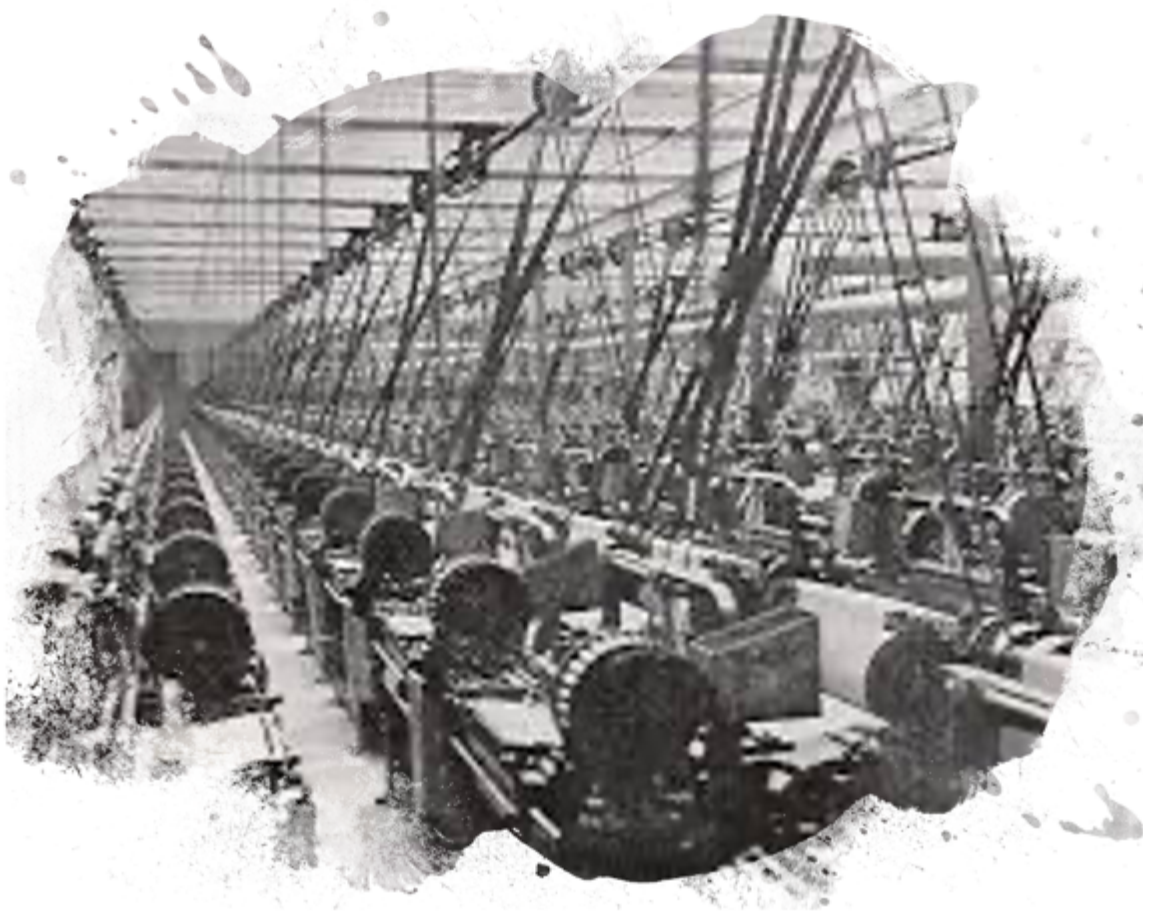
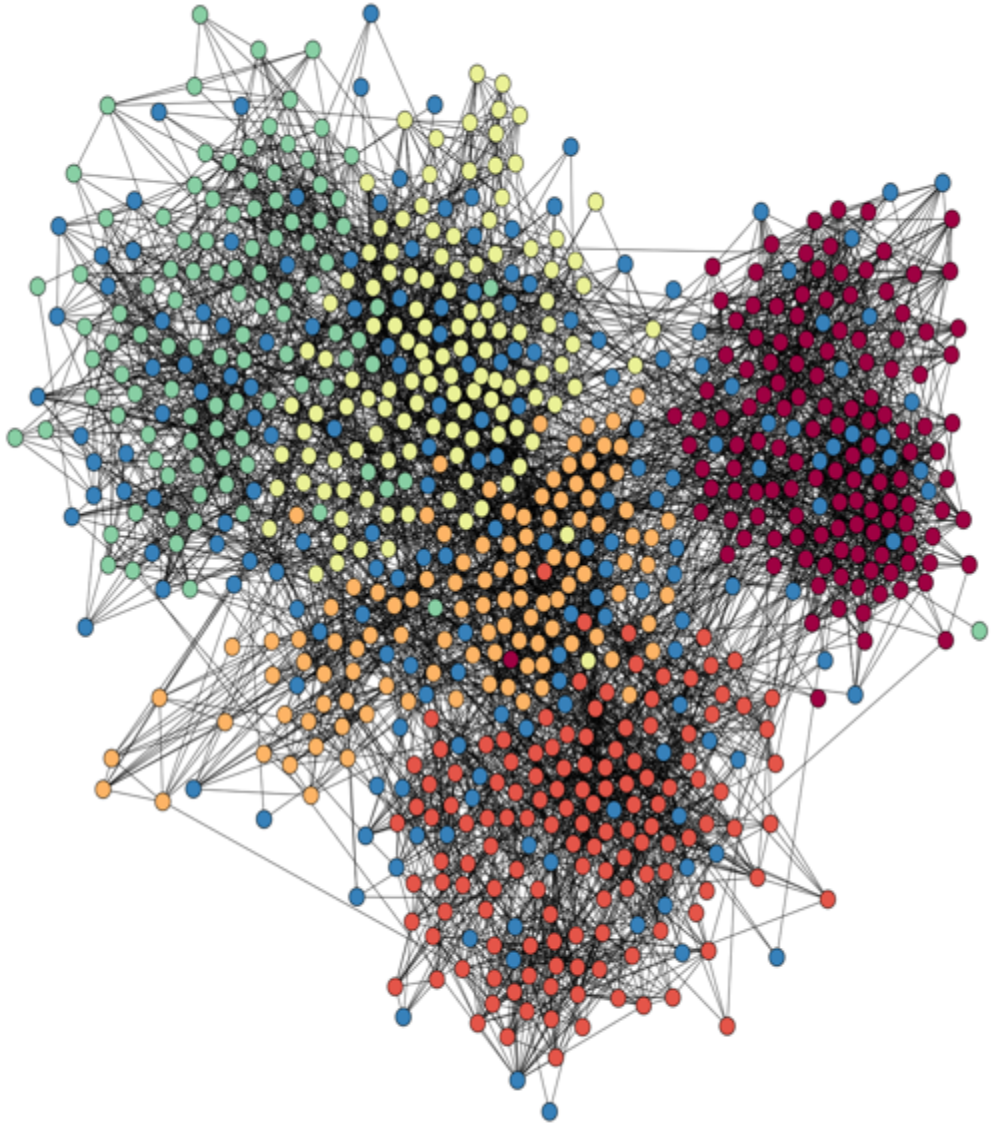
Graphs – A Fundamental shift from Linear to non-linear

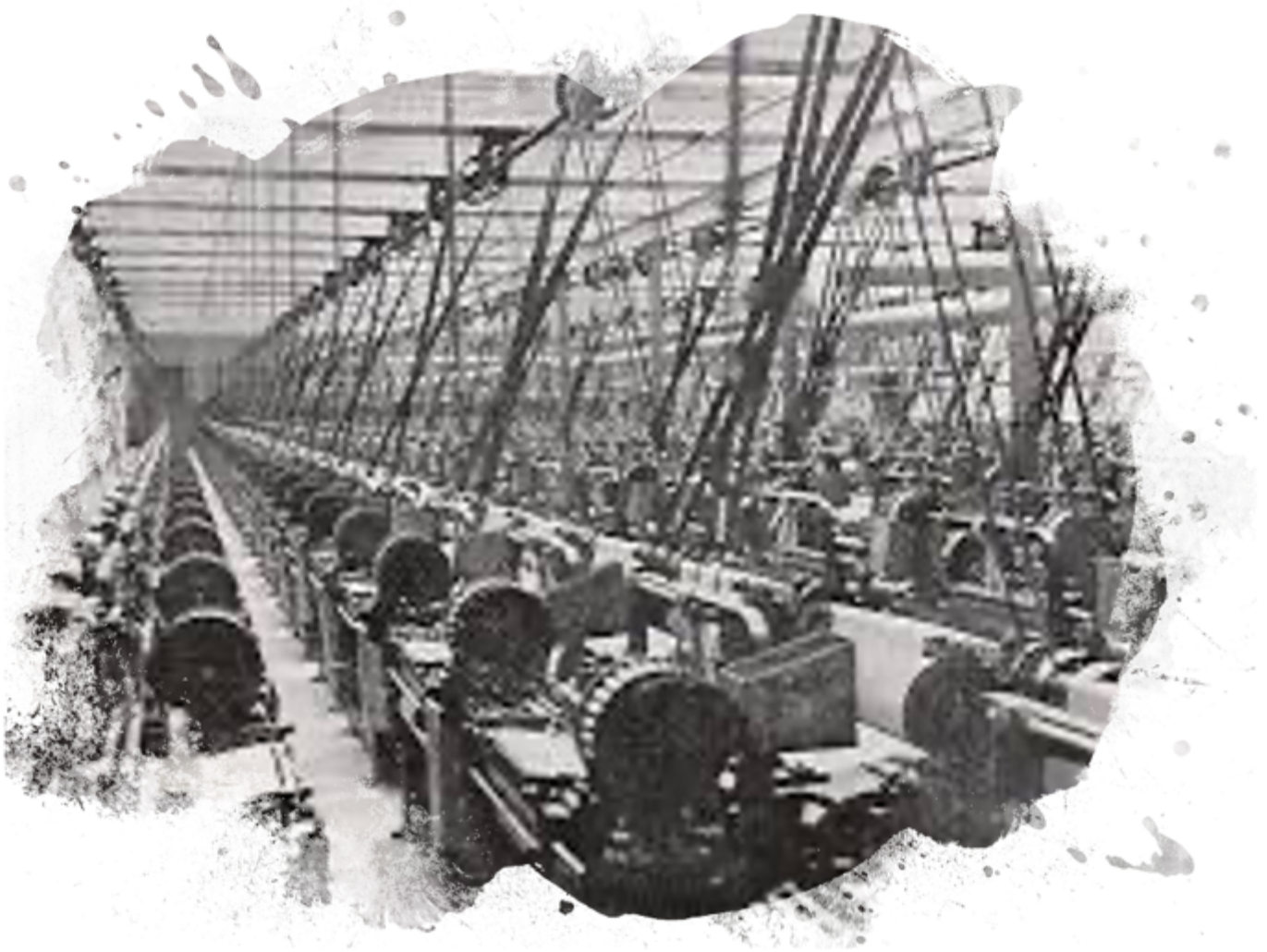




Industrial Scientific Foundation

Newtonian Science

Industrial Era
Cause -> Effect
Linear



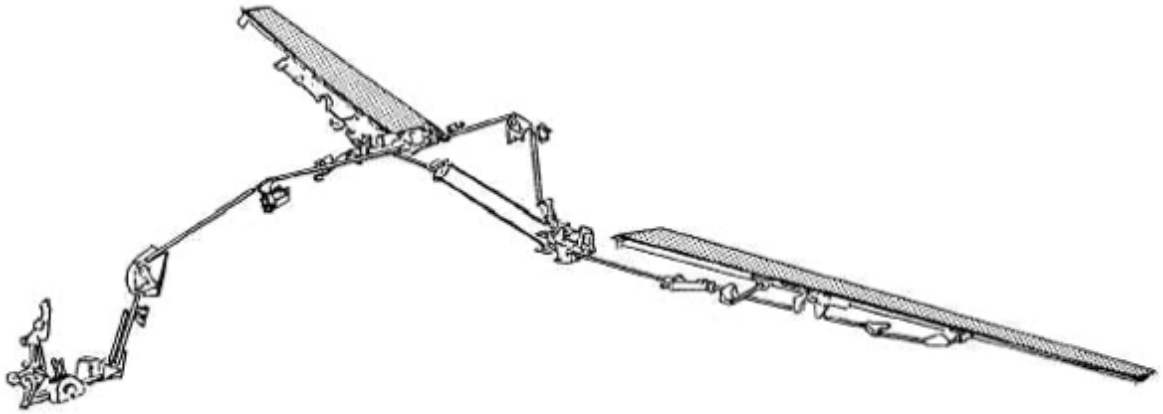
A Recent Scientific Evolution

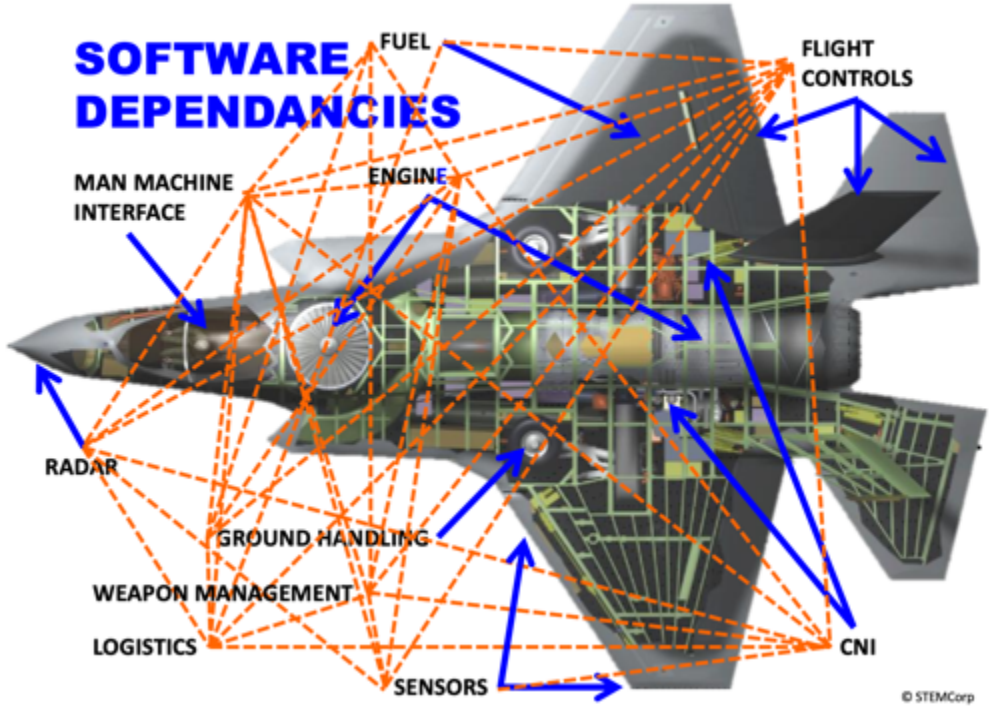
Newtonian Science ----------> **Network Science**

Industrial Era
Cause -> Effect
Linear

Information Era
Causes -> <sparse matrix> -> Effect
Non-linear

HYDRAULIC FLIGHT CONTROL





A Recent Scientific Evolution

Newtonian Science ----------> **Network Science**

Industrial Era
Cause -> Effect
Linear

Information Era
Causes -> <sparse matrix> -> Effect
Non-linear

F=MA ------- >Complexity Theory **------> Chaos ---------- > Network Science**

Diversity
Emergence
Self-Organization

Adaptability

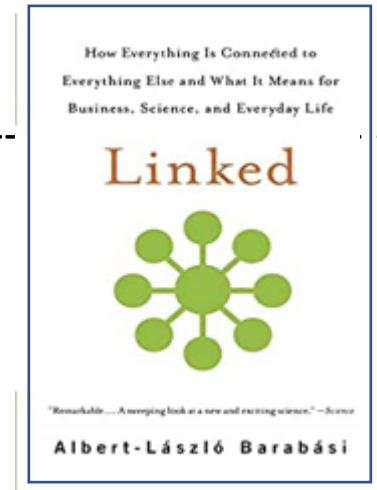
Fractals
Tipping-Points

Data Relationships
Metrics for understanding-relationships
Network ubiquity across

A Recent Scientific Evolution

Newtonian Science ----------

Industrial Era
Cause -> Effect
Literal



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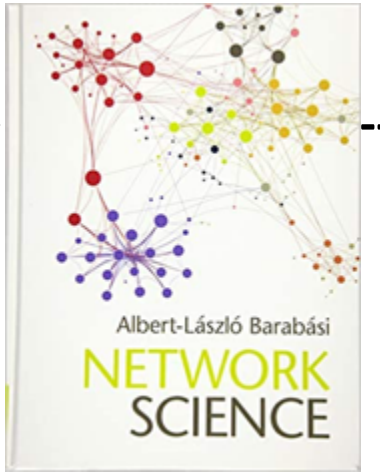

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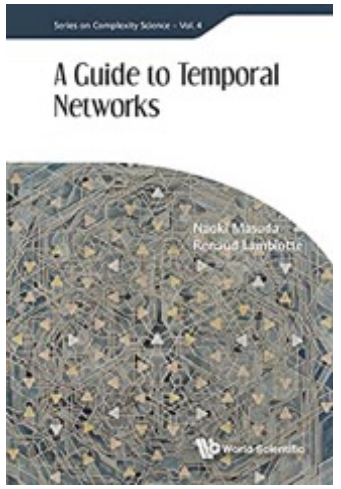
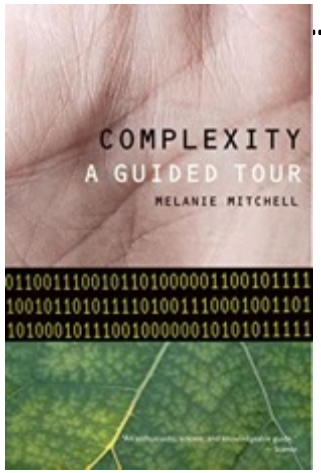


F=MA -------



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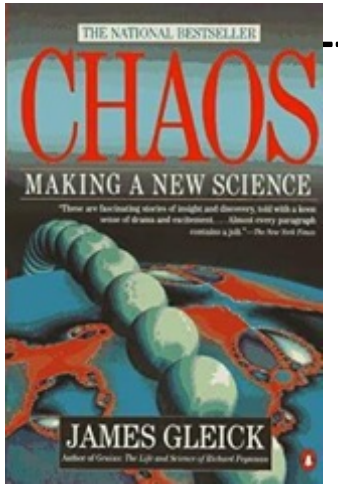

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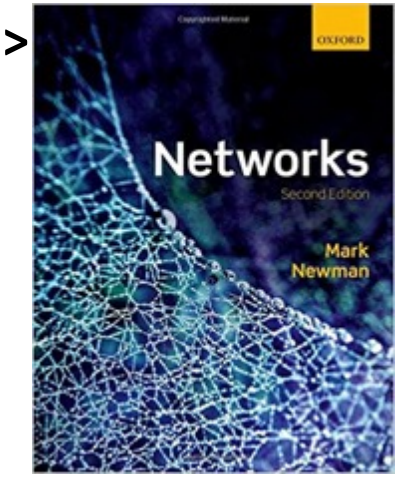

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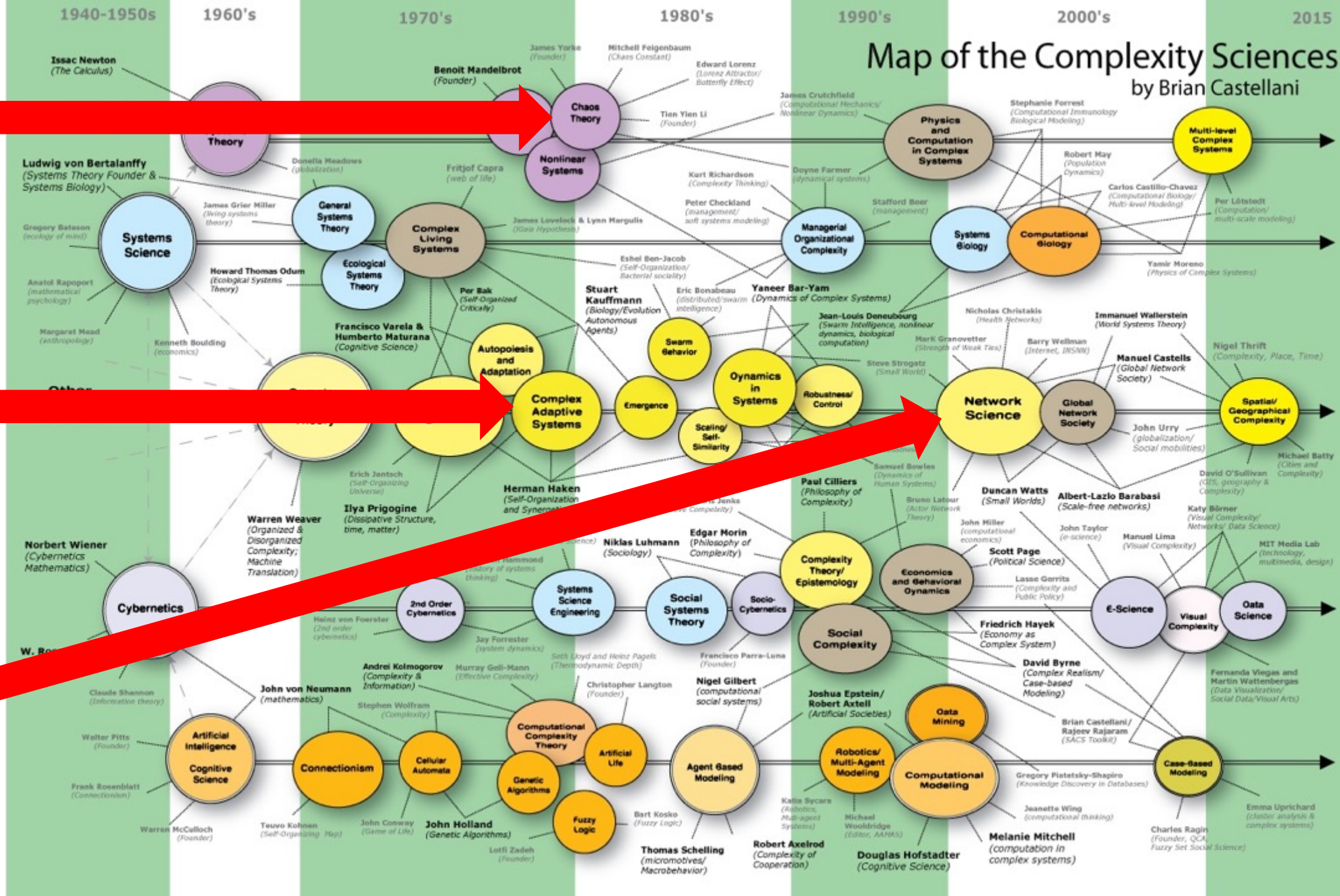
European Origin

CHAOS THEORY

COMPLEX SYSTEMS THEORY

NETWORK SCIENCE



NETWORK SCIENCE – HIGH SCHOOL TO TERMINAL DEGREE

Principals of Network Literacy

Networks

- Are everywhere
- Describe how things connect and interact .
- Reveal patterns.
- Cross Disciplines
- Can be visualized in many ways.
- Permit comparison of a wide variety of systems.

Computer technology allows the study real-world networks.

The structure and state of networks interact dynamically

Network PhD Offerings

Indiana University Informatics PhD track in Complex Networks and Systems, established 2005.

Northeastern: PhD Program, established 2014.

Central European University, established 2015.

UCSB Network Science IGERT, established 2014.

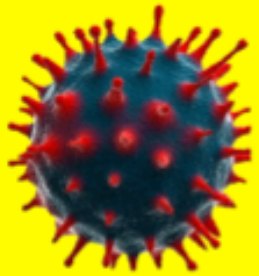
Network Biology, University of Maryland, NRT, beginning 2017.

Indiana University NSF-NRT Dual PhD program in Complex Networks and Systems, established 2017.

NETWORKS ARE EVERYWHERE!

- Technological
  - Electronic
    - Internet
    - PAN, LAN, WAN, MAN
    - Cloud Virtualization
    - IOT, II, IOE, IOA. 4th IR
    - Software Dependency
  - Infrastructure
    - Gas
    - Electricity (Grid)
    - Water
    - Sewer
    - Telephone
  - Transportation
    - Road Vehicles
    - Railroad
    - Airplane
    - Maritime
  - Industry
    - Distribution/Logistics
    - Supply Chain
  - Military
    - Warfare Architecture
- Social (Ego-Centered, Affiliation, SNA)
- Economics (Macro, Micro, Market)
- Information
  - WWW (Internet Virtualization)
  - Citation
    - Academic
    - Patent
    - Legal
    - Peer to peer
  - Recommendation/Keyword Index
- Psychology (Consciousness, Cognition)
- Neurology (Human Brain, neurology)
- Physics (Quantum, String Theory)
- Chemistry (Organic, Nano)
- Biology
  - Epidemiology
  - Biochemical
    - Metabolic and Molecular
    - Protien-Protien Interaction
    - Genetic Regulation (RNA, DNA)
  - Ecological
  - Evolution
- Mathematical

INTERDEPENDENT NETWORK DISRUPTIONS



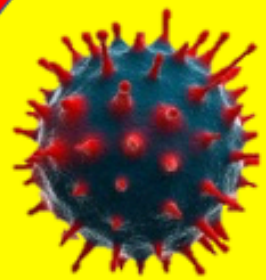
COVID-19

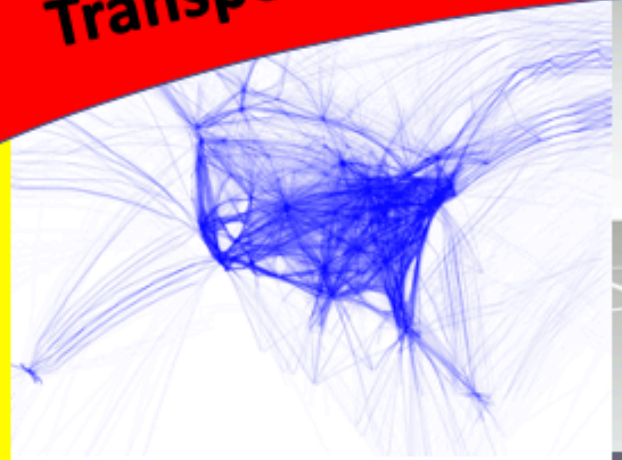
INTERDEPENDENT NETWORK DISRUPTIONS

Transportation

Social Networks

Supply Chain





Education

World Economy

Climate

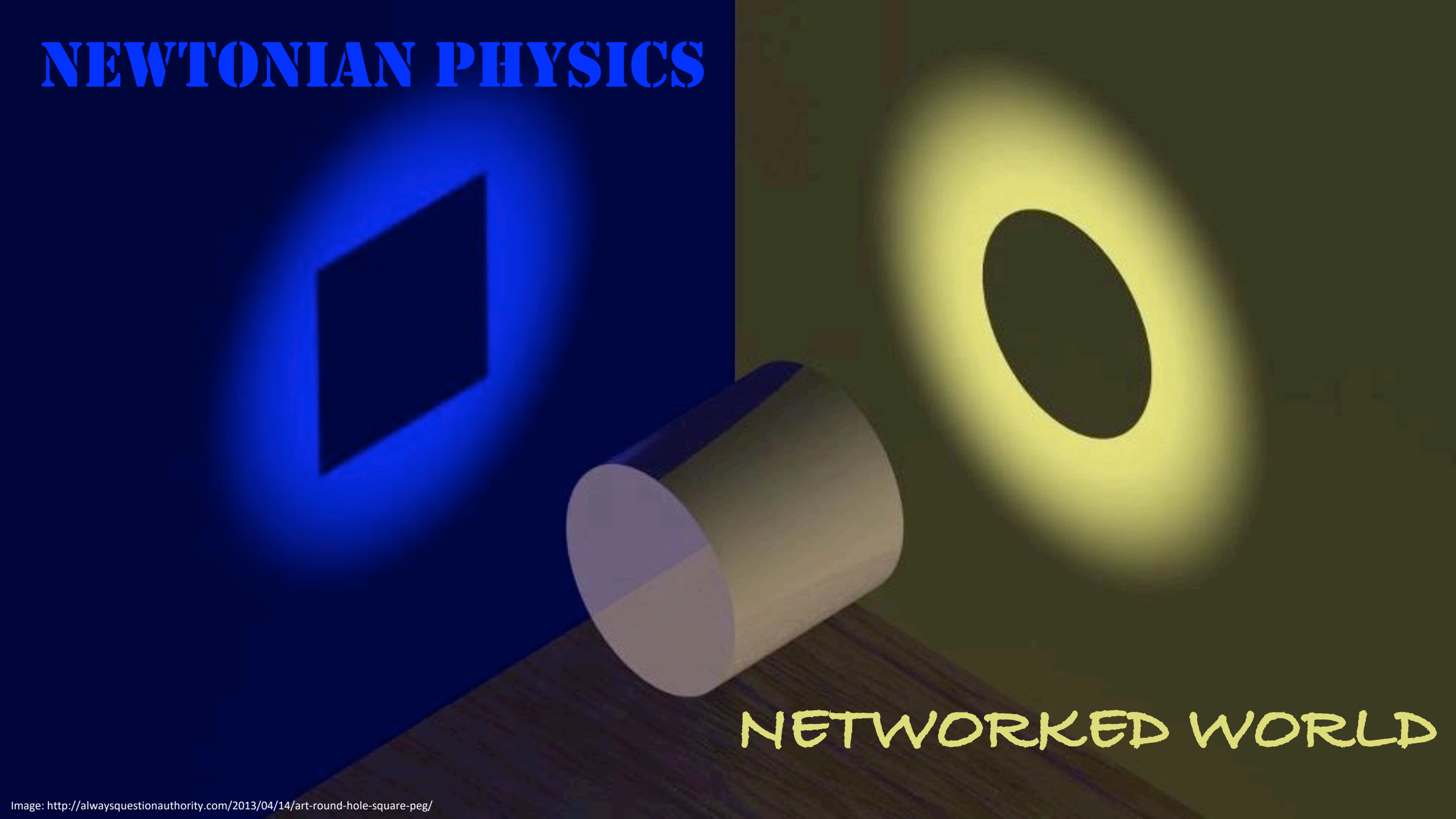
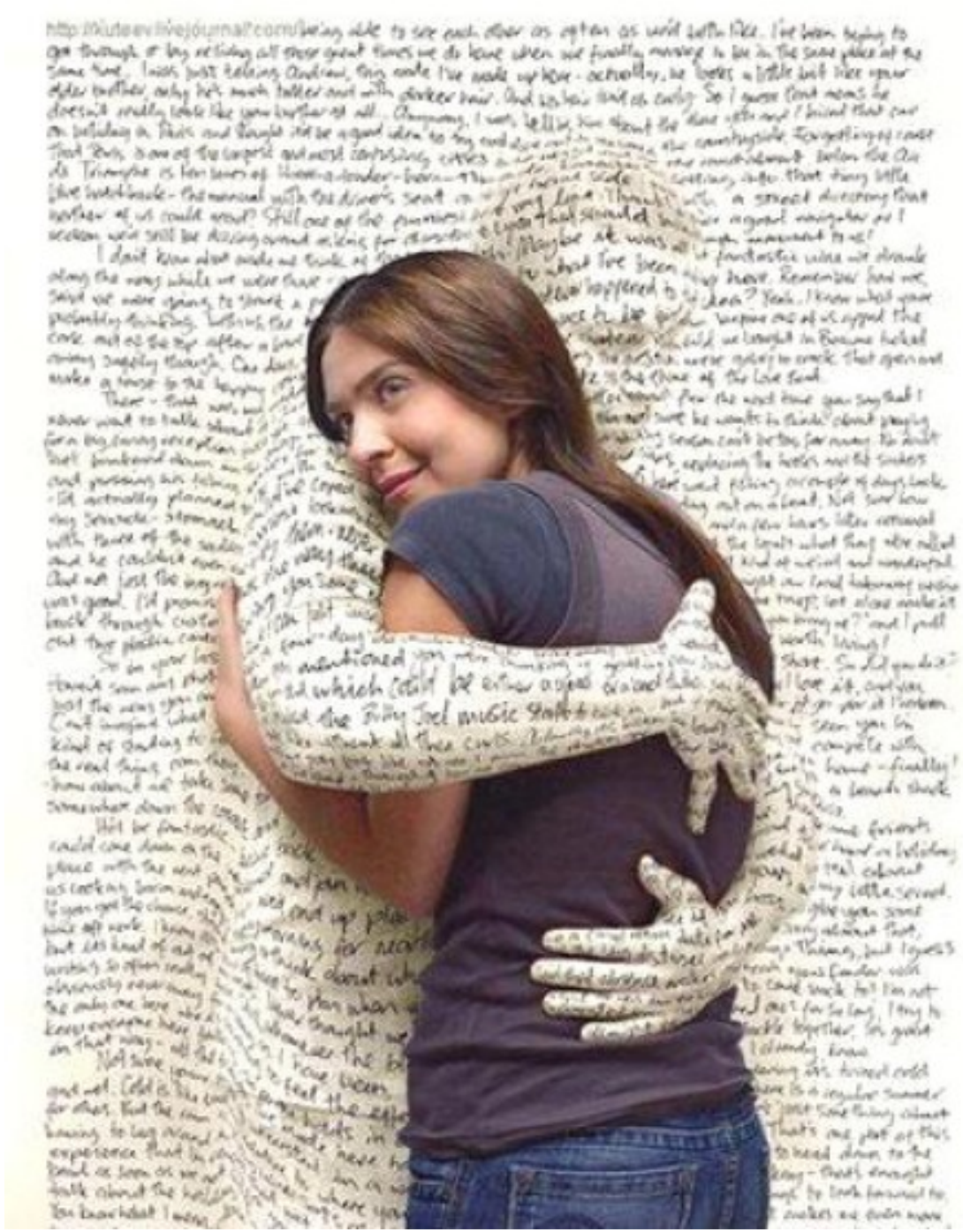


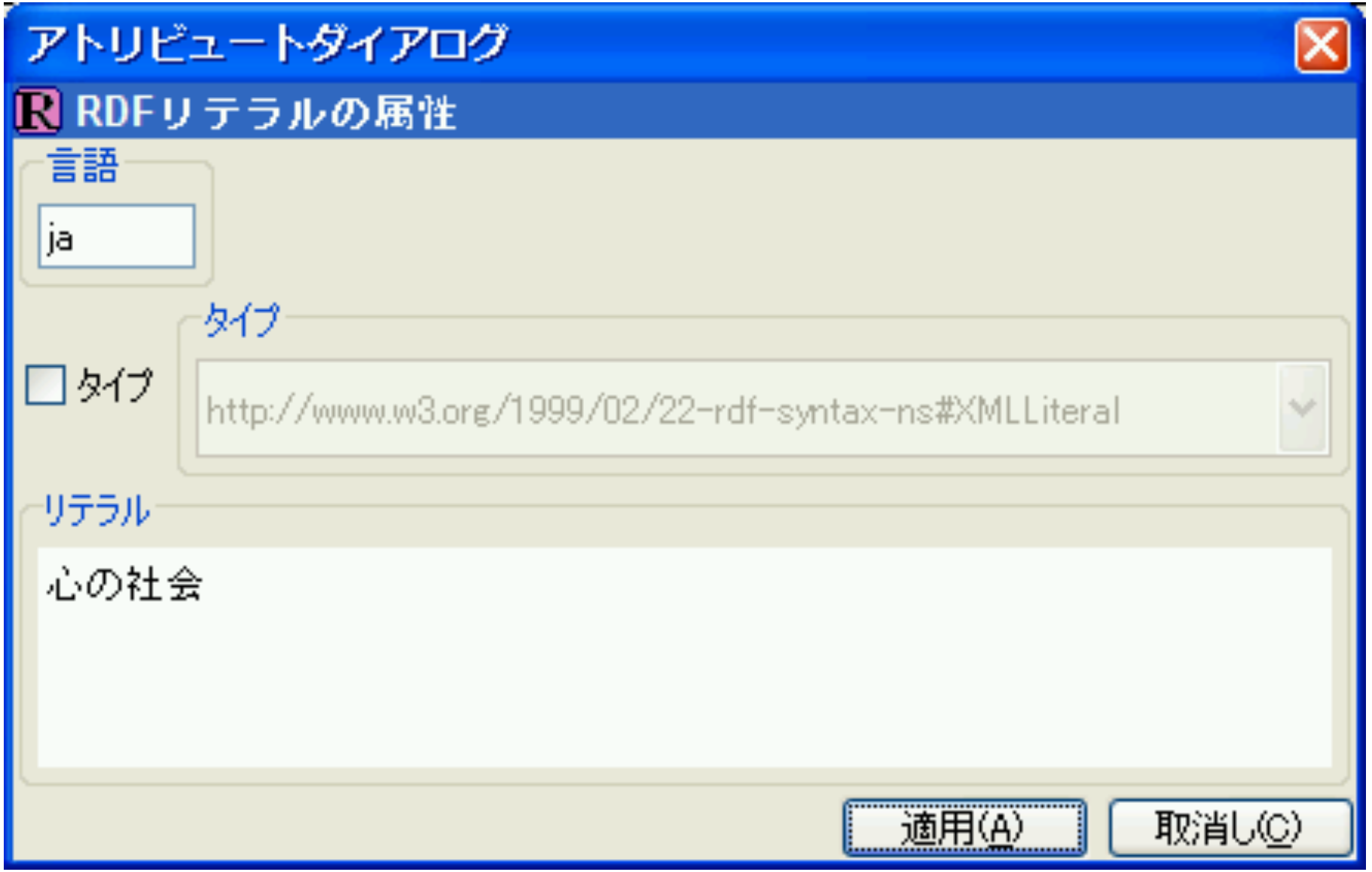
Image: http://alwaysquestionauthority.com/2013/04/14/art-round-hole-square-peg/

PEOPLE TEND TO BE LITERATE

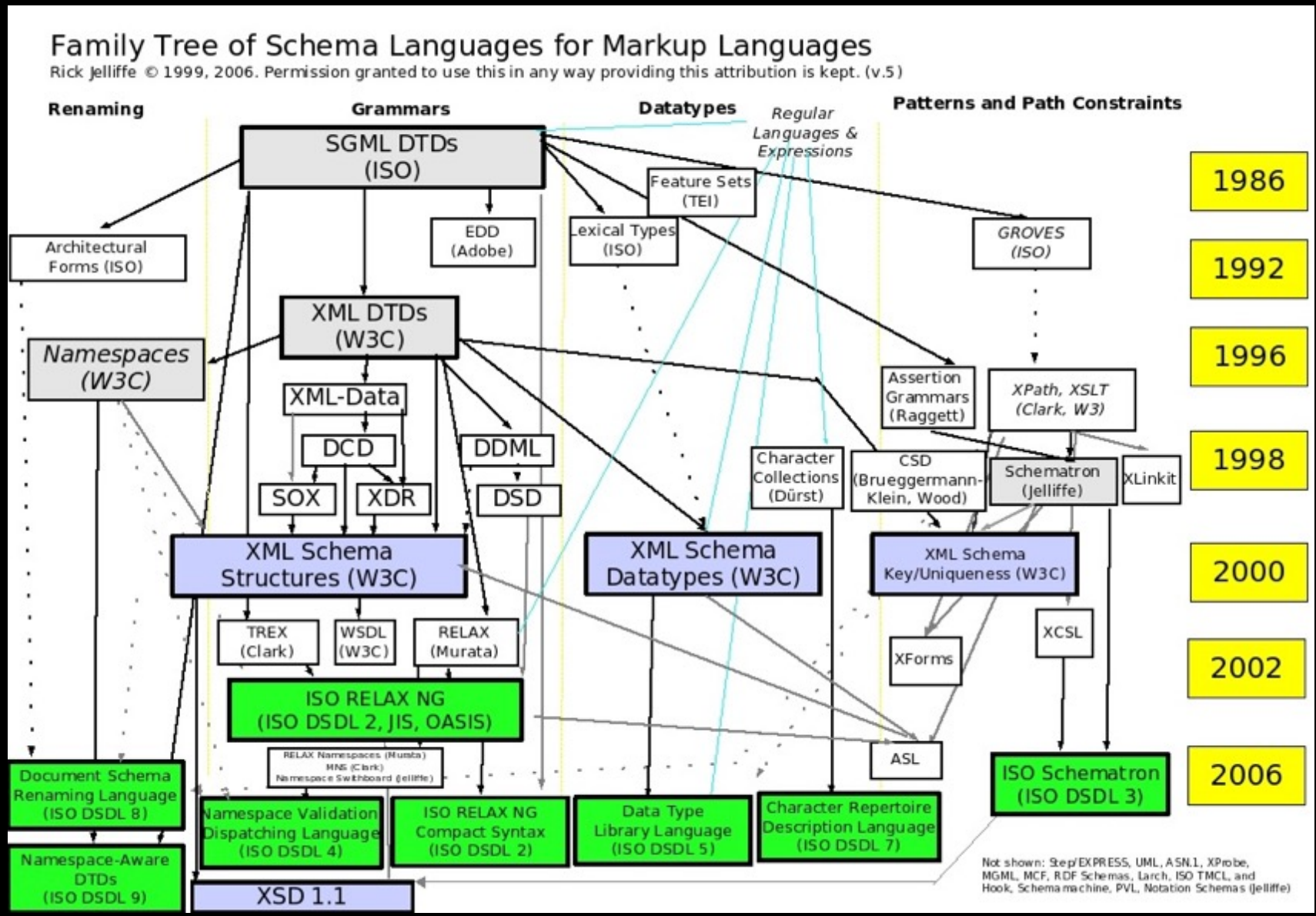


LITERACY BREEDS KNOWLEDGE

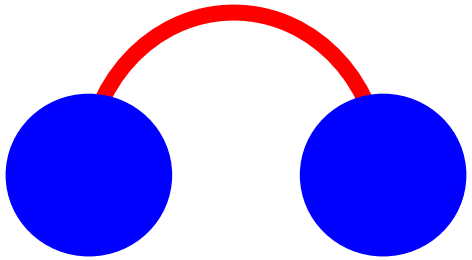
COMPUTERS ARE LITERAL



LITERAL BREEDS MORE LITERAL

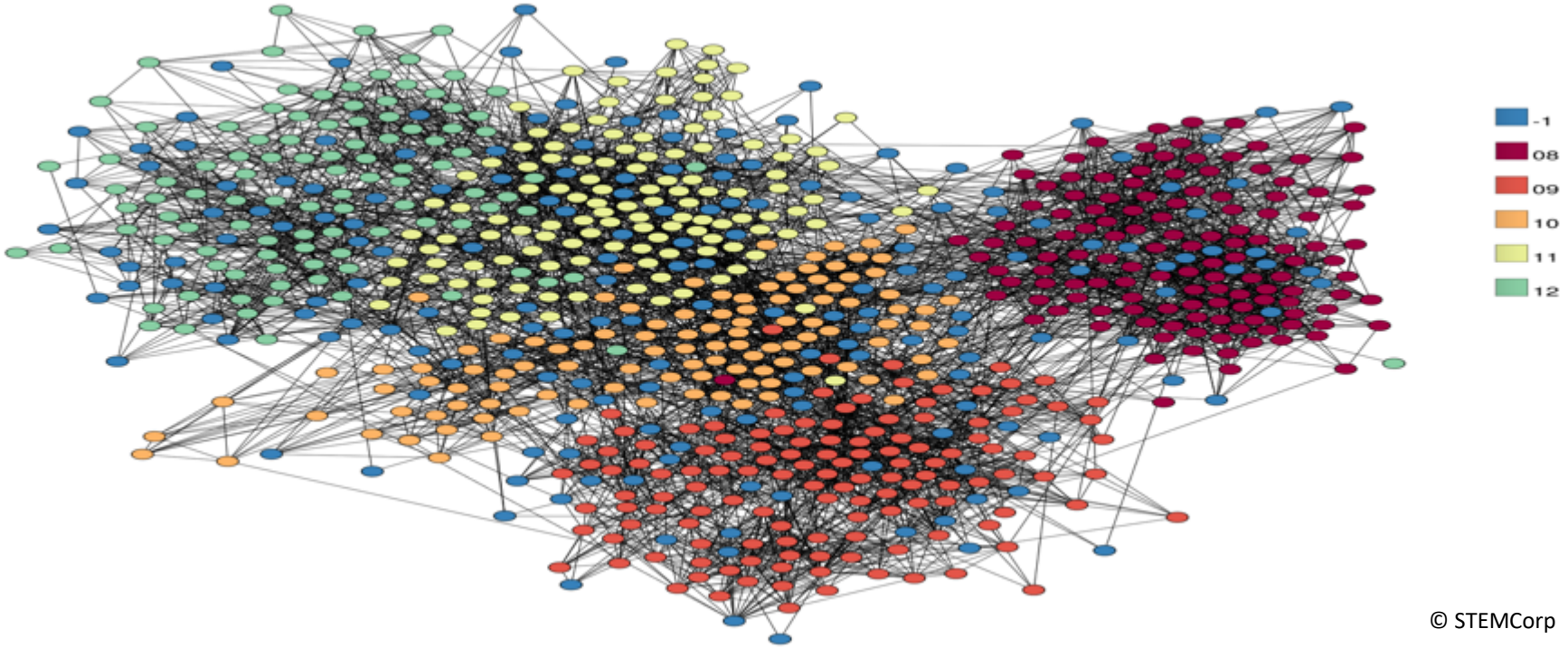


FUNDAMENTAL GRAPH REASONING



Node – Arc – Node

The Triple – Basic Building Block OF ANY NETWORK



GRAPH ALGORITHMS - Empowering the 21st Century

Coloring algorithm
Hopcroft–Karp algorithm
Hungarian algorithm
Prüfer coding
Tarjan's off-line lowest common ancestor's algorithm
Topological sort

Graph drawing
- Force-based algorithms
- Spectral layout
- spring-based algorithm

Network theory
- **Network analysis**
  - **Link analysis**
    - Girvan–Newman algorithm
    - **Web link analysis**
      - Hyperlink-Induced Topic Search
      - PageRank
      - TrustRank
  - **Flow networks**
    - Dinic's algorithm
    - Ford–Fulkerson algorithm
      - Edmonds–Karp algorithm
    - Karger's algorithm
    - Push–relabel algorithm
    - Almost Linear Max Flow

Routing for graphs
- Edmonds' algorithm
- Euclidean minimum spanning tree
- Euclidean shortest path problem
- Longest path problem
- **Minimum spanning tree**
  - Borůvka's algorithm
  - Kruskal's algorithm
  - Prim's algorithm
  - Reverse-delete algorithm
  - Woodhouse-Sharp
- **Nonblocking minimal spanning switch**

Shortest path problem
- Bellman–Ford algorithm
- Dijkstra's algorithm
- Floyd–Warshall algorithm
- Johnson's algorithm

Transitive closure problem

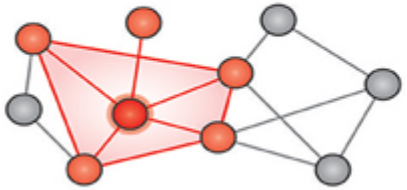
Traveling salesman problem
- Christofides algorithm
- Nearest neighbour algorithm
- Warnsdorff's rule

Graph search
- A* Tree Search
  - Dijkstra's algorithm
  - Jump point search
- B*
- Backtracking
- Beam search
- Beam stack search
- Best-first search
- Bidirectional search
- Breadth-first search
- Brute-force search
- D*
- Depth-first search
- General Problem Solver
- Iterative deepening depth-first search
- Lexicographic breadth-first search
- Uniform-cost search
- State space search

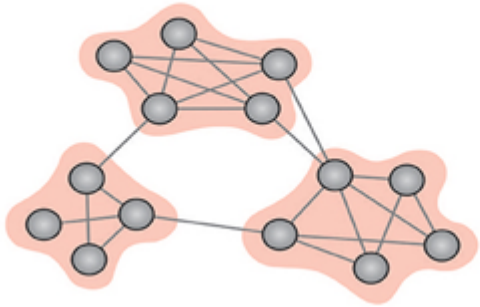
Subgraphs
- **Cliques**
  - Bron–Kerbosch algorithm
  - MaxCliqueDyn maximum clique algorithm
- **Strongly connected components**
  - Path-based strong component algorithm
  - Kosaraju's algorithm
  - Tarjan's strongly connected componens algorithm
- Subgraph isomorphism problem

GRAPHS ARE SUBJECT TO ROBUST METRICS

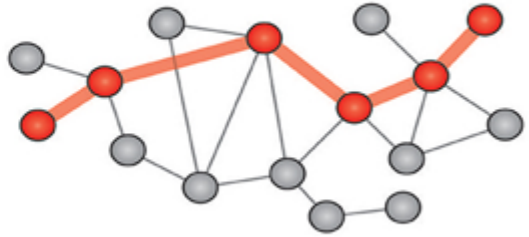
Clustering coefficient



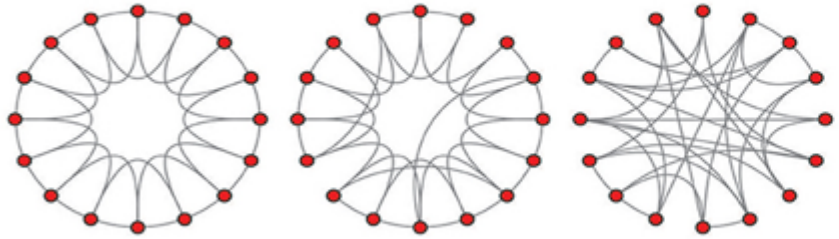
Modularity



Shortest path

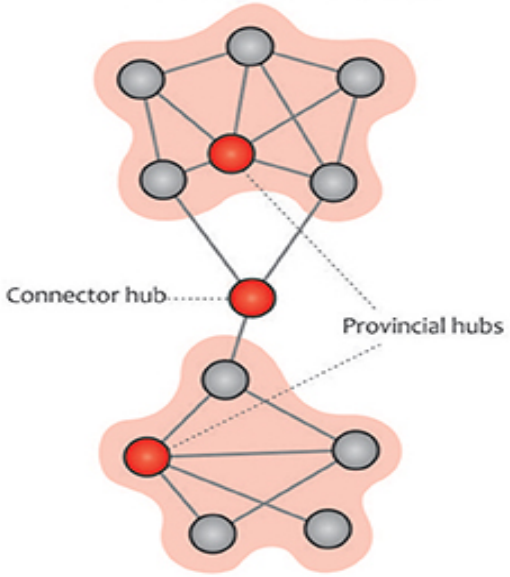


Regular Small-World Random

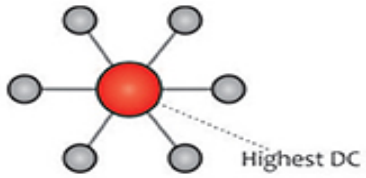


Assortative Disassortative

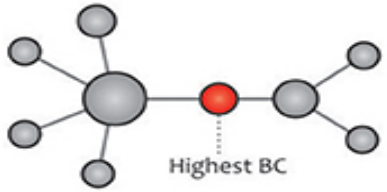
Centrality and hubs



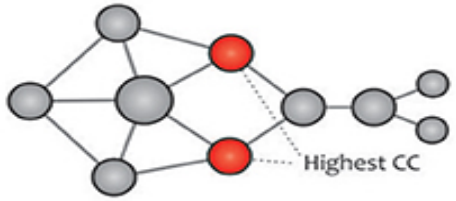
Degree centrality



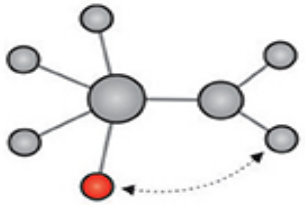
Betweenness centrality



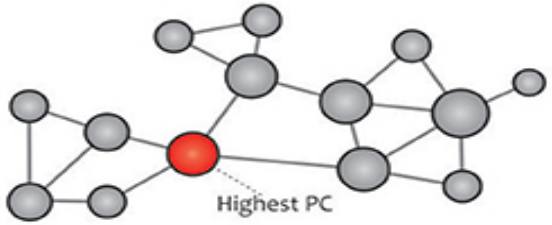
Closeness centrality



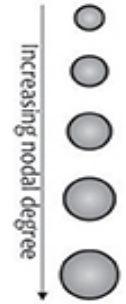
Eigenvector centrality



Participation coefficient

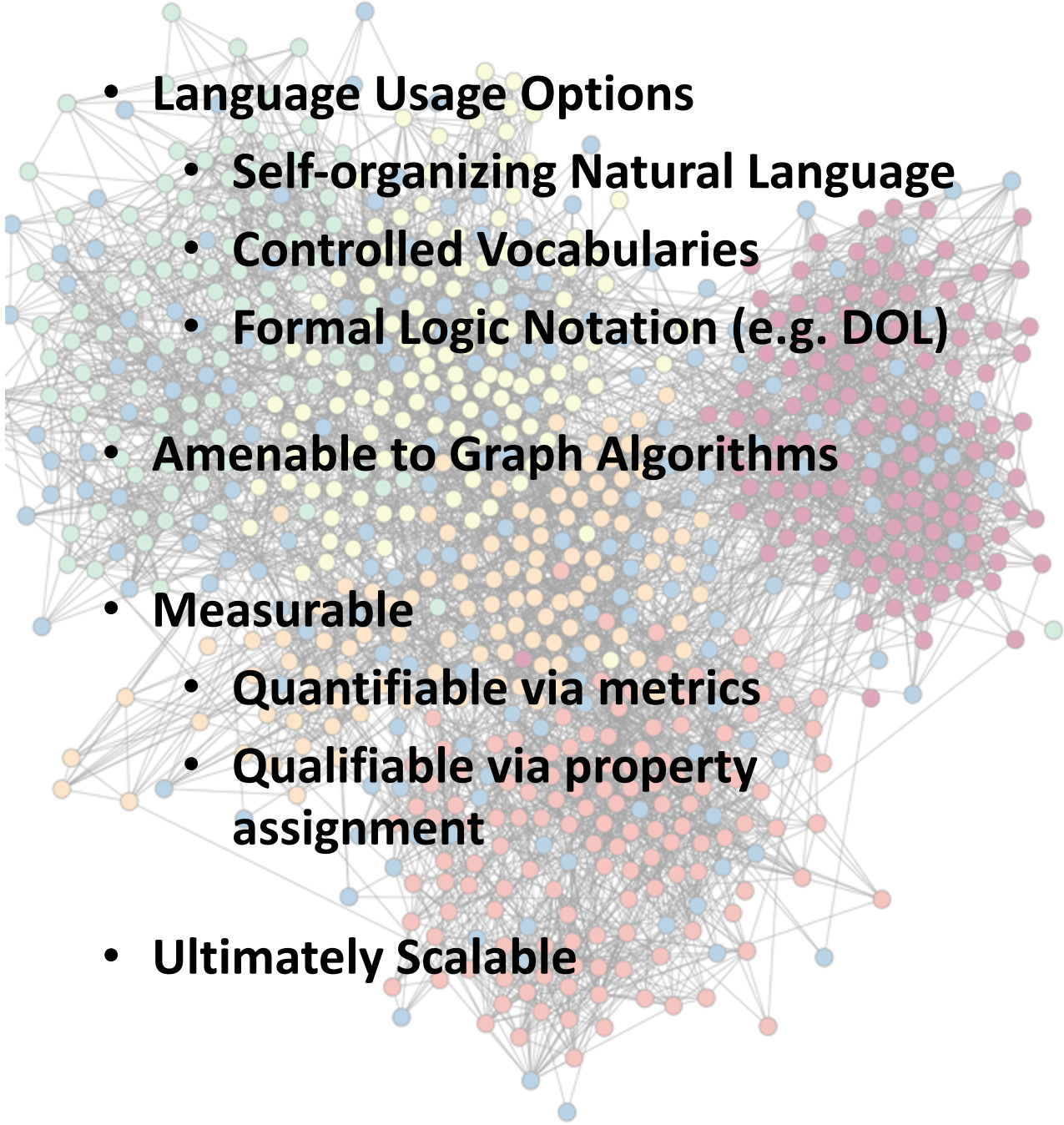


PageRank



GRAPHS ARE ALL ABOUT RELATIONSHIPS

- Describe network phenomena
  - Static (no state changes supported)
  - Dynamic (with mathematical underpinnings)
- Extensible for Interoperability
  - Detachable subgraphs (for functional analysis)
  - Network of Network aggregate (Mathematically describable)
- Flexible Design Options
  - Formal Logic constrained
  - Event driven in real time
  - Emerging Dynamic architecture



- Language Usage Options
  - Self-organizing Natural Language
  - Controlled Vocabularies
  - Formal Logic Notation (e.g. DOL)
- Amenable to Graph Algorithms
- Measurable
  - Quantifiable via metrics
  - Qualifiable via property assignment
- Ultimately Scalable

"Networks are important because if we don't understand networks, we can't understand how markets function, organizations solve problems, or how societies change."

Duncan Watts