Simon's Slice:
Five Fundamental Tradeoffs that Bound the Performance of Human Work Systems

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ABSTRACT

This paper discusses the fundamental trade-offs that bound the performance of all human work systems. Originally, Herbert Simon introduced a single trade-off, which he called "bounded rationality." The five tradeoffs we present emerged from combining empirical generalizations about macrocognitive work systems with basic constraints on complex adaptive systems. Five fundamental tradeoffs were identified, with Simon's notion being recast as just one of them. The five bounding trade-offs integrate empirical laws as the basis for a formal theory of human-machine macrocognitive work systems and an approach to measuring macrocognitive work at this system level.

Keywords

Macrocognition, complexity, trade-offs, laws of cognitive work, measurement

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1. INTRODUCTION

Our goal in this paper is to present a covering law model that integrates the laws of Macrocognitve Work Systems (MWSs).[1] Here are some examples:

- The Cognitive Vacuum Law: Workers develop mental models of the MWS, including the technology.
- Law of Coordinative Entropy: Coordination costs, continuously.
- The Law of Balance: To be adaptive, the MWS must dynamically balance delegation and autonomy, authorization and accountability, centralization and decentralization.
- Law of Surrogate Systems: The MWS will embody the stances, agendas, and goals of the designers.
- Mr. Weasley's Law: Workers develop unjustified trust and unjustified mistrust in their MWS and its technology.
- The Law of the Kluge: MWSs always create a pressure on the workers to adapt by creating kluges and work-arounds.
- The Geenspan-Hollnagel Law: Complexity cannot be reduced; it can only be transformed
- The Leplat-Rasmussen-Suchman Law: While conducting cognitive work within a MWS, people do not conduct tasks, they engage in context-sensitive, knowledge-driven choice among alternative activities.

In the initial formulation (Woods, 2002; see Woods and Hollnaegl, 2006) the laws were organized into groups called "families." But were these families conveniences of exposition or did they represent more fundamental constraints? Did the concept of a "family" do any heavy lifting in a theory, and how would it fit into a metatheory?

In the process of attempting to formulate a stopping rule (i.e., what does it mean in a complexity theory context to assert that a set of laws might be complete?) and an initial attempt at constructing a metatheory (i.e., postulates concerning lawlikeness, and the theory's completeness, consistency, and testability) (Hoffman and Woods, 2005; Hoffman et al., in preparation), we realized that the empirical generalizations are in fact derivatives from a set of five covering laws. In theoretics, a covering law is a second-order nomological generalization that places first-order empirical extensional generalizations into an entailment relation (i.e., any formal model of the covering law will also be a model of the first-order laws). One of the covering laws is Simon's "bounded rationality" thesis (Simon, 1991). Since one of the initial families of laws (Laws of Models) represented variations derived from the fundamental constraint that Simon's bounded rationality described, we re-examined the other families.

Continuing research on the empirical regularities in macrocognitive work systems (Hoffman and Woods, 2005; Woods, 2002; Woods and Hollnagel, 2006) led us to identify additional trade-offs:

- Investigations of complex adaptive systems identified a tradeoff that bounds the performance of adaptive systems. Based on studies of biological and physical systems, Doyle (2000) argued that the pursuit of increases in optimality with respect to some criteria guarantees an increase in brittleness with respect to changes or variations that fell outside of those criteria—a tradeoff between optimality and fragility (Csete and Doyle, 2002).
- Work on proactive safety management and the concept of Resilience Engineering identified two tradeoffs that bound the performance of organizations that carry out risky activities: A tradeoff between acute and chronic goals, and a tradeoff between efficiency and thoroughness criteria (Brown, 2005; Woods, 2006; Hollnagel, 2009; Woods, 2009; Grote, 2009).

Complexity theorists have continued to search for a formalization and explain how observed tradeoffs are derived from the most basic ones (Alderson and Doyle, 2010). For the class of human adaptive systems, this paper provides such a unification.

There are five basic trade-offs that bound the performance of all human work systems. These tradeoffs specify constraints on the performance and adaptive capacities of human-machine work systems. The five bounds, as covering laws, integrate empirical generalizations about work systems. This, in turn, provides the basis for formalization of a measurement methodology (Hoffman and Woods, 2005; Hoffman, Hancock and Bradshaw, 2010; Hoffman et al., in preparation).

2. FIVE BOUNDS

The five tradeoffs express bounding constraints on systems. Table 1 and Figure 1 (both are presented following the References) capture the five bounds on work systems.

- <u>Bounded Ecology</u>

A macrocognitive work system can never match its environment completely. There is always a struggle for fitness though it may ease or intensify. As changes occur and adaptations develop there is an impetus to develop resilience and avoid brittleness in the sense of the need to be able to gracefully degrade in the face of surprise.

- <u>Bounded Cognizance</u>

Macrocognitive work systems are fallible. There is always an "effort after meaning," though it may ease or intensify. This recasts Simon’s Bounded Rationality notion. Algorithms, embodied in any form, operate with finite resources and thus are fallible. This expresses the fact that there are always gaps in plans, models, and procedures relative to the situations where they would be implemented to achieve goals. There are always challenges in bringing knowledge to bear in a context (deploying knowledge to effect). These gaps lead to an impetus to learn to adjust plans to fit the situations actually at hand. (Note: we use the phrase "bounded cognizance" rather than bounded rationality because we do not presume the normative-logical stance and one person-one machine context associated with Simon's idea.)

- Bounded Perspectivity

Macrocognitive work systems are limited in their opportunities, incentives and support to shift perspective. There are limits on an agent's ability to see and assess the world around them. Agents, at any level of abstraction, occupy a point of observation relative to the world they are embedded in, and this relationship defines a perspective (Morison, et al., 2009; Woods, 2000). The view from any single point of observation simultaneously reveals and obscures aspects of the world. Disambiguation arises from the ability to shift and contrast perspectives (Morison, 2010; Woods and Sarter, 2010). Furthermore, situations change in how strongly they signal the need to shift perspectives to reveal what had been hidden. Interestingly, models of complex systems also have found it necessary to include a concept of perspective as a basic parameter (Page, 2007). Since there is never one all-encompassing or omnipresent view of the environment, gaps arise in perceiving the world from any given perspective. This means there is always an invitation for reflection, that is, to shift perspective to see the situation in some contrast. The ability to shift and contrast perspectives has proven to be essential to coordinated activity and collaborative work (Page, 2007; Smith et al., 2010).

- Bounded Responsibility

Macrocognitive work systems divide up roles, responsibilities, and risks. No role is all-knowing or omniscient. This entails a trade-off because the responsibility and risks associated with achieving or failing to achieve goals are divided over roles at different levels or echelons of a system (differential responsibility). All systems pursue multiple goals that interact and can conflict. Gaps arise across roles as different parts of a distributed system are differentially responsible for different subsets of goals. This means that all systems are simultaneously cooperative over shared goals and competitive where goals conflict, whether those conflicts are explicitly recognized or not. Most critically, conflict arises between the acute goals—timely, efficient, effective (or after NASA's policy, the "Faster-Better-Cheaper" goals) and the chronic goals (such as safety or equity; see Woods, 2006).

- Bounded Effectivity

Macrocognitive work systems are restricted in the ways they can act and influence situations. No controller is omnipotent. This bounding arises because systems are restricted in the ways they can act on the world and influence processes underway. Given there is always some potential for surprise, all systems have to work to balance distant plans with local adaptations, in order to fit responses to conditions to make progress toward goals. Thus there are multiple centers of control working in parallel. All centers of control have bounds on their scope of authority for adapting to meet sub-goals within the context of other centers. "Local" centers are sensitive to sources of variability, giving them privileged ability to pick up on surprises, disruptions, and opportunities to plans in progress. "Distant" centers of control provide broader perspectives over time, space, and multiple functions, allowing them to see how to coordinate activities to achieve larger goals under tighter pressures. Bounds on acting to generate progress toward goals arise from tradeoff about distributing authority, initiative, and autonomy across centers or concentrating authority, initiative, and autonomy in a single center of control.

3. INTERCONNECTIONS

These tradeoffs stand in contrast to the myth that there can be a single center of command – centralized, with all information and knowledge available, concentrating authority to match its global responsibility, and the ability to act optimally through intermediaries instantly and effectively regardless of temporal, spatial or functional scales.

Together, these five bounds or covering laws serve to organize the first-order empirical laws of macrocognitive work, and place of those laws in a larger theoretical and metatheoretical framework. For example:

- The Law of Stretched Systems—Every system is stretched to operate at its capacity; as soon as there is some improvement, some new technology, it will be exploited to achieve a new intensity and tempo of activity. This law is entailed by Bounded Ecology. Adaptation to become more optimal with respect to some goals/criteria will leave the system poised more precariously than its designers and managers realize.
- The Reductive Tendency law—agents at all scales must develop/use simplifications (e.g., decomposition to cope with interdependencies and decoupling to cope with dynamic interactions) to meet internal and external pressures for efficient use of resources. This law is entailed by Bounded Cognizance. Adaptation to finite resources inevitably leads to the reliance on simplifications. The question is can a system monitor the limits of these simplifications relative to signals from the world and switch to more complete models that treat interdependencies more systematically (and to do this before the inadequacies of simplifications result in failures, e.g. as in proactive safety management).

Each class of bounds (each covering law) entails a particular trade-off function. Systems can improve at how they perform on a tradeoff dimension but systems cannot escape the risks inherent in the tradeoff. Efforts are underway to develop the principles for resilient and polycentric control architectures (e.g., Alderson and Doyle, 2010; Woods, 2009; Woods and Branlat, 2010) that can regulate how systems change their positioning in the state spaces defined by these tradeoffs. In other words, there is no absolute “correct place” in the five inter-related state spaces; rather, resilient control uses signals about threats/trends to/about “being in control” and makes adjustments over the tradeoffs to re-position the system in the state spaces.

Grounding the modeling of human systems on the five trade-off functions provides the starting point for solving the perennial problem of how to evaluate the performance and adaptive capacity of macrocognitive work systems on principled formal grounds, rather than on ad hoc tabulations chosen to maximize tractability and minimize cost. Because the tradeoff functions are fundamental, efforts at measurement and prediction will change from the traditions in either utility approaches or human performance approaches. The assessment of system performance requires at least two measurables on each of the five bounds. Numerical scales must address interactions across data types, and must be interpretable as measurement scales that address the system's ability to adapt to events and changes in the future (Hoffman et al., 2010; Hoffman et al., 2011; Woods, 2010).

4. DISCUSSION

One way of understanding the advance that we present is to say that Simon only had one slice of the problem when he set out his framework for interpreting computer programs as theories of cognition. Broadening from the context of "one person-one machine" to the context of MWSs, we have found there are four additional bounds on the performance of any human system defined at any level. These tradeoffs are manifested in actual systems and can be illustrated through case studies of the reverberations of change in MWSs

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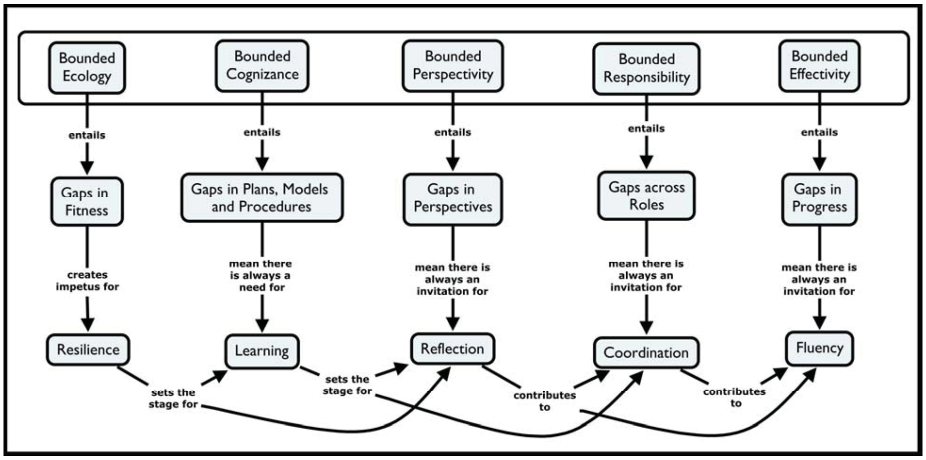

Figure 1. Diagram of relationships that characterize the five bounds on work systems. The top row names the covering laws (i.e., "families"), the middle row indicates how surprise triggers adaptation, and the bottom row expresses the means for adaptation.

Table 1. Five tradeoffs.

GAPS IN FITNESS – BOUNDED ECOLOGY
Optimality-Resilience Trade-off Increasing the scope of the routine increases the opportunities for surprise at the boundaries. The relation between demands and resources defines fitness Optimizing over some demands leads to brittleness when encountering other demands. Resilience requires a capacity to adapt to surprising events, and preparing for surprise requires resources.
GAPS IN PLANS – BOUNDED COGNIZANCE
Efficiency-Thoroughness Trade-off Knowledge defines plans. Plans to generalize best practices for classes of situations. Efficient plans mark well-worn paths but it becomes cumbersome to incorporate contingencies and variations. Thoroughness expands the scope of the plans, expanding assessments, decisions and ambiguities.
GAPS IN PERSPECTIVES – BOUNDED PERSPECTIVITY
Acute-Chronic Trade-off Chronic goals tend to get sacrificed to acute goals, which in turn leads systems to miss how and where they are brittle. Goals define perspectives, and every perspective simultaneously reveals and obscures aspects of the world. Acute goals can be assessed through short run tabulations but chronic goals (e.g., safety) can only be assessed in the long run; they are harder to measure and function more like values.
GAPS ACROSS ROLES – BOUNDED RESPONSIBILITY
Specialist-Generalist Trade-off Responsibility defines roles. Specialist roles increase the ability to handle specific kinds of cases, but challenge the ability to connect the activities together to achieve continuity for cases that cut across roles. Generalist roles enable handling diverse situations but less fluently for specific kinds of situations. Coordination expands scope of activities but must be balanced with new costs associated with coordination. Changes in autonomy for single roles create changes in accountability across roles. Coordination costs and changes in accountability entail risk in the continuing drive to balance continuity versus fragmentation.
GAPS IN PROGRESS – BOUNDED EFFECTIVITY
Distributed-Concentrated Trade-off Distributing activities that define progress toward goals can increase the range of effective action, but increasing the distribution of activities entails some difficulty of keeping them coherent and synchronized. Concentrating activities in single roles can produce more immediate and definitive progress toward landmarks, but also reduces the range of effective action. The challenge is to balance micromanagement with delegation over echelons.