Lecture 20: Modeling overview and other Technological Systems modeling examples

ESD. 342

April 27, 2006

Learning objectives

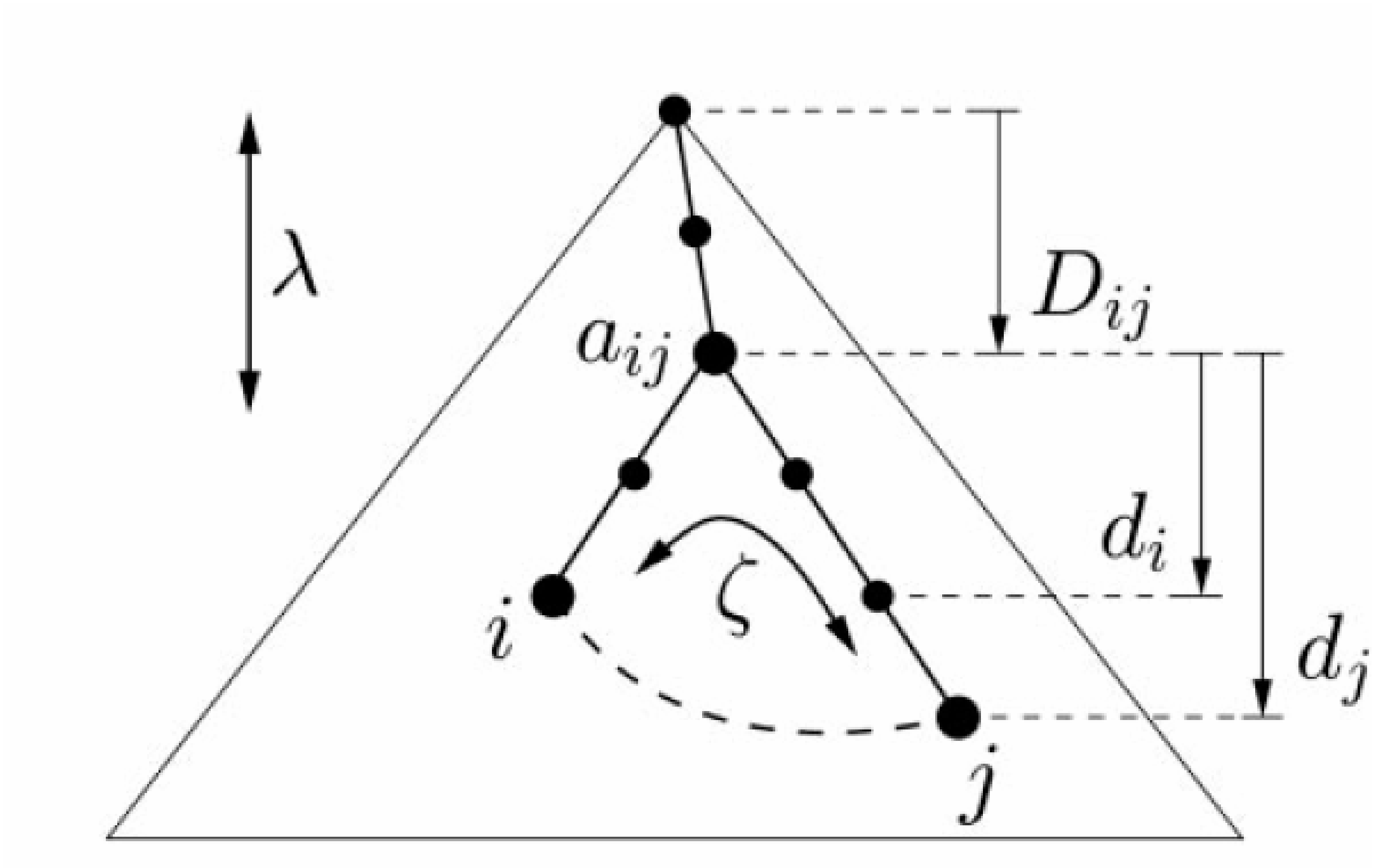
- Examine literature modeling efforts within architecting framework
- Understand the DWS modeling effort in a practical organizational context
- Appreciate/critique the analysis/model developed by Doyle et al for the Internet
- Appreciate/critique the analysis/model developed by Guimera et al regarding air transport
- Explore possible future research suggested by these results

Lecture 20 outline

- Brief summary of DWS (from lecture 17)
- DWS in practical context
- Internet model by Doyle et al
- Air transport by Guimera et al
- Future Research suggestions

Dodds, Watts and Sabel Organizational Modeling for Communication Robustness

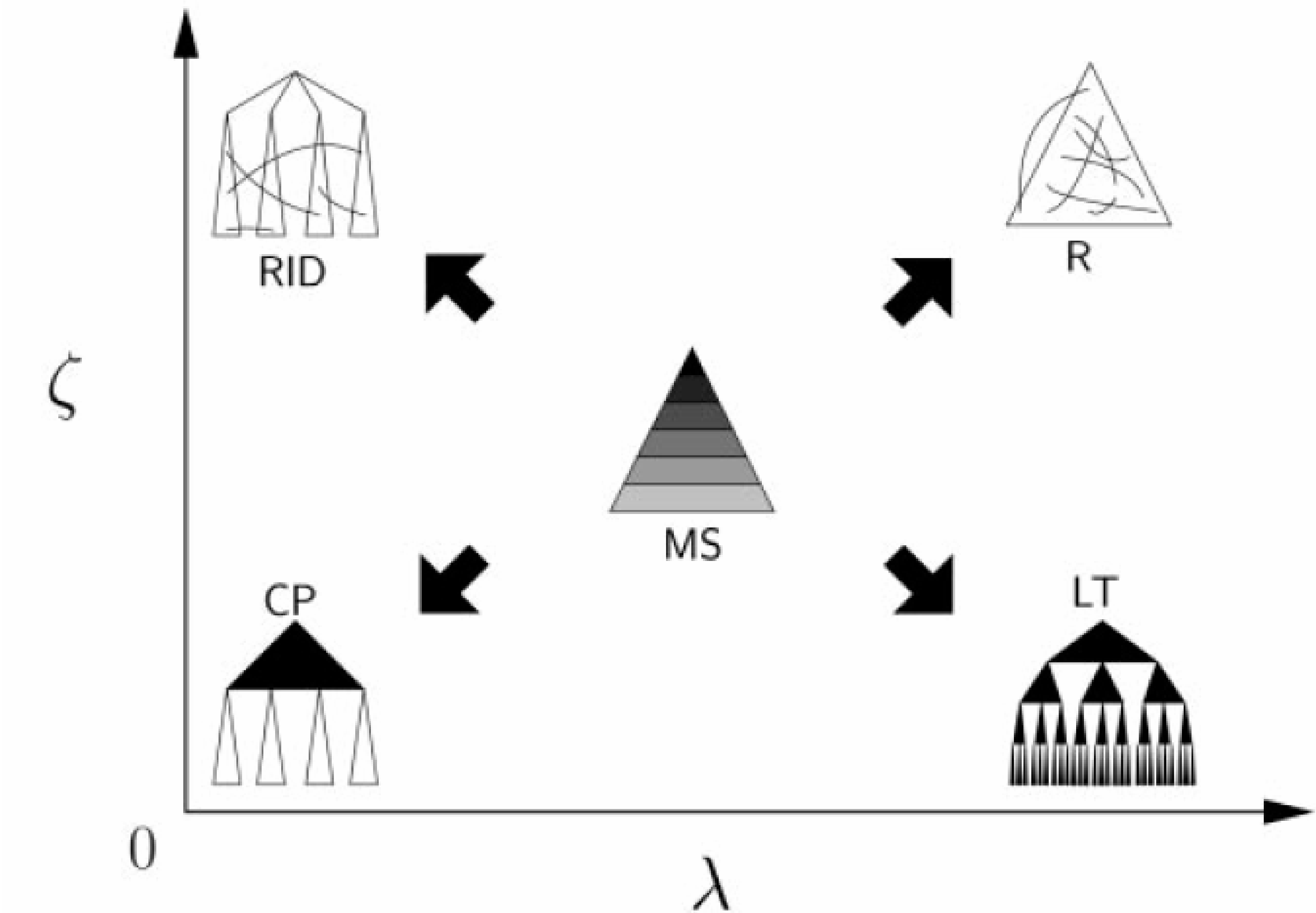
- The contributions were:
  - Assessment of various organizational topologies with regard to robust problem solving
  - The development of an “ ***Organizational Structure Generator***” based on additions to a hierarchical backbone (thus all are hybrids). The structural variation included hierarchical level and organizational distance associated with the added links.



Defining key parameters

Dodds, Watts and Sabel Network Organizational Model for Communication Robustness

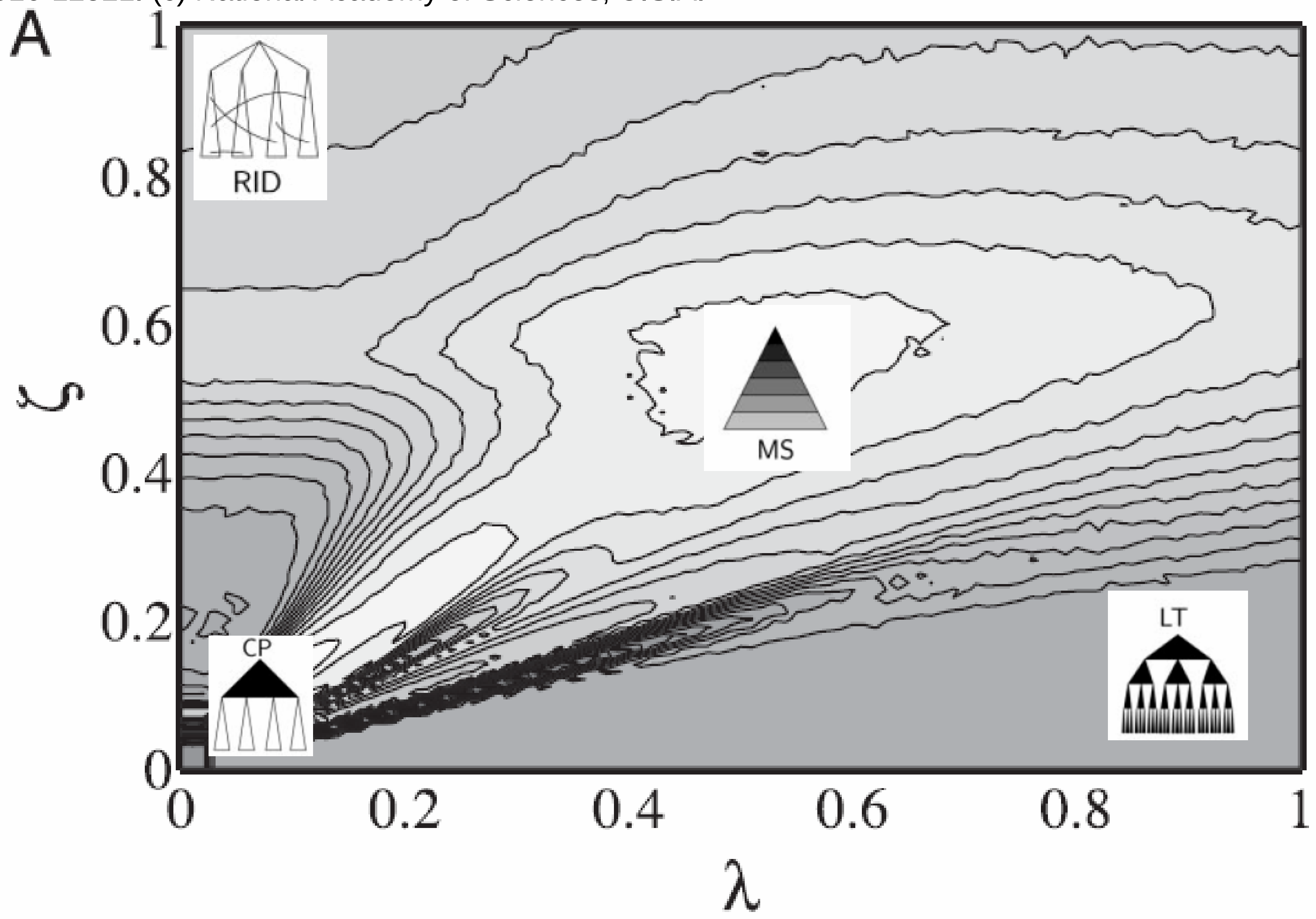
- The organizational structural generator
  - Starts with **hierarchy with L levels** and branching ratio b
  - Randomly **adds m weighted** links
  - Probability of two nodes being linked, P(i,j) depends on depth of lowest common ancestor and also their own depths
  - Organizational distance $x_{ij} = (d_i^2 + d_j^2 - 2)^{\frac{1}{2}}$
  - Overall $P(i, j) \propto e^{\frac{-D_{ij}}{\lambda}} e^{\frac{-x_{ij}}{\zeta}}$
  - Where $\lambda \; and \; \zeta$ are adjustable parameters allowing different organization structures to be generated by their network model. Varying **these parameters** leads to


RID
R
ζ
MS
CP
LT
0
λ

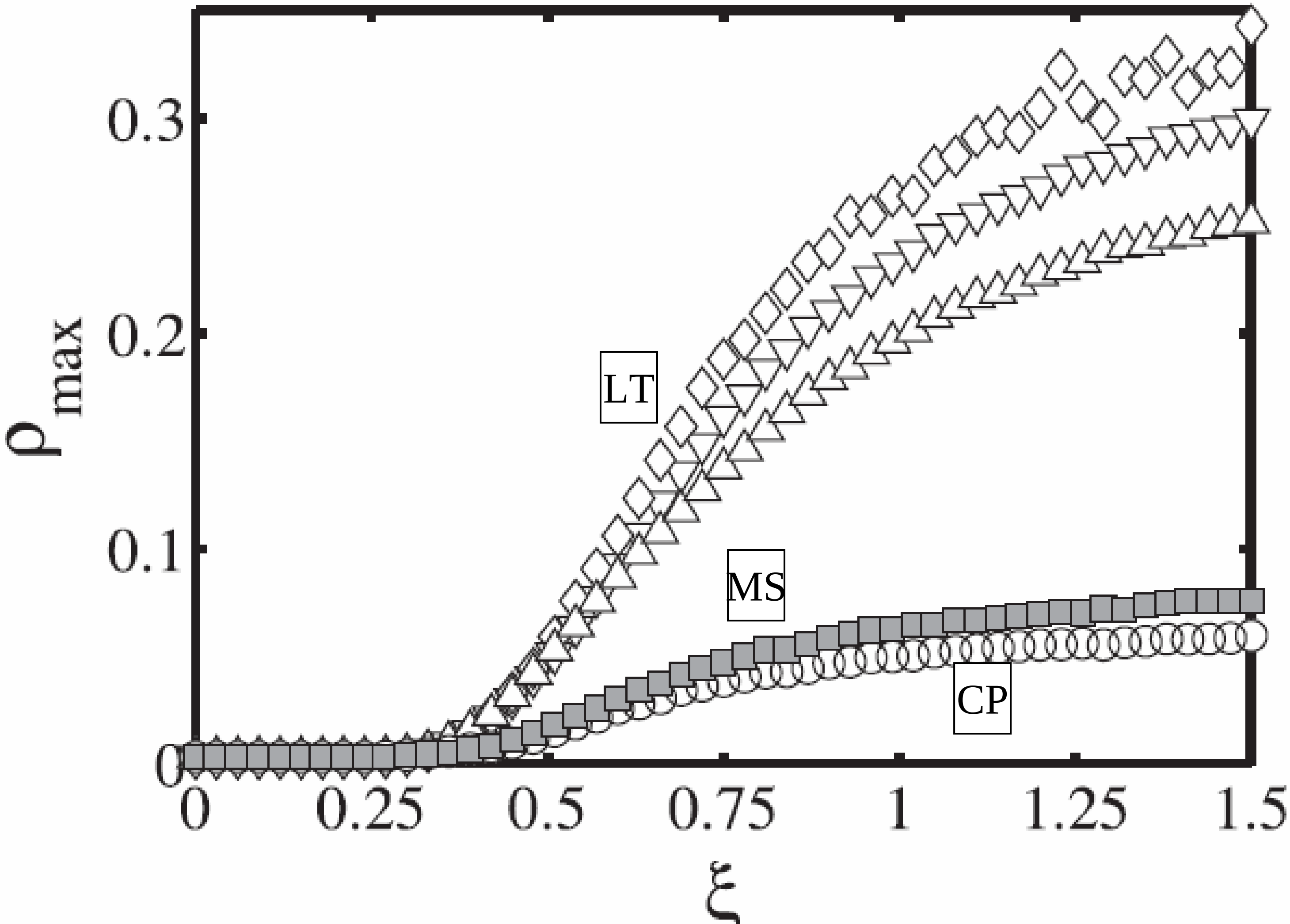
Dodds, Watts and Sabel Organizational Modeling for Communication Robustness

- The contributions were:
  - Assessment of various organizational topologies with regard to robust problem solving
  - The development of an " ***Organizational Structure Generator"*** based on additions to a hierarchical backbone (thus all hybrids). The structural variation included hierarchical level and organizational distance associated with the added links.
  - Development of an information exchange model (applicable to problem solving) which treats variable rate of information transfer (rate of change) and ***variable problem decomposability*** as a function of organizational distance, x_{ij} and the "decomposability" parameter ξ according to

$$s = e^{-\frac{x_{ij}}{\xi}}$$



Congestion metric over the ζ , λ plane



Congestion centrality with **decreasing** task decomposability, ξ

Finding from the Organizational Models as studied by DWS

- Robustness
  - Congestion robustness: the capacity to protect individual nodes from congestion (overload).
    - Minimal congestion centrality is better structure and this is shown for MS (only CP is competitive but not as reliable)
    - All structures are OK with decomposable tasks but MS and CP are best when larger scale interactions are key.
    - **Maximum uncongested size is for MS (CP again second)**

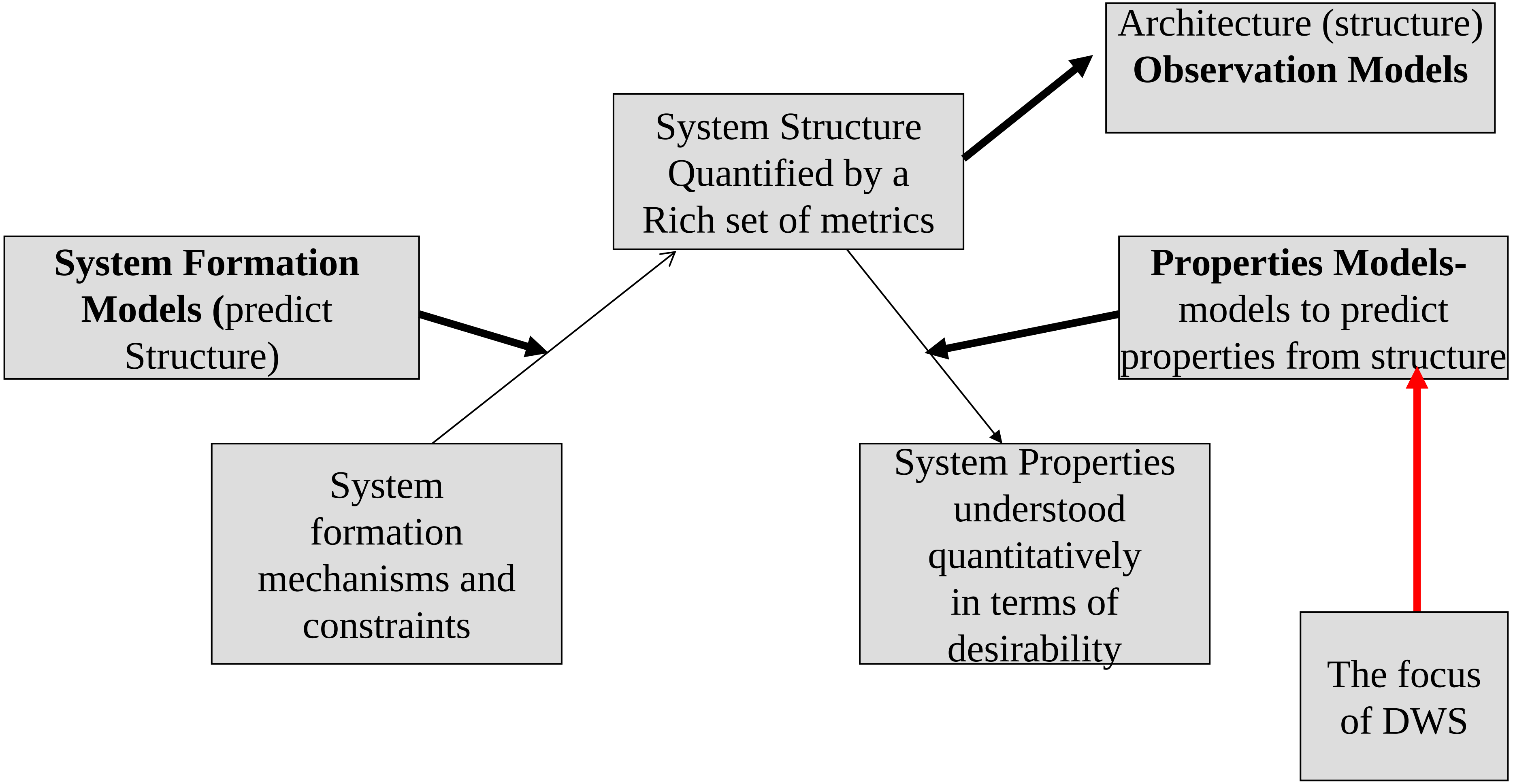
Finding from the Organizational Models as studied by DWS II

- Robustness
  - Congestion robustness: the capacity to protect individual nodes from congestion (overload).
    - Minimal congestion centrality is better structure and this is shown for **MS**
    - All structures are OK with decomposable tasks but **MS** and CP are best when larger scale interactions are key.
    - Maximum uncongested size is for **MS**
  - Connectivity robustness: The capacity to remain connected even when individual failures do occur.
    - Random best for targeted attack but **MS** as good
  - **Ultrarobustness**: A simultaneous capacity to exhibit superior Congestion and Connectivity robustness—clearly **MS** fits this definition by their measures and simulation

Overview Assessment of DWS Paper

- The paper is really only about trying to derive a "structure-property" relationship and *does not cover realistic structure formation*. They do not consider the organizational structure generator as a model of structure formation nor should we.

Schematic of Engineering System Model Types within a Framework



Overview Assessment of DWS Paper II

- The paper is really only about trying to derive a "structure-property" relationship and does not cover realistic structure formation. They do not consider the organizational structure generator as a model of structure formation nor should anyone else.
- The paper combines ideas from sociology and OR (as well as statistical physics) which is an approach Watts pursues and I applaud
- There are two issues to consider when assessing whether this model may have practical relevance:
  - Do real organizations have to deal with (a non-significant number of) problems whose solution requires participation by actors at large organizational distances (problems which are not decomposable) ?
  - How would one realistically arrive at the hybrid structures that DWS identify as best in dealing with such problems?
- I will consider these issues largely from my practical experience

Organizational Problem Decomposition

- In large functionally oriented firms, typical major organizations would include (for large firms 7 or so level) sub-hierarchies for the following functions.

Manu-facturing | Sales & Marketing | Product Develop | Finance | HR | etc

- What problems might exist that require input across large organizational distances ?
- What are some possible solutions?

Organizational Problem Decomposition

- In large functionally oriented firms, typical major organizations would include (for large firms 7 or so level) sub- hierarchies for the following functions.

Manu-facturing	Sales & Marketing	Product Develop	Finance	HR	etc

- One solution is to organize by sectors, markets, location etc. to become essentially smaller. In small firms, the functional organizations (and thus organizational distance through the hierarchy) would be smaller.
- However, if large firms can be decomposed to a set of non-interacting small firms then they will generally be more successful breaking themselves up. Pure conglomerates really do not work. However, one can still strive to organize to minimize the "large-organizational-distance" problems and this is what is often implicitly if not explicitly considered in re-orgs.

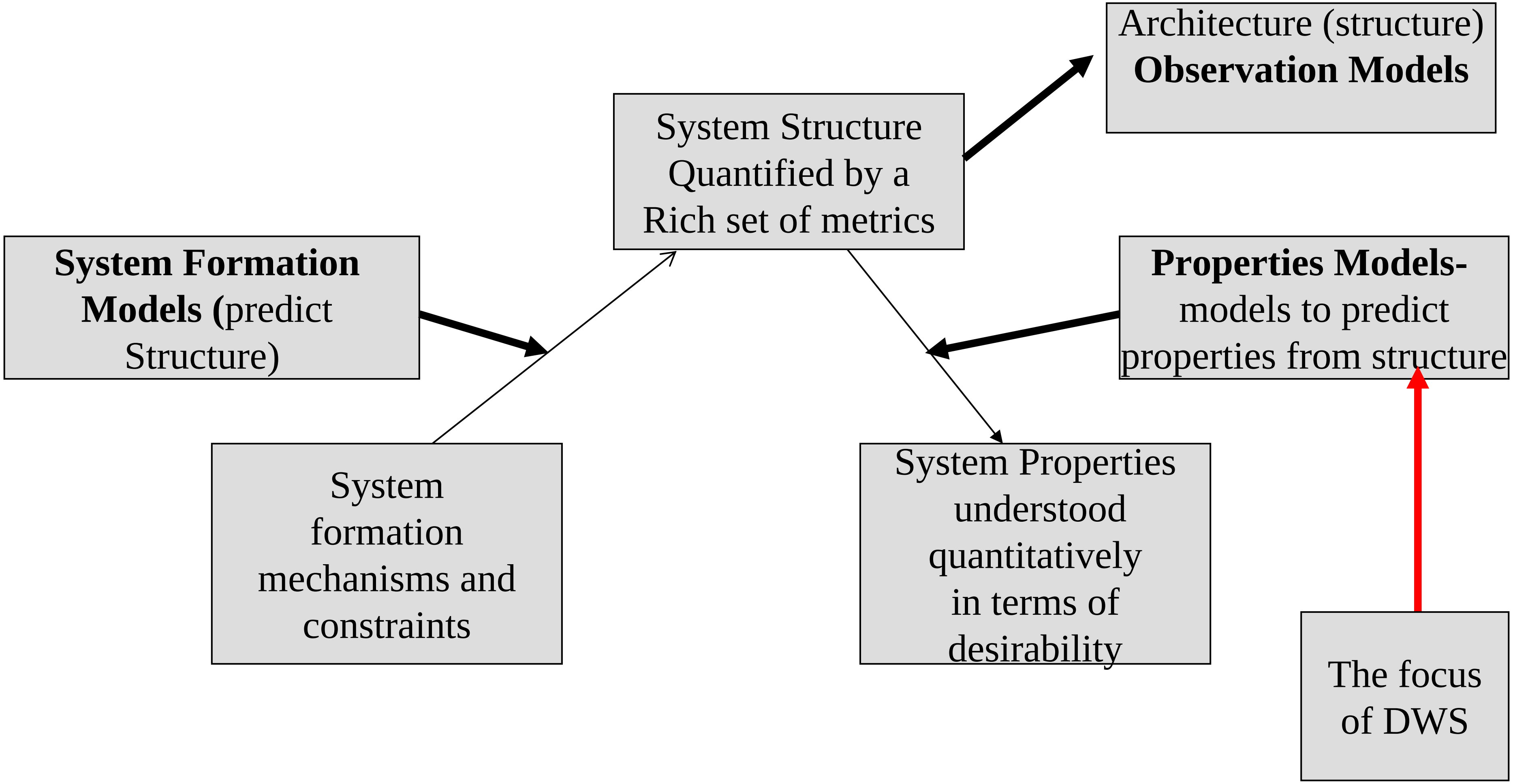
Possible Organizational Solutions to non-decomposable problems

- Have highest levels totally absorb knowledge below them in hierarchy
- Become a small firm or a group of small firms
- Result: Loss of efficiencies of scale and reason for existence of large firms
- Re-organize so the nasty problems come into more closely related organizational entities.
- Result: some success but also *organizational cyclic instability*
- Flatten the organization and rely on “Local Teams”
- Result: manager-coordination overload, how does one person with 15 direct reports know that all 210 relations among his or her reports are being maintained? Multiple levels at this branching ratio do not work.
- Cohort strengthening at large organizational distance, training for and rewarding cross-organizational knowledge and contacts (Japan)
- Matrix Management, co-location vs. rewards structure can work but takes significant coordination efforts
- Importantly, the DWS paper shows that whatever approaches are taken, they should be a little stronger as one goes up the hierarchy and a little stronger with shorter organizational distances **(MS is best)**

Overview Assessment of DWS Paper III

- The paper is really only about trying to derive a "structure-property" relationship and does not cover realistic structure formation. They do not consider the organizational structure generator as a model of structure formation nor should anyone else.
- The paper combines ideas from sociology and OR (as well as statistical physics) which is an approach Watts pursues and I applaud
- The paper gives some practically useful direction to organizational changes.
- The structure generator and the problem decomposability approaches suggest a number of potentially fruitful future research directions (where actual observations of organizations are also pursued).

Schematic of Engineering System Model Types within a Framework



Heuristic Internet Design

- Note that throughout this lecture we are referring to the autonomous Internet not the worldwide web which is “carried upon” the Internet.
- Heuristic Internet Design
  - Fabrikant et. al
  - Doyle et al. (required reading)
- Fabricant et. al. attempt to balance the “last mile costs” and the communication distance in a growing system (the internet).
  - They use (and were the originators) of the already seen

$$w'_{ij} = d_{ij} + \beta l_{j0}.$$

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$$w'_{ij} = d_{ij} + \beta l_{j0}.$$

- They noted (as did Gastner and Newman) the transition between MST and star for this case but unfortunately focused on the ease of obtaining power laws (and got caught by the “scale-free virus” that was active at the time)

Heuristic Internet Design b

- Doyle et al. spend much of their time correcting the previous over-emphasis on power-laws as an indicator of structure. We have covered some of this previously and will cover some more here but we will mainly emphasize their "First-Principles Approach" to the Internet router- level design problem.
- For their "First-Principles Approach, Doyle et. al. ***start simple*** and attempt "*to identify some minimal functional requirements and physical constraints needed to develop simple models that are consistent with engineering reality*". They also focus on single ISP's as the fundamental building block.
- They argue that the best candidates for a minimal set of **constraints** on topology construction (architecture) for a single ISP are:
  - Router technology and
  - Network economics

Heuristic Internet Design c-Router Technology Limits

- Doyle et al point out that for a given router there is a limit on the number of packets that can be processed in any given time. This limits the number of connections and connection speeds and creates a "feasible region" and "efficient frontier" for given router designs

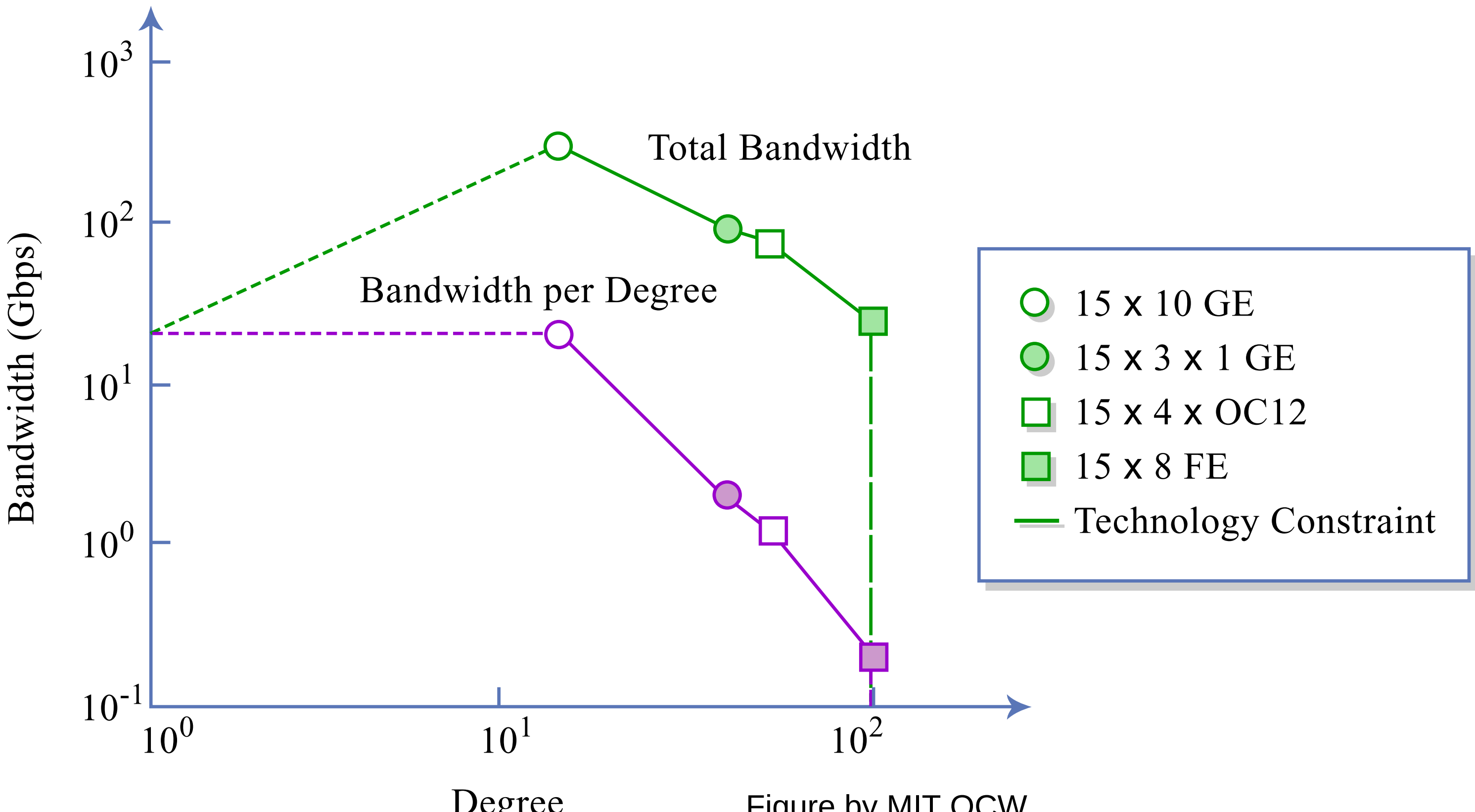

Figure by MIT OCW.

Heuristic Internet Design d- Router Technology Constraints II

Considering multiple routers and other technologies, a feasible region results

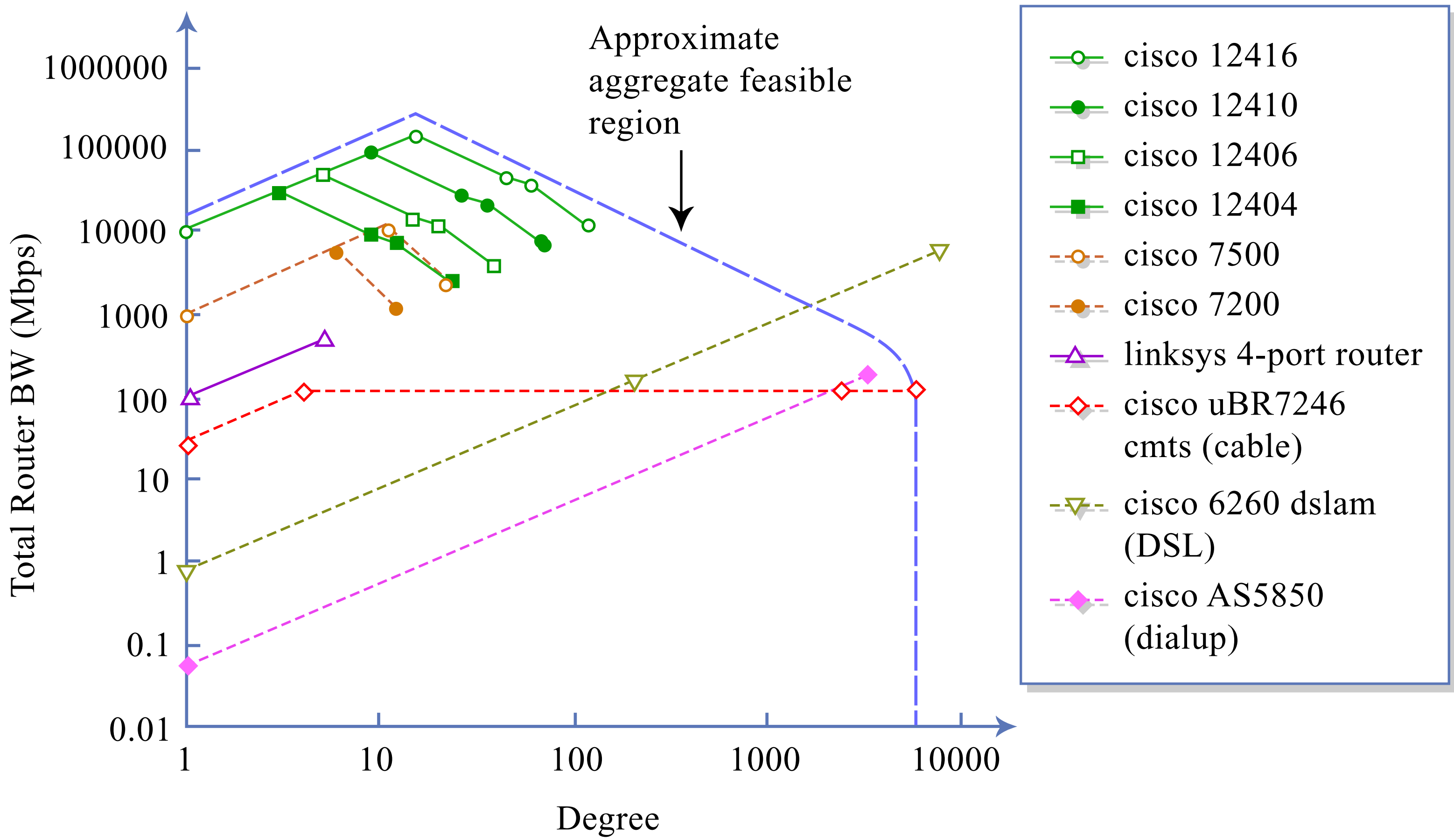

Figure by MIT OCW.

Heuristic Internet Design e- Economic Constraints

- Costs of installing and operating physical links can dominate the cost of the infrastructure so the availability of multiplexing and aggregating throughout the hierarchy is essential
- These technologies are deployed depending upon customer needs and willingness to pay

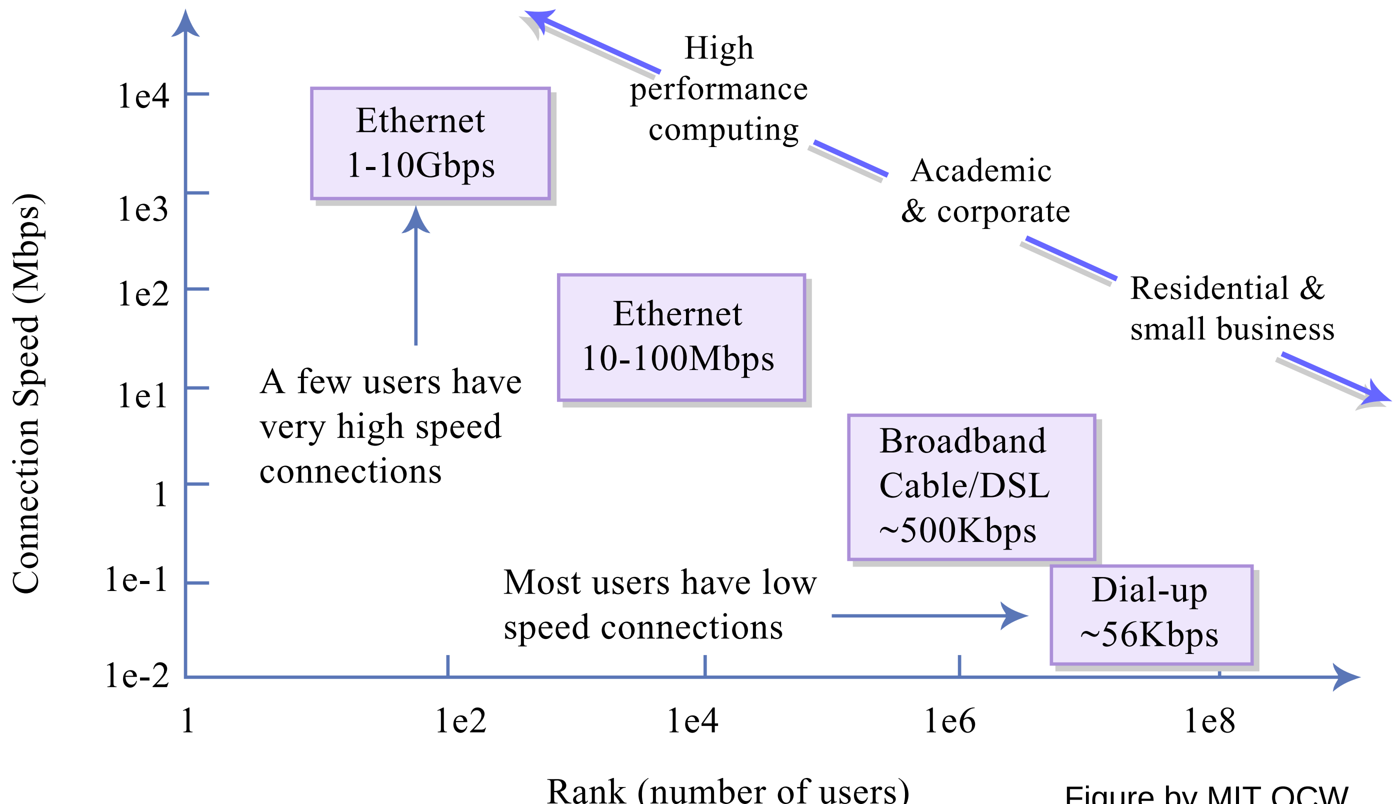

Figure by MIT OCW.

Heuristic Internet Design f: Heuristically Optimal Networks

- Doyle et al define a heuristically optimal network:

> *The simple technological and economic considerations listed above suggest that a reasonably "good" design for a single ISP's network is one in which the core is constructed as a loose mesh of high speed, low connectivity routers which carry heavily aggregated traffic over high bandwidth links. Accordingly, this mesh-like core is supported by a hierarchical tree-like structure at the edges whose purpose is to aggregate traffic through high connectivity. We will refer to this design as heuristically optimal to reflect its consistency with real design considerations.*

- They also show that several real Internet network elements have these broad characteristics (Abilene and CENIC)
- Note the "hierarchical tree" in the quote above would actually be better described by the Gastner-Newman model covered in lecture 18 (a modified MST arrived at by a "growth rule" followed by the ISP).

Heuristic Internet Design g: Properties and designs evaluated

- Performance
  - Throughput
  - Router utilization (distance to frontier)
  - End user bandwidth Distribution
- Robustness to attack

- They constructed a set of Toy Models to illustrate some of their points about the superiority of “constrained” vs. “freely-grown” structures/topologies.

Heuristic Internet Design h: designs

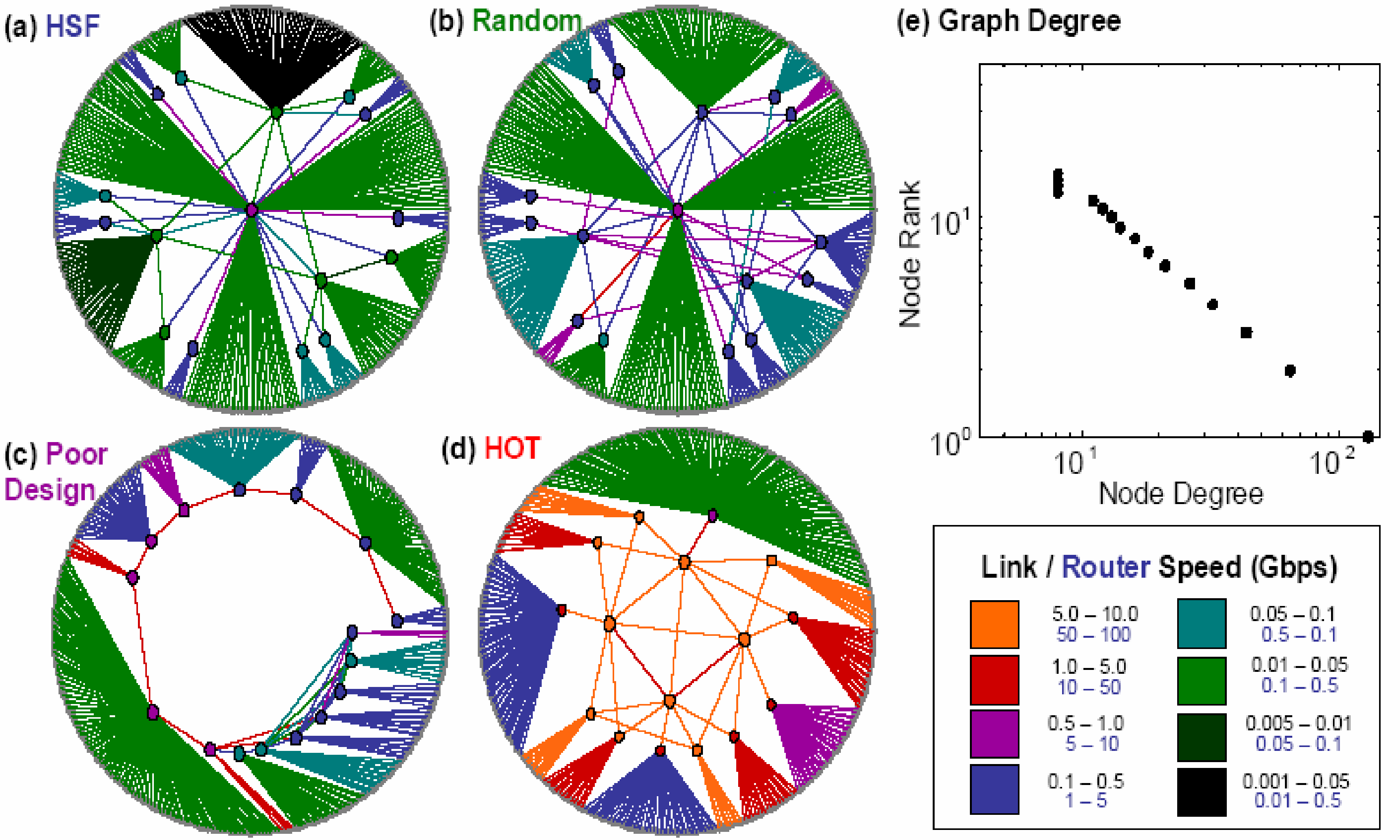

Figure 5 in Li, Lun, David Alderson, John C. Doyle, and Walter Willinger. "Towards a Theory of Scale-Free Graphs: Definition, Properties, and Implications." *Internet Mathematics* 2, no. 4 (2006): 431-523. Reproduced courtesy of A K Peters, Ltd. and David Alderson. Used with permission.

Heuristic Internet Design g: Properties and designs evaluated

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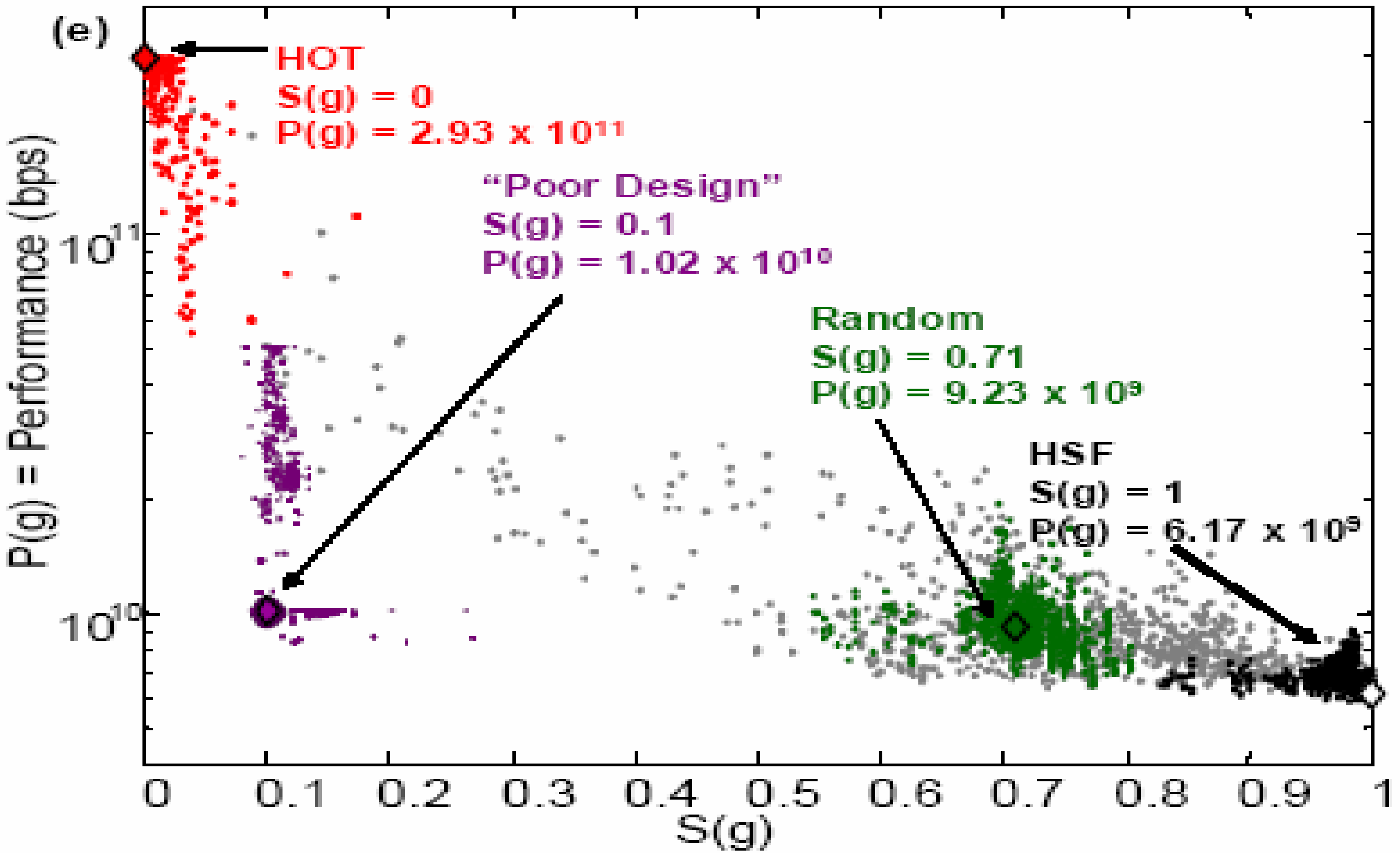
- They constructed a set of Toy Models to illustrate some of their points about the superiority of “constrained” vs. “freely-grown” structures/topologies.

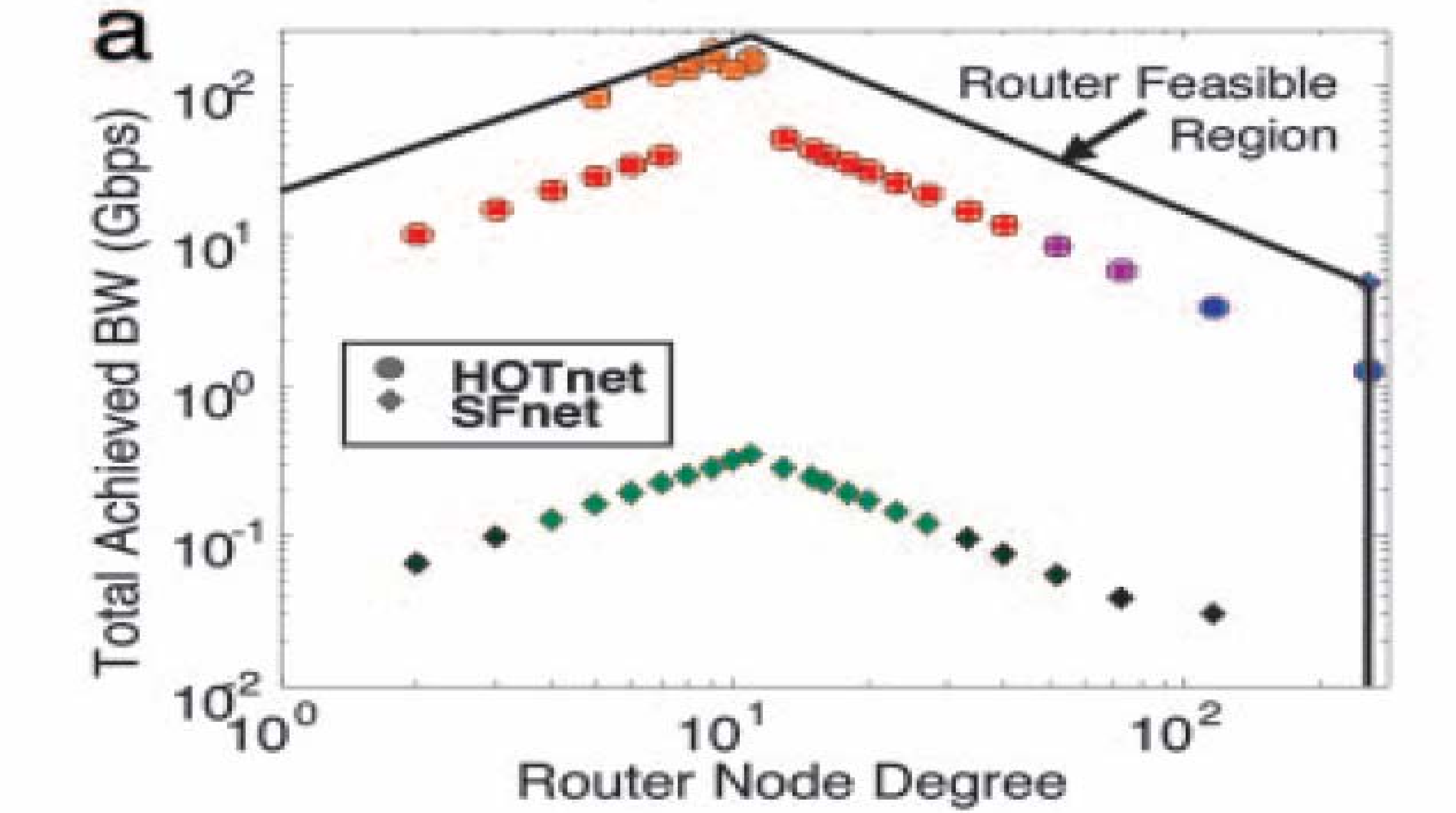
- They evaluated the communication performance of these “Toy Models”.

Heuristic Internet Design i: performance as a function of the Scale-Free parameter

Figure 6 in Li, Lun, Alderson, David, John C. Doyle, and Walter Willinger. "Towards a Theory of Scale-Free Graphs: Definition, Properties, and Implications." *Internet Mathematics* 2, no. 4 (2006): 431-523. Reproduced courtesy of A K Peters, Ltd. and David Alderson. Used with permission.



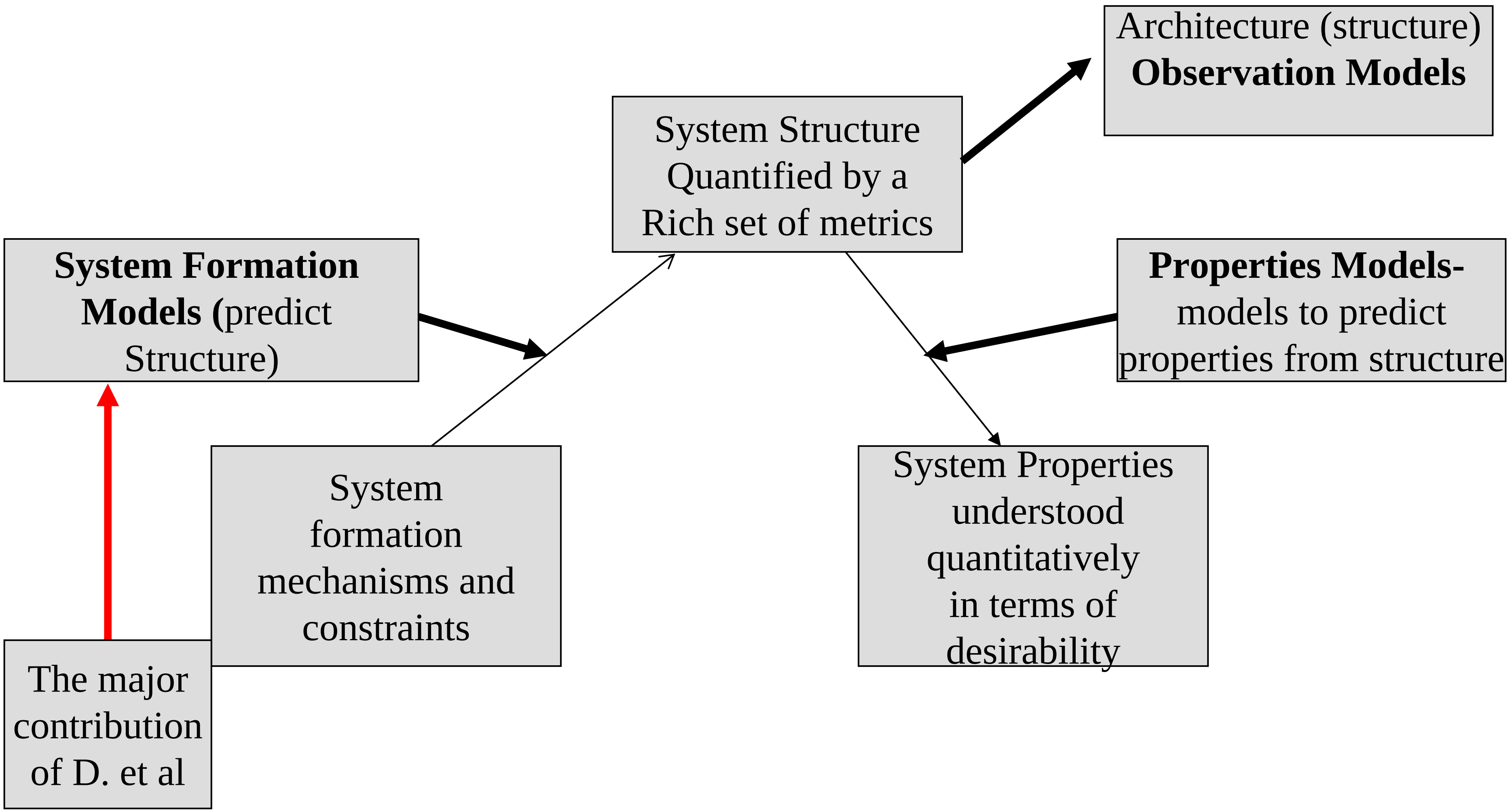
Heuristic Internet Design j; Router utilization comparison



Overview Assessment of Doyle et al

- Doyle et al introduce some additional engineering design constraints and then are able to use this insight to produce simple (toy) models that demonstrate very clearly that the mental image of a scale-free graph is totally inconsistent with real ISP's (but perhaps not web domains).
- They also clearly showed that power laws do not imply a certain type of structure but could be observed with a wide variety of different topologies (or architectures/designs)
- Their approach is strengthened by the combination of an engineering approach with OR and a little bit of economics (as implicitly done by Fabricant et al and Newman and Gastner)
- Their major contribution was in advancing an outline of an approach for improved "Systems Formation Models" for large scale engineering systems (Infrastructures)

Schematic of Engineering System Model Types within a Framework



Network Model types of interest (from lecture 12)

- **Models/algorithms used to "observe" systems**
  - Calculation of structural metrics
  - Communities, motifs, coarse-graining, hierarchy
- **Models for predicting/explaining Structure**
  - Models for formation/growth processes of systems
  - Most network models such as random, small-world etc. implicitly fall in this category
  - Cumulative advantage, preferential attachment, bipartite community formation, heuristic optimization relative to constraints, hierarchy (or heuristics) + random
- **Models for predicting/explaining properties of systems**
  - Predicting properties from structure – architecture
    - Flexibility, robustness, performance of functions
  - Operational processes or functions
    - Communication, problem solving, decision-making, learning
    - Search and navigation
    - Failures and cascades, epidemics

Lecture 6,7, 8 and 18

Sociology

Lectures 12, 14, 18 and 20

Sociology, Engineering CS & OR

Lectures 12, 14, 17, 18 and 20

OR

Overview Assessment of Doyle et al

- Doyle et al introduce some additional engineering design constraints and then are able to use this insight to produce simple (toy) models that demonstrate very clearly that the mental image of a scale-free graph is totally inconsistent with real ISP's.
- They also showed that power laws do not imply a certain type of structure but could be observed with a wide variety of different topologies (or architectures/designs)
- Their approach is strengthened by the combination of an engineering approach with OR and a little bit of economics (as implicitly done by Fabricant et al and Newman and Gastner)
- Their major contribution was in advancing an outline of an approach for improved "Systems Formation and Constraints" models of Infrastructures
- The work suggests some fruitful further research.

Worldwide air transportation Network

- About 5 papers (with more on the way) have been published by Guimera et. al. concerning the global air transport system
  - A required reading for today was the most recent of these and this plus one other is the basis of the following slides
- The data (for all publications thus far):
  - Network of 3883 cities with airports studied to examine the drivers of airport utilization and the evolution of the network
  - All passenger flights from Nov. 1-Nov. 7, 2000 with 531,574 unique flight non-stop flight segments between the 3883 cities
- Guimera et. al. view the airport network as a communication (process ID) network and interpret airports as *routers* (queues that receive passengers and direct them to a new destination).

Worldwide Airport Network b

- Guimera et al in their first paper hypothesized that a star-network was optimal (at least regionally and up to a traffic limit)

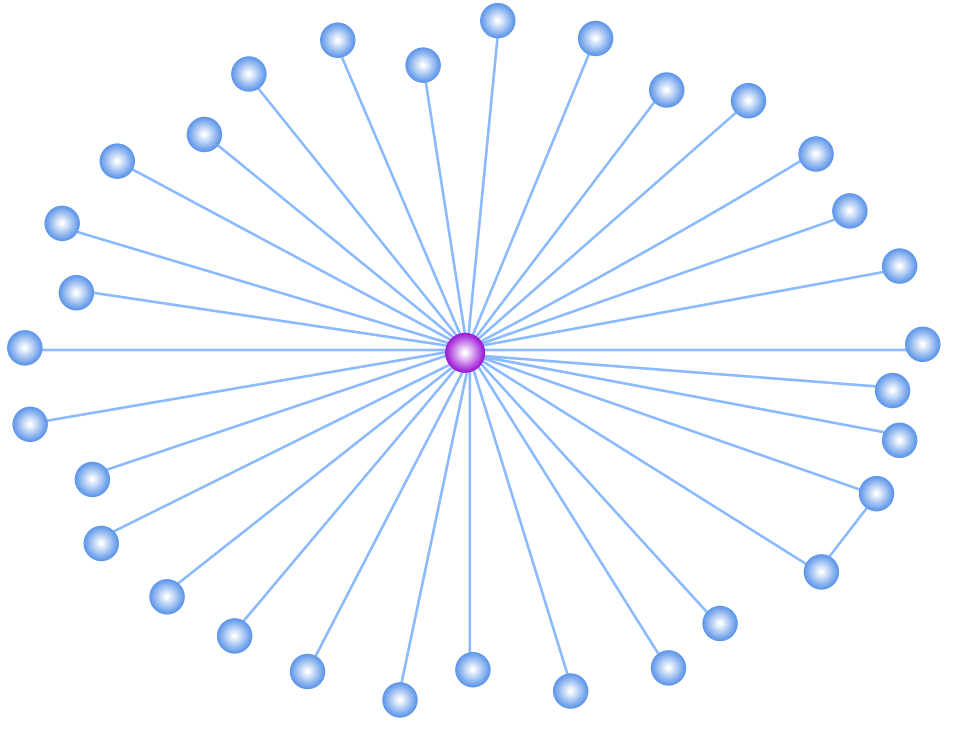


Figure by MIT OCW.

Worldwide Airport Network c

- They also argue that as flight frequency increases, the waiting times for planes and passengers (at the single hub) become unacceptably large, so the star is replaced by a partly decentralized network…

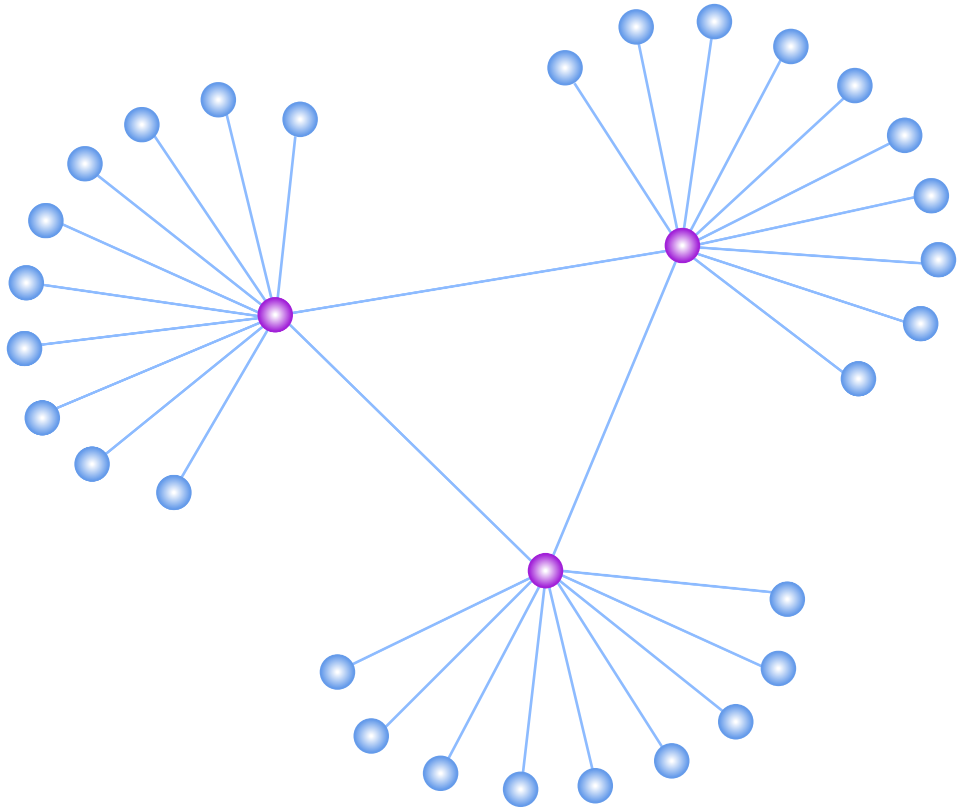


Figure by MIT OCW.

Worldwide Airport Network d

- They test whether the multiple hubs seen in the actual network evolved according to their “principles” and conclude that physical limits in router capacity **do limit** the capacity of a given airport not just saturation

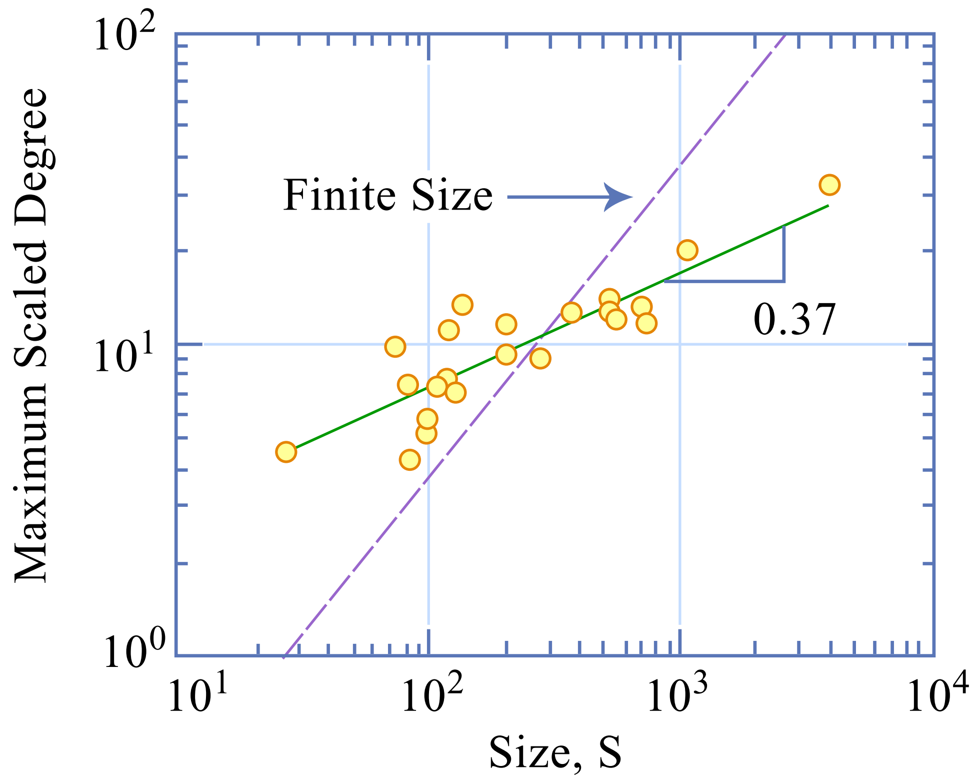


Figure by MIT OCW.

- Guimera et. al. also study betweenness centrality of all the airports and arrive at the same conclusion from this data.

Worldwide Airport Network e

- Guimera et al. (in the required reading) pursue in some depth their earlier observation
  - that the *most connected cities* would also be the *most central cities* from preferential attachment but that the real data do not show this. (*They continue to use the term scale free as equivalent to power laws which is very misleading as the origin of scale-free is clearly structural and should not -in my opinion- be simply used to describe anything showing a power law.)*
- They perform a community analysis of the worldwide airport network (following earlier definitions) but with their own simulated annealing algorithm.

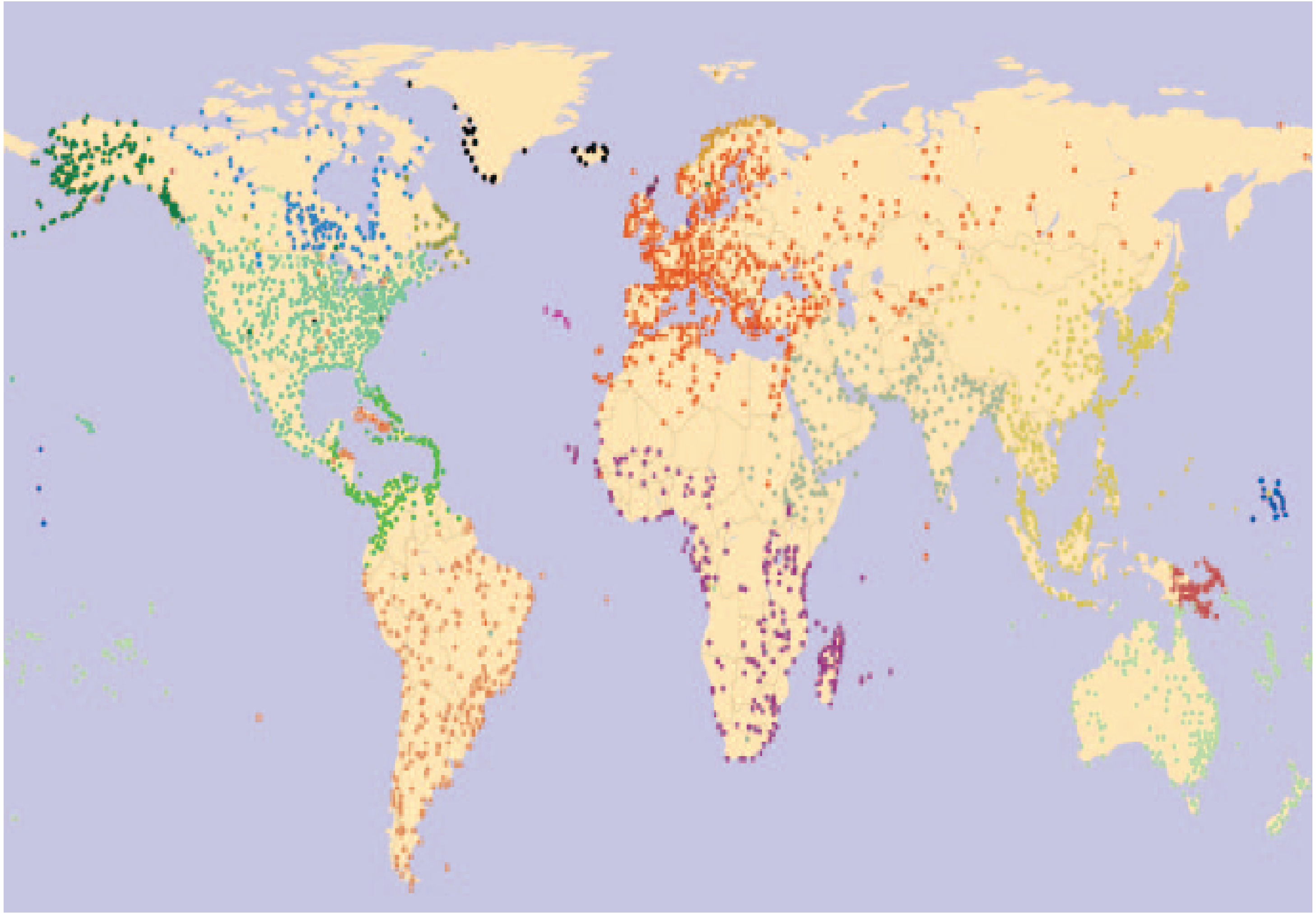


Fig. 3. Communities in the giant component of the worldwide air transportation network. Each node represents a location, and each color corresponds to a community.

Worldwide Airport Network e

- Guimera et al. (in the required reading) pursue in some depth their earlier observation
  - that the *most connected cities* would also be the *most central cities* from preferential attachment but **that the real data do not show this** (they continue to use SF term)
- They perform a community analysis of the worldwide airport network (following earlier definitions) but with their own simulated annealing algorithm.
- They invent and perform a ***node function analysis*** defining
  - Within-community degree dominance score

$$z_i = \frac{\kappa_i - \bar{\kappa}_{s_i}}{\sigma_{\kappa_{s_i}}},$$

  - Outside community participation coefficient

$$P_i = 1 - \sum_{s=1}^{N_M} \left(\frac{\kappa_{is}}{k_i} \right)^2,$$

- They calculate these for all airports

(a) Each point in the zP phase-space corresponds to a city, and different colors indicate different roles. Most cities are classified as ultra-peripheral (black) or peripheral (red) nodes. A small number of non-hub nodes play the role of connectors (green). We find approximately equal fractions of provincial (yellow) and connector (brown) hubs. (b) Same as (a) but for a randomization of the air transportation network. The absence of communities manifests itself in that most hubs become kinless hubs (gray) and in the appearance of kinless non-hubs (blue). (c) Non-hub connectors (green), provincial hubs (yellow), and connector hubs (brown) in the world-wide air transportation network.

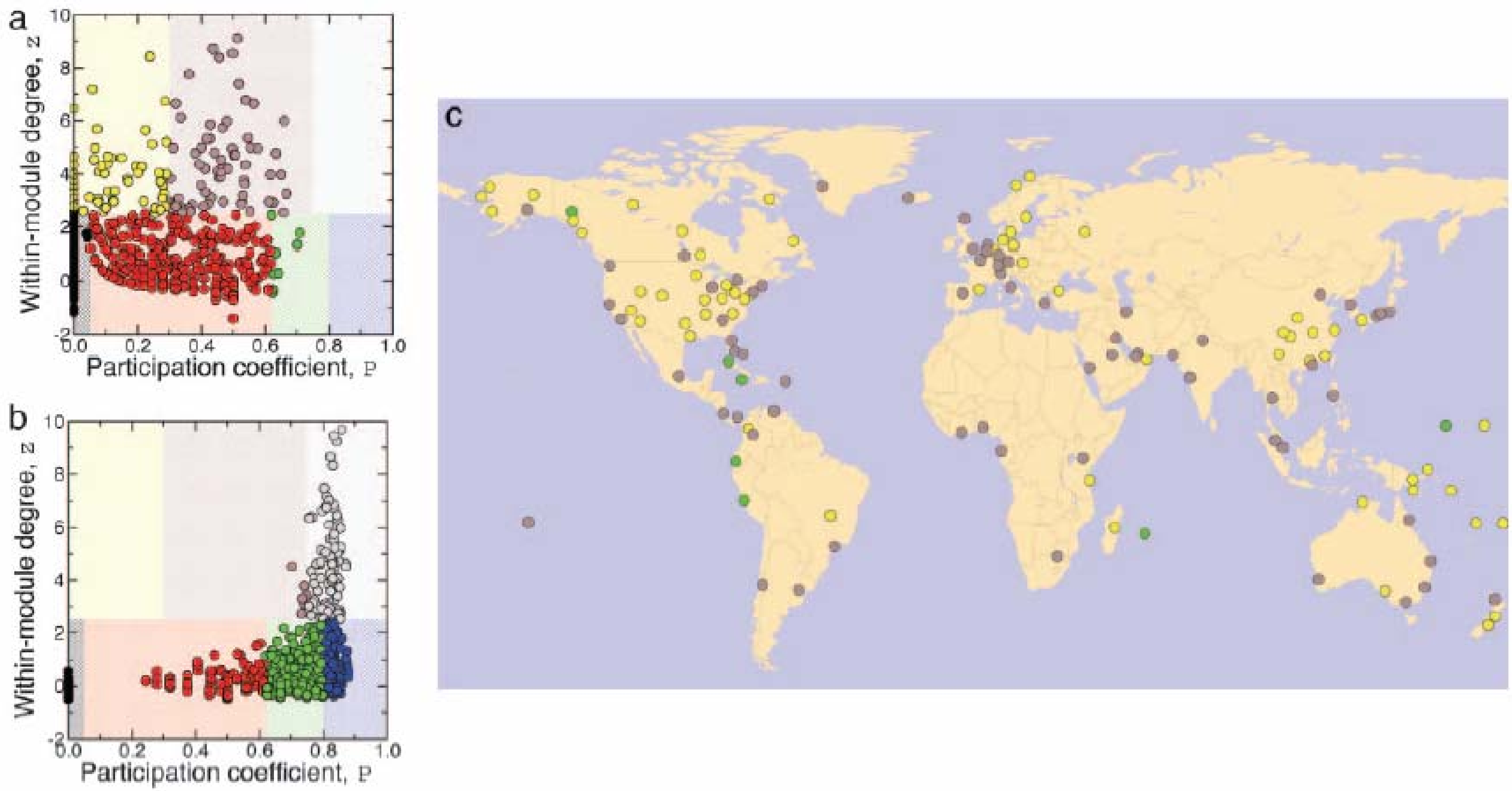


Fig. 4. Toward a scale-specific representation of the worldwide air transportation network. (*a*) Each point in the *zP* phase-space corresponds to a city, and

Overview Assessment of Guimera et al

- The basic contribution of the work is to address constraints (geographical and political) associated with formation of the air transport system.
- The basic thrust of the work (scale-free does not represent real systems) is the same as Doyle et al.
  - They arrive at their conclusion from heuristics, observation and analysis of existing and unique metrics. This is similar to Doyle et al even though they started with little (but growing) domain knowledge compared to Doyle et al.
  - They spend more of their effort on detailed observations and cycles of observe/model whereas Doyle et al spend more time strongly demonstrating the "in principle" incorrectness of some prior work.
- The work suggests some fruitful further research.

Further Work in Internet and Air Transportation based on Doyle et al and Guimera et al

- Apply airline decision rules (derived from the Internet heuristics) to air transport to derive desired macro-structure from a Airline and airport perspective
- Obtain more detailed data about node function for the Internet.
- Build a simulator and investigate how other constraints such as new customer desires for bandwidth, new router technology, wireless technology, cable vs. DSL and other issues may affect internet topology (architecture) and desired **flexibility**
- Build a simulation and investigate other constraints such as non-scheduled flights, growth of small jet traffic, airport capacity, air traffic control technology and regulations affect the evolution of air transport
- Develop set of realistic designs (design generator based on growth algorithms or ?) and investigate performance and ility trade-offs for possible next generation Internet designs and the Next Generation Air Transportation System (NGATS).

Possible Future Research and Applications of Organizational Network Models

1. Observation of Collaborative Problem Solving in Large Organizations
   - Is task decomposability observable and different in different organizations?
   - What communication paths are actually followed in problem solving of non-decomposable problems in selected J/G and US firms?

2. Observation of Hybrid Structures within organizational hierarchies
   - Identification of important characteristics that determine additional links (age, hiring group, educational institution, neighborhood, functional specialty, co-workers, etc.)
   - Possible role/utility in organizational architecture and effectiveness
   - Management rules and practices that affect these social networks including rewards and incentives

Possible Future Research and Applications of Organizational Network Models b.

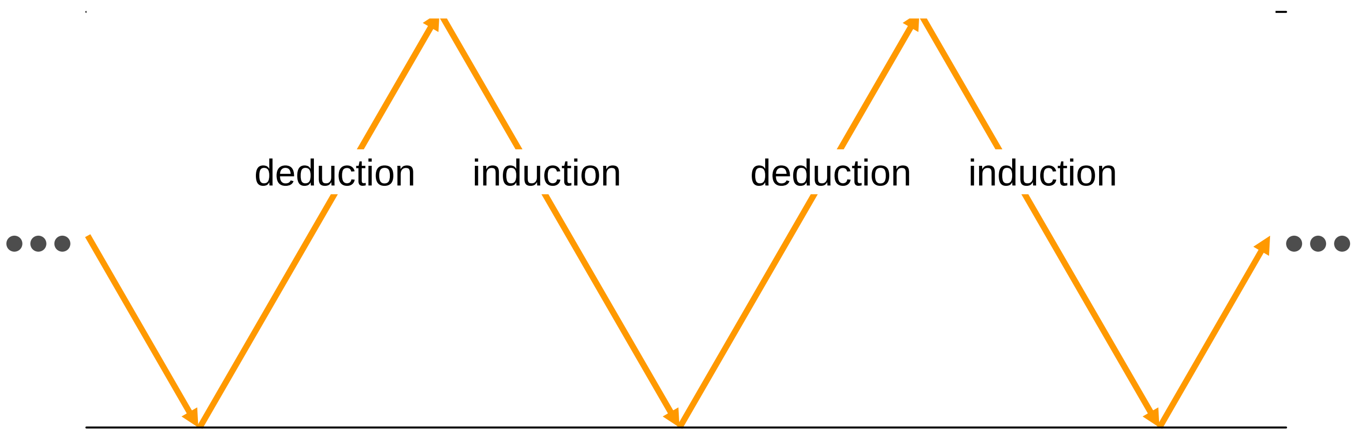
- 3. Modeling of the cost of lateral links
  - based upon effort to forge, impact on “Unity of Command” and accountability
  - Trade-offs with communication and problem-solving at different levels of task decomposability
- 4. Simulation of knowledge-capture and learning processes
  - Accountability for local and global learning
  - Observations in a variety of global and local organizations
- 5. Formal vs. informal lateral links
  - How well do “idealized” matrix organizations compare (robustness simulation) to the ideal organizational types depicted by DWS?
  - How well do specific matrix organizations compare (actual observations as the basis for simulation comparison) to the ideal organizations depicted by DWS?

Possible Future Research and Applications of Organizational Network Models c.

- 6. Observe link formation costs in various existing firms
- 7. Extend the model to simulate decision-making with different decision-making structures (Sah and Stiglitz)
- 8. Extend the model (or build a new one) to simulate **flexibility**
  - Changes in problem-solving intensity
  - Changes in task decomposability
  - Changes in knowledge needed to survive
  - Changes in leadership style needed
- 9. Extend the model to allow the communications to be between intelligent agents (use of MAS)
  - Give agents known **social cognition** patterns from cognitive psychology such as “Machiavellian intelligence”, cooperative intelligence, etc.

The Iterative Learning Process

Objectively obtained quantitative data (facts, phenomena)



hypothesis (model, theory that can be disproved)

As this process matures,
what new can the models accomplish?

The major accomplishment will be the rapid facilitation of a transition to engineering (vs. craft approaches) for the design of complex social/ technological systems

Comparative Progress in Understanding and performance: CLM objective/subjective observations

- 1940-2000 improvement
  - Small-scale electro-mechanical systems (x40-100)
  - Energy transformation systems (x 10-20)
  - Information processing systems (x 10^{12} to 10^{15})
  - Cosmology (x 30-100)
  - Paleontology (x 50)
  - Organizational theory and practice (x ***1.1 to 2***)
  - Economic systems (x ***1.1 to 2***)
  - Complex large-scale socio-technological systems (?)

Learning objectives

- Examine literature modeling efforts within architecting framework
- Understand the DWS modeling effort in a practical organizational context
- Appreciate/critique the analysis/model developed by Doyle et al for the Internet
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- Explore possible future research suggested by these results

References

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