Coming Attractions

How are the characteristics of complex systems generated from, illustrated or measured by:

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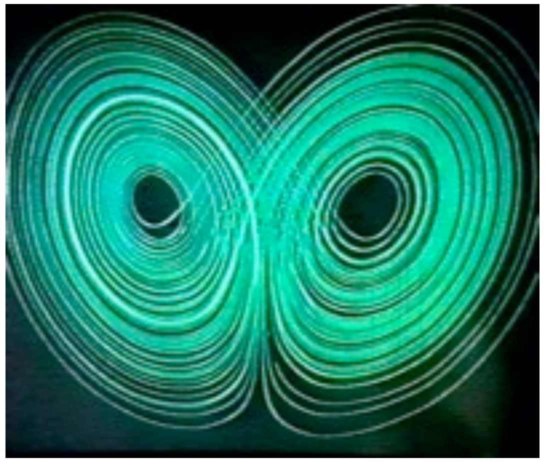

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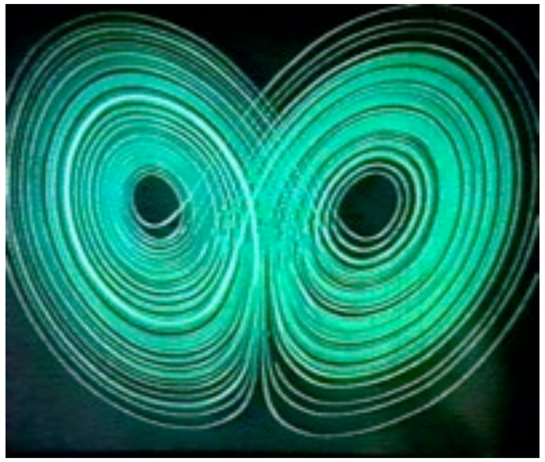
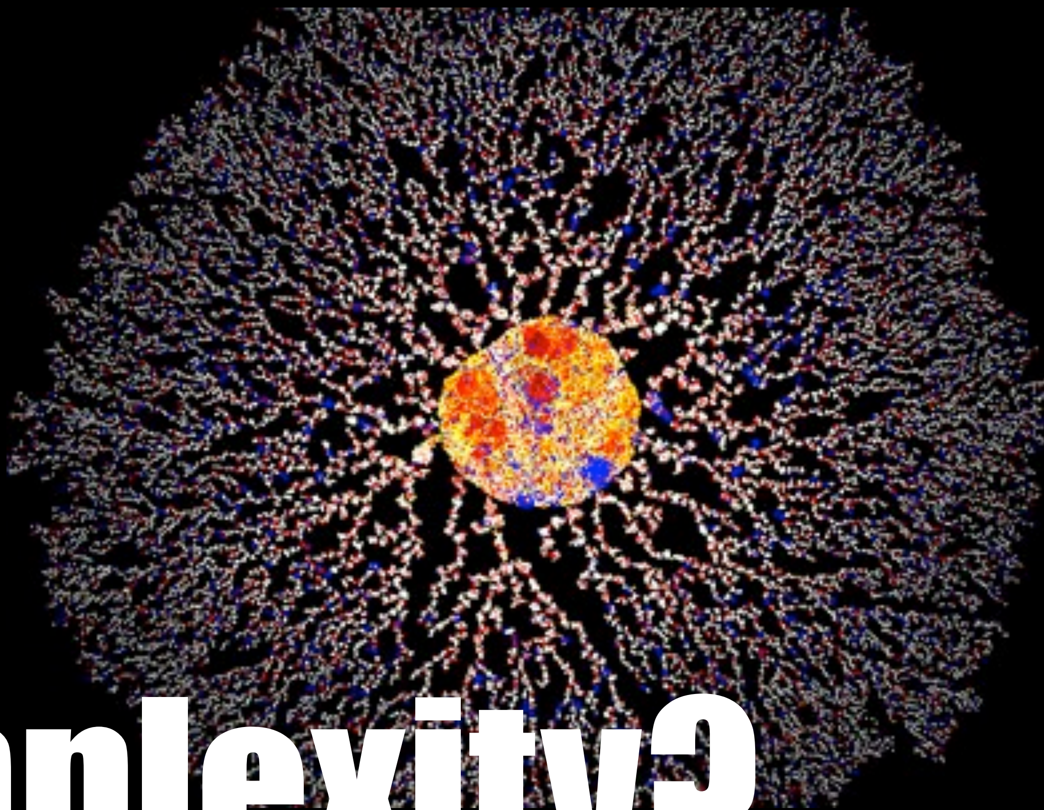


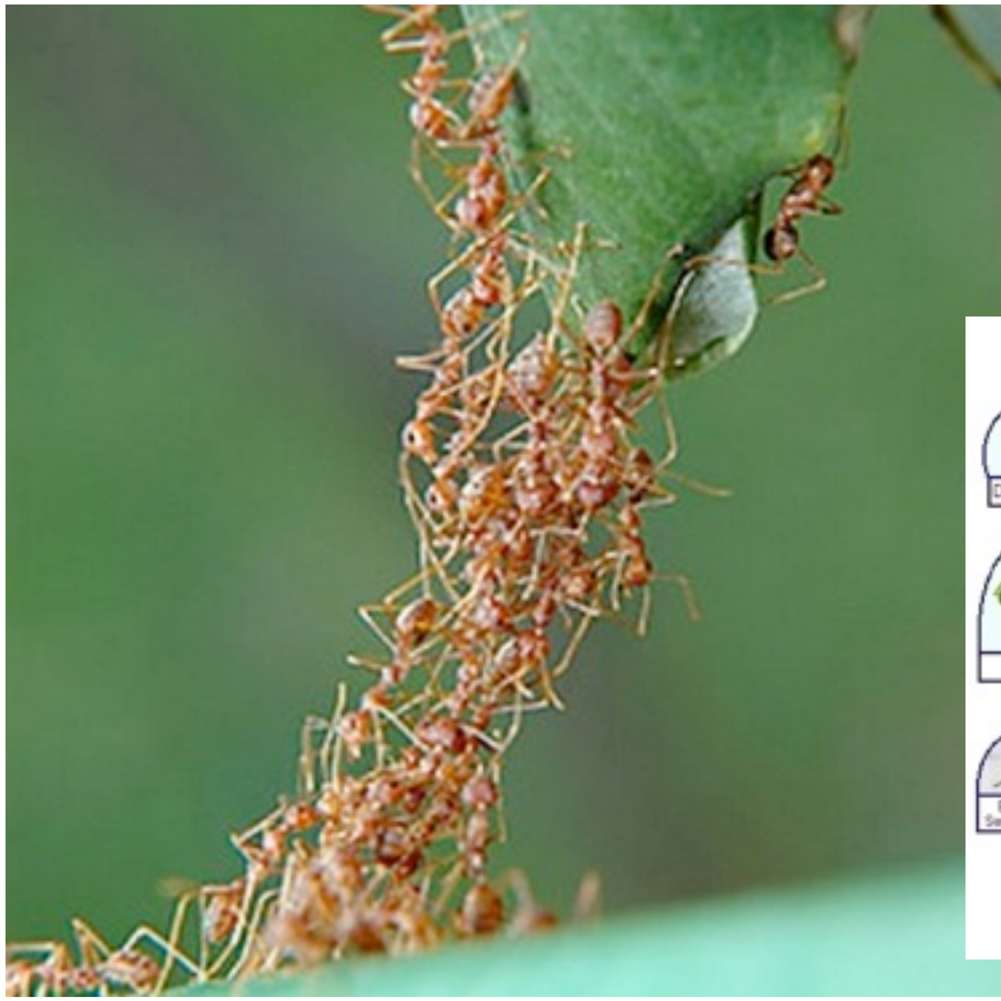
- Emergent Behaviour and Fractals

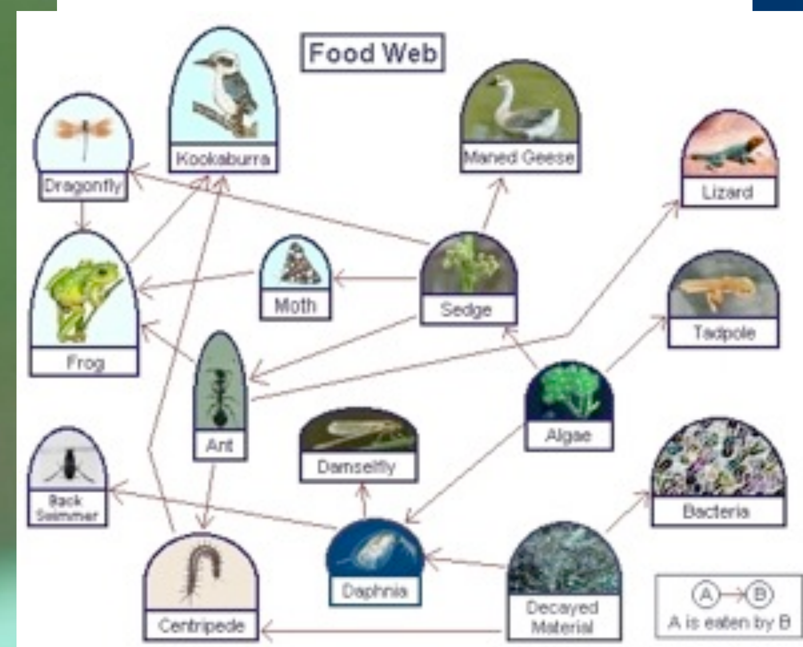


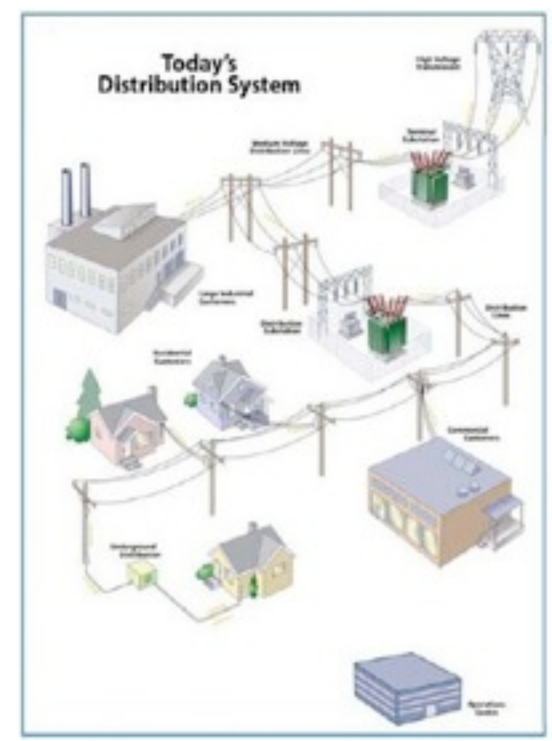
What is Complexity?

Part 1: Information and Networks

Complex Systems are Everywhere...







Complex Systems are Characterized By:

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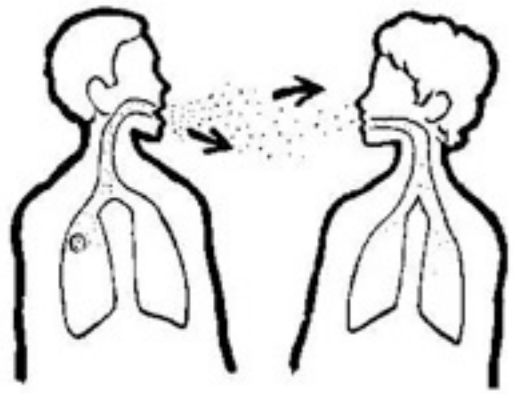
- **Simple Interactions**



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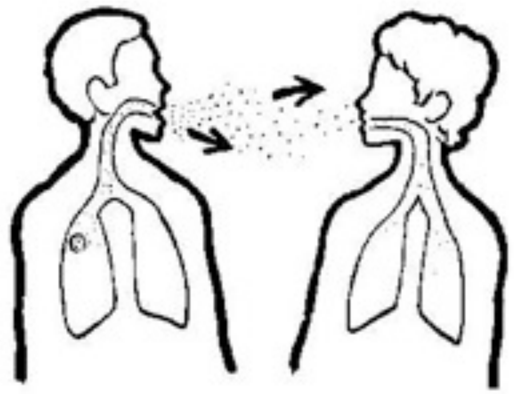
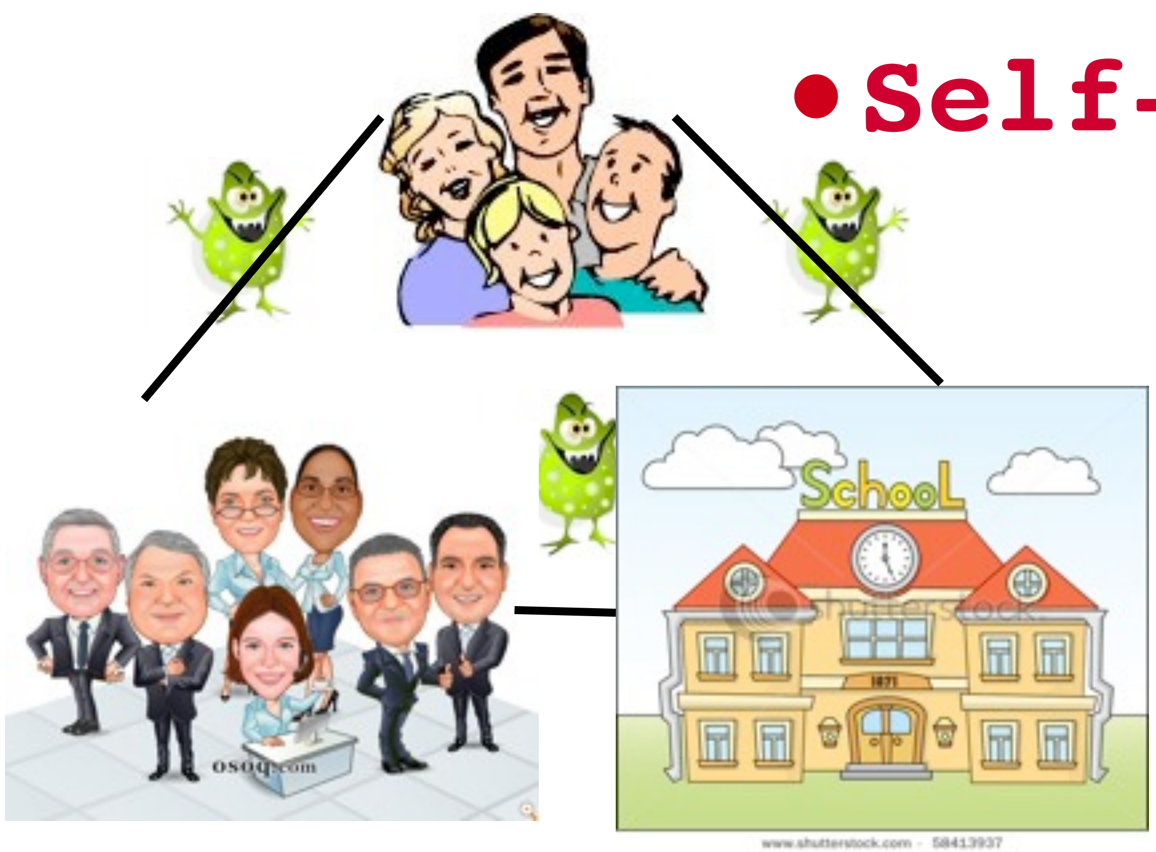


- Self-organizing Behaviors



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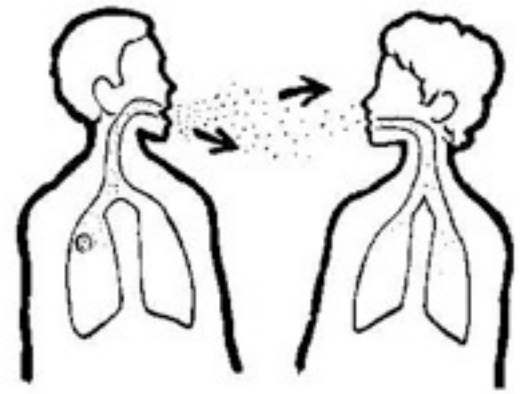
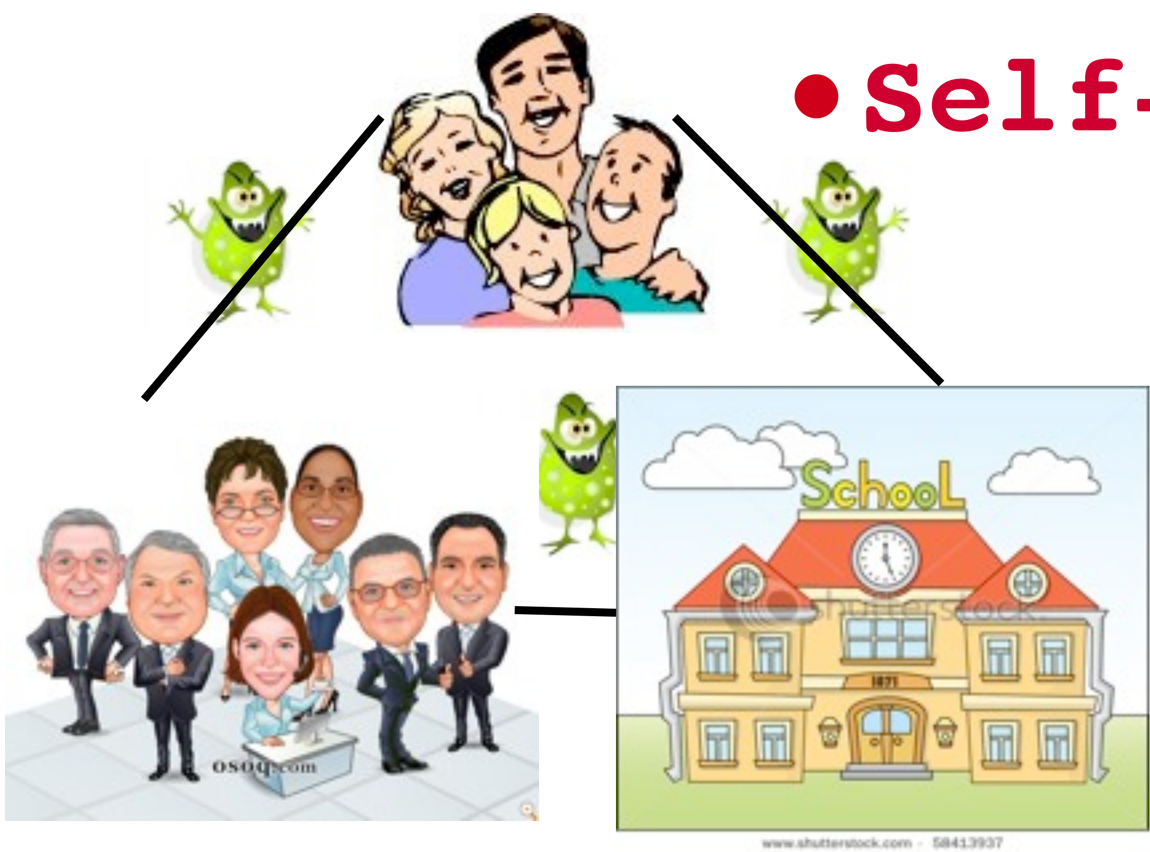


- **Self-organizing Behaviors**



- **Large-scale, Emergent Properties**

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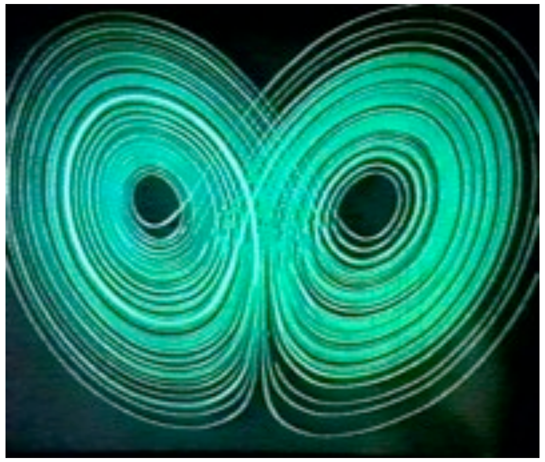

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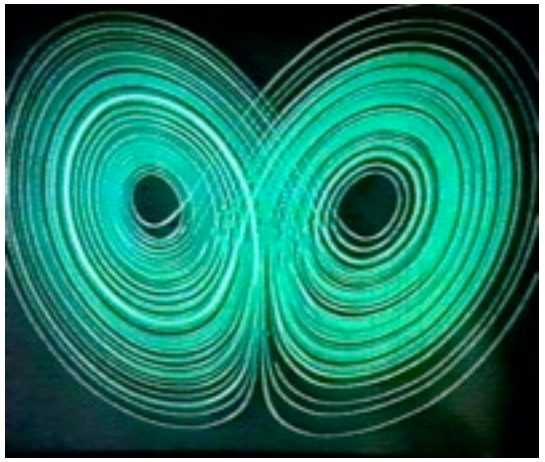

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The Fundamental Task of Complex Systems

Order from Disorder

The Fundamental Task of Complex Systems

Order from Disorder

Self-Organization

The Fundamental Task of Complex Systems

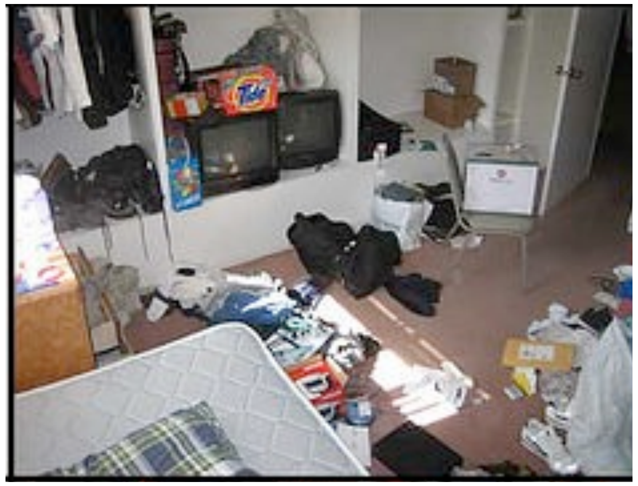
Order from Disorder

Self-Organization

But How Do We *Measure* Order?

Order and Disorder: The Second Law of Thermodynamics

Entropy (disorder) tends to increase.



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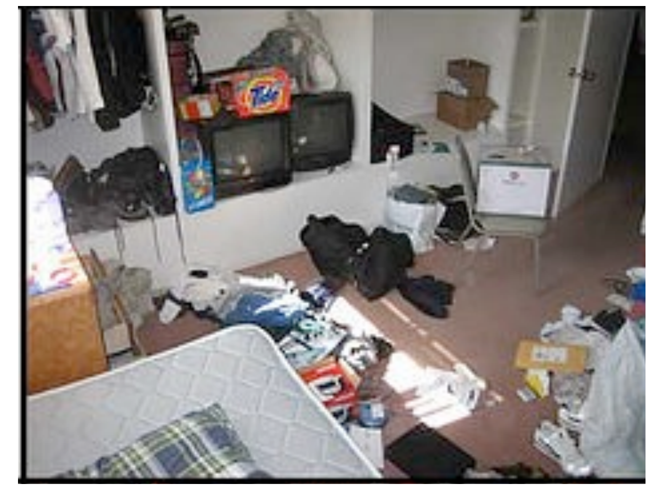
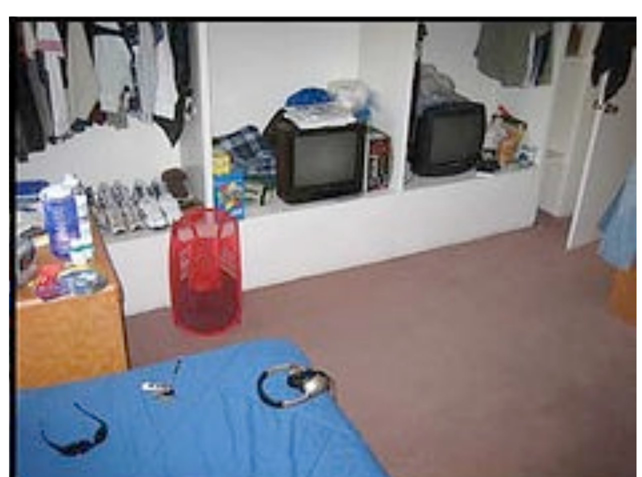


***Unless work* is done to restore order.**



[redacted]echanics (Physics)

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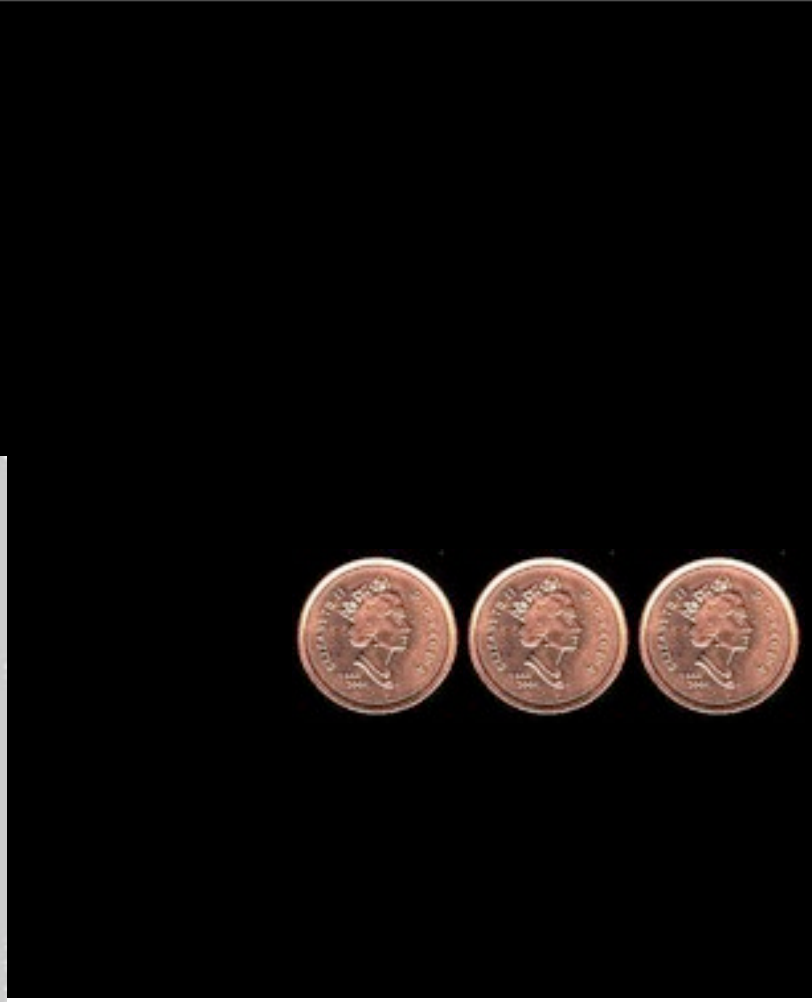
Ludwig Boltzmann



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E.g. “All Heads”

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 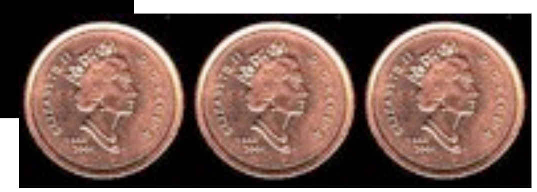

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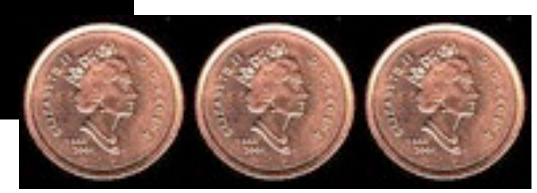

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- System is *most likely* to be found in macrostate with *most* microstates

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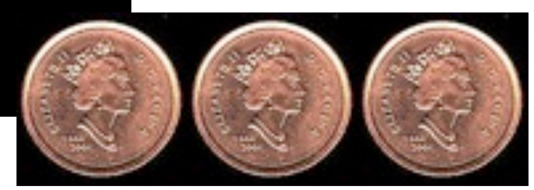

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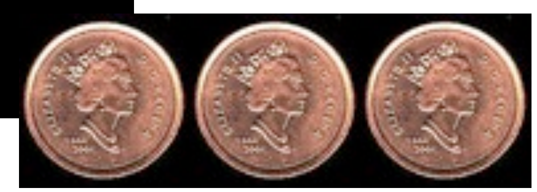

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- System is *most likely* to be found in macrostate with *most* microstates

Is this an ordered state or a disordered state?

Boltzmann says the most likely macrostate is the macrostate with the *greatest entropy*

Summing up...

Microstate

Ways of arranging (ordering) parts of a system

↓

Macrostate

Collection of microstates with same “type” of order

↓

Entropy

Measure of likelihood of system to be in a particular macrostate

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A Problem: Maxwell's Demon

Question: How can entropy decrease if (apparently) no work is done?!

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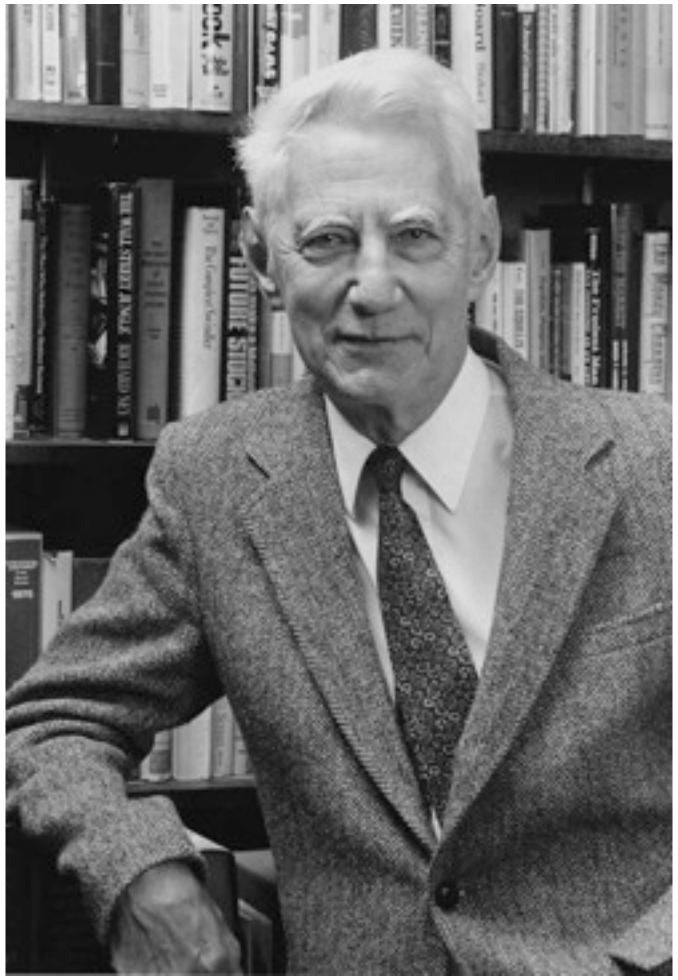
Information ⟷ Order/Disorder ⟷ Entropy

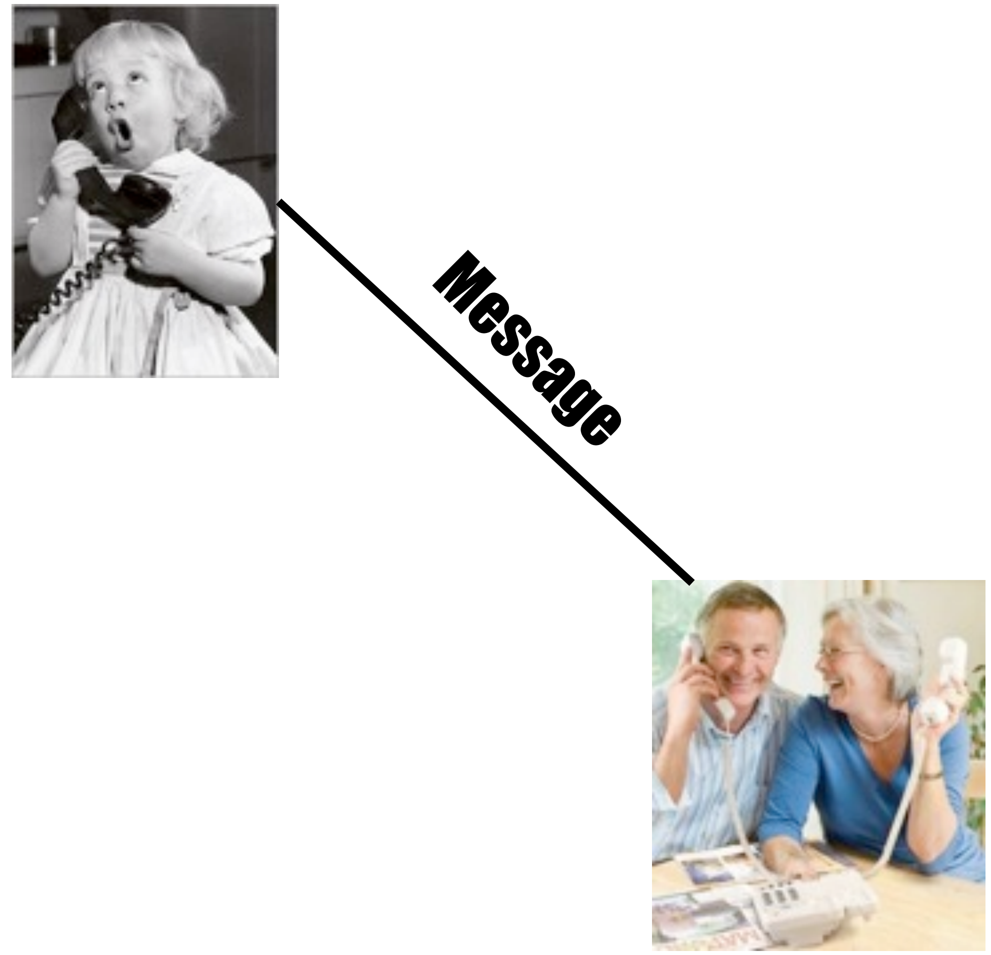
The Next Step: Information Theory

Problem: How can you transmit signals with less loss of information over telegraph and telephone wires?



Claude Shannon

Source



Receiver

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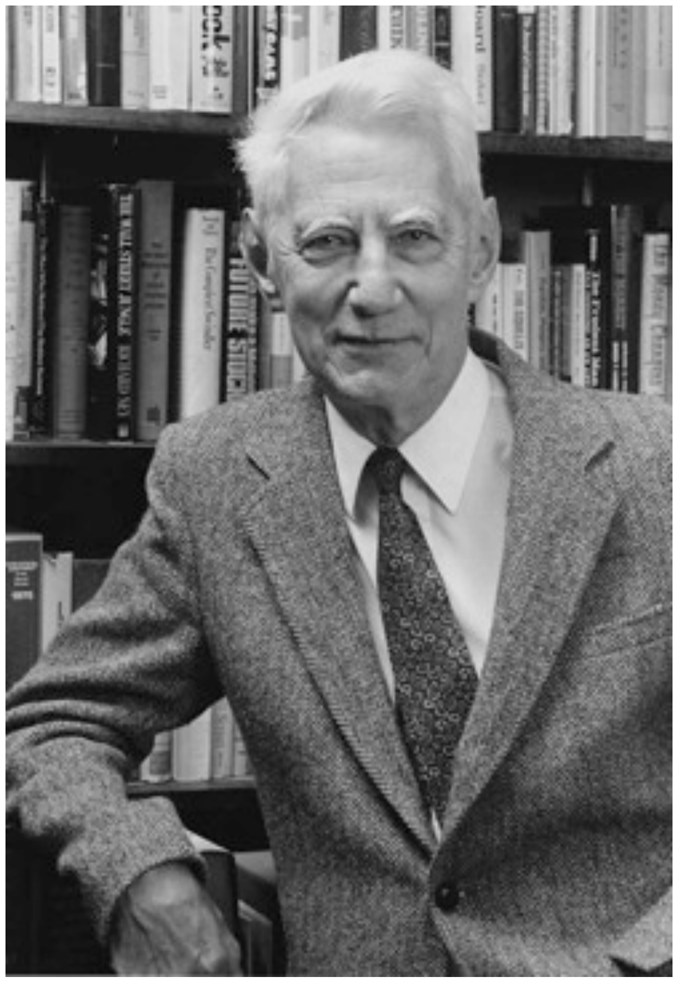

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Source → Macrostate ('made up of' lots of messages)

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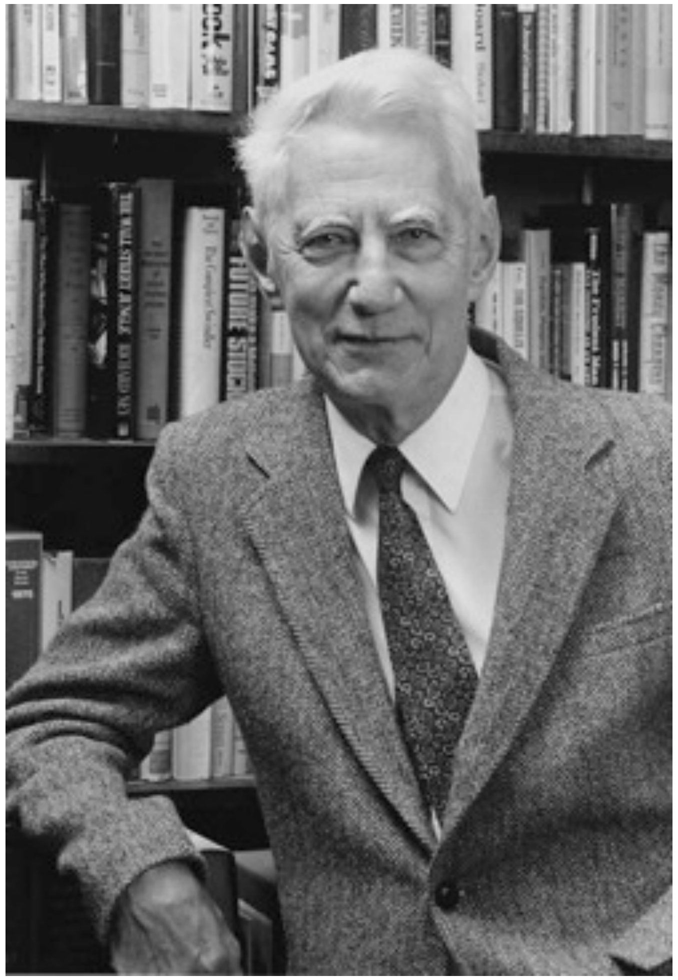

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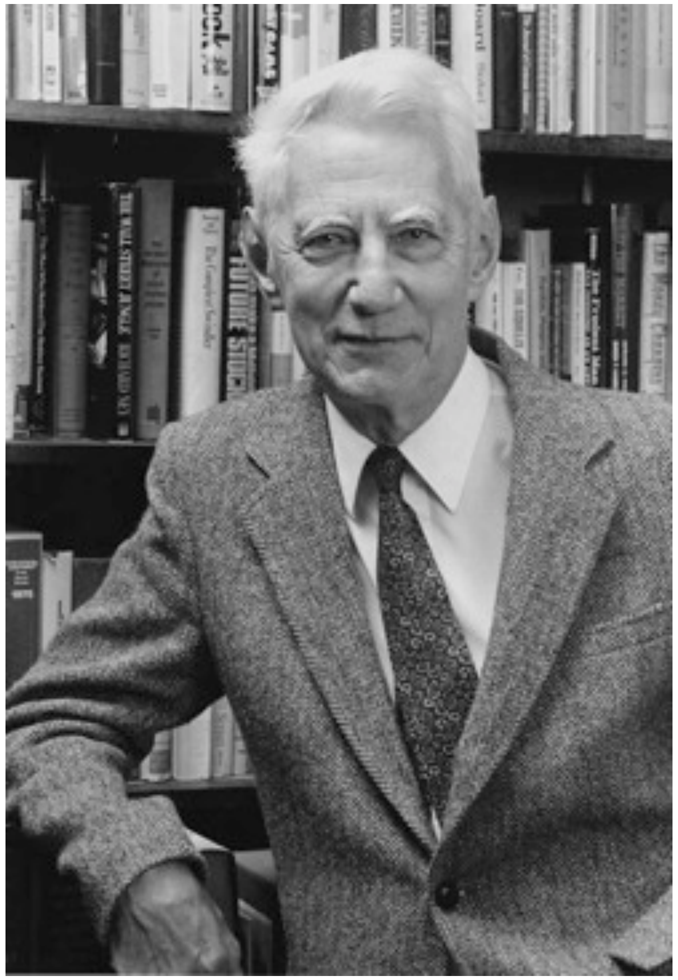

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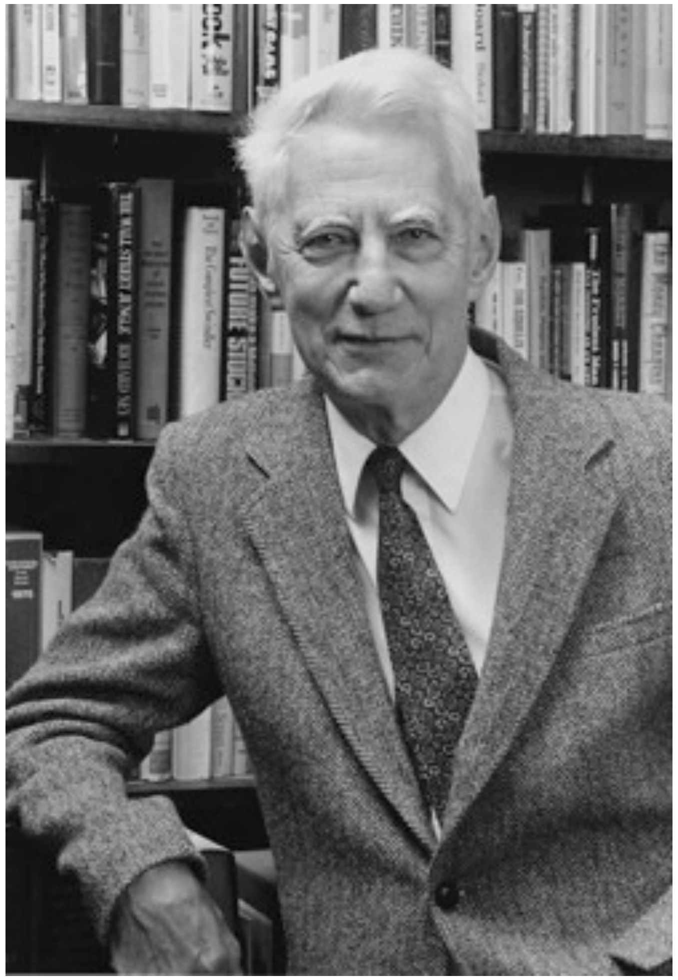

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Shannon Entropy

Where do we use Information Theory?

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- Cryptography (codes and cyphers)
- Computer Science (data compression)
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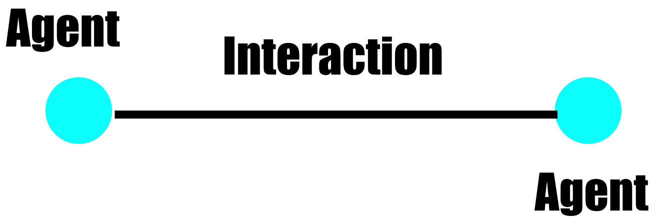
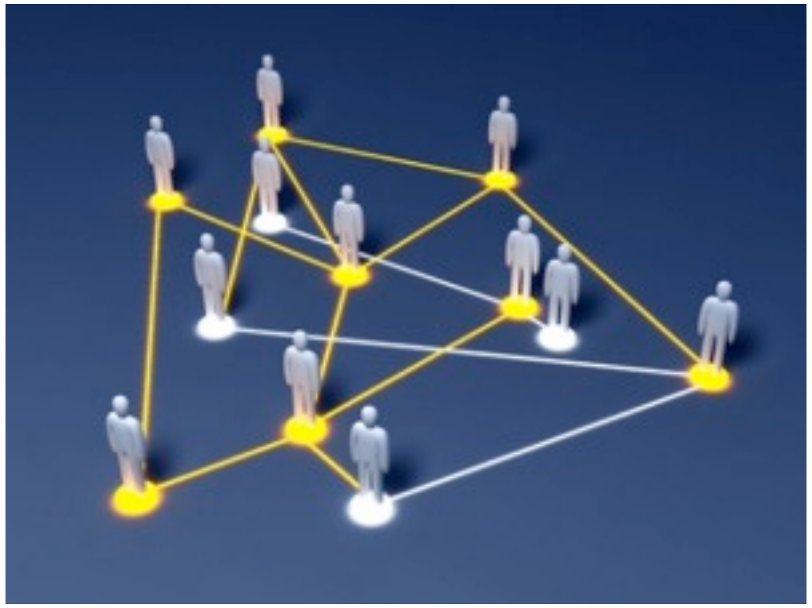
What is the *useful* information in a system?

How *non-random* is the system?

What is Network?

- "Picture" of interactions
- Agents become *nodes*, connected by an *edge* if they interact





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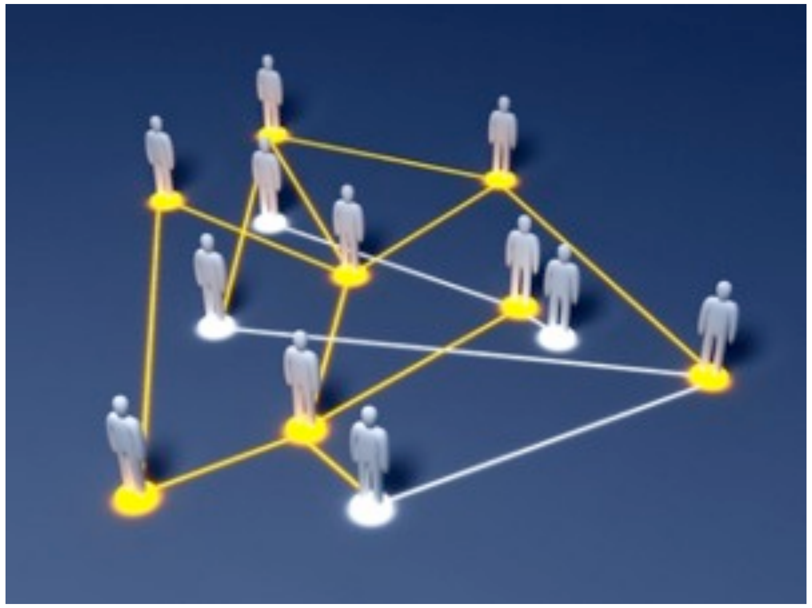

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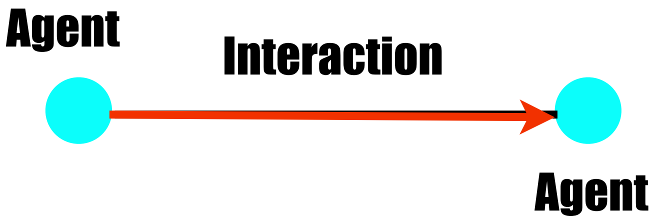

- Edges can be directed

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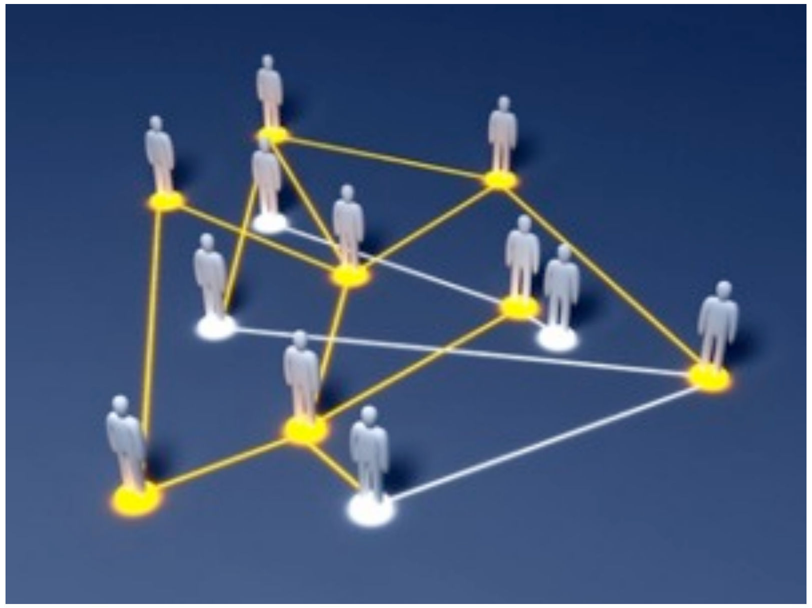

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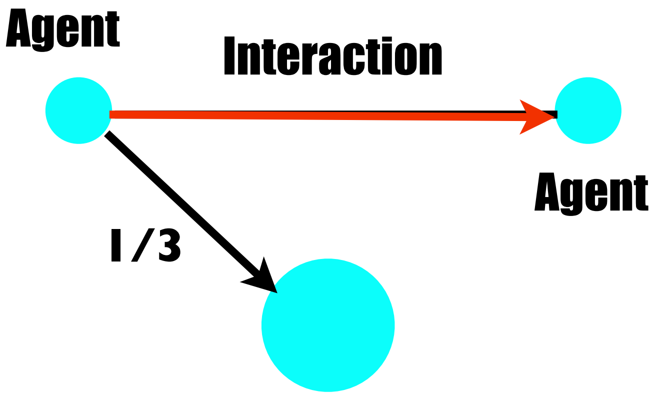

- Edges can be directed
- Nodes/Edges can be *weighted* to convey information about, e.g. strength of interactions

Networks, networks everywhere!

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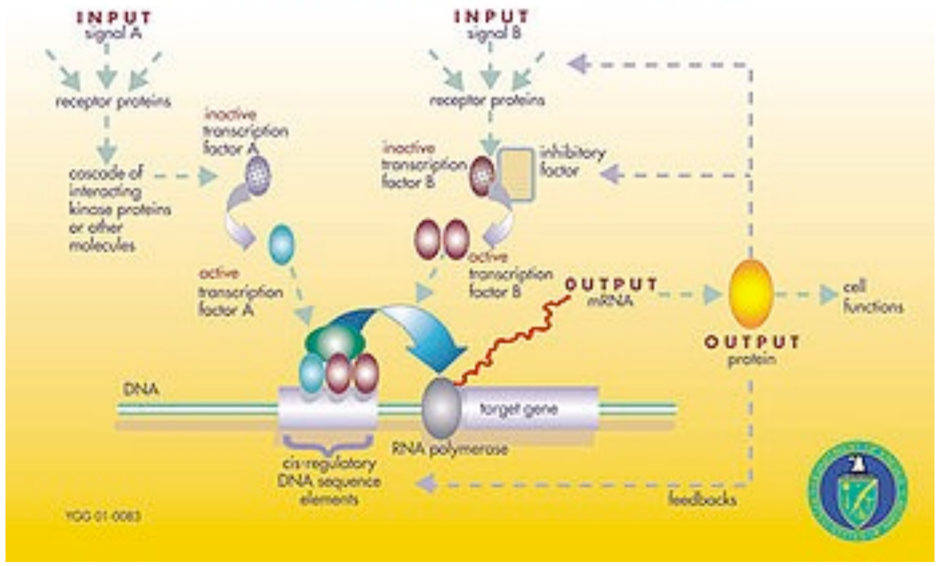
Nodes: Genes (proteins) Edges: Activation/Inhibition



Gene Regulatory Network

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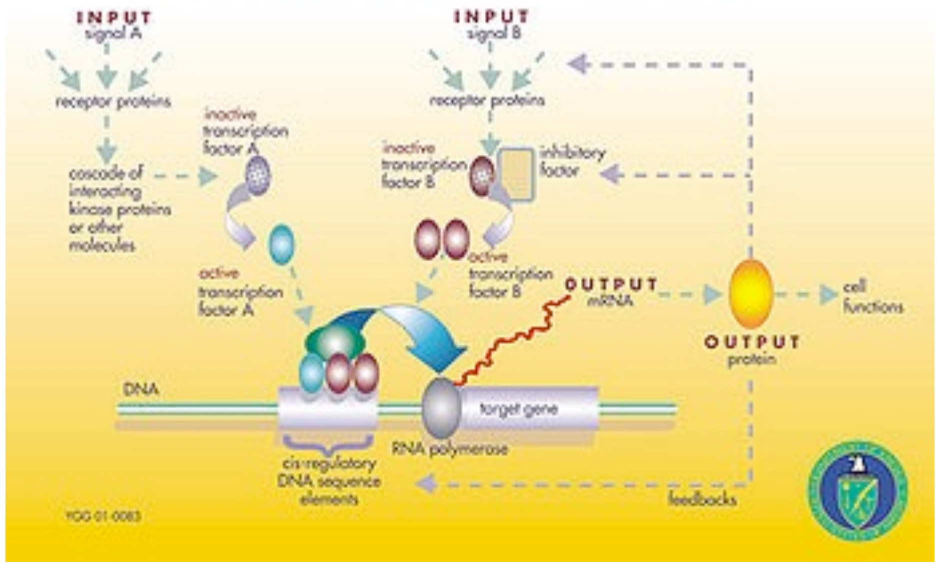
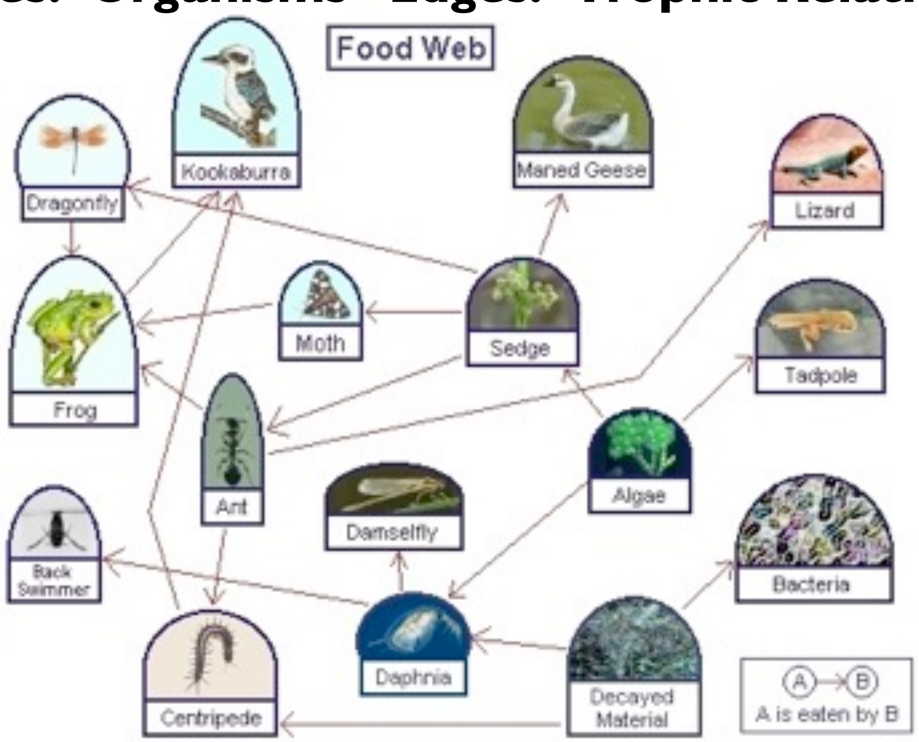


Gene Regulatory Network

Nodes: Organisms Edges: Trophic Relationships



Food Web

Networks, networks everywhere!

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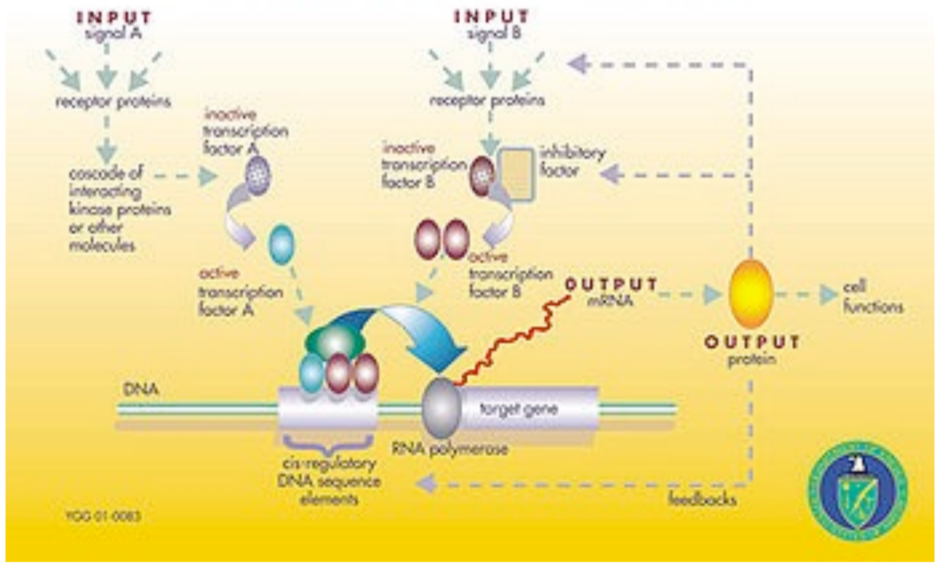

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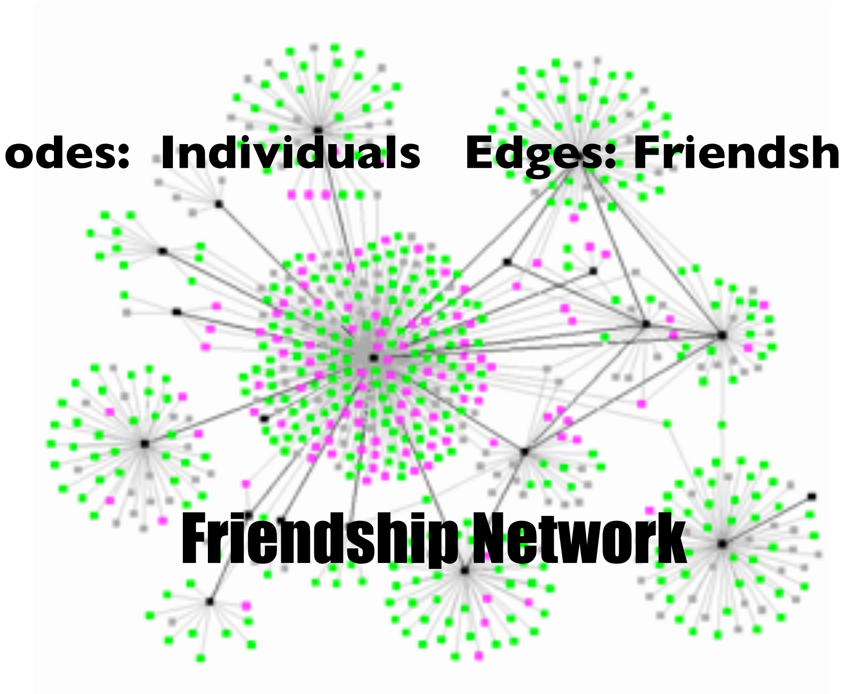
Nodes: Individuals Edges: Friendship



Friendship Network

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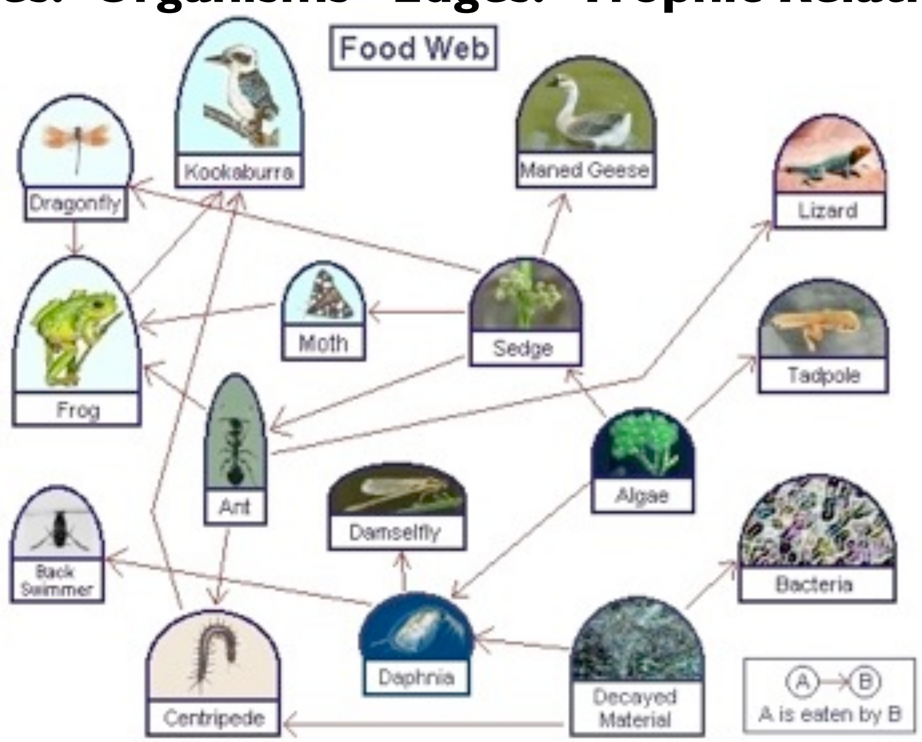

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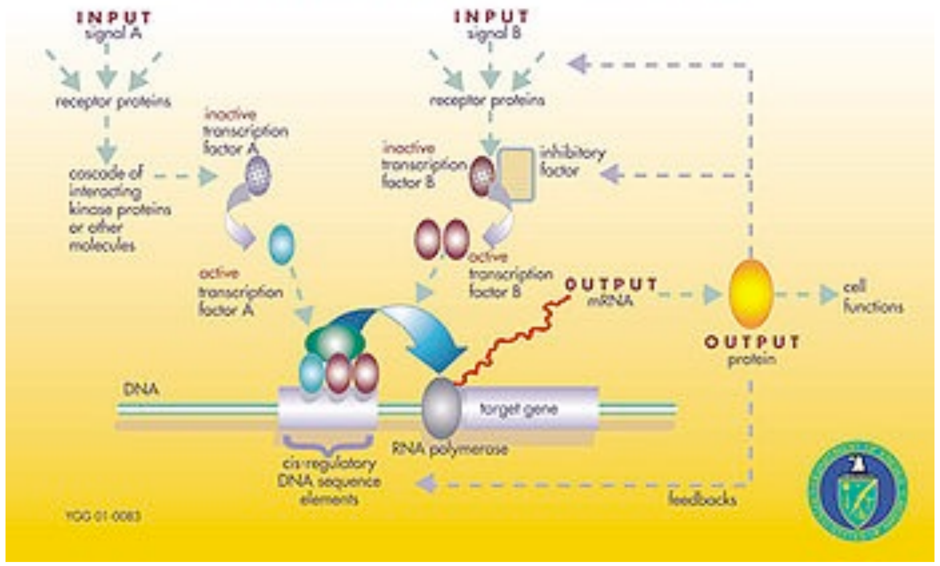

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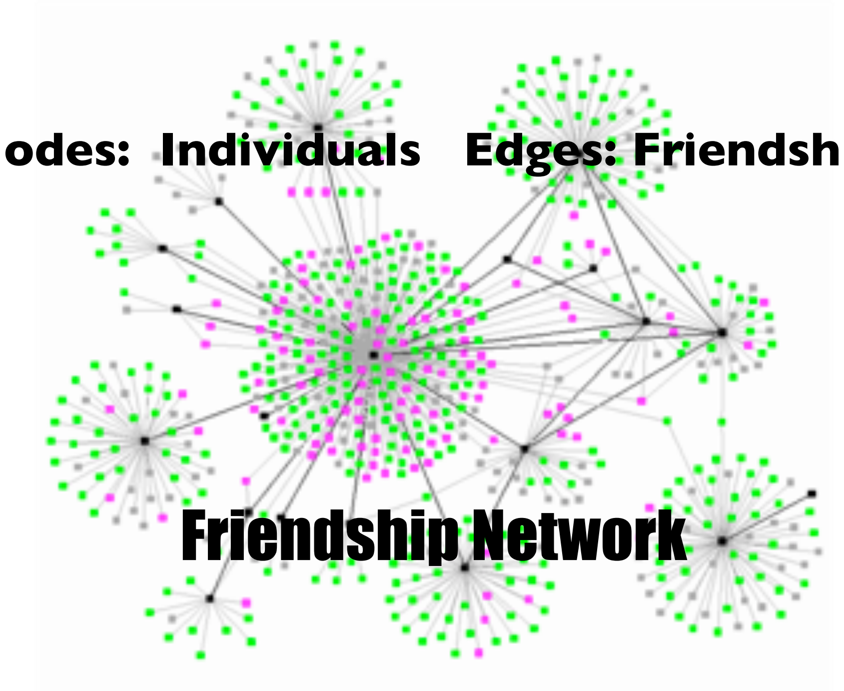

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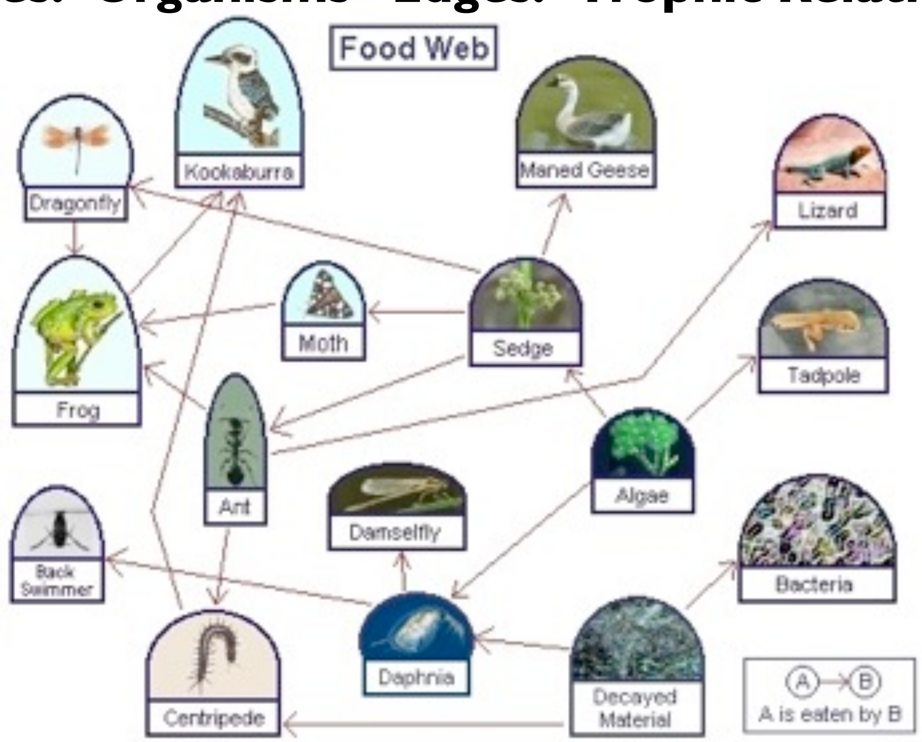
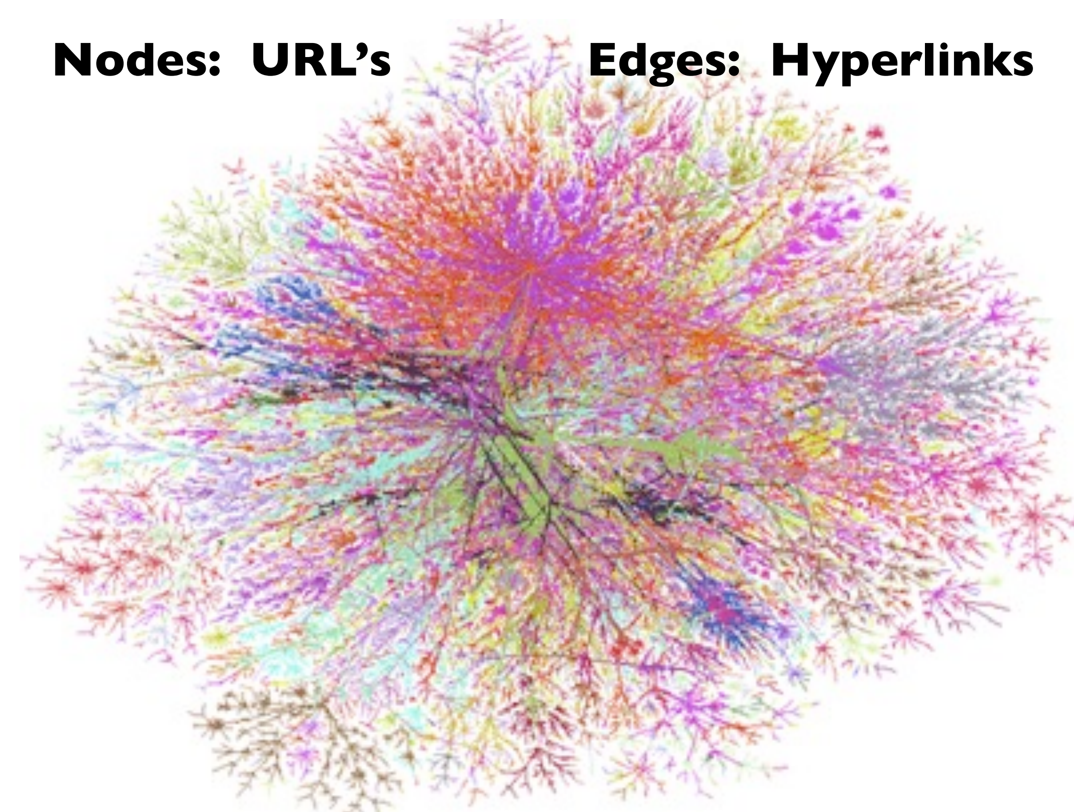


Food Web

Nodes: URL's Edges: Hyperlinks



The "ridiculogram": How do you find *order* or *information* in this mess?!

Structure?

Order?

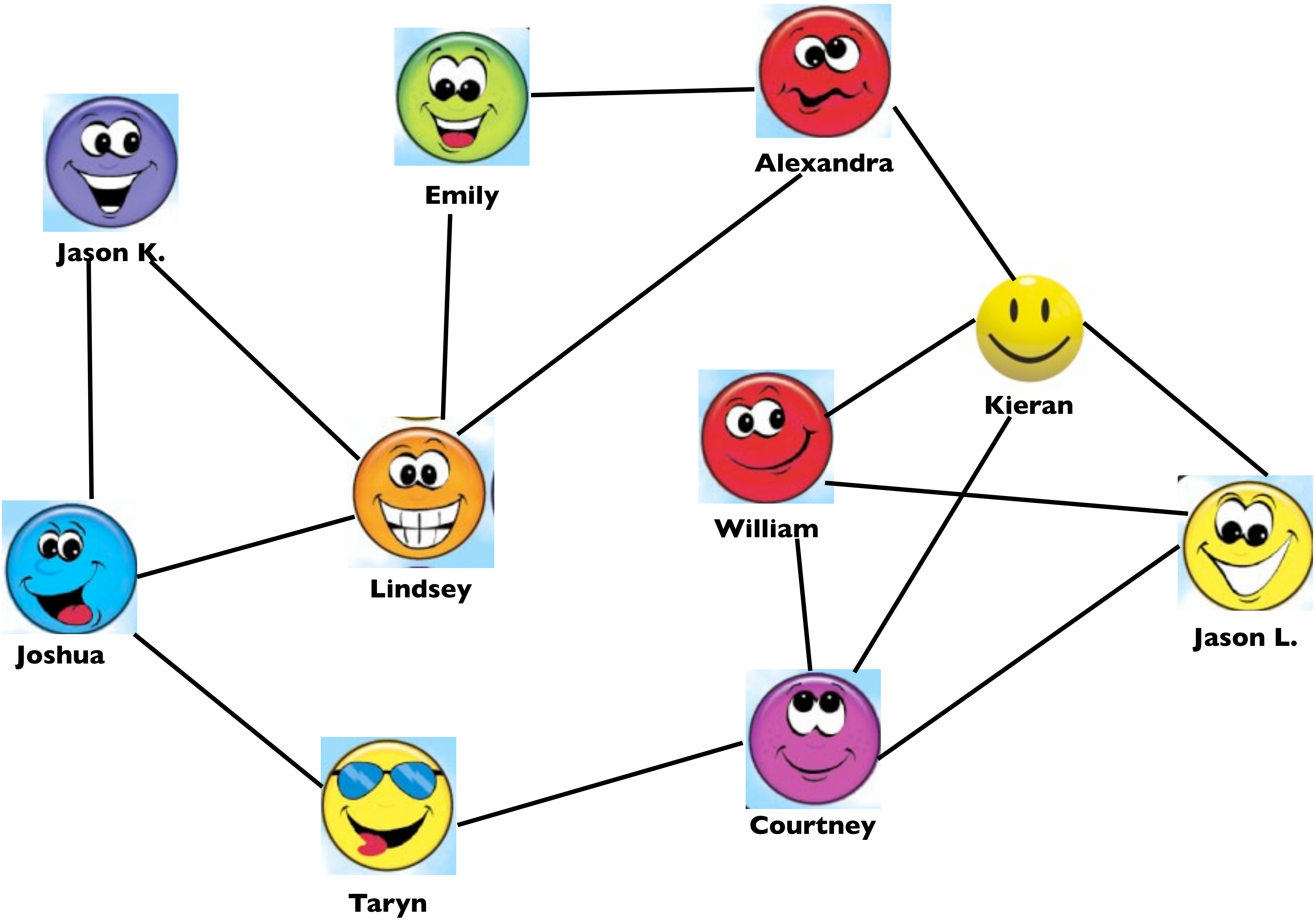
Information?

The World Wide Web

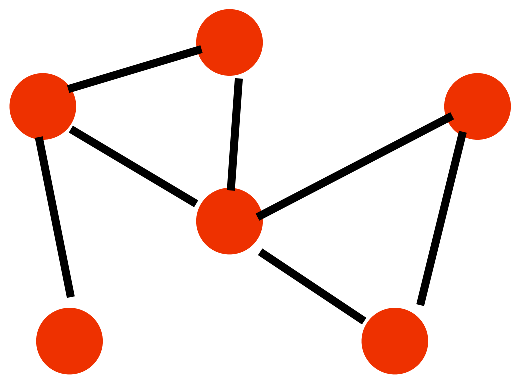
Earlier: *Order* was a measure of information content-- of how much a system *differed* from its *random* counterpart.

An Example...

What are some things you notice about this network?

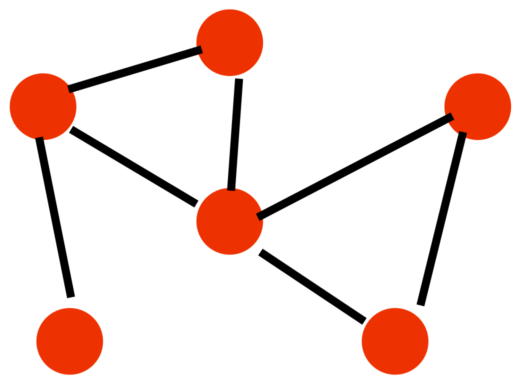


Quantifying Order: Network Measures



Quantifying Order: Network Measures

Degree: How many edges are adjacent to a node



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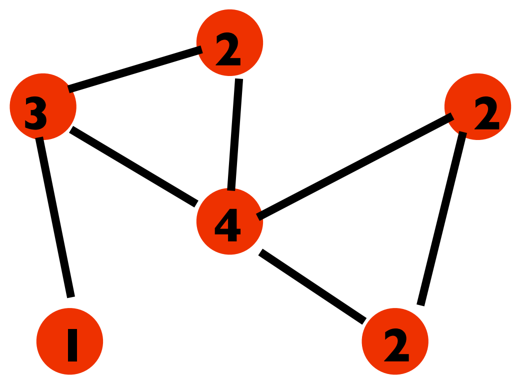

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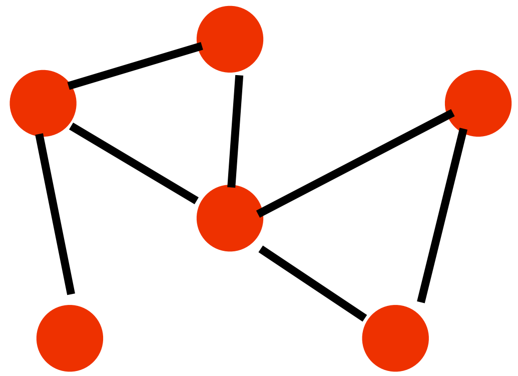

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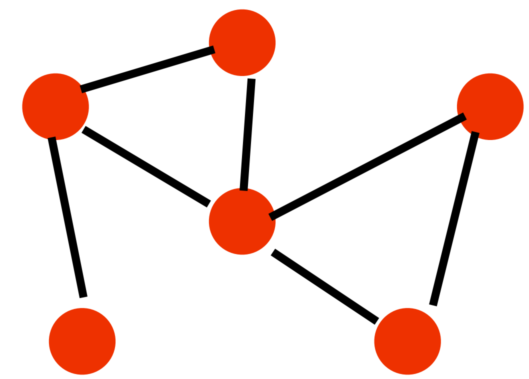

Clustering Coefficient: 3 times number of closed triangles divided by number of possible triads (two edges with a shared node)

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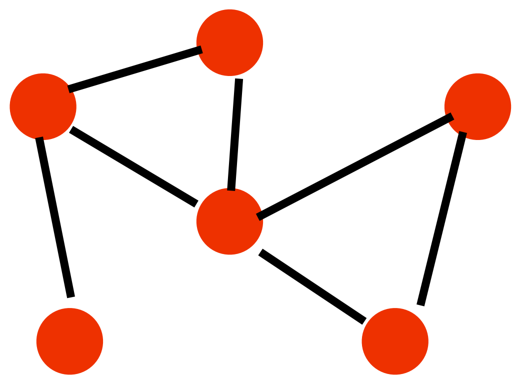

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C=1/2

Quantifying Order: Network Measures

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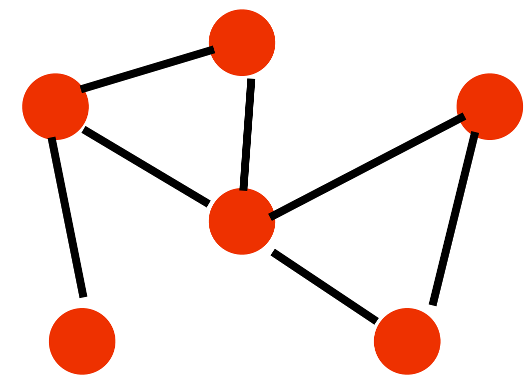

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Distance: (Fewest) Edges between two nodes

Quantifying Order: Network Measures

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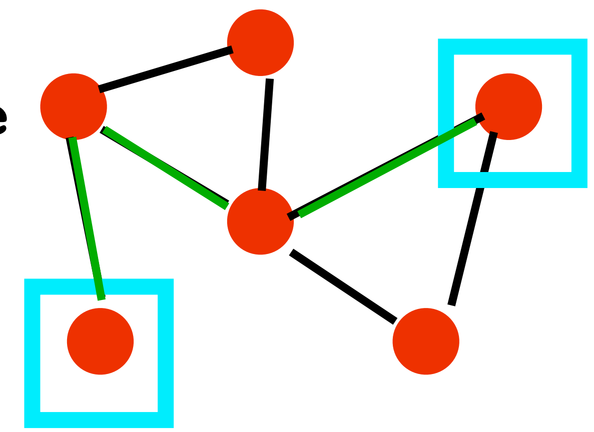

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Distance: (Fewest) Edges between two nodes **d=3**

Quantifying Order: Network Measures

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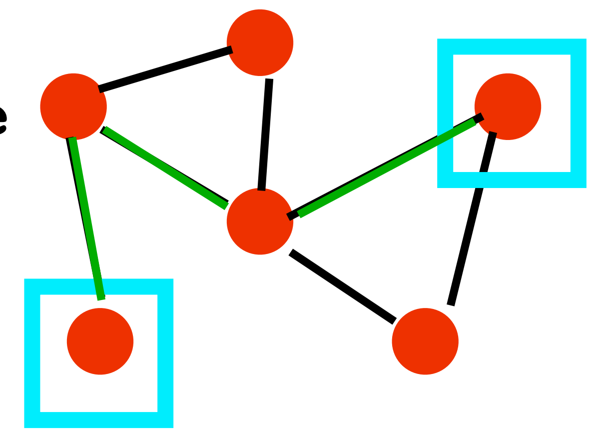

Clustering Coefficient: 3 times number of closed triangles divided by number of possible triads (two edges with a shared node)

C=1/2

Distance: (Fewest) Edges between two nodes **d=3**

MANY other measures...

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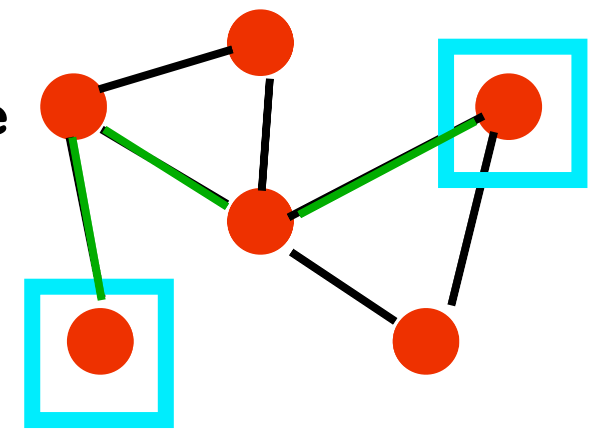

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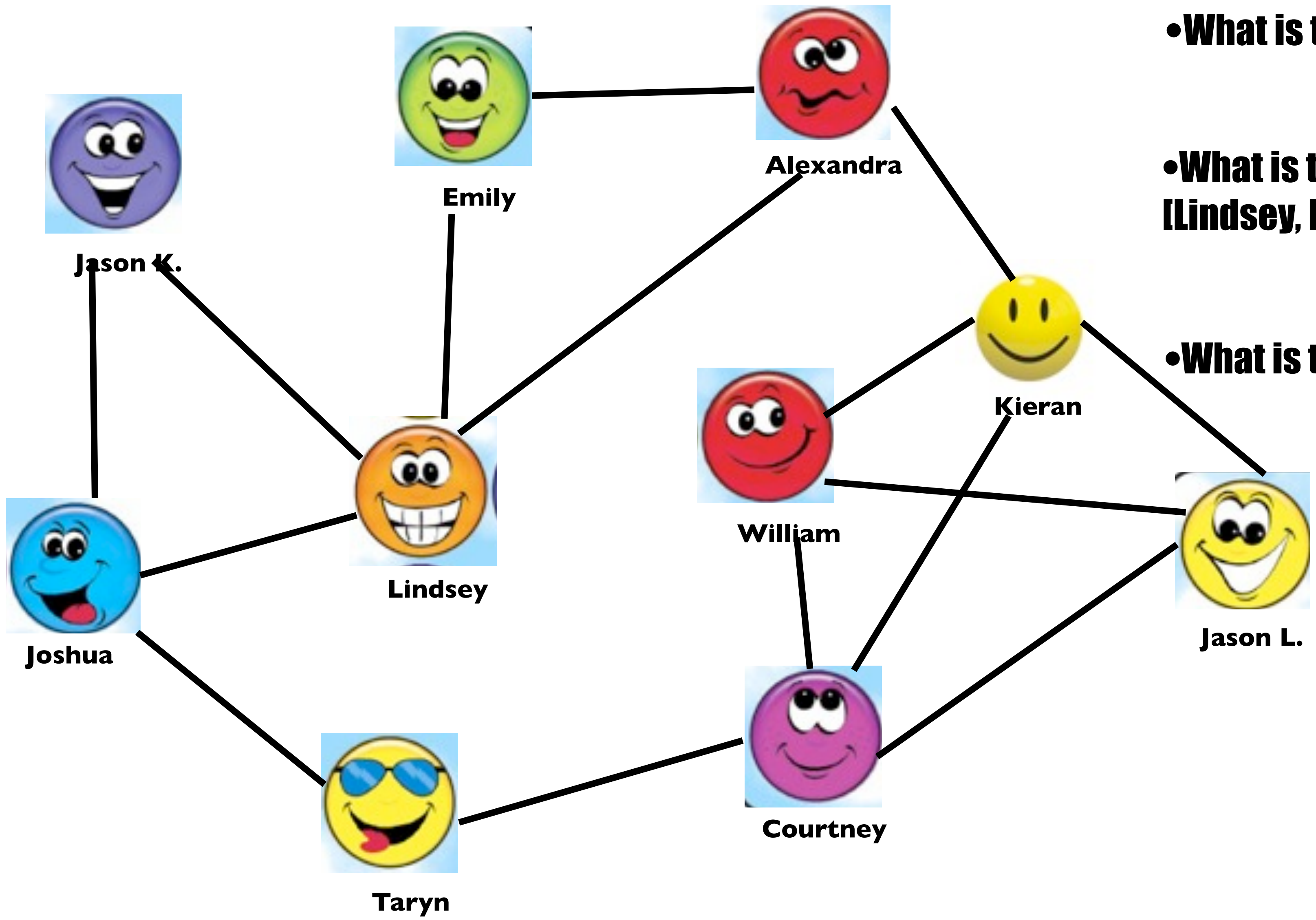
MANY other measures...

How would these measures compare if nodes were attached at random?

Another look at the “EXCEL” network...

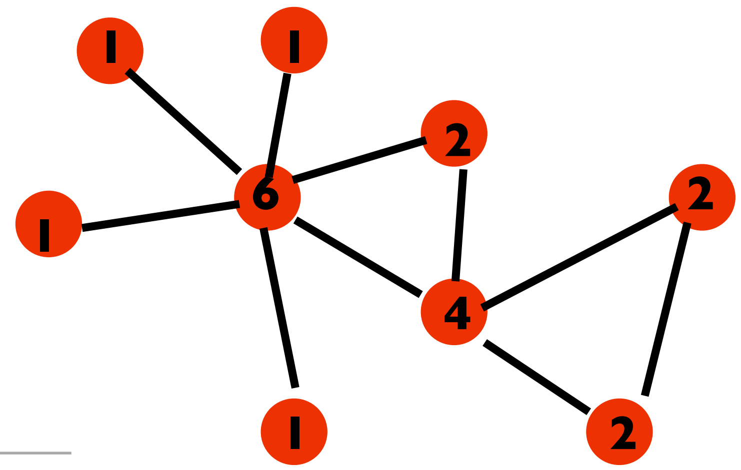


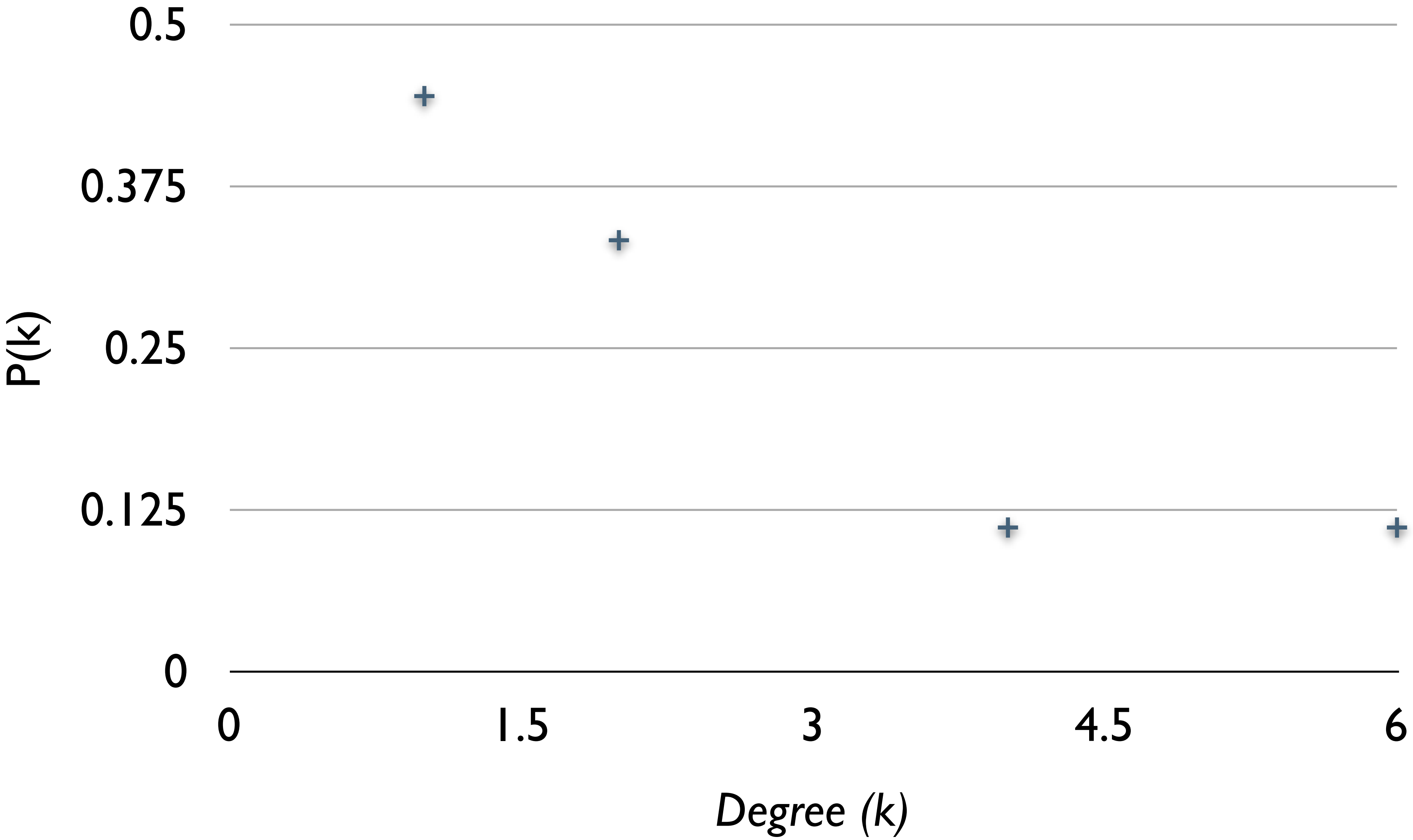
- What is the degree of each node?
- What is the average clustering coefficient of the subset [Lindsey, Emily, Alexandra, Kieran]?
- What is the shortest distance between Joshua and Jason L.?

Information from complex networks: Large-scale patterns

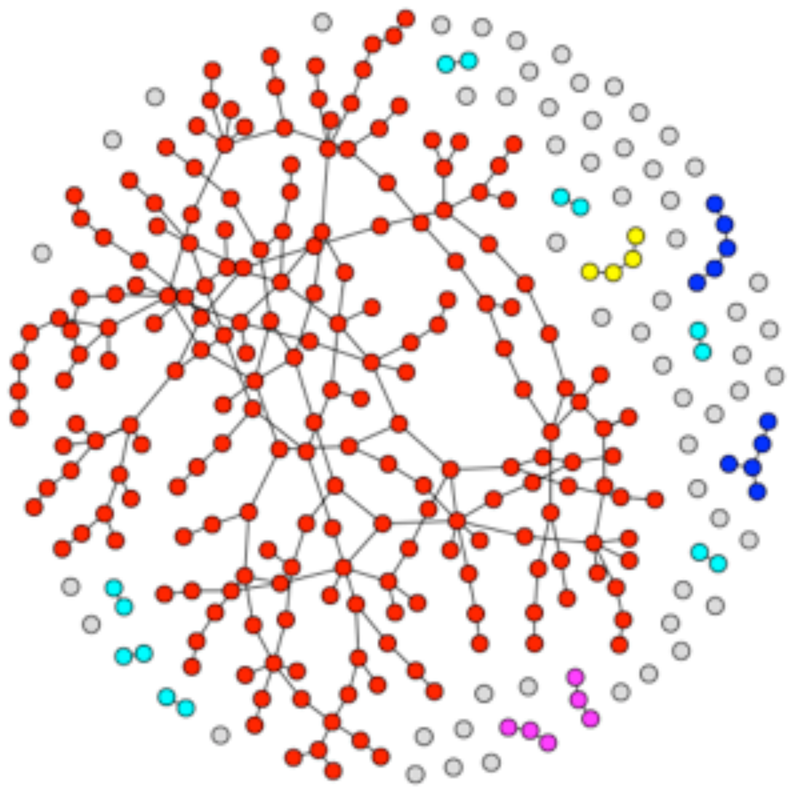
The Degree Distribution

How many nodes of each degree?

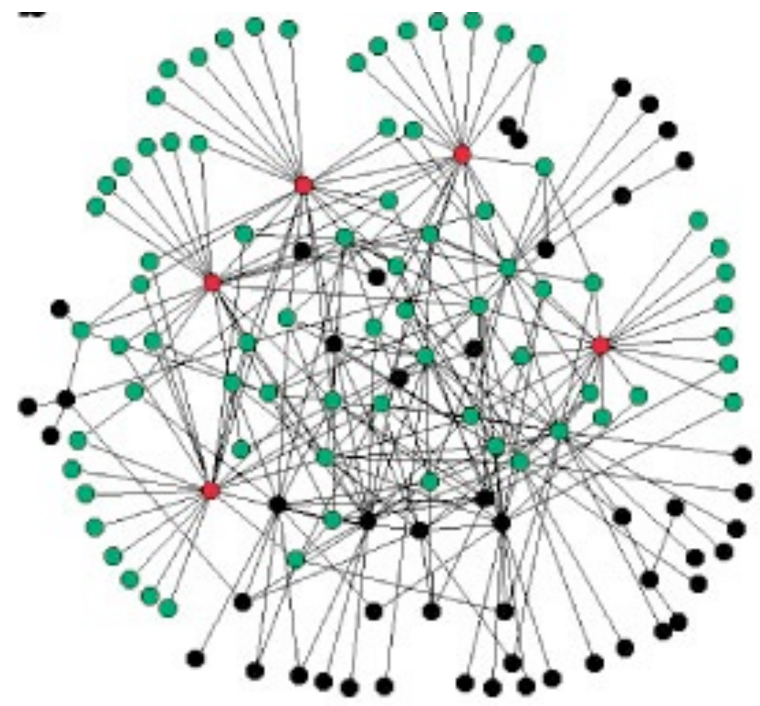




Real-world Networks vs. Random Networks...



Random Graphs



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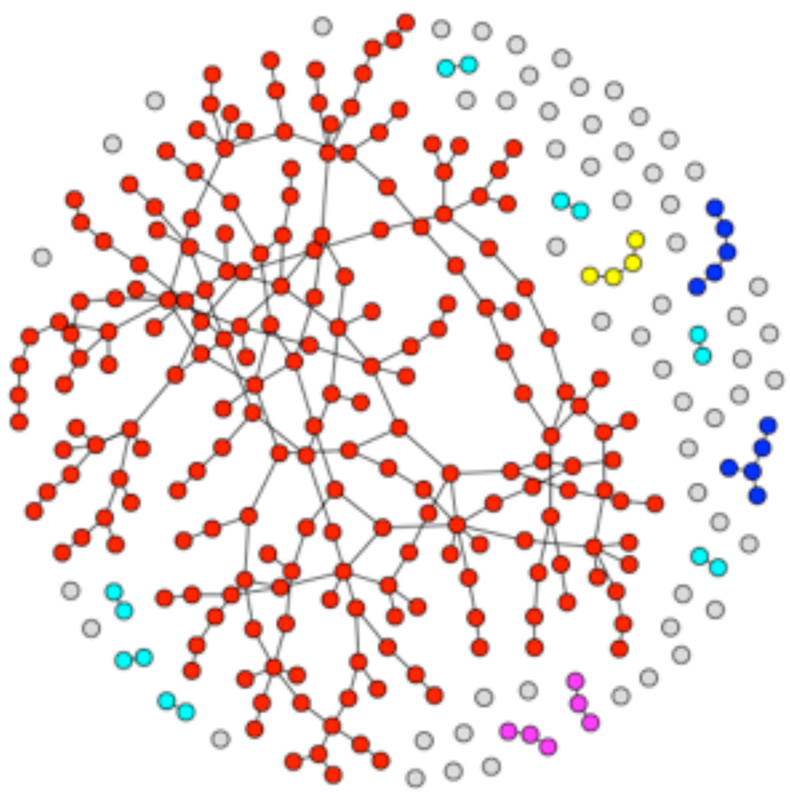

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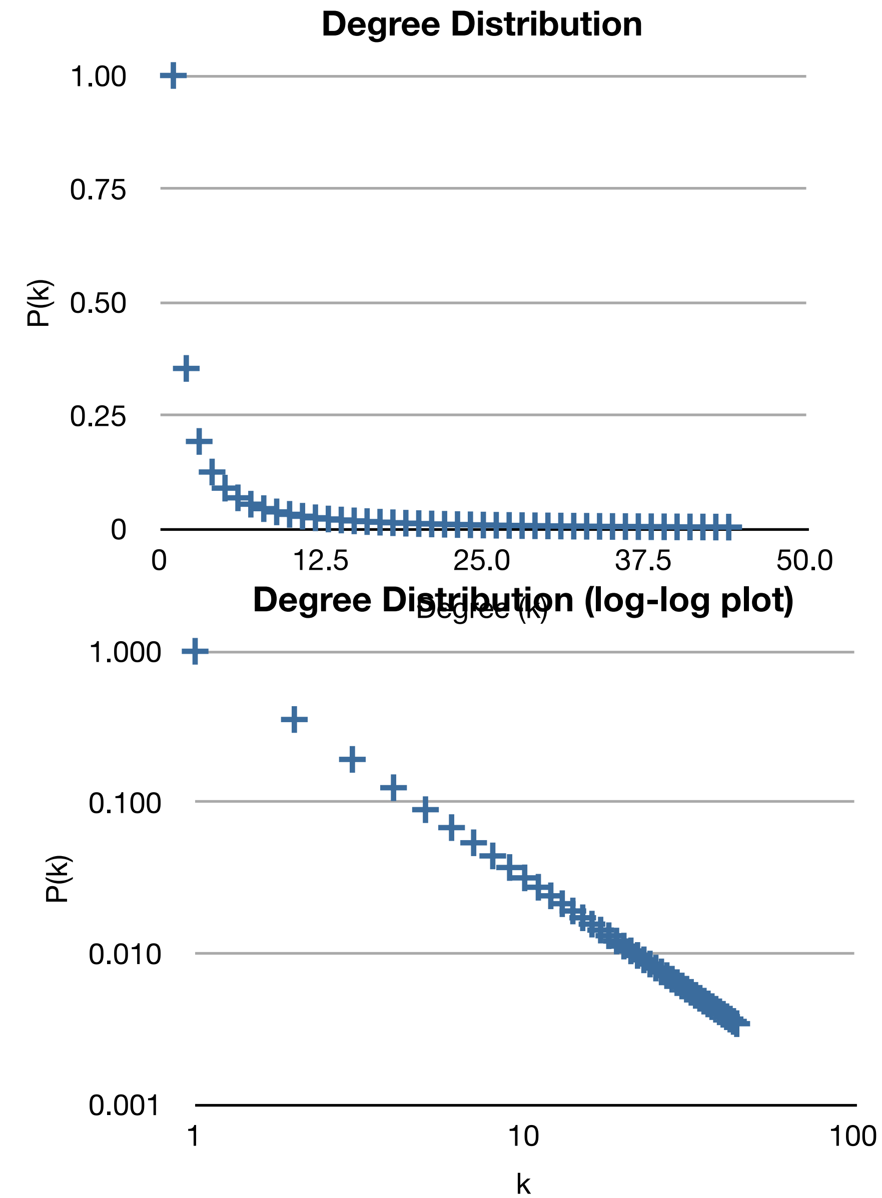

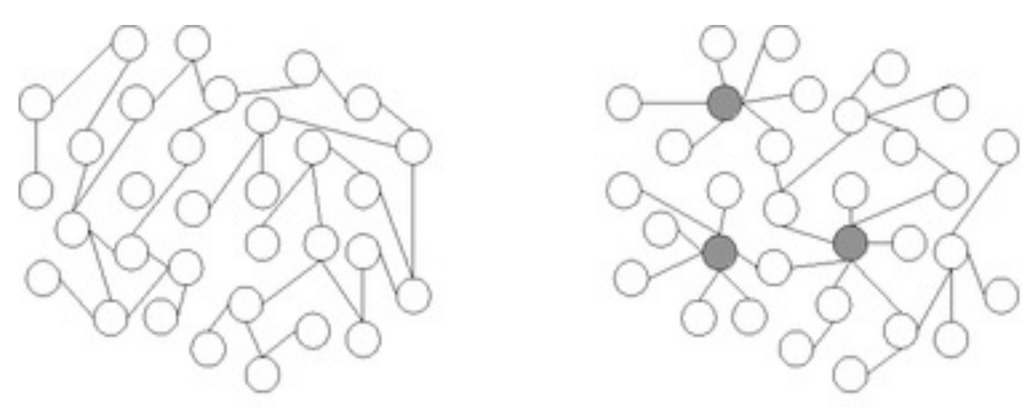

(a) Random network

(b) Scale-free network

Other Patterns in Many Real-World Networks...

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Other Patterns in Many Real-World Networks...

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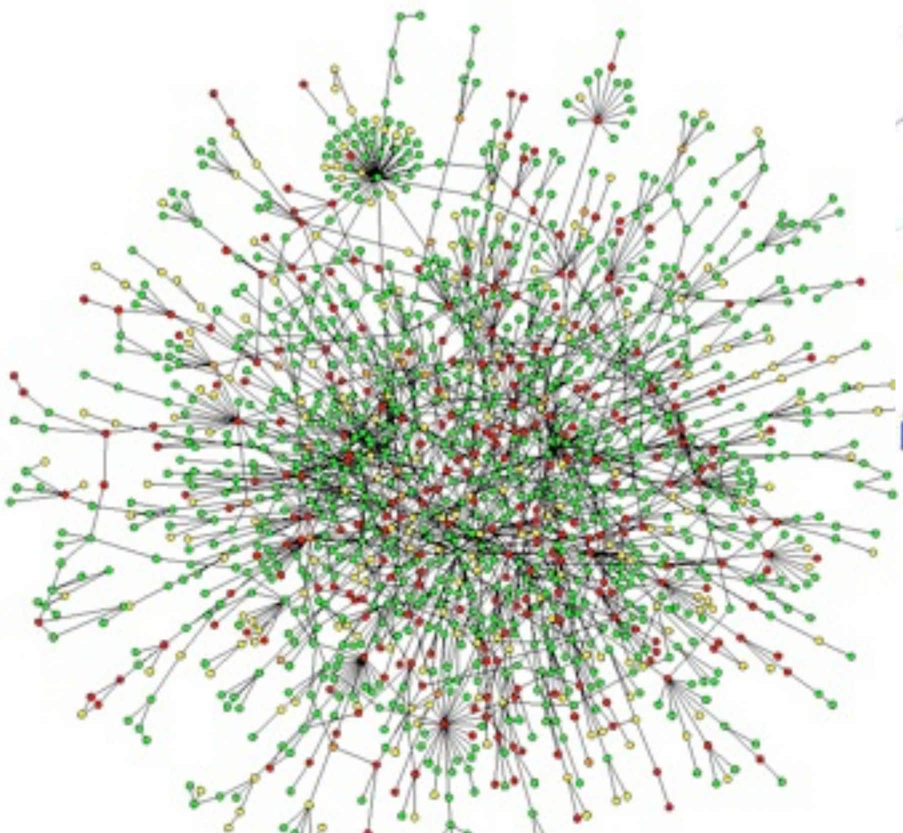
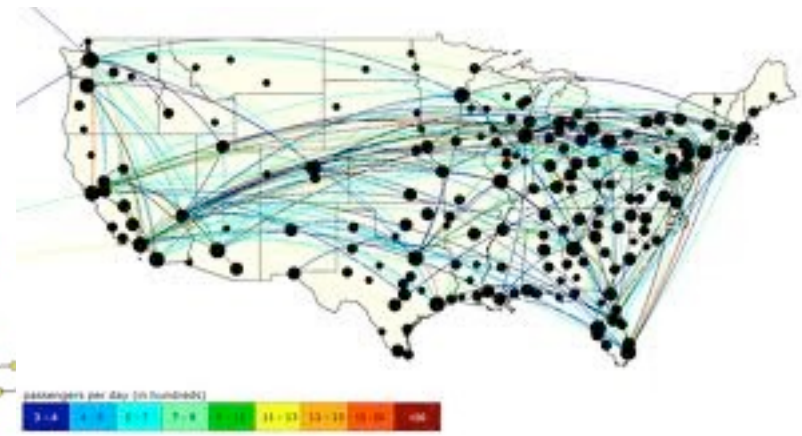
- Large clustering coefficient

- Resilience to random attack

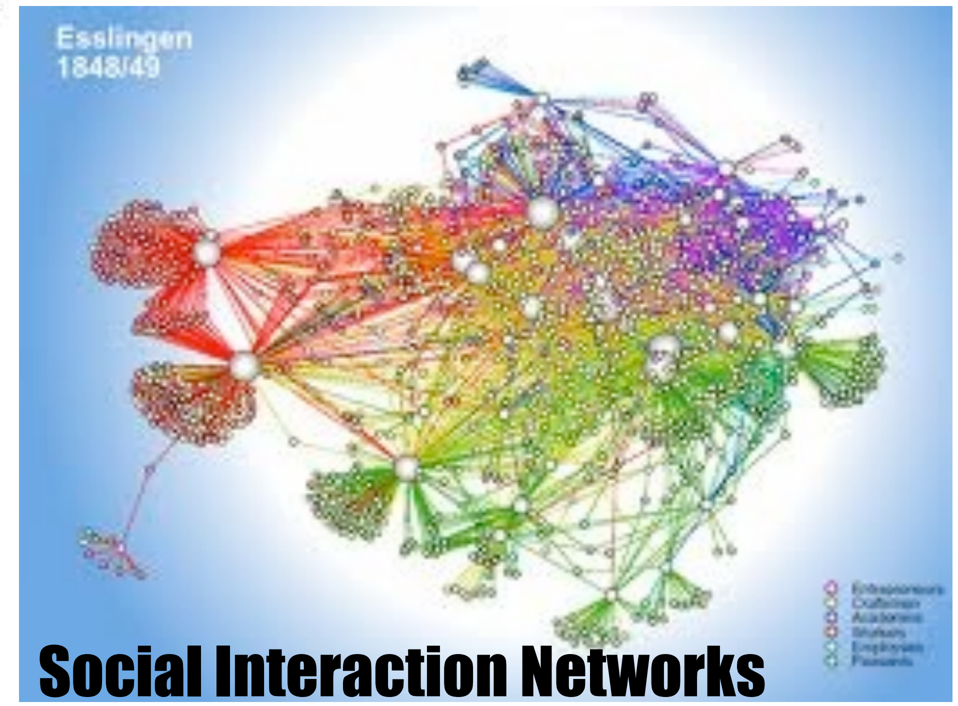
Systems as diverse as...



Protein-protein Interactions



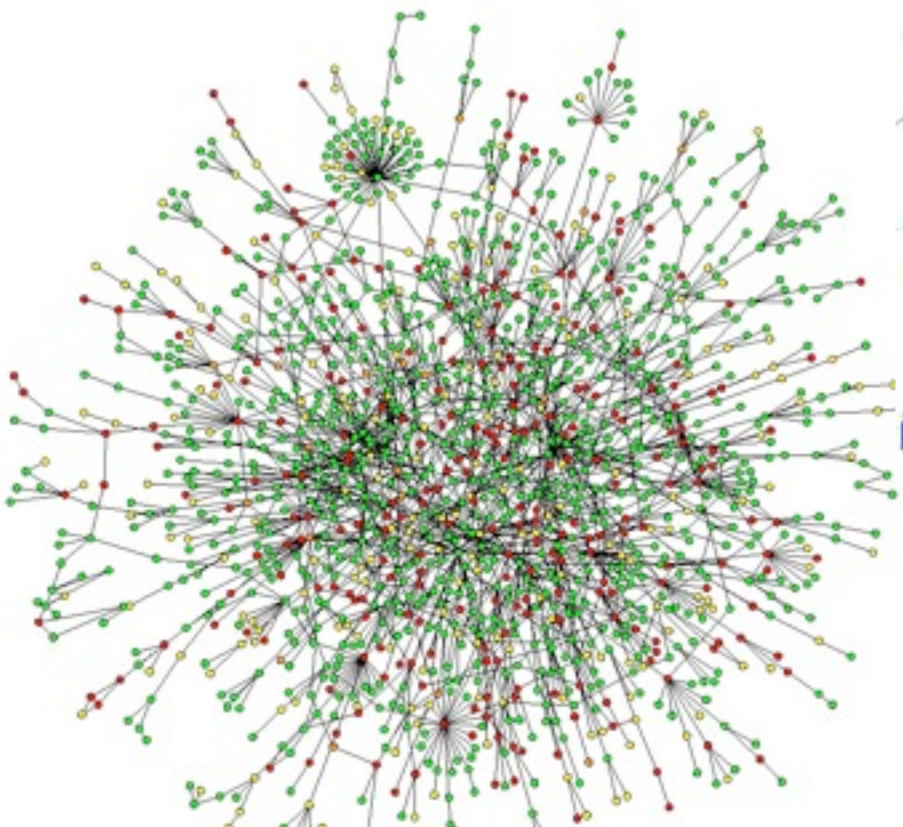
Air Traffic Networks



Social Interaction Networks

Contain similar information on a global scale because of...

Systems as diverse as...



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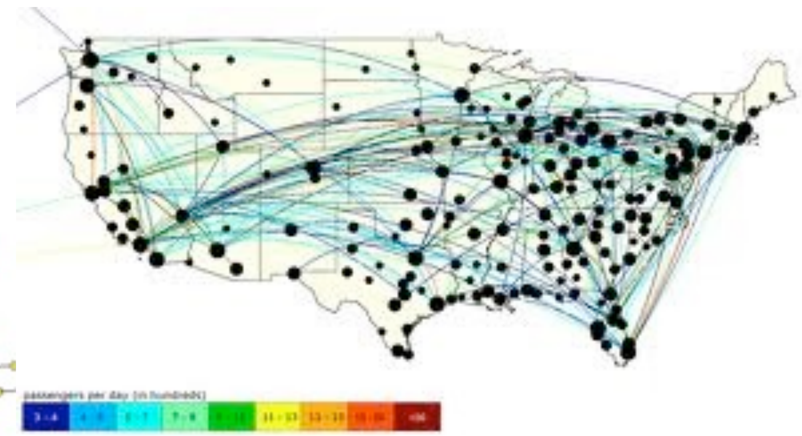

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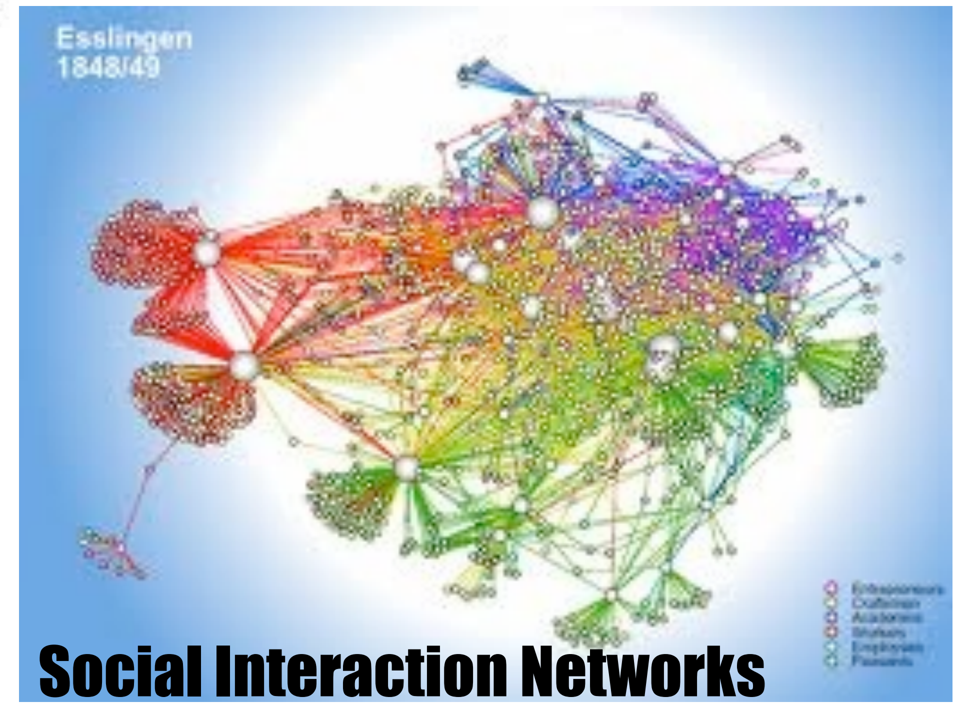

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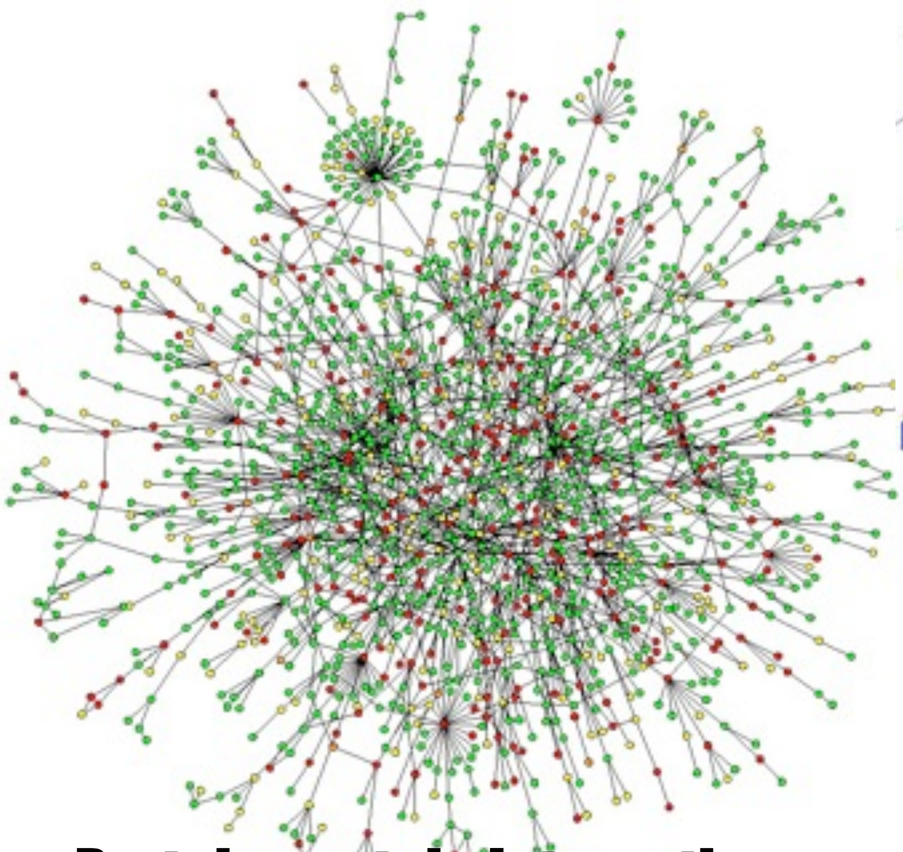

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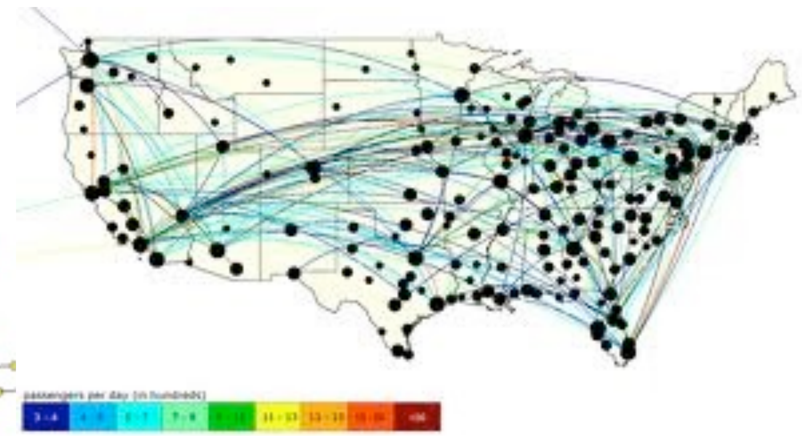
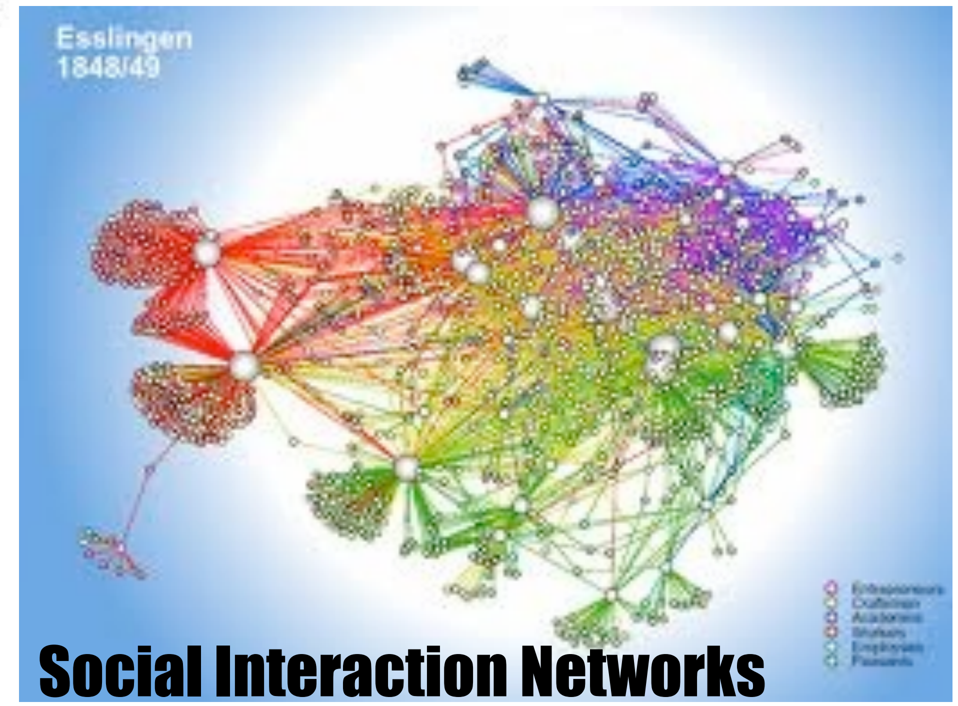


Air Traffic Networks



Social Interaction Networks

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Self-Organizing Behavior

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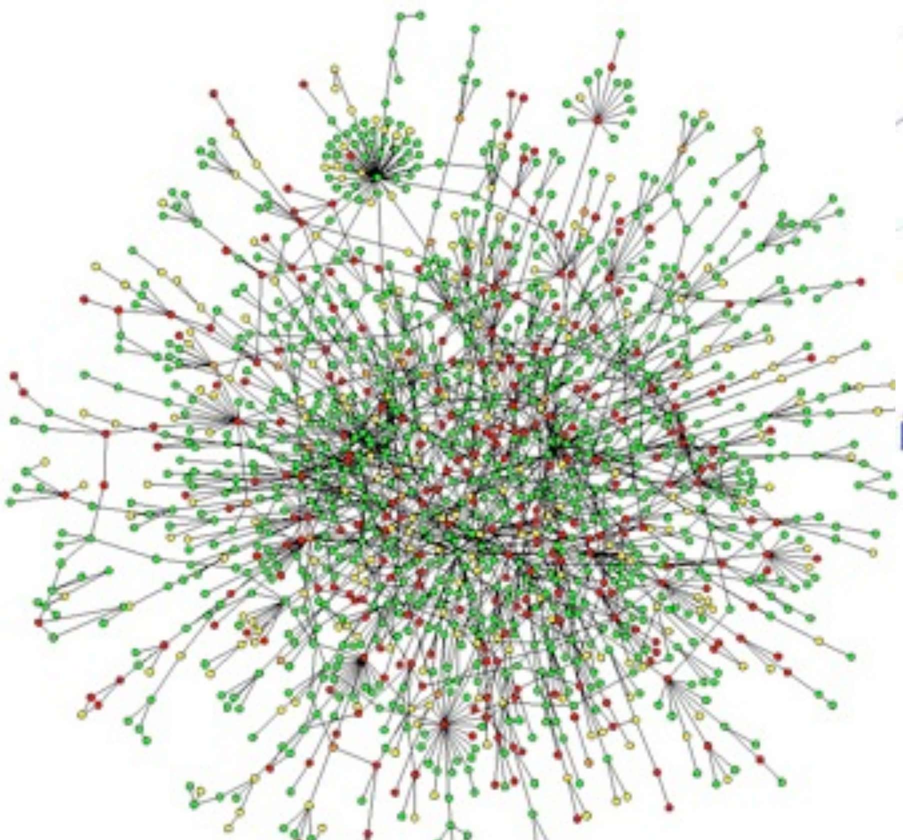

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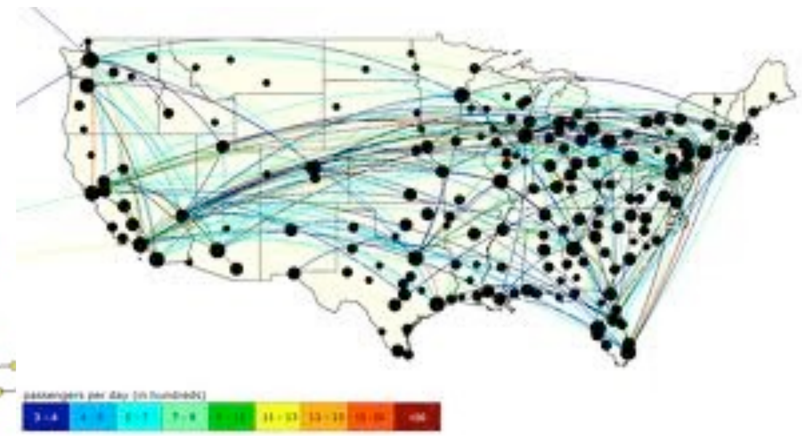

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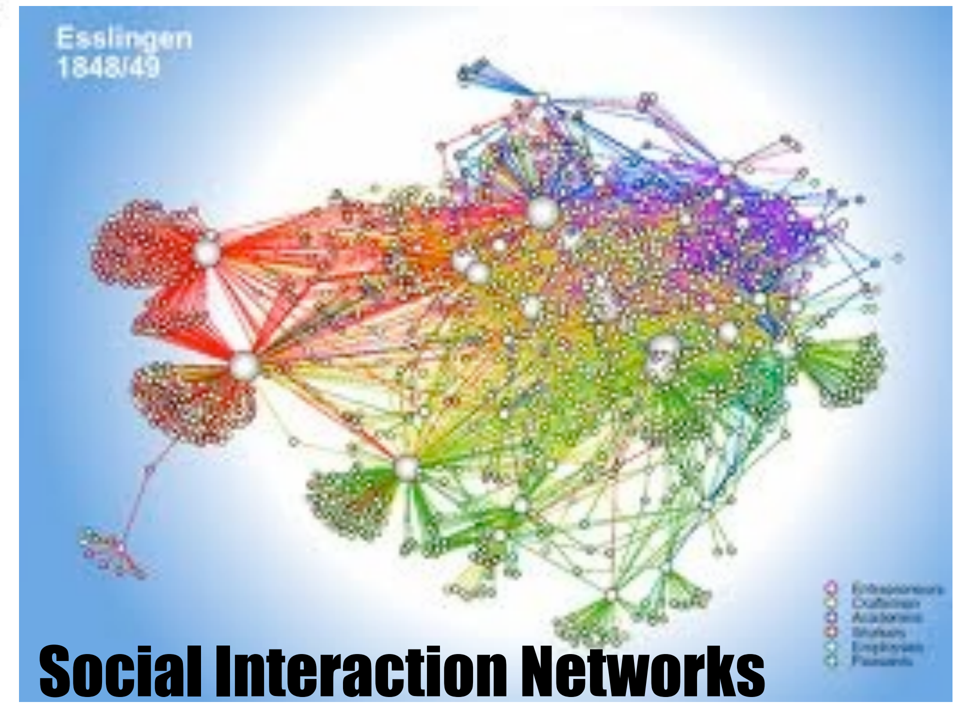

Social Interaction Networks

Contain similar information on a global scale because of...

Simple Interactions

Self-Organizing Behavior

Shared emergent properties!

Where do we use Complex Networks?

- Modeling network formation and structure (e.g. How do large social networks, like Facebook form?)

- Exploring disease/information spread in populations

- Predicting network dynamics (e.g. gene-regulatory networks)

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How do changes in system structure (local or global) affect dynamics?