Can Complexity Science Support the Engineering of Network-Centric Infrastructures?

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Network-Centric Infrastructure Systems

- A mix of human and automated system operators to remotely monitor, manage, and control the physical world

- via the Internet and related communication systems

- These systems support the operation and management of modern society's most vital functions
  - delivery of economic goods and services
  - business processes
  - global financial markets
  - education
  - health care
  - government services

The **GOOD**

Network technology (interpreted broadly) has been wildly successful…

… yielding a "networked planet" for energy, food, information, goods and materials,…

The **BAD**

Network technology has been *too* successful…

… yielding a "networked planet" for good *and bad*…

… and creating vulnerabilities due to our dependence.

The **UGLY**

"Network centric technologies"

Largely deliver what we design them to do.

But fail because they create new problems that we *did not expect.*

Complexity and Robustness: Key Concepts

- Robust yet fragile
- Architecture: “constraints that deconstrain”
- Importance of organized complexity

  (and its absence in mainstream network science)

Main point of this talk:

these concepts are fundamental to the application of complexity science to network-centric infrastructures and other highly organized systems

Robustness

Def: A [property] of [a system] is ***robust*** if it is [invariant] for [a set of perturbations]

Robustness to different kinds of perturbations:

Reliability	component failures
Efficiency	resource scarcity
Scalability	changes in size and complexity of the system as a whole
Modularity	structured component rearrangements
Evolvability	lineages to possibly large changes over long time scales

Strategies for Creating System Robustness

1. Improve robustness of individual components
2. Functional redundancy: components or subsystems
3. Sensors that trigger human intervention
    - Monitor system performance
    - Detect individual component wear
    - Indentify external threats
4. Automated control

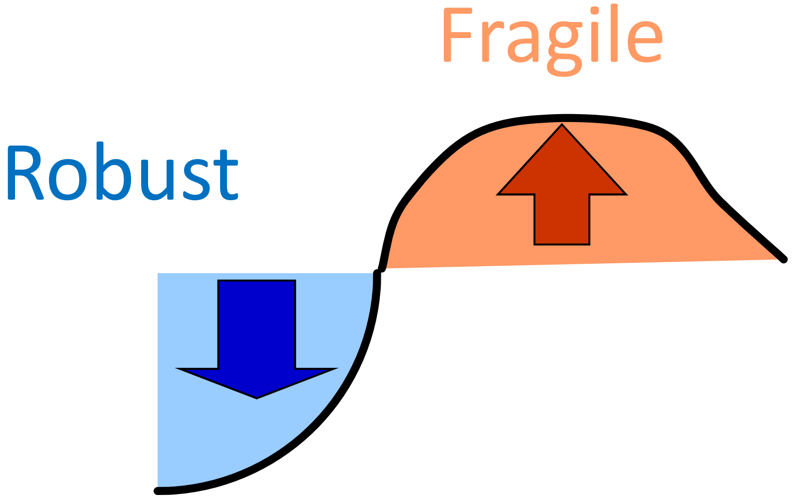
Complexity – Robustness Spiral

- The same mechanisms responsible for robustness to most perturbations
- allows possible extreme fragilities to others
- Usually involving hijacking the robustness mechanism in some way

Robust Yet Fragile (RYF)

[a system] can have
[a property] ***robust*** for
[a set of perturbations]

Yet be ***fragile*** for
[a different property]
Or [a different perturbation]



Proposition :
The RYF tradeoff is a ***hard limit*** that cannot be overcome.

Human complexity

Robust	Yet Fragile
☺ Efficient, flexible metabolism	☹ Obesity and diabetes
☺ Complex development	☹ Rich microbe ecosystem
☺ Immune systems	☹ Inflammation, Auto-Im.
☺ Regeneration & renewal	☹ Cancer
🗐 Complex societies	☠ Epidemics, war, …
⊞ Advanced technologies	💣 Catastrophic failures

- Evolved mechanisms for robustness *allow for,* even *facilitate,* novel, severe fragilities elsewhere
- often involving hijacking/exploiting the same mechanism

- Science deals poorly or not at all with this challenge.

Courtesy: John Doyle

Main Challenge: Managing Complexity

- Designers and operators of the next-generation net-centric infrastructures need to understand and manage the growing complexity of these systems.

<u>We know</u>:

how to design, mass produce, and deploy net-centric devices

<u>Not so easy</u>:

predict or control their collective behavior once deployed

When things fail…

they often do so cryptically and catastrophically.

Managing complexity: the role of ***architecture***

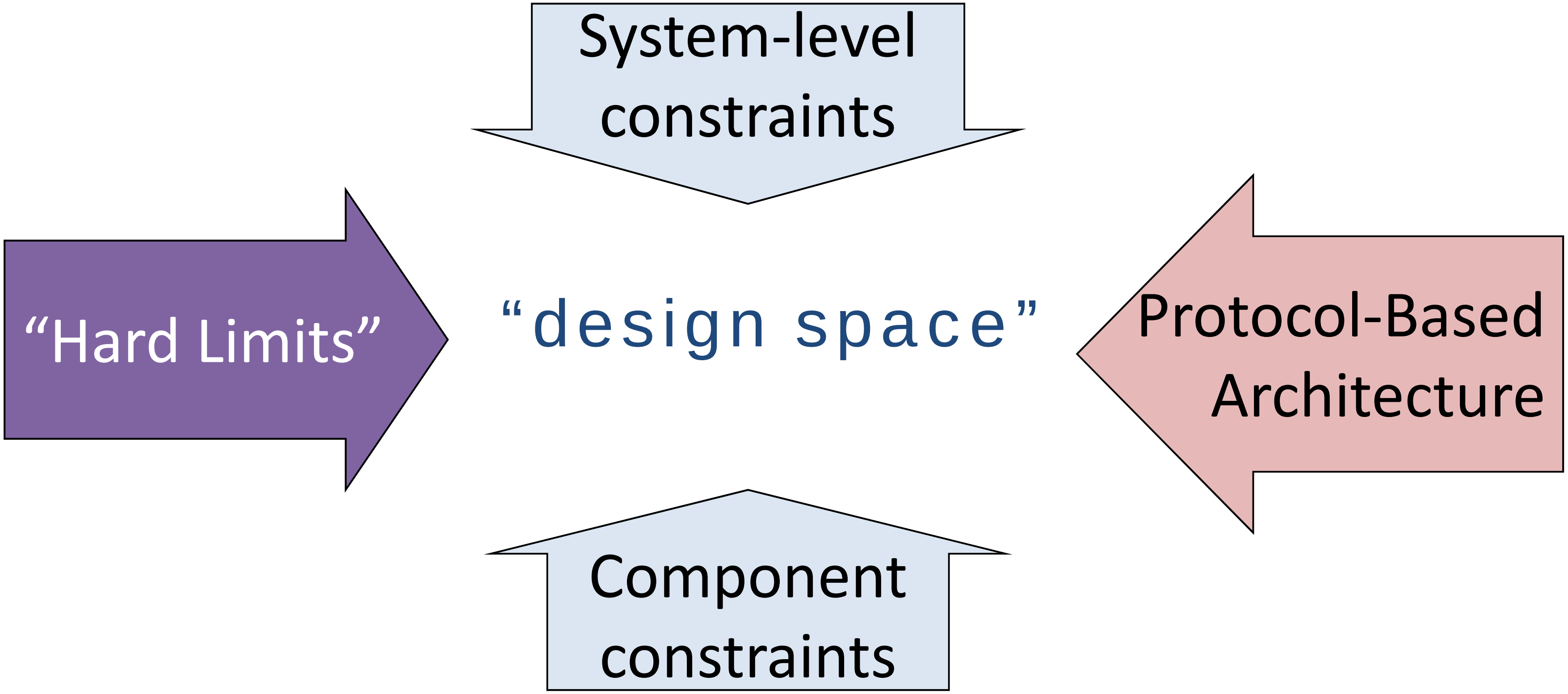
- Persistent, ubiquitous, global features of organization
- Constrains what is possible for good or bad
- Gerhart & Kirschner: “constraints that deconstrain”

Studying architecture

- Most often: instantiations of specific architectures

  Internet, biology, energy, manufacturing, transportation, water, food, waste, law, etc
- Here, as an abstraction…

a constraint-based view of architecture



System-level constraints

"Hard Limits"

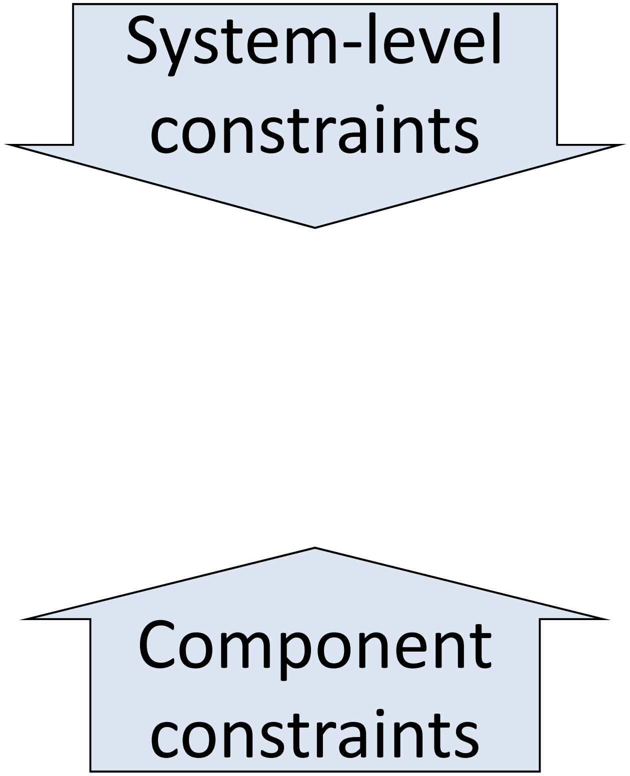
"design space"

Protocol-Based Architecture

Component constraints

Fundamental assumption: complex networks (that we care about) are the result of ***design*** (either evolution or engineering)

a constraint-based view of architecture



System-level constraints

Constraints on the system as a whole (e.g., functional requirements)

Component constraints

Constraints on individual components (e.g., physical, energy, information)

“Hard Limits”

- *Hard limits* on system characteristics
  - *implied by the intersection of component and system constraints*
- Most interesting when they do not follow trivially from the other constraints
- Examples:
  - Entropy/2nd law in thermodynamics
  - Channel capacity theorems in information theory
  - Bode integral and related limits in control theory
  - Undecidability, NP-hardness, etc in computational complexity theory
  - Robust Yet Fragile?

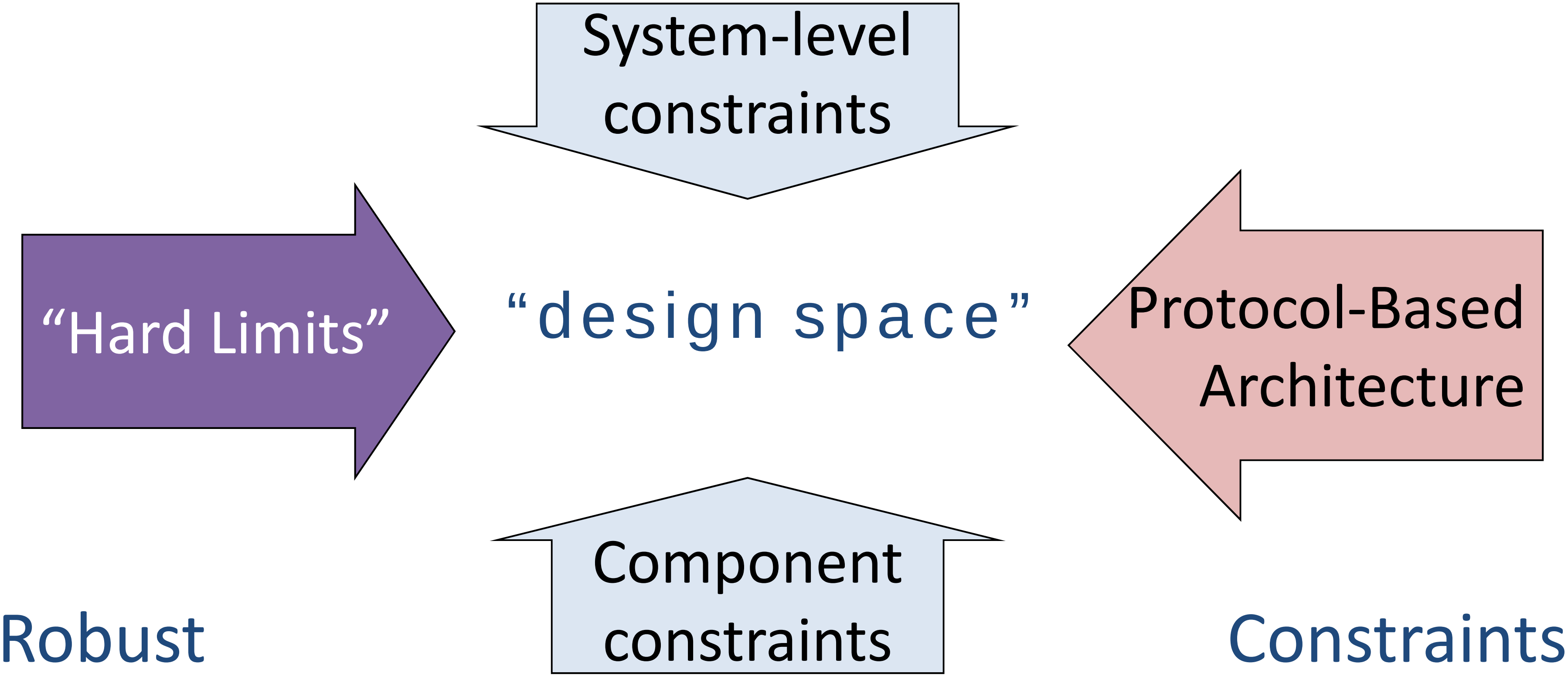
- Emphasis on *protocols*
  (persistent rules of interaction)
  over *modules*
  (that obey protocols and can change)

- In reverse engineering,
  - figure out what rules are being followed
  - and how they govern system features or behavior

Protocol-Based Architecture

- In forward engineering,
  - specify protocols that insure such system behavior

a constraint-based view of architecture



System-level constraints

"Hard Limits"

"design space"

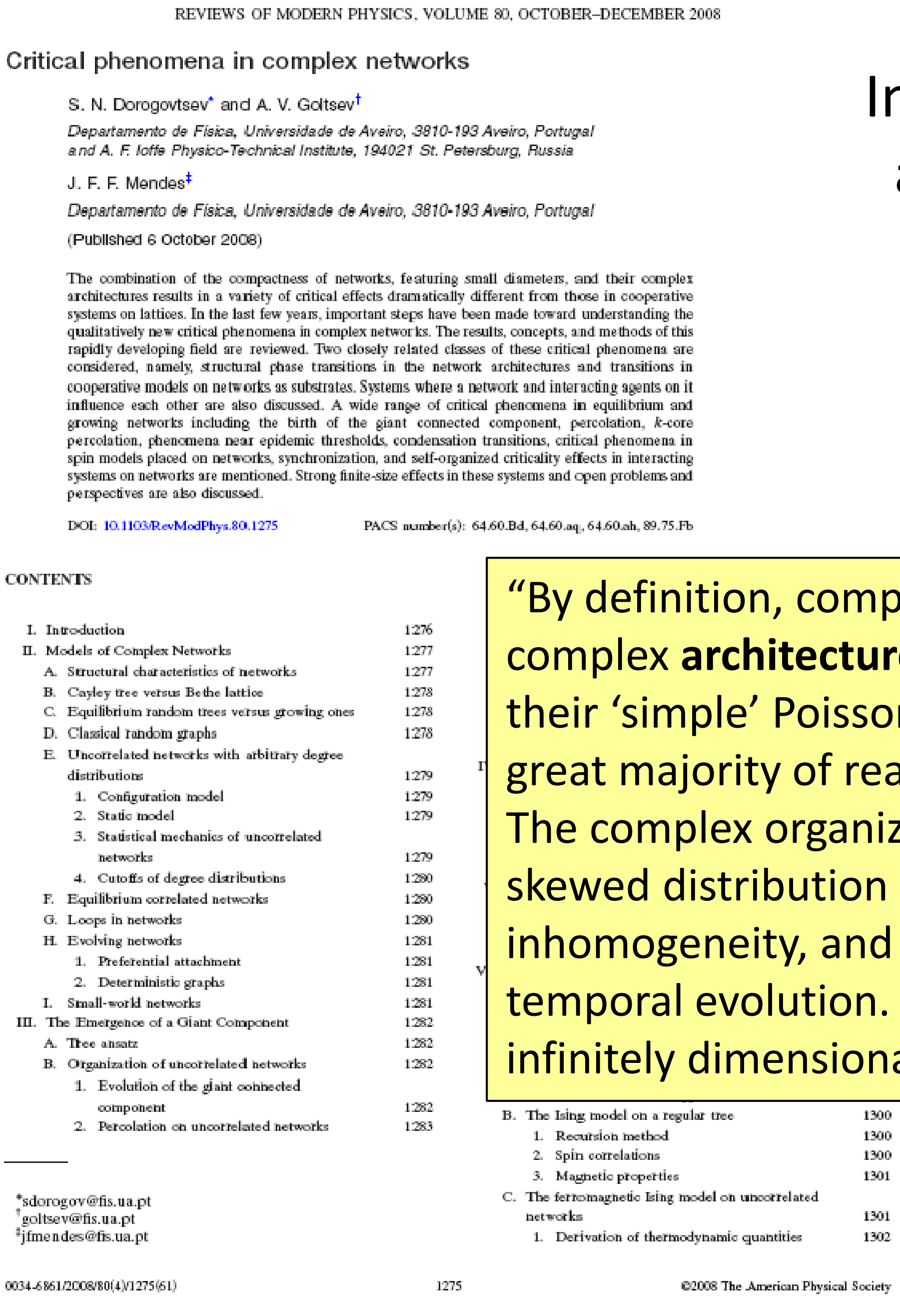
Protocol-Based Architecture

Component constraints

Robust
yet
fragile

Constraints
that
deconstrain

In mainstream network science: architecture = graph topology



REVIEWS OF MODERN PHYSICS, VOLUME 80, OCTOBER–DECEMBER 2008

Critical phenomena in complex networks

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The combination of the compactness of networks, featuring small diameters, and their complex architectures results in a variety of critical effects dramatically different from those in cooperative systems on lattices. In the last few years, important steps have been made toward understanding the qualitatively new critical phenomena in complex networks. The results, concepts, and methods of this rapidly developing field are reviewed. Two closely related classes of these critical phenomena are considered, namely, structural phase transitions in the network architectures and transitions in cooperative models on networks as substrates. Systems where a network and interacting agents on it influence each other are also discussed. A wide range of critical phenomena in equilibrium and growing networks including the birth of the giant connected component, percolation, *k*-core percolation, phenomena near epidemic thresholds, condensation transitions, critical phenomena in spin models placed on networks, synchronization, and self-organized criticality effects in interacting systems on networks are mentioned. Strong finite-size effects in these systems and open problems and perspectives are also discussed.

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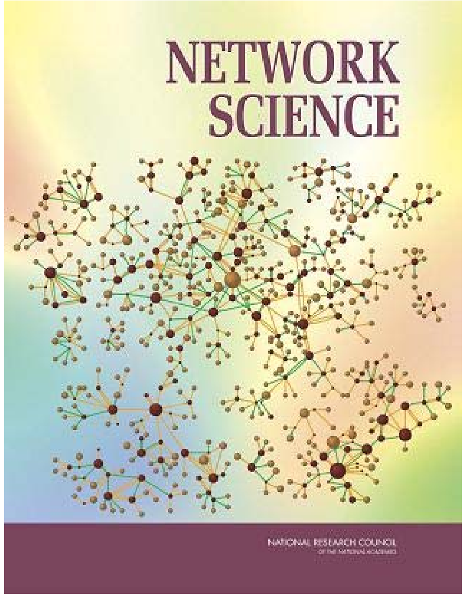
> “By definition, complex networks are networks with more complex **architectures** than classical random graphs with their ‘simple’ Poissonian distributions of connections. The great majority of real-world networks... are complex ones. The complex organization of these nets typically implies a skewed distribution of connections with many hubs, strong inhomogeneity, and high clustering, as well as nontrivial temporal evolution. These **architectures** are quite compact..., infinitely dimensional small worlds.”

Understanding “complexity”



NETWORK
SCIENCE

NATIONAL RESEARCH COUNCIL

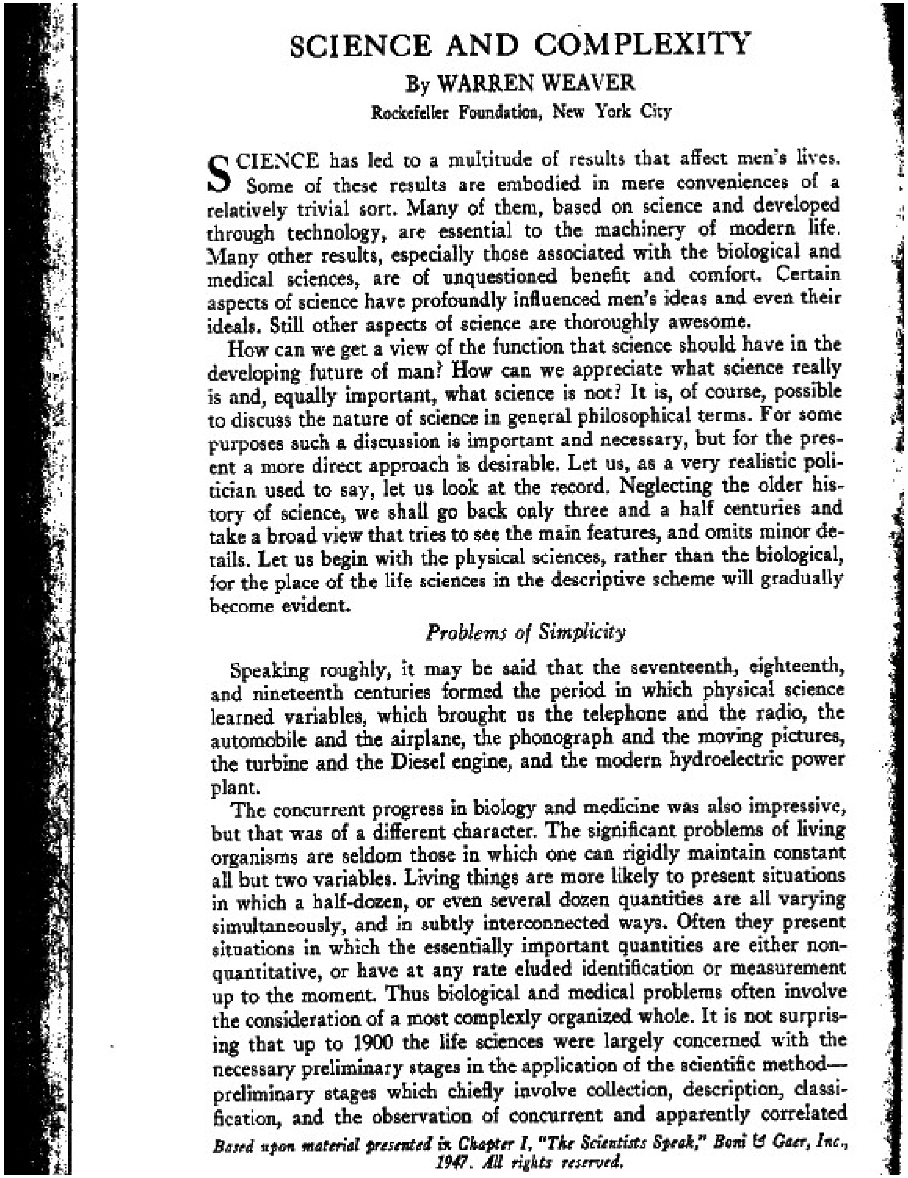
Good news:

Spectacular progress

Bad news:

- Persistent errors and confusion
- Potentially insurmountable obstacles?

- Aim: simple but universal taxonomy
- Widely divergent starting points from math, biology, technology, physics, etc,
- Can organize into a coherent and consistent picture
- Starting point: Warren Weaver (1948)



SCIENCE AND COMPLEXITY

By WARREN WEAVER

Rockefeller Foundation, New York City

SCIENCE has led to a multitude of results that affect men's lives. Some of these results are embodied in mere conveniences of a relatively trivial sort. Many of them, based on science and developed through technology, are essential to the machinery of modern life. Many other results, especially those associated with the biological and medical sciences, are of unquestioned benefit and comfort. Certain aspects of science have profoundly influenced men's ideas and even their ideals. Still other aspects of science are thoroughly awesome.

How can we get a view of the function that science should have in the developing future of man? How can we appreciate what science really is and, equally important, what science is not? It is, of course, possible to discuss the nature of science in general philosophical terms. For some purposes such a discussion is important and necessary, but for the present a more direct approach is desirable. Let us, as a very realistic politician used to say, let us look at the record. Neglecting the older history of science, we shall go back only three and a half centuries and take a broad view that tries to see the main features, and omits minor details. Let us begin with the physical sciences, rather than the biological, for the place of the life sciences in the descriptive scheme will gradually become evident.

Problems of Simplicity

Speaking roughly, it may be said that the seventeenth, eighteenth, and nineteenth centuries formed the period in which physical science learned variables, which brought us the telephone and the radio, the automobile and the airplane, the phonograph and the moving pictures, the turbine and the Diesel engine, and the modern hydroelectric power plant.

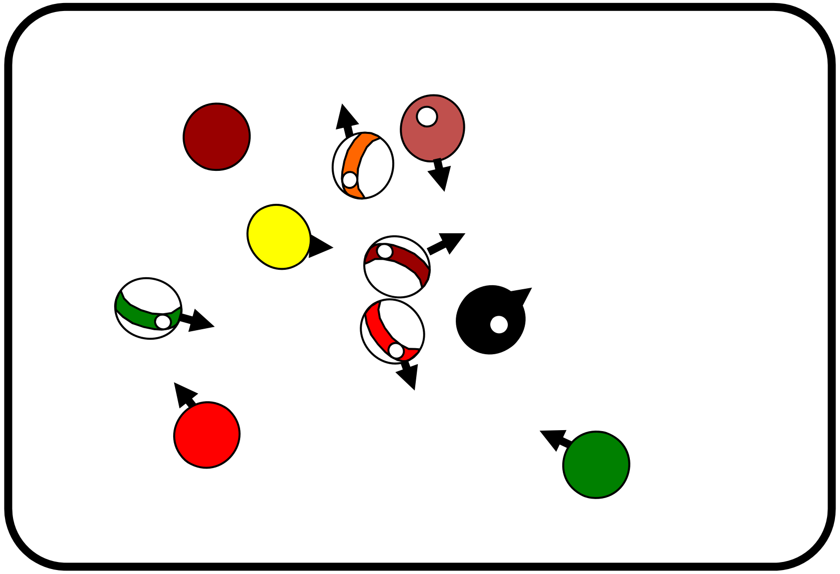
The concurrent progress in biology and medicine was also impressive, but that was of a different character. The significant problems of living organisms are seldom those in which one can rigidly maintain constant all but two variables. Living things are more likely to present situations in which a half-dozen, or even several dozen quantities are all varying simultaneously, and in subtly interconnected ways. Often they present situations in which the essentially important quantities are either nonquantitative, or have at any rate eluded identification or measurement up to the moment. Thus biological and medical problems often involve the consideration of a most complexly organized whole. It is not surprising that up to 1900 the life sciences were largely concerned with the necessary preliminary stages in the application of the scientific method—preliminary stages which chiefly involve collection, description, classification, and the observation of concurrent and apparently correlated

Based upon material presented in Chapter I, "The Scientists Speak," Boni & Gaer, Inc., 1947. All rights reserved.

"problems of simplicity" (Weaver 1948)

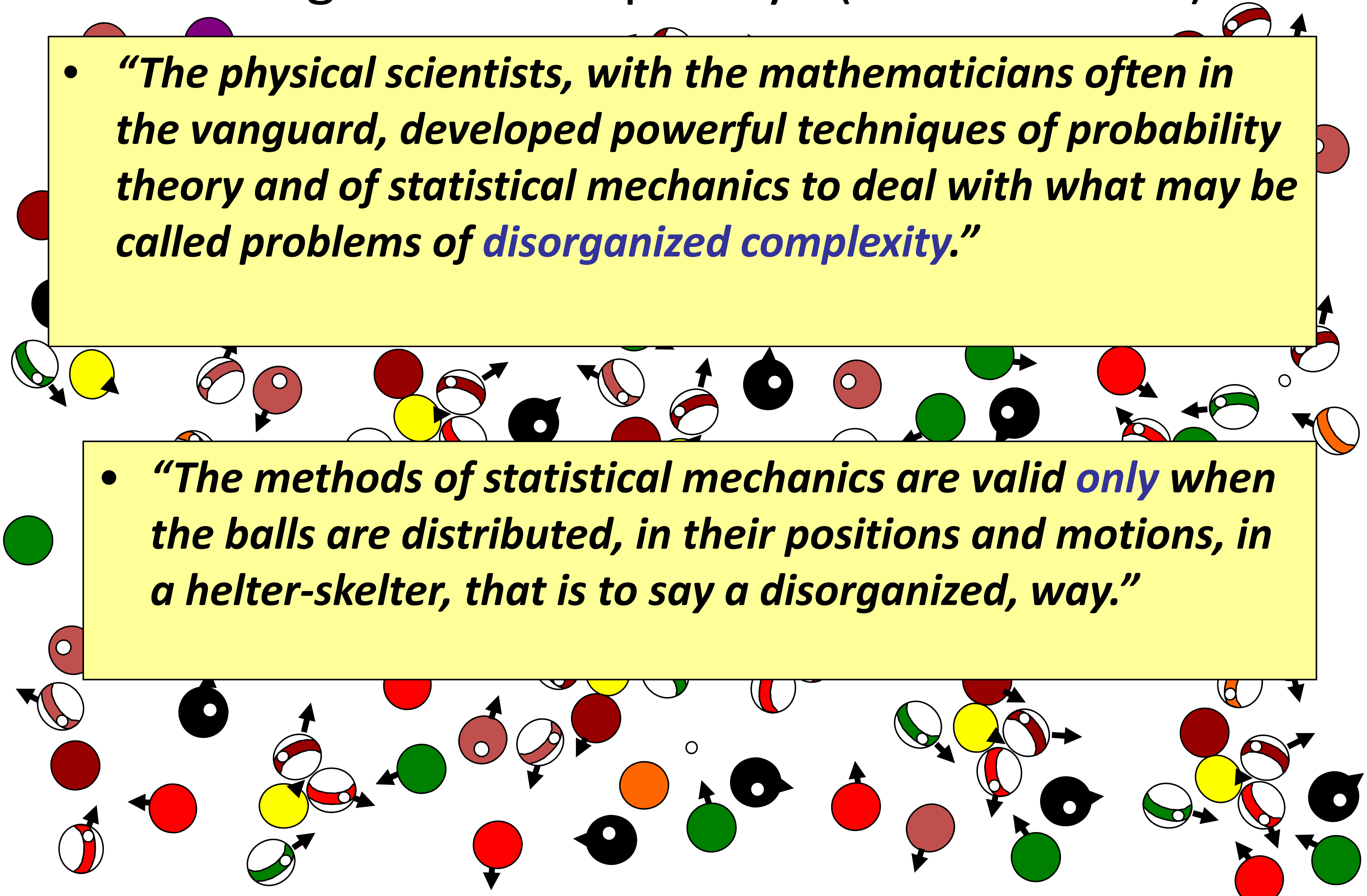
example: billiard balls

- **classical dynamics provide exact descriptions of a <u>small</u> number of balls interacting on a table**



Weaver, W. 1948. Science and complexity. American Scientist 36 536-544. Also available electronically from http://www.ceptualinstitute.com/genre/weaver/weaver-1947b.htm.

“disorganized complexity” (Weaver 1948)

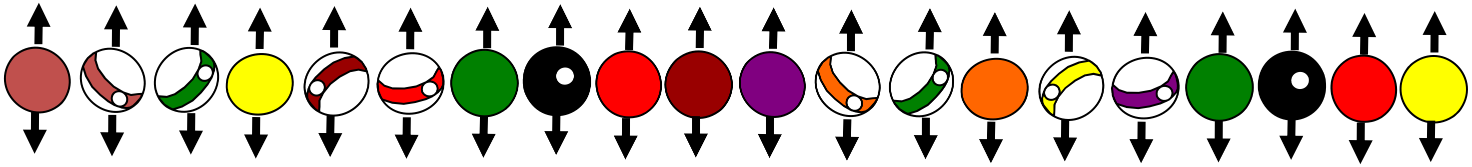


- ***“The physical scientists, with the mathematicians often in the vanguard, developed powerful techniques of probability theory and of statistical mechanics to deal with what may be called problems of disorganized complexity.”***

- ***“The methods of statistical mechanics are valid only when the balls are distributed, in their positions and motions, in a helter-skelter, that is to say a disorganized, way.”***

“organized complexity” (Weaver 1948)

- ***“For example, the statistical methods would not apply if someone were to arrange the balls in a row parallel to one side rail of the table, and then start them all moving in precisely parallel paths perpendicular to the row in which they stand. Then the balls would never collide with each other nor with two of the rails, and one would not have a situation of disorganized complexity."***



Systems exhibiting organized complexity:

- biological systems (Weaver)
- ecosystems
- economies
- social systems
- advanced technologies (e.g., the Internet)

A deeper notion of complexity

Reductionist science: Reduce the *apparent complexity* of the world *directly* to an underlying simplicity.

  - What is “small” or “large” changes over time
  - Weaver’s notion of size is insufficient

- Physics has always epitomized this approach
- Molecular biology has successfully mimicked physics

Weaver’s taxonomy (simplicity – disorganized – organized) does not capture key features of network science…

- How it is currently practiced
- What we need for network centric infrastructures

…but we can build on it!

Two dimensions of complexity

	Small models	Large models
Robust behavior		
Fragile behavior		

1. ***Small vs large*** descriptions or models of systems
2. ***Robust vs fragile*** behavior in response to perturbations in descriptions, components, or the environment.

	Small models	Large models
Robust		
Fragile		

Simple questions:

- Small models
- Elegant experiments
- Elegant theorems

Simple answers:

- Simple outcomes
- Robust, predictable
- Short proofs

Examples: pendulum as simple harmonic oscillator, simple RLC circuits, gravitational 2-body problem, simple Boolean logic circuits

	Small	Large
Robust		
Fragile	chaocritical	

Simple questions:

- Elegant experiments
- Small models
- Elegant theorems

Simple answers:

- ~~Simple outcomes~~
- ~~Robust, predictable~~
- ~~Short proofs~~

- Godel: Incompleteness, Turing: Undecidability
- Even simple questions can be “complex” and fragile
- Profoundly affected mathematics and computation
- We will call this “chaocritical complexity”

1960s-Present: “Chaocritical complexity”

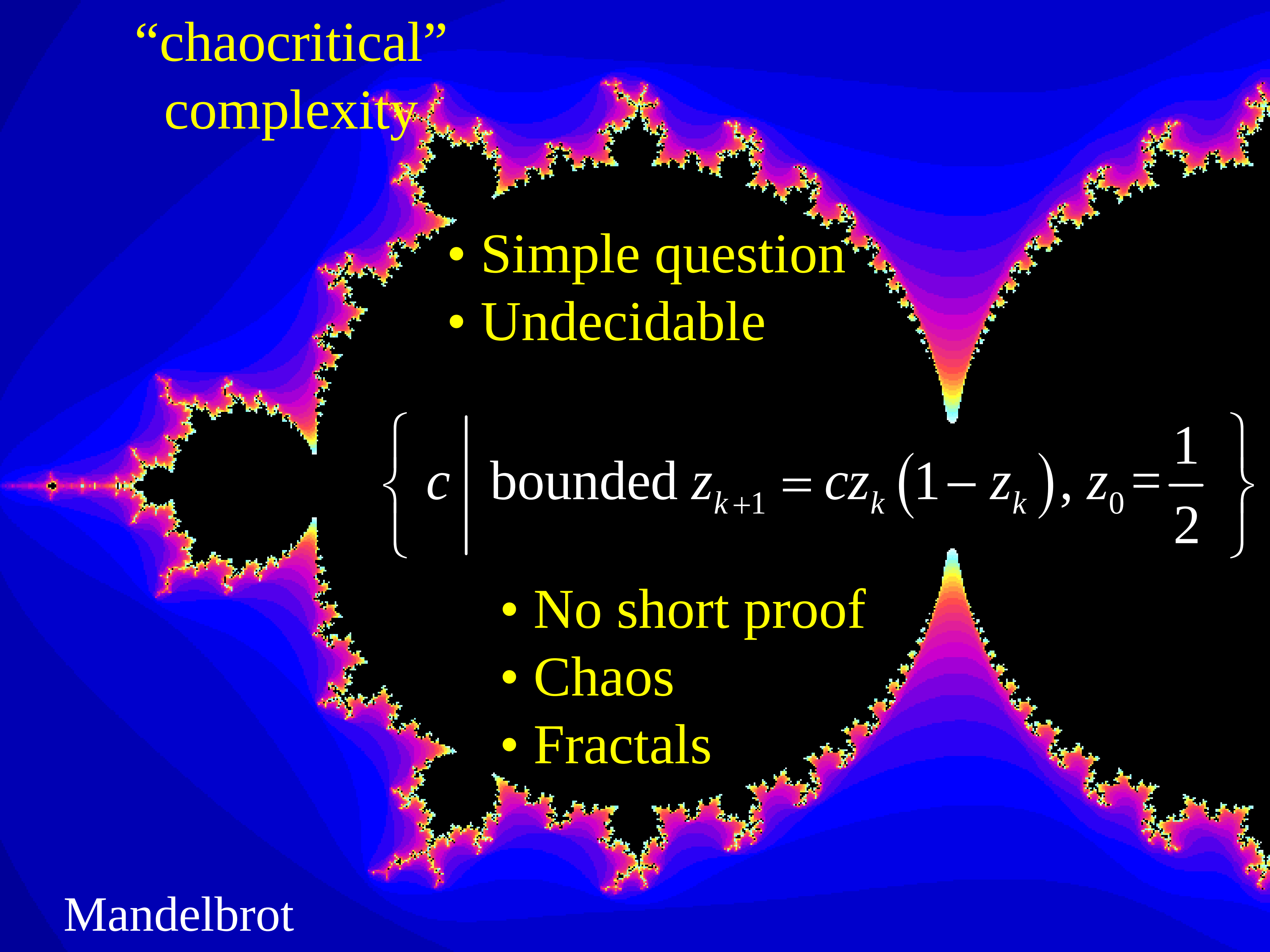
Simple questions:

- Simple models
- Elegant theorems
- Elegant experiments

Dominates today’s scientific thinking about complexity

Features that arise from dis-organization:

- Unpredictabity
- Chaos, fractals
- Critical phase transitions
- Self-similarity
- Universality
- Pattern formation
- Edge-of-chaos
- Order for free
- Self-organized criticality
- Scale-free networks



“chaocritical” complexity

- Simple question
- Undecidable

$$\left\{ c \;\middle|\; \text{bounded } z_{k+1} = c z_k \left(1 - z_k\right),\ z_0 = \frac{1}{2} \right\}$$

- No short proof
- Chaos
- Fractals

Mandelbrot

	Small	**Large**
Robust/Short		Organized
Fragile/Long	chaocritical	

- Revisiting Weaver's notion of **organized complexity**
- Completely different theory and technology from chaocritical

Simple answers:

- Simple outcomes
- Robust, predictable
- Short proofs

- *Small* and *Large* apply to the description of experiments, theorems, models, systems
- Bio and tech systems have enormously long and complex descriptions, yet extraordinarily robust behaviors
- Indeed, robustness drives their complexity, and more fragile systems could be much simpler

Organized

Air bags

Temperature control

EGR control

Electronic fuel injection

Electronic ignition

Electronic transmission

Cruise control

Electric power steering (PAS)

Anti-lock brakes

	Small	Large
Robust		Organized
Fragile	chaocritical	

Making Sense of Network Science

chaocritical complexity and Organized complexity are *opposites*, but can be viewed in this unified framework

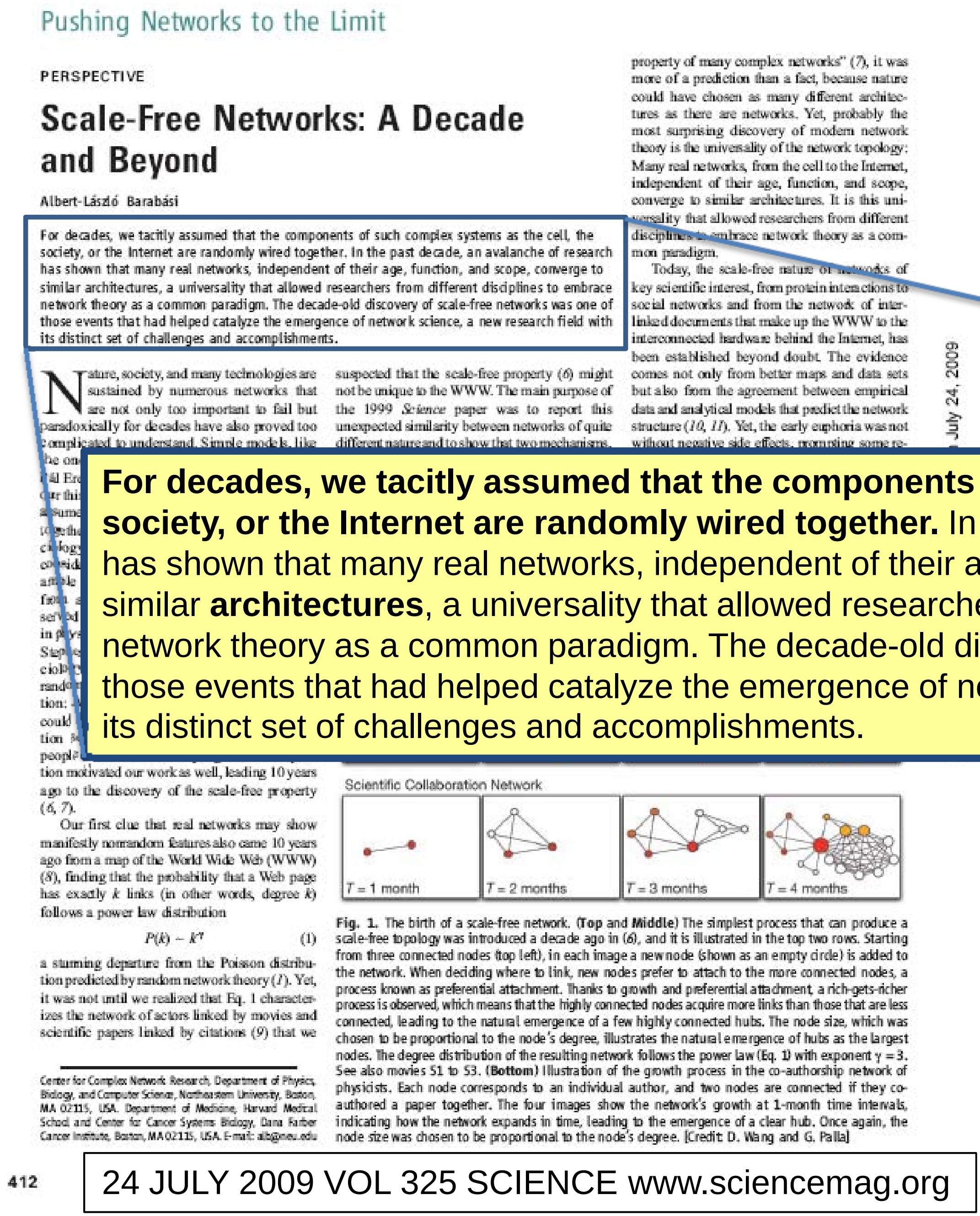
- chaocritical complexity celebrates fragility
- Organized seeks to manage robustness/fragility

These two views are opposite in many respects

A source of considerable confusion…

	Organized Complexity	Chaocritical Complexity
Primitives	structured networks	random ensembles
Function	domain-specific system performance	statistical properties of ensemble
Components	extremely heterogeneous, diverse	largely homogeneous
Architecture	protocols, constraints that deconstrain	graph topology, connectivity
Descriptions	Complex, multi-scale, scale-rich	Simple, self-similar, scale-free
Environment	Complex, uncertain, random and/or adversaria	Simple, random
Uncertainty	*Large*, in both environment and components	*Minimal*, in components or environment
Assembly	evolution, design, architecture	random growth, “self-organization”
Tuning	*High*, via constraints, protocols, interfaces	*Minimal*, via an order parameter
Simulation	Inconclusive (counterexamples, not proofs)	Usually conclusive
“Not Random”	far from random, highly organized, structured	random but skewed, clustered
Proofs	Essential, emphasis on rigor	Secondary
Robust To	common perturbations, targeted attacks	random rewiring
Fragile To	random rewiring, rare or novel perturbations	initial conditions, attack, perturbations
RYF	Primary, due to designed/evolved tradeoffs	secondary

mainstream network science



Pushing Networks to the Limit

PERSPECTIVE

Scale-Free Networks: A Decade and Beyond

Albert-László Barabási

For decades, we tacitly assumed that the components of such complex systems as the cell, the society, or the Internet are randomly wired together. In the past decade, an avalanche of research has shown that many real networks, independent of their age, function, and scope, converge to similar architectures, a universality that allowed researchers from different disciplines to embrace network theory as a common paradigm. The decade-old discovery of scale-free networks was one of those events that had helped catalyze the emergence of network science, a new research field with its distinct set of challenges and accomplishments.

Nature, society, and many technologies are sustained by numerous networks that are not only too important to fail but paradoxically for decades have also proved too complicated to understand. Simple models, like

tion motivated our work as well, leading 10 years ago to the discovery of the scale-free property (*6*, *7*).

Our first clue that real networks may show manifestly nonrandom features also came 10 years ago from a map of the World Wide Web (WWW) (*8*), finding that the probability that a Web page has exactly k links (in other words, degree k) follows a power law distribution

$$P(k) \sim k^{\gamma} \qquad (1)$$

a stunning departure from the Poisson distribution predicted by random network theory (*1*). Yet, it was not until we realized that Eq. 1 characterizes the network of actors linked by movies and scientific papers linked by citations (*9*) that we suspected that the scale-free property (*6*) might not be unique to the WWW. The main purpose of the 1999 *Science* paper was to report this unexpected similarity between networks of quite different nature and to show that two mechanisms,

property of many complex networks" (*7*), it was more of a prediction than a fact, because nature could have chosen as many different architectures as there are networks. Yet, probably the most surprising discovery of modern network theory is the universality of the network topology: Many real networks, from the cell to the Internet, independent of their age, function, and scope, converge to similar architectures. It is this universality that allowed researchers from different disciplines to embrace network theory as a common paradigm.

Today, the scale-free nature of networks of key scientific interest, from protein interactions to social networks and from the network of interlinked documents that make up the WWW to the interconnected hardware behind the Internet, has been established beyond doubt. The evidence comes not only from better maps and data sets but also from the agreement between empirical data and analytical models that predict the network structure (*10*, *11*). Yet, the early euphoria was not without negative side effects, prompting some re-

Fig. 1. The birth of a scale-free network. (**Top** and **Middle**) The simplest process that can produce a scale-free topology was introduced a decade ago in (*6*), and it is illustrated in the top two rows. Starting from three connected nodes (top left), in each image a new node (shown as an empty circle) is added to the network. When deciding where to link, new nodes prefer to attach to the more connected nodes, a process known as preferential attachment. Thanks to growth and preferential attachment, a rich-gets-richer process is observed, which means that the highly connected nodes acquire more links than those that are less connected, leading to the natural emergence of a few highly connected hubs. The node size, which was chosen to be proportional to the node's degree, illustrates the natural emergence of hubs as the largest nodes. The degree distribution of the resulting network follows the power law (Eq. 1) with exponent $\gamma = 3$. See also movies S1 to S3. (**Bottom**) Illustration of the growth process in the co-authorship network of physicists. Each node corresponds to an individual author, and two nodes are connected if they co-authored a paper together. The four images show the network's growth at 1-month time intervals, indicating how the network expands in time, leading to the emergence of a clear hub. Once again, the node size was chosen to be proportional to the node's degree. [Credit: D. Wang and G. Palla]

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For decades, we tacitly assumed that the components of such complex systems as the cell, the society, or the Internet are randomly wired together. In the past decade, an avalanche of research has shown that many real networks, independent of their age, function, and scope, converge to similar **architectures**, a universality that allowed researchers from different disciplines to embrace network theory as a common paradigm. The decade-old discovery of scale-free networks was one of those events that had helped catalyze the emergence of network science, a new research field with its distinct set of challenges and accomplishments.

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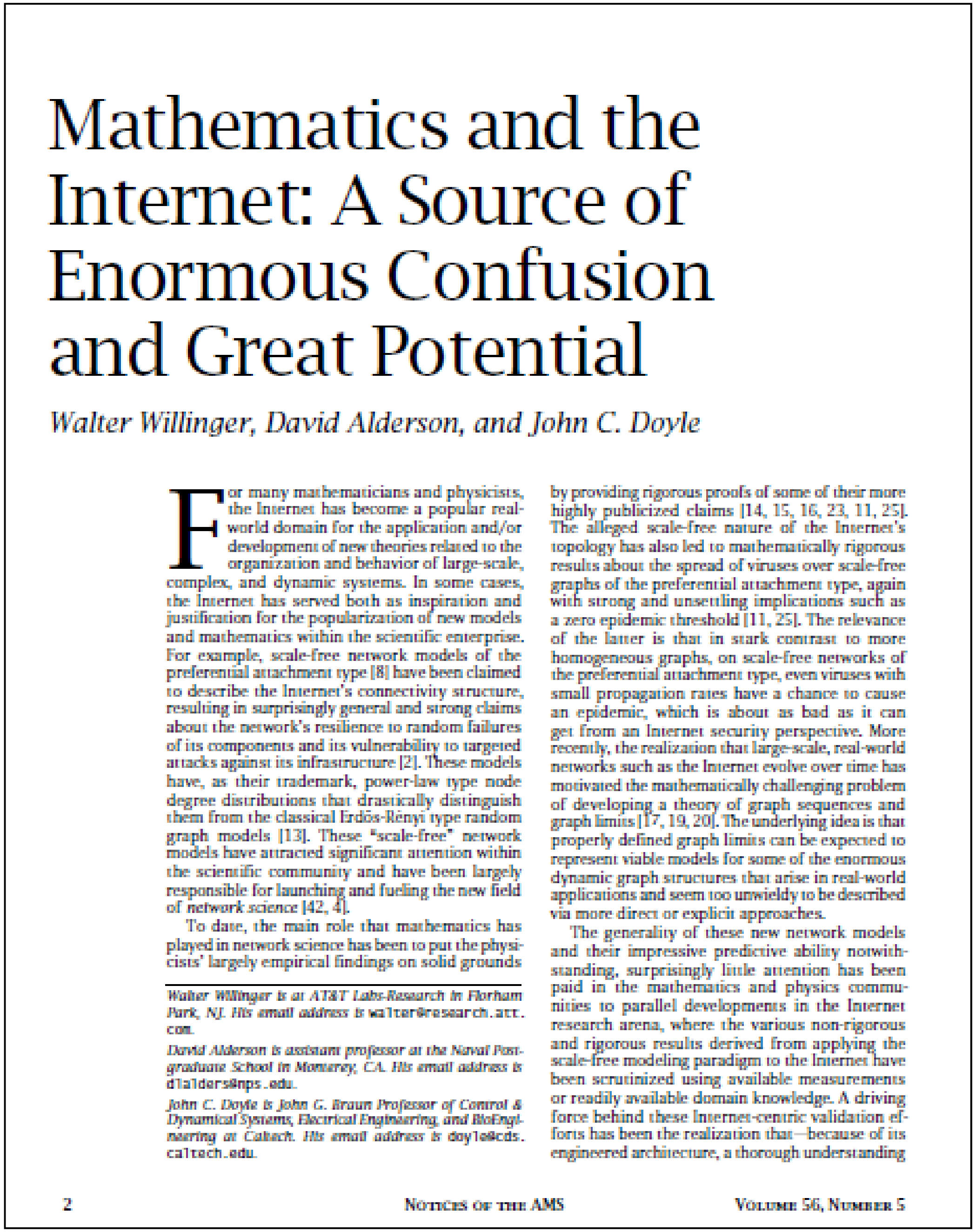
- Notices of the AMS May 2009

- See Also:
  The “Robust Yet Fragile” Internet,
  PNAS 2005.



Mathematics and the Internet: A Source of Enormous Confusion and Great Potential

Walter Willinger, David Alderson, and John C. Doyle

For many mathematicians and physicists, the Internet has become a popular real-world domain for the application and/or development of new theories related to the organization and behavior of large-scale, complex, and dynamic systems. In some cases, the Internet has served both as inspiration and justification for the popularization of new models and mathematics within the scientific enterprise. For example, scale-free network models of the preferential attachment type [8] have been claimed to describe the Internet's connectivity structure, resulting in surprisingly general and strong claims about the network's resilience to random failures of its components and its vulnerability to targeted attacks against its infrastructure [2]. These models have, as their trademark, power-law type node degree distributions that drastically distinguish them from the classical Erdős-Rényi type random graph models [13]. These “scale-free” network models have attracted significant attention within the scientific community and have been largely responsible for launching and fueling the new field of *network science* [42, 4].

To date, the main role that mathematics has played in network science has been to put the physicists' largely empirical findings on solid grounds by providing rigorous proofs of some of their more highly publicized claims [14, 15, 16, 23, 11, 25]. The alleged scale-free nature of the Internet's topology has also led to mathematically rigorous results about the spread of viruses over scale-free graphs of the preferential attachment type, again with strong and unsettling implications such as a zero epidemic threshold [11, 25]. The relevance of the latter is that in stark contrast to more homogeneous graphs, on scale-free networks of the preferential attachment type, even viruses with small propagation rates have a chance to cause an epidemic, which is about as bad as it can get from an Internet security perspective. More recently, the realization that large-scale, real-world networks such as the Internet evolve over time has motivated the mathematically challenging problem of developing a theory of graph sequences and graph limits [17, 19, 20]. The underlying idea is that properly defined graph limits can be expected to represent viable models for some of the enormous dynamic graph structures that arise in real-world applications and seem too unwieldy to be described via more direct or explicit approaches.

The generality of these new network models and their impressive predictive ability notwithstanding, surprisingly little attention has been paid in the mathematics and physics communities to parallel developments in the Internet research arena, where the various non-rigorous and rigorous results derived from applying the scale-free modeling paradigm to the Internet have been scrutinized using available measurements or readily available domain knowledge. A driving force behind these Internet-centric validation efforts has been the realization that—because of its engineered architecture, a thorough understanding

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	Small	Large
Robust		Organized
Fragile	chaocritical	Irreducible

Irreducible Complexity

Biology: We might accumulate more complete parts lists but never "understand" how it all works.

Technology: We might build increasingly complex and incomprehensible systems which will eventually fail completely yet cryptically.

How to focus on "good" RYF tradeoffs…?
Architecture.

Recent Publications

- D. Alderson and J. Doyle, Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructures. *IEEE Transactions on Systems, Man, and Cybernetics-Part A*, to appear, 2009.

- "In Search of the Real Network Science: An Interview with David Alderson” *ACM Ubiquity* Issue 8 (August 4 - 10, 2009).

- W. Willinger, D. Alderson, and J.C. Doyle. Mathematics and the Internet: A source of enormous confusion and great potential, *Notices of the American Mathematical Society* 56(5):286-299, May 2009.

- D. Alderson. Catching the “Network Science” Bug: Insight and Opportunity for the Operations Researcher. *Operations Research* 56, pp. 1047-1065, 2008.