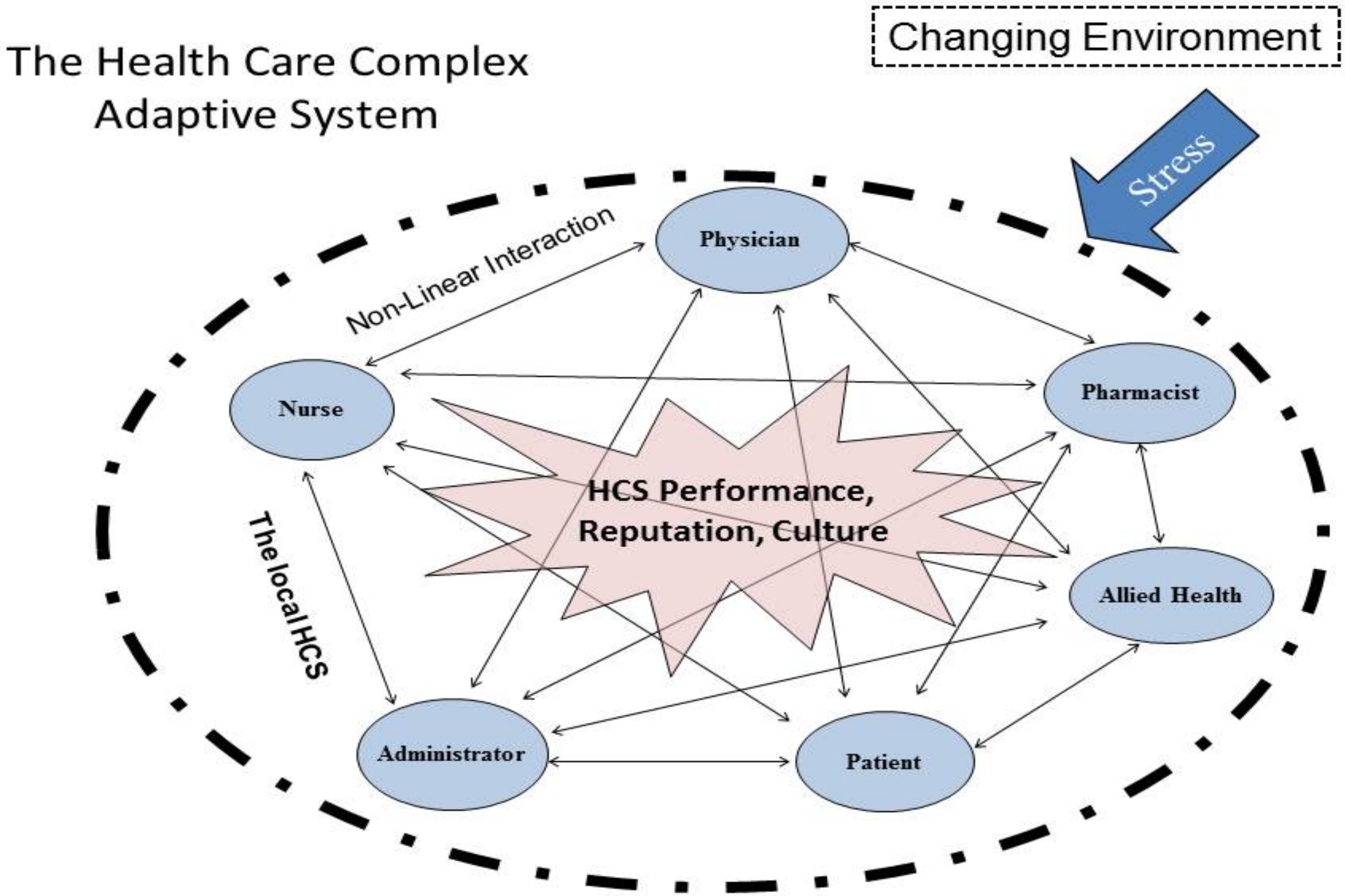
The Complex Adaptive Network Theory and its Scaling Laws of Growth:

Malaz Boustani, MD, MPH

Based on:

Agile implementation, A model for implementing evidence-based healthcare solutions into real-world practice to achieve sustainable change. Malaz Boustani, Jose Azar, and Craig A Solid.
Albert-Laszlo Barabasi. Network science.
Scaling dynamics: The Universal Laws of growth, innovation, sustainability, and the pace of life in organisms, companies, cities, and economies.Geoffrey West: Penguin Press 2017.Identifiers: LCCN 2016056756. ClassificTION: LCC H61.27.W47 2017

Complex Adaptive System (CAS)



Complex Adaptive Health Care System

- Network that is open, dynamic, flexible, adaptive and complex
- **Complex** due to:
  - Numerous interconnected, semi-autonomous, competing, and collaborating members
- **Adaptive** due to:
  - Capability of learning from prior experiences
  - Flexibility to change its members connecting patterns to fit better with its surrounding environment

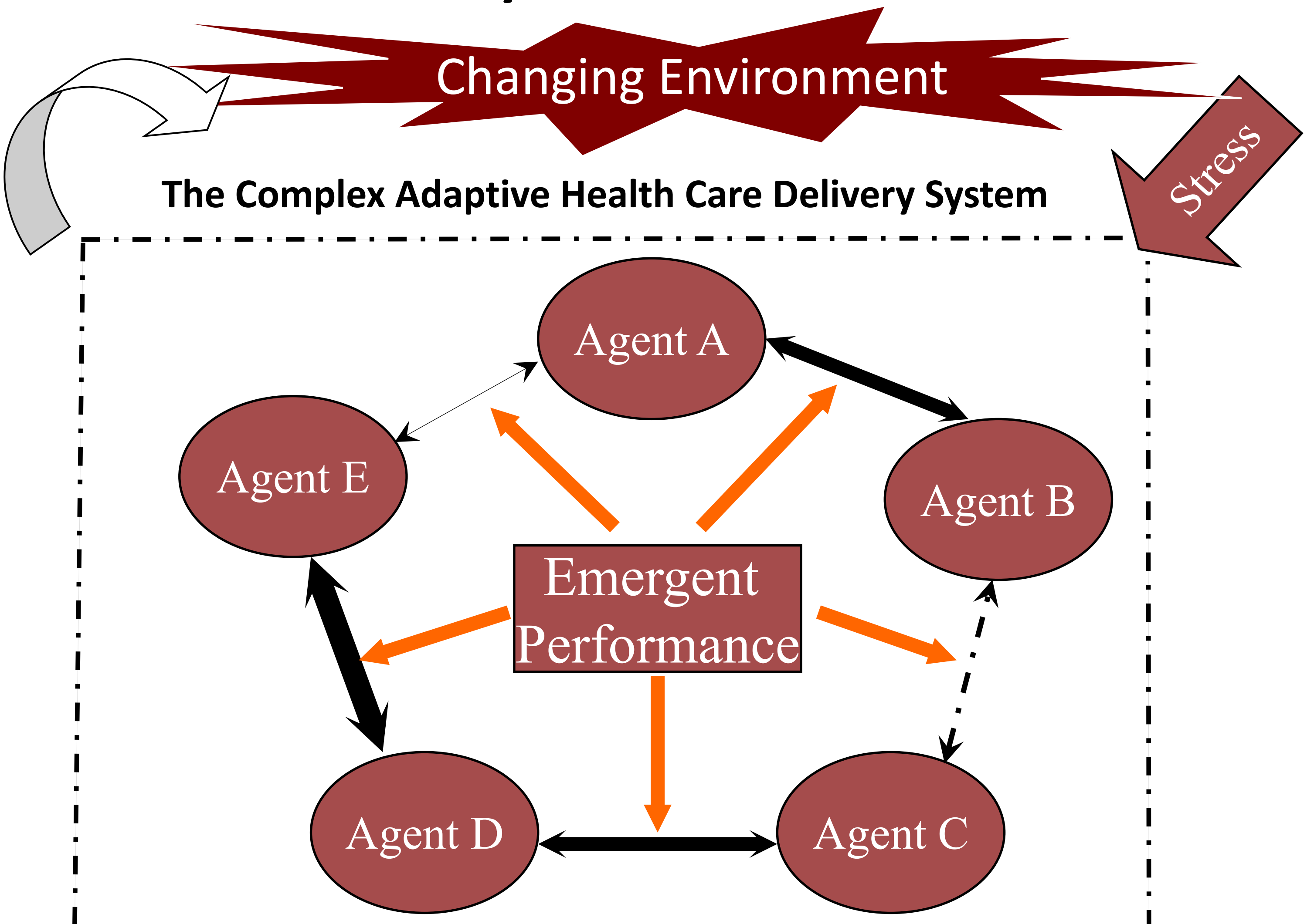
Complex Adaptive Health Care Network

- Each network is unique in its:
  - Member diversity
  - Member interactions
  - Surrounding environment
  - Previous history
  - Evolving and learning process

Complex Adaptive Health Care Network

- The connecting patterns of its members are:
  - Dynamic
  - Change over time
- The performance of a network fluctuates over time due to:
  - Response to the stress or the fitness requirements of its surrounding changing environment

Complex Adaptive Health Care System



Boustani et al, JCIA 2010

The **four** building properties and the **three** building mechanisms in Complex Adaptive Network

Aggregation (Property)

- Emergence of complexity from a network of simpler agents.
- Aggregates can act as agents in higher-level structures (meta-agents):
  - Particle to atoms, atoms to molecules, molecules to protein, proteins to cells, cells to tissues, tissues to organs, organs to organisms, Organisms to families, families to communities, communities to cities, cities to states, states to countries, countries to humanities.

Nonlinearity (Property)

- A function is linear its value can be calculated by adding the values of its parts.
  - i.e. A=B+C
- Nonlinearlity of Pool Ball Example
  - (B+W)(t+1)=(B+W)+c(B)(W)
  - (G+W)(t+1)=(G+W)+c'(G)(W)
  - Can we simplify the model by aggregating B and G into a single category S? (S=B+G)
  - No. There is no coefficient that works for all combinations of B and G.
  - If the function was linear, then we could take the average of c and c'

Flow (Property)

- [node, connector, resource]
- [phones, phone lines, conversations]
- Multiplier Effect
  - Occurs after additional resource is added at a node
  - Initial effect is multiplied as the resource is passed through the network
- Recycling Effect
  - Result of cycles in a network
  - Recycling with the same input produces a greater output at each node

Diversity (Property)

- Not random.
- System will adapt to fill holes.
  - New agent typically occupies same niche as previous agent and provides most of the missing connections
  - Leads to convergence in biology
    - i.e. squid vs. mammalian eye
  - Founder Effect

Diversity (Property)

- Pattern of diversity in *cas* is dynamic.
- Diversity is a product of adaptation. Each new adaptation creates possibilities of new interactions and new niches

Tagging (Mechanism)

- A mechanism that facilitates aggregation by bringing like things together
  - i.e. a flag used to rally a group of people, pheromones and visual patterns that lead to selective mating
- Allow observation of properties hidden by symmetry.
  - i.e. painting a stripe on a cue ball to see changes in the axis of rotation

Internal Models (mechanism)

- Allows for anticipation
- Two types
  - Tactit: prescribes an action under an implicit prediction of a desired future state
    - i.e. a bacteria swimming up a nutrient gradient
  - Overt: used as a basis for explicit explorations of alternatives (*lookahead*)
    - i.e. exploring possible scenarios before moving a chess piece

Building Blocks (mechanism)

- How are internal models built from constantly changing environments?
  - Situations are distilled into useful and relevant building blocks
  - A flat tire while driving a red Saab on the expressway?
  - Decompose into rules about cars, tires, and expressways

Nine Principles of Introducing a Change in CAS

1. View your system through the lens of complexity
2. The “good enough” vision with minimum specifications
3. Balance between clockware and swarmware:
   - Data and intuition
   - Planning and acting
   - Safety and risk

Nine Principles of Introducing a Change in CAS

4. Foster the “right” degree of information flow, diversity and difference (the edge of chaos)
5. Uncover and work with paradox and tension
6. Go for frequent experimentations, let direction arise

You don’t have to be "sure" before you proceed with anything

Nine Principles of Introducing a Change in CAS

7. Listen to and be aware of the “shadow system”:
   - Informal relationships
   - Gossip
   - Rumors
   - Hallway conversations
8. Allow emerging behaviors to grow out of your complex systems
9. Build a community of members who collaborate and compete

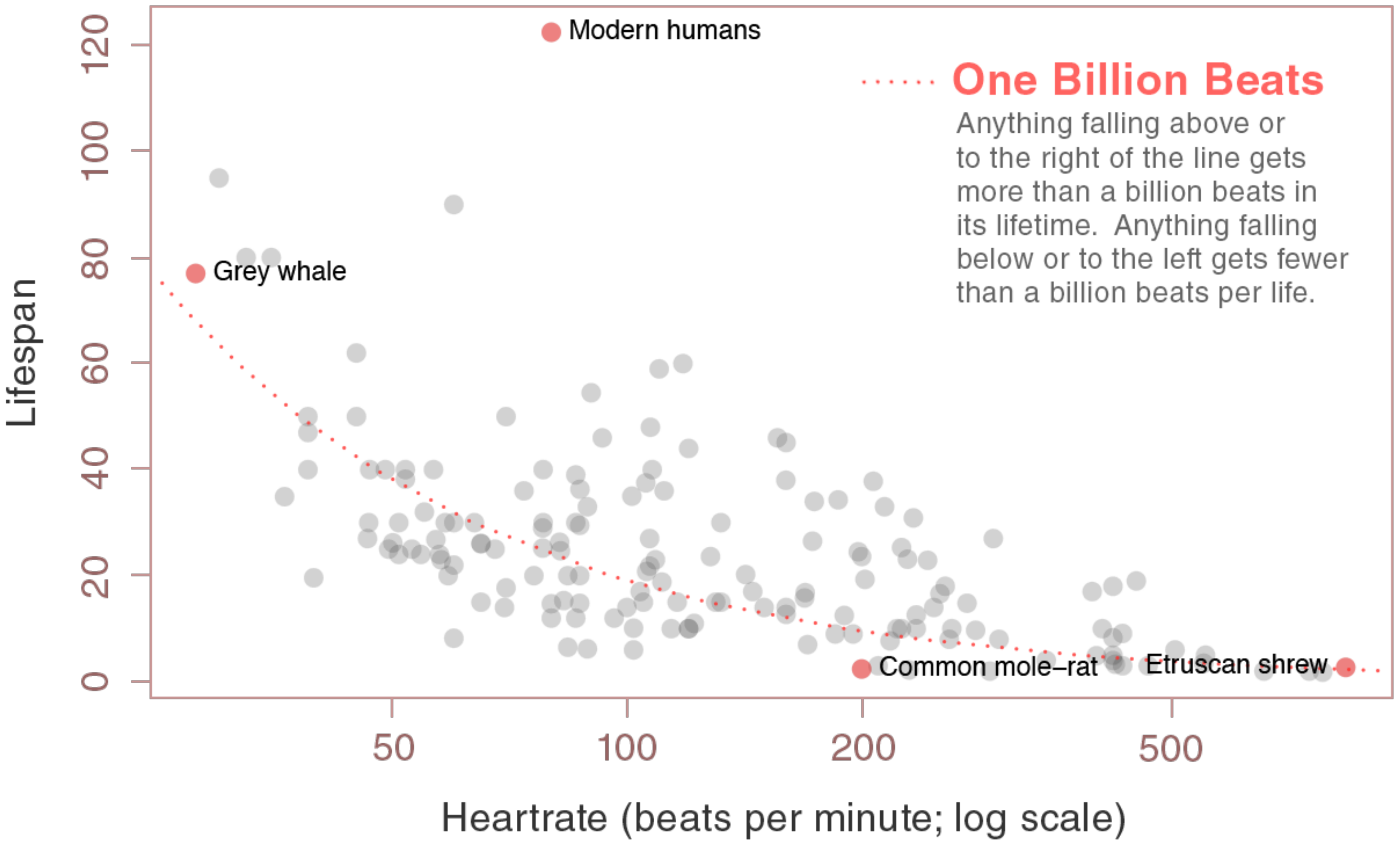
Implications

	Traditional System	Complex Adaptive System
Roles	Management	Leadership
Methods	Command & Control	Incentives & Inhibitions
Measurement	Activities	Outcomes
Focus	Efficiency	Agility
Relationships	Contractual	Personal Commitments
Network	Hierarchy	Heterarchy
Design	Organizational Design	Self Organization

Interesting Observations

Observations

- All Mammals get one billion heart beats per lifetime.
- Cities are resilient.
- Publically traded companies are frail.
- The resiliency and the frailty of other social organizations are somewhere between.

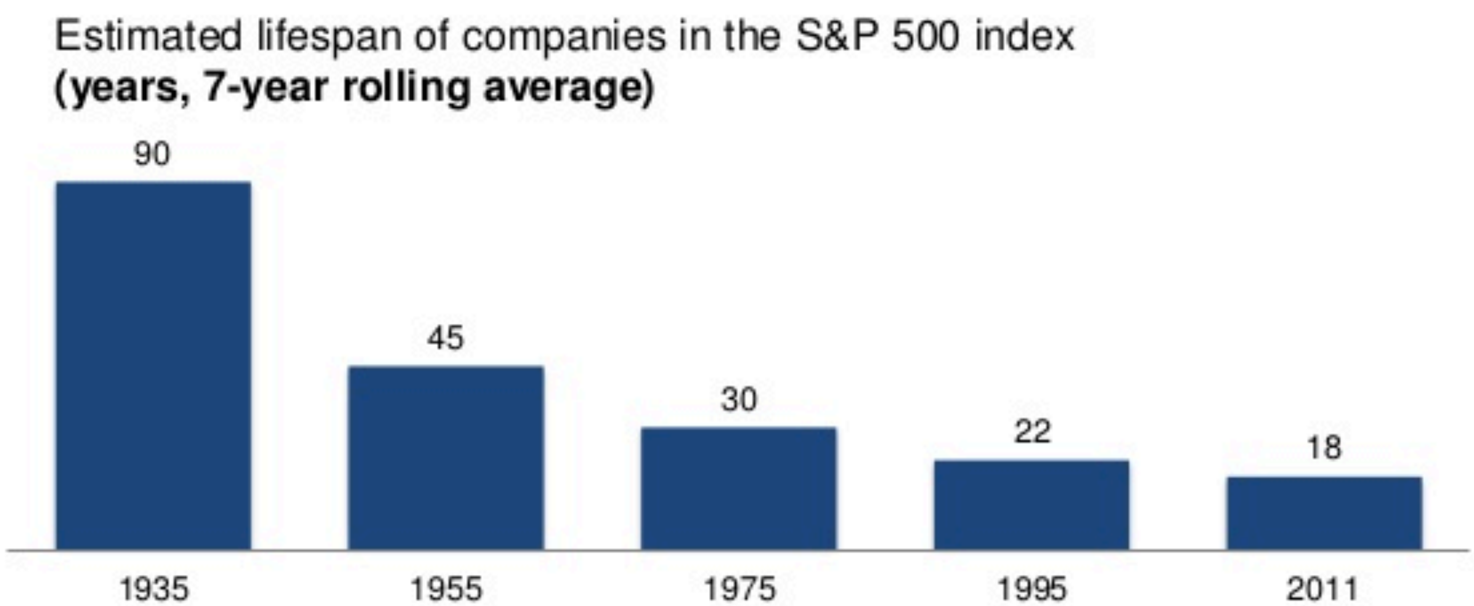


http://robdunnlab.com/projects/beats-per-life/

Observations

- All publicly traded companies in the US worth more than $21 trillion, 15 percent larger than the entire Gross Domestic Products (GDP).
- The half life of US publically traded companies is 10.5 years.
- The probability of a company surviving for one hundred year is 45 in a million and for surviving two hundred years is 1 in a billion.

Average age of large corporates declining



Source: Innosight, Richard Foster, S&P

Questions

Questions?

- How do the things in a universe, all composed of atoms, change in behavior and structure as they get larger?
- How do things that are alive as **units** scale differently from things “alive” as ***interacting*** **units**?
- Are cities and companies just very large biological organisms?
- Why Do Homo Sapiens cluster in social organizations?
- Why is it too easy for a company to die and very hard for a city to die?
- How many close friends do you really have?
- **What are the optimal structures and dynamics of an Agile Social Organization**?

Questions?

- Can we construct a quantitative, predictive, and mathematical theory of the growth, scale, aging, and mortality of social complex adaptive systems (CAS) such as research centers, companies, universities, cities, and countries?
- Is there an optimal, maximum or minimum size of social CASs?
- What is the larger influencer of the dynamics and structures of social CASs, energy or information?
- Do Social CASs obey power law scaling?

Questions

- What are the scaling laws for social CASs?
- What physical, social, cognitive constraints must be satisfied by the architecture of the structures that channel flows of **information**, **matter**, and **energy** within social CASs?
- What is the future of the extraordinary exponentially expanding human-engineered socioeconomic universe?

Basics

Network Science: Scale-free Network

- On average the number of links connecting any two people is 3-4.
- In the scale-free networks the shortest path between nodes is on average a relatively small number and that this number is essentially independent of the size of the population.
- The scale-feee networks have a lot of hubs and a large degree of clustering relative to randomly connected networks.
- Hubs are nodes with an unusually large number of links associated with them.
- Cliques are modular subnetworks that have high connectivity within them so that almost any two nodes are connected.
- Modular group structures are a central feature of our social life including our family, our circle of close friends, our department at work, our neighborhood, or our entire city.

Network Science: Dunmbar Numbers

- An average individual's entire social network can be deconstructed into a hierarchical sequence of discrete nested clusters whose sizes follow a regular mathematical structure obeying simple scaling rule reminiscent of self-similar fractal-like behavior.
- The size of the group at each level systematically increases as one progresses up the hierarch while the strength of the bonding between people within the groups systematically decreases.
  - At the lowest level of hierarch the number of family with whom the average individual has his or her strongest relationships is only **5** at any one time.
  - The number of close friends is **15**.
  - The next circle of friends is **50**.
  - The next level defines the limit of person social horizon as far as personal interactions are concerned and consists of people you might refer to as causal friends is **150** people.

Network Science: Dunbar numbers.

- The Dunbar numbers of social organization is very important in situations where social stability, knowledge of other individuals, and social relationships are integral to improving performance, productivity and the general well being of all members of the social organization.

- Increasing the group size beyond 150 will result in significantly less social stability leading to its disintegration.

- Recent data suggest that these numbers can expand from 5, 15-20, 45-50, 150, 500, 1500, and so on.

Network Science: Zipf's Law and Pareto Principle

- Zipf's law ranking of cities:
  - The largest city in an urban system is twice the size of the second largest, three times the size of the third largest, four times the size of the fourth largest and son on.
- The Pareto principle:
  - 80% of the company profit and 80% of its complaints come from 20% of its customers.
- The Pareto Principle and the Zipf law are simple power law with an exponent of approximately -2.

Findings

Main Findings

- With every 100% increase in the weight of any average mammal, the mammal get 25% more efficient in energy consumption and lives 25% longer.
- For every 100% increase in the population of a city, you need only 85 percent more energy and resources infrastructure, but you get 115 percent more positive or negative socioeconomic activities.
- For every 100% increase in the size of publicly traded companies, the company need 85% more energy But 100% increase in their size does not lead to 115% increase in their socioeconomic activities related innovation.

Scaling dynamics by .Geoffrey West, Penguin Press 2017. http://robdunnlab.com/projects/beats-per-life/

Main Findings

- Complex adaptive systems respond similarly to increases in size due to having a similar hierarchal energy distributing and information exchanging network infrastructures with three common characteristics:
  - First, the networks are "**space filling**" — that is, they service the entire biological or social organism.
  - Second, the **terminal units are largely identical**, whether they are the capillaries in our bodies or the faucets and electrical outlets in our homes.
  - Third, a **natural optimization feedback process** operates within these networks to
    - Minimize energy dissipated in the networks
    - Maximize the scaling of their area of interface with their resources environment.

Scaling dynamics by .Geoffrey West, Penguin Press 2017. http://robdunnlab.com/projects/beats-per-life/

Main Findings

- The geometric and dynamical properties of **biological networks**:
  - Space filling, so every cell of an organism must be serviced by the network.
  - The terminal units are invariant within a given design. The cells and capillaries are approximately the same across all mammals.
  - The networks have evolved to be optimal. The energy used by Hearts to circulate blood and support cells is minimized in order to maximize the energy available for growth, repair, and maintenance.
- The geometric and dynamical properties of **social network**:
  - Each person interacts with a number of other people as well as with groups of people in such a way that collectively their network of interaction fills the available socioeconomic space.
  - The invariant terminal units of the social networks (the analog of cells, capillaries, and leaves) are people and their living spaces.
  - The social networks evolve to minimize cost, energy use, travel time, travel distance, social capital or the connectivity between individuals.

Main Findings

- The hidden regularities within the structure and dynamics of any social organism such as cities and companies are manifestations or functions of the physics and mathematics of the underlying networks that transport energy, resources and information among the semi-independent agents of the social organism.
- The flow of information within any social organism is as a significant as the flow of matter, energy and resources.
- There are sublinear, superlinear and linear types of scaling laws within any social organisms.
- There are physical, cognitive and social variables that constraint the architecture of the network structures that channel flows of information, matter, and energy.

Scaling dynamics by .Geoffrey West, Penguin Press 2017. http://robdunnlab.com/projects/beats-per-life/

Main Findings

General picture

Scaling Exponent	Driving Force	Organization	Growth
b<1	Optimization, Efficiency Stable equilibrium	Biological	Sigmoidal Long term finite attractor
b>1	Creation of Information, Wealth and Resources nonequilibrium, constant adaptation	Social	Boom / Collapse Finite time singularity Increasing acceleration / discontinuities
b=1	Single Individual Maintenance	Trivial, Free	Exponential Infinite time divergence

Human social organization is a compromise over many social activities
Epidemiological dynamics is affected by large-scale
human organization and behavior

SANTA FE INSTITUTE
Celebrating 20 years of Complexity Science

ISCOM
Information Society as a Complex System
University of Modena and Reggio Emilia
Imperial College London
Centre National de la Recherche Scientifique, Paris

L. M. A. Bettencourt, J. Lobo, D. Helbing, C. Kuhnert, G. B. West. (2007) **Growth, innovation, scaling, and the pace of life in cities**. *Proceedings of the National Academy of Sciences* **104**:17, 7301-7306. Online publication date: 24-May-2007

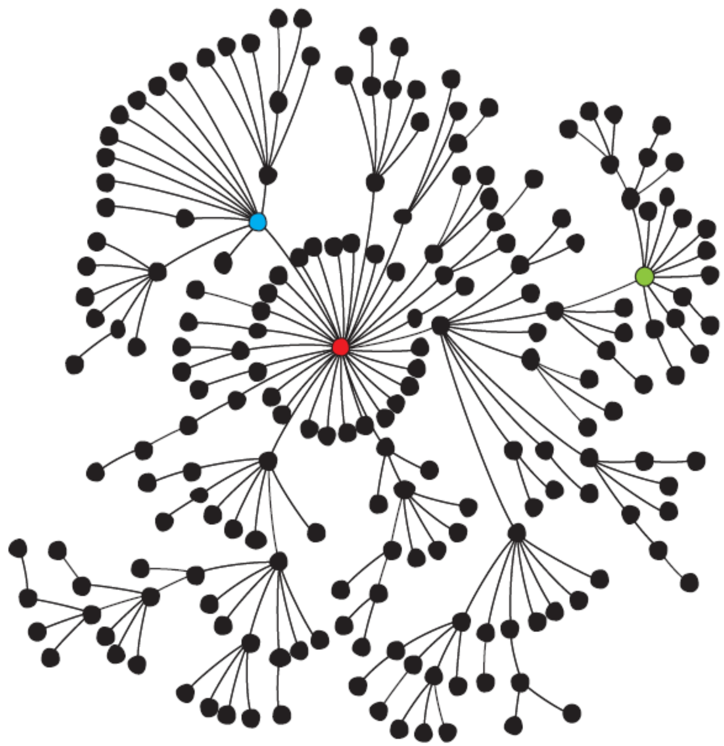
Findings: Science of Companies

- What are the general characteristics of the very long-lived companies (5586 companies in the world have survived more than 200 years by 2008: 3146 are Japanese, 837 are German, 222 are Dutch, and 196 are French):
  - Their size is relatively modest. 90% of the companies that have survived for at least 100 years had fewer than 300 employees.
  - Operate in highly specialized niche markets
  - They have survived NOT by diversifying or innovating but by continuity to produce a perceived high-quality product for a small and dedicated clientele.
  - They maintained their viability through reputation and consistency and have barely grown.
  - 56% of them are Japanese

Conclusion: A New Social CAS

- The support for innovation does not keep up with the bureaucratic and administrative expenses as companies expand. There are no new cells and there are a lot of damaged cells and poorly repaired cells.
- The increasing accumulation of rules and constraints is often accompanied by stagnating relationship with consumers and suppliers that lead companies to become less agile and more rigid and thus less able to respond to significant change.
- **The hallmark of cities is that they become ever more diverse as they grow. Their spectrum of business and economic activities is increasingly expanding as new sectors develop and new opportunities present themselves.**
- Cities are prototypically multidimensional and this is strongly correlates with their superlinear scaling, open-ended growth, expanding social networks leading to their resilience, sustainability and seeming immortality.
- While the dimensionality of cities is continually expanding, the dimensionality of companies typically contracts from birth through adolescence, eventually stagnating or even further contracting as they mature and move into old age.
- As company grows, the feedback mechanisms inherent in the market lead to a narrowing of its product space and inevitably to greater specialization. The great challenge for companies is how to balance the positive feedback from the market forces, which strongly encourage staying with tried and true products versus the long-term strategic need to develop new areas and commodities that may be risky and won’t give immediate return.

1999 Barabasi and Albert's "Scale-free" network



Simple Preferential attachment model:
"*rich get richer*"
yields
Hierarchical structure with "King-pin" nodes

Properties:
tolerant to random failure…

vulnerable to informed attack