Extended abstract for CDC Workshop

Universal laws, architectures, and behaviors of robust, evolvable networks

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This workshop will review recent progress on developing a "unified" theory for complex networks involving several elements: hard limits on achievable robust performance (misnamed "laws"), the organizing principles that succeed or fail in achieving them (architectures and protocols), the resulting high variability data and "robust yet fragile" behavior observed in real systems and case studies (behavior, data), and the processes by which systems evolve (variation, selection, design).

Hard limits on measurement, prediction, communication, computation, decision, and control, as well as the underlying physical energy and material conversion mechanism necessary to implement these abstract process are at the heart of modern mathematical theories of systems in engineering and science (often associated with names such as Shannon, Poincare, Turing, Gödel, Bode, Wiener, Heisenberg, Carnot,…). They form the foundation for rich and deep subjects that are nevertheless now introduced at the undergraduate level. Unfortunately, these subjects remain largely fragmented and incompatible, even as the tradeoffs *between* these limits are of growing importance in building integrated and sustainable systems. An essential research direction then is an integrated theory based on optimization that deals systematically with uncertainty, robustness, and risk in complex systems.

Insights into what the potential universal laws, architecture, and organizational principles are can be drawn from three converging research themes. First, detailed description of components and a growing attention to systems in biology and neuroscience, the organizational principles of organisms and evolution are becoming increasingly apparent. Biologists are articulating richly detailed explanations of biological complexity, robustness, and evolvability that point to universal principles and architectures. We will give a brief tutorial introduction to this subject suitable for the typical CDC attendee.

Second, while the components differ and the system processes are far less integrated, advanced technology's complexity is now approaching biology's and there are striking convergences at the level of organization and architecture, and the role of layering, protocols, and feedback control in structuring complex multiscale modularity. Determining what is essential about this convergence and what is merely historical accident requires a deeper understanding of architecture — the most universal, high-level, persistent elements of organization — and protocols. Protocols define how diverse modules interact, and architecture defines how sets of protocols are organized. Most CDC attendees will be familiar with the many examples of protocols and architectures in technology, and we will build on this shared understanding to highlight fundamentals and principles.

Third, new mathematical frameworks for the study of complex networks suggests that this apparent network-level evolutionary convergence within/between biology/technology is not accidental, but follows necessarily from their universal system requirements to be fast, efficient, adaptive, evolvable, and most importantly, robust to perturbations in their environment and component parts. The universal hard limits on systems and their components have until recently been studied separately in fragmented domains of physics, chemistry, biology, communications, computation, and control, but a unified theory is needed and appears feasible. We have the beginnings of the underlying mathematical framework and also a series of case studies in classical problems in complexity from statistical mechanics, turbulence, cell biology, human physiology and medicine, neuroscience, wildfire ecology, earthquakes, economics, the Internet, and smartgrid. This will be the heart of the workshop, and will build on theory that has grown out of the controls community. There will be many papers at the CDC that will connect with this part of the workshop, and we will try to focus again on those aspects that are most important but perhaps least familiar. This would especially involve new case studies that are published in the broader scientific or engineer literature.

Not surprisingly, we will emphasize robustness and optimization as central unifying themes. Generally, organisms and their lineages are robust and evolvable in the face of even large changes in environment and system components, yet can simultaneously be extremely fragile to other small perturbations. Such universally "robust yet fragile" (RYF) complexity is found wherever we look. The amazing evolution of microbes into humans (robustness of lineages on long timescales) is punctuated by mass extinctions (extreme fragility). Diabetes, obesity, cancer, and autoimmune diseases are side-effects of physiological control and compensatory mechanisms so robust as to normally go unnoticed. RYF complexity is not confined to biology.

The complexity of modern institutions and technologies is exploding, but in ways that remain largely hidden. They facilitate robustness, scalability, and accelerate evolution, but enable catastrophes on a scale unimaginable without them (from network and market crashes to war, epidemics, and global warming). Network-centric technology promises to provide unprecedented levels of performance, efficiency, and robustness. The ultimate challenge will not be to make this apparent in demonstrations and typical scenarios, but to avoid the rare but catastrophic real-world failures that seem to inevitably accompany new levels of complexity.

Below is a list of papers that could serve as background reading for this workshop, and we plan to have a more extensive guide available to attendees before CDC. In the workshop, we will attempt to summarize the last decade or so of research that has branched out substantially from mainstream control into other areas of engineering, but also science and medicine, but still maintains strong thematic contact with controls.

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