Survival Guide to the Future

"Role of Scaling in Developing an Understanding of How Systems Work"

Dr. Norman L. Johnson

norman@santafe.edu
http://CollectiveScience.com

How “*SFI-ish*” is your System?

Local ⟷	Global
Distributed ⟷	Centralized
Diverse ⟷	Uniform
Synergistic ⟷	Selective
Noise ⟷	Structure
Robust ⟷	Fragile
Dynamic ⟷	Static
Scale-free ⟷	Clustered
Emergent ⟷	Top-down

Qualities to consider in the above measures

- Dimensionality (spatially, functionally)
- Connectivity – Access to information
- Governing equations / Rules
- Fitness function, quality/performance measures
- Scalability

Power Laws and Complexity: Not without some controversy

“Over the last decade or so, it has become reasonably common to see people (**especially physicists**) claiming that some system or other is complex, because it exhibits a power law distribution of event sizes. Despite its popularity, this is simply a fallacy. No one has demonstrated any relation between power laws and any kind of formal complexity measure. Nor is there any link tying power laws to our intuitive idea of complex systems as ones with strongly interdependent parts.”

In “METHODS AND TECHNIQUES OFCOMPLEX SYSTEMS SCIENCE: AN OVERVIEW” by Cosma Shalizi

My Background

Polymer physics

Star Wars

Novel fusion device

Combustion modeling

Hydrogen Fuel Program

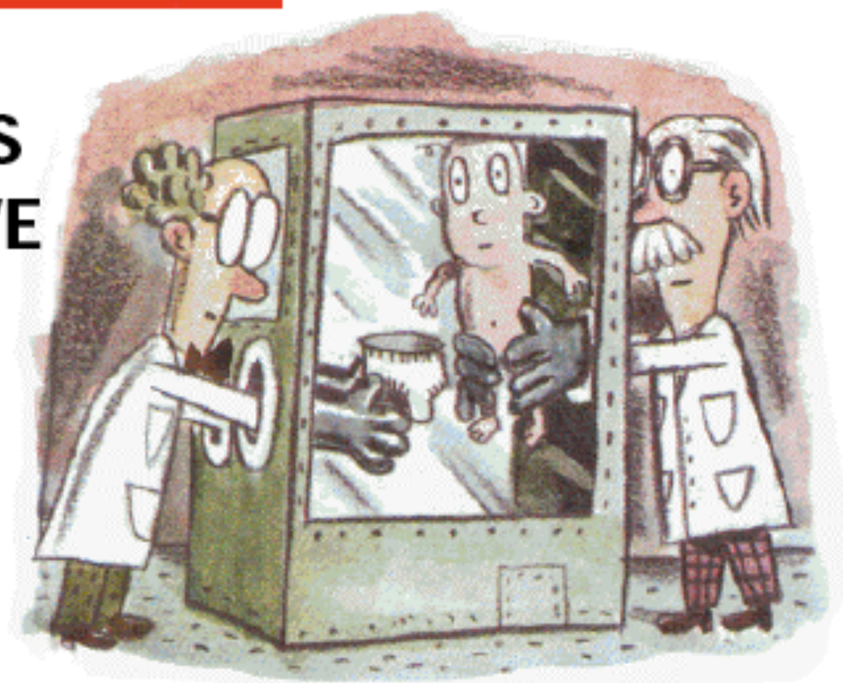
P&G multi-phase flows

P&G Application Area?

Up Front

GONE FISSION

DR. SPOCK MEETS DR. STRANGELOVE



BUSINESS WEEK / July 10, 2000

My Background

Polymer physics

Star Wars

Novel fusion device

Combustion modeling

Hydrogen Fuel Program

P&G multi-phase flows

Biological threat reduction & homeland security

Bird Flu - Mitigation development

My Real Background

Polymer physics

Star Wars

Novel fusion device

Combustion modeling

Hydrogen Fuel Program

P&G multi-phase flows

Biological threat reduction & homeland security

Bird Flu - Mitigation development

Future of the internet

Self-organizing collectives

Diversity and emergent problem solving
- Finance applications

Developmental view of evolution
- Finance applications

Failure of Experts

Effects of rapid change on collectives
- Finance applications

Identity formation and interaction
- Psycho-social simulation models
- Coexistence applications

Challenges Facing Business

Increased 'complexity' (too vague)

Change happening faster and faster

Data-Poor to Data-Rich environment

"Fall of the House of Experts"

Globalization - connected markets

Technology surprise / reset

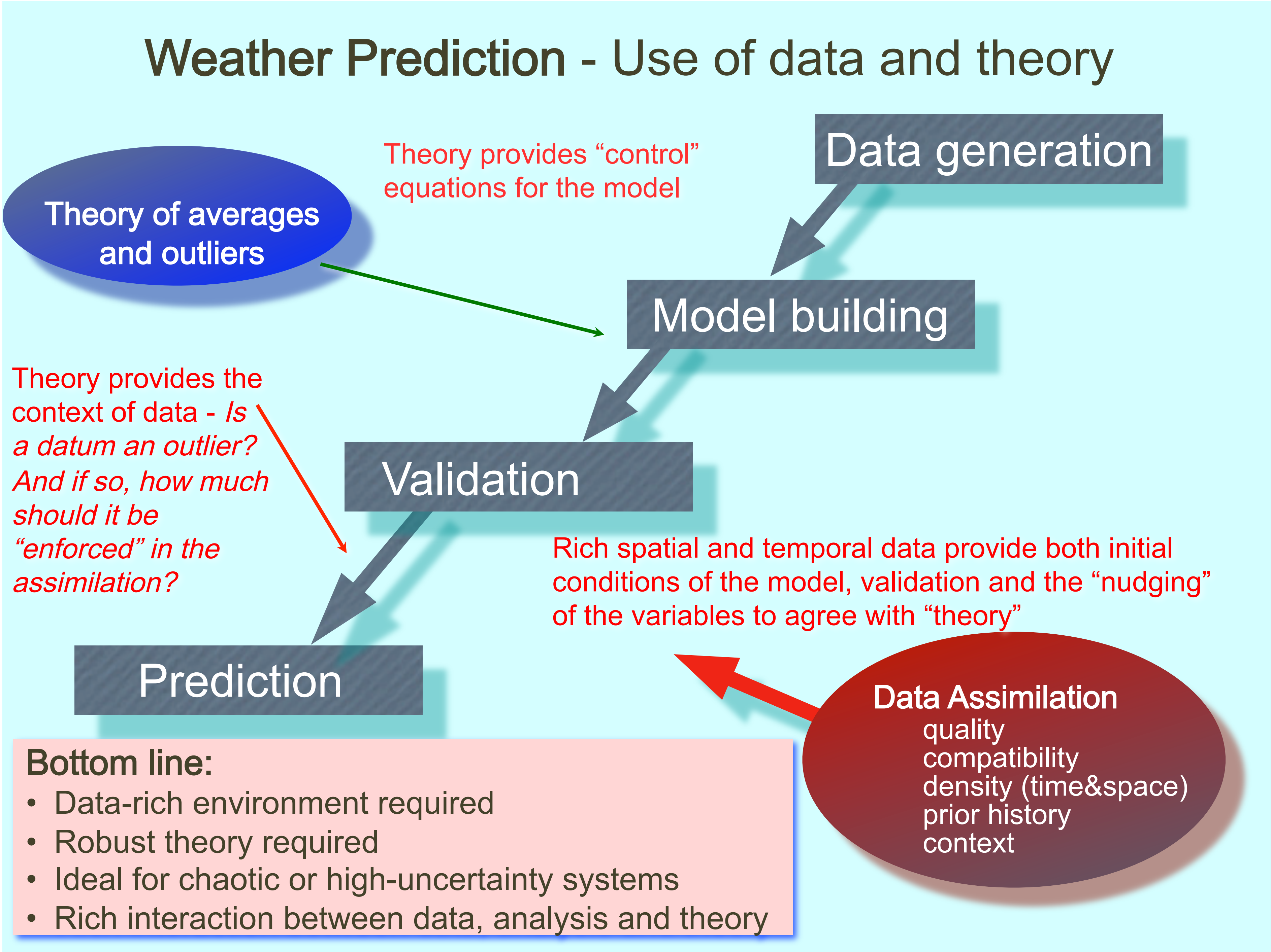
??

Opportunities Facing Business

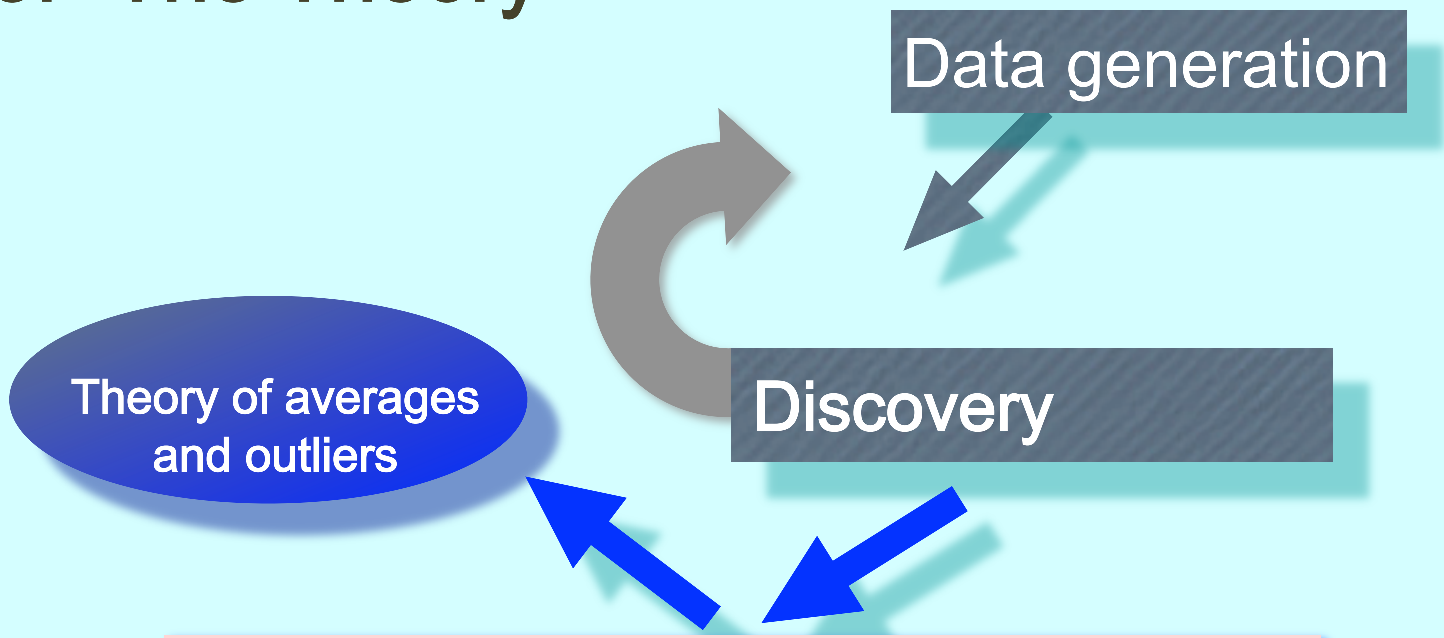
Increased 'complexity'	Success for adaptive businesses
Faster Change	"Creative destruction"
Data-Rich environment	Data-driven solutions
"Fall of the House of Experts"	Collective solutions
Globalization - connected markets	Expanding markets
Technology surprise	Large payoffs

Above opportunities are not just additive

All required understanding changing data, context, & knowledge


Weather Prediction - Use of data and theory
Theory provides "control" equations for the model
Data generation
Theory of averages and outliers
Model building
Theory provides the context of data - *Is a datum an outlier? And if so, how much should it be "enforced" in the assimilation?*
Validation
Rich spatial and temporal data provide both initial conditions of the model, validation and the "nudging" of the variables to agree with "theory"
Prediction
Data Assimilation
quality
compatibility
density (time&space)
prior history
context
Bottom line:
• Data-rich environment required
• Robust theory required
• Ideal for chaotic or high-uncertainty systems
• Rich interaction between data, analysis and theory

Origin of “The Theory”



Increasing levels of discovery:

- Statistical characterization
- Dimensionless functionality (correlations)
- Scaling - self-similarity
- Descriptive “Laws”
- Functional relationships
    - Static
    - Dynamic (governing equations of change)
- Higher moments (variation within)
- Error generation

Drucker's *Age of Discontinuity (1968)*

Method: Observe trends and predict changes, not details

- New Global information economy - Knowledge is new capital
  - New technologies create new technologies
  - High mobility of men, capital, and ideas
- New pluralism (diversity)
  - Will make obsolete old theories of economy, government and society
- New structure based on social responsibility and accountability

Drucker's prediction of globalization and faster change was 28 years ago, in the time of greatest IT change.

The context in 1968

"In fact, IBM currently is selling 100s of computers a month."

Power Laws and Complexity (con't)

"… it has been known for half a century that there are many, many ways of generating power laws, just as there are many mechanisms which can produce Poisson distributions, or Gaussians.

"Perhaps the simplest one is that recently demonstrated by Reed and Hughes, namely exponential growth coupled with random observation times.

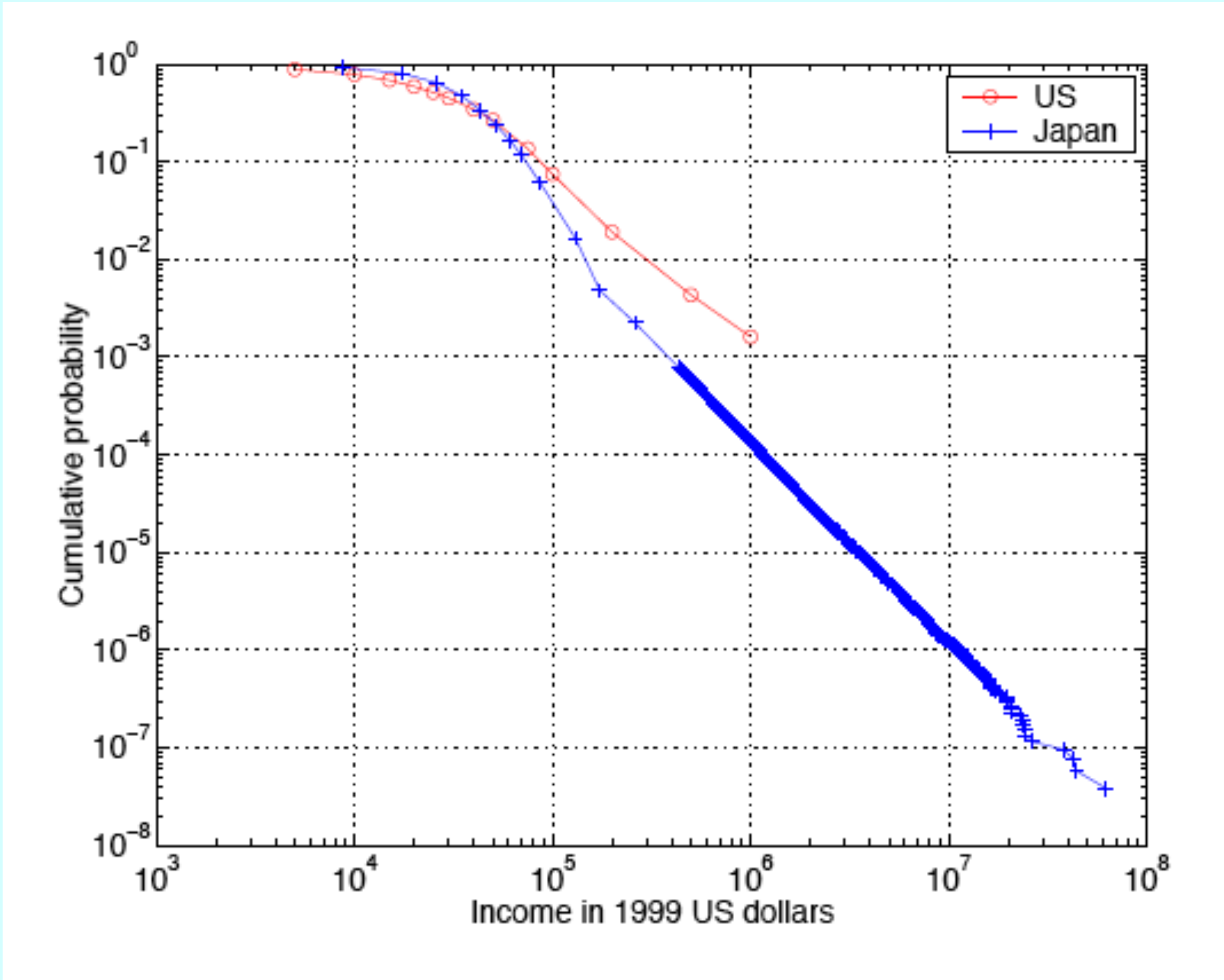
"The observation of power laws alone thus says nothing about complexity (except in thermodynamic equilibrium), and certainly is not a reliable sign of some specific favored mechanism, such as self-organized criticality or highly-optimized tolerance."

In "METHODS AND TECHNIQUES OFCOMPLEX SYSTEMS SCIENCE: AN OVERVIEW" by Cosma Shalizi, Center for the Study of Complex Systems, University of Michigan, Ann Arbor

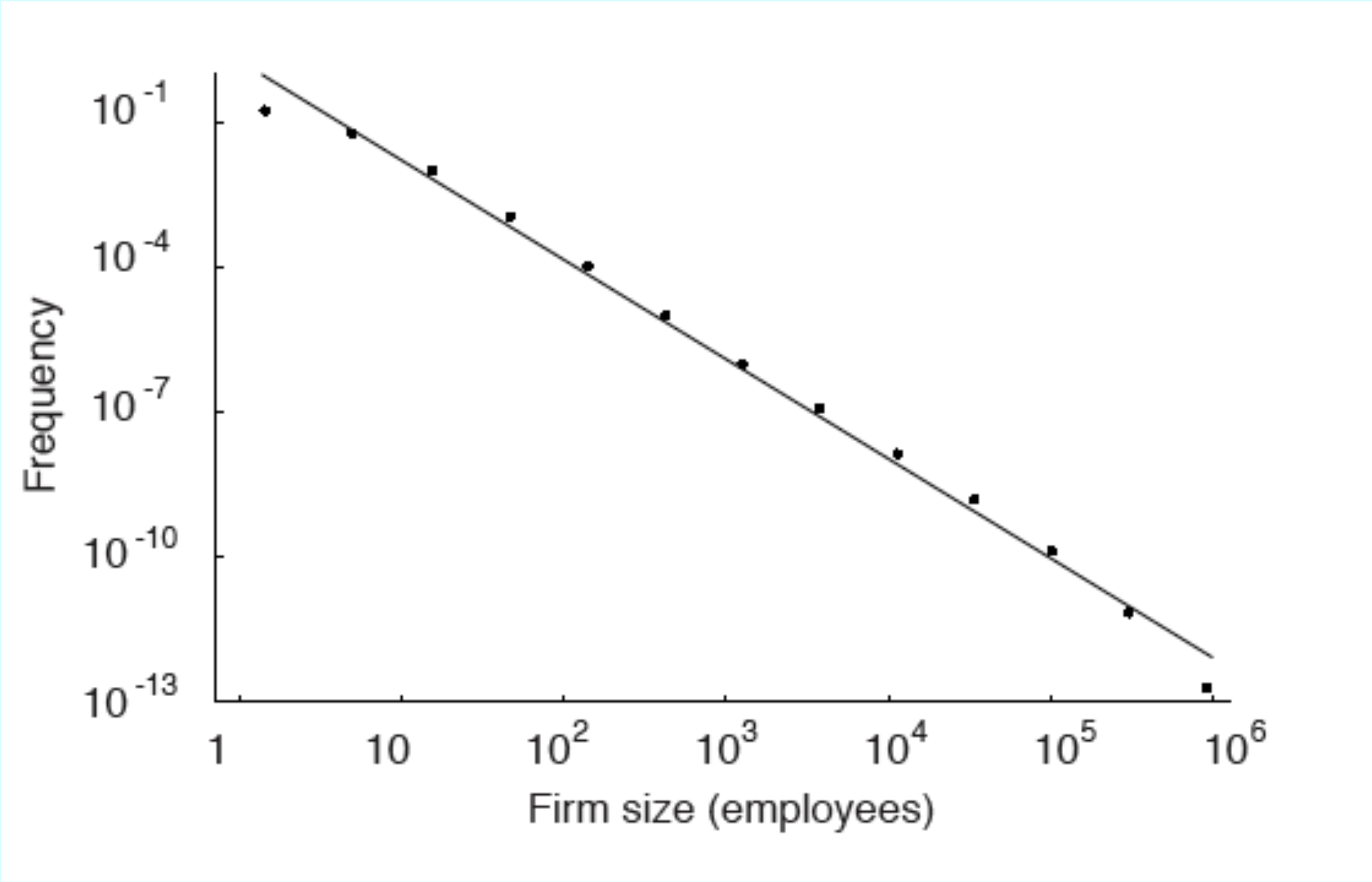
Importance of Power Laws - Farmer

"Scale free behavior has important scientific implications because it strongly suggests that the same mechanism is at work across a range of different scales."

Income distribution in US and Japan



US Firm Size by Employees



Why care about distributions?

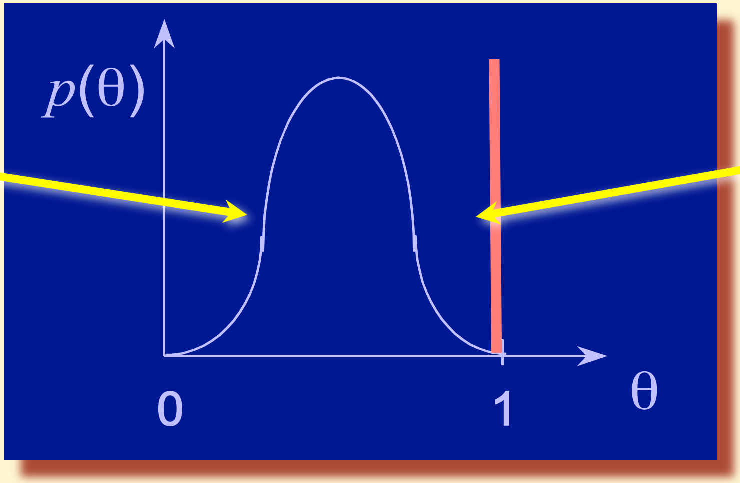
One approach to prediction is a dynamical theory, e.g., non-equilibrium statistical mechanics

Analytical forms of dynamical theories require "nice" distributions for probability distribution functions (PDFs)

PDFs map variables into observables

Nice distributions

Gaussian distribution



"Delta" or point distribution

Los Alamos

Probability Distributions (ref. Farmer)

Normal (Gaussian) distribution

$$P(x) \sim \exp(-\frac{x^2}{2\sigma^2}).$$

Defined on (−∞, ∞)

Natural explanation: Central limit theorem: Sum of many random variables (second moment finite).

Many applications: Maxwell: velocity distribution of particles in a gas
Heights of individuals, IQ, ...

Distribution is thin tailed: No one is 10 feet tall

Probability Distributions (ref. Farmer)

Normal (Gaussian) distribution

$$P(x) \sim \exp(-\frac{x^2}{2\sigma^2}).$$

Defined on (−∞, ∞)

Natural explanation: Central limit theorem: Sum of many random variables (second moment finite).

Many applications: Maxwell: velocity distribution of particles in a gas Heights of individuals, IQ, ...

Distribution is thin tailed: No one is 10 feet tall

Probability Distributions (ref. Farmer)

Exponential distribution

$$P(x) \sim \exp(-x/x_0)$$

Defined on [0, ∞)

Natural explanation (1): Survival times for constant probability of decay

Natural explanation (2): Equilibrium statistical mechanics
(Maximum entropy subject to constraint on mean)

Many applications: Radioactive decay, Energy distribution at equilibrium, ...

Distribution is also thin tailed: characteristic scale x_0.

Probability Distributions (ref. Farmer)

Power law

$$P(x) \sim x^{-\alpha}$$

Defined on [a, ∞). α, a > 0.

Natural explanation?

Distribution is heavy tailed, no characteristic scale.

Many applications –
is there a common link?

A power law is a linear relation between logarithms

$$\begin{aligned} f(x) &= Kx^{-\alpha} \\ \log f(x) &= -\alpha \log x + \log K \end{aligned}$$

Difference between Thin and Thick Tailed distributions

Similar for frequent events

1/1000 event is twice as large for a power law

1/10,000 event is three and a half times as large

“The probability of observing a fluctuation of 21% (the size of the famous negative S&P return on October 19, 1987) under the normal hypothesis is less than 10^{-16}, whereas the probability under the power law distribution is 0.08%. Under the normal distribution it is essentially impossible that this event could ever have occurred, whereas under a power law distribution such an event is to be expected.” - Farmer

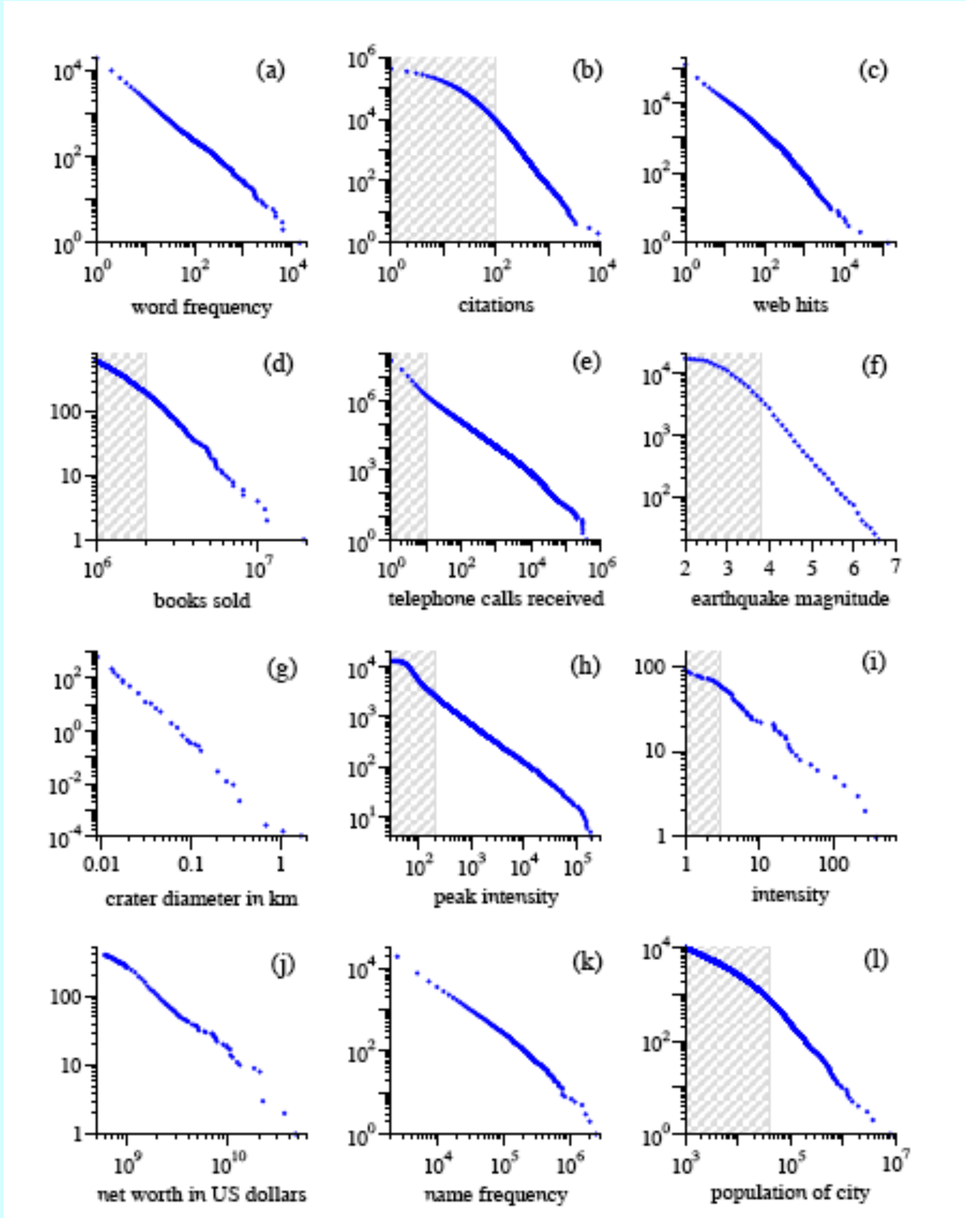
Many Examples of Power-Law Distributions

Frequency vs. measure

- earthquakes
- flood levels
- rainfall
- craters
- insurance claims
- income
- price changes
- firm size
- transaction volume
- price for order placement
- city size
- intensity of wars
- length of strikes
- DoD cost overruns
- frequency of word usage
- name frequency
- authored papers citations to papers
- patent profitability
- music sales
- movie sales
- book sales
- telephone calls
- number of email messages
- size of computer files
- hits on web page
- links to web sites

Many Examples of Power-Law Distributions

Frequency
vs.
measure



What's Special about Power Laws

Power laws are scale invariant

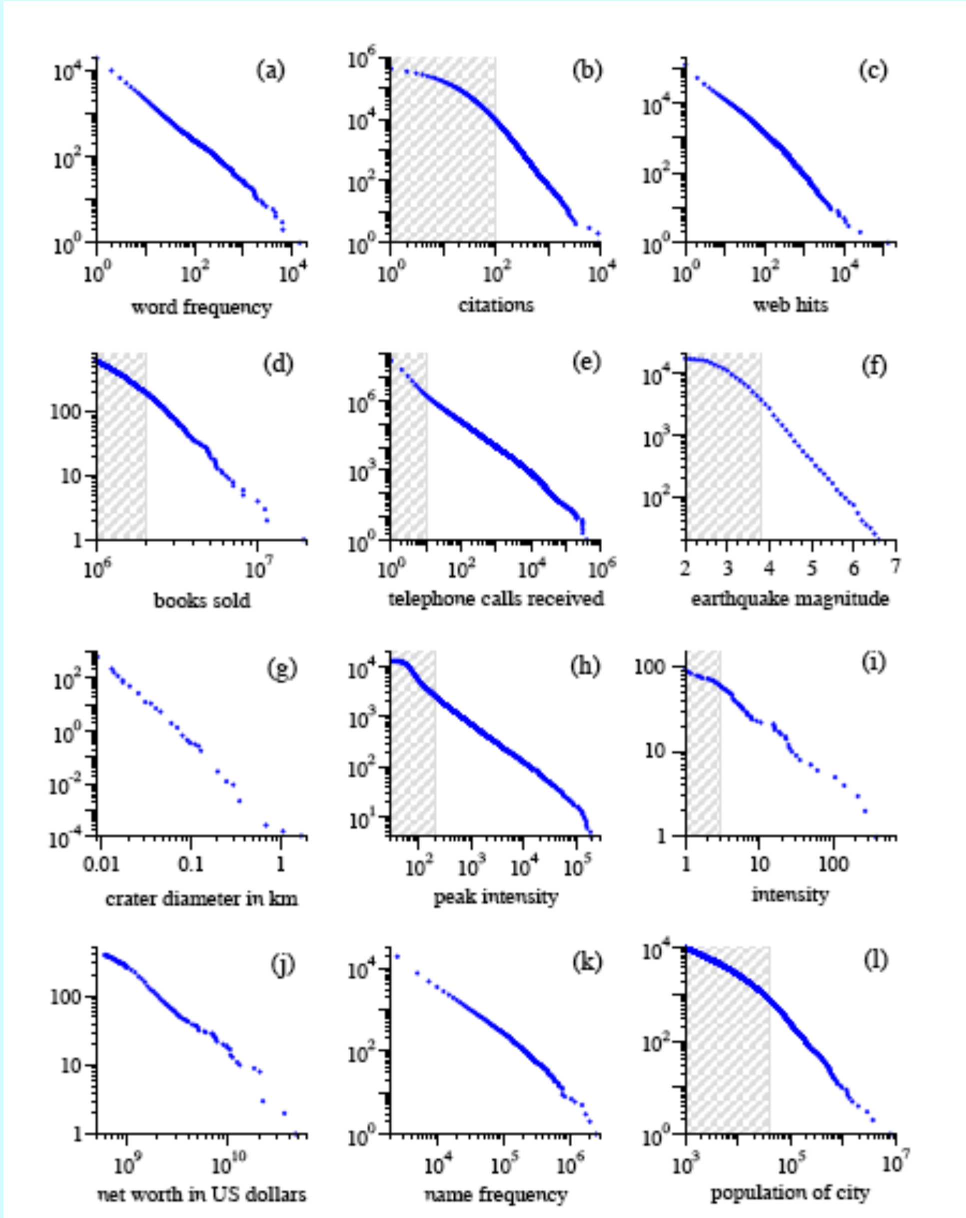
- Retains functional form under scaling

Power law is an asymptotic relation

- Only meaning full in a bounded region
- Practically, real problems always have cut-offs

Unshaded region - Asymptotic

Frequency
vs.
measure



What's Special about Power Laws

Power laws are scale invariant

- Retains functional form under scaling

Power law is an asymptotic relation

- Only meaning full in a bounded region
- Practically, real problems always have cut-offs

Power laws have a threshold above which moments don't exist

- For this reason there is no such thing as an "average flood" - it is only possible to measure flood likelihoods in terms of quantiles, as in the statement "this is a 100 year flood". (Farmer)

Combinations (aggregations) of power laws remain a power law

Any "reasonable" function with moments that don't exist, i.e. "truly heavy tails", is a power law

Power Laws vs. **Long-Memory**

Difficult to determine whether power laws or long-memory are present by empirical sampling

Tails by definition only have a small number of events. May not have enough data to probe tails.

Can have slow convergence to tail (slowly varying functions)

Can have cutoffs of tail due to finite size effects (e.g. physical limits)

Thin tailed distributions may mimic power law behavior over a wide range

Statistical convergence for long-memory processes is very slow

Importance of Power Laws - Farmer

"Scale free behavior has important scientific implications because it strongly suggests that the same mechanism is at work across a range of different scales."

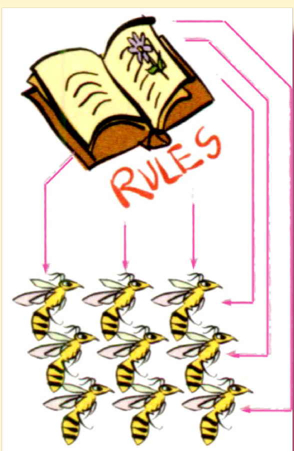
"The real test is whether power laws can improve our predictive or explanatory power by leading to better models. Self-similarity is such a strong constraint that, even if only an approximation over a finite range, it is an important clue about mechanism."

"Ultimately, the best method to demonstrate that power laws are applicable is to construct theories that also have more detailed testable predictions."

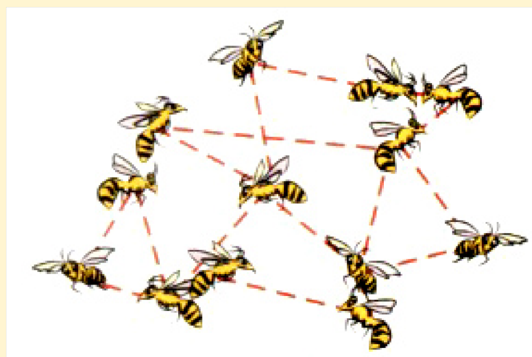
Diversity and Collective Prediction

Prediction of *collective* behavior is generally easier at extremes of diversity or variation

Locally and Globally Predictable



Unpredictable



Globally Predictable

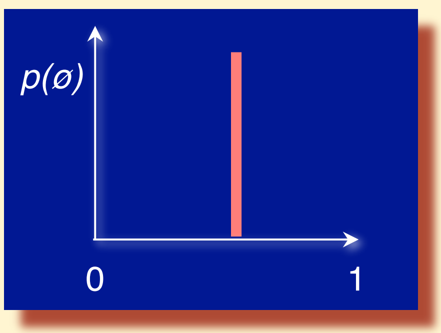
Low Diversity ⟷ **High Diversity**

Los Alamos

Diversity and Collective Prediction

How does this translate to distribution functions?

Locally and Globally Predictable



Unpredictable

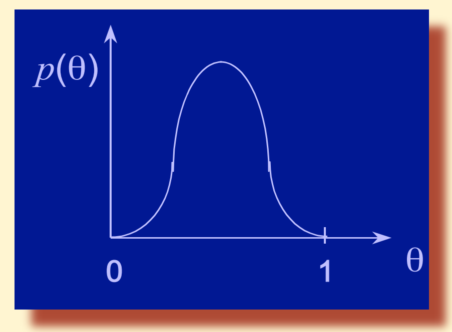
Problem distributions:

- Discrete distributions
- Multi-modal distributions
- Long-tailed distributions

(e.g., power law,

instead of Gaussian statistics)

Globally Predictable



Low Diversity ⟷ **High Diversity**

Los Alamos

Mechanisms for Generating Power Laws

Critical points and deterministic dynamics

Random processes

Sampling from (terminated) exponential growth (Reed and Hughes)

Mixtures

Dimensional constraints

Maximization principles

Preferential attachment

Non-equilibrium statistical mechanics

Causes of Anomalous Distributions

Incomplete sampling

- Habitual behavior

Non-equilibrium dynamics

- Co-evolving systems - markets

"Structures" limit options

- Regulations, cultures, …

Boundary effects dominate

- Behavior at borders

Coupling or interdependence of different levels

- Hierarchical organizations

Clustering or localized regions of interaction

- Typical of social, information and power networks

Statistical Issues Relating to Power Laws
"some common mistakes"

Parameter Estimation

Use linear regression to find the line of best fit to the points on the log-log plot. But the line minimizing the sum of squared errors is not a valid probability distribution, and so this is simply not a reliable way to estimate the distribution.

Error Estimation

Estimate of the standard error in the estimated slope and report this as the uncertainty in the power law. "This is an entirely unacceptable procedure." On a log-log plot this violates the assumption that measured values have Gaussian fluctuations around their true means.

Validation

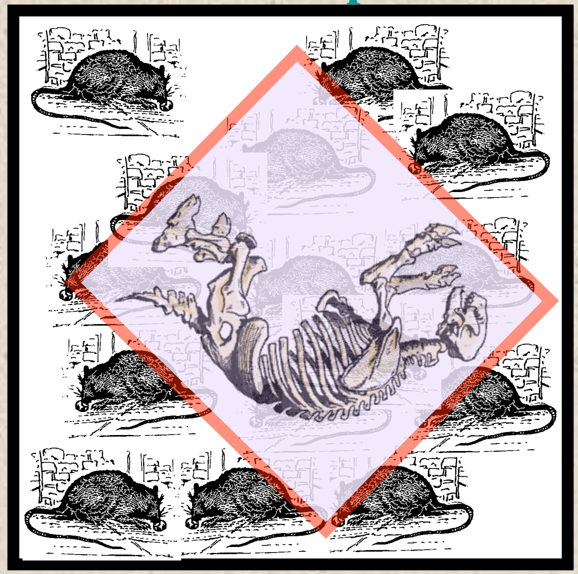
"The basic problem here is that any smooth curve looks like a straight line, if you confine your attention to a sufficiently small region and for some non-power-law distributions, such sufficiently smallŦ regions can extend over multiple orders of magnitude.

In "METHODS AND TECHNIQUES OFCOMPLEX SYSTEMS SCIENCE: AN OVERVIEW" by Cosma Shalizi

Rat Studies of Maximum Carrying Capacity

Cooperative social structure

Control - no imposed social structure

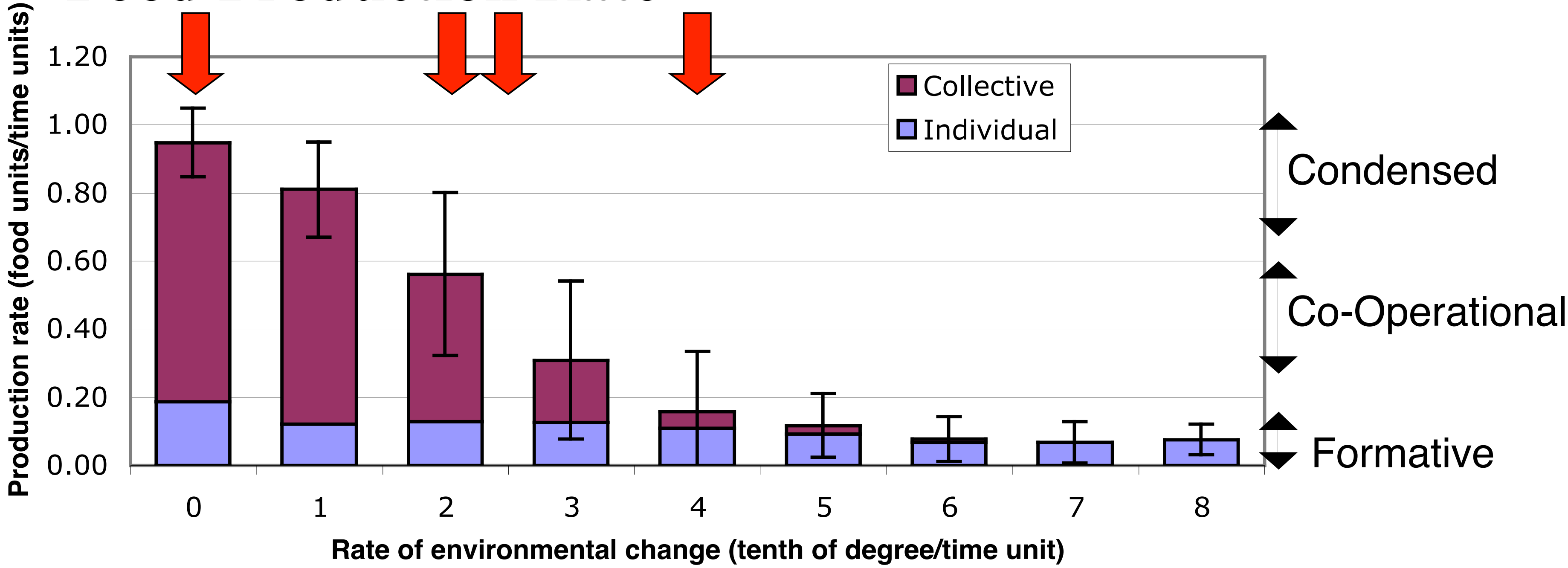


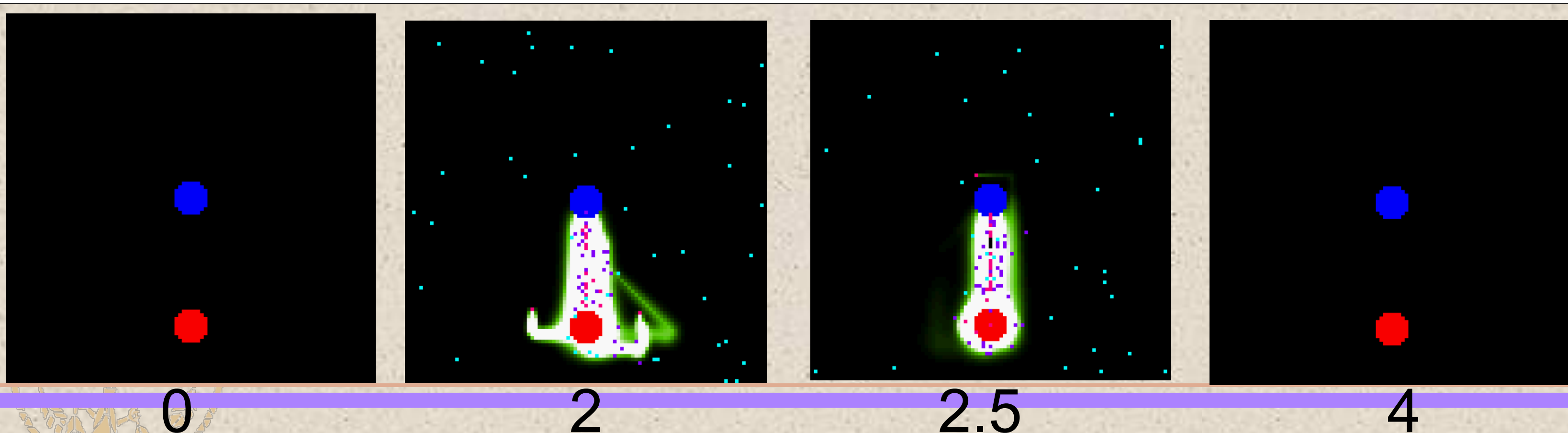
NIMH psychologist John B. Calhoun, 1971

Both systems loaded to 2 1/2 times the optimal capacity.

Social order system can carry 8 times the optimal capacity.

Food Production Rate





Collective Response to Rates of Change

Stages in Development	Unimpeded development	Innovators are essential	Collective actions lead to inefficiencies	Potential system-wide failure
Condensed (optimization of collective)				
Co-Operational (synergism from individuals)				
Formative (creation of individual features)				
Featureless				
	Stable "no change"	Change slower than collective response	Change faster than collective response	Change faster than individual response

Rate of Change

On Constructing Theories (Models) and Testing

1. **Replication is essential.**

2. **It is a good idea to share not just data but programs.**

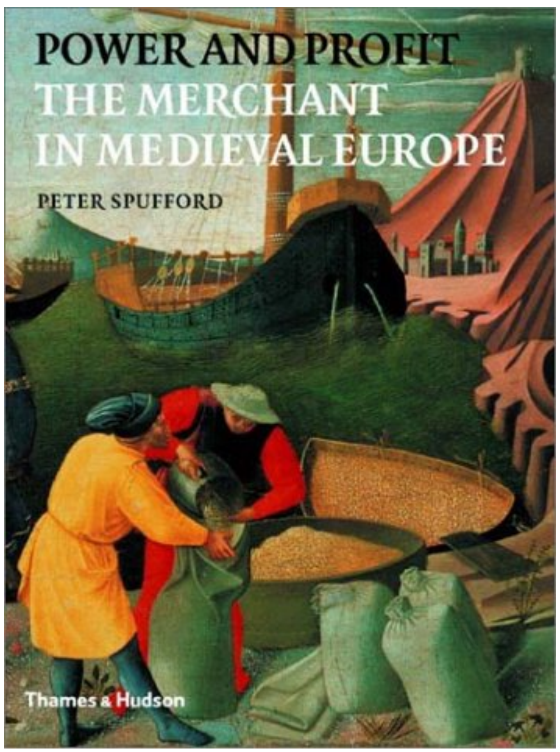
3. **Always test the robustness of your model to changes in its parameters. (This is fairly common.)**

4. **Always test your model for robustness to small changes in qualitative assumptions. If your model calls for a given effect, there are usually several mechanisms which could accomplish it. If it does not matter which mechanism you actually use, the result is that much more robust. Conversely, if it does matter, the over-all adequacy of the model can be tested by checking whether that mechanism is actually present in the system. Altogether too few people perform such tests.**

In "METHODS AND TECHNIQUES OFCOMPLEX SYSTEMS SCIENCE: AN OVERVIEW" by Cosma Shalizi

European Conference on Complex Systems Paris, 14-18 November 2005

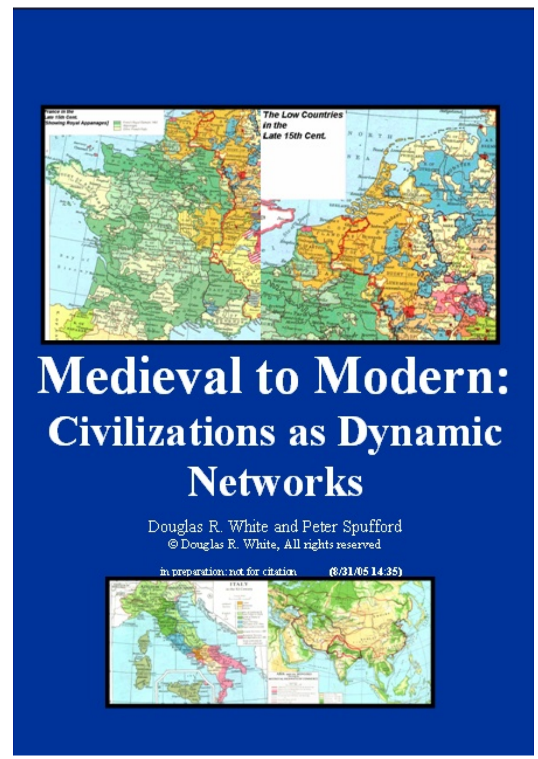
Civilizations as dynamic networks



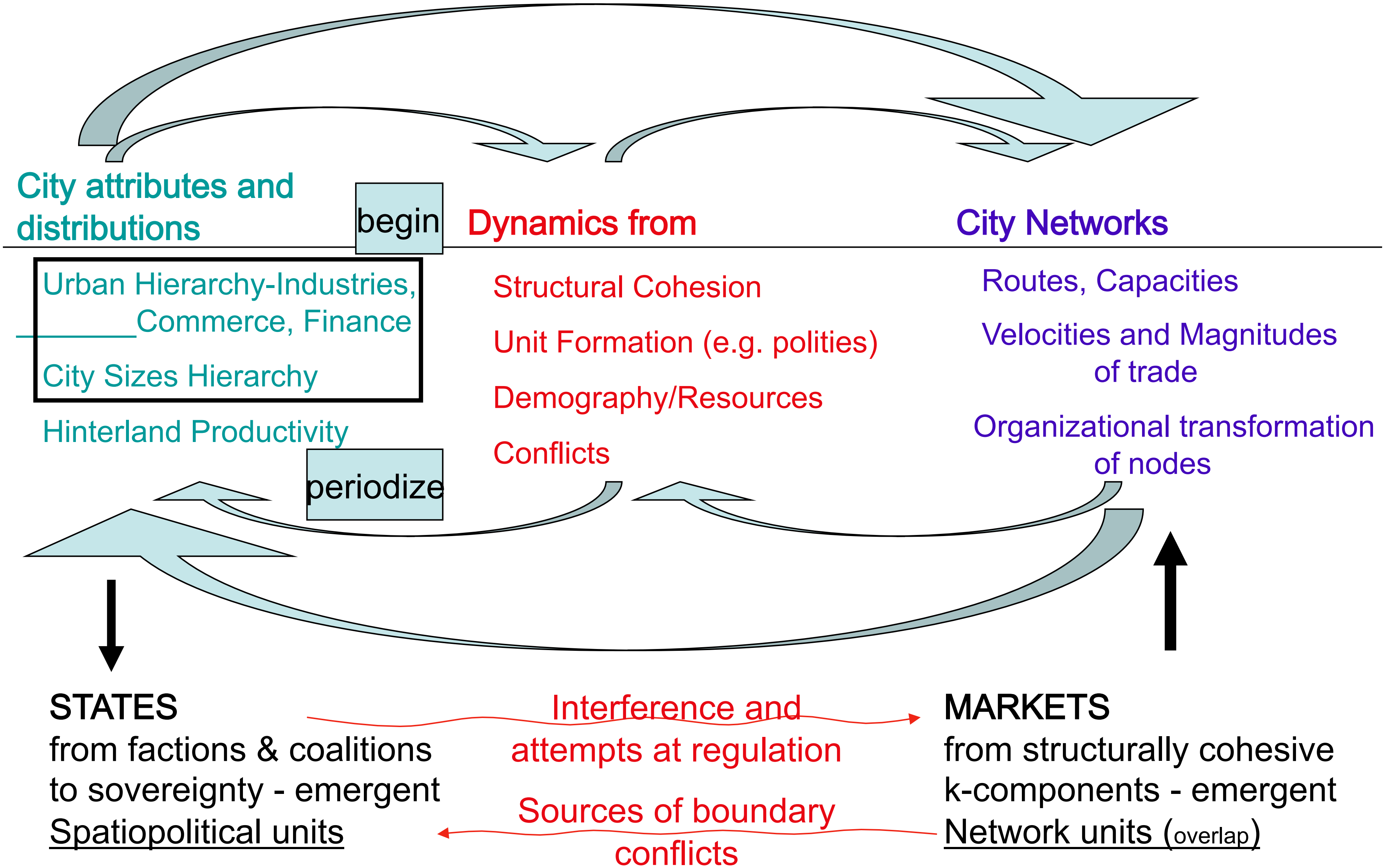
Cities, hinterlands, populations, industries, trade and conflict

Douglas R. White

50 slides - also viewable on drw conference paper website version 1.3 of 11/12/2005

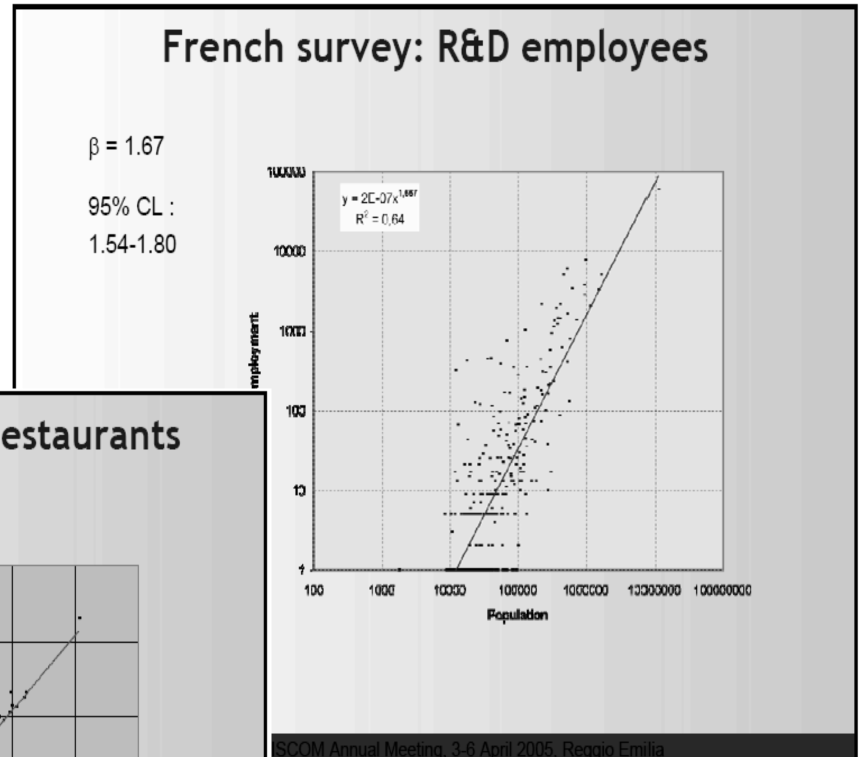


Co-evolution time-series of Cities and City Networks



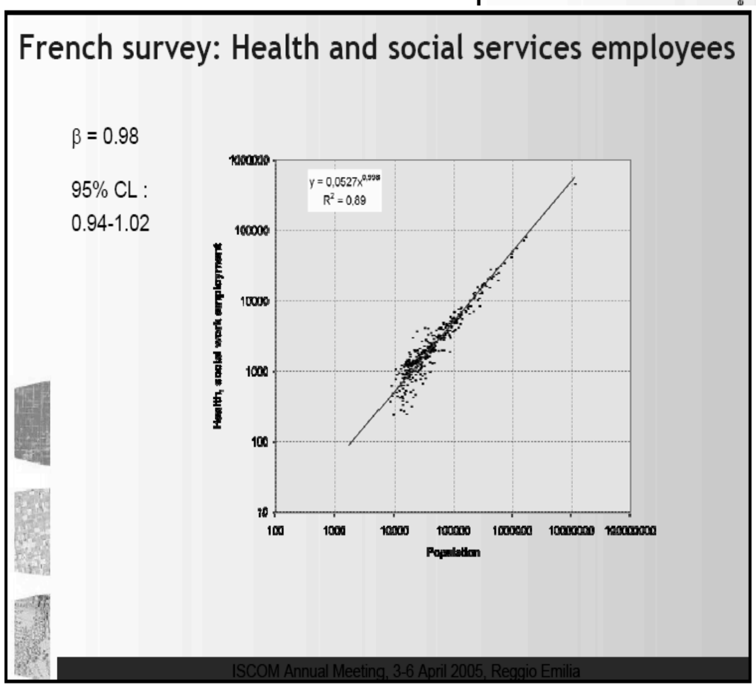
Comparative scaling measurements and urban functions: French examples

Superlinear ~ 1.67



Linear ~ 1

Sublinear ~ .85



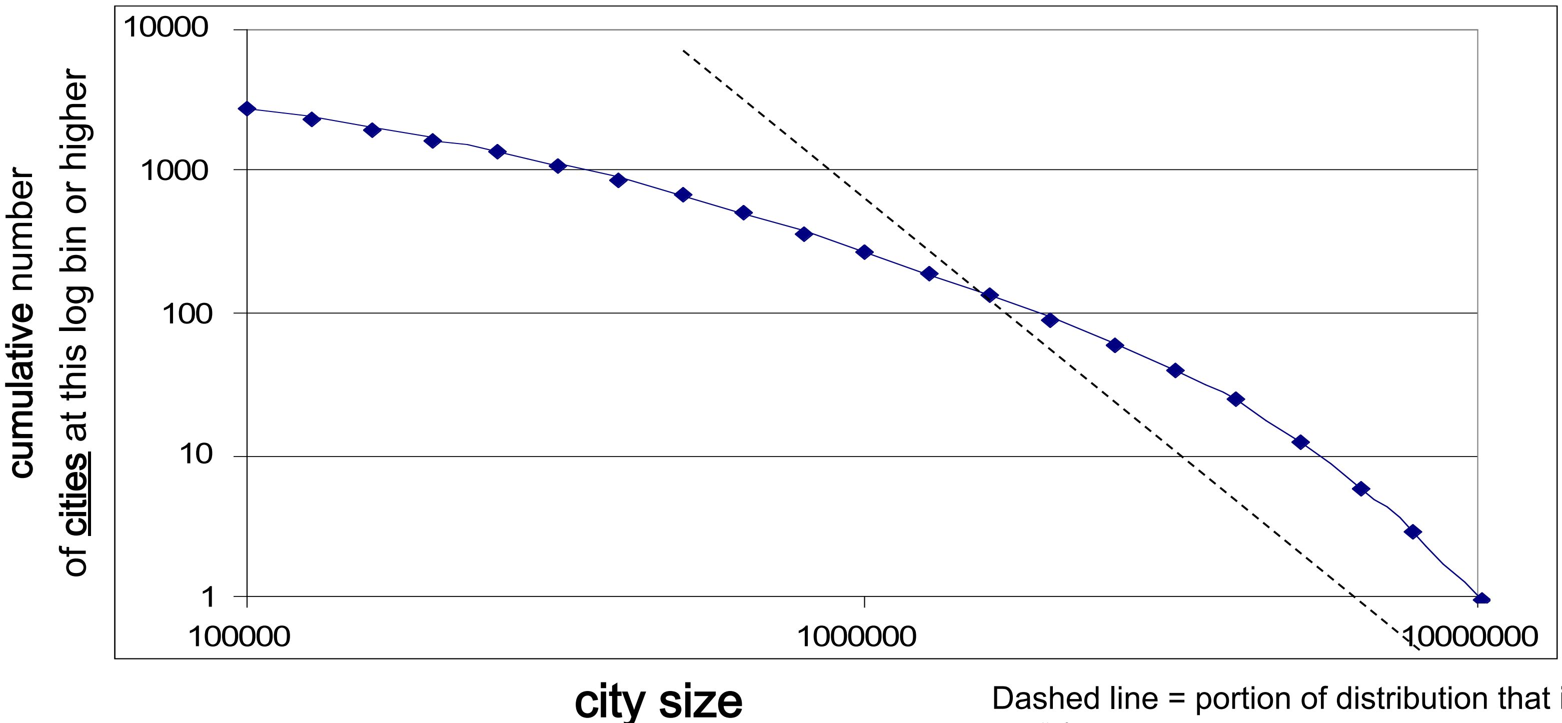
Fabien PAULUS
Denise PUMAIN

ISCOM working paper

Urban Scaling: City Sizes - 1950 United Nations data for world cities

Compare the scale K and α coefficients of the power-law $y(x) \approx K x^{-\alpha}$ (and Pareto β=_α+1) with the q-exponential parameters for q slope and scale κ in $y(x) \sim [1 + (1-q)\, x/\kappa)]^{1/(1-q)}$, fitted to entire size curves

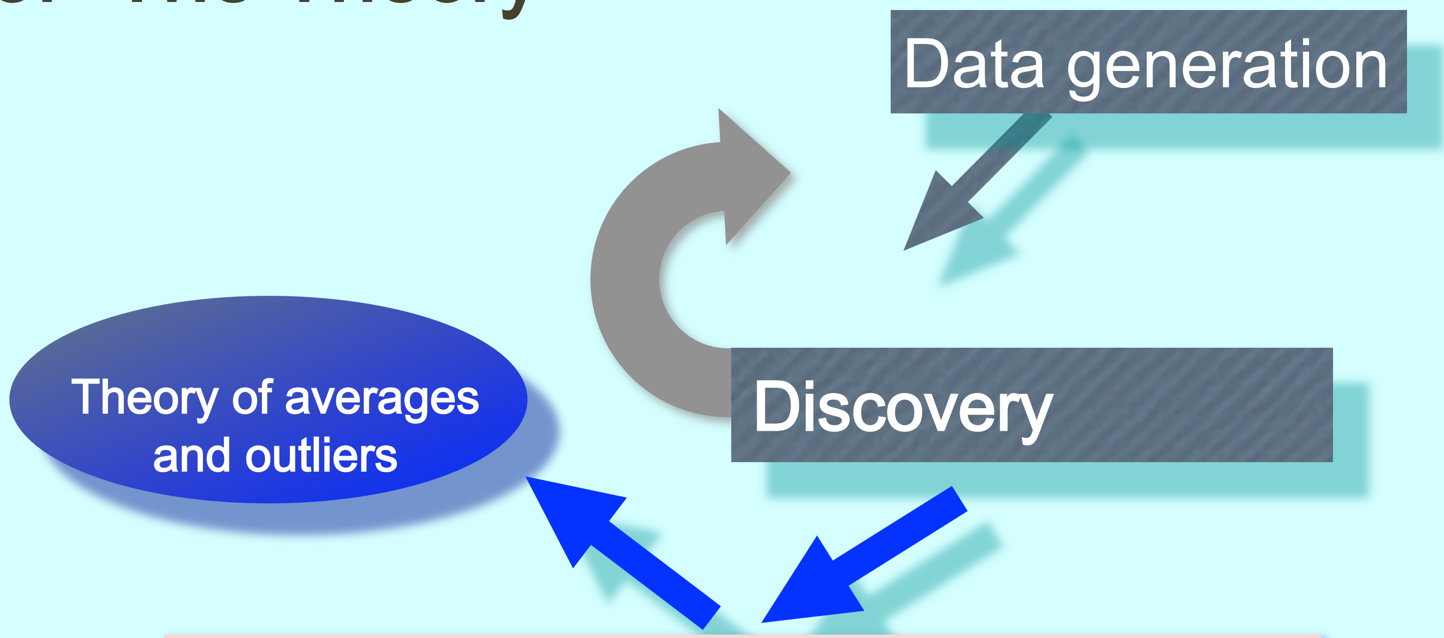
Power laws and Zipf's law might fit upper bin frequencies for city sizes but not the whole curve



Dashed line = portion of distribution that is "power-law“ (but is exaggerated in the upper bins)

(White, Kejžar, Tsallis, and Rozenblat © 2005 working paper)

Origin of “The Theory”



Increasing levels of discovery:

- Statistical characterization
- Dimensionless functionality (correlations)
- **Scaling - self-similarity**
- Descriptive “Laws”
- Functional relationships
    - Static
    - Dynamic (governing equations of change)
- Higher moments (variation within)
- Error generation

Summary

Why true power law observations are exciting

- Essential to discovery of governing "laws"
- Often from a critical process in a complex system

But power laws are only part of the process to developing a broader understanding. Not meaningful without a model or theory.

Power laws behavior doesn't mean complexity

Power laws are

- (Idealized) asymptotic behavior - beware of the boundaries!
- Represent thick tails, rather than thin tailed distributions

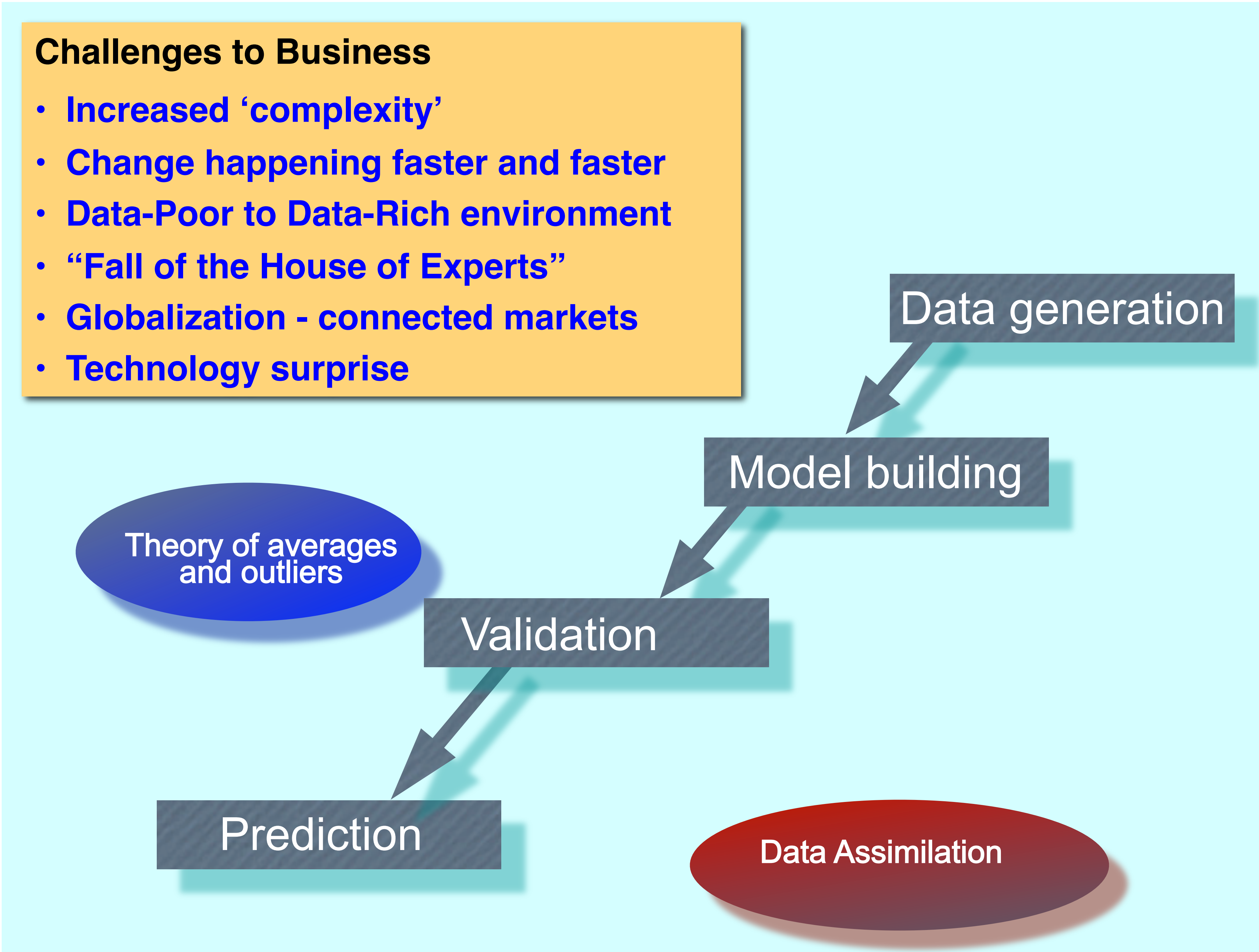
In general, anomalous distributions may dominate real systems

Consider maturity of system evolution - "young" systems may be very different

- Or mixed maturity of sub-systems

Consider optimization versus robustness

Best resources on the subject (appear to be) from SFI


Challenges to Business
• Increased ‘complexity’
• Change happening faster and faster
• Data-Poor to Data-Rich environment
• “Fall of the House of Experts”
• Globalization - connected markets
• Technology surprise
Data generation
Model building
Validation
Prediction
Theory of averages and outliers
Data Assimilation

References

Shalizi, Cosma R., "METHODS AND TECHNIQUES OF COMPLEX SYSTEMS SCIENCE: AN OVERVIEW", Chapter 1 (pp. 33-114) in Thomas S. Deisboeck and J. Yasha Kresh (eds.), Complex Systems Science in Biomedicine (New York:Springer, 2006) http://arxiv.org/abs/nlin/0307015

Farmer, J. Doyne & John Geanakoplos, "Power laws in economics and elsewhere", DRAFT April 4, 2005 (chapter from a preliminary draft of a book called "Beyond equilibrium and efficiency") - Contact the authors for a copy.

Farmer, J. Doyne, "Power laws", Santa Fe Institute Summer School June 29, 2005. Contact the author for a copy.

Holbrook, Morris B.. 2003. "Adventures in Complexity: An Essay on Dynamic Open Complex Adaptive Systems, Butterfly Effects, Self-Organizing Order, Co-evolution, the Ecological Perspective, Fitness Landscapes, Market Spaces, Emergent Beauty at the Edge of Chaos, and All That Jazz http://www.amsreview.org/articles/holbrook06-2003.pdf

White, Douglas R., "Civilizations as dynamic networks: Cities, hinterlands, populations, industries, trade and conflict", European Conference on Complex Systems Paris, 14-18 November 2005. http://eclectic.ss.uci.edu/~drwhite/ ppt/CivilizationsasDynamicNetworksParis.ppt

For exceptional talks on Complexity in financial systems, see the Thought Leaders Forums:

- http://www.leggmason.com/thoughtleaderforum/2006/index.asp for 2003-2006
- http://www.capatcolumbia.com/CSFB%20Thought%20Leader%20Forum.htm for 2000-2003

Topics for Discussion?

What are the implications in your application area of the shift to being "data rich"?

Are the moments around the norm important? Are you driven by the outliers or norms?

How much can the results presented today be generalized?

- Stephanie's table of correspondence? Worth more development / study?
- Are global properties always determined by the "supply chain" - as Geoff observed in organisms?
- How do physical/operational restrictions dominate the growth of a system?
- In complex composite systems, does the host always dominate the dynamics?

Can human-designed systems be better planned by using general "laws"?

Bio-inspired solutions - where/when valid?

- Are ant colonies more like bio organisms or human societies?
- What about material versus information differences?
  - (If I give you an apple, I don't have an apple; is information the same, why not?)
- How does basic scales affect the system: e.g., cell size is fixed, but computer size is not

What can be concluded about network scaling and global system performance?

Social systems and innovative reset (Singularity horizon?)

- Assumes infrastructure is largely unchanged
- Can innovation reset infrastructure?

What about optimization of Efficiency versus Robustness?

- In times of faster change, robustness is maybe more important

Stages of development and maturity

- How much what has been observed today is only for mature, well developed systems?
- How do early innovative systems behave? How do opportunities and approaches differ?

Others?