

# Lecture 19: Advanced Models for Technological Systems

ESD. 342

April 15, 2010



Massachusetts Institute of Technology  
Engineering Systems Division



# Lecture 19 outline

---

- Internet model by Doyle et al
  - Power laws and distributions
- Air transport by Guimera et al
- Future Research suggestions
- Organizational Design issues

# 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

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

- 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 particularly 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 previously discussed that correction and 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

# 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

# Heuristic Internet Design f: Heuristically Optimal Networks

- Doyle et al define a heuristically optimal network:
- 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 17 ( 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.

# Degree Distributions- from lecture 7

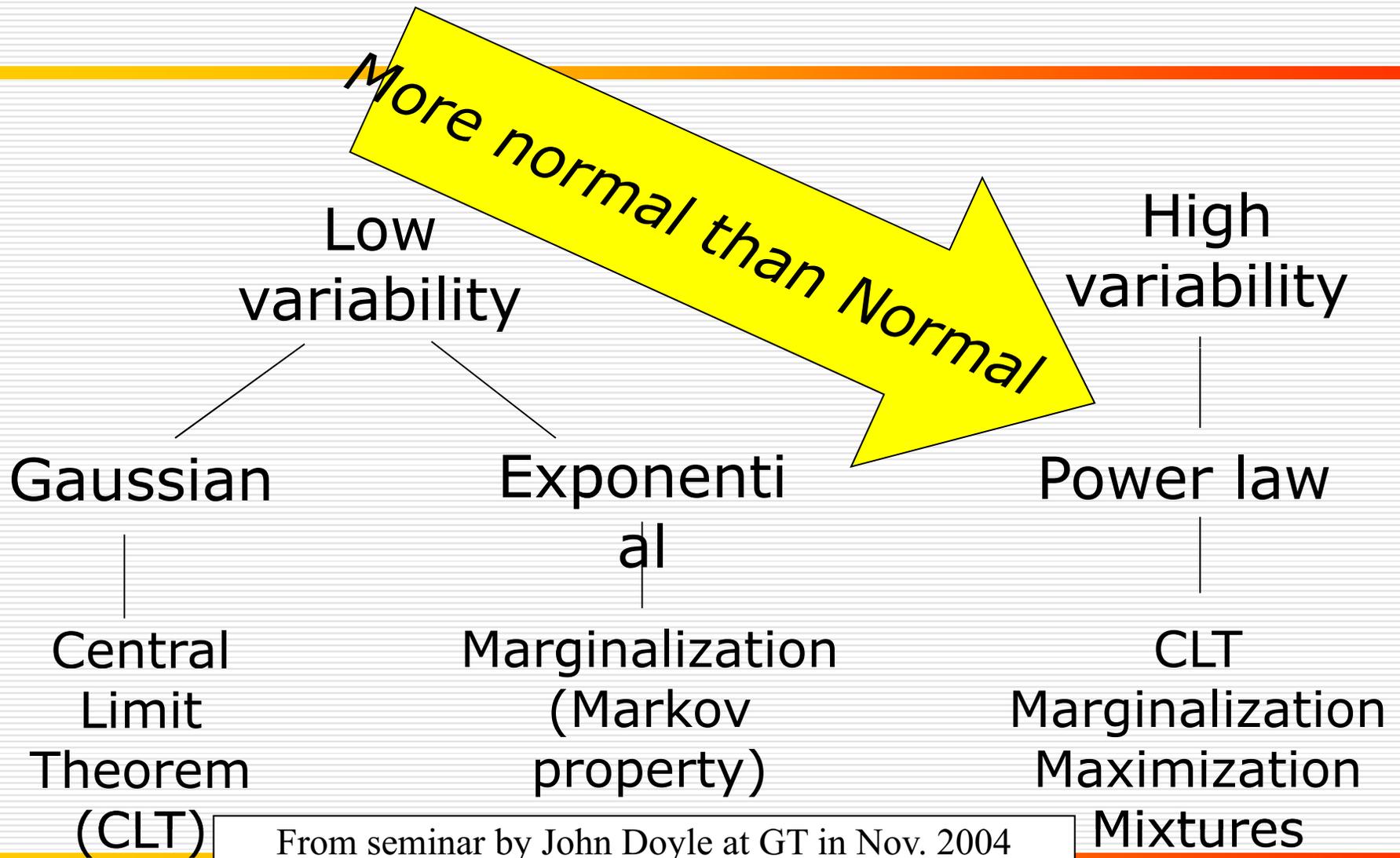
- Define  $p_k$  as the fraction of nodes in a network with degree  $k$ . This is equivalent to the probability of randomly picking a node of degree  $k$
- A plot of  $p_k$  can be formed by making a histogram of the degrees of the nodes. **This is the degree distribution of the network.**
- Histograms
  - Normal (and nearly so)
  - Skewed (and heavily skewed)
- Suggest some normal or nearly normal distributions..and some not likely to be normal

# Degree Distributions II

- Define  $p_k$  as the fraction of nodes in a network with degree  $k$ . This is equivalent to the probability of randomly picking a node of degree  $k$
- A plot of  $p_k$  can be formed by making a histogram of the degrees of the nodes. **This is the degree distribution of the network.**
- Histograms
  - Normal (and nearly so)
  - Skewed (and heavily skewed)
- Reasons for normal vs. skewed?
- Power law (skewed)
- Why power laws?

$$p_k \sim k^{-\alpha}$$

# Power laws are ubiquitous



# 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.

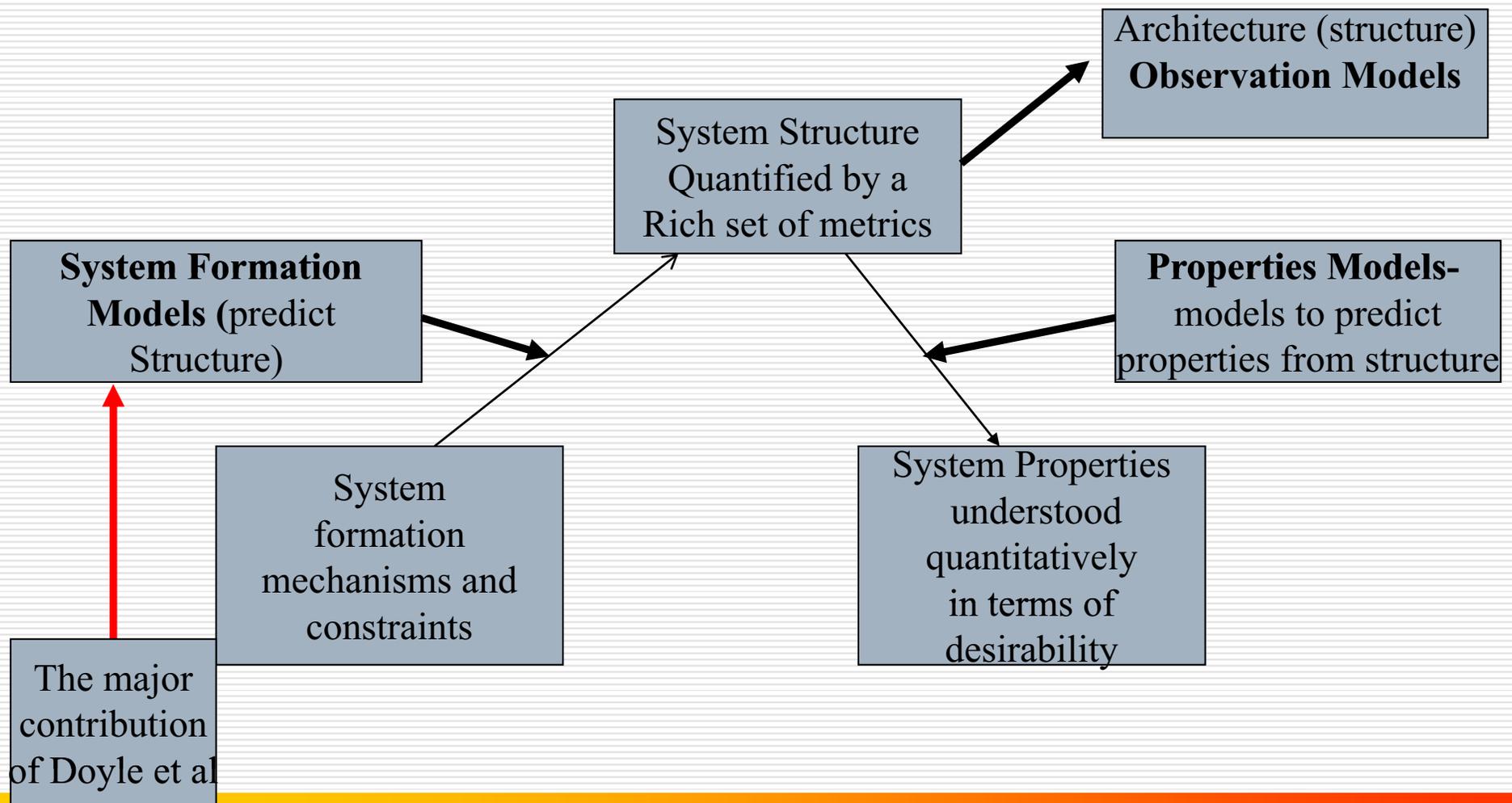
# Heuristic Internet Design g: Properties and designs evaluated

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

# 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



# 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 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 (27,051 distinct city pairs)
- 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)

# 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...



# Worldwide Airport Network

- Guimerà 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 term scale-free implies structure and should not in my opinion be simply used to describe systems following a power law.*)
- They perform a decomposition of the worldwide airport network (following earlier definitions) but with their own simulated annealing algorithm.

# 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
  - Outside community participation coefficient
- They calculate these for all airports

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

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

# 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 an 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).

# Lecture 19 outline

---

- Internet model by Doyle et al
  - Power laws and distributions
- Air transport by Guimera et al
- Future Research suggestions
- □ Introduce organizational design-background for organizational modeling in lecture 20

# (Organizational) Learning objectives

- Appreciate some *additional range* of organizational research
- Understand what organizational design entails including the possible design variables
- Examine a few simple models *related* to organizational design to understand status and possible applicability (L 20)
- Appreciate one organizational modeling approach relative to our growing understanding of the use of network models (L 20)
- Some limits to keep in mind: The emphasis is on ways of thinking/modeling- not very prescriptive about how to organize. I also do not consider the very important issue of culture dealt with by JM

# Lecture 19/20 Organizational models: Outline

- A brief historical tour of research on organizations
- The organizational design problem
  - Design variables, fundamental metrics and the bottom line
  - Processes
  - Properties
- Organizational Design/Architectural Analysis by selected, simple quantitative models and a “modeling framework”.
  - Arrow; Sah and Stiglitz
    - Simple decision-making non-network models
  - Dodds, Watts and Sabel
    - Network model incorporating hierarchy as base
    - Information transfer for problem solving
    - Robustness assessments and identification of superior structure
    - Assessment of the contribution of DWS paper
- Possible future work and Conclusions

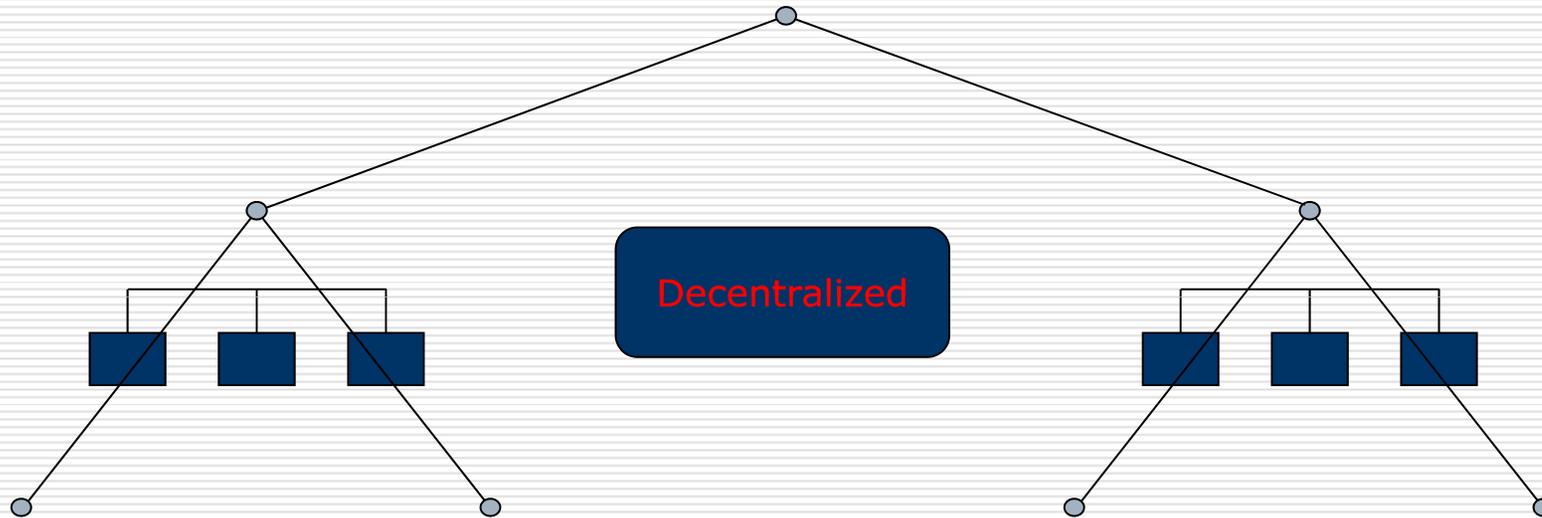
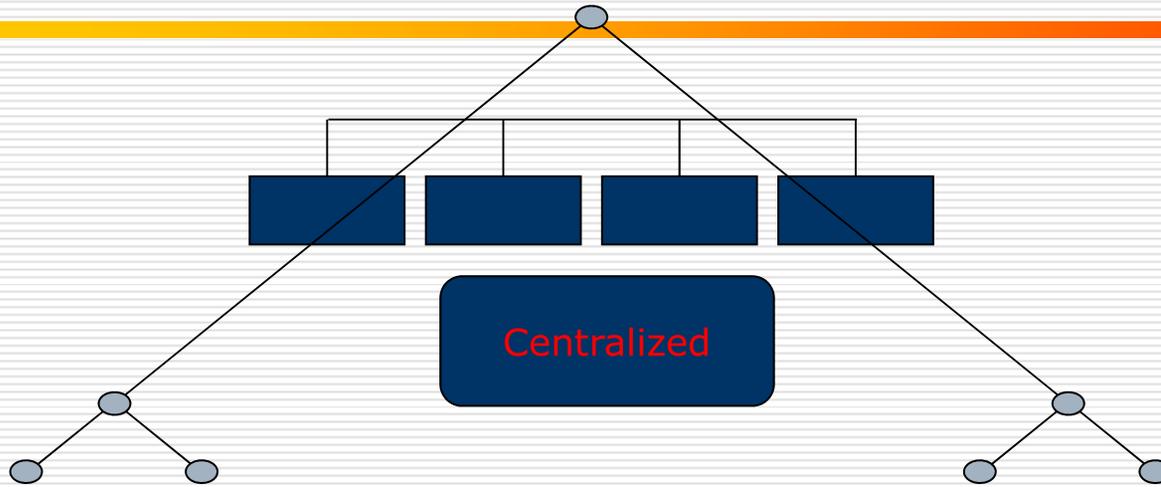
# Organizational thinking

## Theory area

## Concerns

- “Classical” Organizational Theory (1900-19xx)  
Carnegie, Taylor, *task breakdowns*, practitioners  
–Sloan; *levels and span of control, staffs*
- Efficiency, division of labor in production and in management, hierarchy, authority and motivation, power distribution, centralization

# Line-staff models of organization.



# Organizational thinking b

## Theory area

## Concerns

- “Classical” Organizational Theory (1900-19xx)  
Taylor, *task definition*;  
practitioners –Sloan;  
*levels and span of control*,  
*staffs*
- □ “Human Relations” School  
, Hawthorne effect (1930-  
1965)

- Efficiency, division of labor in production and in management, hierarchy, authority and motivation, power distribution, centralization
- *Incentives* and leadership style

# The organizational problem stated in “classical + incentives” form

- “The artificial quality of organizations, their high concern with performance, their tendency to be far more complex than natural units, all make informal control inadequate and reliance on identification with the job impossible. Most organizations most of the time cannot rely on most of their participants to internalize their obligations to carry out their assignments voluntarily, without additional incentives”

- A. Etzioni(1963, p. 59)

- Reactions??

# Organizational thinking

## Theory area

## Concerns

□ “Classical” Organizational Theory (1900-19xx)  
Taylor, practitioners – Sloan; *levels and span of control, staffs*

□ “Human Relations” School, Hawthorne effect (1930-1965)

→ □ Information flow and decision-making (1945-present), Simon, Simon and March, Arrow, Galbraith and many others

□ Efficiency, division of labor in production and in management, hierarchy, authority and motivation, power distribution, centralization

□ *Incentives* and leadership style

□ Information quality, human cognition, communication and noise, decision quality, strategies, etc.

# Organizational thinking

## Theory area

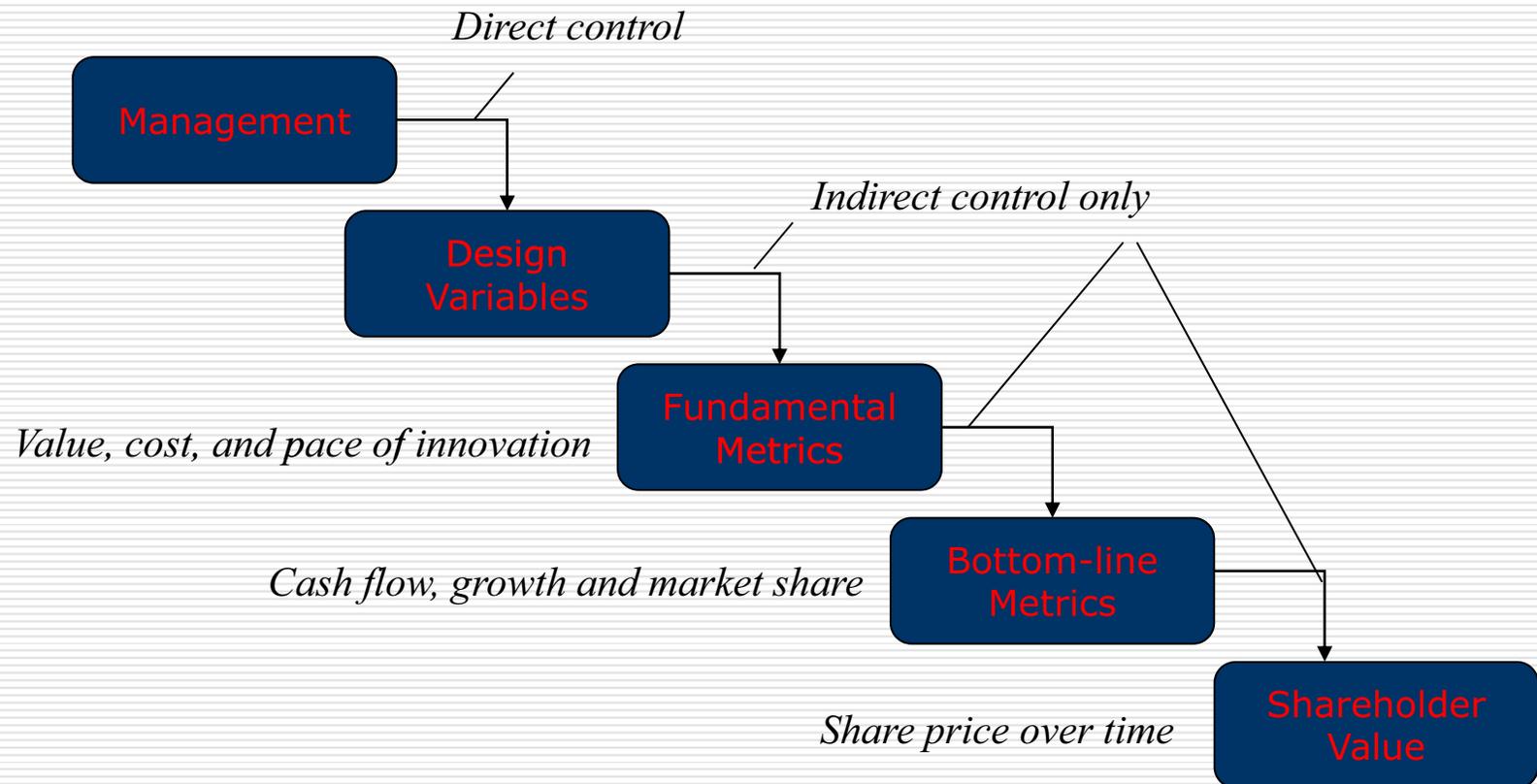
## Concerns

- “Classical” Organizational Theory (1900-19xx) Taylor, practitioners –Sloan; *levels and span of control, staffs*
  - “Human Relations” School , Hawthorne effect (1930-1965)
  - Information flow and decision-making (1945-present), Simon, Simon and March, Arrow, Galbraith and many others
  - □ **Contingency** theory (1960-present), Burns and Stalker, Lawrence and Lorsch) **people** (McGregor, Schein, Oishi), **process, culture, learning, lean**, etc. “paradigm de jour”,
- Efficiency, division of labor in production and in management, hierarchy, authority and motivation, power distribution, centralization
  - *Incentives* and leadership style
  - Information quality, human cognition, communication and noise, decision quality, strategies, etc.
  - Rate of change, reward systems, socialization and teams, structure variation within the larger structure, leadership style as a function of all else, etc.

# Function/Purposes of organizations

- ❑ Managers work for owners – to maximize owners' **long-term** satisfaction-usually =wealth
- ❑ To **satisfy** the organization's **customers**
- ❑ To satisfy other "stakeholders"
  - In order for managers and other employees to maximize their wealth (or have "good" jobs or feel respected or be part of a social community-loyalty, pride, etc.)
  - To be a good citizen
- ❑ For non-profits (&Gov't?): Managers work to **fulfill a mission-**to educate , to assure long-term survival of a worthwhile entity
- ❑ It is apparently easier to substitute some manager and employee goals in not-for-profits but the possibility of worse transgressions at the top of for-profits is still an assumption
- ❑ Does management in general design the organization in a way to **directly** affect purpose/function?

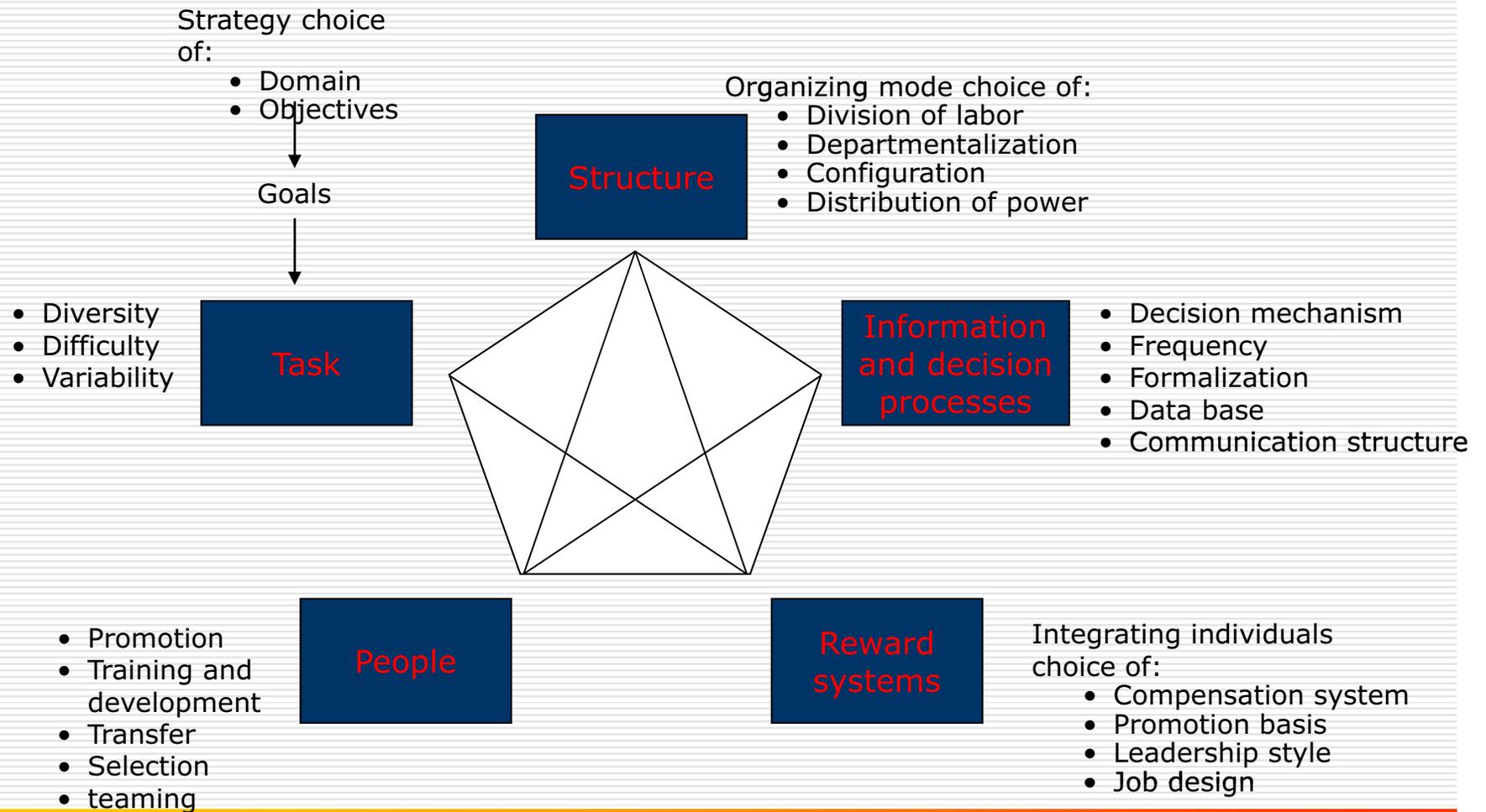
# Management is three steps from managing the bottom line directly.



# The strategic metrics are divided into fundamental and bottom-line.

Strategic Metrics	
Fundamental	Bottom Line
Value to customer	Cash flow
Cost (variable, fixed, investment)	Market share
Pace of innovation	Price
	Return on investment
	<b>Growth rate of Profit</b>
	<b>Share Price</b>

# Organization design



# Organizational or Enterprise Architecting

- ❑ Assume the previous slide lists the organizational variables, what do you think **organizational architecting** involves?
- ❑ Thus, how do we describe different **organizational architectures**?
- ❑ Mental Models-culture
- ❑ Standards and protocols such as roles of key people (middle-management)
- ❑ The hard-to-change or longest lived design variables is my preferred means of assessing which variables in a complex system are the architecture
- ❑ Those design variables with the **greatest leverage** and are hardest to change are the **essential** architecture

# Organizational Design/architecting: CLM bias

- ❑ Least effective efforts focus on boxes and lines on organizational charts
- ❑ More effective efforts focus on identifying the design variables which can most effectively improve key processes
- ❑ Most effective efforts (perhaps) will focus on identifying the key design variables which accomplish the best tradeoff among the **properties** associated with key *processes*.

# Key Organizational Processes that enable fulfilling of the Organizational Purposes

- Planning and coordinating
- Decision-making about
  - Personnel-hiring, evaluation and rewards,
  - Products, technologies, manufacturing and supply chains
  - Markets, distribution channels, locations
- Problem identifying and problem solving
- Task and process structure development for adding value
- Building capability
  - People development-education and socialization
  - Process and interaction development
  - Knowledge capture
  - Knowledge generation
- Conflict management and resolution
- Rule development and enforcement
- Communication to analysts and business reporters
- Fund-raising from donors (not-for-profit major process)

# Key Organizational Processes that enable fulfilling of the Organizational Purposes

- Planning and coordinating
- **Decision-making** about
  - Personnel-hiring, evaluation and rewards,
  - Products, technologies, manufacturing and supply chains
  - Markets, distribution channels, locations
- **Problem identifying** and **problem solving**
- Task and process structure development for adding value
- **Building capability**
  - People development-education and socialization
  - Process and interaction development
  - Knowledge capture
  - Knowledge generation
- Conflict management and resolution
- **Rule development and enforcement**
- Communication to analysts and business reporters
- Fund-raising from donors (not-for-profit major process)

# Key organizational Properties

## □ **Decision-making**

- speed and time coordination
- correctness
- efficiency (minimal resources)

## □ **Problem-recognizing and problem-solving**

- Speed
- Correctness
- efficiency

## □ **Robustness**

- To node removal (personnel turnover) and to unexpected “failures” in links
- To variability in loads due to normal environmental changes
- To major unexpected events such as fires, natural disasters

## □ **Flexibility**

- For significant competitive thrusts
- For change in methods and products
- For need for new skills and knowledge

# Modeling Organizational issues

After this introduction about organizational design, several aspects of modeling that relate to **organizational structure** (or architecture) are now briefly explored:

- **Decision Theory**
  
- **Communication**
  
- Note that both of these are properties models and do not discuss or try to look at models for formation or evolution of actual organizational structure or the development of rules, etc.

# References- advanced infrastructure

- R. Guimera and L.A. N. Amaral, "Modeling the Worldwide Airport Network", *Eur. Phys. J. B*, 38 pp 381-385 (2004)
- R. Guimera, S. Mossa, A. Turtschi and L. A. N. Amaral, "The Worldwide air transportation network: Anamalous centrality, community structure and cities' global roles." *PNAS*, 2005
- A. Fabrikant, E. Koutsoupias, and C. H. Papadimitriou, "Heuristically optimized trade-offs: A new paradigm for Power Laws in the Internet, in *Proceedings of the International Colloquium on Automata, Languages and Programming*, vol 2380 ;in *lecture notes in Computer Science*,pp110-112, 2002
- L. Li, D. Alderson, J. Doyle and W. Willinger, "Towards a Theory of Scale-Free Graphs: Definitions, Properties and Implications", *Journal of Internet Mathematics*, 2006
- J. C. Doyle, D. L. Anderson, L. Li, S. Low, M. Roughan, S. Shalunov, R. Tanaka and W. Willinger, "The "robust but fragile" nature of the Internet", *PNAS*, 2005



MIT OpenCourseWare  
<http://ocw.mit.edu>

ESD.342 Network Representations of Complex Engineering Systems  
Spring 2010

For information about citing these materials or our Terms of Use, visit: <http://ocw.mit.edu/terms>.