Robustness and dynamics in biological networks

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It is becoming widely recognized that important research challenges in biology have many parallels with those in complex engineering systems.
Emphasis is shifting from components and molecules to the study of the vast networks that biological molecules create that regulate and control life. And the central role that robustness plays in complex systems has begun to move from an exclusively engineering perspective to one of interest to biologists as well.
Through design or evolution, complex systems in engineering and biology develop highly structured, elaborate internal configurations, with layers of feedback and signaling. This makes them robust to the uncertainties in their environment and components for which such complexity was selected, but also makes the resulting system potentially vulnerable, sometimes catastophically, to rare, unanticipated or apparently innocuous perturbations. Such fragility can lead to large cascading failures from tiny initiating events. Perturbation of one gene or a single line of software code, or the introduction of an exotic specie or trace amounts of a toxin, rarely causes significant system-wide impact, yet occasionally can cascade into complete system failure.
Biological systems are "robust, yet fragile." This is the most critical and universal characteristic of complexity, not only in biology, but also in technological and social systems, and is motivating new efforts to extend and integrate the currently fragmented theoretical foundations for studying robustness and complexity. This is in sharp contrast to the emphasis on self-organization, emergence, phase transitions, criticality, fractals, self-similarity, edge-of-chaos, and so on, that have been popularized as a "new science of complexity." This talk will take a look at several issues relevant to biological complexity, and particularly how "robust, yet fragile" features dominate a systems view of everything from gene regulation to medical treatment to ecosystem structure.

The extreme "robust, yet fragile" character of complex systems severely complicates the challenge of connecting phenomena on widely different time and space scales, and in particular, exactly those phenomena most critical to understanding and preventing large cascading events. A consequence is that "typical" behavior of complex systems is often quite simple, so that a naive view leads to simple models and (wrong) explanations of most phenomena. Only extreme circumstances not easily replicable in laboratory experiments or simulations reveal the role of the enormous internal complexity in biological and engineering systems.

This talk will argue that "robust, yet fragile" is not an accident, but is the inevitable result of fundamental tradeoffs. Motivating examples will be drawn from gene regulation and signal transduction networks, and compared with phenomena from web/internet traffic, power outages, forest fires and other large ecosystem events, stock market volatility, distributed software, commercial aircraft design, automobile airbags, weather and climate forecasting, and formula one racing.