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The Evolution of "Co-evolution" (Part II): The Biological Analogy, Different Kinds of Co-evolution, and Proposals for Conceptual Expansion

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Abstract
Descriptions of problem-solution "co-evolution" either explicitly or implicitly draw an analogy between processes of design and processes of biological evolution. Analogies of this kind are common in research because of their potential to assist in explanation and discovery. However, reviewing the design literature reveals that the discussion of design co-evolution has become disconnected from the biological analogy on which it is founded, and from which other disciplines draw. Here, I explore the function of the co-evolution analogy, provide an illustrative example from biology, and explore the varieties of co-evolution to which design might be compared. By doing so, I propose two possible directions for expanding the design co-evolution concept: (i) examining what co-evolves in addition to, or instead of, problems and solutions, and (ii) examining the different levels at which co-evolution occurs. Both of these proposals are illustrated with a variant of the design co-evolution diagram.

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Introduction[1]

In the first part of this two-part article, I summarized how design researchers have used the concept of "co-evolution" to describe how representations of problems and solutions change during a project. I also connected these discussions to related work in other disciplines studying other creative practices. Given the very long history of discussions about something *like* co-evolution in design, and the wealth of relevant descriptions of *similar* processes in other fields, what distinguishes the actual concept of co-evolution? I argue here that it is separated from other similar concepts by the biological analogy on which it is founded. This analogy is sometimes explicitly invoked with reference to biological mechanisms. However, more often it is merely implicit in the use of the term "co-evolution," perhaps only suggesting that ideas are somehow alive, and that they influence each other as they change. The connection to biological processes, whether explicit or implicit, might be productive because analogies are useful tools for thought, for example when generating new research questions.

In this second part of the article, I explore the biological analogy further, as a basis for proposing expansions to the design co-evolution concept. First, I consider the general analogy that design ideas evolve like biological systems, before examining the more specific analogy that problems and solutions co-evolve in design. I recount this analogy as it was first introduced, examining the degree to which this has been taken up, and also promoting the analogy in a different form and with an example. This discussion is then extended with reference to contemporary discussions of biological co-evolution to establish the different kinds of co-evolution to which design activities might be compared. Finally, by considering and integrating the preceding discussions, some directions for future expansion of the design co-evolution concept are proposed. (In the first part of this article I recommend that the distinction between problems and solutions should, at least sometimes, be seen as relative. The proposals I make here are independent of that because further development is possible whether or not this recommendation is taken up.)

The Evolution of Ideas

Biological analogies in design have a long history, ranging from descriptions of how different generations of products evolve to descriptions of how ideas evolve during a design process.[2] Accounts of design co-evolution most often refer to the way ideas change within a session, meeting, or project, either for an individual designer or a group, so we can limit ourselves here to discussions of the evolution of ideas during design processes rather than across technological generations. This form of biological analogy is sometimes criticized because undirected processes of biological evolution are being compared to intentional processes in design.[3] However, just because there are limits to the similarities that analogies point to needn't prevent them from being useful. In fact, something like the opposite analogy has precedent in the work of Charles Darwin. The first chapter of his 1859 book On the Origin of Species focuses on "variation under domestication" in which he describes the intentional selections that breeders make to shape future

1 This is the second part of a two-part article. For Part I, see Nathan Crilly, "The Evolution of 'Co-evolution' (Part I): Problem Solving, Problem Finding, and Their Interaction in Design and Other Creative Practices," *She Ji: The Journal of Design, Economics, and Innovation* 7, no. 3 (2021): 309–32, DOI: https://doi.org/10.1016/j.sheji.2021.07.003.

2 George Basalla, *The Evolution of Technology* (Cambridge, UK: Cambridge University Press, 1988); Philip Steadman, *The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts* (Cambridge, UK: Cambridge University Press, 1979); W. Brian Arthur, *The Nature of Technology: What It Is and How It Evolves* (New York: Free Press, 2009).

3 Jennifer Whyte, "Evolutionary Theories and Design Practices," *Design Issues* 23, no. 2 (2007): 46, 53, DOI: https://doi.org/10.1162/desi.2007.23.2.46. In describing the debates and developments characteristic of biological evolution, Whyte notes the concept of gene-culture co-evolution (p. 51), but does not refer to design co-evolution.

generations of animals and plants.[4] From this, he develops the analogy that just as people intentionally use their selections to change the characteristics of a particular breed, nature could also select from and thus change a wild species.[5] In this sense, Darwin's theory of natural selection was founded on an explicit analogy with design even if intentionality is not present in the resulting theory.[6] An analogy can be a point of departure, and needn't define the destination.

The evolution of ideas is perhaps most prominently advocated by Donald Campbell's description of creative thought as a process of "blind variation and selective retention," a process that is similar to, although not identical to biological evolution.[7] In this psychological account, new ideas result from a series of naïve (but not random) variations which are then knowingly selected from by cognitive processes.[8] In his detailed review of Campbell's theory and its influence, Dean Simonton provides examples of self-report data from creative individuals whose personal accounts of creative work correspond to a psychological process of blind variation and selective retention.[9]

A more social account of ideas evolving is found in Richard Dawkins's concept of self-replicating ideas, or "memes," which are subject to the same processes of mutation, combination, and selection as genes are in biological processes.[10] This meme concept is applied to design by John Langrish, who says, "Ideas compete for resources, first within the head of an individual designer, then within an organization, and then in the selective world of purchasers and users."[11] According to Langrish, what evolves during design are ideas about problems, needs, and requirements (called "selectemes") and ideas about possibilities for solving or satisfying those (called "recipemes"). "These ideas *and their interactions* can be said to evolve … involving competition for resources to ensure their survival but … the 'rules' of the competition keep changing."[12]

The Co-evolution of Ideas

Campbell, Simonton, and Dawkins describe *ideas* evolving, and Langrish describes the *interactions* between ideas evolving, but they stop short of describing different ideas as "co-evolving." Raymond Yeh,[13] Kumiyo Nakakoji, and Gerhard Fischer[14] describe design ideas as co-evolving, but this is not with reference to any biological process. However, a biological analogy is explicit in the work of Mary Lou Maher and colleagues, who connect the development of creative design ideas with the biological process of co-evolution (see Part I).[15] This analogy is expressed in terms of genetics because that is their basis for applying computational genetic algorithms to design challenges.[16] In those early works, a biological phenotype (an individual animal's observable traits) is compared to a design solution, and the genotype is considered as the representation of information from which the phenotype is produced. Computational design creativity is then described in terms of reproduction, crossovers, selection, survival, and fitness. However, this approach is contrasted to that of conventional genetic algorithms, where the goal remains fixed: "The co-evolution of design genes (design space) and

4 Charles Darwin, *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*, rev. ed. (London: John Murray, 1859), 29–31.

5 Darwin, *Origin of Species*, 80–84. For analysis, see Mark A. Largent, "Darwin's Analogy between Artificial and Natural Selection in the *Origin of Species*," in *The Cambridge Companion to the* Origin of Species, ed. Michael Ruse and Robert J. Richards (Cambridge, UK: Cambridge University Press, 2008), 14, DOI: https://doi.org/10.1017/CCOL9780521870795.004; Also see T. Ryan Gregory, "Artificial Selection and Domestication: Modern Lessons from Darwin's Enduring Analogy," *Evolution: Education and Outreach* 2, no. 1 (2009): 5–27, DOI: https://doi.org/10.1007/s12052-008-0114-z; Bert Theunissen, "Darwin and His Pigeons. The Analogy between Artificial and Natural Selection Revisited," *Journal of the History of Biology* 45, no. 2 (2012): 179–212, DOI: https://doi.org/10.1007/s10739-011-9310-8.

6 In a statement invoking notions of design, Darwin quotes Lord Somerville speaking of what breeders have done in developing sheep: "It would seem as if they had chalked out upon a wall a form perfect in itself, and then given it existence." Darwin later says, "As man can produce and certainly has produced a great result by his methodical and unconscious means of selection, what may not nature effect?" Darwin, *Origin of Species*, 31, 83. For related discussions of design in evolution, see Stephen Jay Gould, "Darwin's Untimely Burial," in *Philosophy of Biology: An Anthology*, ed. Alex Rosenberg and Robert Arp (Chichester: John Wiley & Sons Ltd., 2009), 100; Also see Stephen Jay Gould, *The Panda's Thumb: More Reflections in Natural History* (New York: W. W. Norton & Company, Inc., 2010), 66.

7 Donald T. Campbell, "Blind Variation and Selective Retentions in Creative Thought as in Other Knowledge Processes," *Psychological Review* 67, no. 6 (1960): 380–400, DOI: https://doi.org/10.1037/h0040373. For criticisms of such "Universal Darwinism," see Maria Kronfeldner, *Darwinian Creativity and Memetics* (London: Routledge, 2014); Liane Gabora, "Creative Thought as a Non Darwinian Evolutionary Process," *The Journal of Creative Behavior* 39, no. 4 (2005): 262–83, DOI: https://doi.org/10.1002/j.2162-6057.2005.tb01261.x.

8 This account of creativity corresponds with the standard requirements for creative ideas (novelty and usefulness) as they map onto the two-step process (variation and selection). For definitions, see Mark A. Runco and Garrett J. Jaeger, "The Standard Definition of Creativity," *Creativity Research Journal* 24, no. 1 (2012): 92–96, DOI: https://doi.org/10.1080/10400419.2012.650092.

the fitness function (performance space) provides a model for design as exploration."[17] These spaces are later renamed "solution space" and "problem space," respectively.[18]

When Maher and Josiah Poon's design co-evolution diagram was later introduced (see Part I), "co-evolution" appeared in the titles of the works,[19] and co-evolutionary algorithms were cited as a foundation for the approach taken.[20] In those works, different computational approaches to design co-evolution are compared, and "emergence" is observed in the relationship between the problem space and the solution space.[21] Some further elaboration of the biological analogy is offered when it is explicitly stated that design co-evolution is like *mutualistic* co-evolution in nature, where the interacting populations raise each other's fitness, rather than the two populations existing in a competitive or parasitic relationship.[22]

Despite the care taken by Maher and colleagues to establish the analogy behind co-evolutionary accounts of design, biological processes are seldom explicitly referred to in the subsequent works on human design behavior. A rare exception is the closing paragraph of Kees Dorst and Nigel Cross's article, where they compare design creativity to the bursts of development in biological adaptation to a changing environment, but there is no reference to biological co-evolution.[23] For the rest, the most that is typically seen is some acknowledgment of the biological basis of Maher's work.[24] Otherwise there is little evidence in the design literature that the co-evolution of problems and solutions is being viewed through a biological lens.

Failure to adopt and develop the biological analogy is surprising because design researchers invoking co-evolutionary accounts generally do so to explain creativity, and that same research community promotes the role of analogies, especially biological analogies, in stimulating creativity in design.[25] Perhaps exploring the biological analogy implicit in co-evolutionary accounts might similarly stimulate creativity in design research, which would satisfy calls for creativity researchers and design researchers to apply their research findings to their own work.[26] Other social science disciplines invoking the concept of co-evolution have evidently adopted the biological analogy to develop their ideas, resulting in a rich set of related concepts.[27] For design researchers to not exploit this analogy cuts them off from this other work, just as describing design as a process of co-evolution has cut the field off from other work that uses different language to describe similar creative processes (see Part I).

Explanation and Discovery

One reason that the biological analogy might not have been widely adopted is that it was initially described from a genetic perspective. Whilst this is an obvious approach to adopt if genetic algorithms are being proposed, it might not be the most helpful foundation from which to describe human design activities. The process of evolution by natural selection is counter-intuitive to many people,[28] even more so when genetic explanations are required.[29] Perhaps because of this, most beginners' guides to biological co-evolution are careful to introduce the subject from an ecological rather than a genetic

9 Dean Keith Simonton, "Creativity as Blind Variation and Selective Retention: Is the Creative Process Darwinian?," *Psychological Inquiry* 10, no. 4 (1999): 309–28, available at https://www.jstor.org/stable/1449455. Although, also see criticisms and counter-examples from Subrata Dasgupta, "Contesting (Simonton's) Blind Variation, Selective Retention Theory of Creativity," *Creativity Research Journal* 23, no. 2 (2011): 166–82, DOI: https://doi.org/10.1080/10400419.2011.571190; Howard Gardner, "Was Darwin's Creativity Darwinian?," *Psychological Inquiry* 10, no. 4 (1999): 338–40, available at https://www.jstor.org/stable/1449458.

10 Richard Dawkins, *The Selfish Gene* (Oxford: Oxford University Press, 1976), 189–201.

11 John Z. Langrish, "Darwinian Design: The Memetic Evolution of Design Ideas," *Design Issues* 20, no. 4 (2004): 12, DOI: https://doi.org/10.1162/0747936042311968.

12 Emphasis added. Langrish, "Darwinian Design," 18–19. Langrish also refers to ideas about what justifies selection (called "explanemes").

13 Raymond T. Yeh, "System Development as a Wicked Problem," *International Journal of Software Engineering and Knowledge Engineering* 01, no. 02 (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.

14 Kumiyo Nakakoji and Gerhard Fischer, "CATALOG EXPLORER: Exploiting the Synergy of Integrated Design Environments," in *Proceedings of Software Symposium '90* (Kyoto, 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. J.S. Gero (London: Butterworth-Heinemann, 1991), 191–209, DOI: 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.

perspective, even if they later include genetic explanations.[30] I propose that the ecological perspective is also useful for re-introducing and extending the analogy between biological co-evolution and design co-evolution.[31] However, before elaborating an ecological perspective on co-evolution it is important to review the different mechanisms by which analogies function, so that the analogy inherent in co-evolutionary accounts can be approached in the most useful way.

Analogies typically serve one of two functions: explanation or discovery.[32] When explanatory analogies are used, they most often compare something to be understood with something that is already understood.[33] For example, if physics students are learning about electrical circuits then they might be told to think of such circuits as though they have water flowing around them. The students’ prior knowledge of things like pumps and pipes can then be used to reason about things like batteries and wires. In this example, the water system is the analogical “source” which helps the student understand the electrical circuit, the analogical “target.”[34] However, in the co-evolution analogy, it is not clear that biological processes (especially on a genetic account) are a productive analogical source for explaining design. People trying to understand human behavior might be expected to know more about thought processes than about evolutionary processes, and so the unfamiliar source is being used to explain the more familiar target. Clearly, there is a reason why electrical circuits are explained with reference to the flow of water, but the flow of water is not explained with reference to electrical circuits.

In addition to their explanatory function, analogies can also be used for discovery. By comparing a well-elaborated source to a relatively unelaborated target, we can engage in exploratory processes that allow us to see the target in new ways and look for things that we hadn’t previously considered. This discovery function of analogies is widely reported in the practice of science and other research disciplines,[35] and also in the practice of design and invention.[36] Put another way, we can see new things in old places when we view them as though they are something else, or like something else in certain respects. In this sense, analogies are metacognitive tools for creative work (including research), tools which are useful because of how they guide further questioning.[37] Even if the biological source is not the most intuitive basis from which to understand design behavior, it is very well elaborated. Therefore, it might still be a productive basis from which to explore that behavior, and for constructing new representations of the phenomena of interest, or questions about them.

Despite their potentially useful role in explanation and discovery, the application of analogies also requires caution because there are limits to the relational similarities that can be identified between the source and the target. Analogical thinking can tend to overemphasize these similarities, and de-emphasize the differences, including those differences that truly characterize the phenomenon of interest.[38] With respect to design, Jennifer Whyte observes that analogies to evolutionary processes have often been constructed without adequately acknowledging such differences,[39] and Langrish observes that they are also sometimes founded on

15 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; 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; 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.

16 Genetic algorithms are a computer science approach to optimization and search problems, which simulate evolutionary processes, including the combination, mutation, and selection of information. For example, see John H. Holland, “Outline for a Logical Theory of Adaptive Systems,” *Journal of the ACM* 9, no. 3 (1962): 297–314, DOI: https://doi.org/10.1145/321127.321128.

17 Maher, “Genetic Algorithm,” 2019.

18 For example, in Maher and Poon, “Modeling Design Exploration,” 196.

19 Ibid., 195–209; 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), 3–30, DOI: https://doi.org/10.1007/978-0-387-34925-1_1.

20 For example, with reference to the work of John R. Koza, *Genetic Programming: On the Programming of Computers by Means of Natural Selection* (Cambridge, MA: MIT Press, 1992), 431.

21 Josiah Poon and Mary Lou Maher, “Co-evolution and Emergence in Design,” *Artificial Intelligence in Engineering* 11, no. 3 (1997): 319–27, DOI: https://doi.org/10.1016/S0954-1810(96)00047-7.

22 Mary Lou Maher and Peter Xianghua Wu, “Reconsidering Fitness and Convergence in Co-evolutionary Design,” in *Advanced Topics in Artificial Intelligence*, ed. Norman Foo (Berlin: Springer, 1999), 488, DOI: https://doi.org/10.1007/3-540-46695-9_50. Also see earlier related distinctions in the 1996 and 1997 works with Poon.

23 Kees Dorst and Nigel Cross, “Creativity in the Design Process: Co-evolution of Problem-Solution,” *Design Studies* 22, no. 5 (2001): 437, DOI: https://doi.org/10.1016/S0142-694X(01)00009-6.

a misunderstanding of the relevant biology.[40] Because of this, it is worth acknowledging that interrogation of the structural similarities between processes of change in design and biology can raise a number of questions about the validity of drawing analogies between them. Can theories of biological evolution describe both gradual and sudden change, consistent with observations of design progress?[41] Can such theories describe both how designers modify existing forms and also produce entirely new forms?[42] Can design ideas be thought to exist in "populations" that exhibit variation, from which selections are made?[43] Are processes of intentional selection and modification in design comparable to biological evolution?[44] Can the time-bound aspects of design projects be modelled on the seemingly unending processes of biological change?[45]

How questions like those above are answered depends on the aspects of biology and design that we attend to, and the degree of similarity we require between them. In some instances, the sudden, radical, singular, intentional, and final nature of design ideas might make the biological analogy seem misplaced, unhelpful, or counterproductive. In such instances, there are other perspectives to adopt, and analogical thinking shouldn't constrain opportunities to view design phenomena for what they are, rather than through the lens of something they are not.[46] However, even if such questions are answered negatively—and I hope the preceding notes indicate that this need not always be the case—the analogy between design developments and biological evolution is already being invoked, either explicitly or implicitly for design ideation in general, and for problem-solution co-evolution in particular.[47] Exploring the potential implications of the analogy is therefore valuable for understanding previous and ongoing discourse, and for shaping future research possibilities. Ultimately, even imperfect analogical reasoning can inspire questions and hypotheses that might then be addressed and tested through inquiries that do not depend on the analogy.

Evolution and Co-evolution

In biology, descriptions of evolution by natural selection refer to a process by which the characteristics of populations change over time. A population is composed of individuals who exhibit different traits, with some traits better suited to the environment than others. This results in a selective pressure on the population: individuals with advantageous traits survive and reproduce more than those with disadvantageous traits. The next generation will consequently inherit more of the advantageous traits, along with new mutations.[48] For example, a population of moths may include some individuals with traits that are better suited to the surrounding air temperature or humidity. Those environmental characteristics may change over time—rising temperatures, or falling humidity, for example—which changes the selective pressure that is exerted on the population of moths and therefore the traits that are exhibited by the next generation. While the moth population evolves with the changing environment, that environment does not evolve with the moths (at least for abiotic components of the environment, such as the atmospheric conditions considered here).[49]

24 For example, see Stefan Wiltschnig, Bo T. Christensen, and Linden J. Ball, "Collaborative Problem-Solution Co-evolution in Creative Design," *Design Studies* 34, no. 5 (2013): 516, DOI: https://doi.org/10.1016/j.destud.2013.01.002; David C. Wynn and P. John Clarkson, "Process Models in Design and Development," *Research in Engineering Design* 29, no. 2 (2018): 171, DOI: https://doi.org/10.1007/s00163-017-0262-7.

25 For example, see Jon-Michael Deldin and Megan Schuknecht, "The AskNature Database: Enabling Solutions in Biomimetic Design," in *Biologically Inspired Design: Computational Methods and Tools*, ed. Ashok K. Goel, Daniel A. McAdams, and Robert B. Stone (London: Springer-Verlag, 2013), 17–27, DOI: https://doi.org/10.1007/978-1-4471-5248-4_2; Julie S. Linsey, Arthur B. Markman, and Kristin L. Wood, "Design by Analogy: A Study of the Wordtree Method for Problem Re-representation," *Journal of Mechanical Design* 134, no. 4 (2012): 041009, DOI: https://doi.org/10.1115/1.4006145; Gülşen Töre Yargin and Nathan Crilly, "Information and Interaction Requirements for Software Tools Supporting Analogical Design," *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing* 29, no. 2 (2015): 203–14, DOI: https://doi.org/10.1017/S0890060415000074; Swaroop S. Vattam, Michael E. Helms, and Ashok K. Goel, "A Content Account of Creative Analogies in Biologically Inspired Design," *AI EDAM* 24, no. 4 (2010): 467–81, DOI: https://doi.org/10.1017/S089006041000034X.

26 Mark A. Runco, "Meta-creativity: Being Creative about Creativity," *Creativity Research Journal* 27, no. 3 (2015): 295–98, DOI: https://doi.org/10.1080/10400419.2015.1065134; Yoram Reich, "The Principle of Reflexive Practice," *Design Science* 3 (May 2017): e4, DOI: https://doi.org/10.1017/dsj.2017.3.

27 For a review, see Eve Mitleton-Kelly and Laura K. Davy, "The Concept of 'Co-evolution' and Its Application in the Social Sciences: A Review of the Literature," in *Co-evolution of Intelligent Socio-technical Systems: Modelling and Applications in Large Scale Emergency and Transport Domains*, ed. Eve Mitleton-Kelly (Berlin: Springer, 2013), 43–57, DOI: https://doi.org/10.1007/978-3-642-36614-7_3.

28 Ross H. Nehm, Sun Young Kim, and Keith Sheppard, "Academic Preparation in Biology and Advocacy for Teaching Evolution: Biology versus Non-biology Teachers," *Science Education* 93, no. 6 (2009): 1122–46, DOI: https://doi.org/10.1002/sce.20340; Amy Spiegel et al., "Museum Visitors' Understanding of Evolution," *Museums & Social Issues* 1, no. 1 (2006): 69–86, DOI: https://doi.org/10.1179/msi.2006.1.1.69.

In contrast to simple evolutionary accounts, descriptions of co-evolution emphasize that something in the population’s environment is evolving too, and does so in response to that populations’ evolution. Continuing our example of the moths, their environment may include orchids, which provide the moths with nectar, a high-energy food source. Conversely, the orchid’s environment includes the moths, which transport pollen between the flowers as they feed, supporting the plants’ reproduction. The moths experience a changing selective pressure from their environment, including the orchids; the orchids experience a changing selective pressure from their environment, including the moths. The moths and orchids are said to co-evolve because the evolution of each species is influenced by the evolution of the other.[50]

Under certain analyses, much of evolution involves co-evolution, because most species evolve in environments that include reciprocally evolving species with which they interact, such as predators, prey, hosts, and parasites.[51] In such co-evolutionary accounts, because the reciprocal evolution of two or more populations is being considered, the sharp distinction between a population and its environment is replaced with the view that populations interact within ecosystems.

Moths and Orchids

Although there have been many accounts of design co-evolution, the biological analogy has seemingly never been illustrated with an example such as the one outlined above. As a result, the analogy has remained abstract when it has not remained entirely implicit. However, to promote analogical reasoning it is valuable to develop an example of biological co-evolution to which design co-evolution can be compared. Here, I elaborate the moth-orchid example with specific species: Darwin’s hawkmoth and the Malagasy star orchid. The benefit of this is that it is a well-documented example of the kind of mutualistic co-evolution that Maher referred to, and it is a rare instance of biological co-evolution being illustrated in a form that bears some resemblance to design co-evolution diagrams.

Although he didn’t use the term, the theory of co-evolution is often credited to Darwin, especially for ideas in his 1862 book, *On the Various Contrivances by Which British and Foreign Orchids are Fertilised by Insects*,[52] and for related ideas he advanced three years earlier in the *Origin*.[53] While working on *Contrivances*, Darwin was sent a collection of orchid specimens, including *Angraecum sesquipedale*, a native of Madagascar with an especially long nectary, or spur: a thin vessel that hangs down from the orchid containing nectar at the bottom. Darwin predicted that the same geographical region must be home to a species of moth with a similarly long proboscis, or tongue.[54] This was based on his reasoning that deeply held nectar would advantage the orchid in drawing the moth into the flower for pollination, while a long proboscis would advantage the moth in accessing all of the available nectar. The result would be an evolutionary “race” in the length of the nectary and proboscis, and the survival of each species would be influenced by the other (see Figure 1).[55] Four decades after Darwin’s receipt of

29 Chi-Yan Tsui and David Treagust, “Evaluating Secondary Students’ Scientific Reasoning in Genetics Using a Two-Tier Diagnostic Instrument,” *International Journal of Science Education* 32, no. 8 (2010): 1073–98, DOI: https://doi.org/10.1080/09500690902951429.

30 For example, see Steven D. Johnson and Bruce Anderson, “Coevolution between Food-Rewarding Flowers and Their Pollinators,” *Evolution: Education and Outreach* 3, no. 1 (2010): 32–39, DOI: https://doi.org/10.1007/s12052-009-0192-6; Randall B. Langerhans, “Coevolution,” in *Encyclopedia of Ecology*, vol. 3, 2nd ed., ed. Brian Fath (Oxford: Elsevier, 2008), 32–36, DOI: https://doi.org/10.1016/B978-0-444-63768-0.00471-6.

31 This is an elaboration of the “ecology” mentioned but not explored in Maher and Wu, “Reconsidering Fitness,” 488–89.

32 Keith J. Holyoak and Paul Thagard, *Mental Leaps: Analogy in Creative Thought* (Cambridge, MA: MIT Press, 1995); Stella Vosniadou and Andrew Ortony, eds., *Similarity and Analogical Reasoning* (Cambridge, UK: Cambridge University Press, 1989).

33 Marie K. Iding, “How Analogies Foster Learning from Science Texts,” *Instructional Science* 25, no. 4 (1997): 233–53, DOI: https://doi.org/10.1023/A:1002987126719; Philip N. Johnson-Laird, “Analogy and the Exercise of Creativity,” in *Similarity and Analogical Reasoning*, ed. Stella Vosniadou and Andrew Ortony (Cambridge, UK: Cambridge University Press, 1989), 313–31.

34 Paul Bartha, s. v. “Analogy and Analogical Reasoning,” in *Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, last modified January 25, 2019, https://plato.stanford.edu/archives/spr2019/entries/reasoning-analogy/; Dedre Gentner and Francisco Maravilla, “Analogical Reasoning,” in *International Handbook of Thinking and Reasoning*, ed. Linden. J. Ball and Valerie. A. Thompson (Abingdon: Routledge, 2018), 186–203.

35 Kevin Niall Dunbar, “How Scientists Think: On-Line Creativity and Conceptual Change in Science,” in *Conceptual Structures and Processes*, ed. Thomas B. Ward, Steven M. Smith, and Jyotsna Vaid (Washington, DC: American Psychological Association, 1997), 461–93; Kevin Dunbar, “The Analogical Paradox: Why Analogy Is so Easy in Naturalistic Settings yet so Difficult in the Psychological Laboratory,” in *The Analogical Mind: Perspectives from Cognitive Science*, ed. Dedre Gentner, Keith James Holyoak, and Boicho N. Kokinov (Cambridge, MA: MIT Press, 2001), 313–34; Thomas S. Kuhn, “Metaphor in Science,” in *Metaphor and Thought*, 2nd ed., ed. Andrew Ortony (Cambridge, UK: Cambridge University Press, 1993), 533–42, DOI: https://doi.org/10.1017/CBO9781139173865.024.

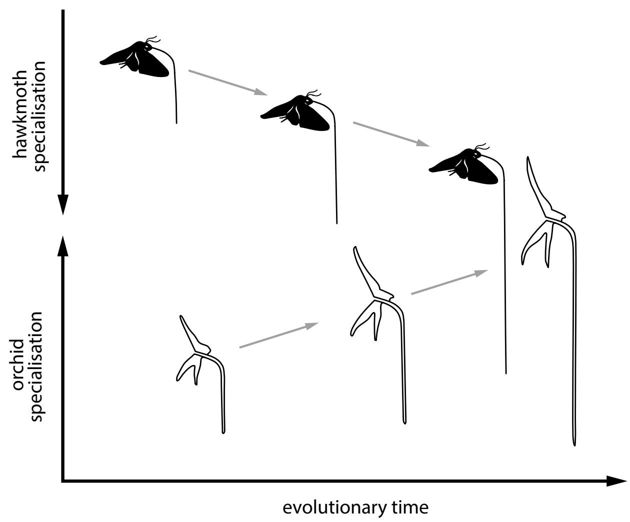

Figure 1
Graphical representation of the co-evolution of Darwin's Hawkmoth and the Malagasy star orchid, adapted from original illustrations by Lutz Wasserthal. See Lutz Thilo Wasserthal, "The Pollinators of the Malagasy Star Orchids *Angraecum sesquipedale, A. sororium* and *A. compactum* and the Evolution of Extremely Long Spurs by Pollinator Shift," *Botanica Acta* 110, no. 5 (1997): p. 347, Figure 4; p. 357, Figure 12. In Wasserthal's article, this representation of a co-evolutionary "race" is compared to the competing model of "pollinator shift." © 2021 Nathan Crilly.

the orchid specimen, a hawkmoth species was identified in Madagascar that had a suitably long proboscis: *Xanthopan morganii praedicta,* the last part of the name recognizing its long-standing prediction.[56] A further nine decades later, in the early 1990s, it was confirmed that this moth species pollinates the orchid *A. sesquipedale*.[57]

For Darwin's hawkmoth and the Malagasy star orchid, the similar length of the proboscis and nectary is typically explained in co-evolutionary terms,[58] although now with additional complications.[59] On this account, each species is part of the other's changing environment, with each exerting selective pressure on the other. By analogy, describing problems and solutions as co-evolving is to suggest that problems are to solutions as moths are to orchids (problems : solutions :: moths : orchids).[60] Problems and solutions each form an environment for the other, exerting reciprocal selective pressures. A new interpretation of the problem changes the environment in which existing solution ideas can survive or thrive, or into which new solution ideas emerge. The opposite is also true, and generally treated as more interesting: a new idea for a solution changes the environment in which existing interpretations of the problem must fit, or into which new problem interpretations are developed. As with the moths and orchids, this reciprocal selective pressure can lead the problems and solutions to converge on mutually compatible features.[61]

Even as a loose description, the notion of problems and solutions exerting reciprocal selective pressure on each other is "stricter" than the notion of reciprocal influence, which has long been explained without invoking co-evolutionary accounts (see Part I). To develop the analogy further, let's look beyond our simple example of mutualistic co-evolution between species and consider the different kinds of co-evolution that are discussed in contemporary studies of evolutionary biology.

36 Linden J. Ball, Thomas C. Ormerod, and Nicola J. Morley, "Spontaneous Analogising in Engineering Design: A Comparative Analysis of Experts and Novices," *Design Studies* 25, no. 5 (2004): 495–508, DOI: https://doi.org/10.1016/j.destud.2004.05.004; Bo T. Christensen and Christian D. Schunn, "The Relationship of Analogical Distance to Analogical Function and Preinventive Structure: The Case of Engineering Design," *Memory & Cognition* 35, no. 1 (2007): 29–38, DOI: https://doi.org/10.3758/BF03195939; Donald A. Schön, "Generative Metaphor: A Perspective on Problem-Setting in Social Policy," in *Metaphor and Thought*, 2nd ed., ed. Andrew Ortony (Cambridge, UK: Cambridge University Press, 1993), 137–63, DOI: https://doi.org/10.1017/CBO9781139173865.011.
37 Johnson-Laird, "Analogy and the Exercise of Creativity."
38 Summer Johnson and Ingrid Burger, "Limitations and Justifications for Analogical Reasoning," *The American Journal of Bioethics* 6, no. 6 (2006): 59–61, DOI: https://doi.org/10.1080/15265160600939011.
39 Whyte, "Evolutionary Theories and Design Practices," 46–54. See note 3.
40 Langrish, "Darwinian Design," 4–19.
41 For a discussion of how accounts of continuous gradual biological evolution are complemented by accounts of stasis interrupted by sudden change, see Stephan Jay Gould and Niles Eldredge, "Punctuated Equilibrium Comes of Age," *Nature* 366, no. 6452 (1993): 223–27, DOI: https://doi.org/10.1038/366223a0.

For further discussion, see Stephen Jay Gould, *Punctuated Equilibrium* (Cambridge, MA: Harvard University Press, 2009), e.g. 184.

42 For a discussion of different perspectives on "innovation," "novelty," and "emergence" in biological evolution (including large, sudden and unexpected steps), see Matthew H. Nitecki, "The Plurality of Evolutionary Innovations," in *Evolutionary Innovations*, ed. Matthew H. Nitecki (Chicago: University of Chicago Press, 1990), 3–18.

43 For a discussion of how the ideas of individuals and groups can be thought of as simultaneously constituting populations subject to evolutionary processes, see Robin Nicole, Peter Sollich, and Tobias Galla, "Stochastic Evolution in Populations of Ideas," *Scientific Reports* 7, no. 1 (2017): 1–2, DOI: https://doi.org/10.1038/srep40580.

44 See notes 4 and 5. For a discussion of how designers might intentionally guide biological evolution to realize new functions, see Frances H. Arnold, "Design by Directed Evolution," *Accounts of Chemical Research* 31, no. 3 (1998): 125–31, DOI: https://doi.org/10.1021/ar960017f. For a separate discussion of the potential for biological evolution to be influenced by the intentions of the evolving entities, see Atsushi Iriki and Osamu Sakura, "The Neuroscience of Primate Intellectual Evolution: Natural Selection and Passive and Intentional Niche Construction," *Philosophical Transactions of the Royal Society B: Biological Sciences* 363, no. 1500 (2008): 2235–37, DOI: https://doi.org/10.1098/rstb.2008.2274.

45 For the idea that evolutionary stasis is the normal outcome of evolutionary change, see Gould, *Punctuated Equilibrium*. The issue of "termination conditions" in design co-evolution was discussed by Maher in 1994: Maher, "Genetic Algorithm," 2020.

46 Although, for the argument that some form of analogy is unavoidable, see Douglas R. Hofstadter, "Analogy as the Core of Cognition," in *The Analogical Mind: Perspectives from Cognitive Science*, ed. Dedre Gentner, Keith J. Holyoak, and Boicho N. Kokinov (Cambridge, MA: MIT Press, 2001), 499–538.

47 Note that Maher describes the connection as "very loose and metaphorical." Maher, "Genetic Algorithm," 2014.

48 For a brief introduction, see Kent E. Holsinger, s. v. "Natural Selection," in *Encyclopedia of Ecology*, vol. 3, 2nd ed., ed. Brian Fath (Oxford: Elsevier, 2008), 165–71, DOI: https://doi.org/10.1016/B978-0-444-63768-0.01020-9.

Kinds of Co-evolution

Despite earlier relevant work by Darwin and others,[62] the origin of the term "co-evolution" and the popularization of the concept is generally credited to Paul Ehrlich and Peter Raven for their 1964 article titled "Butterflies and Plants: A Study in Coevolution." Their concern was for understanding "community evolution" in response to what they saw as scientists assuming that one species evolves while the surrounding species could be treated as constant.[63] Since then, studies of co-evolutionary processes have become widespread in the biological and ecological sciences, with co-evolution sometimes being presented as the foundation for all species-rich ecosystems.[64] The biological sciences now describe a number of different kinds of co-evolution and the different levels at which co-evolution operates.

Many descriptions of biological co-evolution only refer to a pair of co-evolving species, such as Ehrlich and Raven's specific species of butterflies and plants, or in many discussions of Darwin's hawkmoth and the Malagasy star orchid. However, this restriction to just two species is a simplification of a more complicated situation. More generally, co-evolution describes the reciprocal influence that two *or more* entities have on each other's evolutionary path.[65] As stated above, Ehrlich and Raven were concerned with understanding *community* evolution; they saw examining co-evolution between a pair of species as just one approach to that.[66] Even the example of Darwin's hawkmoth and the Malagasy star orchid is now described with additional reference to the spiders that prey on the moths: "It is necessary to describe a tripartite co-evolution between orchids, their pollinators, and predators which prey on the latter."[67] More generally, biologists and ecologists study the co-evolution of multiple species within a community or ecosystem. This is called "diffuse" co-evolution, as compared to "pairwise" co-evolution.[68] Diffuse co-evolution is of increasing interest as biologists and ecologists examine the relationships and developments that are exhibited in multi-species interactions.[69] In such circumstances, several species in a community may, *as a group*, exert a selective pressure on another species with which they interact.[70]

In addition to distinguishing between pairwise and diffuse co-evolution, distinctions can also be made between different types of co-evolutionary relationships. For example, the account of moth-orchid-spider co-evolution refers to a combination of mutualistic and predatory relationships. Five forms of interaction between species are generally described: antagonism (both members of the interaction are harmed), parasitism (one member benefits while the other is harmed), amensalism (one member is harmed while the other member is neither positively nor negatively affected), commensalism (one member benefits while the other member is neither positively nor negatively affected), and mutualism (both members benefit).[71] Mutualism can also be further divided into "converging" and "complementary" forms, where species either specialize to each other and become mutually dependent (as with the simplified example of the hawkmoth and star orchid), or where they remain capable of interacting with a wider range of species.[72] Whatever relationships and interactions are observed between species at a point in time, these need not remain stable, as reciprocal selective pressures can emerge and disappear, and relationships can change, for example from mutualistic to antagonistic.[73] An additional distinction is between "symmetrical" and "non-symmetrical" co-evolutionary pressures: just because co-evolution involves reciprocal influence does not mean that the influence is symmetrically powerful, even if such symmetry has often been assumed.[74]

The discussion above considers "inter-specific" co-evolution, where the entities that are co-evolving are separate species, such as particular species of moths and orchids. Many definitions of co-evolution refer to the process in these terms, with "species" being presented as the relevant unit of analysis.[75] However, biological co-evolution has more recently been re-defined with reference to the more abstract "entities" that co-evolve, whether those are nucleotides, amino acids, proteins, organisms, or ecosystems.[76] Each of these entities operates at a different scale, and some are contained within others. This provides for multi-level representations of co-evolution in which there is co-evolution *between* species (whether based on predation, parasitism, competition, or mutualism), and co-evolution *within* species (whether at a molecular or genomic level).[77] The overall structure of co-evolution between moths and orchids can also be seen within each of them, and between the different ecosystems that they and other species live in.

Conceptual Expansion

In the preceding sections I have examined the basis of the biological analogy on which discussions of design co-evolution are at least implicitly founded, and on which they might be extended. Reflecting on this, I now ask two questions about design co-evolution as a way to propose future expansions of the concept: (i) *what co-evolves during design?* and (ii) *at what levels does co-evolution occur?* In addressing these questions and exploring their implications, my objective is to make the co-evolution concept more flexible in accounting for the variety of design behaviors that researchers might want to investigate and explain. For that it is important to consider the way in which those researchers have already used co-evolution accounts and how they might use them in future.

From reviewing the history of design co-evolution concepts and reflecting on their uptake and development (see Part I), I believe that much of the appeal and influence of co-evolution can be explained by its ambiguous or open nature.[78] The terminology surrounding design co-evolution often paints an impressionistic rather than precise image of the mutual influence of developing ideas, and the diagrams permit various interpretations of what the ellipses and arrows represent. The creative benefits of these open representations are well known in studies of design,[79] and they are an important feature of research.[80] As such, I do not attempt here to close down interpretations of design co-evolution, but instead to open them further, pointing to some directions in which the concept could be expanded, or by which existing expansions could be consolidated. Future work could usefully formalize these expansions, developing strict definitions and notations, offering prescriptions for revised diagram sets, outlining the most pressing

49 More complex accounts recognize that species do clearly modify their environment (both its biotic and abiotic components), which influences the selective pressure that that environment exerts on those species and others. John Odling-Smee et al., "Niche Construction Theory: A Practical Guide for Ecologists," *The Quarterly Review of Biology* 88, no. 1 (2013): 3–28, DOI: https://doi.org/10.1086/669266.

50 For a brief introduction, see Langerhans, "Coevolution."

51 John N. Thompson, "Four Central Points about Coevolution," *Evolution: Education and Outreach* 3, no. 1 (2010): 7–13, DOI: https://doi.org/10.1007/s12052-009-0200-x. However, also see Daniel H. Janzen, "When Is It Coevolution?," *Evolution* 34, no. 3 (1980): 611–12, DOI: https://doi.org/10.1111/j.1558-5646.1980.tb04849.x; Mark Sagoff, "When Is It Co-evolution? A Reply to Steen and Co-authors," *Biology & Philosophy* 34, no. 1 (2019): article no. 10, DOI: https://doi.org/10.1007/s10539-018-9656-9.

52 Charles Darwin, *The Various Contrivances by Which Orchids Are Fertilised by Insects, and on the Effect of Good Intercrossing* (London: John Murray, 1862). For theory attribution, see Gene Kritsky, "Entomological Reactions to Darwin's Theory in the Nineteenth Century," *Annual Review of Entomology* 53, no. 1 (2008): 345–60, DOI: https://doi.org/10.1146/annurev.ento.53.103106.093436; Justen B. Whittall and Scott A. Hodges, "Pollinator Shifts Drive Increasingly Long Nectar Spurs in Columbine Flowers," *Nature* 447, no. 7145 (2007): 706–9, DOI: https://doi.org/10.1038/nature05857.

53 Darwin, *Origin of Species*, 94–95. For theory attribution, see Anton Pauw, Jaco Stofberg, and Richard J. Waterman, "Flies and Flowers in Darwin's Race," *Evolution* 63, no. 1 (2009): 268, DOI: https://doi.org/10.1111/j.1558-5646.2008.00547.x; Anna-Liisa Laine, "Role of Coevolution in Generating Biological Diversity: Spatially Divergent Selection Trajectories," *Journal of Experimental Botany* 60, no. 11 (2009): 2957, DOI: https://doi.org/10.1093/jxb/erp168.

54 Darwin, *Various Contrivances*, 197–203.

55 Lutz Thilo Wasserthal, "The Pollinators of the Malagasy Star Orchids *Angraecum sesquipedale*, *A. sororium* and *A. compactum* and the Evolution of Extremely Long Spurs by Pollinator Shift," *Botanica Acta* 110, no. 5 (1997): 347, 357, DOI: https://doi.org/10.1111/j.1438-8677.1997.tb00650.x. In this image, Wasserthal's figure has been rotated clockwise to allow time to run horizontally (for easier comparison with the design co-evolution diagrams) and

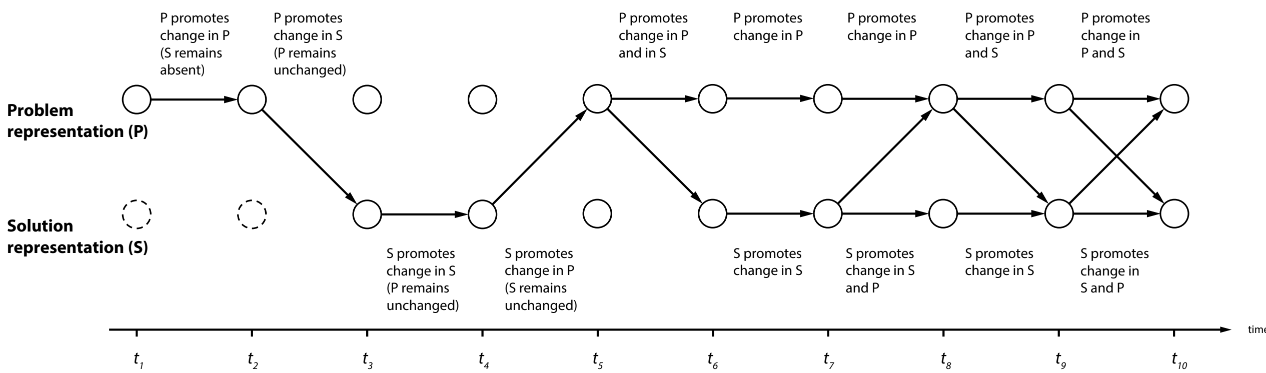

Figure 2
Illustration of a process of problem-solution co-evolution extended over ten time points. The four standard transitions are indicated between t_1 and t_5, after which, combinations of these are indicated. © 2021 Nathan Crilly.

research questions, and describing the methods and data that would be required to answer them. However, I leave this for other researchers and to community efforts, focusing here on some broad areas into which such efforts might be directed.

To illustrate possible expansions to the design co-evolution account, I first introduce a basic co-evolution diagram from which I will derive variants. Maher and Poon’s diagram neatly represented all possible transitions between problems and solutions (P-P, S-S, P-S, S-P) overlaid on top of each other with just two time points (see Part I).[81] However, this leaves implicit the possibility of parallel transitions. I take a different approach here, sketching out a less formal illustration of a series of changes (see Figure 2). As in the standard design co-evolution diagrams, time proceeds from left to right, but problem and solution pairs can be considered at the same point in time, and so are vertically aligned.[82] The same four transitions are possible, but so too is the parallel development of problems and solutions (P-P *with* S-S). Parallel “outgoing” influences are also possible (P-PS, S-SP, represented with diverging arrows), as are parallel “incoming” influences (SP-P, PS-S, represented with converging arrows). This is simply because something might influence more than one thing, and might be influenced by more than one thing.[83] Throughout a co-evolutionary process, the “fit” or “match” between problems and solutions might be assessed at any point through comparison of what the current problem representation demands and what the current solution representation promises.

What Co-evolves During Design?

Definitions of biological co-evolution typically describe the reciprocal interaction of two *or more* entities (such as species), and this is the kind of definition that Maher refers to.[84] However, just as the early discussions of biological co-evolution only considered the pairwise co-evolution of two species,[85] discussions of design co-evolution have mostly focused on the pair-wise co-evolution of problems and solutions. There are a few exceptions though, where another type of thing is also introduced. For example, there are descriptions of the co-evolution of problem, solution, *and audience*;[86] the co-evolution of problem, solution, *and knowledge*;[87] and the co-evolution of context, design space, and artifact.[88] Reporting on a set industrial case studies, Roxana Moroşanu Firth and Nathan Crilly more generally promote

species specialization has been changed from a unidirectional to a bidirectional axis (similar to the convergence of problems and solutions indicated by Rosa Storm, Jeffrey van Maanen, and Milene Gonçalves). See 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, https://doi.org/10.1017/dsi.2019.39.

56 It is possible that this was in recognition of Arthur Russell Wallace’s development and promotion of Darwin’s prediction.

57 For a detailed historical account, see Joseph Arditti et al., “‘Good Heavens What Insect Can Suck It’ — Charles Darwin, *Angraecum Sesquipedale* and *Xanthopan Morganii Praedicta*,” *Botanical Journal of the Linnean Society* 169, no. 3 (2012): 403–32, DOI: https://doi.org/10.1111/j.1095-8339.2012.01250.x.

58 For example, see Steven D. Johnson et al., “The Long and the Short of It: A Global Analysis of Hawkmoth Pollination Niches and Interaction Networks,” *Functional Ecology* 31, no. 1 (2017): 101–15, DOI: https://doi.org/10.1111/1365-2435.12753; Miguel A. Rodríguez-Gironés and Ana L. Llandres, “Resource Competition Triggers the Co-evolution of Long Tongues and Deep Corolla Tubes,” *PLOS ONE* 3, no. 8 (2008): e2992, DOI: https://doi.org/10.1371/journal.pone.0002992.

the idea of an ecology of co-evolving ideas, including ideas about problems and solutions, but also ideas about design processes, users, and application domains.[89] If design is modeled as a process of searching interacting spaces, it need not just be a two-space search,[90] three-space search,[91] or four-space search,[92] but might more generally be a multi-space search.[93]

Moving beyond the default position of pair-wise co-evolution to consider diffuse co-evolution would encourage a richer view of the various kinds of thing that co-evolve during a design process.[94] Taking this broader view of what co-evolves would mean that the elements of existing typologies could be viewed from a co-evolutionary perspective. For example, we could talk about the co-evolution of design concepts and design knowledge, as described in "C-K" theory.[95] In fact, Armand Hatchuel and Benoit Weil do say that design is defined as "the co-evolution of C and K through four types of interdependent operators (C-C, C-K, K-C, K-K),"[96] which echoes the four transitions that are commonly derived from Maher and Poon's diagram. However, these descriptions of iterative transitions between knowledge and concepts are not connected to any of the design co-evolution literature, and C-K theory and co-evolution theory remain separate today.

Alternatively, instead of talking about the co-evolution of problems and solutions, or concepts and knowledge, we could talk about the co-evolution of functions, behaviors, and structures (or states), as in "FBS" ontologies.[97] This would unite two of the most influential concepts in design research.[98] In fact, considering design co-evolution in relation to function, behavior, and structure has a long history. Maher and Poon equate the problem space with "functional requirements,"[99] while also equating it with "expected behavior," and the solution space with "structure."[100] Elsewhere, Hatchuel and Weil use the term "co-evolution"[101] to refer to Dan Braha and Yoram Reich's model[102] of design as a dynamic mapping between a function space and a structural space—although again without connection to the design co-evolution literature. Similarly, Frido Smulders, Isabelle Reyman, and Kees Dorst equate problems with functions and solutions with structures (with reference to John Gero's FBS ontology), but additionally include an intermediary layer for the "use" of the artifact, which they equate with Gero's concept of behavior.[103] They don't go so far as describing the tripartite co-evolution of function, behavior, and structure, but this would be an obvious description to explore further.

One benefit of adopting function-structure language, as opposed to problem-solution language, is that it would avoid the sometimes challenging distinction between problems and solutions. Especially in cases of technology-push innovation, or solution-driven design,[104] we could then talk about the "function" to be performed (rather than the problem to be solved) and the "structure" to realize that function (rather than the solution to the problem). It would then be possible to make statements about designers tackling the "problem" of how to identify the right functional requirements for their structural proposals, and the type of "solution" they arrived at. This would resolve the difficulty of describing Maher and Poon's "inverse operation," where solutions become problems, and problems become solutions, as the terminology switches from one moment to another (see Part I). Some

59 For example, the "pollinator shift" model is contrasted with Darwin's evolutionary race model. Johnson and Anderson, "Coevolution between Food-Rewarding Flowers"; Wasserthal, "Pollinators," 343–59; Whittall and Hodges, "Pollinator Shifts," 706–09.

60 Alternatively, we could say that problems are to solutions as orchids are to moths (problems : solutions :: orchids : moths). It is arbitrary how moths and orchids are mapped to problems and solutions.

61 Storm et al., "Reframing the Design Process," 366.

62 For a discussion of early work, see David H. Hembry, Jeremy B. Yoder, and Kari Roesch Goodman, "Coevolution and the Diversification of Life," *The American Naturalist* 184, no. 4 (October 2014): 426–27, DOI: https://doi.org/10.1086/677928.

63 Paul R. Ehrlich and Peter H. Raven, "Butterflies and Plants: A Study in Coevolution," *Evolution* 18, no. 4 (1964): 586, DOI: https://doi.org/doi:10.2307/2406212. Note the similarity here to discussions in design research, or creativity more generally, where those studying problem reframing might not consider solution conjectures, and those studying problem solving might not consider problem finding. Co-evolution accounts (in both biology and design) require attention to more than one evolving thing.

64 Thompson, "Four Central Points."

65 Hembry et al., "Diversification of Life," 425–38.

66 "One approach to what we would like to call coevolution is the examination of patterns of interaction between two major groups of organisms with a close and evident ecological relationship, such as plants and herbivores." Ehrlich and Raven, "Butterflies and Plants," 586.

67 Arditti et al., "'Good Heavens What Insect Can Suck It,'" 420; also see Wasserthal, "Pollinators," 343–59.

68 Langerhans, "Coevolution"; Sharon Y. Strauss, Heather Sahli, and Jeffrey K. Conner, "Toward a More Trait-Centered Approach to Diffuse (Co)Evolution," *New Phytologist* 165, no. 1 (2005): 81–90, DOI: https://doi.org/10.1111/j.1469-8137.2004.01228.x. There is also gene-for-gene ("matching gene") co-evolution, which describes cases where co-evolution involves direct gene-for-gene correspondence among species (e.g. when hosts and parasites have complementary genes for resistance and virulence).

69 Mark Urban et al., "The Evolutionary Ecology of Metacommunities," *Trends in Ecology & Evolution* 23, no. 6 (2008): 311–17, https://doi.org/10.1016/j.tree.2008.02.007; Diego Carmona,

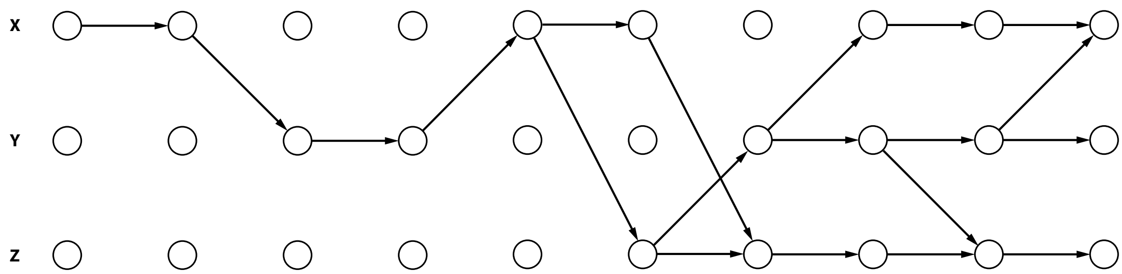

Figure 3
Illustration of a possible co-evolution process where three systems are co-evolving (*X*, *Y*, and *Z*). These might represent, for example, problems, solutions, and something else (e.g., processes, audiences, or knowledge); or function, behavior, and structure; or three designers; or three design teams; or three design projects. Any number of co-evolving systems (not just three) might be identified and represented this way. © 2021 Nathan Crilly.

caution is required though. Moving away from the problem-solution terminology would open up further divisions between design researchers and those in other disciplines studying related behavior in problem solving and problem finding.

In summary, a wide range of co-evolving things might be considered, including, but not limited to, problems and solutions, processes, knowledge, concepts, functions, behaviors, and structures. Which of these is most relevant will depend on the types of creative work being undertaken, the contexts in which they are studied and the analytic perspectives of the researchers. Some might prefer to incorporate these different categories within the categories of problems and solutions—the problem of what method to use, the solution of what market to serve—but that should be a choice rather than an assumption. For any number of different kinds of ideas, or kinds of system more generally, a process of co-evolution could be represented by adding more rows to the design co-evolution diagrams (see Figure 3).

At What Levels Does Co-evolution Occur?

The biological literature describes co-evolutionary processes within species and between species, uniting descriptions at different levels of analysis under a common framework.[105] Design research could take a similar approach if co-evolution was used to describe reciprocal influence at different levels. At more micro levels, we could examine co-evolution *within* problems and *within* solutions.[106] For example, we might observe co-evolution between a designer's ideas about the requirements for the overall architecture of a system and the requirements for a detail of its implementation.[107] At more macro levels, we could examine the co-evolution of larger units. For example, in a design team with several designers sharing ideas, what each person shares might be seen as reciprocally shaping the environment within which other people's ideas are developing. More generally, a project might be represented as having several design teams, each with several members, each with their own ideas.[108] The co-evolution of ideas might be evident within and between individuals, teams and projects.[109] Those ideas might themselves be composed of co-evolving problems and solutions, each with co-evolving sub-problems and sub-solutions. Co-evolution might thus appear self-similar at multiple levels of analysis (see Figure 4).[110] Researching creative work from this perspective would go some way to address the perceived

Connor R. Fitzpatrick, and Marc T. J. Johnson, "Fifty Years of Co-evolution and beyond: Integrating Co-evolution from Molecules to Species," *Molecular Ecology* 24, no. 21 (2015): 5315–29, DOI: https://doi.org/10.1111/mec.13389.
70 Pauw et al., "Flies and Flowers," 277.
71 Langerhans, "Coevolution," 32–33.
72 Thompson, "Four Central Points," 10. Thompson identifies seven types of co-evolution: coevolving complementarity, coevolutionary convergence, coevolutionary escalation, coevolving polymorphisms, coevolutionary alternation, coevolutionary displacement, attenuated antagonism.
73 Pauw et al., "Flies and Flowers," 270.
74 Carmona et al., "Fifty Years," 5318.
75 Langerhans, "Coevolution," 32.
76 Hunter B. Fraser et al., "Coevolution of Gene Expression among Interacting Proteins," *Proceedings of the National Academy of Sciences* 101, no. 24 (2004): 9033, DOI: https://doi.org/10.1073/pnas.0402591101.
77 Carmona et al., "Fifty Years," 5316.
78 Umberto Eco, *The Role of the Reader: Explorations in the Semiotics of Texts* (Bloomington: Indiana University Press, 1984), 9.

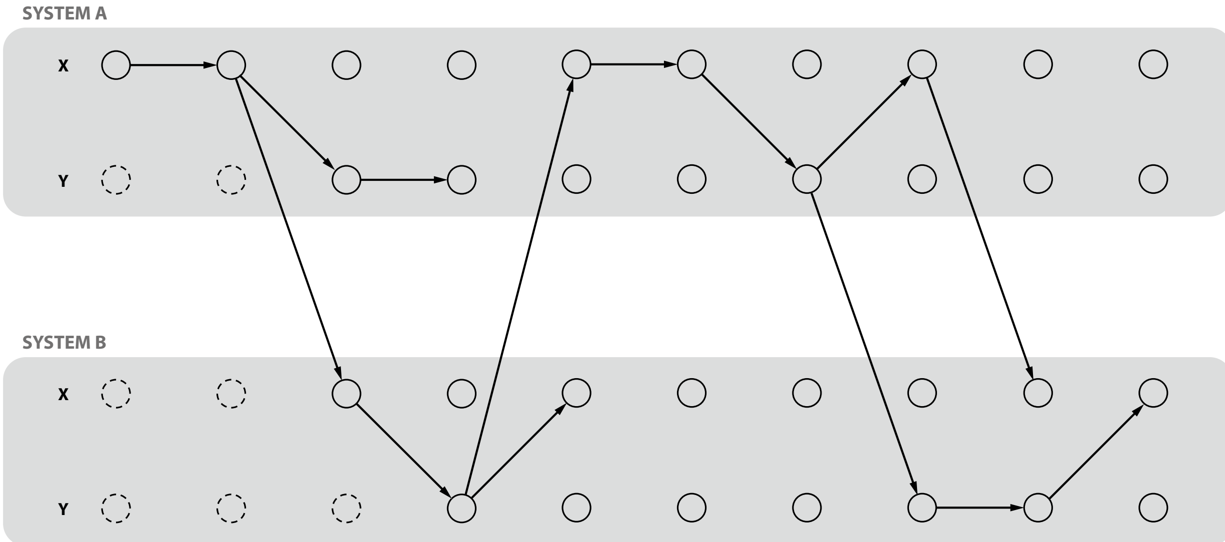

Figure 4
Illustration of a possible multi-level co-evolution process where two systems (*A* and *B*) are co-evolving with each other, and they also have two sub-systems co-evolving within each of them (*X* and *Y*). The diagram might represent, for example, two designers (*A* and *B*) individually and collectively working on problems and solutions (*X* and *Y*). Any number of systems, subsystems, and levels of analysis might be identified and represented this way. © 2021 Nathan Crilly.

gaps in understanding the multi-level linkages between individual and team creativity.[111]

Attention to co-evolution within and between individuals and groups connects with a much wider discussion of co-evolutionary processes that shape the people, organizations and institutions that designers and their products are part of. Looking at literatures on organizational and industrial ecology, we find explicit "co-evolutionary" accounts of knowledge, capabilities, and products at the organizational level;[112] products, processes, and production at the industry level;[113] and firms, technology, and institutions at the national level.[114] More generally, co-evolutionary frameworks have been used to investigate the reciprocal influence between two or more social systems (or actors) in disciplines studying economics, socio-technical systems, human ecology, and human geography.[115] Such works all build on a long history of studying groups and organizations as adaptive systems which co-evolve with their environment. This includes attention to a wide range of co-evolution factors that design researchers would benefit from considering, including multi-level analysis.[116] In fact, a multi-level co-evolutionary account of design has already been offered, but in the organizational ecology literature rather than the design literature. Dermot Breslin describes the product design process in terms of the co-evolution of cognitive structures at the levels of the individuals, groups and organizations, which are progressively nested within each other.[117]

Across a range of disciplines, researchers employing co-evolutionary frameworks see them as having the potential to integrate and consolidate research streams that are otherwise fragmented, an issue that remains a challenge in design research.[118] For example, in Arie Lewin and Henk Volberda's analysis of organization studies, they say, "The coevolution lens has the potential for integrating micro- and macro-level evolution within a unifying framework, incorporating multiple levels of analyses and contingent effects, and leading to new insights, new theories, new empirical methods, and new

79 For a review and criticism, see Martin Stacey and Claudia Eckert, "Against Ambiguity," *Computer Supported Cooperative Work (CSCW)* 12, no. 2 (2003): 153–83, DOI: https://doi.org/10.1023/A:1023924110279.

80 For a discussion of diagram interpretation specifically, see Emily R. Grosholz, *Representation and Productive Ambiguity in Mathematics and the Sciences* (New York: Oxford University Press, 2007), 219.

81 Maher and Poon, "Modeling Design Exploration," 196.

82 For other examples of this vertical alignment see Fischer and Nakakoji, "Empowering Designers," 198; Storm et al., "Reframing the Design Process," 336; Tomislav Martinec et al., "Revisiting Problem-Solution Co-evolution in the Context of Team Conceptual Design Activity," *Applied Sciences* 10, no. 18 (2020): 6030: 7, DOI: https://doi.org/10.3390/app10186303.

understanding."[119] This reflects comments from Diego Carmona, Connor Fitzpatrick, and Marc Johnson describing the integrative power of the co-evolution concept in its originating discipline: "The study of co-evolution has the potential to unify seemingly disparate phenomenon, from the molecular evolution of proteins critical to cellular processes, to the evolution of genomes and phenotypes resulting from interactions between species."[120]

If design researchers find the co-evolution concept useful for describing the development of design ideas within and between people, then they are likely to also find it useful for describing the development of those ideas in broader social systems that are relevant to design processes, not just in projects but also in organizations, at multiple levels of analysis. The different levels to be identified and the different things that are seen to co-evolve within and between those levels should be determined by researchers, depending on their questions and their data. For many such analyses it would be valuable to consider more than just mutualistic co-evolution. Even problems and solutions might only exhibit convergence when a project is progressing towards some acceptable resolution of the changing requirements and proposals. We should question the assumption of mutualism when considering less "productive" processes, or when considering more than just problems and solutions, or more than just individual designers. The wider design ecosystem within which problems and solutions develop might involve many other kinds of interaction,[121] including antagonism and parasitism, even if these kinds of interaction can change over time, and even if their reciprocal influence is not symmetrically powerful.

Conclusions

For thirty years, design researchers have used the term "co-evolution" to refer to how representations of problems and solutions change during a project. In the first part of this two-part article, I connected these discussions to each other and to related discussions in other creative practices. This revealed the different ways in which the core concept is interpreted, and the different ways in which it has been developed. These modifications have resulted from isolated considerations of specific issues rather than a unified approach to more generally improving the scope and applicability of co-evolution accounts.

One way forward is to consider the biological analogy underpinning accounts of design co-evolution, especially from an ecological perspective. In this second part of the article, I have considered the way in which this analogy might productively function, introduced an example to help illustrate this, and identified different kinds of co-evolution to which design activities might be compared. Combining this with observations made in the literature on design and organizations suggests that we should explore two things: (i) the question of what co-evolves during creative work, and (ii) the different levels at which that creative co-evolution occurs. These possible directions could be combined with the recommendation made in Part I of this article, that problems and solutions should be defined in relative rather than absolute terms, an observation that will extend to other analytic categories too.

83 For other examples of such parallel processes, see Fischer and Nakakoji, "Empowering Designers," 198; 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), 446, available at http://papers.cumincad.org/data/works/att/4925.content.pdf; Dorst and Cross, "Creativity in the Design Process," 435.

84 For example, see Maher and Poon, "Modeling Design Exploration," 195–209; Maher and Wu, "Reconsidering Fitness," 488–89.

85 For example, see Ehrlich and Raven, "Butterflies and Plants," 586–608.

86 Per Liljenberg Halstrøm and Per Galle, "Design as Co-evolution of Problem, Solution, and Audience," *Artifact* 3, no. 4 (2015): 3.1–3.13, DOI: https://doi.org/10.14434/artifact.v3i4.12815.

87 Qian Hui et al., "Triple-Helix Structured Model Based on Problem-Knowledge-Solution Co-evolution for Innovative Product Design Process," *Chinese Journal of Mechanical Engineering* 33, no. 94 (2020): article no. 94, DOI: https://doi.org/10.1186/s10033-020-00519-2.

88 Paul Ralph, "The Sensemaking-Coevolution-Implementation Theory of Software Design," *Science of Computer Programming* 101 (April 2015): 21, DOI: https://doi.org/10.1016/j.scico.2014.11.007.

89 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): 169–212, DOI: https://doi.org/10.1016/j.destud.2019.07.003.

90 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.

91 Saskia Kistner et al., "An Explorative Study of Search of Model Space in Problem-Solving," *Journal of Cognitive Psychology* 26, no. 7 (2014): 818–29, DOI: https://doi.org/10.1080/20445911.2014.960872.

92 Christian D. Schunn and David Klahr, "A 4-Space Model of Scientific Discovery," in *Proceedings of the 17th Annual Conference of the Cognitive Science Society*, ed. Johanna D. Moore and Jill Fain Lehman (Mahwah: Lawrence Erlbaum Associates, 1995), 106–11, available at https://www.cmu.edu/dietrich/psychology/pdf/klahr/PDFs/s-kcogsci95.pdf.

93 See Part I for the suggestion that these spaces might also be modelled as a single space.

94 Just as there have been calls for design co-evolution research to move past its

Recent work in biological co-evolution has acknowledged the origin of the concept, while also pushing against the assumptions that are seen to have constrained its development. In this article I have attempted to do the same, in the hope that one of the most influential and elaborated accounts of design can continue to be usefully explored and expanded. Just as we describe the co-evolution of moths and orchids, or problems and solutions, we can also describe the co-evolution of the things we want to understand and the ways in which we represent them. In this sense, the questions we ask about design co-evolution can be expected to co-evolve with our representations of that process. By exploring alternative representations of co-evolution and new questions about it, I hope here to have contributed to this development.

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There are no conflicts of interest involved in this article.

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95 Armand Hatchuel and Benoit Weil, "C-K Design Theory: An Advanced Formulation," *Research in Engineering Design* 19, no. 4 (2009): 181–92, DOI: https://doi.org/10.1007/s00163-008-0043-4; Armand Hatchuel, Pascal Le Masson, and Benoit Weil, "Teaching Innovative Design Reasoning: How Concept-Knowledge Theory Can Help Overcome Fixation Effects," *AI EDAM* 25, no. 1 (2011): 77–92, DOI: https://doi.org/10.1017/S089006041000048X.

96 Armand Hatchuel and Benoît Weil, "C-K Theory: Notions and Applications of a Unified Design Theory" (paper presented at the Herbert Simon International Conference on Design Sciences, Lyon, March 15–16, 2002), 1.

97 John S. Gero, "Design Prototypes: A Knowledge Representation Schema for Design," *AI Magazine* 11, no. 4 (1990): 26–36, DOI: https://doi.org/10.1609/aimag.v11i4.854; Yasushi Umeda et al., "Function, Behaviour, and Structure," in *Design*, Vol. 1 of *Applications of Artificial Intelligence in Engineering V*, ed. John S. Gero (Berlin: Springer-Verlag, 1990), 177–93, available at http://www-kasm.nii.ac.jp/papers/takeda/p90/umeda90fbs.pdf; Ashok K. Goel, Spencer Rugaber, and Swaroop Vattam, "Structure, Behavior, and Function of Complex Systems: The Structure, Behavior, and Function Modeling Language," *AI EDAM* 23, no. 1 (2009): 23–35, DOI: https://doi.org/10.1017/S0890060409000080.

98 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 (November 2019): 29, DOI: https://doi.org/10.1016/j.destud.2019.10.001; 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.

99 Maher and Poon, "Modeling Design Exploration," 198.

100 Poon and Maher, "Co-evolution and Emergence in Design," 326. This shouldn't be mistaken for Maher's combination of Gero's FBS categories with problem-solution categories because there FBS

categories are used to make *sub-categories* of problems and solutions (see Table 1 in Part I of this article).

101 Hatchuel and Weil, “C-K Design Theory,” 183.

102 Dan Braha and Yoram Reich, “Topological Structures for Modeling Engineering Design Processes,” *Research in Engineering Design* 14, no. 4 (2003): 185–99, DOI: https://doi.org/10.1007/s00163-003-0035-3. Braha and Reich do not use the term “co-evolution.”

103 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), 344, available at https://www.designsociety.org/publication/28597/Modelling+Co-Evolution+in+Design+Practice.

104 See Part I. For discussion and examples, see 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.

105 Carmona et al., “Fifty Years.”

106 Moves towards multi-level analysis have been prepared for in some of the modifications outlined in the work summarized in Table 1 of Part I of this article.

107 Crilly and Moroşanu Firth, “Creativity and Fixation,” 169–212.

108 John Gero and Julie Milovanovic, “The Situated Function-Behavior-Structure Co-design Model,” *CoDesign* 17, no. 2 (2019): 211–36, DOI: https://doi.org/10.1080/15710882.2019.1654524.

109 For other arguments that co-evolution accounts should be extended to span projects, see Dorst, “Co-evolution and Emergence in Design,” 75. Outside design research, for an example of an account where ideas or discoveries “co-evolve” between people, with an explicit biological analogy, see Robert Gibson, “Co-evolution: Not Much Happens by Itself,” *A/J: Alternatives Journal* 38, no. 1 (2012): 48, available at https://www.proquest.com/openview/7e4d213a88ec116a54b7dde9f60c2f32/1?pq-origsite=gscholar&cbl=35934.

110 For the interaction between micro- and macro-co-evolution in organizations, see Bill McKelvey, “Managing Coevolutionary Dynamics” (paper presented at the 18th European Group for Organizational Studies Conference (Barcelona, July 4–6, 2002), available at https://www.researchgate.net/profile/Bill-Mckelvey/publication/228559005. For a diagram indicating multi-level design co-evolution, see Poon and Maher, “Co-evolution and Emergence in Design,” 324.

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117 **Dermot Breslin, “Interpreting Futures through the Multi-Level Co-evolution of Organizational Practices,” *Futures* 43, no. 9 (2011): 1024–26, DOI: https://doi.org/10.1016/j.futures.2011.07.001; Breslin, “What Evolves,” 58–59.**

118 Chris A. McMahon, "Reflections on Diversity in Design Research," *Journal of Engineering Design* 23, no. 8 (2012): 563–76, DOI: https://doi.org/10.1080/09544828.2012.676634; Cash, "Theory-Driven Design Research," 94.

119 Lewin and Volberda, "Prolegomena on Coevolution," 520; Weisz and Clark, "Society-Nature Coevolution," 285.

120 Carmona et al., "Fifty Years," 5326. Also see discussions of how niche construction theory helps link ecosystem ecology to evolutionary biology: Odling-Smee et al., "Niche Construction Theory".

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