Task Group Summary 3

How can we enhance the robustness via interconnectivity?

Challenge Summary

In contrast with most human designs, which are prone to failures once their components fail, natural and some human-made but self-organized systems display a high degree of robustness to component failures. Indeed, living systems can carry on their activity despite the many molecular errors at the cellular level and the Internet does not collapse despite the fact that at any moment hundreds of routers are not functional. Many living systems, like bacteria, have been shown to be able to withstand the removal of several key enzymes. It is increasingly believed that the robustness of these systems is rooted in their networked nature. Early attempts to address a network's response to attack and failures indicated that real networks are highly robust to random failures but fragile against attacks. Subsequent work has shown that the interplay between the resources and the demand can lead to cascading failures, uncovering a high degree of fragility of some systems. A good example is offered by the US electrical power grid, whose cascading East Coast breakdown was initiated by local failures. In general, a series of recent studies suggest that networked systems are not only robust but also suffer from *vulnerability due to interconnectivity,* as local failures can spread and turn global.

Despite the recent fundamental advances, a deep understanding of the origins and mechanism or robustness across many complex systems is lacking. Little is known, for example, of the role of the dynamics (communication protocols, flow processes) on the network, and how the dynamics and the topology influence each other to promote or undermine robustness. Thus the role of the present working group is to explore what factors contribute to a system's robustness. To achieve this goal, the group is asked to choose a system that is of major importance for the research community and explore the origins of robustness in this system. The system of choice could range from manmade systems, like the Internet or other communication networks, to natural systems, like the cell or an organism.

Key Questions

- What are the proper metrics of robustness?
- How does one quantify the relative contributions of network structure and dynamical effects to robustness?
- Are there universal design principles to robust systems?
- Is robustness more than redundancy?
- Designing networks that are robust to both failures and attacks.
- Cascading failures—can they ever be remedied?
- What measures are appropriate to enhance robustness on a given system?

Required Reading

Albert R, Jeong H, Barabási A-L. Error and attack tolerance of complex networks. *Nature* 2000;406:378–482.

Motter AE. Cascade control and defense in complex networks. *Phys Rev* L*ett* 2004;93(9):098701. [http://lanl.arxiv.org/PS_cache/condmat/pdf/0401/0401074v2.pdf.}

Barabási A-L, Bonabeau E. Scale-free networks. *Scientific American* 2003:May:50-59.

Suggested Reading

Levin SA, Lubchenco J. Resilience, robustness, and marine ecosystem-based management *Bioscience* 2008;58(1):27-32.

Paul G, Sreenivasan S, Havlin S, Stanley HE. Optimization of network robustness to random breakdowns. *Physica A*2006;370:854-862.

Barkai N, Leibler S. Robustness in simple biochemical networks. *Nature* 1997;387(6636):913-917.

Due to the popularity of this topic, two groups explored this subject. Please be sure to review the other write-up.

TASK GROUP MEMBERS – GROUP A

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At the 2008 National Academies Keck *Futures Initiative* Conference on Complex Systems, one of two Task Groups (3A) charged with thinking about how to enhance robustness via interconnectivity, considered several areas on which to focus. Group members from universities and government research centers saw complex systems from a variety of different perspectives: nanoscale bond interactions; microtubules and systems of self-organization in cell growth; sensor networks in the coordination of robots; human disaster relief social networks; water and turbulence; virus life cycles in the human body; and gene interaction networks derived by quantitative phenotyping.

What Is Robustness?

The group initially grappled with what we mean by robustness. The general consensus was that we needed to define what the system is before we talk about its robustness. For example, is the system a cell, an organism or species? Because there are many facets to complex systems across different scale-levels, different perturbations and performance measures need to be considered. One must be careful of what scale is selected when initially defining the complex system (and related optimization goals). In certain systems, one might find performance fluctuations on a small scale that would not appear at a larger scale. Or, a loss of robustness at a certain scale might be accompanied by a gain in robustness at another scale. These robustness trade-offs, where performance or robustness of a system is sacrificed at one level to be enhanced at another level, exist and must be taken into account when robustness of a complex system is measured. A complex system is also typically fluid. Connections within an engineered or biological complex system are always breaking, reforming, and changing. Perturbances often seem inseparable from the networks and complex systems themselves.

Everyone in Task Group (3A) seemed to agree that robustness is a continuum, not a case of have or have not.

Exploring the nature of robustness and fragility in complex systems, Task Group (3A) attempted to abstract from real-life examples of complex systems how connectivity within the system might influence its robustness.

"Networks" provide a useful way to depict a complex system through component nodes and functional connections. For convenience of discussion, the group identified four systems that were deemed relatively easy to deconstruct into their component parts: power grid structures, health care, the Internet, and yeast genetic interactions. For example, power grids have as nodes houses/businesses, substations, and central power stations; highly connected nodes (central stations) are considered as hubs. Similarly, nodes of a health care system could consist of patients, doctors and other health providers, connected by their respective encounters. The Internet can be broken down into personal computers as nodes and servers as hubs of information distribution. A genetic interaction network has genes as nodes, and connectivity between the nodes represent "interactions," defined as dependencies that genes share with respect to expression of a phenotype, like cell growth.

An abstract examination of network dynamics and degree of interconnectivity within the structure of our selected complex systems allowed us to make recommendations for increasing robustness. A network's behavior can be thought of as based on its performance in a particular context due to the effect of a particular perturbation. We delineated hypothetical performance objectives and relevant perturbations for selected complex systems, with an eye toward abstracting general robustness strategies from one system that could be applied in an analogous way to increase robustness in other systems.

In the case of power grids, the objective in enhancing robustness was to maximize the number of people with electrical power and to minimize the risk of cascading power failure. In the case of health care, the objective was to prevent epidemics caused by a novel pathogen. In the case of the Internet, the objective was to maximize available online time for each individual while preventing service failures. In the case of yeast genetic interactions, the objective was to characterize robustness by "reverse-bioengineering;" cell proliferation is a robust property of cells based on the observation that individual deletion of most yeast genes has little effect on growth. However, high throughput phenotypic analysis of cell proliferation of all 5000 gene deletion mutants in many different types of media provides a systematic, quantitative means to ascertain how genes contribute to the cellular robustness and ability to adapt to changing environments.

Interconnectivity and Dynamics

Imagining the effect of a particular perturbance, as it would spread throughout each model complex system, it is clear that interconnectivity can lead to both robustness and vulnerability. For example, "essential genes" (deletion results in lethality) have a greater number of physical (protein-protein) interactions than non-essential genes, and thus can be considered as cellular "hubs" of function. Likewise, the more interconnected a power substation, the more people it supplies, but it is also an easy target for a blackout. A perturbance, such as a novel disease, would spread through and weaken a complex system, such as the health care system, through nodes that are highly connected. But spread of a perturbance is also greatly affected by system dynamics. For example, a sick individual, one node of the health care system, may have a particularly virulent strain of a specific disease (or be somehow better at transmitting the disease). Though they are not well connected to the rest of the system, the disease would pass through the system more quickly due to the strength of this nodal connection. Additional factors that can affect network dynamics are directionality and strength of links; both of which can be used to determine where a perturbance will flow and where vulnerabilities in the system will arise.

Knowledge of directionality and strength of interconnectivity can potentially be exploited to increase robustness. For example, such knowledge would allow us to “park” fragilities where they are least vulnerable and most easily managed. A simple example of this is power stations, which as sources of electrical power in the power grid system should be the most protected hubs in the system in order to lessen the consequences of a malfunction or attack that would otherwise result in a catastrophic breakdown of the system. In the case of genetic interactions, understanding fragilities that result from cancer-causing mutations would reveal targets for selectively killing cancer cells. Control in a complex system does not necessarily have to coincide with hubs of that system. In most dynamic complex systems, blending of centralized and distributed control would enhance robustness. In addition to active control, adaptability of system topography increases robustness in a complex system. The group discussed random and scale-free networks as two kinds of network topologies that respond differently to perturbations/attacks and would thus affect robustness. A random network is one where the nodes are equally interconnected and/or evenly distributed throughout the network while a scale-free network has a few hubs that are highly interconnected, with the majority of nodes having fewer connections.

One way to enhance robustness in a complex system is to create a topology that is an adaptive mix of a random and scale-free network. With some knowledge of the kind of an attack or perturbation to a complex system, the system would be able to switch states depending on the nature of the perturbation. For example, if substations of a power grid were attacked, the system could switch topologies and begin to distribute power evenly through all its nodes, switching from a discrete to diversified network. This adaptability increases robustness of the system, but would require a tradeoff in expense to implement and maintain necessary resources.

The group also discussed vertical connections and redundancies as attributes of a complex system that could contribute to robustness of the system. Some biological systems are among the most robust complex systems in existence. Experimental data from yeast genetic interaction experiments, indicate, for example, that simple redundancy of function accounts for a small amount of the observed robustness. It seems “alternative pathways” and dynamic rerouting of system fluxes in response to perturbation are often the adaptive mechanisms that contribute to robustness in biological systems. “Vertical connections” are also very important in robustness considerations. These are connections in a network of a complex system that span different hierarchical levels, scales, or employ different definitions within a sub-system.

Additional mechanisms are required of a system to maintain and enhance robustness. These include feedback mechanisms in networks, self-organization and self-repair mechanisms. Feedback is also important for establishing buffering mechanisms that increase robustness by stabilizing a dynamic system against perturbations. A simple example of this would be Internet servers. Often, if one server is down, information gets passed to another server in a cluster so that Internet clients can still access information though their home computers. This buffering mechanism ensures that clients have maximal access to the Internet at all times. Gene-gene and gene-environment interactions reveal buffering relationships through analysis of combinations of perturbations that are synergistic or antagonistic with respect to cellular robustness. Self-organization and self-repair are also present in biological systems and are beneficial for enhancing robustness in any complex system.

Moving Forward

As the group moved from thought experiments, and attempted to extrapolate findings into the real world, it became possible to generally but solidly define the task of seeking robustness in a system as:

Keeping the magnitude of the change in a set of performances (with respect to a set of perturbations) within some limits, and doing so subject to given restraints.

Definitions of complex systems in real life can be difficult. There is a hierarchical structure of biological systems such that different measurement scales apply to different levels of the system; different types of perturbations are relevant, and different performance measures must be considered. One must be careful of what scale is selected when initially defining the complex system (and related optimization goals). In certain systems, one might find performance fluctuations on a small scale that would not appear at a larger scale. Or, a loss of robustness at a certain scale might be accompanied by a gain in robustness at another scale. These robustness trade-offs, where performance or robustness of a system is sacrificed at one level to be enhanced at another level, exist and must be taken into account when robustness of a complex system is measured.

Defining a complex system is also difficult due to inherent dynamics. Connections within an engineered or biological complex system are always breaking, reforming, and changing. Perturbances (e.g., signal transduction) often seem intrinsic to the networks and complex systems themselves.

It is challenging to study a robust system that by definition consists of dynamic interactions rendering it resistant to observable change. Despite this challenge, we can still make recommendations for enhancing its robustness. Robustness is incremental and non-linear, so we need to establish quantitative models and tools to measure sources of buffering capacity and better model phenomena such as stability thresholds. Adaptability of network topology within system structure is also key to enhancing robustness, as are built-in feedback mechanisms and active control. When enhancing robustness or minimizing vulnerability, it is highly advantageous to know as much as possible about the interconnectivity and dynamics of a system. For example, if biological attack were to be mounted within our health care system, it would be advantageous for the attackers to know which individuals are the most connected, and would spread the disease most quickly. This knowledge could be used to attack fragilities as well as hide them, to decrease or enhance robustness of this system. System dynamics, along with interconnectedness, allow prediction of how the system will function and respond. Analysis of diverse types of complex systems, such as biological and manmade systems, is an important aspect of our aspiration to derive principles for how robustness is achieved through network structure and connectivity.