COMPLEX, SOCIOTECHNICAL SYSTEMS (CSS): SOME FUNDAMENTAL CONCEPTS

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November 4, 2009

Introduction and Proviso

Our interests in ESD are largely focused on complex, sociotechnical systems (CSS)—understanding and improving them and developing methods for representing and designing them. By CSS, we mean (for our purposes here), large-impact, difficult-to-understand systems that have important technology issues *and* important societal implications. We will spare you, for the most part, the myriad definitions of "complexity" If you are interested, see these two references on the ESD Working Paper site

http://esd.mit.edu/WPS/default.htm

Lloyd, Seth, ESD Internal Symposium: Complex systems: a review (ESD-WP-2003-01.16)

Sussman, Joseph, Ideas on Complexity in Systems – Twenty Views (ESD-WP-2000-02)

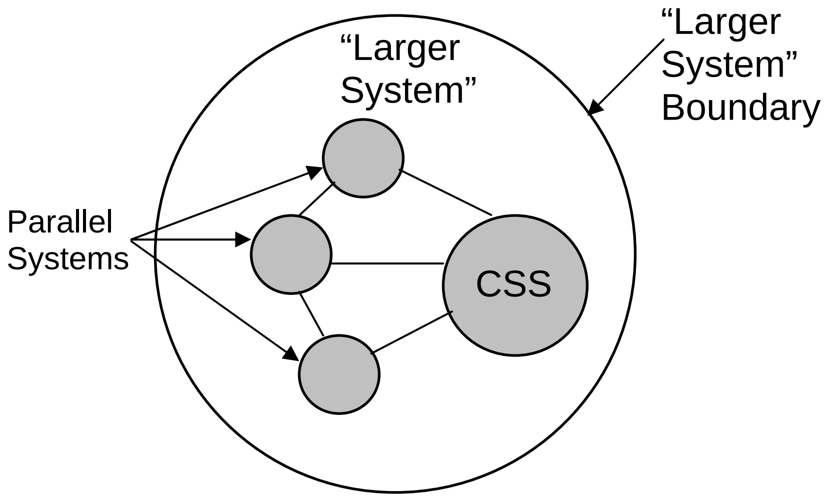
Throughout this note we will refer to CSS, but we recognize that much of what we say about CSS is true of other systems too—technical systems, social systems and others too.

This note attempts to capture many concepts that we experientially have found to be of value when one tries to characterize/analyze/design/think about a CSS. No claim is made for completeness; there are doubtless other valuable concepts. Nor, except in a few situations, do we claim originality; many of these concepts will be familiar to you and have been documented in texts, professional papers and so forth. We owe a huge debt to seminal systems authors including (but not limited to) Forrester, Simon, Senge, Lorenz, Weiner and others. Also we have drawn on the work of ESD colleagues including (but not limited to) Sterman, Moses, Magee, de Weck and others.

CSS Concepts

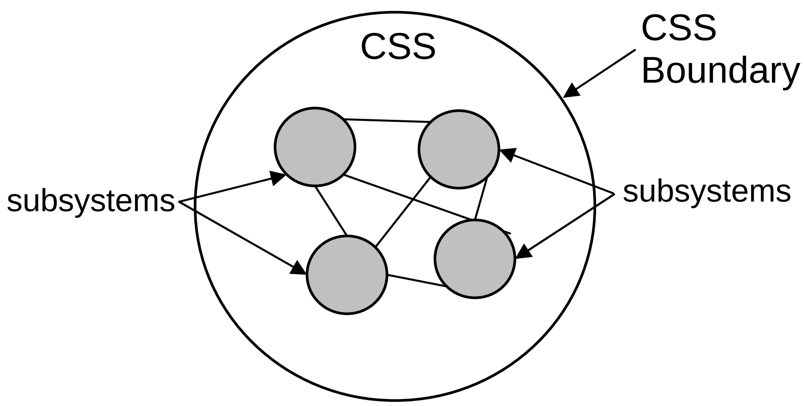
When we study CSS, we need to take a broad view of the problem space, recognizing there are interactions of **"our"** CSS with other systems external to it that often need to be explicitly considered. This concept can be thought of as "horizontal" in that while considering our CSS, we should consider other parallel systems to which it is connected.

Our CSS of interest is always part of a larger system composed of our CSS and these parallel systems; our CSS affects the behavior of the parallel systems and hence the larger system; in turn our CSS's behavior is affected by the parallel systems and the larger system.



Some like to think as the set of parallel subsystems as the "environment" of the CSS and we will do that in this document.

It follows that our CSS is composed, in part, of smaller systems—often referred to as "subsystems".



Of course, these two diagrams represent the same concept at different levels of hierarchy.

The micro-macro question

A key systems issue is the relationship between the macro-behavior of our CSS, and the micro-behavior of subsystems. It is important to understand how that micro-behavior affects macro-behavior of our CSS, and at what level-of-detail we have to understand the micro-behavior in order to properly understand the macro-behavior. Further, we need to understand how the subsystems affect each other and how those interactions impact on the macro-behavior of the CSS. So perhaps there are rules of thumb about how deeply we need understand the micro and its relationship to the macro—but in practice, we go up and down the chain, down into the micro (the subsystems), back up to the macro, and so on as one iterates until we find out what we "want to know" with some level of confidence, which of course will vary from person to person.

For example, we may be interested in the electric power grid, at a macro-scale. So, this is our CSS. The behavior of this CSS is affected by user behavior at a micro-scale, such as the household use of devices like an "energy box" to optimize household energy costs. At what level-of-detail do we need to understand how the energy box affects household use in order to have a good understanding of the behavior of the CSS of interest, the electric power grid? Similarly, thinking "horizontally", the interaction between our CSS and the regional environmental CSS may be of interest as well.

We need to recognize that the optimizing of each of the subsystems of a CSS may lead to overall CSS performance that is far from optimal. *"Everyone"* understands this, but in real life, it is a huge temptation to do exactly that and sub-optimize your CSS! Of course, not trying to optimize even the subsystems—also a temptation when faced with all this complexity-- likely will lead to even poorer CSS performance.

Feedback

So put another way, we need to understand the implications and impacts of *feedback* among subsystems internal to the CSS, and between the system environment—made up of the parallel systems-- and the CSS itself. Also we must recognize the *time delays* inherent in feedback and their effect on CSS behavior.

Emergent behavior

In our consideration of CSS, we need to train ourselves to look for emergent behavior—defined here as CSS behavior that is not predictable simply by considering the behavior of the subsystems-- and unanticipated consequences characteristic of these CSSs. These behaviors and consequences can be "good" or "bad".

Non-linearity

We must recognize the implications and impacts on CSS behavior of *non-linearity*, in subsystem behavior internal to the CSS, and between the CSS environment—made up of the parallel systems--and the CSS itself and in feedback that may be non-linear in nature

Stochasticity

We must consider the implications and impacts on CSS behavior of *stochasticity* in subsystem behavior internal to the CSS, and between the CSS environment—made up of the parallel systems-- and the CSS itself and in feedback that may be stochastic in nature.

Cause and Effect in CSS

Cause and effect may differ in time: occur at different times

Cause and effect may differ in space: be geographically distant from each other
Cause and effect may differ in kind—e.g. changes in the transportation system causing health effects (we know this now, but didn't always know it—what connections between cause and effect are we unaware of now that will bite us someday?)

It may be difficult to understand the directionality of cause and effect—e.g. in developing countries, is the rise in income causing the fall in infant mortality or does the fall in infant mortality cause a rise in income? Or e.g. does transportation investment drive land use or does land use change lead to transportation investment or perhaps are both true?

Effects may arise from multiple causes; further, causes may result in many effects. In considering cause and effect, it is important not to confuse correlation and causality. Small changes in initial conditions or in a parameter can lead to very large differences in CSS behavior over time.

Long-term vs. Short-term behavior

There are usually considerable differences between the long-term and short-term behavior of CSSs. Positive short-term behavior, in response to an intervention we implement, may give us false confidence; this positive behavior may be followed by negative behavior in the long-term.

Time scales

Components of CSSs may operate at very different time scales. For example, in transportation systems, operating policies may be changed in the short-term; vehicle purchases may occur in the medium-term; and building infrastructure will take place in the long-term.

Humility

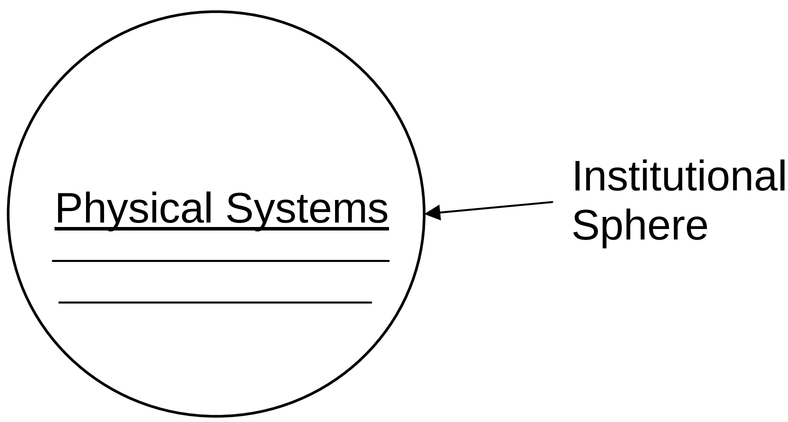
The points above create considerable difficulties in predicting system behavior; when we make design decisions that affect that behavior, it requires humility on our part. Often we are happy simply to be able to predict "the sign" of system change in response to actions we might take. It is clear that for successful design, we would like to predict the behavior fairly accurately but at present this may not be possible. While this does not suggest that we do nothing, we must try to understand the characteristics and behavior of a CSS, as well as we can (see Wulf, William (2000). "Great Achievements and Grand Challenges" in *The Bridge*. 30(3/4): 5-10.

Evaluative Complexity

Multiple stakeholders of complex, sociotechnical systems have their disparate interests and hence their different ways of evaluating system performance. We call this *evaluative* *complexity*. Resolving evaluative complexity often creates ethical dilemmas as, in effect, choices among stakeholders are made by the system designers and operators.

Nested Complexity

A CSS can be complex from both a “physical” perspective and an “institutional” perspective. We can think of the physical system housed within the institutional sphere embodying the organizations involved; both the physical system and the institutional sphere exhibit complexities of various sorts. *Nested complexity* is the term we use to describe the interaction of these two kinds of complexity. It is difficult (and perhaps impossible) to make important changes in CSSs without implementing changes in the institutional sphere (and the latter is especially difficult).



The author has seen the interaction between the physical and institution parts of a CSS shown with the institutions nested within the physical “sphere” or with the physical and institutional parts intertwined. This is largely the taste of the observer; the important point is the interconnection between them, however represented. In general, one can’t change either one without changing the other.

Rationality

People and organizations are *not* always “rational” in the way they make decisions and hence the initiatives we implement as an intervention may not produce the behavior we expect if we assume “rationality”.

Further, there are limits to human capability to understand a CSS. This is an illustration of what Herbert A. Simon calls “bounded rationality”.

People and organizations respond to incentives (e.g. through pricing) or at least how they perceive their incentives. This can be a means of altering their behavior and hence overall system behavior. But as noted, we may not see their behavior as “rational”.

Information

Information—its availability, its accuracy, its timeliness, its volume and its processibility— are central to making decisions about complex, sociotechnical systems. Further, different stakeholders may have different information available to them. We call this information asymmetry.

Costs and Functionality

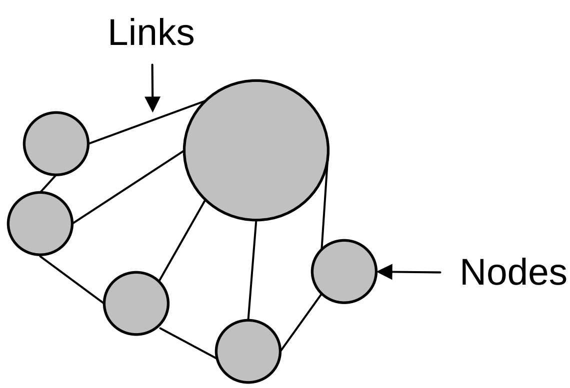
The level-of-service or functionality provided to CSS users often are multi-dimensional in nature (e.g. in transportation, average travel time, reliability, comfort, price).

The cost for a CSS to provide a particular level-of-service or functionality and the price charged for it may not be consistent (e.g. in non-competitive situations).

The computation of cost for a system to provide a particular level-of-service or functionality is often difficult and ambiguous (e.g. allocating infrastructure maintenance costs to different services, like passenger and freight on a rail system).

Network structure and beyond

We often find complex systems are structured as networks—physical, logical and organizational—with flows on the links of these networks of matter, energy and information, traveling between nodes.



Performance of network-based systems is affected by the behavior of the links and nodes. Nodes may be more critical in some cases and links in others, depending of the type of network. For example, in rail freight networks, experience has taught us that node (terminal) performance dominates overall system performance.

Investment in these systems is often "lumpy"—that is, binary. For example, you build a link or you don't, making that decision (often an expensive one) difficult to resolve.

The behavior of a system component is often highly non-linear as the volume it carries approaches the "capacity" of that component, with often dramatic effects for the overall system. [Think about a highway link and the network of which it is a part] This together with the immediately preceding point, creates difficult design challenges. [Don't add the link and see performance degrade, or add the link at great cost to gain more capacity than you need.]

Layers of Abstraction

Thinking beyond networks, the concept of *layers of abstraction* may lead to organizational architectures that are different from classic tree structures or networks, but which have links and nodes similar in function to those of a classic network (Moses).

CSS Design

Sustainability

Sustainability--- defined by the three Es, **E**conomic development, concern with the **E**nvironment and social **E**quity--- is the overarching design principle for complex, sociotechnical systems (simply a Sussman assertion, I freely admit).

The "ilities"

The "ilities"—flexibility, stability, robustness, scalability and so on—are "macro-characteristics" we strive to achieve in the design of CSSs (Moses). Almost always, these are difficult to simultaneously achieve and choices among them must be made. (I recognize that defining the individual "ilities" is a difficult and sometimes contentious task).

Goals, Objectives and Performance Measures

The design process requires the development of system goals and objectives as well as performance measures. Doing this in the face of the evaluative complexity, described above, is often a difficult task.

Design Stages

The broad concept of "design" of CSSss can be usefully divided into stages:
- System representation
- Design, evaluation and selection
- Implementation

These are generally executed in an iterative fashion.

Strategic Alternatives and Robust Bundles

The creative aspect of system *design* is the generation of individual *"strategic alternatives"* dealing with decisions about technology, operating practices, investment, organizational change and changes in relationships among organizations, and so forth and then the formation of these individual strategic alternatives into robust *bundles* (since there is never a "silver bullet") to *evaluate, select among and finally to implement.*

CSS evolution

Further, as we design, we must recognize that complex systems may change of their own accord during the design process; they evolve and are never are static. Physical systems mainly grow through aggregation; social and knowledge systems tend to grow by coalescence (de Weck).

Centralization and Hierarchy

Fundamental design decisions for CSS include the degrees of centralization and hierarchy in the way they are designed and controlled.

Considering External Response

A common error in CSS design is that we do not consider the *External response adequately (competition, customers, regulators, suppliers, etc.)*. We often do not understand the change in expectations of customers or others external to the system, based on system performance and level-of-service provided. For example, we often have a static assumption about what our competition will do when we introduce new concepts; if the US builds high speed rail in regional corridors, we can't expect the airlines to simply watch it happen without reacting.

"Satisficing"

In CSS design, optimization is often beyond the pale. We are happy enough to find a few feasible "solutions", never mind optimal. We search for alternatives that are "good enough" -- "satisficing" -- especially when there is limited analysis capability or limited information or limited time.

<u>Conclusion</u>

We hope you find this list of "systems concepts" of some value; perhaps it can help guide you in the way you think about systems.

To close, here is a useful construct to tie together many of the ideas herein:

Structure, Function and Dynamics

We need to understand the relationship between the *structure, function and dynamics* of a CSS and further understand that each of the three is a key determinant of system behavior (Magee).