ward, "Cognition, Creativity, and Entrepreneurship," *Journal of Business Venturing* 19, no. 2 (2004): 173–88, DOI: https://doi.org/10.1016/S0883-9026(03)00005-3.

75 See Saras Sarasvathy's distinction between "causation" processes (where the effect is pre-determined and the relevant means to achieve that effect must be identified) and "effectuation" processes (where the means are pre-determined and the possible effects must be identified and selected. "Both causation and effectuation are integral parts of human reasoning that can occur simultaneously, overlapping and intertwining over different contexts of decisions and actions." Saras D. Sarasvathy, "Causation and Effectuation: Toward a Theoretical Shift from Economic Inevitability to Entrepreneurial Contingency," *The Academy*

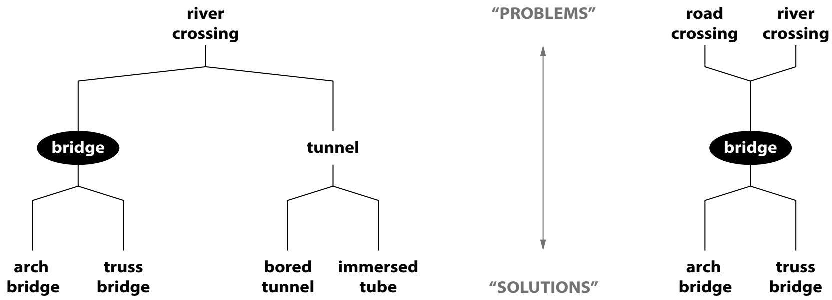

Figure 3
Example hierarchy of problems with possible solutions (left), and illustration of how a single item in the hierarchy (here *bridge*) is both a problem for multiple solutions, and a solution for multiple problems (right). The number of levels and the number of branches at those levels would depend on the scope of the design project, how completely it is explored, and how fine-grained that exploration is. © 2021 Nathan Crilly.

a solution to multiple possible problems (branching out above it).[108] Co-evolution can then be understood not as the exploration of two different spaces (problems and solutions), but as the exploration of a single space of ideas (see Figure 4).[109] During creative work, designers explore the heterarchical design space, navigating up and down multiple levels as more general and more specific ideas are represented, refined, challenged, and connected. Any single idea might at one point be viewed as a problem that prompts exploration of possible solutions (lower down), but that same idea might, perhaps later, be viewed as a solution that prompts exploration of the possible problems that it solves (higher up) (see Figure 5). The problem-solution terminology is here just used for consistency with analytic convention and needn't reflect how the ideas are regarded by the designer at any point in time, or the role they play in any psychological processes (processes of problem solving or problem finding, for example).

Viewing co-evolution as the navigation of a single space need not mean that problem-driven design is the same as solution-driven design. The process of navigating upwards or sideways through the unified heterarchy (problem exploration) might depend more on information, abstract reasoning, and conceptual development, while navigating downwards or sideways (solution exploration) might depend more on knowledge, representation, and perceptual skills.[110] However, even if there are different processes available for moving from one idea to another, this does not necessarily mean that the ideas are of fundamentally different kinds. A concrete representation of a solution can be abstracted into a general category of problem and vice versa.

Although traditional representations of design co-evolution indicate that changes are made to the problem space and the solution space, the nature of those changes is not indicated. On the one hand, these changes might only be incremental, as an understanding of the design spaces is developed and refined. For example, exploring solution proposals might drive understanding that the problem has an extra constraint, which might suggest that a slightly different form of solution is appropriate. On the other hand, co-evolution changes might also be more radical, opening up previously unexplored parts of the design space. For example, developing a solution might prompt recognition that the wrong problem is being addressed altogether, leading to entirely new categories of solution being proposed, solutions that

of Management Review 26, no. 2 (2001): 245, DOI: https://doi.org/10.2307/259121. For a recent review of the interaction between causation and effectuation logics, see Johanna Vanderstraeten et al., "SME Innovativeness in a Dynamic Environment: Is There Any Value in Combining Causation and Effectuation?," *Technology Analysis & Strategic Management* 32, no. 11 (2020): 1277–93, DOI: https://doi.org/10.1080/09537325.2020.1766672.

76 Eric Ries, *The Lean Startup: How Constant Innovation Creates Radically Successful Businesses* (New York: Penguin, 2011), 149, 154.

77 Nathan Crilly, "'Fixation' and 'the Pivot': Balancing Persistence with Flexibility in Design and Entrepreneurship," *International Journal of Design Creativity and Innovation* 6, no. 1-2 (2018): 52–65, DOI: https://doi.org/10.1080/21650349.2017.1362359; Matthew G. Grimes, "The Pivot: How Founders Respond to Feedback through Idea and Identity Work," *Academy of Management Journal* 61, no. 5 (2017): 1692–1717, DOI: https://doi.org/10.5465/amj.2015.0823.

78 Crilly and Moroşanu Firth, "Creativity and Fixation," 202.

79 Steven M. Hoover and John F. Feldhusen, "Scientific Problem Solving and Problem Finding: A Theoretical Model," in *Problem Finding, Problem Solving, and Creativity*, illustrated edition, ed. Mark A. Runco (Norwood: Ablex Publishing Corporation, 1994), 201–19.

80 David Klahr and Kevin Dunbar, "Dual Space Search During Scientific Reasoning," *Cognitive Science* 12, no. 1 (1988): 1–48, DOI: https://doi.org/10.1207/s15516709cog1201_1; also see Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1996), 111, 122.

81 Katia P. Sycara, "Problem Restructuring in Negotiation," *Management Science* 37, no. 10 (1991): 1248, DOI: https://doi.org/10.1287/mnsc.37.10.1248.

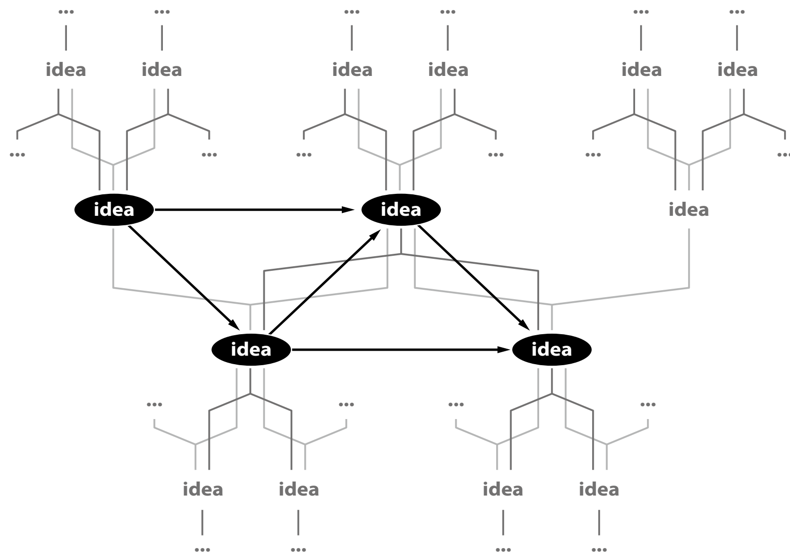

Figure 4
Heterarchy of design ideas composed of overlapping, top-down hierarchies (problem to solutions) intersecting with bottom-up hierarchies (solution to problems). The basic structure of the standard co-evolution diagram is overlaid. For comparison with that diagram, design exploration is here restricted to just two levels of the heterarchy, and with time proceeding from left to right. More generally, exploration may proceed across all levels and in any direction. Again, the number of levels and the number of branches at those levels would depend on the scope of the design project, how completely it is explored and how fine-grained that exploration is. © 2021 Nathan Crilly.

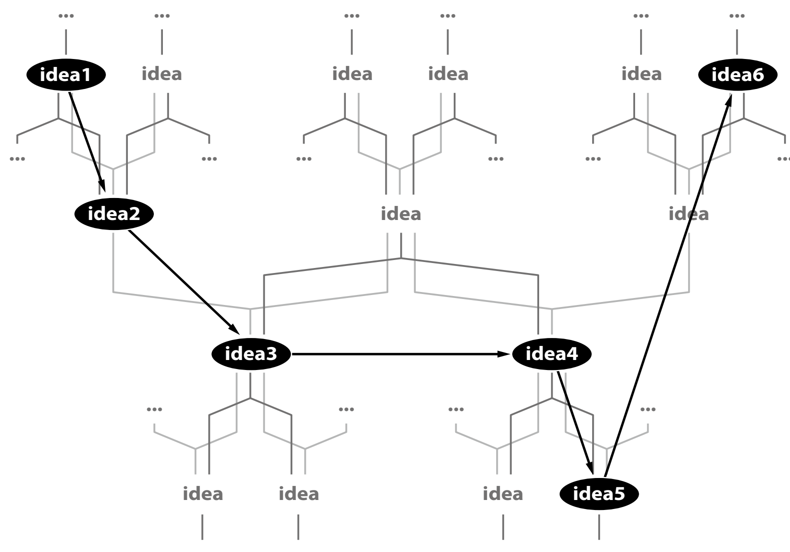

Figure 5
Co-evolution through multiple levels of a heterarchy of design ideas. In the sequence of exploration, *idea1* is the problem that *idea2* might solve, which is the problem that *idea3* might solve. The transition from *idea3* to *idea4* is a S-S transition relative to the problem of *idea2*, but is a P-P transition relative to the solution of *idea5*. The transition from *idea5* to *idea6* spans two intervening levels of ideas, but the identification of such levels is subjective, determined by the perspective of the analyst or the designer, as is the branching density at any perceived level. © 2021 Nathan Crilly.

would have been irrelevant to the prior problem.[111] Considering co-evolution as the exploration of a heterarchically structured design space allows representation of a range of possible design changes, from the incremental to the radical. Such exploration can be limited to well-bounded areas, permitting a more complete understanding of these areas (moving up, down, and sideways on the local branches). Other explorations might move from one area to another, permitting completely different parts of the space to be investigated (moving further up, down, and sideways through the wider trees), permitting more creative outcomes (compare the first and last transitions in Figure 5).

82 Sarah Harvey and Chia-Yu Kou, "Collective Engagement in Creative Tasks: The Role of Evaluation in the Creative Process in Groups," *Administrative Science Quarterly* 58, no. 3 (2013): 361–63, DOI: https://doi.org/10.1177/0001839213498591. Such work is relevant to discussions of design co-evolution with multiple design "agents." For example, see Smulders et al., "Modelling Co-evolution," 335–46; Wiltschnig et al., "Collaborative Problem-Solution Co-evolution."

Creativity and Fixation

Co-evolutionary accounts of design are often presented in contrast to, or in opposition to, stage-based descriptive models of the design process, which emphasize problem clarification preceding solution generation.[112] Such "analysis-synthesis" models have long been criticized for failing to adequately represent the creative work that designers do, something better accommodated by "conjecture-analysis" models.[113] Co-evolution accounts combine both approaches, so it is unsurprising that creativity has remained at the center of discussions of design co-evolution. However, perhaps it is surprising that co-evolution accounts are not integrated with accounts of design fixation, a concept which gained prominence at around the same time,[114] and which has become similarly influential in the study of design creativity.[115]

The disconnect between design co-evolution and design fixation might be explained by design researchers primarily studying design fixation in short-duration controlled experiments, where the problem is not negotiable and the repetition of solution features is used as a measure of fixation.[116] However, if fixation is more broadly considered as prior experience leading to implicit assumptions that restrict imagination, then fixation can be seen inhibiting the creative work that designers might do with both solutions and problems.[117] Of course, if problems and solutions are defined relative to each other, then problem fixation and solution fixation are relative also, but can be seen as distinct for any problem-solution pair.

Concepts of co-evolution and fixation are both related to the exploration of the design space. So, the connection between co-evolution and fixation can be visualized using representations like that in Figure 5. At a given point in the design exploration process, prior assumptions might result in a failure to recognize the possibility of movement from or to an idea or set of ideas. Such failures will leave parts of the heterarchy unexplored, preventing the co-evolution process from proceeding in certain directions or into certain levels. Conversely, the co-evolution of problems and solutions might be interpreted as evidence that problem fixation and solution fixation are being avoided or overcome to some extent. Co-evolution might even drive defixation. If, for example, a designer is fixated on one part of a problem-solution pair, a change in the other part might re-open the investigation. In the same way that co-evolution can be seen as a process of iteratively changing problem and solution representations, fixation and defixation can be seen as occurring and recurring in sequence, both for problems and for solutions.[118] The relationship between these processes has not yet received much attention, and yet there is considerable scope for theoretical and methodological integration.

Conclusions

In the first part of this two-part article, I have connected discussions of design-co-evolution to each other, revealing the different ways in which the core concept is interpreted, and the different ways in which it has been extended. I have also connected these discussions to related work from the history of design research, and to other disciplines that study other creative practices. This has demonstrated that design co-evolution research could

83 Jacob W. Getzels and Mihaly Csikszentmihalyi, *The Creative Vision: A Longitudinal Study of Problem Finding in Art* (New York: Wiley, 1976); Sandra Kay, "The Figural Problem Solving and Problem Finding of Professional and Semiprofessional Artists and Nonartists," *Creativity Research Journal* 4, no. 3 (1991): 233–52, DOI: https://doi.org/10.1080/10400419109534396; Susan Merrill Rostan, "Problem Finding, Problem Solving, and Cognitive Controls: An Empirical Investigation of Critically Acclaimed Productivity," *Creativity Research Journal* 7, no. 2 (1994): 97–110, DOI: https://doi.org/10.1080/10400419409534517.

84 David Collins, "A Synthesis Process Model of Creative Thinking in Music Composition," *Psychology of Music* 33, no. 2 (2005): 205, 210, DOI: https://doi.org/10.1177/0305735605050651.

85 Linda Flower and John R. Hayes, "The Cognition of Discovery: Defining a Rhetorical Problem," *College Composition and Communication* 31, no. 1 (1980): 22, 29, DOI: https://doi.org/10.2307/356630.

86 Brian Lawson, *How Designers Think* (London: The Architectural Press, 1980).

87 Mike Sharples, *How We Write: Writing as Creative Design* (London: Psychology Press, 1999).

88 Stephen R. Grossman and Edward E. Wiseman, "Seven Operating Principles for Enhanced Creative Problem Solving Training," *The Journal of Creative Behavior* 27, no. 1 (1993): 7, DOI: https://doi.org/10.1002/j.2162-6057.1993.tb01382.x. Note also the similarity to Dorst and Cross's concept of "bridging," Dorst and Cross, "Creativity in the Design Process," 435.

89 Donald J. Treffinger, "Creative Problem Solving: Overview and Educational Implications," *Educational Psychology Review* 7, no. 3 (1995): 306, DOI: https://doi.org/10.1007/BF02213375.

90 For a review of their relevant works, see Stellan Ohlsson, "Restructuring Revisited: I. Summary and Critique of the Gestalt Theory of Problem Solving," *Scandinavian Journal of Psychology* 25, no. 1 (1984): 65–78, DOI: https://doi.org/10.1111/j.1467-9450.1984.tb01001.x.

91 Ohlsson, "Restructuring Revisited," 68.

92 Howard E. Gruber and Katja Bödeker, eds., *Creativity, Psychology and the History of Science* (Dordrecht: Springer, 2005), 106, DOI: https://doi.org/10.1007/1-4020-3509-8.

93 Howard E. Gruber, "The Evolving Systems Approach to Creative Work," *Creativity Research Journal* 1, no. 1 (1988): 32, DOI: https://doi.org/10.1080/10400418809534285.

both draw from and contribute to a wider literature than it does presently. It could also question more critically the assumptions that are inherited from representations of how computers can perform creative design work when the work of human designers is instead being investigated.

Research into design co-evolution could be considerably strengthened through better integration and coordinated development. Much of the development to date has evidently been isolated and piecemeal, focused on modifying co-evolution accounts to accommodate the specific features or findings of individual studies. Here, I have attempted to promote a more general approach to examining the foundations of the co-evolution account and how they can be strengthened. In the second part of this article, I will take this further by considering the biological analogy on which co-evolution accounts are implicitly or explicitly based. I will use this to propose further expansions to the design co-evolution concept for future research to explore, whether that is focused on design disciplines or other creative practices.

Acknowledgments

In writing this article I benefited from productive exchanges with Nigel Cross, Kees Dorst, John Gero, Udo Kannengiesser, Philip Cash, Milene Gonçalves, Colin Gray, Chris McMahon, Anja Maier, Tomislav Martinec, Per Galle, Linden Ball, Bo Christensen, and participants in a Cambridge seminar given in March 2021. I am also grateful to the suggestions made by three anonymous journal-nominated reviewers.

Declaration of Interests

There are no conflicts of interest involved in this article.

References

Abdulla, Ahmed M., S. H. Paek, B. Cramond, and M.A. Runco. "Problem Finding and Creativity: A Meta-Analytic Review." *Psychology of Aesthetics, Creativity, and the Arts* 14, no. 1 (2020): 3–14. DOI: https://doi.org/10.1037/aca0000194.

Agogué, Marine, Akin Kazakçi, Benoit Weil, and Mathieu Cassotti. "The Impacts of Examples on Creative Design: Explaining Fixation and Stimulation Effects." In *Design Theory and Research Methodology*. Vol. 2 of *DS 68-2: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design*, edited by Steve J. Culley, B.J. Hicks, T.C. McAloone, T.J. Howard, and Y. Reich, 266–74. Glasgow, UK: The Design Society, 2011. https://www.designsociety.org/publication/30477/.

Alem, Leila, and Mary Lou Maher. "A Model of Creative Design Using a Genetic Metaphor." Paper presented at the Symposium on AI Reasoning and Creativity, Queensland, Australia, August 1991, 1–4.

Alem, Leila, and Mary Lou Maher. "A Model of Creative Design Using a Genetic Metaphor." In *Artificial Intelligence and Creativity: An Interdisciplinary Approach*, edited by Terry Dartnall, 283–93. Dordrecht, NL: Springer Netherlands, 1994. DOI: https://doi.org/10.1007/978-94-017-0793-0_20.

Alexander, Christopher. *Notes on the Synthesis of Form*. Cambridge, MA: Harvard University Press, 1964.

94 Susan M. Rostan, "In the Spirit of Howard E. Gruber's Gift: Case Studies of Two Young Artists' Evolving Systems," *Creativity Research Journal* 15, no. 1 (2003): 46, DOI: https://doi.org/10.1207/S15326934CRJ1501_6.

95 Michael Mumford, Roni Reiter-Palmon, and Matthew Redmond call for more work in this area when, with respect to creativity, they refer to the "need for studies examining [the factors] which influence the effectiveness of solution monitoring and the quality of the resulting problem representations." Michael D. Mumford, Roni Reiter-Palmon, and Matthew Redmond, "Problem Construction and Cognition: Applying Problem Representations in Ill-Defined Domains," in *Problem Finding, Problem Solving, and Creativity*, ed. Mark A. Runco (Norwood, NJ: Ablex Publishing Corporation, 1994), 34.

96 In design, the co-evolution of problems and solutions is often introduced as though it is characteristic of the discipline, or even unique to it (although see Halstrøm and Galle, "Design as Co-evolution of Problem, Solution, and Audience," 3.1–3.13). These essentialist and exceptionalist perspectives are easier to maintain when co-evolutionary accounts of other practices are overlooked.

97 For a more general form of such claims, see Cash, "Theory-Driven Design Research," 85; Cash, "Where Next for Design Research?," 129.

98 Smulders et al., "Modelling Co-evolution," 342. Italics added.

99 Dorst, "Co-evolution and Emergence," 64.

100 Maher and Tang, "Computational and Cognitive Model," 49.

101 For a more general discussion of the difficult nature of design problems, see Kees Dorst, "Design Problems and Design Paradoxes," *Design Issues* 22, no. 3 (2006): 4–17, DOI: https://doi.org/10.1162/desi.2006.22.3.4; Steve Harfield, "On Design 'Problematization': Theorising Differences in Designed Outcomes," *Design Studies* 28, no. 2 (2007): 159–73, DOI: https://doi.org/10.1016/j.destud.2006.11.005; Jonas, "Design as Problem-Solving?," 157–70.

102 For a similar discussion, see Eric von Hippel and Georg von Krogh, "Identifying Viable 'Need-Solution Pairs': Problem Solving Without Problem Formulation," *Organization Science* 27, no. 1 (2015): 211, DOI: https://doi.org/10.1287/orsc.2015.1023.

103 Karl Duncker, "On Problem-Solving," trans. Lynne S. Lees, *Psychological Monographs* 58, no. 5 (1945): 18, DOI: https://doi.org/10.1037/h0093599; also see Gruber, "The Evolving Systems Approach," 32.

104 For definitions and the connections to co-evolution, see Corinne Kruger and Nigel Cross, "Solution Driven versus Problem Driven Design: Strategies and Outcomes," *Design Studies* 27, no. 5 (2006): 527–48, DOI: https://doi.org/10.1016/j.destud.2006.01.001. For examples, see Woo Lee et al., "Cognitive Strategies," 100967.

105 Crilly and Moroşanu Firth, "Creativity and Fixation," 202.

106 Maher and Poon, "Modeling Design Exploration," 197.

107 For the connection between various tree diagrams and co-evolution, see Ang Liu and Stephen C.-Y. Lu, "A New Coevolution Process for Conceptual Design," *CIRP Annals* 64, no. 1 (2015): 153–56, DOI: https://doi.org/10.1016/j.cirp.2015.04.020.

108 For related diagrams, see Nathan Crilly, "The Proliferation of Functions: Multiple Systems Playing Multiple Roles in Multiple Supersystems," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 29, no. 1 (2015): 83–92, DOI: https://doi.org/10.1017/S0890060414000626; Marine Agogué et al., "The Impacts of Examples on Creative Design: Explaining Fixation and Stimulation Effects," in *Design Theory and Research Methodology*, Vol. 2 of *DS 68-2: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design*, ed. Steve J. Culley et al. (Glasgow, UK: The Design Society, 2011), 270, available at https://www.designsociety.org/publication/30477/; Marples, "The Decisions of Engineering Design," 60.

109 Describing co-evolution as only involving one kind of entity diverges from the biological analogy on which the concept is based. However, that analogy is seldom explicit or elaborated in design research (see Part II).

110 Kruger and Cross, "Solution Driven versus Problem Driven Design," 533–34.

111 For an early discussion of the distinction between changing and refining problems during co-evolution, see Mihaly Lenart and Mary Lou Maher, "Discussion: Evolutionary Methods in Design: Discussion," in *Advances in Formal Design Methods for CAD: Proceedings of the IFIP WG5.2 Workshop on Formal Design Methods for Computer-Aided Design, June 1995*, ed. John S. Gero and Fay Sudweeks (Dordrecht, NL: Springer-Science + Business Media BV, 1996), 52, DOI: https://doi.org/10.1007/978-0-387-34925-1_3.

112 Martinec et al., "Revisiting Problem-Solution Co-evolution," 1–2; Wiltschnig et al., "Collaborative Problem-Solution Co-evolution," 515.

Amabile, Teresa M. "Entrepreneurial Creativity through Motivational Synergy." *The Journal of Creative Behavior* 31, no. 1 (1997): 18–26. DOI: https://doi.org/10.1002/j.2162-6057.1997.tb00778.x.

Archer, Bruce. "Design as a Discipline." *Design Studies* 1, no. 1 (1979): 17–20. DOI: https://doi.org/10.1016/0142-694X(79)90023-1.

Van der Bijl-Brouwer, Mieke. "Problem Framing Expertise in Public and Social Innovation." *She Ji: The Journal of Design, Economics, and Innovation* 5, no. 1 (2019): 29–43. https://doi.org/10.1016/j.sheji.2019.01.003.

Biskjaer, Michael Mose, and Bo T. Christensen. "A Second Look at Primary Generators." *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 1 (2021): 7–23. https://doi.org/10.1016/j.sheji.2020.08.007.

Brissaud, Daniel, Olivier Garro, and Oscar Poveda. "Design Process Rationale Capture and Support by Abstraction of Criteria." *Research in Engineering Design* 14, no. 3 (2003): 162–72. DOI: https://doi.org/10.1007/s00163-003-0038-0.

Cai, Jinfa, and Victor V. Cifarelli. "Exploring Mathematical Exploration: How Two College Students Formulated and Solved Their Own Mathematical Problems?" *Focus on Learning Problems in Mathematics* 27, no. 3 (2005): 43–72. https://researchgate.net/publication/288351412.

Cash, Philip, and Milene Gonçalves. "Information-Triggered Co-evolution: A Combined Process Perspective." In *Analysing Design Thinking: Studies of Cross-Cultural Co-creation*, edited by Bo T. Christensen, Linden J Ball, and Kim Halskov, 501–20. Boca Raton: CRC Press, 2017. DOI: https://doi.org/10.1201/9781315208169-27.

Cash, Philip J. "Developing Theory-Driven Design Research." *Design Studies* 56 (May 2018): 84–119. DOI: https://doi.org/10.1016/j.destud.2018.03.002.

Cash, Philip. "Where Next for Design Research? Understanding Research Impact and Theory Building." *Design Studies* 68 (May 2020): 113–41. DOI: https://doi.org/10.1016/j.destud.2020.03.001.

Chivukula, Sai Shruthi, and Colin Gray. "Co-evolving Towards Evil Design Outcomes: Mapping Problem and Solution Process Moves." In *Proceedings of DRS 2020 International Conference: Synergy*, edited by Stella Boess, Ming Cheung, and Rebecca Cain, 1707–26. London: Design Research Society Digital Library, 2020. DOI: https://doi.org/10.21606/drs.2020.107.

Christensen, Bo T., and Linden J. Ball. "Building a Discipline: Indicators of Expansion, Integration and Consolidation in Design Research across Four Decades." *Design Studies* 65 (2019): 18–34. DOI: https://doi.org/10.1016/j.destud.2019.10.001.

Chua, Soo Meng Jude. "Donald Schön, Herbert Simon, and *The Sciences of the Artificial*." *Design Studies* 30, no. 1 (2009): 60–68. DOI: https://doi.org/10.1016/j.destud.2008.09.001.

Chua, Soo Meng Jude. "Design Without Final Goals: Getting Around Our Bounded Rationality." *Artifact* 3, no. 4 (2015): 2.1–2.7. DOI: https://doi.org/10.14434/artifact.v3i4.12787.

Cifarelli, Victor V., and Jinfa Cai. "The Evolution of Mathematical Explorations in Open-Ended Problem-Solving Situations." *The Journal of Mathematical Behavior* 24, no. 3-4 (2005): 302–24. https://doi.org/10.1016/j.jmathb.2005.09.007.

Collins, David. "A Synthesis Process Model of Creative Thinking in Music Composition." *Psychology of Music* 33, no. 2 (2005): 193–216. DOI: https://doi.org/10.1177/0305735605050651.

Crilly, Nathan. "The Structure of Design Revolutions: Kuhnian Paradigm Shifts in Creative Problem Solving." *Design Issues* 26, no. 1 (2010): 54–66. DOI: https://doi.org/10.1162/desi.2010.26.1.54.

Crilly, Nathan. "Fixation and Creativity in Concept Development: The Attitudes and Practices of Expert Designers." *Design Studies* 38 (May 2015): 54–91. DOI: https://doi.org/10.1016/j.destud.2015.01.002.

Crilly, Nathan. "The Proliferation of Functions: Multiple Systems Playing Multiple Roles in Multiple Supersystems." *Artificial Intelligence for Engineering Design,*

113 Roozenburg and Cross, "Models of the Design Process," 215–20. Also see iterative models that develop system requirements in response to emerging design proposals, for example, J. Harvey Evans, "Basic Design Concepts," *Journal of the American Society for Naval Engineers* 71, no. 4 (1959): 671–78, DOI: https://doi.org/10.1111/j.1559-3584.1959.tb01836.x.

114 David G. Jansson and Steven M. Smith, "Design Fixation," *Design Studies* 12, no. 1 (1991): 3–11, DOI: https://doi.org/10.1016/0142-694X(91)90003-F; A. Terry Purcell and John S. Gero, "Design and Other Types of Fixation," *Design Studies (Special Issue: Design Cognition and Computation)* 17, no. 4 (1996): 363–83, DOI: https://doi.org/10.1016/S0142-694X(96)00023-3.

115 Christensen and Ball, "Building a Discipline," 29; Cash, "Where Next for Design Research?," 125.

116 For reviews see Ut Na Sio, Kenneth Kotovsky, and Jonathan Cagan, "Fixation or Inspiration? A Meta-Analytic Review of the Role of Examples on Design Processes," *Design Studies* 39 (May 2015): 70–99, DOI: https://doi.org/10.1016/j.destud.2015.04.004; Luis A. Vasconcelos and Nathan Crilly, "Inspiration and Fixation: Questions, Methods, Findings, and Challenges," *Design Studies* 42 (2016): 1–32, DOI: https://doi.org/10.1016/j.destud.2015.11.001. For criticisms, see Nathan Crilly, "Methodological Diversity and Theoretical Integration: Research in Design Fixation as an Example of Fixation in Research Design?," *Design Studies* 65 (2019): 78–106, DOI: https://doi.org/10.1016/j.destud.2019.10.006.

117 Nathan Crilly, "Fixation and Creativity in Concept Development: The Attitudes and Practices of Expert Designers," *Design Studies* 38 (2015): 77, DOI: https://doi.org/10.1016/j.destud.2015.01.002; Rahul Mohanani, Paul Ralph, and Ben Shreeve, "Requirements Fixation," in *ICSE 2014: Proceedings of the 36th International Conference on Software Engineering*, ed. Pankaj Jalote, Lionel Briand, and André van der Hoek (New York: ACM, 2014), 895–906, DOI: https://doi.org/10.1145/2568225.2568235.

118 Crilly and Moroşanu Firth, "Creativity and Fixation," 201; Nathan Crilly, "The Structure of Design Revolutions: Kuhnian Paradigm Shifts in Creative Problem Solving," *Design Issues* 26, no. 1 (2010): 54–66, DOI: https://doi.org/10.1162/desi.2010.26.1.54.

Analysis and Manufacturing 29, no. 1 (2015): 83–92. DOI: https://doi.org/10.1017/S0890060414000626.

Crilly, Nathan. "'Fixation' and 'the Pivot': Balancing Persistence with Flexibility in Design and Entrepreneurship." *International Journal of Design Creativity and Innovation* 6, no. 1-2 (2018): 52–65. DOI: https://doi.org/10.1080/21650349.2017.1362359.

Crilly, Nathan. "Methodological Diversity and Theoretical Integration: Research in Design Fixation as an Example of Fixation in Research Design?" *Design Studies* 65 (2019): 78–106. DOI: https://doi.org/10.1016/j.destud.2019.10.006.

Crilly, Nathan, and Roxana Moroşanu Firth. "Creativity and Fixation in the Real World: Three Case Studies of Invention, Design and Innovation." *Design Studies* 64 (September 2019): 169–212. DOI: https://doi.org/10.1016/j.destud.2019.07.003.

Crilly, Nathan. "The Evolution of 'Co-evolution' (Part II): The Biological Analogy, Different Kinds of Co-evolution, and Proposals for Conceptual Expansion." *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 3 (2021): 333–55. DOI: https://doi.org/10.1016/j.sheji.2021.07.004.

Cross, Nigel, ed. *Developments in Design Methodology*. Chichester: Wiley–Blackwell, 1984.

Cross, Nigel. "Research in Design Thinking." In *Research in Design Thinking*, edited by Nigel Cross, Kees Dorst, and Norbert F. M. Roozenburg, 3–10. Delft: Delft University Press, 1992. http://resolver.tudelft.nl/uuid:83a0d981-d053-4944-90af-3d165b9d079e.

Cross, Nigel, and Anita Clayburn Cross. "Expert Designers." In *Designers: The Key to Successful Product Development*, edited by Eckart Frankenberger, Petra Badke-Schaub, and Herbert Birkhofer, 71–84. London: Springer, 1998. DOI: https://doi.org/10.1007/978-1-4471-1268-6_7.

Cross, Nigel. *Designerly Ways of Knowing*. London: Springer, 2006.

D'Hondt, Theo, Kris De Volder, Kim Mens, and Roel Wuyts. "Co-evolution of Object-Oriented Software Design and Implementation." In *Software Architectures and Component Technology*, edited by Mehmet Akşit, 207–24. Boston: Springer US, 2002. DOI: https://doi.org/10.1007/978-1-4615-0883-0_7.

Daly, Shanna R., Seda McKilligan, Jaryn A. Studer, Jaclyn K. Murray, and Colleen M. Seifert. "Innovative Solutions through Innovated Problems." *International Journal of Engineering Education* 34, no. 2(B) (2018): 695–707. https://www.ijee.ie/contents/c340218B.html.

Dankfort, Zoë, Luuk Roos, and Milene Gonçalves. "Inspiring Co-evolution Moves and Creativity in Design Teams." In *ICDC 2018: Proceedings of The Fifth International Conference on Design Creativity*, edited by Elies Dekoninck, Andrew Wodehouse, Chris Snider, Georgi Georgiev, and Gaetano Cascini, 395–402. Glasgow: The Design Society, 2018. https://www.designsociety.org/publication/40743/.

Darke, Jane. "The Primary Generator and the Design Process." *Design Studies* 1, no. 1 (1979): 36–44. DOI: https://doi.org/10.1016/0142-694X(79)90027-9.

Davis, Philip J. "What Do I Know? A Study of Mathematical Self-Awareness." *The College Mathematics Journal* 16, no. 1 (1985): 22–41. DOI: https://doi.org/10.1080/07468342.1985.11972847.

Dorst, Kees, and Nigel Cross. "Creativity in the Design Process: Co-evolution of Problem-Solution," *Design Studies* 22, no. 5 (2001): 425–37. DOI: https://doi.org/10.1016/S0142-694X(01)00009-6.

Dorst, Kees. "Design Problems and Design Paradoxes." *Design Issues* 22, no. 3 (2006): 4–17. DOI: https://doi.org/10.1162/desi.2006.22.3.4.

Dorst, Kees. "Co-evolution and Emergence in Design." *Design Studies* 65 (November 2019): 60–77. DOI: https://doi.org/10.1016/j.destud.2019.10.005.

Duncker, Karl. "On Problem-Solving." Translated by Lynne S. Lees. *Psychological Monographs* 58, no. 5 (1945): i–113. DOI: https://doi.org/10.1037/h0093599.

Evans, J. Harvey. "Basic Design Concepts." *Journal of the American Society for Naval Engineers* 71, no. 4 (1959): 671–78. DOI: https://doi.org/10.1111/j.1559-3584.1959.tb01836.x.

Fischer, Gerhard, and Kumiyo Nakakoji. "Empowering Designers with Integrated Design Environments." In *Artificial Intelligence in Design '91*, edited by J. S. Gero, 191–209. Oxford: Butterworth-Heinemann, 1991. DOI: https://doi.org/10.1016/B978-0-7506-1188-6.50014-4.

Fischer, Gerhard, and Kumiyo Nakakoji. "Beyond the Macho Approach of Artificial Intelligence: Empower Human Designers—Do Not Replace Them." *Knowledge-Based Systems* 5, no. 1 (1992): 15–30. DOI: https://doi.org/10.1016/0950-7051(92)90021-7.

Flower, Linda, and John R. Hayes. "The Cognition of Discovery: Defining a Rhetorical Problem." *College Composition and Communication* 31, no. 1 (1980): 21–32. DOI: https://doi.org/10.2307/356630.

Gero, John S. "Towards a Model of Exploration in Computer-Aided Design." In Gero and Tyugu, *Proceedings of the IFIP TC5/WG5.2 Workshop*, 315–36. https://cs.gmu.edu/~jgero/publications/1994/94GeroIFIPFormalMethodsCAD.pdf.

Gero, John S., and Enn Tyugu, eds. *Proceedings of the IFIP TC5/WG5.2 Workshop on Formal Design Methods for CAD*. New York: Elsevier Science Inc., 1994.

Gero, John S., and Fay Sudweeks, eds. *Advances in Formal Design Methods for CAD: Proceedings of the IFIP WG5.2 Workshop on Formal Design Methods for Computer-Aided Design, June 1995*. Dordrecht, NL: Springer-Science + Business Media BV, 1996.

Gero, John S., and Julie Milovanovic. "A Framework for Studying Design Thinking through Measuring Designers' Minds, Bodies and Brains." *Design Science* 6 (2020): e19, DOI: https://doi.org/10.1017/dsj.2020.15.

Getzels, Jacob W., and Mihaly Csikszentmihalyi. *The Creative Vision: A Longitudinal Study of Problem Finding in Art*. New York: Wiley, 1976.

Glaveanu, Vlad Petre, Michael Hanchett Hanson, John Baer, Baptiste Barbot, Edward P. Clapp, Giovanni Emanuele Corazza, Beth Hennessey, et al. "Advancing Creativity Theory and Research: A Socio-Cultural Manifesto." *The Journal of Creative Behavior* 54, no. 3 (2020): 741–45. DOI: https://doi.org/10.1002/jocb.395.

Gonçalves, Milene, and Philip Cash. "The Life Cycle of Creative Ideas: Towards a Dual-Process Theory of Ideation." *Design Studies* 72 (January 2021): 100988. https://doi.org/10.1016/j.destud.2020.100988.

Grimes, Matthew G. "The Pivot: How Founders Respond to Feedback through Idea and Identity Work." *Academy of Management Journal* 61, no. 5 (2017): 1692–1717. DOI: https://doi.org/10.5465/amj.2015.0823.

Grossman, Stephen R., and Edward E. Wiseman. "Seven Operating Principles for Enhanced Creative Problem Solving Training." *The Journal of Creative Behavior* 27, no. 1 (1993): 1–16. DOI: https://doi.org/10.1002/j.2162-6057.1993.tb01382.x.

Gruber, Howard E. "The Evolving Systems Approach to Creative Work." *Creativity Research Journal* 1, no. 1 (1988): 7–51. DOI: https://doi.org/10.1080/10400418809534285.

Gruber, Howard E., and Katja Bödeker, eds. *Creativity, Psychology and the History of Science*. Dordrecht: Springer, 2005. DOI: https://doi.org/10.1007/1-4020-3509-8.

Halstrøm, Per Liljenberg, and Per Galle. "Design as Co-evolution of Problem, Solution, and Audience." *Artifact* 3, no. 4 (2015): 3. DOI: https://doi.org/10.14434/artifact.v3i4.12815.

Harfield, Steve. "On Design 'Problematization': Theorising Differences in Designed Outcomes." *Design Studies* 28, no. 2 (2007): 159–73. DOI: https://doi.org/10.1016/j.destud.2006.11.005.

Harvey, Sarah, and Chia-Yu Kou. "Collective Engagement in Creative Tasks: The Role of Evaluation in the Creative Process in Groups." *Administrative Science Quarterly* 58, no. 3 (2013): 346–86. DOI: https://doi.org/10.1177/0001839213498591.

Von Hippel, Eric, and Georg von Krogh. "Identifying Viable 'Need-Solution Pairs': Problem Solving Without Problem Formulation." *Organization Science* 27, no. 1 (2015): 207–21. DOI: https://doi.org/10.1287/orsc.2015.1023.

Hodges, Peter, Stan Ruecker, Celso Scaletsky, Jaime Rivera, Roberto Faller, and Amanda Geppert. "Four Criteria for Design Theories." *She Ji: The Journal of Design, Economics, and Innovation* 3, no. 1 (2017): 65–74. DOI: https://doi.org/10.1016/j.sheji.2017.02.003.

Hoover, Steven M., and John F. Feldhusen. "Scientific Problem Solving and Problem Finding: A Theoretical Model." In Runco, *Problem Finding, Problem Solving, and Creativity*, 201–19.

Jansson, David G., and Steven M. Smith. "Design Fixation." *Design Studies* 12, no. 1 (1991): 3–11. DOI: https://doi.org/10.1016/0142-694X(91)90003-F.

Jonas, Wolfgang. "Design as Problem-Solving? Or: Here Is the Solution—What Was the Problem?" *Design Studies* 14, no. 2 (1993): 157–70. DOI: https://doi.org/10.1016/0142-694X(93)80045-E.

Kay, Sandra. "The Figural Problem Solving and Problem Finding of Professional and Semiprofessional Artists and Nonartists." *Creativity Research Journal* 4, no. 3 (1991): 233–52. DOI: https://doi.org/10.1080/10400419109534396.

Kimbell, Lucy. "Rethinking Design Thinking: Part I." *Design and Culture* 3, no. 3 (2011): 285–306. DOI: https://doi.org/10.2752/175470811X13071166525216.

Klahr, David, and Kevin Dunbar. "Dual Space Search During Scientific Reasoning." *Cognitive Science* 12, no. 1 (1988): 1–48. DOI: https://doi.org/10.1207/s15516709cog1201_1.

Krish, Sivam. "A Practical Generative Design Method." *Computer-Aided Design* 43, no. 1 (2011): 88–100. DOI: https://doi.org/10.1016/j.cad.2010.09.009.

Kruger, Corinne, and Nigel Cross. "Solution Driven versus Problem Driven Design: Strategies and Outcomes." *Design Studies* 27, no. 5 (2006): 527–48. DOI: https://doi.org/10.1016/j.destud.2006.01.001.

Kuhn, Thomas S. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1996.

Lawson, Brian. *How Designers Think*. London: The Architectural Press, 1980.

Lee, Jin Woo, Shanna R. Daly, Aileen Huang-Saad, Gabriella Rodriguez, and Colleen M. Seifert. "Cognitive Strategies in Solution Mapping: How Engineering Designers Identify Problems for Technological Solutions." *Design Studies* 71 (November 2020): 100967. DOI: https://doi.org/10.1016/j.destud.2020.100967.

Lenart, Mihaly, and Mary Lou Maher. "Discussion: Evolutionary Methods in Design: Discussion." In Gero and Sudweeks, *Advances in Formal Design Methods for CAD*, 51–55. DOI: https://doi.org/10.1007/978-0-387-34925-1_3.

Liu, Ang, and Stephen C.-Y. Lu. "A New Coevolution Process for Conceptual Design." *CIRP Annals* 64, no. 1 (2015): 153–56. DOI: https://doi.org/10.1016/j.cirp.2015.04.020.

Logan, Brian, and Tim Smithers. "Creativity and Design as Exploration." In *Modelling Creativity and Knowledge-Based Creative Design*, edited by John S. Gero and Mary Lou Maher, 139–75. Hillsdale: Lawrence Erlbaum Associates, 1993. http://papers.cumincad.org/cgi-bin/works/paper/c9cf.

Lonchampt, Pierre, Guy Prudhomme, and Daniel Brissaud. "Engineering Design Problem in a Co-evolutionary Model of the Design Process." In *DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference* (Dubrovnik, Croatia, 2004), 361–66. https://www.designsociety.org/publication/19776/.

MacCormac, R. "The Evolution of the Design." *Archer De* (October 1971): 617.

Maher, Mary Lou, and Josiah Poon. "Modeling Design Exploration as Co-evolution." *Computer-Aided Civil and Infrastructure Engineering* 11, no. 3 (1996): 195–209. DOI: https://doi.org/10.1111/j.1467-8667.1996.tb00323.x.

Maher, Mary Lou. "Creative Design Using a Genetic Algorithm." In *Proceedings of the First Annual Conference on Computing in Civil Engineering*, vol. 2, edited by Khalil Khozeimeh, 2014–21. Washington, DC: American Society of Civil Engineers (ASCE), 1994. https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0090304.

Maher, Mary Lou, Josiah Poon, and Sylvie Boulanger. "Formalising Design Exploration as Co-evolution." In Gero and Sudweeks, *Advances in Formal Design Methods for CAD*, 3–30. DOI: https://doi.org/10.1007/978-0-387-34925-1_1.

Maher, Mary Lou, and Hsien-Hui Tang. "Co-evolution as a Computational and Cognitive Model of Design." *Research in Engineering Design* 14, no. 1 (2003): 47–64. DOI: https://doi.org/10.1007/s00163-002-0016-y.

Marples, David L. "The Decisions of Engineering Design." *IRE Transactions on Engineering Management* EM-8, no. 2 (1961): 55–71. DOI: https://doi.org/10.1109/IRET-EM.1961.5007593.

Martinec, Tomislav, Stanko Škec, Marija Majda Perišić, and Mario Štorga. "Revisiting Problem-Solution Co-evolution in the Context of Team Conceptual Design Activity." *Applied Sciences* 10, no. 18 (2020): 1–29. DOI: https://doi.org/10.3390/app10186303.

Mohanani, Rahul, Paul Ralph, and Ben Shreeve. "Requirements Fixation." In *ICSE 2014: Proceedings of the 36th International Conference on Software Engineering*, edited by Pankaj Jalote, Lionel Briand, and André van der Hoek, 895–906. New York: ACM, 2014. DOI: https://doi.org/10.1145/2568225.2568235.

Mumford, Michael D., Roni Reiter-Palmon, and Matthew Redmond. "Problem Construction and Cognition: Applying Problem Representations in Ill-Defined Domains." In Runco, *Problem Finding, Problem Solving, and Creativity*, 3–39.

Nakakoji, Kumiyo, and Gerhard Fischer. "CATALOG EXPLORER: Exploiting the Synergy of Integrated Design Environments." In *Proceedings of Software Symposium '90*, 264–71. Kyoto, June 7–8, 1990. http://l3d.cs.colorado.edu/~gerhard/papers/Scanned/1990-Catalog-Explorer-10th-SoftSym90.pdf.

Nakakoji, Kumiyo, and Gerhard Fischer. "Knowledge Delivery: Facilitating Human-Computer Collaboration in Integrated Design Environments." In *Human-Computer Collaboration: Reconciling Theory, Synthesizing Practice, Papers from the 1993 Fall Symposium, Technical Report FS-93-05*, edited by Loren Terveen, 63–69. Menlo Park: The AAAI Press, 1993. https://aaai.org/Papers/Symposia/Fall/1993/FS-93-05/FS93-05-012.pdf.

Navinchandra, Dundee. *Exploration and Innovation in Design: Towards a Computational Model*. New York: Springer-Verlag, 1991. DOI: https://doi.org/10.1007/978-1-4612-3114-1.

Ohlsson, Stellan. "Restructuring Revisited: I. Summary and Critique of the Gestalt Theory of Problem Solving." *Scandinavian Journal of Psychology* 25, no. 1 (1984): 65–78. DOI: https://doi.org/10.1111/j.1467-9450.1984.tb01001.x.

Poon, Josiah, and Mary Lou Maher. "Co-evolution in Design: A Case Study of the Sydney Opera House." In *CAADRIA '97: Proceedings of the Second Conference on Computer-Aided Architectural Design Research*, edited by Y-T Liu, J-Y Tsou, and J-H Hou, 439–48. Hsinchu: National Chioa Tung University. http://papers.cumincad.org/data/works/att/4925.content.pdf.

Purcell, A. Terry, and John S. Gero. "Design and Other Types of Fixation." *Design Studies (Special Issue: Design Cognition and Computation)* 17, no. 4 (1996): 363–83. DOI: https://doi.org/10.1016/S0142-694X(96)00023-3.

Reiter-Palmon, Roni, and Erika J. Robinson. "Problem Identification and Construction: What Do We Know, What Is the Future?" *Psychology of Aesthetics, Creativity, and the Arts* 3, no. 1 (2009): 43–47. DOI: https://doi.org/10.1037/a0014629.

Ries, Eric. *The Lean Startup: How Constant Innovation Creates Radically Successful Businesses*. New York: Penguin, 2011.

Rittel, Horst W.J. "On the Planning Crisis: Systems Analysis of the 'First and Second Generations.'" *Bedriftsøkonomen* 8 (1972): 390–96. DOI: https://doi.org/10.1007/978-94-009-7651-1_4.

Rittel, Horst W.J., and Melvin M. Webber. "Dilemmas in a General Theory of Planning." *Policy Sciences* 4, no. 2 (1973): 155–69. DOI: https://doi.org/10.1007/BF01405730.

Rittel, Horst W.J. "Second-Generation Design Methods." In Cross, *Developments in Design Methodology*, 317–27.

Roozenburg, Norbert F.M., and Nigel. G. Cross. "Models of the Design Process: Integrating across the Disciplines." *Design Studies* 12, no. 4 (1991): 215–20. https://doi.org/10.1016/0142-694X(91)90034-T.
Rostan, Susan Merrill. "Problem Finding, Problem Solving, and Cognitive Controls: An Empirical Investigation of Critically Acclaimed Productivity." *Creativity Research Journal* 7, no. 2 (1994): 97–110. DOI: https://doi.org/10.1080/10400419409534517.
Rostan, Susan M. "In the Spirit of Howard E. Gruber's Gift: Case Studies of Two Young Artists' Evolving Systems." *Creativity Research Journal* 15, no. 1 (2003): 45–60. DOI: https://doi.org/10.1207/S15326934CRJ1501_6.
Runco, Mark A., ed. *Problem Finding, Problem Solving, and Creativity*, illustrated edition. Norwood: Ablex Publishing Corporation, 1994.
Sarasvathy, Saras D. "Causation and Effectuation: Toward a Theoretical Shift from Economic Inevitability to Entrepreneurial Contingency." *The Academy of Management Review* 26, no. 2 (2001): 243–63. DOI: https://doi.org/10.2307/259121.
Schön, Donald A. *The Reflective Practitioner: How Professionals Think in Action*. London: Temple Smith, 1983.
Sharples, Mike. *How We Write: Writing as Creative Design*. London: Psychology Press, 1999.
Shih, Yi Teng, and Willy Sher. "Exploring the Role of CAD and Its Application in Design Education." *Computer-Aided Design and Applications* 18, no. 6 (2021): 1410–24. DOI: https://doi.org/10.14733/cadaps.2021.1410-1424.
Simon, Herbert A. "The Structure of Ill Structured Problems." *Artificial Intelligence* 4, no. 3-4 (1973): 181–201. DOI: https://doi.org/10.1016/0004-3702(73)90011-8.
Simon, Herbert A. "Problem Forming, Problem Finding, and Problem Solving in Design." Paper presented at the 1987 International Congress of Planning and Design Theory, Boston, August 20, 1987.
Simon, Herbert A. "Problem Forming, Problem Finding, and Problem Solving in Design." In *Design and Systems: General Applications of Methodology*, edited by Arne Collen and Wojciech W. Gasparski, 245–57. Piscataway: Transaction Publishers, 1995. http://digitalcollections.library.cmu.edu/awweb/awarchive?type=file&item=34208.
Simon, Herbert A. *The Sciences of the Artificial*. Cambridge, MA: MIT Press, 1996.
Sio, Ut Na, Kenneth Kotovsky, and Jonathan Cagan. "Fixation or Inspiration? A Meta-Analytic Review of the Role of Examples on Design Processes." *Design Studies* 39 (2015): 70–99. DOI: https://doi.org/10.1016/j.destud.2015.04.004.
Smithers, Tim, Dave Corne, and Peter Ross. "On Computing Exploration and Solving Design Problems." In Gero and Tyugu, *Proceedings of the IFIP TC5/WG5.2 Workshop*, 293–313. https://www.academia.edu/30972621/.
Smulders, Frido E., Isabelle M. Reyman, and Kees Dorst. "Modelling Co-evolution in Design Practice." In *Design Theory and Research Methodology*. Vol. 2 of *DS 58-2: Proceedings of ICED '09: The 17th International Conference on Engineering Design*, edited by Margareta Norell Bergendahl, M. Grimheden, L. Leifer, P. Skogstad, and U. Lindemann, 335–46. Glasgow: The Design Society, 2009. https://www.designsociety.org/publication/28597/.
Sosa, Ricardo. "Accretion Theory of Ideation: Evaluation Regimes for Ideation Stages." *Design Science* 5 (2019): e23, DOI: https://doi.org/10.1017/dsj.2019.22.
Storm, Rosa, Jeffrey van Maanen, and Milene Gonçalves. "Reframing the Design Process: Integrating Goals, Methods and Manifestation into the Co-evolution Model." In *Proceedings of the Design Society: International Conference on Engineering Design* 1, no. 1 (2019): 359–68. DOI: https://doi.org/10.1017/dsi.2019.39.
Swartout, William, and Robert Balzer. "On the Inevitable Intertwining of Specification and Implementation." *Communications of the ACM* 25, no. 7 (1982): 438–40. DOI: https://doi.org/10.1145/358557.358572.
Sycara, Katia P. "Problem Restructuring in Negotiation." *Management Science* 37, no. 10 (1991): 1248–68. DOI: https://doi.org/10.1287/mnsc.37.10.1248.

Tang, Antony, Aldeida Aleti, Janet Burge, and Hans van Vliet. "What Makes Software Design Effective?" *Design Studies* 31, no. 6 (2010): 614–40. DOI: https://doi.org/10.1016/j.destud.2010.09.004.

Tang, Antony, Peng Liang, Viktor Clerc, and Hans van Vliet. "Traceability in the Co-evolution of Architectural Requirements and Design." In *Relating Software Requirements and Architectures*, edited by Paris Avgeriou, John Grundy, Jon G. Hall, Patricia Lago, Ivan Mistrík, 35–60. Berlin: Springer Verlag Berlin Heidelberg, 2011. DOI: https://doi.org/10.1007/978-3-642-21001-3_4.

Treffinger, Donald J. "Creative Problem Solving: Overview and Educational Implications." *Educational Psychology Review* 7, no. 3 (1995): 301–12. DOI: https://doi.org/10.1007/BF02213375.

Vanderstraeten, Johanna, Julie Hermans, Arjen van Witteloostuijn, and Marcus Dejardin. "SME Innovativeness in a Dynamic Environment: Is There Any Value in Combining Causation and Effectuation?" *Technology Analysis & Strategic Management* 32, no. 11 (2020): 1277–93. DOI: https://doi.org/10.1080/09537325.2020.1766672.

Vasconcelos, Luis A., and Nathan Crilly. "Inspiration and Fixation: Questions, Methods, Findings, and Challenges." *Design Studies* 42 (2016): 1–32. DOI: https://doi.org/10.1016/j.destud.2015.11.001.

Vermaas, Pieter E., and Udo Pesch. "Revisiting Rittel and Webber's Dilemmas: Designerly Thinking Against the Background of New Societal Distrust." *She Ji: The Journal of Design, Economics, and Innovation* 6, no. 4 (2020): 530–45. DOI: https://doi.org/10.1016/j.sheji.2020.11.001.

Visser, Willemien. "Design: One, But in Different Forms." *Design Studies* 30, no. 3 (2009): 187–223. DOI: https://doi.org/10.1016/j.destud.2008.11.004.

Volkema, Roger J. "Problem Formulation in Planning and Design." *Management Science* 29, no. 6 (1983): 639–52. DOI: https://doi.org/10.1287/mnsc.29.6.639.

Wacker, John G. "A Definition of Theory: Research Guidelines for Different Theory-Building Research Methods in Operations Management." *Journal of Operations Management* 16, no. 4 (1998): 361–85. DOI: https://doi.org/10.1016/S0272-6963(98)00019-9.

Ward, Thomas B. "Cognition, Creativity, and Entrepreneurship." *Journal of Business Venturing* 19, no. 2 (2004): 173–88. DOI: https://doi.org/10.1016/S0883-9026(03)00005-3.

Wiltschnig, Stefan, Bo T. Christensen, and Linden J. Ball. "Collaborative Problem-Solution Co-evolution in Creative Design." *Design Studies* 34, no. 5 (2013): 515–42. DOI: https://doi.org/10.1016/j.destud.2013.01.002.

Wrigley, Cara, Genevieve Mosely, and Michael Mosely. "Defining Military Design Thinking: An Extensive, Critical Literature Review." *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 1 (2021): 104–43. DOI: https://doi.org/10.1016/j.sheji.2020.12.002.

Wynn, David C., and P. John Clarkson. "Process Models in Design and Development." *Research in Engineering Design* 29, no. 2 (2018): 161–202. DOI: https://doi.org/10.1007/s00163-017-0262-7.

Yeh, Raymond T. "System Development as a Wicked Problem." *International Journal of Software Engineering and Knowledge Engineering* 1, no. 2 (1991): 117–30. DOI: https://doi.org/10.1142/S0218194091000123.

Yeh, Raymond. T., D.A. Naumann, R.T. Mittermeir, R.A. Schlemmer, W.S. Gilmowe, G.E. Sumrall, and J.T. Lebaron. "A Commonsense Management Model." *IEEE Software* 8, no. 6 (1991): 23–33. DOI: https://doi.org/10.1109/52.103574.

You, Xinya, and David Hands. "A Reflection upon Herbert Simon's Vision of Design in *The Sciences of the Artificial*." *The Design Journal* 22, no. sup1 (2019): 1345–56. DOI: https://doi.org/10.1080/14606925.2019.1594961.

Yu, Rongrong, Ning Gu, Michael Ostwald, and John S. Gero. "Empirical Support for Problem–Solution Coevolution in a Parametric Design Environment." *AI EDAM* 29, no. 1 (2015): 33–44. DOI: https://doi.org/10.1017/S0890060414000316.