The Structure of Design Revolutions: Kuhnian Paradigm Shifts in Creative Problem Solving

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> Design and other difficult problem solving is punctuated by moments of *discovery*.… These are the moments when something new and important is suddenly “seen.”[1]

Introduction

Researchers interested in understanding creative design have studied the genesis, development, and implementation of new ideas in design projects. The findings from such studies can be divided into those that emphasize the sudden emergence of new ideas, and those that emphasize how new ideas are gradually built upon those that precede them. In this article, a unification of these different perspectives is proposed by describing a general structure of creative design progress that accounts for both cumulative and disruptive episodes. This description is based on Thomas S. Kuhn’s book *The Structure of Scientific Revolutions*,[2] an historically informed account of scientific progress in which we can find many parallels with observed phenomena in creative design.[3] It is argued that viewing creative design episodes through a Kuhnian lens yields two distinct benefits: first, it can sensitize researchers to the existence of phenomena that are not emphasized by existing accounts; and second, it can sensitize designers to the nature and dynamics of creative progress, and thereby aid reflective practice.

Creativity and design are topics that are studied from a variety of perspectives, and before proceeding further it is worth clarifying our particular frame of reference and the scope of the arguments we will explore. First, because our interest is in design rather than technology, emphasis is placed on the activities that occur *within* particular design projects rather than historical design developments across different product generations.[4] We are also only interested here in *the structure* of creative progress, and not in assessing the degree of creativity attained or in the efficacy of creative methods.[5] It follows that our focus is on descriptive accounts of creative design *as it occurs*, rather than normative models of design as it should be.[6] Finally, we shall be restricted to considering the production and acceptance of ideas that are somehow new to the individuals and groups involved in a design project; we are unconcerned with whether such ideas are also new to the world because it is *psychological* rather than historical phenomena that are

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1 Elaine Kant and Allen Newell, “Problem Solving Techniques for the Design of Algorithms,” *Information Processing and Management* 20:1–2 (1984), 109. Emphasis in original.

2 Thomas S. Kuhn, *The Structure of Scientific Revolutions*, (Chicago: University of Chicago Press, 1996 [3rd edition]).

3 In this article reference is made to scientific “progress,” “advance,” and “development” in the sense that Kuhn used these terms, not as an increasing convergence on truth, but as an ongoing change in perspective. See Kuhn, *The Structure of Scientific Revolutions*, 205–6.

4 For studies of design developments across product generations see Henry Petroski, *The Evolution of Useful Things* (London: Pavilion, 1993); Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore: Johns Hopkins University Press, 1990).

5 c.f. Jami J. Shaha, Steve M. Smith, and Noe Vargas-Hernandeza, “Metrics for Measuring Ideation Effectiveness,” *Design Studies* 24:2 (2003), 111–34.

of relevance.[7] As the title indicates, we are interested in the structure by which acts of creative problem solving advance design. This is irrespective of the design discipline within which those acts are situated or the products towards which they are directed.

The article is divided into several sections, intended not just to develop a Kuhnian perspective on creative design, but also to more generally explore the many issues that surround such a perspective. We begin by reviewing different accounts of creative design progress, and by then reviewing Kuhn's account of scientific advance. To explain how the latter relates to the former, it is argued that processes of scientific discovery mirror activities of creative design. The influence of Kuhn's work is then discussed, looking for precedents in which his concepts have been used to illuminate the way in which design projects move forward. Having done this, we are able to read Kuhn's work as though he is describing observed design behavior, and nine key propositions are derived that collectively describe the structure of creative progress in design projects. Finally, opportunities for further theoretical and empirical work are discussed as we consider the broader implications of relating scientific discovery to creative design.

Creative Design Progress

Creative design has always proved a difficult activity to define satisfactorily, and there have been many problems in establishing criteria by which it might be identified.[8] Despite this, the literature on creativity and design often requires a creative idea to be recognized as both novel and appropriate.[9] While different design activities demand or permit different levels of creativity, design solutions that are not immediately obvious from the problem statement must require the generation of novel and appropriate ideas, and must therefore require creativity. Creativity is consequently considered to be an important aspect of design performance and is the stated objective of much design education.[10] As a contributor to product innovation, creative design is also a key determinant of many organizations' commercial success and of a nation's economic health.[11] In combination, these factors all serve to promote the importance of modeling, enhancing, and assessing creative design. Developing a basic understanding of creative design underpins these activities, and descriptive accounts of creative progress provide a foundation for such understanding.

Design progress within projects is often described in terms of suddenly emerging ideas that are variously termed "eureka events," "ah-ha moments," or "creative leaps."[12] Such ideas may seemingly lack preparation or precedence but can subsequently define a new and fruitful direction for the project.[13] While often considered obvious once they have been recognized, these sudden insights may appear to share little logical connection with previous solution attempts.[14] One reason that these moments of insight are necessary at all is

6 Unlike his predecessors and contemporaries in the history and philosophy of science, Kuhn insisted that interesting and important things could be said about how science is actually practiced rather than just how it should be practiced. This is one reason why we might base our proposed descriptive account on Kuhn rather than other philosophers of science. However, there is a subtle complication here because Kuhn believed that science operates effectively and that scientists should behave as they already do. He therefore asserted that his account of science is both descriptive *and* normative. See Thomas S. Kuhn, "Reflections on My Critics," in *Criticism and the Growth of Knowledge: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965, Volume 4*, ed. Imre Lakatos and Alan Musgrave (Cambridge: Cambridge University Press, 1970), 237.

7 Margaret Boden famously distinguishes between individuals who are psychologically creative (*P-creative*)—having a more or less sustained capacity to produce ideas that are new to them, and those who are historically creative (*H-creative*)—having arrived at one or more ideas that are new to the world. Both types of creativity are initially defined with respect to ideas, but then these ideas are used to define the people responsible for them. See Margaret A. Boden, *The Creative Mind: Myths and Mechanisms* (London: Weidenfeld and Nicolson, 1990), 32–35. For application of these ideas to design see Subrata Dasgupta, *Creativity in Invention and Design: Computational and Cognitive Explorations of Technological Originality* (Cambridge: Cambridge University Press, 1994), 18; Christiaan Redelinghuys, "Proposed Criteria for the Detection of Invention in Engineering Design," *Journal of Engineering Design* 11:3 (2000), 273.

8 This follows from problems in defining creativity itself. For example, see Robert J. Sternberg and Todd I. Lubart, "The Concept of Creativity: Prospects and Paradigms," in *Handbook of Creativity*, ed. Robert J. Sternberg (Cambridge: Cambridge University Press, 1999), 4.

because designers confronted with a problem can assume or infer constraints that limit the solutions they explore.[15] The boundaries of this exploration are expanded when the problem is reframed and designers learn to see things in new ways and to look for new kinds of solution.[16] This suggests that sudden insights might not just relate to the production of creative solutions to a given problem, but also to the creative formulation of the problem itself.[17]

Creative acts often result from long periods of difficult, purposeful struggle—a struggle not only with the idea produced, but also with maintaining the contexts and self-concepts that make such ideas possible.[18] Therefore, although sudden insights (such as those described above) might at first appear to yield an instantaneous solution to the problem, they are often prefigured by similar ideas that were previously neglected or are later forgotten.[19] With respect to design, such observations lead to the suggestion that what might otherwise be considered a creative leap between analysis and synthesis could actually involve incrementally "bridging" between the problem and solution with various sub-problems and sub-solutions.[20] This corresponds with Ullman et al.'s fine-grained, empirically derived model of the design process, in which progress is gradual and cumulative.[21] In the absence of right or wrong answers, there would appear to be little basis for abandoning interim design solutions, and therefore design information is said to increase monotonically throughout a project.[22]

The two preceding paragraphs outline two apparently conflicting perspectives on creative design progress. The first promotes the notion of sudden, revolutionary leaps forward, while the second focuses on how ideas are incrementally built upon those that precede them.[23] There is generally little attempt made to relate these different types of developmental episodes and their interdependence remains unexamined. This is in contrast to perspectives on science, where disruptive and incremental episodes of development were famously integrated into a single account by Thomas S. Kuhn in his 1962 book *The Structure of Scientific Revolutions*.[24] Considering creative design from this perspective suggests that a similar integration is necessary for design theory if the structure of creative design progress is to be better understood. To address this, we shall now turn our attention to Kuhn's work, both to gain an understanding of how disruptive and incremental episodes might be characterized, and also of how they might be related.

The Structure of Scientific Revolutions

Kuhn's account of scientific development distinguishes between relatively stable periods of cumulative progress called "normal science," and disruptive episodes of relatively sudden change called "revolutionary science." In normal science, the research community shares a common set of beliefs, values, and techniques, and they also agree on what work can be regarded as exemplary.

9 Raymond S. Nickerson, "Enhancing Creativity," in *Handbook of Creativity*, ed. Sternberg, 392–93; T. J. Howard, S. J. Culley, and E. Dekoninck, "Describing the Creative Design Process by the Integration of Engineering Design and Cognitive Psychology Literature," *Design Studies* 29:2 (2008), 172–73. In addition to being novel and appropriate, a third condition is sometimes imposed, such as the requirement to be non-obvious, surprising, transformative, or efficient, ibid.

10 Henri H. C. M. Christiaans, *Creativity in Design: The Role of Domain Knowledge in Designing* (Utrecht: Lemma, 1992), ix, xi, 1, 2, 11.

11 George Cox, "Cox Review of Creativity in Business: Building on the UK's Strengths" (London: HM Treasury & Department of Trade and Industry, 2005).

12 Ömer Akin and Cem Akin, "Frames of Reference in Architectural Design: Analysing the Hyperacclamation (a-H-a-!)," *Design Studies* 17:4 (1996), 341–61; Nigel Cross, "Descriptive Models of Creative Design: Application to an Example," *Design Studies* 18:4 (1997), 427–40; Kees Dorst and Nigel Cross, "Creativity in the Design Process: Co-Evolution of Problem–Solution," *Design Studies* 22:5 (2001), 434.

13 Kant and Newell, "Problem Solving Techniques," 109.

14 Donald T. Campbell, "Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes," *Psychological Review* 67:6 (1960), 384.

15 David G. Jansson and Steven M. Smith, "Design Fixation," *Design Studies* 12:1 (1991), 3–11; A. Terry Purcell and John S. Gero, "Design and Other Types of Fixation," *Design Studies* 17:4 (1996), 363–83; Evangelia G. Chrysikou and Robert W. Weisberg, "Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task," *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31:5 (2005), 1134–48. For an industrial example of fixation see Michael. J. French, *Conceptual Design for Engineers* (London: Design Council, 1985 [2nd edition]), 187–88.

These characteristics collectively define the prevailing "paradigm" within which scientists work. This paradigm directs attention to the scientific puzzles that must be solved, and scientists are focused on the extension and articulation of the paradigm rather than seeking its replacement. Over time, the cumulative refinement of the paradigm generates a range of observations that are seen as being anomalous with theory, and, despite resistance, these anomalies eventually provoke crisis.

In response to mounting crises, revolutionary science involves the proposal of a new perspective that fundamentally challenges the assumptions, orientations, and expectations of the community. This proposal may be accepted and thereby replace the existing paradigm if it promises to resolve some remaining problems while also preserving some of what has already been achieved. These "paradigm shifts" often demand the re-examination of previously established knowledge as not all of the preceding paradigm survives the revolution. Such shifts also define new directions for research by rendering previous puzzles unproblematic and by pointing to new puzzles that must be solved. In time, the newly accepted paradigm becomes the basis for another period of normal science which may in the future encounter crises that again provoke revolution. (For readers unfamiliar with Kuhn's thesis, an illustrative example of a scientific paradigm shift—the "Copernican revolution" in astronomy—is provided in the appendix.)

Relating Scientific Discovery to Creative Design

Kuhn's account of scientific progress clearly integrates cumulative and disruptive episodes, and also suggests how each type of episode is related to the other. What is not immediately clear, however, is why an historically informed account of the processes that lead to and follow scientific discovery should be considered relevant to the episodes of creativity that occur within contemporary design projects. Science and design are ostensibly distinct branches of human activity, as exemplified by the educational, cultural, and professional divisions that typically separate them.[25] As such, the suggestion that studying one can illuminate the other demands further scrutiny. Before asserting Kuhn's relevance to design, we must therefore first seek to establish the plausibility of such an assertion, and identify the precedents upon which it might be based.

Many studies of creativity examine the work of artists and scientists in an attempt to uncover the cognitive processes that are common to both.[26] Such studies seldom make reference to design, but like design, both artistic creativity and scientific discovery can be considered as problem solving activities.[27] Acts of discovery and creation can thus be established as lying on a continuum where the solutions to highly constrained problems must be *discovered* while the solutions to relatively unconstrained problems are *created*.[28] From this perspective, the nature of creative acts is not defined by the

16 Donald A. Schön, *Invention and the Evolution of Ideas* (London: Tavistock, 1967); Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action* (London: Temple Smith, 1983); Rianne Valkenburg and Kees Dorst, "The Reflective Practice of Design Teams," *Design Studies* 19:3 (1998), 249–71. Such reframing may take place with respect to an understanding of the problem or an understanding of how design is to be conducted. See Raymonde Guindon, Herb Krasner, and Bill Curtis, "Breakdowns and Processes During the Early Activities of Software Design by Professionals" (paper presented at the Empirical studies of programmers: second workshop, Norwood, NJ, 1987), 71–74.

17 Mary Lou Maher and Josiah Poon, "Modeling Design Exploration as Co-Evolution," *Microcomputers in Civil Engineering* 11:3 (1996), 195–209; Dorst and Cross, "Creativity in the Design Process," 434.

18 Howard E. Gruber, "The Evolving Systems Approach to Creative Work," in *Creative People at Work: Twelve Cognitive Case Studies*, ed. Doris B. Wallace and Howard E. Gruber (Oxford: Oxford University Press, 1989), 3–24.

19 David N. Perkins, *The Mind's Best Work* (Cambridge: Harvard University Press, 1981), 43–49.

20 Cross, "Descriptive Models of Creative Design," 432, 439; Nigel Cross, *Designerly Ways of Knowing*, (London: Springer, 2006), 92.

21 David. G. Ullman, Thomas. G. Dietterich, and Larry A. Stauffer, "A Model of the Mechanical Design Process Based on Empirical Data," *Artificial Intelligence in Engineering Design and Manufacturing* 2:1 (1988): 35, 41.

22 Vinod Goel and Peter Pirollia, "The Structure of Design Problem Spaces," *Cognitive Science* 16:3 (1992): 406, 420–21; Subrata Dasgupta, *Design Theory and Computer Science: Processes and Methodology of Computer Systems Design* (Cambridge: Cambridge University Press, 1991), 77ff.

fields to which they are directed (e.g. art, technology, science), but by how tightly bound the solution space is, and by what factors determine that boundary (e.g. cultural, economic, physical).[29] Such observations permit Dasgupta's view that "the process of inventing artifactual forms (or creating original designs) in the artificial sciences is cognitively indistinguishable at the knowledge level from the processes of inventing theories or discovering laws in the natural sciences."[30] Intuitive support for this may be found in the language that is used to describe the production of new ideas in science and design: while natural phenomena are *discovered*, the theories to explain those phenomena are *invented*; conversely, while artifacts might be *invented*, the process of invention involves moments of *discovery*.[31]

In his substantial study of creativity in different times and cultures, Koestler argues that the basic pattern of progress observed in creative individuals is similar to that observed in the history of the fields they serve.[32] In both, there are short bursts of revolutionary discovery that punctuate longer periods of assimilation, consolidation, and interpretation. Furthermore, Koestler claims that the mechanism that underlies this pattern is also similar: revolutions are held at bay by a personal or cultural "blindness" that is imposed by the existing paradigm.[33] From a psychological perspective, Perkins makes similar arguments, claiming that Kuhn's idea of collectively accepted paradigms fits the general notion of personally established schemata (where schemata are the mental structures that allow a person to perceive or act effectively by anticipating the organization of what is apprehended or produced).[34] This leads Perkins to propose that, like paradigms, schemata enable skilled performance within their scope, while severely inhibiting creativity beyond their scope.[35] Such claims allow the possibility of drawing parallels between historical accounts of collective discovery on the one hand, and shorter episodes of individual creativity on the other.

The arguments above suggest: first, that similarities might be observed between the nature of scientific discovery and that of creative design; and second, that the patterns enacted on an historic scale may mirror those observable on a personal scale. With respect to the first point, Kuhn acknowledged this by claiming that long before his own work on the structure of scientific advance, historians had portrayed the humanities as developing through a similar succession of traditions punctuated by revolutionary shifts in style, taste, viewpoint, and goal.[36] With respect to the second point, Kuhn's applicability to personally creative acts should perhaps not surprise us because Kuhn was generally interested in the nature of conceptual change, not just in infrequent scientific change.[37] He asked what sort of ideas could be thought of at any one time, and what sort of impact a given idea could have on collective understanding and action. Such questions are clearly relevant to progress in design and

23 Such a distinction might typically be labeled "revolutionary" versus "evolutionary," but this terminology is avoided here because evolutionary theories can also account for sudden change. See Niles Eldredge and Stephen Jay Gould, "Punctuated equilibria: an alternative to phyletic gradualism," in *Models in paleobiology*, ed. Thomas. J. M. Schopf. (San Francisco: Freeman, Cooper & Co, 1972), 82–115. Nevertheless, accounts of design progress frequently make reference to the concepts of biological evolution because they provide an interesting analogical approach to describing the creative development of ideas. For psychological perspectives, see Dean K. Simonton, "Creativity as Blind Variation and Selective Retention: Is the Creative Process Darwinian?" *Psychological Inquiry* 10:4 (1999), 309–28. For design perspectives see Philip Steadman, *The evolution of designs: biological analogy in architecture and the applied arts,* (Cambridge: Cambridge University Press, 1979); John Z. Langrish, "Darwinian Design: The Memetic Evolution of Design Ideas," *Design Issues* 20:4 (2004), 4–19; Jennifer Whyte, "Evolutionary Theories and Design Practices," *Design Issues* 23:2 (2007), 46–54. Note that Whyte supports the notion that evolutionary theories are relevant to product development across different generations, but not within a particular design project, ibid., 53. For Kuhn's perspective on evolutionary accounts of conceptual progress see Kuhn, *The Structure of Scientific Revolutions* , 170–72; "A Discussion with Thomas S. Kuhn," in *The Road since Structure: Philosophical Essays, 1970–1993*, ed. James Conant and John Haugeland (Chicago: University of Chicago Press, 2000), 307.

therefore Kuhn's ideas might be applied there just as they have been successfully applied to other areas that he did not anticipate.[38]

Applying Kuhn to Design

Since its first publication in 1962, *The Structure of Scientific Revolutions* has sold over one million copies in over 20 languages.[39] It has been listed as the most highly cited work in the arts and humanities,[40] and is considered to be one of the most influential books ever written.[41] What is particularly striking is that despite Kuhn's intuitions,[42] his concepts and arguments have been adopted across the social sciences.[43] Furthermore, although often divorced from his originally intended meanings, his terminology—especially "paradigm shift"—has entered into common usage and has been co-opted by disciplines such as marketing, management, and information technology.[44] Because of his extensive influence, it is often remarked—and often seriously—that Kuhn prompted his own paradigm shift within the sociology of knowledge.[45]

Considering the widespread impact of Kuhn's work, there is surprisingly little reference to Kuhn in the design literature. Those who do cite Kuhn often do so summarily, not to support the notion that *design projects* operate within distinct paradigms, but that *design research* does (or might or should).[46] This is understandable given Kuhn's arguments, but is in contrast to the closely related field of technology studies where his concepts have been applied to accounts of technological progress.[47] In particular, Anderson and Tushman build on Kuhn's work to develop a cyclical model where incremental technological progress is punctuated by sudden "technological discontinuities."[48] Constant also builds on Kuhn's work to define periods of "normal technology" and "technological revolution," and Dosi extends Kuhn's concept of paradigms to define "technological paradigms" that account for continuous and discontinuous innovation.[49] Vincenti's study of engineering knowledge brings us closer to design by further building on Constant's work to define the terms "normal design" and "radical design."[50] Unfortunately his focus is on the former, which he describes as an evolutionary process that does not require the invention of new forms, functions, or features. In contrast, Wake's work on "design paradigms" does emphasize paradigm shifts, but primarily with a view to promoting creative progress rather than understanding its structure.[51]

Although the work mentioned above makes reference to Kuhn's terminology and concepts, none focuses on the details of his arguments.[52] For a more extensive exploration of Kuhn's relevance to design we must turn to the work of Dasgupta. Dasgupta exploits the Kuhnian definition of a scientific paradigm to describe not only the research traditions from which design creativity can be studied,[53] but also the models of the design process that designers subscribe to.[54] However, what interests us most here is that Dasgupta's attention to Kuhn leads him to make a comparison between "normal and revolu-

24 *The Structure of Scientific Revolutions* was first published in 1962 as a monograph in the Vienna Circle's *International Encyclopedia of Unified Science.* At Kuhn's request, it was also published as a separate book that same year by the same publisher, University of Chicago Press. In this article we refer to the third edition of the book (1996), which includes a new index and retains the second edition's extensive explanatory postscript (a postscript that Kuhn wrote in 1969 to address critics' responses to the first edition). Despite making various suggestions that a revised and expanded version of the book was necessary, Kuhn had not published this by his death in 1996. For examples of the criticisms to which Kuhn's postscript responds, see Imre Lakatos and Alan Musgrave, eds., *Criticism and the Growth of Knowledge: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965, Volume 4* (Cambridge: Cambridge University Press, 1970).

25 For specific arguments about the relationship between design and science see Nigel Cross, "Designerly Ways of Knowing: Design Discipline Versus Design Science," *Design Issues* 17:3 (2001), 49–55; Jonathan Cagan, Kenneth Kotovsky, and Herbert A. Simon, "Scientific Discovery and Inventive Engineering Design," in *Formal Engineering Design Synthesis*, edited by Erik K. Antonsson and Jonathan Cagan, 442–65. (Cambridge: Cambridge University Press, 2001). For related arguments about the divisions between the sciences and humanities, see C. P. Snow, *The Two Cultures*. (Cambridge: Cambridge University Press, 1993. Includes the 1959 text "The Two Cultures and the Scientific Revolution," together with its 1964 successor piece, "A Second Look").

tionary science" on the one hand and "routine and inventive design" on the other. With routine design, the artifact's general form and behavior are known at the outset, while inventive design involves establishing a new form of artifact or a new approach to the creation of artifacts. Routine design operates within an existing paradigm whereas inventive design proposes a new paradigm that may eventually replace the old.[55] Although Dasgupta may at first appear to be embarking on a project similar to that undertaken here, Kuhn is only one of many scholars who inform Dasgupta's work, and the hypotheses Dasgupta develops do not in themselves represent a Kuhnian perspective on creative design.[56]

Despite the promise that Kuhn's work would seem to hold, his detailed account of the structure within which new ideas are developed, accepted, refined, and superseded appears not to have been applied to the study of creative design. However, it is argued here that Kuhn's historically informed account of scientific progress provides a useful vantage point from which creative design practice might be viewed. Accepting this permits a close reading of *The Structure of Scientific Revolutions* to yield interesting propositions about the structure of progress in creative design projects.

The Structure of Creative Design Progress

If we read Kuhn as though he is describing design rather than science, we can derive a new account of the nature and dynamics of creative design progress. This account is divided into nine propositions which are presented below. Each proposition is introduced with a short quotation from Kuhn, which is then followed by a statement of elaboration. As mentioned earlier, the direct translation of Kuhn's terminology into the design domain has already been performed by authors interested in the historical development of products across different generations. Therefore, to avoid confusing design progress within projects with that between projects, use of the terms "normal design," "revolutionary design," and "design paradigm" are avoided here. Instead, the terms "cumulative design" and "conceptual reorientation" are used to describe the phases through which creative design proceeds.

P1: Pre-cumulative design is undirected.

> In the absence of a paradigm or some candidate for paradigm, all of the facts that could possibly pertain to the development of a given science are likely to seem equally relevant.[57]

If a design problem is considered without any strong conceptual orientation, the many pieces of available design information can become difficult to identify and sort. To address this, various different concepts are tried, and eventually an initial orientation toward the problem, the solution, or the process emerges.

26 For example, see Arthur Koestler, *The Act of Creation* (London: Hutchinson, 1964); Vera John-Steiner, *Notebooks of the Mind: Explorations of Thinking* (Oxford: Oxford University Press, 1997 [revised edition]); Perkins, *The Mind's Best Work*; Teresa M. Amabile, *Creativity in Context: Update to 'The Social Psychology of Creativity'* (Boulder: Westview Press, 1996); Doris B. Wallace and Howard E. Gruber, *Creative People at Work: Twelve Cognitive Case Studies* (Oxford: Oxford University Press, 1989).

27 For design as problem solving, see Herbert A. Simon, *The Sciences of the Artificial* (Cambridge: MIT Press, 1981 [2nd edition]). For art as problem solving, see David Ecker, "The Artistic Process as Qualitative Problem Solving," *Journal of Aesthetics and Art Criticism* 21:3 (1963), 283–90. For science as problem solving, see Pat Langley, Herbert A. Simon, Gary L. Bradshaw, and Jan M. Zytkow, *Scientific Discovery: Computational Explorations of the Creative Processes* (Cambridge: MIT Press, 1987), 5–7.

28 Robert M. French, "Discovery and Creation: Opposite Ends of a Continuum of Constraints," unpublished manuscript, Université de Bourgogne. Although it can be argued that (unlike creation) discovery only involves the "uncovering" of that which already exists, such views are criticized for failing to recognize that discovery is a gradual process of conceptual change involving cognitive re-orientation towards the subject of interest. See Jacob Bronowski, "The Creative Process," *Leonardo* 18:4 (1985), 245; Barnes, *T. S. Kuhn and the Social Science*, 41–45; Kuhn, *The Structure of Scientific Revolutions*, 52–56.

P2: Cumulative design is conservative.

> Normal science does not aim at novelties of fact or theory and, when successful, finds none.[58]

With some particular conceptual orientation established, much work is devoted to exploring its possibilities, and refining its performance. During these periods of cumulative design, efforts are not directed towards generating alternative new concepts, but to developing the existing concept as much as possible.

P3: Cumulative design is productive.

> Normal science…is a highly cumulative enterprise, eminently successful in its aim, the steady extension of the scope and precision of scientific knowledge.[59]

Periods of cumulative design are extremely effective because designers understand the problems to be addressed and know where to direct their efforts. Progress is incrementally achieved because none of the developments fundamentally challenge the underlying concept and therefore retrograde design moves are not encountered.

P4: Cumulative design leads to perceived inadequacies.

> Discovery commences with the awareness of anomaly… It then continues with a more or less extended exploration of the area of anomaly.[60]

Despite the effective progress made during periods of cumulative design, this progress also leads to the perception of various inadequacies that bring into question the underlying conceptual orientation. However, without a new candidate concept to consider, this only provokes renewed efforts to understand how the existing concept can be made to work.

P5: Perceived inadequacies provoke conceptual reorientation.

> Scientists…often speak of the "scales falling from the eyes" or of the "lightning flash" that "inundates" a previously obscure puzzle, enabling its components to be seen in a new way….[61]

Immersed in the inadequacies that are perceived in the existing concept, designers experience a sudden insight that reveals a new possible solution to the problem or a new perspective on the problem itself. Despite its apparent novelty, this insight may have been prefigured by other related ideas, and it is therefore the recognition of these insights rather than their formation that is disruptive.

P6: Conceptual reorientation reveals new problem-solution spaces.

> Led by a new paradigm, scientists adopt new instruments and look in new places. Even more important, during revolutions scientists see new and different things when looking with familiar instruments in places they have looked before.[62]

Conceptual reorientation influences which aspects of the situation are attended to, and also what is perceived in those aspects. Therefore,

29 In this sense, Hafner claims that while distinguishing artists from scientists is an intuitively obvious thing to do, doing so with any precision is a difficult task because each requires a combination of knowledge and skill, each proceeds through processes of creation and discovery, each is sustained by aesthetic and structural sensitivities, and each demands discipline while benefiting from fortune. E. M. Hafner, "The New Reality in Art and Science," *Comparative Studies in Society and History (Special Issue on Cultural Innovation)* 11:4 (1969), 390. Kuhn recognized this view but did not welcome it. See Thomas S. Kuhn, "[The New Reality in Art and Science]: Comment," *Comparative Studies in Society and History* 11:4 (1969), 403–12. For further reading on this matter see David R. Topper and John H. Holloway, "Interrelationships between the Visual Arts, Science and Technology: A Bibliography," *Leonardo* 13:1 (1980), 29–33.

30 Dasgupta, *Creativity in Invention and Design*, 210–11. Also see Dasgupta, *Design Theory and Computer Science*, 353–80. This is perhaps only a specific instance of the more general claim that, like natural scientists, people form and test hypotheses to generate everyday knowledge. George A. Kelly, *The Psychology of Personal Constructs: Volume One—A Theory of Personality* (London: Routledge, 1991 [reprint]), 4–5, 9–11.

31 For invention in science, see Kuhn, *The Structure of Scientific Revolutions*, 8, 52, 66; for discovery in art and design see Ernst H. Gombrich, *Art and Illusion: A Study in the Psychology of Pictorial Representation*, *Mellon Lectures in the Fine Arts* (London: Phaidon Press, 1968 [3rd Edition]); Donald A. Schön and Glen Wiggins, "Kinds of Seeing and Their Functions in Designing," *Design Studies* 13:2 (1992), 135–56.

32 Koestler, *The Act of Creation*, 224–25, 53.

33 Ibid., 236.

34 Perkins, *The Mind's Best Work* , 178.

35 Ibid., 173.

the degree to which the previous concept had prevented exploration (or even perception) of the alternatives becomes apparent as new problem-solution spaces are uncovered.

P7: Conceptual reorientation is resisted.

> In science, … novelty emerges only with difficulty, manifested by resistance, against a background provided by expectation.[63]

Even once recognized, the newly proposed concept proves to be both difficult to comprehend and difficult to accept. Comprehension is inhibited by the fundamentally different perspective that is required, while acceptance is inhibited by the recognition that prior work will be invalidated and future work must proceed from a less well-developed foundation.

P8: Candidate concepts are accepted on promise.

> [T]he new theory is said to be "neater," "more suitable," or "simpler" than the old.… [T]he importance of [these] aesthetic considerations can sometimes be decisive.[64]

Given the potentially well-refined state of the existing concept, new candidate concepts may at first not compete well with those they are proposed to replace. Consequently, new concepts must be accepted for development on the basis of their apparent promise rather than their current performance. This promise may be assessed with respect to qualities that cannot be defended rationally, and with recourse to intuition rather than measurement.

P9: Conceptual reorientations are incomplete.

> [T]he puzzles that constitute normal science exist only because no paradigm that provides a basis for scientific research ever completely resolves all of its problems.[65]

The acceptance of a new concept prompts a renewed process of cumulative design in the hope of developing that concept into a more effective solution to the problem. However, while some of the inadequacies perceived in the preceding concept will now be resolved, some will still remain and others will have been introduced. Later perception of these inadequacies may prompt further conceptual reorientations.

These nine propositions collectively describe creative design as a process of cumulative development punctuated by disruptive reorientations. However, the opportunity to progress from one episode to the next—and to do so repeatedly—is determined by the resources available (e.g. time) and other contextual factors (e.g. motivation). Consequently, any particular project may be entirely constrained to a single period of cumulative design, or may be punctuated by one or more disruptive episodes. These disruptions may also vary in scope, sometimes involving large-scale revolutions in which the entire problem-solution is re-conceptualized, and sometimes involv-

36 Kuhn, "Reflections on My Critics," 243; Kuhn, *The Structure of Scientific Revolutions*, 208; Thomas S. Kuhn, "Comments on the Relations of Science and Art," in *The Essential Tension: Selected Studies in Scientific Tradition and Change* (Chicago: University of Chicago Press, 1977), 348. It is elsewhere claimed that the historical development of art, and also of design, craft, and technology practices can be described in terms similar to those used to describe the development of the natural sciences. For art, see Koestler, *The Act of Creation*, 252, 396; for design, craft, and technology, see Stephen Toulmin, *Human Understanding* (Oxford, UK: Clarendon Press, 1972), 364. Hafner exploits this similarity by using Seuphor's comments on modern art to describe the public's view of science, and also Kuhn's account of scientific revolutions to describe changes in artistic perception. See Hafner, "The New Reality in Art and Science," 390; Michel Seuphor, *Abstract Painting* (New York: Dell, 1964).

37 Kuhn, "Reflections on My Critics," 249–50.

38 Barnes, *T. S. Kuhn and the Social Science*, 15.

39 Wes W. Sharrock and Rupert J. Read, *Kuhn: Philosopher of Scientific Revolution* (Cambridge: Polity Press, 2002); Thomas Nickles, *Thomas Kuhn* (Cambridge: Cambridge University Press, 2003), 1.

40 Eugene Garfield, "A Different Sort of Great-Books List: The 50 Twentieth-Century Works Most Cited in the Arts & Humanities Citation Index, 1976–1983," *Essays of an Information Scientist* 10, (Current Comments 16, 1987), 101–5.

41 Martin Seymour-Smith, *The 100 Most Influential Books Ever Written: The History of Thought from Ancient Times to Today* (Secaucus, NJ: Citadel Press, 1998); also see "The Hundred Most Influential Books since the War," *The Times Literary Supplement* (October 6, 1995).

42 For Kuhn's views on the differences between the natural and social sciences, see Kuhn, *The Structure of Scientific Revolutions*, x, 162–63; and Thomas S. Kuhn, "The Natural and Human Sciences," in *The Road since Structure*.

ing only relatively small-scale shifts in how the purpose, process, or product is regarded. Furthermore, episodes of reorientation may be confined to a single individual, or may be distributed across various stakeholders in the design process. Despite these variations in the frequency of reorientation, its scope, or its distribution, in following Kuhn's arguments it is suggested here that the general structure of creative design progress follows the basic pattern outlined above.

Further Work

This article has drawn on *The Structure of Scientific Revolutions* to propose an account of creative design progress. Despite any similarities that might be found between episodes of scientific progress and those of creative design, Kuhn was essentially intending to describe different phenomena than those that have interested us here. There are consequently aspects of Kuhn's account that are not relevant to the study of creative design, and in particular, he placed special emphasis on issues of incommensurability and narrative reconstruction. Such concepts have not warranted discussion here, and no propositions have been derived from them. However, these concepts and many other aspects of Kuhn's work may be of interest to design scholars attending to other topics, especially those interested in the history of designed objects, and the practice of design research and design education.[66]

This article has argued generally for some connection between scientific discovery and creative design, but we have been limited to exploring the work of only one science scholar—Thomas S. Kuhn. If analogies between scientific discovery and creative design are considered useful, then future work might also benefit from accounts of scientific progress provided by other scholars. Of particular note are Popper's proposed system of conjectures and refutations and Feyerabend's notions of counter-inductive moves.[67] Viewing creative design progress through the various lenses that these and other scholars offer may lead to accounts that support, refine, or challenge those offered here. Whichever of these might occur, attending to work from the well-established and intellectually attractive field of philosophy of science can be expected to yield valuable contributions for design theory.

While there is benefit in using the philosophy of science to develop theoretical accounts of design, it might also be used to inform the planning of empirical studies. For example, we have seen here how viewing creative design episodes through a Kuhnian lens can yield a number of interesting propositions. Such propositions might then be used as the basis for a number of empirical studies that seek to establish the prevalence, determinants, and impact of the described phenomena. These investigations might employ a variety of well-established creativity research methods, including retrospective self-report, controlled experimentation, and protocol analysis. Such work could provide greater insight into the nature of creative

43 For general comments on Kuhn's impact on the social sciences, see Barry Barnes, *T. S. Kuhn and the Social Science* (New York: Columbia University Press, 1982); Steve Fuller, *Thomas Kuhn: A Philosophical History for Our Times* (Chicago: University of Chicago Press, 2000), 1. For application to particular disciplines see, for example, Alfred W. Coats, "Is There a 'Structure of Scientific Revolutions' in Economics?" *Kyklos* 22:2 (1969), 289–96; Allan R. Buss, "The Structure of Psychological Revolutions," *Journal of the History of the Behavioral Sciences* 14:1 (2006), 57–64.

44 For example, see Don Tapscott and Art Caston, *Paradigm Shift: The New Promise of Information Technology* (New York: McGraw-Hill, 1993); Christian Grönroos, "Keynote Paper: From Marketing Mix to Relationship Marketing—Towards a Paradigm Shift in Marketing," *Management Decision* 35:4 (1997), 322–39; Ikujiro Nonaka, Katsuhiro Umemoto, and Dai Senoo, "From Information Processing to Knowledge Creation: A Paradigm Shift in Business Management," *Technology in Society* 18:2 (1996), 203–18.

45 It is worth noting that in comparison to the work of his peers, Kuhn's book is relatively short and accessible, and written in a quite poetic rather than strictly logical manner. Furthermore, Kuhn's book is a comparatively open text that permits or inspires a wide variety of interpretations. In acknowledgment of this, Kuhn stated that: "Part of the reason for its success is, I regretfully conclude, that it can be nearly all things to all people." See Thomas S. Kuhn, "Second Thoughts on Paradigms," in *The Essential Tension*, 293. For a more critical socio-historical explanation of Kuhn's impact, see Fuller, *Thomas Kuhn*.

design in general, and more specifically into how different aspects of creative design progress are related.

In addition to assessing the fidelity of the account provided here, there is also promise in studying what effect an awareness of that account has on design practice. For example, researchers might prime designers with a Kuhnian perspective on creative design and observe what effect the anticipation of conceptual reorientation has on its occurrence. One possibility is that designers would be encouraged to consider any particular perspective on the design problem to be productive while also recognizing it as partial, contingent, and temporary. Phenomena such as "fixation" or "conceptual lock" might therefore be effectively guarded against if designers were to more readily anticipate and accept the disruptive influence of reorientation. Empirical work could potentially determine whether this effect is realized or whether some other unanticipated effect occurs.

Conclusions

This article began by stating that two perspectives on creative progress predominate in the design literature. On the one hand are those accounts that emphasize the effect of sudden insights, and on the other hand are those that emphasize gradual and cumulative change. Unfortunately, these different perspectives have largely existed in mutual isolation or are presented in mutual opposition. In contrast, this article has sought to show that these two perspectives can not only coexist, but should actually be combined. Sudden insights are prompted by—*and resisted because of*—the periods of incremental development that precede them. Each type of episode can only be understood in relation to the other because they are interdependent.

With reference to Kuhn's account of scientific advance, a series of propositions have been developed that characterize periods of cumulative design and episodes of conceptual reorientation. It is contended here that taken as a set, these propositions can sensitize researchers to interesting phenomena that are not emphasized by existing accounts. It is also contended that these propositions can sensitize designers to the structure of creative design progress and thereby aid reflective practice. Future work may be conducted to examine the validity of the propositions presented here, and also the utility they offer to researchers and designers. However, if this article only serves to stimulate interest in the structure of creative progress *in design*, or the promise that Kuhn and other philosophers of science hold *for design*, then this present project will have been worthwhile.

46 For example, see Terence Love, "Philosophy of Design: A Meta-Theoretical Structure for Design Theory," *Design Studies* 21:3 (2000), 295; Terence Love, "Constructing a Coherent Cross-Disciplinary Body of Theory About Designing and Designs: Some Philosophical Issues," *Design Studies* 23:3 (2002), 352; Martin Stacey and Claudia Eckert, "Against Ambiguity," *Computer Supported Cooperative Work* 12:2 (2003), 179; Marco Cantamessa, "An Empirical Perspective Upon Design Research," *Journal of Engineering Design* 14:1 (2003): 3; Kees Dorst, "Design Problems and Paradoxes," *Design Issues* 22:3 (2006), 15; Ipek Ozkaya and Ömer Akin, "Requirement-Driven Design: Assistance for Information Traceability in Design Computing," *Design Studies* 27:3 (2006), 383. For a more extensive consideration of paradigms in design research see Kees Dorst. "Describing Design: A Comparison of Paradigms," PhD Thesis, Delft University of Technology, 1997; Derrick Tate and Mats Nordlund, "Research Methods for Design Theory" (paper presented at the Proceedings of ASME Design Theory and Methodology Conference, Pittsburgh, PA, 2001 [DETC2001/DTM-21694]).

47 This approach, however, is not without its critics. For example, see Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," *Social Studies of Science* 14:3 (1984): 407, 437.

48 Philip Anderson and Michael L. Tushman, "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change," *Administrative Science Quarterly* 35:4 (1990), 604–33. Also see Michael L. Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly* 31:3 (1986), 439–65. For a related perspective in design research see Jerome Jarrett and P. John Clarkson, "The Surge–Stagnate Model for Complex Design," *Journal of Engineering Design* 13:3 (2002), 189–96.

Appendix

To illustrate the rather abstract summary of Kuhn's thesis offered in the main text, an historical example is provided here in which the important features of a scientific paradigm shift can be identified. Kuhn supported his arguments with examples drawn from various scientific disciplines, including Lavoisier's discovery of oxygen, Dalton's invention of atomic theory, and Maxwell's work on electromagnetism. However, we will restrict ourselves to an example from the history of astronomy, in particular, the transition from a geocentric to a heliocentric cosmology. This has the advantage of being a generally well-known scientific advance and of involving episodes that can rightly be regarded as design activities.[68] "The Copernican Revolution" and its aftermath are therefore outlined below, both to clarify the salient features of Kuhn's thesis and also to provide a reference for the propositions developed in the article.

For approximately 1400 years, Man's conception of his place in the cosmos was dominated by an astronomical model proposed by Ptolemy in the first century AD. This held that the Earth was the fixed center of the universe and that the moon, planets, and stars rotated on a number of concentric spheres. Difficulties in achieving a good match between predicted celestial movements and those that were observed led to the development of a complicated Ptolemaic system that involved placing the planets on an ever increasing number of epicycles ("wheels within wheels"). This geocentric system was eventually challenged in the 16th century by Copernicus, who proposed a heliocentric model, with the Earth and other planets orbiting the Sun, and the moon orbiting the earth.

Although Copernicus' model brought us closer to our present understanding of the solar system, he preserved the circular orbits required by Aristotelian dogma. For that reason and others, his model was initially more complex in its details than the well-refined Ptolemaic system with which it was competing. In the century and a half following Copernicus' death, Brahe made more precise observations of the heavens, Kepler defined the nature of elliptical orbits, Galileo developed the law of inertia, and Newton the law of universal gravitation. All these contributions refined the Copernican system into a logically coherent and comparatively precise astronomical model. This model guided observation and theory for over 200 years until Einstein published his work on relativity in the early twentieth century.[69]

In Kuhnian terms, these developments in the history of astronomy would be described as a long period of normal science (the refinement of the Ptolemaic system) that eventually suffered from mounting crises (complications and inaccuracies).[70] A rival paradigm was then proposed (the Copernican system) which was at first resisted (on ideological and technical grounds) but which eventually prompted a paradigm shift (including numerous conceptual reorientations). The articulation and refinement of the

49 Edward W. Constant, *The Origins of the Turbojet Revolution* (Baltimore: Johns Hopkins University Press, 1980), 10–19; Giovanni Dosi, "Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change," *Research Policy* 11:3 (1982): 152–53.

50 Vincenti, *What Engineers Know and How They Know It*, 7–8. Vincenti acknowledges that the term "revolutionary design" might be more historiographically consistent, but he uses the term "radical design" because it implies something less extreme and more in line with engineering terminology, ibid., 260.

51 Warren K. Wake, *Design Paradigms: A Sourcebook for Creative Visualization* (New York: John Wiley & Sons Inc., 2000), 266–71. For a different use of the term "design paradigm," see Henry Petroski, *Design Paradigms: Case Histories of Error and Judgment in Engineering* (Cambridge: Cambridge University Press, 1994).

52 For an exception, see John S. Gero and Mary Lou Maher, *Modeling Creativity and Knowledge-Based Creative Design* (Hillsdale, NJ: Lawrence Erlbaum Associates, 1993), 63. Here, Kuhn is cited to support the contention that what is deemed creative will be determined by society. This might be in reference to comments such as the following: "as in political revolutions, so in paradigm choice—there is no standard higher than the assent of the relevant community." Kuhn, *The Structure of Scientific Revolutions*, 94.

53 Dasgupta, *Creativity in Invention and Design*, 21, 215; Subrata Dasgupta, *Technology and Creativity* (Oxford: Oxford University Press, 1996), 7.

54 Dasgupta, *Design Theory and Computer Science*, 141–42.

55 Dasgupta, *Creativity in Invention and Design*, 8; Dasgupta, *Technology and Creativity*, 52, 84.

56 Dasgupta, *Creativity in Invention and Design*, 208–9.

57 Kuhn, *The Structure of Scientific Revolutions*, 15.

58 Ibid., 52.

59 Ibid.

60 Ibid., 52–53.

new (heliocentric) system constituted another period of normal science. Eventually this too was challenged by an alternative candidate paradigm (Einstein's), one that promised to resolve some of the still existing anomalies (e.g., the advance of the perihelion of Mercury).[71]

61 Ibid., 122.

62 Ibid., 111.

63 Ibid., 64.

64 Ibid., 155–56.

65 Ibid., 79.

66 For comments on the role of education in fostering creativity, see Thomas S. Kuhn, "The Essential Tension: Tradition and Innovation in Scientific Research," in *The Essential Tension*, 237–39.

67 Karl R. Popper, *The Logic of Scientific Discovery* (London: Hutchinson, 1959); Paul Feyerabend, *Against Method: Outline of an Anarchistic Theory of Knowledge* (London: Humanities Press, 1975). For suggestions that Popper provides an appropriate foundation for studying innovation, see Reginald Shareef, "A Popperian View of Change in Innovative Organizations," *Human Relations* 50:6 (1997): 655–70. For Popper's relevance to design see Greg Bamford, "From Analysis/Synthesis to Conjecture/Analysis: A Review of Karl Popper's Influence on Design Methodology in Architecture," *Design Studies* 23:3 (2002), 245–61.

68 Kepler and his contemporaries conceived of the astronomers' task as involving artifice rather than just technical accomplishment. They constructed plans and models of their cosmologies in imitation of the design that they imagined "the Divine Architect" had created. See Nicholas Jardine, "The Places of Astronomy in Early-Modern Culture," *Journal for the History of Astronomy* 29:1 (1998): 53–56.

69 Thomas S. Kuhn, *The Copernican Revolution* (Cambridge: Harvard University Press, 1957); Arthur Koestler, *The Sleepwalkers: A History of Man's Changing Vision of the Universe* (London: Hutchinson, 1959); Jacob Bronowski, *The Ascent of Man* (Boston: Little Brown & Co, 1976).

70 Although Kuhn believed that the Ptolemaic system was in crisis, this point is debated elsewhere by his critics. See Hanne Andersen, Peter Barker, and Xiang Chen, *The Cognitive Structure of Scientific Revolutions* (Cambridge: Cambridge University Press, 2006): 4–5.

71 Kuhn, *The Structure of Scientific Revolutions*, 68–75, 116, 154–56.