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DesignX: Complex Sociotechnical Systems

Abstract This paper is a follow up to DesignX, a position paper written in 2014, which introduced the design challenges of complex sociotechnical systems such as healthcare, transportation, governmental policy, and environmental protection. We conclude that the major challenges presented by DesignX problems stem not from trying to understand or address the issues, but rather arise during implementation, when political, economic, cultural, organizational, and structural problems overwhelm all else. We suggest that designers cannot stop at the design stage: they must play an active role in implementation, and develop solutions through small, incremental steps – minimizing budgets and the resources required for each step – to reduce political, social, and cultural disruptions. This approach requires tolerance for existing constraints and trade-offs, and a modularity that allows for measures that do not compromise the whole. These designs satisfice rather than optimize and are related to the technique of making progress by "muddling through," a form of incrementalism championed by Lindblom.

Keywords
Sociotechnical systems
DesignX
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Complex Sociotechnical Problems

In the fall of 2014, a number of us found ourselves in Shanghai as advisors to the newly formed College of Design and Innovation at Tongji University. We asked ourselves how design could address the complex issues that the world currently faces. The issues are not new: many have grappled with them for some time. But how can designers play a role? And how should design professionals be educated to prepare for that role?

Complex societal systems such as healthcare, transportation, government policy implementation, and environmental protection have many components – technical and otherwise – whose interactions are critical to the system's overall behavior. Many different fields contribute to the efficiency of these systems, including in recent years, design. Fulfilling this role is very different from producing the traditional craftwork that originally characterized the design profession. With the advent of human-centered design methods and design thinking, many designers and design consultancies have started to work in complex sociotechnical arenas.

Do the current methods taught in design education, especially considering its emphasis upon traditional craft, prepare designers for work in and with complex sociotechnical systems? What can design add, and what needs to be added to design? The emphasis on perfecting craftsmanship using a variety of materials would seem no longer necessary, while enhancing problem-finding and observational skills, and cultivating an ability to manage iterations of prototyping and testing do seem relevant.

The 2014 DesignX position paper described the nature of these issues, and offered a framework for designers to address them.[1] We didn't know what to call the kind of design that might be associated with our approach, and after many iterations of the name, we simply called it 'X' – as in the algebraic variable traditionally used to represent an unknown value. The authors of the position paper do not claim to be the first to tackle these issues; the field of sociotechnical systems (STS) has long grappled with them.[2] The Systemic Design Network, and its series of conferences on Systems Thinking and Design,[3] and the Transition Design program at the School of Design at Carnegie Mellon University – among others[4] – are addressing many of these same concerns. Many individual designers have also, of course, considered these issues.[5]

The aim of the present work is to build upon the foundations laid in the 2014 DesignX paper. Our writing has been informed by the passage of time, and the input of a large number of researchers, published works, and conferences – including a DesignX two-day workshop at the College of Design and Innovation at Tongji University, Shanghai, in October 2015. That workshop produced a number of case studies and a lively discussion that we seek to continue here. This paper reflects our learnings from all these encounters, but only represents the opinions of its two authors, and thus should not be taken to represent the conclusions of the workshop or any other participant. Our goal is to provide readers with a piece that provokes thought and stimulates discussion.

DesignX Problems: An Example

Abstract principles require concrete examples. The Design Lab at the University of California, San Diego (UCSD) has recently started several major projects in collaboration with the UCSD Health Sciences departments and university hospital system to examine and – ideally – enhance the care of cancer patients receiving radiation treatment (Radiation Oncology).

Administration of radiation oncology treatment typifies the complexity of DesignX tasks. At least twelve different medical specialties are involved. A typical

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[1] Friedman, Ken, Yongqi Lou, Don Norman, Pieter Jan Stappers, Ena Voûte, and Patrick Whitney, "DesignX: A Future Path for Design," *jnd.org*, last modified December 4, 2014, accessed November 11, 2015, http://www.jnd.org/dn.mss/designx_a_future_pa.html, also available at http://tinyurl.com/designx-statement; Donald A. Norman, "Why DesignX? Designers and Complex Systems," *Core77* (blog), December 6, 2014, http://www.core77.com/posts/27986/why-designx-designers-and-complex-systems-27986.

[2] According to one definition, STS is "an approach to complex organizational work design that recognizes the interaction between people and technology in workplaces." See "Sociotechnical system," *Wikipedia*, last modified November 12, 2015, cited version accessed October 19, 2015, https://en.wikipedia.org/w/index.php?title=Sociotechnical_system&oldid=680567062.

[3] RSD5 Symposium: Systemic Design for Social Complexity: Relating Systems Thinking and Design, accessed November 11, 2015, http://systemic-design.net/.

[4] "Transition design," *Wikipedia*, last modified December 5, 2015, accessed October 19, 2015, https://en.wikipedia.org/wiki/Transition_design.

[5] For example, see Peter H. Jones, *Design for Care: Innovating Healthcare Experience* (Brooklyn, NY.: Rosenfeld Media, 2013); Peter H. Jones, "Systemic Design Principles for Complex Social Systems," in *Social Systems and Design*, ed. Gary S. Metcalf (Tokyo: Springer Japan, 2014), 91–128.

radiation treatment uses one of several large linear accelerator machines that can rotate the beam around the body, shaping the beam as required, with the center of rotation of the delivery mechanism calibrated to minimize exposure of intervening tissue and organs and maximize exposure at the target area. Typical treatment plans might involve 15-minute treatments once a day, five days a week, for six to eight weeks.

Radiation oncology treatment requires consultation with multiple specialists, as well as with multi-disciplinary review boards. Obtaining an appropriate diagnosis and then determining the appropriate radiation prescription draws on the expertise of a number of different departments, each with its own scheduling difficulties, each requiring the patient's up to date medical history and results of any ongoing tests, including MRIs, CT scans, and X-rays. Once a patient is admitted for treatment, a number of specialists are involved in confirming, reviewing and then administering the prescribed radiation dosage to precisely the desired treatment location. Daily treatments might last for months. The flow diagram of the processes and stages in each process is extremely complex, requiring multiple diagrams at different levels of detail. There are multiple feedback loops.

The real complexity, however, arises from issues that are seldom portrayed in flow charts: disciplinary differences and priorities, facilities availability, and scheduling issues between patients and core staff. Even something as simple as a scheduling conflict can have serious repercussions, because a typical treatment requires daily treatment for six to eight weeks: if the lengthy series of daily treatments turns out not to be possible for the patient, a completely different course of treatment must be substituted.

It is important to note that departments have very different organizational structures, even within the same hospital. Thus, Design Lab researchers' initial observations of the Emergency Department in the same hospital as the Radiation Oncology clinic reveal very different characteristics. Once a diagnosis and treatment plan have been determined, the day-to-day operations of Radiation Oncology are very straightforward, with most patients following a reasonably standard daily treatment plan over many weeks. All events are scheduled. As a result, there are few emergencies, few unexpected cases and contingencies. Naturally, the Emergency Department follows a completely different pattern: it must deal with a wide variety of medical situations, from cuts and bruises to life-threatening injuries. Unexpected events are the usual state of affairs. Patients seldom stay longer than a few hours before they are either discharged or transferred to a ward in the hospital. The organizational structure is flexible, and although operations seem somewhat chaotic, the considerable amount of structure and discipline involved are clearly not apparent to a casual observer.

The two different departments – Radiation Oncology and Emergency – lie at two extremes of the healthcare spectrum, one with well-established protocols and scheduled treatment processes, the other contending with continual surprises and unexpected events. They each represent different aspects of DesignX problems, with Radiation Oncology having the added complexity of establishing long-term compatibility across multiple disciplines, departments, and individual schedules. In addition, the shifting trajectory of the disease being treated requires multiple types of imaging and invasive testing, including biopsies. Then there are the difficulties related to precisely controlling the radiation beam, or contending with internal organ shifting between the time they were imaged and the time of radiation treatment. Although the Emergency Department differs from Radiation Oncology in that all its events are unscheduled, its collaborative element has similar requirements. In the case of Radiation Oncology, it is usually permissible to wait until all the relevant specialists have completed their analyses, whereas in the

Emergency Department time is of the essence, and sometimes work must begin before the relevant specialists arrive.

Healthcare presents DesignX problems composed of multiple DesignX components, each of which has different characteristics.

What Makes a Design Problem DesignX?

Although new to the design community, complex sociotechnical systems have been studied for decades. We have taken our findings from the literature on sociotechnical systems theory (especially those concerned with "soft" systems), the human factors and ergonomics community and, more recently, the field of cognitive systems engineering.[6] From this work plus our own analyses, we propose that there are nine properties, divided into three categories, that characterize DesignX problems. The first category, *The Psychology of Human Behavior and Cognition*, has to do with human psychology and the natural human tendency to seek simple explanations and answers even for complex problems. This category describes why people have such difficulty comprehending and dealing with the issues. The second category, *The Social, Political, and Economic Framework of Complex Sociotechnical Systems*, reflects fundamental characteristics of sociotechnical systems that require most solutions to involve complex tradeoffs, which means that almost any approach will be viewed as beneficial by some and harmful by others. Finally, the third category, *The Technical Issues that Contribute to the Complexity of DesignX Problems*, contains additional technical issues that contribute to the complexity of DesignX systems. All three categories contribute to the difficulty in understanding the problems but the first two categories dominate the attempt to implement a solution. To summarize, here are the nine properties, divided into the three categories:

The Psychology of Human Behavior and Cognition

1. System Design that Does Not Take into Account Human Psychology.
2. Human Cognition: The Human Tendency to Want Simple Answers, Decomposable Systems, and Straightforward Linear Causality.

The Social, Political, and Economic Framework of Complex Sociotechnical Systems

3. Multiple Disciplines and Perspectives
4. Mutually Incompatible Constraints

The Technical Issues that Contribute to the Complexity of DesignX Problems

5. Non-Independence of Elements
6. Non-Linear Causal Relations: Feedback
7. Long and Unpredictable Latencies
8. Multiple Scale Sizes
9. Dynamically Changing Operating Characteristics

The Psychology of Human Behavior and Cognition

1. System Design that Does Not Take into Account Human Psychology

Engineers have been heard to say "if it weren't for people, our systems would work just fine," usually uttered after some accident has been blamed on "human error." On the contrary, when it comes to complex systems, if it weren't for people, the system wouldn't have worked at all. Moreover, the whole point of these systems is to aid some component of human or societal life, so you could say that "if it weren't for people, we wouldn't have to build complex systems such as healthcare, environmental control, education, transportation, etc."

Most of the major disasters in complex sociotechnical systems have been severely impacted and sometimes caused by a lack of good human-factors and human-centered design. The Human-Systems Integration division of the American

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[6] Our sources are too numerous to list here, but representative sources include the works of Pascale Carayon, "Human Factors of Complex Sociotechnical Systems," *Applied Ergonomics* 37, no. 4 (2006): 525–35; Peter Checkland, *Systems Thinking, Systems Practice* (New York: John Wiley & Sons, 1981); Michael C. Jackson, *Systems Thinking: Creative Holism for Managers* (Chichester, England; Hoboken, NJ.: John Wiley & Sons, 2003); Jones, *Design for Care*; W.B. Rouse, K. R. Boff, and P. Sanderson, *Complex Socio-Technical Systems: Understanding and Influencing the Causality of Change*, Tennenbaum Institute Series on Enterprise Systems (Amsterdam: IOS Press, 2012); Dean F. Sittig and Hardeep Singh, "A New Socio-Technical Model for Studying Health Information Technology in Complex Adaptive Healthcare Systems," supplement, *Quality & Safety in Health Care* 19, no. 3 (2010): i68–i74, http://dx.doi.org/10.1136/qshc.2010.042085; Dean F. Sittig and Hardeep Singh, "Defining Health Information Technology-Related Errors: New Developments Since *To Err is Human*," *Archives of Internal Medicine* 171, no. 14 (2011): 1281–84; Gordon Baxter and Ian Sommerville, "Socio-Technical Systems: From Design Methods to Systems Engineering," *Interacting with Computers* 23, no. 1 (2011): 4–17.

National Academies has carefully analyzed major system failures for decades, pinpointing the design deficiencies.[7]

The existing designs often reveal incompatibility between people's capabilities and the requirements put upon them. For example, people are asked to monitor events for long periods with little happening, yet to be able to take over rapidly when some abnormality occurs. Moreover, people are asked to provide the accuracy and precision required by the technology. All these conditions are well known and documented to be poor fits to human capabilities. Finally, human strengths in devising creative solutions to novel situations, to be flexible and accommodating, and to improvise where there technology falters are badly supported, sometimes even forbidden.

There is a tendency to design complex sociotechnical systems around technological requirements, with the technology doing whatever it is capable of, leaving people to do the rest. The real problem is not that people err; it is that they err because the system design asks them to do tasks they are ill suited for. Unfortunately, there is a tendency to blame people for the error rather than to find the root cause and eliminate it. On the whole, complex sociotechnical systems are poorly designed to fit the capabilities and powers of the people who must operate them.

2. Human Cognition: The Human Tendency to Want Simple Answers, Decomposable Systems, and Straightforward Linear Causality

People have multiple capabilities, including the great creativity and flexibility to devise workarounds to problems, allowing systems to keep running despite equipment failures and the occurrence of unexpected events that the normal system cannot deal with. People are good at visualizing and understanding systems – ones that have relatively independent components with linear causal relationships – but this ability becomes a handicap when complex systems are non-linear, with multiple feedback loops and long latencies. In these cases, people are predisposed to discover simple causal relationships, even where there are none. As a result, people tend to oversimplify complex systems, to seek relatively simple and straightforward answers, and to expect results within a relatively short time.

These tendencies cause difficulties when dealing with non-decomposable, non-linear causal systems. A major difficulty in both understanding and then dealing with DesignX problems is the human tendency to seek simple answers to complex problems.

The Social, Political, and Economic Framework of Complex Sociotechnical Systems

3. Multiple Disciplines and Perspectives

The presence of multiple disciplines and perspectives has its largest influence in design and maintenance, for each discipline brings different forms of expertise, and perspectives, resulting in emphasizing different aspects of the problem. Each discipline has different value systems. In addition, they all are apt to speak different technical languages, where quite often the same terms are used with quite different meanings. These differences can also impact the smooth running of the system. In the best of cases, these different participants combine their expertise in creative, effective ways, often compromising goals and principles for the greater good. In the worst of cases, there can be strong ideological and political arguments behind the scenes that disrupt collaboration.

4. Mutually Incompatible Constraints

DesignX problems often have numerous constraints, often contradictory, not readily comparable with one another. Constraints arise from regulatory agencies,

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[7] **"Board on Human-Systems Integration," National Academies of Sciences, Engineering, Medicine, accessed November 11, 2015, http://sites.nationalacademies.org/dbasse/bohsi/index.htm.**

laws, economic and business issues, safety concerns, the quest for efficiency and productivity, and different cultural practices among the disciplines. Although dealing with incompatible constraints has long been a key component of design, with DesignX problems, the scale of the resulting political and cultural debates is novel.

The Technical Issues that Contribute to the Complexity of DesignX Problems

5. Non-Independence of Elements

Engineering designers have the luxury of designing complex technical systems that lack the social/human component of sociotechnical systems. As a result, they can take a more idealistic approach to the construction of the system. Thus Nam Suh, in his *Axiomatic Design*,[8] points out that systems are much simpler to understand, manage, and design and are far more orderly and predictable if they are comprised of independent parts. In fact, this is such a basic need that it becomes *Axiom 1* of Suh's *Axiomatic Design*. The aim is notable. The designer should attempt to maximize the independence of stages, and if dependence is required, make it be one-way, not two-way. That is, ideally any two components, A and B, should be independent of one another, but if B depends upon A, even indirectly, ensure that A does not depend upon B, not even indirectly. Two-way dependencies (where A affects B and vice-versa) should be avoided. Most complex physical systems cannot entirely avoid these interdependencies, but minimizing their number and scope is a worthwhile technique.

Modularity is, of course, a well-known design principle in every design discipline, including engineering design, computer systems, and programming. But although modularity – and the implication of independence of modules – is obvious and easy in relatively simple products and services, it becomes extremely difficult or impossible in large, complex systems. With sociotechnical systems, it is seldom possible to follow the Independence Axiom: two-way or even *n*-way interdependencies are common. Moreover, these interdependencies are often unknown, discovered only after the fact.

One example is the scheduling difficulties discussed earlier for healthcare: the normal flow of operations is to diagnose the ailment and decide upon a treatment plan. The plan then determines the schedule of treatment: a one-way dependency. But when the patient (or the organization) is unable to maintain the multi-day schedule, or complications arise, this requires revision of the treatment plan: creating a two way-dependency. When patients have multiple chronic conditions, a common occurrence in the elderly, there are numerous different professionals involved in the treatment, with complex interconnections among them (including, in some cases, a lack of communication). These problems defy easy analysis.

6. Non-Linear Causal Relations: Feedback

Probably the most important characteristic of a DesignX problem is the existence of feedback loops. Feedback changes the behavior of the system, making it impossible to understand the whole through understanding each of its parts. Instead, the system must be analyzed for emergent behavior. It is no longer possible to solve each step independently of the others. Issues of delayed effects, amplification, and stability arise, along with unforeseen emergent behaviors. Feedback can also be coupled with learning, thus dynamically changing the system's operating characteristics.

The non-independence of elements combined with non-linear causal relations and feedback reveals yet another component of these sociotechnical

[8] Nam Pyo Suh, *Axiomatic Design: Advances and Applications*, The MIT-Pappalardo Series in Mechanical Engineering (New York: Oxford University Press, 2001).

systems: the inter-relationships among the components can be more important than the components; but the notation used for the diagrammatic representation of these systems is often not helpful. It often has numerous boxes connected by arrows that show the flow of information and the sequencing of steps. These box-and-arrow diagrams invite the reader to track a linear storyline, instead of considering a complex set of balances.[9] These diagrams hide the informal communications that take place within the arrows, and often ignore the operational situation. For example, in all the charts we have seen of medical procedures, there is no hint of scheduling differences, of the large number of interruptions that lead to errors, or of the workaround that happens when critical information – so neatly depicted by a box or arrow – is not available.

7. Long and Unpredictable Latencies

One of the complexities is that the time scales of the various system components vary. Moreover, the necessary feedback loops are often uncertain and with long and often unpredictable latencies. Feedback is essential for stability, and when latency is long, it can lead to undesirable outcomes, sometimes in the opposite direction than intended, or to instabilities (oscillations). In some areas – for example, treatment of patients in emergency rooms – feedback is often impossible. When patients are discharged, the ones that recover never return, so their recovery cannot be documented. Similarly, patients who do not recover may decide to go to a different facility for further treatment, making it difficult to track the patient's history.

8. Multiple Scale Sizes

DesignX problems require understanding and action from micro to larger macro sizes, from short time periods to long ones. On the one hand, individual components can be small or with a short time scale, such as decisions about an interface element or a procedural step. On the other hand, things like supply chains, standards that serve multiple stakeholders in different situations, legal constraints, decision making groups, scheduling issues, and long-term productivity often are large, complex processes in themselves, with time frames measured in hours, days, and even years. Moreover, there are interactions between the levels of scale and abstraction.

As is common with each of DesignX's critical properties, each has often been the focus of considerable study. For example, in the case of multiple scale sizes, the field of ecological interface design uses an explicit analysis of the different levels of abstraction in systems to guide the design process.[10]

9. Dynamically Changing Operating Characteristics

The properties of complex systems are continually undergoing change. Sometimes it is due to component failure, sometimes due to modification of the system, or the replacement of an aging or failing component with a new one whose characteristics are different from those of the original. Sometimes it is deliberate, as more and more systems are self-adjusting and capable of learning.

In our studies of human error and, more recently, how people interact with autonomous vehicles,[11] we have found other sources of change. People learn to manipulate the systems to do completely new activities, ones not contemplated in the design. Sometimes safety features are used as fundamental controls, so they are no longer safety checks. Sometimes people discover how to take advantage of the system design, deliberately misusing the systems when they discover that by doing so, they get beneficial results.

One of the difficulties of studying and trying to enhance these systems is that when they become large and complex enough, many independent committees,

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[9] Pieter Jan Stappers and John M. Flach, "Visualizing Cognitive Systems: Getting Past Block Diagrams," in *IEEE International Conference on Systems, Man and Cybernetics (SMC), 2004*, vol. 1 (The Hague: IEEE, 2004): 821–26, http://dx.doi.org/10.1109/ICSMC.2004.1398404.

[10] Kim J. Vicente, "Ecological Interface Design: Progress and Challenges," *Human Factors* 44, no. 1 (2002): 62–78; Jens Rasmussen, *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*, North-Holland Series in System Science and Engineering, vol. 12 (New York: Elsevier Science Ltd., 1986).

[11] Donald A. Norman, *The Design of Future Things* (New York: Basic Books, 2007); Donald A. Norman, *The Design of Everyday Things: Revised and Expanded Edition* (New York; London: Basic Books; MIT Press (British Isles only), 2013); Donald A. Norman, "The Human Side of Automation," in *Road Vehicle Automation 2*, ed. Gereon Meyer and Sven Beiker (Cham, Switzerland: Springer, 2015), 73–79.

decision makers, and rule-makers are simultaneously making changes, often without informing all the relevant parties. Sometimes these are mechanical and structural changes. Sometimes new technologies will be introduced. Sometimes there will be a major organizational restructuring, with new groups formed and old ones disbanded. Sometimes there will be new regulatory, safety, or cost efficiency policies that change the nature of the operation.

Approaches to Complex Sociotechnical Problems

DesignX problems involve complex sociotechnical systems, which by definition involve a complex, non-linear mix of people and technology. The mix of human and social aspects is the major contributor to the difficulty in managing, understanding, and implementing these systems. The Wikipedia treatment of sociotechnical systems provides an excellent review of their properties and the history of attempts to deal with them.[12]

Many organizations deal with complex problems. After all, large-scale computer systems, any large infrastructural project (dams, highways, water systems, electrical power grids, and even structures such as bridges, and large scale architectural proposals) can exhibit many of the issues ascribed to DesignX. Many of these problems fall under the rubric of "wicked problems," long a staple of economists, management science, operations researchers, and design theorists. The fields of operations research and systems thinking deal with many of these issues. Thus, although our list of nine properties differs slightly from that of other lists, they are all conceptually similar, for all are facing the very same kinds of difficulties. For example, the systems theorists Monat and Gannon[13] define a systems problem in terms very similar to the discussion here. They also point out the difficulties of discovering the critical variables, a problem they capture with the label "Iceberg Model": the situation where what is observable is "but the tip of the iceberg," with the important variables and influences hidden below the surface, requiring great effort to discover and understand. In their words:

> "Systems thinking is 1) a perspective that recognizes systems as collections of components that are all interrelated and necessary, and whose interrelationships are at least as important as the components themselves; 2) a language centered on the Iceberg Model, unintended consequences, causal loops, emergence, and system dynamics, and 3) a collection of tools comprising systemigrams, archetypes, causal loops with feedback and delays, stock and flow diagrams, behavior-over-time graphs, main chain infrastructures, system dynamics/computer modeling, interpretive structural modeling, and systemic root cause analysis.
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> Systems thinking ... focuses on the relationships among system components, as well as on the components themselves; those relationships often dominate system performance. It focuses on the properties of the whole that are neither attributable to nor predictable from the properties of the components."[14]

Given that other fields tackle DesignX-like problems, what is it that the design profession can add? The answer, we believe, lies in the way that human-centered design treats the human part of systems. Human-centered design analyzes the operation from the point of view of individual participants, starting with observations in the field of real, situated behavior, analyzing and following each individual job category. This human-centered approach is not present in the methods employed within engineering design, operations, or industrial engineering. The emphasis upon field observations allows one to understand the social, regulatory, and economic pressures upon the people involved, noting where deviations from prescribed methods are necessary. When designers work on a problem, they often

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[12] Wikipedia, "Sociotechnical system."

[13] Jamie P. Monat and Thomas F. Gannon, "What is Systems Thinking? A Review of Selected Literature Plus Recommendations," *American Journal of Systems Science* 4, no. 1 (2015): 11–26.

[14] Monat and Gannon, "What Is Systems Thinking," 24–25.

illuminate issues that were completely absent from results of traditional systems analyses. These observations result from field observations by design researchers and ethnographers.

A difference between the design point of view and that of the traditional analyst can be seen in the language used to describe the same behavior. Traditional analyses often blame system failures upon human error, such as "lack of attention" or "failure to follow procedures." The solution is admonishment or retraining. To the designer, however, these are not causes: they are symptoms of underlying difficulties. From the design perspective, the proper solution is to discover the underlying causes of the human behavior and redesign the system so as to eliminate them.

In examining the role of design, there are four important caveats:

A. Design is a supplement and collaborator to other actors. Designers cannot do it alone, but must build upon the foundations of the other approaches and, given the size and complexity of the issues, work collaboratively with systems thinkers and other actors.

B. Many existing design methods were developed for relatively simple situations. When designers come to large, complex systems with interacting parts, where, as Monat & Gannon say, "inter-relationships are at least as important as the components themselves," they lack experience and methods. This is where designers must develop new ways of dealing with these complex systems.

C. As discussed previously in the section "*1. System Design that Does Not Take into Account Human Psychology,*" the lack of appropriate consideration of human psychology, human factors principles, and human-centered design is a major cause of difficulties, accidents, and failure to recover in a timely way in these large, complex systems.

D. Designers tend to focus upon the front of the development cycle, developing a clearly defined end-result, leaving implementation to others. With complex systems and services, as we discuss later in this paper, this is no longer a viable solution: designers must continue through the implementation stage.

Implementation: The Core Difficulty

At the October 2015 workshop on DesignX at the College of Design and Innovation at Tongji University, Shanghai, several example cases of DesignX were discussed. These discussions convinced us that the major difficulties with these complex problems did not lie with understanding or in devising various approaches to deal with them. The major difficulties were in implementation. Indeed, if one looks at the history of large scale sociotechnical systems, the number of failures during implementation is astounding, and even where the system eventually was deployed, most were subject to large cost and time overruns.

As indicated by the very definition of a DesignX problem, the issues tend to be large and complex. Nonetheless, many of the traditional design methods, especially those of observations, finding the core issues, and repeated interventions (prototypes), observations, and iterations of the process are still appropriate and often successful. But when the designers finish, the remaining task of implementing the recommendations frequently proves difficult, long and lengthy, subject to repeated revisions, and in many cases, impossible. The design process never ends. The real difficulties for large, complex DesignX problems are those of implementation. Of the three categories that define a DesignX problem, the easiest to deal with turns out to be the one initially thought to be the most difficult: *The Technical Issues that Contribute to the Complexity of DesignX Problems.* The technical issues are indeed real and complex, but the major difficulties lie in implementation of recommendations. The roadblocks here lie in the first two categories: *The Psychology of Human Behavior and Cognition* and *The Social, Political, and Economic Framework of Complex Sociotechnical Systems*. These two categories identify four properties as the source of most difficulties:

1. System Design that Does Not Take into Account Human Psychology
2. Human Cognition: The Human Tendency to Want Simple Answers, Decomposable Systems, and Straightforward Linear Causality
3. Multiple Disciplines and Perspectives
4. Mutually Incompatible Constraints

These properties all involve complex human and social elements, exacerbated by the lack of understanding of fundamental human capabilities and limitations in the design and analyses of these systems. Moreover, the incompatible constraints coupled with the different perspectives of those involved in the analysis and decision-making process means that any solution requires collaboration and agreement of multiple social entities and political actors, each of which may have to change its current ways of doing things. These mutually incompatible constraints require compromises. In the best cases, these involve numerous technical, social, and cultural adjustments. In the worst cases, they block any effective resolution. Even where progress is made, it may require so many compromises that the eventual implementation tends to be delayed or cancelled, or if completed, unsatisfying to all.

The four properties that are the major impediments to implementation can completely derail the entire effort. If analysis and understanding of a DesignX problem is difficult, implementation of an improvement may be close to impossible. The implications of this are clear: If designers do not address the issues raised by these four properties from the beginning, during the design stages, the implementation will most likely fail.

Moving Forward Despite the Problems

When one looks at complex sociotechnical systems, one can easily be surprised that they function at all, given the severe difficulties they face. Why is this? One possible answer is that the limited capability of humans to fully comprehend complex systems leads them naturally to the construction of systems that they can understand, even if imperfectly. A second point is that people have taken huge liberties with the systems, and amazingly, often manage to tame them.

How can this be? There are several reasons.

First, because human minds strive for simple explanations and understandable systems, humans create only those systems that can survive being done this way. When people create systems that cannot be decomposed, simplified, or approximated by linearization, we postulate that they do not survive, and then are forgotten.

The systems we now view as successful often took decades or longer to grow into place. Although complex systems such as healthcare are indeed complicated, they didn't appear all at once. It took many decades for each of the multiple components to develop, each component being relatively self-contained and understandable. When they are put together into a modern hospital system, discrepancies occur, but as long as the parts are operated relatively independently of one another – with each discipline mostly keeping to itself – things continue to work. To people who now encounter the health system, it can seem natural and necessary: the multiple, historical origins are hidden from view.

When we examine these systems with the eyes of a designer, we can see that the system's structure is questionable at best: it is chaotic, lacking in cohesion, and conflicted. In fact, it wasn't designed at all: it just happened gradually, each decade adding new components, divisions, specialties, and services. A similar story holds for all of our massive social systems: healthcare, generation and transmission of electricity across a continent, air-traffic control, environmental protection, transportation systems, and even containment of criminal activities. All have had similar trajectories, evolving over many decades. Despite what appear to be fundamental flaws, these systems appear to function.

We suggest that our systems function because the limitations of human cognition (property 2) become virtues. Human-constructed systems are constrained by people's abilities to understand complex systems. As a result, most systems are somewhat modular, with each part relatively independent of the others. Because people prefer systems with linear, casual relationships, the systems that are constructed are reasonably well described by these properties. The systems may in fact be non-linear and complex, but the deviation is not great enough to hamper ordinary operation.

As a result, even complex systems are resilient enough that they continue to work well under normal conditions. Moreover, when problems arise people are good at responding to the resulting difficulties, making changes that maintain a system's operations, even where neither the system nor the full implications of the changes are well understood. As a result, systems slowly grow and improve over time, to keep operating. It is only when a major disaster occurs that the underlying difficulties are revealed. Then, the oversimplified models no longer work. But in the absence of major critical events, these complex sociotechnical systems are amazingly robust despite fundamental flaws.

Muddling Through, Satisficing, and Approximation

How can designers deal with the complexity of implementation with so many social, economic, and political issues? We suggest that the secret is to divide and conquer, to avoid trying to construct or redesign a large, complex system in one step. Instead, the solution should be reached through modularity, and the introduction of numerous small, incremental steps.

Incrementalism as a strategy for dealing with large, complex systems has a respectable history. The major argument was put forward by the political scientist Charles Lindblom, made popular in his papers entitled "muddling through."[15] Incrementalism is the process of moving forward in small, considered steps, fitting the opportunities offered by each successive present, rather than by tackling the entire problem all at once with a single leap into an unknown future. Why? Because major projects involve so many cultural issues, changes in work practices, and changes in the division of work across different professional categories of workers, as well as strong contrasting viewpoints that make the political issues dominate, either leading to stalemate or requiring so many compromises that it is not feasible to make a solid prediction of the future state on the basis of current knowledge, so the future vision is extremely likely to overlook important emerging effects, and the project is slated for failure.

"Muddling through" means acting opportunistically, taking whatever action is possible at the moment. Small steps do not ignite the passions as much as large ones, so they can often be approved. Moreover, success in small steps simplifies the approval process for future steps, whereas failure of a small step does not lead to failure of the entire effort. The operations don't have to be perfect: they simply need to be approximations to the desired end result, to be "good enough," or in Simon's terms, they should "satisfice" rather than optimize.[16] Also see Bendor[17] and Flach[18] for further discussions of "muddling through" as a deliberate design strategy.

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[15] See Charles E. Lindblom, "The Science of 'Muddling Through'," *Public Administration Review* 19, no. 2 (1959): 79–88; Charles E. Lindblom, "Still Muddling, Not Yet Through," *Public Administration Review* 39, no. 6 (1979): 517–26. Lest the reader be skeptical of a 57-year old paper (and its 37-year old renewal), see Bendor's 2015 review of Lindblom's contributions: Jonathan Bendor, "Incrementalism: Dead yet Flourishing," *Public Administration Review* 75, no. 2 (2015): 194–205. His invited review of the work appeared in the same journal as Lindblom's two papers, the 1959 one being described by the journal editor as "the most cited, reprinted, and downloaded article in the history of PAR" (the journal *Public Administration Review*). Bendor describes the large impact and application of Lindblom's work, which is really applied cognitive science: a collection of useful heuristics. These include splitting the problem into modules, the use of local optimization, and the power of distributed intelligence—borrowed from Hayek, but obviously related to the Cognitive Science Approach of Distributed Cognition. An excellent treatment of the relationship can be found in Hélène Landemore, "Democratic Reason and Distributed Intelligence: Lessons from the Cognitive Sciences," paper presented at the Annual Meeting of the American Political Science Association, Chicago, IL., August 2007.

[16] Herbert Alexander Simon, *The Sciences of the Artificial*, 3rd ed. (Cambridge, Mass.: MIT Press, 1996).

[17] Bendor, "Incrementalism."

[18] John M. Flach, "Complexity: Learning to Muddle Through," *Cognition, Technology & Work* 14, no. 3 (2012): 187–97.

This approach requires a different design philosophy than might be used when considering the project as a whole. Now, the design must be modular, with multiple small, relatively independent parts, incremental changes that can be implemented, and linkages that are designed for flexibility. Moreover, The end result is likely not to be as good as the one idealistic cohesive total proposal, but at least some change and improvement would have occurred.

Lindblom's prescription for muddling through by opportunistic incrementalism makes for an effective applied science. As Bendor points out, "the differences between trying to solve hard real-world problems versus describing and explaining phenomena can help us understand what Lindblom was doing."[19] Alas, in academia, applied work is not nearly as esteemed as theoretical work, even though it is the applications that actually impact the world. As a result, his work has not had the impact it deserves.

Designing for Difficulties in Implementation

Given the complexity of these issues, especially in implementation, what can designers do? We make several recommendations. Some of these are familiar, some are novel. None have been sufficiently tested. All, however, are highly in tune with implications of the nine properties discussed in this paper.

First, one should try for modularity: divide the problem into multiple small, digestible units. Multiple small steps can triumph over one large one, even if the many small steps do not lead to quite the same final eloquence and functionality of the one large one. The advantage of this incrementalist approach is that, because it is so much more feasible to get approval and resources for a small step, something will actually get done. The alterative, large optimal solution may never make it through the political process.

The decomposition of a DesignX problem into quasi-independent modules may lead to inconsistencies and difficulties. The partitioning of a large problem into multiple small modules will probably affect the interactions between modules. But imperfect action is often far preferable to no action.

But even when the problem has been subdivided into manageable modules, considerable attention must be paid to social, cultural, and political issues. Observations of projects that have been successful suggest that the design process be one of co-design, where all stakeholders have ownership of the solution, the willingness to make multiple compromises, and of course, modularity, which promotes incrementalism (and muddling through).

Large, complex problems will always require a combination of deep analysis, incremental "muddling through," and satisficing. For these reasons, designers must also focus upon the practical, cultural, social, economic, and political issues that will delay, impair, and compromise the implementation.

Design for the real world means designing to allow for compromise – for resolution through small, incremental steps. It requires co-design, the willingness to tolerate compromises, and a modularity of design that allows for these small steps to be implemented without compromising the whole.

Acknowledgments

We thank all the participants of the DesignX collaborative and of the Tongji workshop on DesignX in October 2015 for their help in educating us about the field of systemic system design, sending us numerous papers to read and then, at the workshop, discussing these ideas with us. We learned much from them, but we emphasize that the ideas in this paper are ours, and may not necessarily reflect those of the other participants.

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[19] Bendor, "Incrementalism," 195.

Commentary

Supporting Self-Designing Organizations

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DesignX?

To begin with, I would like to thank Don Norman and P.J. Stappers, together with the other organizers of the DesignX workshop and the very kind and generous hosts from the College of Design and Innovation at Tongji University for the opportunity to participate in discussions about the future of design and design education at the Fall 2015 meeting in Shanghai. This was a unique opportunity for me to learn from a collection of some of the world's leading design educators. I was particularly eager to participate in these discussions, because the themes behind the DesignX initiative that Norman and Stappers articulated so well prior to the meeting – and in the commentary in this volume[1] – are themes that are very important to my research interests relative to Cognitive Systems Engineering, and my teaching interests as a professor of applied cognitive psychology.

Norman and Stappers'[2] example of Radiation Oncology provides a concrete illustration of the many difficulties associated with managing complex, sociotechnical systems. These difficulties are not unique to healthcare; they are becoming the norm in a society that is increasingly dominated by information technologies. These technologies open many new opportunities for innovation, but also new challenges – for example, improved methods for diagnosing and treating cancer point to a need to make sense of increasing amounts of data, and coordinate treatments across multiple cooperating agents. By and large, I agree with Norman and Stappers'[3] characterization of some of the challenges and some of the solutions. However, I welcome an opportunity to present my own perspective from the context of my experiences in Cognitive Systems Engineering (CSE) – a field that overlaps with design in terms of the ultimate goal to positively impact the world through innovation, yet has come from somewhat different academic traditions.[4]

Cognitive Systems Engineering

Cognitive Systems Engineering (CSE) evolved to meet the design challenges associated with transformations in the nature of work resulting from increased automation. Advances due to the integration of information technologies into domains such as industrial process control and aviation had changed the role of humans from being manual controllers to being supervisory controllers. For example, the primary role played by humans in nuclear power plants was no longer direct control of the processes, but rather to supervise the automatic control systems. This involved tuning the automation in anticipation of potential problems, and diagnosing and intervening when problems inevitably arose that had not been anticipated by the designers of the automatic control systems.[5]

In these contexts, the challenge for information technologies designers shifted from design to ensure that humans conformed to pre-established norms or procedures, to design to support productive thinking – anticipating and diagnosing problems, for example. In other words, the design challenge shifted from using the technology to shape *behavior* (ensuring procedural compliance) to using it to shape *cognition* (increasing perspicacity and insight).

Over the years, CSE has learned from many examples in which technologies that were designed to improve performance actually introduced new unintended problems, sometimes making things worse.[6] Wiener coined the term "clumsy automation"[7] to describe a recurring pattern where technological innovations solved the easy problems, but made solving the hard problems more difficult. The potential for clumsy automation typically arises when the designers of the automation lose sight of either (1) the work domain, for example by trivializing aspects of a complex problem); or (2) the people using the technology, for example by overloading limited resources.

In contrast to more classical approaches to human performance in sociotechnical systems (Human Factors; HCI) that focused on the human-technology interaction with an emphasis on matching the users' internal models, CSE focused on the human-work domain interaction with an emphasis on shaping the users' internal models to be consistent with the pragmatic realities of the complex work domain.[8] In the domain of aviation, for example, interfaces were designed to make underlying process constraints – like the aerodynamic constraints associated with potential and kinetic energy – apparent to the pilot, allowing a deeper understanding of the functions of various controls – like the stick and throttle.[9] Thus, from the perspective of CSE, information technology is viewed as a window on the work domain, and the design emphasis is on using representations to make the technology transparent, so that the human's attention is focused on the deep structures of the work problems. This approach is directly inspired by the classical work of Gestalt Psychologists who studied the impact of representations on problem solving,[10] as well as more current work on situated cognition[11] and direct manipulation[12] that illustrates how representation can impact the problem solving process – for example, how different map projections impact the navigation process.

Requisite Variety and Bounded Rationality

Ashby's Law of Requisite Variety[13] makes an important claim about the requirements for full control over any process. This law essentially states that in order to achieve full control of a process, the controller must have the *same* degree of variety – the same number of degrees of freedom or the same complexity – as the process being controlled. As Norman and Stappers[14] note, the limitations of human controllers are well established, so one attraction of advanced information systems has been the opportunity to increase the capability – the requisite variety – of control systems, using advanced sensing and computation capabilities. However, many of the early pioneers of CSE realized that the construct of "bounded rationality" did not apply uniquely to humans,[15] All computational systems are also bounded, relative to the complexity or variety of many complex work domains such as a nuclear power plant, or – as we are becoming increasingly aware – a healthcare system. For example, CSE realized that it was not possible for the designers of the automatic control systems in nuclear power plants to anticipate every possible future situation that could potentially impact the safety and efficiency of a nuclear power plant. Therefore, the long-term stability of the nuclear power plant ultimately depended on the ability of its human operators to creatively intervene when situations arose that were not anticipated in the design of automatic control systems. CSE recognized that the creative problem-solving abilities and diverse expertise of smart humans were valuable resources for meeting the demands presented by Ashby's law.

While I don't fully disagree with Norman and Stappers'[16] characterization of human limitations with respect to managing complexity, and while I realize that they appreciate the important and essential contributions of smart humans in solving complex problems, I do think it is unfortunate that they single out the local rationality of humans as a special problem with respect to DesignX. I worry that this will reinforce a tendency, shown by more classical approaches to human factors, to identify the human as the 'weakest link' that is often the source of 'errors' in complex systems.[17] One theme that I would like to see associated with the DesignX initiative is the recognition that *all agents – including the smartest humans and the most powerful automatons – are bounded* relative to the complexities of many work domains such as healthcare. Rationality is always *local*, especially in a rapidly changing world. The important implication of this, relative to the Law of Requisite Variety, is that long term stability will ultimately depend on cooperation among multiple agents – including humans and computers/automatons – none of which alone are capable of satisfying the requirements of Ashby's Law. As illustrated in fig. C1, the observability and controllability demands in many sociotechnical systems require cooperation among many diverse human and autonomous agents, none of which have either access to all the relevant information, or the capability to perform all the necessary control actions without cooperating with other agents.

Adaptive Control

With respect to Ashby's Law of Requisite Variety, it is important to realize that the 'requisite variety' of the process being controlled does not simply refer to the variety at the time the process is initiated, or when the controller is designed. Rather, it reflects the variety associated with all possible future situations that might come to pass. So, if there are changes in the functional demands of a system or organization that were not anticipated in the design of the control processes, then control will be compromised. At best, uncertainty about the future eventually leads to inefficiencies; and at worse, it could result in catastrophic instability and extinction. Thus, one bound on all fixed control solutions is the ability to predict the future.

One strategy for meeting the demands of an uncertain future is adaptive control. An adaptive control system is essentially a learning system. In fig. C1, the learning process is represented by a secondary feedback loop. The block arrows in this secondary loop are used to indicate that the input through this loop changes the internal structure – the transfer functions – of the boxes to which they point. Thus, the

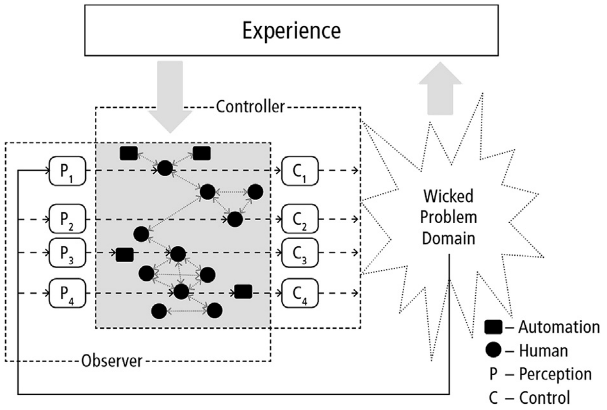

Figure C1 (Flach) An adaptive control organization.

consequences of action relative to the wicked problems of complex work domains feed back to change the experience base of the organization – there is a capacity to learn from past successes and failures – and, in turn, this experience base can feed into the observer and control functions to change their properties. Potentially, these changes reflect the discovery or experience of 'process variety' that was not anticipated previously.

An adaptive control system is essentially a *self-organizing system*, or a self-designing system, to the extent that the internal logic coupling perception and action is potentially changing as a function of experience. In essence, this system is continuously rewriting the internal logic guiding its behavior to reflect discoveries resulting from past behaviors. In other words, it is a learning organization.[18] Thus, the two loops are consistent with the dynamics of cognitive development identified by Piaget and Inhelder.[19] The inner loop corresponds to *assimilation*, where actions (behaviors) are based on what has been learned from prior experience (current schema or current control law). The outer loop corresponds with *accommodation*, where the schema are changed or updated to reflect the surprises or errors that result from application of the current schema (or control laws). In this closed-loop dynamic, the schemas are simultaneously shaping behavior and being shaped by the consequences of that behavior. This dynamic is also consistent with Peirce's logic of *abduction*,[20] where beliefs (schema) are tested relative to the pragmatic consequences of acting on them.

Muddling and Essential Friction

A key implication of the image of the sociotechnical system illustrated in fig. C1 is that meeting the challenge of the Law of Requisite Variety requires cooperation among the diverse humans and technologies – computational tools, autonomous agents – within the organization. Thus, a critical question for system designers and managers is, "What does effective cooperation look like?" This is the question that Lindblom[21] addresses in his classical papers on muddling through. The key insight is that incrementalism – the messy politics of argument, negotiation, and compromise among diverse interest groups that is observed in social policymaking, and that typically results in only incremental change – is actually a very good solution for meeting the Law of Requisite Variety. When considered through the lens of evolution, it might be hypothesized that humans have evolved special skills for cooperation as a result of selective pressures that required effective social interactions for survival. Thus, stable social systems – messy though they are – provide examples of natural solutions to the challenge of effective collaboration.

Through the lens of normative models of rationality and optimization, the messiness associated with the muddling process appears to be a kind of friction, an obstacle to progress, a source of wasted energy. However, as Åkerman observes, "If it [friction] stops schemes from being completely fulfilled, it also stops them from going totally awry….Friction provides a perpetual contact with the world."[22] In this context, the constructs of *muddling* and *essential friction*[23] are consistent with the prescriptions of control theory for stable control for processes that require high degrees of integration and/or have long feedback lags. Such process dynamics require low gain, damped control laws for stability. In other words, the control laws have to be somewhat conservative. Thus, the implication of these constructs is that the messiness of social negotiations and consensus building among diverse groups is essential to grounding the control or management processes in the pragmatic realities of complex work domains in order to meet the requirements for stability – or to satisfy Ashby's Law.

Increasingly, people in the social and management sciences are questioning how properties of the organization impact the muddling process. On one hand, there seems to be a growing consensus that fixed hierarchical organizations are too slow, due to the time it takes to accumulate information at a centralized command center and then disseminate instructions out to distributed, front line operators.[24] On the other hand, completely flattened network organizations can be overwhelmed by noise in the communication network that makes it difficult to pull out the information – the signals – essential for observation and control.[25] Some patterns of organization that appear to be potential solutions include heterarchies and federalism. For example, Rochlin, La Porte, and Roberts[26] suggest that heterarchical forms of organization in which the locus of control shifts within the organization based on changing access to information helps to increase the reliability of organization in meeting the demands of high tempo, high risk control problems such as aircraft carrier landings. Sage and Cuppan[27] suggest that federalism is a form of organization that underlies successful, large-scale emergency operations. They define the particular case of a "federation of systems" as a system of system with "little central power or authority for 'command and control.'"[28] In a federation of systems, a number of smaller organizations – fire, police, hospitals, etc. – collaborate to achieve a common goal. Each sub-agency has its own authority structure, and the primary function of any centralized emergency operations center is not to control, but rather to facilitate communications among the diverse agencies.[29] The federalist solution is one example of a more 'modular' approach to the muddling through approach that Norman and Stappers[30] recommend.

Self-Designing Organizations

As Norman and Stappers[31] observe, the increasing complexity and the demands of satisfying the Law of Requisite Variety have important implications regarding the ability of designers to implement change in sociotechnical systems. In order to make change happen, designers have to be prepared to participate in the muddling through process. In order to make changes, designers cannot sit outside the sociotechnical system and throw solutions over the fence. Rather, they have to engage with the social dynamic of sensemaking within the organization; they have to negotiate with multiple stakeholders; and they have to be satisfied with the incremental changes that typically result from such processes. Thus, it is not sufficient for designers to be skilled with respect to the classical design arts. Designers who expect to make an impact at the level of sociotechnical systems will also have to be skilled in the politics of muddling through.

In closing, I concur with Norman and Stappers' hypothesis that designers who hope to have an impact at the level of sociotechnical systems (e.g., healthcare) will have to expand their horizons beyond the classical design arts to consider the implications of complexity and the demands for the social and political skills associated with effective muddling. Finally, I would like to amplify what I think is the most important observation made in their commentary: "The design process never ends."[32]

The implications of this statement go far beyond design education. It is becoming increasingly clear that organizations that aspire to achieve stability in the face of rapid changes and future uncertainties will have to continuously learn and adapt. These organizations have to be self-organizing, continuously redesigning themselves in order to make the incremental changes necessary to maintain stability. The implication is that "design thinking" may be important to all the people who are participating in the muddling through process – managers, engineers, scientists, operators etc. So, my takeaway from the Design X discussions in Shanghai and the commentary of Norman and Stappers is that educators in every discipline should be thinking about how they can prepare their students to think like designers – looking for creative opportunities for positive change – and participate in the messy muddling process necessary for incremental, stable progress in an increasingly complex world.

Acknowledgments

Thanks to the organizers and all the participants in the Tongji workshop on DesignX in October 2015 for the opportunity to explore the implications of complex sociotechnical systems for design, and the implications of design thinking for sociotechnical systems. Also, thanks to the editors of *She Ji* for the opportunity to share my reflections with a wider audience.

[1] Don A. Norman and Pieter Jan Stappers, "DesignX: Complex Sociotechnical Systems," *She Ji: The Journal of Design, Economics, and Innovation* 1, no. 2 (Winter 2015): 83–106.

[2] Norman and Stappers, "DesignX."

[3] Norman and Stappers, "DesignX."

[4] Control engineering and ecological psychology are examples.

[5] For example, see Jens Rasmussen, *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering* (New York: North-Holland, 1986); John M. Flach, "Supporting Productive Thinking: The Semiotic Context for Cognitive Systems Engineering," *Applied Ergonomics* (forthcoming), available online September 26, 2015, http://dx.doi.org/10.1016/j.apergo.2015.09.001.

[6] For example, see Charles E. Billings, *Aviation Automation: The Search for a Human-Centered Approach* (Mahwah, NJ: Erlbaum, 1997).

[7] Earl L. Wiener, "Cockpit Automation," in *Human Factors in Aviation*, ed. Earl L. Wiener and David C. Nagel (San Diego: Academic Press, 1988), 433–61.

[8] Kevin B. Bennett and John M. Flach, *Display and Interface Design: Subtle Science, Exact Art* (Boca Raton, FL: CRC Press, 2011); Jens Rasmussen and Kim J. Vicente, "Coping with Human Errors Through System Design: Implications for Ecological Interface Design," *International*

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9 Matthijs H.J. Amelink, Max Mulder, M. M. (Rene) van Paassen, and John Flach, “Theoretical foundations for a total energy-based perspective flight-path display,” *The International Journal of Aviation Psychology* 15, no. 3 (2005): 205–31; Clark Borst, John M. Flach, and Joost Ellerbroek, “Beyond Ecological Interface Design: Lessons from Concerns and Misconceptions,” *Human-Machine Systems, IEEE Transactions on Systems, Man, and Cybernetics* 45, no. 2 (2015): 164–75.

10 For example, see Otto Seltz, *Zur Psychologie des Produktiven Denkens und des Irrtums* (Bonn: Friederich Cohen, 1922); Karl Duncker and Lynne S. Lees, “On Problem-Solving,” *Psychological Monographs* 58, no. 5 (1945): i–113; Max Wertheimer, *Productive Thinking* (New York: Harper and Brothers, 1945).

11 Edwin Hutchins, *Cognition in the Wild* (Cambridge, Mass.: MIT Press, 1985).

12 Ben Shneiderman, *Designing the User Interface: Strategies for Effective Human-Computer Interaction*, 2nd ed. (Reading, Mass.: Addison-Wesley, 1992).

13 William Ross Ashby, *An Introduction to Cybernetics* (London: Chapman & Hall, 1956). See in particular Chapter 13 “Regulating the Very Large System.”

14 Norman and Stappers, “DesignX.”

15 Rasmussen, *Information Processing*; Flach, “Supporting Productive Thinking.”

16 Norman and Stappers, “DesignX.”

17 See, for example, Barry H. Kantowitz and Robert D. Sorkin, *Human Factors: Understanding People-System Relationships* (New York: John Wiley & Sons, 1983). For an alternative perspective on human error, see Sidney Dekker, *Drift into Failure: From Hunting Broken Components to Understanding Complex* Systems (Surrey, UK: Ashgate, 2011).

18 See, for example, Peter M. Senge, *The Fifth Discipline: The Art and Practice of the Learning Organization* (London: Random House, 2006).

19 Jean Piaget and Bärbel Inhelder, *The Psychology of the Child* (New York: Basic Books, 1969).

20 Charles S. Peirce, “The Fixation of Belief,” *Popular Science Monthly* 12 (November 1877): 1–15.

21 Charles E. Lindblom, “The Science of ‘Muddling Through’,” *Public Administration Review* 19, no. 2 (1959): 79–88; Charles E. Lindblom, “Still Muddling, Not Yet Through,” *Public Administration Review* 39, no. 6 (1979): 517–26.

22 Nordal Åkerman, ed., *The Necessity of Friction* (Boulder, Colorado: Westview Press, 1998), 6.

23 Gene I. Rochlin, “Essential Friction: Error-Control in Organizational Behavior, in *The Necessity of Friction*, ed. Nordal Åkerman (Boulder, Colorado: Westview Press, 1998), 196–232.

24 See, for example, John Arquilla and David Ronfeldt, *In Athena’s Camp: Preparing for Conflict in the Information Age* (Santa Monica: RAND Corporation, 1997); Fredrich August Hayek, *Individualism and Economic Order* (Chicago: University of Chicago Press, 1948).

25 See, for example, Gene I. Rochlin, *Trapped in the Net: The Unintended Consequences of Computerization* (Princeton: Princeton University Press, 1997).

26 Gene I. Rochlin, Todd R. La Porte, and Karlene H. Roberts, “The Self-Designing High-Reliability Organization: Aircraft Carrier Flight Operations at Sea,” *Naval War College Review* 40, no. 4 (1987): 76–90.

27 Andrew P. Sage and Christopher D. Cuppan, “On the Systems Engineering and Management of Systems of Systems and Federations of Systems,” *Information, Knowledge, Systems Management* 2, no. 4 (2001): 325–45.

28 Sage and Cuppan, “On Systems,” 327.

29 John M. Flach, Debra Steele-Johnson, Valerie L. Shalin, and Glenn C. Hamilton, “Coordination and control in emergency response” in *Handbook of Emergency Response: Human Factors and Systems Engineering Approach,* ed. Adedeji B. Badiru and LeeAnn Racz (Boca Raton: CRC Press, 2014), 533–48.

30 Norman and Stappers, “DesignX.”

31 Norman and Stappers, “DesignX.”

32 Norman and Stappers, “DesignX.”

Small Modular Steps Versus Giant Creative Leaps

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Don Norman and PJ Stappers have done the international design research community some service in first positioning the concept of DesignX in relation to the growth of complex sociotechnical systems, and then following up with this substantial paper after a workshop in Shanghai in autumn 2015 interrogated and re-cast some central ideas on the subject.

I took part in that DesignX workshop, speaking up for human-centered design and its real, situated ethnographic processes in the field, on behalf of that grouping of academics who come from a design practice and design thinking background, as opposed to systems theory or cognitive science.

So I was pleased to see the authors assert in this paper the singular importance of human-centered design as a distinctive contribution that the design profession brings to tackling DesignX problems. “When designers work on the problem, they often illuminate issues that were completely absent from the traditional analyses,” declare Norman and Stappers.[1] Hurrah for that!

But the trouble with cheerleading the importance of the designer’s role within complex sociotechnical systems – as I am prone to do myself – is that there is an uncomfortable truth lurking just below the surface: the deep expertise entailed in the practice of most design disciplines – from industrial and automotive to environmental and communication design – lends itself to narrow focus rather than broader, big picture thinking.

Although things are now changing, and service designers in particular are moving towards being entrusted with whole-system thinking, the vast majority of design professionals at work on the planet today still give form and meaning to the different touchpoints through which the users of complex systems experience the system.

These single touchpoints are often complex and difficult to design in themselves, and require great patience and insight to get right, whether a ticket machine in a transport system, school classroom lighting in an education system, or a hospital emergency room in a healthcare system.

The tougher the touchpoint challenge, the more designers become focused and ‘heads down in the engine room’ of a design problem, and the more they become isolated from the bigger system. DesignX, I can guarantee, will not be on the radar of most designers, because the field of vision is simply too wide.

Even when design teams begin by exploring the bigger system, their creative instincts and expertise lead them towards detailing just one component of that system – effectively coloring in just small part of the whole map. I shared an example of this at the Shanghai DesignX workshop from the Helen Hamlyn Centre for Design at the RCA: the redesign of the London emergency ambulance,[2] which has received much interest and won several design awards but has yet to be implemented.

This project grew out of a big-picture analysis of emergency mobile healthcare in London – a complex sociotechnical system if ever there was one. Working over several years with clinical colleagues at Imperial College London and the London Ambulance Service, we re-imagined the whole system to improve patient safety, enhance the work experience for paramedics, reduce operating costs, and relieve pressure on hospitals with more community-based care.

The design of the standard emergency ambulance itself became the vehicle – literally so – used to deliver a large part of this complex system change. We calculated that if the tools, communications and general environment of the ambulance were redesigned, many patients could be treated immediately, in their own communities – within a sterile, properly equipped ambulance interior – without being ferried back to overcrowded London hospitals.

So the logical thing, we decided, was to get that ambulance treatment space right. The design team went into a ‘deep dive’ co-design process with London paramedics, resulting in a system touchpoint with several innovations, including: modular treatment packs, natural daylighting, 360 degree access to the patient, easy-clean surfaces, and a mock-up of a digital diagnostic system providing unprecedented connectivity with clinical experts back at the hospital.

Human-centered design research was placed on a pedestal, and the RCA’s ambulance interior won major awards from the Design Museum in the UK and the Industrial Designers Society of America, among others. But then, as Norman and Stappers describe in this paper, the “core difficulty”[3] of implementation became a stumbling block.

Despite the warm glow of publicity and acclaim, we could not take the full-size ambulance demonstrator we had designed and fabricated into a real healthcare system and onto the streets. That struggle continues today. The truth is that the changes to the wider system (emergency mobile healthcare) required to make sense of the design touchpoint (the ambulance) have simply not happened at the speed and in the way we intended.

If you introduce just-in-time modular treatment packs inside the ambulance – such as a burns pack for a fire emergency, or a maternity pack for a pregnancy emergency – then a culture change is required relative to how London ambulances are restocked and paramedics are trained. If you envisage a scenario in which the ambulance crew can instantly access the electronic patient records of the road crash victim the ambulance is speeding towards, then those digital records need to be readily available.

Our design work simply ran in advance of a complete systems re-boot, resulting in a compelling vehicle design proposition that was out of step with the stop-start, politically compromised, inherently fraught mobile healthcare setup in London.

If we take the DesignX characteristics outlined in this paper, it is not the psychology of human behavior and cognition that is the stumbling block – frontline ambulance paramedics were intimately involved in the redesign. Nor do the technical issues that contribute to complexity emerge as the main culprits here, as everything the authors describe – dynamically changing operating characteristics, non-independence of elements, and so on – can be attributed to mobile healthcare systems; yet these aren’t necessarily responsible for applying the brakes.

Undeniably, the biggest barriers to implementation can be found in the social, political and economic frameworks: changes in the political and funding climate have blown our ambulance project off course – temporarily, we hope.

Advice from Norman and Stappers that designers should avert their gaze from the sprawling imperfections of big systems, and "'muddle through'"[4] by taking small, modular steps rather than big leaps of creative faith is probably sensible. But it goes against the grain of more than 50 years of project-based design education in which designers have been taught to think big and bold outside the constraints of any system, and to learn through trying, making, and failing.

The gap between the demands of today's complex systems and how most trained, hyper-focusing designers see the world is a chasm that even those most precise – and welcome – categorizations of DesignX might struggle to bridge.

[1] Don A. Norman and Pieter Jan Stappers, "DesignX: Complex Sociotechnical Systems," *She Ji: The Journal of Design, Economics, and Innovation* 1, no. 2 (Winter 2015): 83–106.

[2] For more information, see http://www.smartambulanceproject.eu/wp-content/uploads/2015/02/Redesigning_the_Ambulance_Lo-Res.pdf.

[3] Norman and Stappers, "DesignX."

[4] Charles E. Lindblom, "The Science of 'Muddling Through'," *Public Administration Review* 19, no. 2 (1959): 79–88, quoted in Norman and Stappers, "DesignX.".

Designing for X: The Challenge of Complex Socio-X Systems

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We might observe across the social disciplines that the complexity of modern existence has led to calls for more systemic and design-led approaches to deal with unmanageable complexity. While it has been more than 40 years since the publication of Rittel and Weber's *Dilemmas in a General Theory of Planning*,[1] it appears that it has taken until well into the 21st century for the strategy of designing for wicked problems to have shaped courses of collective action. The exploration of DesignX problems redirects the project toward defining and educating for advanced practices capable of validating design for complex sociotechnical systems.

Perhaps this has come about from acknowledging a manifested breakdown in the ability of conventional management and policy to enact effective and predictable outcomes consistent with societal goals – in other words, our practices have become too complex to redesign them effectively for what might better serve human social needs. Bruno Latour's recent call to embrace validated modernist institutions[2] suggests that cooperation and collaboration across disciplines might be crucial at this point in history. After all, the sciences and engineering have demonstrated effective approaches to deal with significant technical problems, so we might trust the hard sciences to deal with global crises, whether climate change, economic development, geopolitical policy, or food supply systems.

Such is the nature of DesignX problems – or perhaps emerging DesignX situations – that we can examine through the lens of the DesignX manifesto. As one of the case presenters in the Shanghai meeting described by Norman and Stappers, I might acknowledge that the inaugural discussion was not only composed of a group of true believers, but a notional starting point, a grounding of perspectives in a continuing dialectic. The sharing of complex sociotechnical systems as design cases was not novel, as the material could have been presented as relevant at many different symposia; neither was the call to discuss and engage questions of appropriate design evidence, or the identity of "systems," or the hows and whys of systemics in complex design problems. The difference in the DesignX discourse was an intent toward achieving solidarity – if not consensus – that as design educators, "we must do something." The case studies and discussions yielded the demonstration that the fields and models of design remain richly diverse, and we have many models and methods perhaps suitable for addressing societal and sociotechnical concerns. However, we still have very little deeply-shared vocabulary with which to address the different types of problems, their systematic relationships – within and across system types, their functional elements, and their human behavioral relationships. Securing some agreement toward a common taxonomy will make a difference in inter-disciplinary communication, and this is one aspect of evidence-oriented design that would help across the range of design practices.

In this issue, the article "DesignX: Complex Sociotechnical Systems"[3] presents nine issues or dynamics that are proposed as characteristic in sociotechnical problems. I might simplify them as follows:

Social and psychological factors of system participants and designers:

- The role of psychological factors in system design
- The role of cognitive biases and human uses needs that ignore systemic behaviors
- The need to integrate multiple disciplines and perspectives in sociotechnical design
- Design dilemmas in the conflicts of incompatible constraints

Technical and systemic factors within STS problems:

- Interconnected (but largely concealed) internal functions
- Nonlinear causality and multi-casual feedback processes
- Undisclosed delays, lags, and latencies in feedback and control
- Irreconcilable scales of time and space
- Dynamic operational changes

I repeat these because it's worth rethinking their meaning in different expressions. Another reader might configure them in yet different terms, and determine whether they fit their cases, or perhaps remain incomplete until other general applications are proposed and tested across cases. These nine are consistent with the sociotechnical systems (STS) literature, in general, but we might also recognize other factors, perhaps significant, that might help to assert and test, even if such factors are not generalizable across all STS.

Designing for Complex Social Domains

One of the facilities gained with domain expertise is the ability to distinguish important features that contribute to a domain's overall complexity, and not just the systemic or operational complexity that we might analyze in an engineering exercise, for example. I believe the DesignX construct – if meaningful across design disciplines at all – requires us to reimagine how we might design within domains, rather than apply toolkits of advanced design skills across them. A constructivist epistemology – which we might also claim as consistent with designing for these systemic factors – further requires us to develop categories *within* these domains as appropriate in the domains as worlds constructed by their everyday participants. New systemic design approaches are emerging within healthcare delivery, bioregional sustainability, business models and services, food and shelter security, corporate and civic governance, and several others. I mention these in particular because each of these domains can be assessed as complex, publicly accessible, and yet contained as a system governed by its own rules and legacies.

When we consider interactive work systems for productive goals, the focal perspective adopted by designers is the sociotechnical, endorsed and developed in cognitive engineering, technological work studies, and significantly in healthcare informatics.[4] The sociotechnical perspective is not widely embraced in design education, and even its treatment in human factors programs can be charitably indicated as variable.

More significantly, each of these domains not only contains sociotechnical systems – as we have noted as relevant to DesignX – but can be identified as larger, more socially complex domains represented as *socioecological* systems. The rich body of work from the Tavistock legacy developed across three perspectives, or levels, of social systems, designated the socioecological, sociotechnical, and sociopsychological.[5]

Within most domains or organizations with complex STS problems, we can identify complex socioecological systems wherein a collective social system interacts with its environment. When expanding the problem of mental health – to use my DesignX case for example – or even radiation oncology, the healthcare context implicates its environment as the source of the disease conditions: the family, lifestyle, and social determinants of disease, as well as the construction of "patients" in a healthcare system.

Consider the additional complexity factors we might face as systemic designers choosing to work with the socioecological system as well as the technical work practices. We can find, study, and design for the social ecologies associated with the production of health in a community. The social determinants of health arise from a socioecological viewpoint, and this view helps reveal the mutually determining factors that enable health outcomes from a mental health intervention or cancer care.

The literatures and research methods between these "socio-*x*" perspectives are quite different. Because it's unlikely that graduate design education will sufficiently touch on these perspectives and their case studies, we risk ignorance of this extraordinary, developed knowledge – possibly dimly reinventing their models when faced with correlated insights, yet not benefitting from appropriating the wisdom of 60-plus years of deep experience in these systemic perspectives.

However, we might ask: if "we" across the design disciplines are not designing for complex socio-technical systems, then who is? Are we ignoring these problems to some extent from conflict with aesthetic tastes, or because actually resolving these problems resists the rapid satisfaction of creative "design thinking?" Or, are we shunning involvement with the depth of complexity, a lengthy commitment to a problem, and the inherent risks of bad design decisions? We might start finding in these critical problems the moral equivalent of infrastructure – we have to improve design for technological integration, because our lives and social ecologies depend on it.

Designing a DesignX Theory of Change

While a popular principle of complexity thinking is that small changes at the right place can make outsized differences, such theories of change often seem wishful. In modern societies, the interconnectedness of governance and funding with information technology and legacy systems means, more likely, that complex systems become densely, internally connected, and so resist either planned or designed interventions. Because of complex networks, we have an Internet that prefers monopolies to interesting innovations. In the United States, we have public policies – such as cold war era military base proliferation and subsidies of oil majors – that continue apparently without guidance from any citizens. As social systems planners warned 50 years ago, we now have completely interconnected issues, mutually locked-in and path dependent. These are not requisite conditions for organization-centered change, but require multiple stakeholders committed to future betterment. As Flach[6] notes in his endorsement of an incrementalist theory of change, we might explore a shift from "resolving complexity" and transformational programs to skills of coping in the face of the unreality of control. Such an approach recalls Latour's[7] entreaty for design as a modest, self-aware process of coping with "matters of concern" as opposed to the normative "matters of fact" of desirable outcomes.

In practical design terms, we must also consider the problem of *initial conditions* of both the system and the human designers, another factor that cuts across all three sets in the framework. The initial brief, sponsoring team, and system owners significantly influence the way a design team approaches the goals for change and intervention. While we might wish to believe that, as designers, we can invoke the requisite magic of independent thinking and reframing;[8] but when given a complex problem sponsors care about, we find ways to satisfice something of the concern. We muddle through more often than heroically reframe with the perfect framing proposal. As designers we are almost never experts in a domain, and our own initial conditions might be creatively speculative, but weakly informed.

Consider that in policy and organizational domains, social systems associated with institutions sometimes involve many different levels of authority responsible for interdependent decisions. Therefore, we almost never have the ability to "design the change" directly, but are constrained to negotiating the scope and brief of our initial sponsors. The most powerful knowledge for changing any system – and the minds of sponsors – lies with its deep users and stakeholders. These participants must be identified and often discovered over time, another incremental process that challenges the ability to reframe an STS design project. Yet, even when new stakeholders are discovered, we are biased toward an initial investment of sunk cost time and learning that can establish a path dependency, so initial conditions and framing iterations remain critical tools in the systemic design approach.

Perhaps then much of the fashionable rhetoric about transformational system change is hubris and wishful optimism expressed by inexperienced designers that have not directly witnessed cascading failures in products, organizations, or businesses. After all, system failures follow the same rules and factors as indicated in the five technical concerns in the list.[9] We may not have seen sufficient history to imagine and simulate the kinds of human connections that fail to obey system prototypes or expected rules. Designers rarely have to live with the consequences of their proposals, as has been seen in the wishful thinking of innovative design proposals for bottom of the pyramid problems such as clean water supplies and clean cook stoves in subsistence living conditions.

Norman and Stappers are on the right track by recommending a revaluation of Lindblom's incrementalism. Long held in disregard as the enemy of innovation, the argument against muddling through falls apart when we consider the meaning of "successful design" in high complexity. These domains have less demand for disruptive transformation – a demand that often boils down to commercial market disruption to return fabulous wealth to innovation investors. Therefore, systemic design approaches might develop rather incremental change approaches, with stakeholders "discovered" over longer cycles than in contained STS, as there might be significant knowledge and experience across stakeholders inaccessible to the design team initially. Careful analysis and an iterative learning approach to design yield greater team understanding, reducing the probability of a Type I, false positive error – as when design teams rush into action, and believe an initial successful prototype demonstrates transformation.

Within complex domains, we also see significant legacy effects and path dependency for incremental or discontinuous design approaches. Technical and technology regimes from different eras and applications are extremely complicated and highly constrained; these are problematics that can be more time consuming than the "merely" complex. A chief constraint in most established information systems is the volume and complexity of legacy software, databases, and expensive custom interfaces between systems developed over time by long-gone programmers and sometimes archaic languages. Many software modules are black boxes that cannot be modified effectively without complete transformation of the system.[10]

Conclusions

Norman and Stappers reach optimistic conclusions that help move discourse beyond problematizing and into design action. Their conclusions suggest that an incrementalist approach to designing for complex work practices that implicate a range of stakeholders can be constructed in a modular way to yield successful progress, and enable stakeholder participation and effective design management. While there are risks of under conceptualizing the social system under inquiry, some scholars[11] would argue that stakeholders can never cognitively appreciate the system sufficiently under any conditions.

With respect to their conclusion to pay considerable attention to social, cultural, and political issues with complex systems design, I address the proposal to evaluate complex social interdependencies as socio-ecological systems. This perspective deserves its own methodological and design discussion separately from the DesignX treatment of sociotechnical systems. I would recommend the expansion of DesignX to consider the range of socio-*x* problems that DesignX might entail. While we might consider all of these domains or problem types as opportunities for systemic design, I would maintain systemic design as a field of advanced design methodologies applicable to all types of complex system problems, across social and ecological domains. The position of DesignX seems resonant as a problematic of system challenges for which design theory, practice, and pedagogy remain currently insufficient to the task. In this regard, I consider DesignX a challenge trade space for resolution of the most modern, that calls for a more deliberative, systematic, and scientifically-informed multidisciplinary challenge.

[1] Horst W.J. Rittel and Melvin M. Webber, "Dilemmas in a General Theory of Planning," *Policy sciences* 4, no. 2 (1973): 155–69.

[2] Bruno Latour, *An Inquiry into Modes of Existence* (Cambridge, Mass.: Harvard University Press, 2013).

[3] Don A. Norman and Pieter Jan Stappers, "DesignX: Complex Sociotechnical Systems," *She Ji: The Journal of Design, Economics, and Innovation* 1, no. 2 (2015): 83–106.

[4] See, by way of comparison, Joan S. Ash, Marc Berg, and Enrico Coiera, "Some Unintended Consequences of Information Technology in Health Care: The Nature of Patient Care Information System-Related Errors," *Journal of the American Medical Informatics Association* 11, no. 2 (2004): 104–12; Michael I. Harrison, Ross Koppel, and Shirly Bar-Lev, "Unintended Consequences of Information Technologies in Health Care—An Interactive Sociotechnical Analysis," *Journal of the American medical informatics Association* 14, no. 5 (2007): 542–49; Andre Kushniruk and Paul Turner, "Who's Users? Participation and Empowerment in Socio-Technical Approaches to Health IT Developments," in *International Perspectives in Health Informatics: Information Technology and Communications in Health* (*ITCH*), ed. Elizabeth M. Borycki et al. (Clifton, VA: IOS Press, 2011), 280–85; Christopher Nemeth et al., "Minding the Gaps: Creating Resilience in Healthcare," *Advances in Patient Safety: New Directions and Alternative Approaches* 3 (2008): 1–13.

[5] For more information, see http://www.tavinstitute.org.

[6] John M. Flach, "Complexity: Learning to Muddle Through," *Cognition, Technology & Work* 14, no. 3 (2012): 187–97.

[7] Bruno Latour, "A Cautious Prometheus? A Few Steps Toward a Philosophy of Design (with Special Attention to Peter Sloterdijk)," in *Proceedings of the 2008 Annual International Conference of the Design History Society* (*UK*), ed. Fiona Hackney, Jonathan Glynne, and Viv Minton (Falmouth, Cornwall: University College Falmouth, 2008), 2–10.

[8] Kees Dorst, "Frame Creation and Design in the Expanded Field," *She Ji: The Journal of Design, Economics, and Innovation* 1, no. 1 (2015): 22–33.

[9] Takafumi Nakamura and Kyoichi Kijima, *System of System Failure: Meta Methodology to Prevent System Failures* (Rijeka, Croatia: INTECH Open Access Publisher, 2012).

[10] An extreme case might be the US air traffic control system, of which several major programs failed to incrementally revise in the 1980's and 1990's.

[11] John N. Warfield, "Twenty Laws of Complexity: Science Applicable in Organizations," *Systems Research and Behavioral Science* 16, no. 1 (1999): 3–40.

Authors' Response

DesignX: For Complex Sociotechnical Problems, Design Is Not Limited to One Person, One Phase, or One Solution

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We thank the three commentators to our article – John Flach, Jeremy Myerson, and Peter Jones – for their thoughtful and constructive reviews. Their comments are precisely the sort of responses we had hoped for – useful extensions and critiques of our article. It is only through such detailed critiques that the field of design can make progress.

It is a simple statement that complex problems are not simple ones. It is more complex to go beyond that and keep the message simple. In our struggle to make sense of what is going on in the upcoming future of design, we are delighted to see the constructive reactions the commentators who are also struggling with these problems, addressing the changes and potential solutions from different perspectives, consolidated frameworks, and descriptions.

These commentaries exemplify the variety in framing and focus of our academic disciplines. They extend the range of cited works and areas of application. All of us are using design to link the social and the technical. Our different perspectives resonate nevertheless; and although they arise from different traditions, their combination is extremely rewarding.

John Flach eloquently brings together topics from engineering and psychology. He introduces Ashby's principle of requisite variety: namely, that the controls available to the operators must match the dimensions of complexity of the system. He also expands the literature of previous works in this area. We do disagree with his interpretation of the value of Ashby's Law. To us, this is a statement that we must reduce system complexity, thereby reducing its degrees of freedom. In our paper, we argued that human limitations require the simplification of systems – and Ashby's Law can be used in reverse to justify this. If people are unable to cope with the requisite variety, then reduce the requisite variety. Flach believes that this attempt – to reduce complexity – is wishful thinking, easier said than done. Which approach is correct? This is an empirical question, one that will be answered only through the efforts of designers to reduce system complexity and/or to match that complexity with the control structures available to human (or technological) operators.

Flach warns against blaming the human operator for the consequences of unrealistic demands imposed by defective design. He sharpens our discussion of the "human tendency to want simple answers" through his discussion of bounded rationality.

We agree with these points. This indicates that our paper was not clear in our discussion of human capability: We certainly did not intend that people be thought of as the weak link. The argument that we should recognize that all systems, natural or artificial, have bounded rationality is excellent. Our point was that, today, engineers design for the characteristics of the technology, ignoring human capabilities – except the ability to fill in where the technology is lacking. We argue that instead, things should be designed with the limits of human capability in mind. This point can be misunderstood to imply that people are the weak link; to us, however, it argues that people are the most important component in terms of design requirements.

Flach elaborates rightly that the limits of human cognition – both of the human operator and of the human designer – should be included in the design process, just like any of the other constraints presented by technical, or social, components.

We are grateful to Jeremy Myerson for providing the story of the redesign of the London emergency ambulance service that was also presented during the Shanghai workshop. Despite its clear success in winning design prizes, it has still not been implemented. This provides a powerful case study of the critical problems involved in implementation. As he put it, "Undeniably, the biggest barriers to implementation can be found in the social, political and economic frameworks: changes in the political and funding climate have blown our ambulance project off course…."

Furthermore, he emphasizes the limitations of the designers. Again, in his words, "The gap between the demands of today's complex systems and how most trained, hyper-focusing designers see the world is a chasm which all the categorizations of DesignX will struggle to bridge."

Peter Jones brought both a case study and a theoretical framework to the Shanghai workshop. In his comments, he further emphasizes a wary attitude about what a single design step can achieve. From his experience he brings both practical and formalized discussion of the social emphasis: perhaps instead of DesignX we need a "Socio-X" perspective. He also reminds us that these issues have a long history of study, providing a rich source of citations to the literature that we failed to provide – and in some cases were unaware of. Both Jones and Flach rightly criticize us for our ignorance.

The problems of working in these complex systems stem from the diversity of actors present in the arena; very few are aware of all the relevant work. We called for a different kind of design education, but Jones warns us that "Because it's unlikely that graduate design education will sufficiently touch on these perspectives and their case studies, we risk ignorance of this extraordinary developed knowledge – possibly dimly reinventing their models when faced with correlated insights, yet not benefit from appropriating the wisdom of 60-plus years of deep experience in these systemic perspectives."

All three commentators see that design and implementation are not only the remit of designers, but will involve a creative collaboration between a variety of actors and stakeholders. Design education will have to prepare future professionals for this dimension of collaboration. As Jones says, "we might ask: if 'we' across the design disciplines are not designing for complex sociotechnical systems, then who is? Are we ignoring these problems to some extent from conflict with aesthetic tastes, or because actually resolving these problems resists the rapid satisfaction of creative 'design thinking?' Or, are we shunning involvement with the depth of complexity, a lengthy commitment to a problem, and the inherent risks of bad design decisions? We might start finding in these critical problems the moral equivalent of infrastructure – we have to improve design for technological integration, because our lives and social ecologies depend on it."

What next? This combination of paper and commentary does not provide the answer to DesignX problems, but the discussion puts together a range of experiences, narratives, and framings from diverse design angles, identifying a number of issues and ingredients that have a shared perspective. The next steps will require addressing these issues. The result should be productive: better solutions and approaches for these large, complex, important problems of modern society, plus an enhanced, strengthened scope for design education.