

# Task Group Summary 9

## *Can one control flow and transport in complex systems?*

### Challenge Summary

Transport in complex systems involves the flow of a quantity—information, power, mass, material, etc.—among the individual component elements. The nature of this transport depends both on the properties of the individual components and on the overall geometrical and topological structure of the system. In simple physical systems, we typically find either “ballistic” transport—that is, the distance travelled is proportional to time, as in the flight of a projectile—or “diffusive” transport—that is, the distance traveled is proportional to the square-root of time, as in Brownian motion describing the spread of a drop of dye in an unstirred liquid. In complex systems, as a consequence of inherent nonlinearities and complicated connectivity, transport becomes—no pun intended—much more complex. Two examples related to but distinct from standard diffusion will illustrate this complexity. Random walks in which the increments are distributed according to distributions with “fat tails” (instead of Gaussians) are known to produce “Lévy flights,” in which interspersed with the small jumps typical of Brownian motion are long jumps that lead to “anomalous” (super-diffusive) transport. Such Lévy flights can occur in the spatial or temporal domain and are observed in analysis of data from earthquakes, finance, fluid flows, and animal foraging, among many other systems. When nonlinear effects—arising from predator-prey interactions or chemical reactions—are added to diffusion, the resulting “reaction-diffusion” equations can exhibit pattern-forming instabilities that can lead to “morphogenesis” or to wave-like transport with ballistic properties. A celebrated example is the model studied by Murray for the spread of a potential rabies epidemic in England. Murray showed that the underlying model (based on the Fisher equation) led to a narrow wave-front of contagion moving at a definite speed through the countryside.

When we consider complex systems involving networked structures, the problem becomes, technically, the study of transport on (arbitrary) graphs. Intuitively, it is clear that the nature of the network/graph—e.g., hub and spoke, long-range connections, random, etc.—will affect the transport dramatically.

Our attempt to understand the nature of transport in complex systems is in large part driven by the goal of controlling this transport. In some cases, we want to enhance transport: for instance, increasing the ability of the Internet to carry messages, enhancing traffic flow, increasing the rate of oil recovery or the efficiency of mixing and disseminating information in the case of a crisis, etc. In other cases, we want to inhibit transport—halting the spread of a virus or other contagion, preventing the collapse of an economic structure (the savings and loan sector, home mortgage sector), etc. *Apriori*, we can imagine controls that work on the components (nodes) of the system—e.g., changing interest rates or leverage requirements, vaccinating individuals—as well as controls that work on the connections (links)—changing diffusion constants, limiting travel, severing links. Overall, the challenge is to use these various controls to manage transport in a complex system so as to optimize it for a desired outcome.

To define this challenge more precisely, different task groups might consider one or more of the following four “case studies” from four very different disciplines.

1. In economic systems, the recent sub-prime mortgage fiasco represented “transport” by catastrophic cascading collapse; might it have been avoided if, in addition to interest rates, the

government controlled the “leverage” that firms could use? The infamous collapse in 1998 of Long Term Capital Management (LTCM), which failed due to margin calls, had its origin in an incorrect evaluation (by the world’s experts!) of the actual risks involved in some of the investments; technically, their models failed to take account of the “fat tails” of the risk distribution. Can we create, before the fact, reliable models of risks in complex economic structures (or, what part of “derivatives” don’t we understand)?

2. In oncology, we need to consider transport at both the molecular and organism levels. At the molecular level, cancer is usually a disease caused by mutations in genes important for cellular regulation such as cell cycle, development, apoptosis, etc. Although undeniably a good start, this description of cancer fails to explain fully the progression from quiescent, non-cancerous, to fully malignant and eventually metastatic cells and the accumulation of multiple cancer mutations along the way. Macromolecules such as proteins and RNAs encoded by cellular genes interact with each other to form a molecular dynamic system of great complexity. The systems properties of such molecular “interactome” networks have remained largely unknown until recently, primarily due to the lack of empirical description. In the aftermath of the human genome sequencing project, systems biologists are developing concepts, tools, and resources to model interactome networks with the goal of modeling differences of systems properties between cancerous and non-cancerous cellular networks. The ultimate goal of this endeavor is the design of drugs that would be able to alter systems properties of cancer cells to either kill them specifically or dramatically slow their malignant progression. At the organism level, we need to consider both how the primary tumor “transports” its malignancy—basically, by rapid localized (diffusive?) growth and displacement of normal cells—and how secondary tumors are created by metastasizing cells transported through the body by lymph or blood networks (Lévy flights?). Can we develop (perhaps different) appropriate therapies that will be needed to attack these two different forms of transport?

3. In public health systems, the challenges are both highly visible and daunting. Preventing the spread of various epidemics—SARS, Avian flu—and limiting the damage of the AIDS pandemic are among the most important problems facing society today. It is important to recognize that air travel—quite literally, a Lévy flight—played a significant role in the initial spread of AIDS between San Francisco and New York and the later studies that showed (*post-hoc*) that the spread of the SARS epidemic could have been predicted by air travel patterns, suggesting that restricting such travel in times and from regions of high contagion might be, despite its Draconian nature, an appropriate policy. Would this really be a workable and effective policy?

4. Much of our key societal infrastructure exists in the form of networks—the electrical power grid and the Internet are two important examples. The celebrated Northeast electrical blackout of 1965 was thought to have provided a transformative lesson, but a very similar cascading failure occurred in 2003 and likely could occur again. What lessons should we have learned from these failures? How can we control the system so as to keep the effects of power plant failures localized? Regarding the Internet, there are at least two key questions. First, the rapid spread of computer viruses with pandemic consequences is enabled by the Internet: can we develop a means of identifying these viruses as they travel and prevent them from attacking individual computers (i.e., severing the links)? Alternatively, the “mono-culture” of operating systems renders the individual computers much more susceptible to viral attacks: can we design operating systems that are sufficiently individualized so as resist these attacks (i.e., modify the nodes). Second, recent studies have shown that the Internet itself is particularly vulnerable to

attacks on its key hubs; how can we improve the systems to make it more resistant to these attacks? Clearly, both of these infrastructure “transport” issues overlap very strongly with the studies of robustness in other task groups.

### Key Questions

- In addition to the questions already posed in the individual case studies above, are there other overarching questions that we should consider?
  - To what extent do the transport mechanism given in the examples above exhaust those likely to be found in complex systems? What can we add to this “taxonomy of transport”?
  - Are there any universal aspects of transport in complex systems?
  - What instructive “case study” examples can we find from other disciplines?
  - What is the optimal mix of controls on the nodes versus controls on the links? How does this vary across different complex systems?
  - How should we proceed to develop strategies to enhance desired flows and to inhibit undesired flows?

### Required Reading

#### *For Lévy Flights*

- Geisel T, Nierwetberg J, and Zacherl A. Accelerated diffusion in Josephson junctions and related chaotic systems. *Phys Rev Lett* 1985;54:616-620. *For the Study of the Spread of Rabies in England*
- Murray JD, Stanley EA, and Brown DL. On the spatial spread of rabies among foxes. *Proc Roy Soc (Lond)* 1986;B229:111-150.
- Murray JD. Modeling the spread of rabies. *American Scientist* 1987;(May-June):280-284.
- Solomon T, Weeks E, and Stanley H. Observations of anomalous diffusion and Lévy Flights in a two-dimensional rotating flow,” *Phys Rev Lett* 71, 3975-3979. [Accessed online July 31, 2008: <http://www.physics.emory.edu/~weeks/abs/nice95.html>.]

#### *For Cancer*

- Huang S and Ingber DE. A non-genetic basis for cancer progression and metastasis: self organizing attractors in cell regulatory networks. *Breast Disease* 2007;26:27-54.
- Kitano H. Cancer as a robust system: implications for anticancer therapy. *Nature Reviews Cancer* 2004;4(Mar):227-235.

#### *For Public Health and Epidemics*

- Hufnagel L, Brockmann D, Geisel T. Forecast and control of epidemics in a globalized world. *Proc Natl Acad Sci USA* 2004;101:15124-15129.
- Severe Acute Respiratory Syndrome (SARS) background. Wikipedia reference. [Accessed online August 13, 2008: <http://en.wikipedia.org/wiki/SARS>.]

#### *For Economic “Collapsing Cascades”*

Long-Term Capital Management. Wikipedia reference. [Accessed online August 13, 2008: [http://en.wikipedia.org/wiki/LongTerm\\_Capital\\_Management](http://en.wikipedia.org/wiki/LongTerm_Capital_Management).]

Report of the CRMPG III August 6, 2008 (Counterparty Risk Management Policy Group III). Containing systemic risk: the road to reform.[Accessed online August 13, 2008: <http://www.crmpolicygroup.org>.]

#### *For Power Grid Failures*

Kinney R, Crucitti P, Albert R, Latora V. Modeling cascading failures in the North American power grid. *Eur Phys J* 2005;B46:101-107.

### **Suggested Reading**

Barabási AL. The day the lights went out; we're all on the grid together. *New York Times* 2008. Opinion. [Accessed online August 13, 2008: <http://query.nytimes.com/gst/fullpage.html?res=950CE5D91430F935A2575BC0A9659C8B63&scp=9&sq=barabasi&st=cse>.]

Goldberger AL. Non-linear dynamics for clinicians: chaos theory, fractals, and complexity at the bedside. *The Lancet* 1996;437:1312-1314.

Källén A, Acuri P, and Murray JD. A simple model for the spatial spread of rabies. *J Theor Bio* 1985;116:377-393. Lengyel I and Epstein IR. A chemical approach to designing Turing patterns in reaction diffusion systems. *Proc Natl Acad Sci USA* 1992;89:3977-3979.

Levine H and Rappel WJ. Membrane bound Turing patterns. *Phys Rev E* 2005;72:061912.

Mandelbrot B. *The Fractal Geometry of Nature*. W.H. Freeman and Company 1982.

Murray JD and Seward WL. On the spatial spread of rabies among foxes with immunity. *J Theor Biol* 1992;156:327-348.

Turing AM. The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society B (London)* 1952;237:37-72.

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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### **TASK GROUP SUMMARY – GROUP A**

By Anne-Marie Corley, Graduate Science Writing Student, MIT

A group of scientists, representing many disciplines at the 2008 National Academies Keck Futures Initiative Conference in Irvine, California, was asked to consider this question: Can one control flow and transport in a complex system?

Understanding the nature of transport in complex systems is essential to controlling it. In some cases the goal is to enhance transport: for instance, increasing the ability of the Internet to carry messages, enhancing traffic flow, increasing the rate of oil recovery, or increasing the efficiency of disseminating information in a crisis. In other cases, the goal is to inhibit transport, for example halting the spread of a virus or preventing the collapse of an economic structure.

The first challenge in rallying diverse backgrounds to consider this question was to ask how the group might constrain the systems under examination. Would they analyze systems under duress (such as market crisis and power grid failure), or look at systems under normal conditions (healthy markets, smoothly functioning power grids, 'green-light' conditions for transportation systems)? In other words, at what point did they seek to control flow?

After considering a range of ideas such as detecting the next zoonotic disease to hop from animals to humans, locating networks of terrorists interacting in space and time, or controlling transportation flow to inhibit the spread of epidemics, the group decided to focus on two example application areas—namely the financial system's credit flow and the role of commuting patterns in the spread of epidemics. The group placed primary emphasis on the financial system's credit flow and used the spread of epidemics example as a check for logical clarity.

Once the example application areas were selected, the scientists developed a two-pronged approach, aiming first to *detect* an economic system in peril, and then to *control* it. This led to the identification of a *Detection Problem* and a *Control Problem*. The Detection Problem is 'what are the key observable features of the transition from normal uncorrelated (i.e., decoherent) behavior to abnormal correlated (i.e., coherent) behavior?' The Control Problem is that 'given a system with amenable characteristics, are there parsimonious and indigenous mechanisms to "control" flow and transport and how do you chose among them?' Parsimonious here means minimum energy or cost. Indigenous here means a natural or normal part of the system.

The group felt that the concepts of coherence and decoherence were critical to solving both the Detection Problem and the Control Problem. Coherence occurs when the individual behavior of different actors in a system correlate. What it means is that individual actions converge from random, independent actions to dependent, 'matching' behavior. The classic economic example is a run on a bank. Think *It's a Wonderful Life*.

Many aspects of both human engineered and evolved systems depend on uncorrelated behaviors for proper functioning. For example, when behavior is comparatively random—decoherent, or uncorrelated—an economic system proceeds as normal. Some people put money into banks while others draw it out, but they do so independently. In this case decoherence is the norm, while correlated coherent behavior presents a problem. It can lead to the kind of convergence that brings down markets.

Obviously, real systems always exist in a state somewhere between complete coherence and decoherence. Systems run into trouble when the level of coherence and decoherence, or more generally the distributions of individual behaviors, diverge significantly from the original design assumptions or evolutionary conditions. It is also possible for coherence to be the normal healthy state and for decoherence to be a problem. However, as the bank run example suggests, excessive coherence in particular is a major threat to economic systems.

Detecting whether a system is about to head into a coherent phase is essential to influencing the outcome. The group hypothesized that there are indeed markers to indicate the onset of coherence. If they could then postulate a detection system, they might also imagine a way to intervene, turn the control valve, and keep the system from excessively cohering.

To address the Detection Problem the group asked, 'can we develop something analogous to an afferent (i.e., sensory) nervous systems for complex systems?' Financial system examples include: (1) number of web browser read accesses of official informational web sites, (2) patterns of search engine queries (e.g., Google searches), and (3) patterns of visits to relevant non-official web sites (e.g., number of web browser read accesses of Wikipedia entries). For epidemic spread in transportation systems examples include: (1) patterns found in mobile device usage (e.g., global positioning system or mapping data access on mobile phones), (2) geo-coded patterns of search engine queries (e.g., Google searches), and (3) geo-coded patterns of visits to relevant web sites (e.g., Wikipedia entry accesses). Along the way the group recognized that some organizations such as Google are actively working in these areas. The group concluded that these efforts should be cooperatively leveraged as much as possible.

To address the Control Problem the group hypothesized that the transition from decoherence to coherence is triggered by psychological contagion amplified by feedback loops. This creates the opportunity for early, low energy interventions and thus efficient control.

The group felt that modeling may be important. They postulated a conceptual model of the financial system that takes into account the economic, psychological, and social drivers of decision making. They also postulated that strong parallels hold for epidemic spread in transportation systems.

A critical research gap is real time psychological and behavioral data on human decision making that drives financial and transport feedback loops. In particular, what are the tipping points in the drive toward coherent behavior, when many people make the same move? How does accidental correlation factor in? Such information could aid in the creation of a model to predict or control the flow and transport of cash, emotion and ideas in an economic system.