"A Science of Design" is a Misled and Misleading Goal[i]

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Abstract

Simon, in advocating for a Science of Design, proposed a linear Rational Model of design as his science's central concept. Such a model occurs naturally to engineers. Indeed, it has been independently formally set forth several times: e.g., by Simon, by Paul & Beitz, and by Royce.

Having a visual, geometric representation of a design process model is crucial, for designers are spatial thinkers. We most easily learn, think about, share, and talk in terms of a model with a clear geometric picture. But the linear, step-by-step Rational Model is **misled** in goal and approach. It does not accurately reflect what real designers do, nor what the best design thinkers identify as the essence of the design process. Science and design are fundamentally different activities.

The goal of a Science of Design is also **misleading**. Its Rational Model leads to the too-early binding of requirements, leading in turn to bloated products and schedule/budget/performance disasters. The Rational Model has persisted in practice despite its inadequacies and plenty of cogent critiques. This is because builders and clients need contracts. Several alternative process models have been proposed. I find Boehm's Spiral Model the most promising. We also need to develop alternative contracting processes, perhaps adapting those from the building community.

1. Design and Science are Fundamentally Different Activities

"Science *n,…*contradistincted from *art.* The distinction as commonly apprehended is that a science is concerned with theoretic truth and an art with methods for achieving certain results." *Oxford English Dictionary*

The Definition Says the Main Point. Scientists learn; designers make. Even when scientists do elaborate engineering to construct their instruments and their experiments, they **make in order to learn.** Even when engineers do elaborate research on particular materials, algorithms, or mathematical models, they **learn in order to make.** The designer's motivation is to "achieve certain results." Hence to talk about a "science of design" seems contradictory. What exactly do we mean?

2. Simon's "Science of Design"

Herbert Simon in his ground-breaking work *The Sciences of the Artificial* (1969) introduced the concept of a "science of design"[ii] (pp. 55-83):

"a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the process of design itself" (p. 58).[iii]

He goes on to set forth the Rational Model of design: a problem-solving model prescribing first the precise formulation of a problem, desiderata, constraints, and utility function; and *then* the systematic search of a hierarchical design space of possible satisficing solutions by generation-followed-by-testing. He says, "…for the theory of design is that general theory of search … through large combinatorial spaces on the side of the task environment." Simon seems to see this Rational Model as the basis for the science he seeks.

I cannot escape the conclusion that Simon originally thought the process of design to be a fruitful target for artificial intelligence, as more sophisticated search and evaluation methods were developed.

Meanwhile, the German mechanical engineering community was evolving a very similar linear (with iteration and feedback loops) model of design, set forth most clearly in Pahl & Beitz's *Konstruktionslehre* (1977; English translation: *Engineering Design,* 1984). This methodology has been widely taught in engineering schools.

In the software field, Winton Royce introduced the Waterfall Model, which is essentially the same linear model. He criticized it as inadequate, but his proposed fix involved adding feedback loops two stages back from the current stage, in addition to those to one stage back.[iv]

A Natural Model. The Rational Model as presented above may seem naïve. But it is a very natural model for people to come up with. This naturalness is strongly corroborated by the independent creation of the Waterfall Model version, the Pahl and Beitz version, and the Simon version.

3. But a Science of Design based on the Rational Model is Sorely Misled

Most Designers Simply Don't Work That Way. Perhaps the most devastating critique of the Rational Model, although perhaps the hardest to prove, is that most experienced designers just don't work that way. So, from its enunciation by Simon in 1969, designers have spoken out with detailed critiques of it.[v] [vi] Interestingly, these critiques have only rarely made the "Emperor has no clothes" statement that the model simply does not reflect professional practice; although as one reads them, one senses that overriding conviction behind all the detailed analyses.

Nigel Cross, in his gentlemanly way, is perhaps the most articulate exception. Citing many careful studies, he says bluntly:

> Conventional wisdom about problem-solving seems often to be contradicted by the behavior of expert designers. But designing has many differences from conventional problem-solving….we must be very wary about importing models of design behavior from other fields. Empirical studies of design activity have frequently found 'intuitive' features of design ability to be the most effective and relevant to the intrinsic nature of design. Some aspects of design theory, however, have tried to develop counter-intuitive models *and prescriptions* for design behavior [emphasis added].[vii]

And,

> The appositional nature of design reasoning has been neglected in most models of the design process. Consensus models of the design process, such as that promulgated by the Verein Deutscher Ingenieure [VDI, 1987]…propose that designing should proceed in a sequence of stages….In practice, designing seems to proceed by oscillating between sub-solution and sub-problem areas, as well as by decomposing the problem and combining sub-solutions."[viii]

Schön's Critique of the Underlying Philosophy. Donald Schön made what seems to me to be the most fundamental of all the critiques. He says that the Rational Model, as enunciated by Simon, is a natural outgrowth of a much more pervasive philosophical mindset, which he calls Technical Rationality and identifies as a heritage of now-discredited Positivism. He finds the underlying philosophy itself totally inadequate for understanding or describing design:[ix]

> According to the model of Technical Rationality—the view of professional knowledge which has most powerfully shaped both our thinking about the professions and the institutional relations of research, education, and practice—professional activity consists in instrumental problem solving made rigorous by the application of scientific theory and technique….From the point of view of Technical Rationality institutionalized in the

> professional curriculum, real knowledge lies in the theory and techniques of basic and applied science…Technical Rationality is the Positivist epistemology of practice….In the light of such Positivist doctrines as these, practice appeared as a puzzling anomaly. Practical knowledge exists, but it does not fit neatly into Positivist categories….[But] Increasingly we have become aware of the importance to actual practice of phenomena—complexity, uncertainty, instability, and value-conflict—which do not fit the model of Technical Rationality….
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> From the perspective of Technical Rationality, professional practice is a process of problem solving. Problems of choice are decision are solved through the selection, from available means, of the one best suited to established ends. But with this emphasis on problem solving, we ignore problem setting, the process by which we defined the decision to be made, the ends to be achieved, the means which may be chosen. In real-world practice, problems do not present themselves to the practitioner as givens. They must be constructed from the materials of problematic situations which are puzzling, troubling, and uncertain….a practitioner must do a certain kind of work. He must make sense of an uncertain situation that initially makes no sense….It is this sort of situation that professionals are coming increasingly to see as central to their practice….Technical Rationality depends on agreement about ends.
>
> [Simon] has identified a gap between professional knowledge and the demands of real-world practice….Simon proposes to fill the gap…with a science of design, his science can be applied only to well-formed problems already extracted from situations of practice.
>
> If the model of Technical Rationality…fails to account for practical competence in "divergent" situations, so much the worse for the model. Let us search, instead, for an epistemology of practice implicit in the artistic, intuitive processes which some practitioners do bring to situations of uncertainty, instability, uniqueness, and value conflict.[x]

Kalay and Carrara. A less polemical but also more specific early critique from the architectural community provides a hint as to what form a better design model might take.

> The assumption that, in architecture, the characteristics of the desired solution can be formulated prior to and independently of the search for the solution that satisfies them was rejected by critics like Archea [1987][xi] and Bijl [1987][xii]. They argued that such knowledge cannot exist prior to the search itself, since the sought solution is unique, and the process of finding it is characterized by discovery and has to contend with uncertainty. Kim [1987][xiii] and others have argued that the brief that architects are given by their clients, and which often constitutes the basis for design goals, is much too vague, in most cases, to form a complete goal statement. Rather, it is merely a statement of întents, which defines a general framework for the sought solution, and some of the constraints it must abide by. Instead, they suggest that architects must gradually develop the statement of goals [requirements] as they proceed with the design process itself. The additional information needed to complete the goal statement must either be invented as part of the search process, or adapted from generalized precedents, prototypes, and other relevant past experiences [of the designers themselves or the whole design community]. Since the relationship between [this information and these precedents] can be discovered only as the problem becomes clearer, the adaptation itself is problem-specific and cannot be accomplished prior to engaging in the search process itself."[xiv]

4. Despite These Flaws, the Rational Model Persists as the Basis of a "Science of Design"

Writing as recently as 2006, design researcher Keest Dorst has to admit,

> Although there have been many developments since then, the original work on problem solving and the nature of ill-structured problems, written by Herbert Simon, still looms large of the field of design methodology. The rational problem-solving paradigm, based on the conceptual framework that Simon introduced, is still a dominant paradigm in the field. Design models and methods have been developed within this paradigm; the

conceptual framework of rational problem solving has become the normal "language of thinking and talking about design".[xv]

Indeed so! In the field of software engineering, we all too often still slavishly follow the Waterfall Model.

Verein Deutscher Ingenieure Standard VDI-2221. The Verein Deutscher Ingenieure in 1986 adopted the Rational Model, essentially as set forth by Pahl & Beitz, as an official standard for German mechanical engineering.[xvi] I have seen many rigidities in thinking engendered by this move.

DoD Standard 2167. Similarly the U.S. Department of Defense in 1985 enshrined the Waterfall Model in DoD Standard 2167.[xvii] Only in 1994 did they, under the leadership of Barry Boehm, open up their acquisition by admitting other models.

Why Has This Flawed Model Persisted? How can we explain the persistence of the waterfall model, when the greater fidelity of the spiral and co-evolutionary models has been seen for more than a quarter-century?

The one-word answer is *sin*. Because humans are fallen, we cannot trust each other's motivations. Because humans are fallen, we cannot communicate perfectly. For these reasons, "Get it in writing". We need written agreements for clarity of communication; we need enforceable contracts for protection from misdeeds by others and temptations for ourselves. We need detailed enforceable contracts even more when the players are multi-person organizations, not just individuals. Organizations often behave worse than any member would.

Clearly, it is the necessity for contracts, whether within an organization or between organizations, that force the too-early binding of goals, requirements, constraints, etc. Everyone recognizes the fact that these must later be changed. (This opens new opportunities for wrong-doing. "Low-ball on the contract; make it up on the change orders.") So it seems that the necessity for contracts best explains the persistence of the waterfall model for designing and building complex systems.

A Model for Contracting. The pressure for a complete and agreed-upon set of requirements comes ultimately from the desire for a fixed-price contract for a specific deliverable. This is especially true for software engineering, where the habit of fixed-price contracts got established before we knew what we were doing. This desire comes irreconcilably up against the hard fact that it is essentially **impossible to specify a complete and accurate set of requirements for any complex system except in interaction with the design process**.

How have the centuries-old building design disciplines handled this quandary? Fundamentally, by a quite different contracting model. Consider a normal building design process:

- The client develops a **brief,** which is a **functional program** not a specification, and a **target budget** for the building.
- He contracts with an **architect,** usually on an hourly or percentage basis, for **services**, not for a **specified product.**
- The architect **elicits** from the client, the users, and other stakeholders, a **more complete program,** which even then does not pretend to be a rigid contractable product specification.
- The architect does a **conceptual design** which approximates the reconciliation of program and budget, schedule, and constraints. This serves as a first **prototype,** to be **conceptually tested** by the stakeholders. In this design and this testing a much more precise statement of goals (requirements) evolves, often iteratively.

- The architect performs **design development**, often producing more detailed drawings, a 3-D scale model, mock-ups, etc. These typically enable a rough cost estimate. After stakeholder iteration, the architect produces **construction drawings and specifications.**
- The client uses these drawings and specifications to enter into a **fixed-price contract** for the product.

Notice how this long-evolved model separates the contract for design from the contract for construction. Even when both are performed by the same organization, this separation clarifies many things.

Of course, this model isn't really linear, either. Construction problems will occasion design changes and hence contract changes. Client assessment of the developing product will independently occasion needed changes not discovered from any of the prototypes.

The wisdom of this approach has been recognized by a study group of the Air Force Studies Board. In their report, "Pre-Milestone A and Early-Phase Systems Engineering", they conclude:

> The committee believes that getting to a state of clear and complete system-level requirements requires the interaction with potential contractors that occurs between Milestones A and B.[xviii]

5. So What? Does a Mistaken Design Process Model Mislead Us?

Why all this fuss about the process model? Does the model we and others use to think about our design process really affect our designing itself? I believe it does.

Not Every Design Thinker Agrees with Me. Prof. Ken Wallace of Cambridge, who translated three editions of Pahl and Beitz's work into English, believes the major step forward is to have some model that is readily understood and communicated. He points out how useful it is for beginning designers. The Pahl and Beitz model gives the novice a place to start work on a design, so he doesn't just wander. Wallace says, "I put up the Pahl and Beitz diagram, and explain it. And then my very next slide says, 'But this is not the way real designers work.'"[xix] Hooray! But I am concerned that younger teachers with less personal design experience do not always say that.

Suzanne and James Robertson, internationally practiced consultants and authors of excellent major works on requirements engineering, also feel that the deficiencies in the Rational Model don't really matter. "Everybody knows better."[xx]

Nevertheless, I believe our inadequate model and its slavish following leads to fat, cumbersome, over-featured products and to schedule, budget, and product performance disasters.

Right-Brained Designers. Designers are right-brained people, visually and spatially oriented. Indeed, one of my curbstone tests for potential design talent is to ask, "Where is next November?". If my listener is puzzled, I elaborate, "Do you have a spatial mental model of the calendar? Many folks do. If you do, would describe it for me?" The strong candidates almost always have one; the models themselves vary wildly.

Similarly, software design groups invariably scrawl diagrams, not words or code, on their shared whiteboards. Architects consider the broad-pen sketch on "trash" an indispensable tool for communication, but even more for solo thinking.

Since we designers are spatial people, our process models live deep in our minds as diagrams, whether Pahl & Beitz's vertical rectangle, Simon's tree, or even the waterfall Royce draws and condemns. The diagrams subconsciously influence much of our thinking. Hence I believe a deficient process model hinders us in ways we cannot fully know and can barely suspect.

Mis-educating Designers. One obvious injury done by accepting the Rational Model is that we mis-educate our successors. We teach them modes of working that we ourselves do not follow. Hence we leave them unaided in arriving at their own real-world working modes.

I doubt if this is the case with more senior teachers, particularly those with design experience in industry. We are keenly aware that models are intentional over-simplifications to help us with real-life problems that are frighteningly complicated. So we warn our students that "the map is not the terrain"; the model is not a complete picture; it may even be inaccurate in what it does incorporate.

Requirements Before Design. In our own discipline, software engineering, the most serious harm can readily be spotted—the Rational Model, in any of its forms, leads us to demand up-front statements of design requirements. It leads us to believe that such can be formulated. But they can't. As Pahl says in his latest edition,

"Any attempt to formulate all possible requirements at the start of a project will fail and would cause considerable delays."[xxi]

This demand for up-front requirements leads us to make contracts with one another on the basis of this enshrined ignorance. A more realistic process model would make design work more efficient, obviating many arguments with clients and much rework.

5. But Perhaps I'm Just Plain Wrong

I may be just plain wrong in identifying the current pursuit of a "Science of Design" with Simon's goal and consequently with the Rational Problem-Solving Model of design. If so, I would welcome a clear statement of what contemporary advocates mean precisely by *a science of design*.

Notes and References

[i] This position paper is taken with modifications from my forthcoming book, *The Design of Design,* to be published by Addison-Wesley in 2009. Both book and this paper © Frederick P. Brooks, Jr.

[ii] Simon, Herbert A., (1969, 1981, 1996), *The Sciences of the Artificial,* Cambridge MA, MIT Press. 123 pp.

[iii] There is indeed already a "science of design," if by that one means the psychological study of the mental processes of designers, or the anthropological study of the culture and interactions of design teams, clients, implementers, other stakeholders. This discipline is called *design research.* Its first journal, *Design Studies,* is in its 29th year; now there are many more journals, conferences, Ph.D. degree programs. But that does not seem to be what Simon is talking about; he is clearly proposing a science with prescriptions as to how to do design and methodologies for doing it rigorously. And Simon's science seems to be what the NSF and others in fact mean by "Science of Design." This paper shall assume Simon's meaning for the term.

[iv] Royce, Winton [1970], "Managing the Development of Large Software Systems," *Proceedings of IEEE Wescon*.

[v] Surprisingly, I found few critiques of the Pahl and Beitz formulation of the Rational Model and many of Simon's formulation. Pahl and Beitz themselves recognized the inadequacy of the model: in successive editions of their work, their model includes more and more explicit iteration steps [Pahl & Beitz, 1984, 1996, 2007]. Simon's three editions of *The Sciences of the Artificial* do not reflect any change in the model as proposed, although in personal conversation with me in November, 2000, he said that his own

understanding of the model had evolved, but that he had had no opportunity to rethink and rewrite accordingly.

Willemien Visser's *The Cognitive Artifacts of Designing* [2006] has an excellent Section 9.2, "Simon's More Nuanced Positions in Later Work," which examines Simon's evolution as embodied in later papers. Visser shares my surprise that this evolution didn't get reflected in the later editions of *The Sciences of the Artificial*.

[vi] J. E. Holt, D. F. Radcliffe and D. Schoorl [1985], "Design or problem solving — a critical choice for the engineering profession", *Design Studies*, **6**, 2, 107-110:

> There are two distinct interpretations of engineering design. The problem-solving approach, popular in many tertiary institutions and with an emphasis on solving structured, well defined problems using standardized techniques, may be traced to 'hard' systems thinking. The creative design approach, on the other hand, combines analytical and systems thinking with human factors in engineering design to create and take advantage of opportunities to serve society. This paper discusses the limitations of the problem-solving approach in dealing with many real world tasks.

[vii] Cross, Nigel [2006], *Designerly Ways of Knowing,* London: Springer, p. 27

[viii] Cross, [2006], p. 57

[ix] Schon, D., *The Reflective Practitioner* [1983], pages 21-49

[x] Dorst, K. and J. Dijkhuis [1995], "Comparing paradigms for describing design activity", in *Design Studies,* **16**, 2, have an especially good discussion of Simon vs Schön. Their journal article is reprinted in Cross, Kristiaans, & Dorst, *Analysing Design Activity*[1996]. Dorst & Dijkhuis also show that for the Delft II protocols, Schön's model fits the observed designer behavior much more accurately.

[xi] Archea, J., [1987], "Puzzle-making: What architects do when no one is looking", in Kalay, Y. (ed.) Computability of Design, New York: Wiley.

[xii] Bijl, A. [1987], "An approach to design theory", in Yoshikawa, H. & E. Warman, (eds), *Design Theory in CAD*, Amsterdam: North Holland"

[xiii] Kim, M.K [1987], "Development of machine intelligence for inference of design intents implicit in design specifications", in Kalay [1987].

[xiv] Kalay, Y. & G. Carrara [1995], "A Performance-Based Paradigm of Design" in Gero, J. & F. Sudweeks, *Advances in Formal Methods for CAD*, London: Chapman & Hall, pp. 111-112.

[xv] Dorst, K. [2006], "Design Problems and Design Paradoxes", Design Issues, **22**, 3.

[xvi] Verein Deutscher Ingenieure [1986], *VDI-2221: Systematic Approach to the Design of Technical Systems and Products.*

[xvii] DOD-STD-2167A tried to fix this, but unfortunately put a waterfall diagram in a prominent place and left things pretty much as they were.

[xviii] Air Force Studies Board, National Research Council, Committee on Pre-Milestone A System Engineering [2008]. This summary quote is a personal communication to me from James Garcia, staff officer for the committee.

[xix] Personal communication, 2008.

[xx] Personal communication, 2008.

[xxi] Pahl & Beitz [2007], *Engineering Design.*