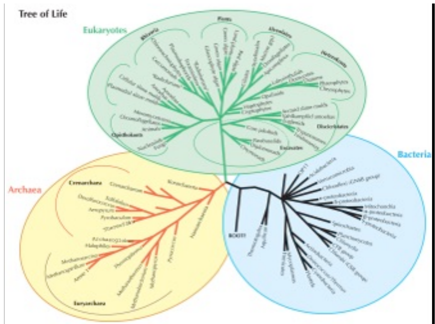
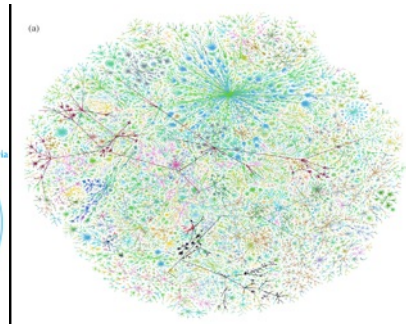
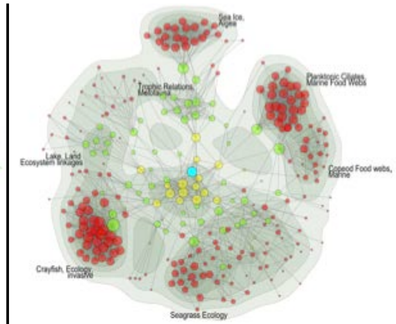
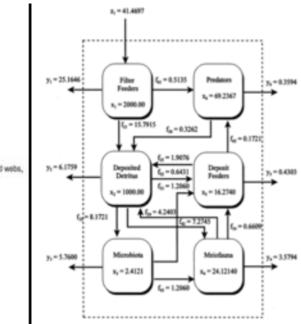
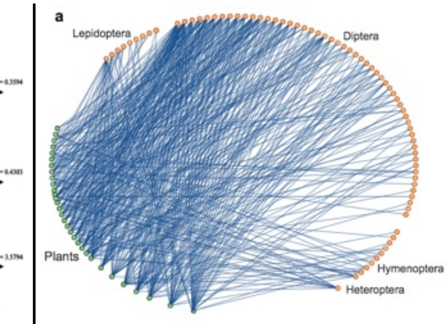


Introduction to Networks

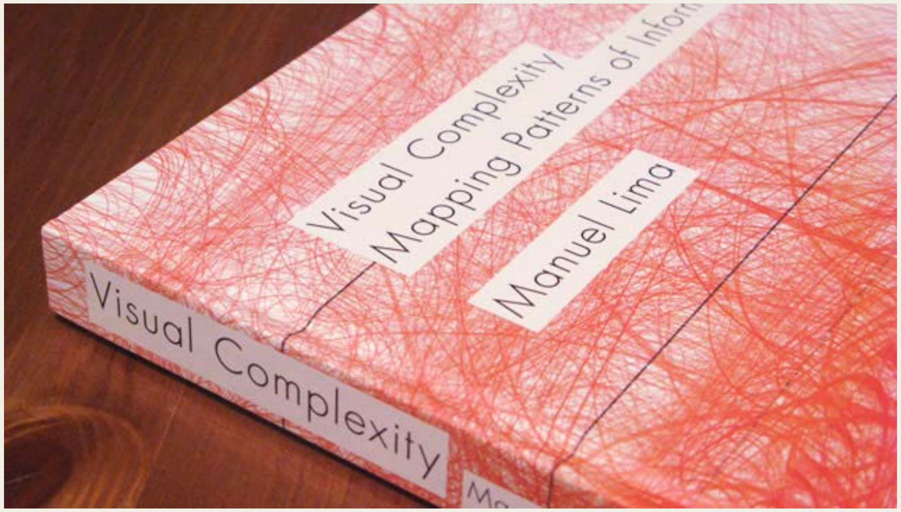
Stuart R. Borrett

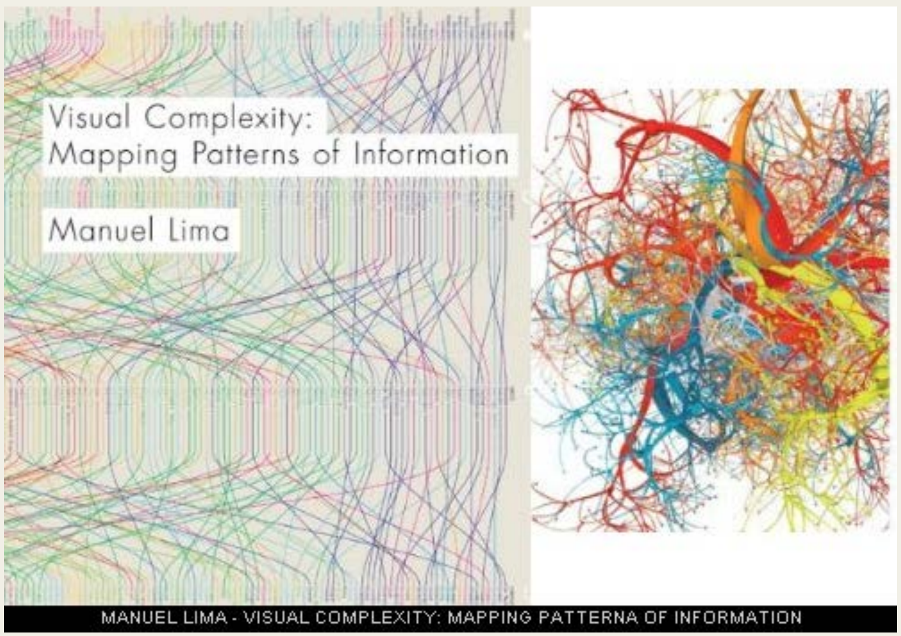
Dept. Biology & Marine Biology

SYSTEMS ECOLOGY AND ECOINFORMATICS LABORATORY

@ UNIVERSITY OF NORTH CAROLINA WILMINGTON

@ International Society for Ecological Modelling, May 2016, Towson, MD



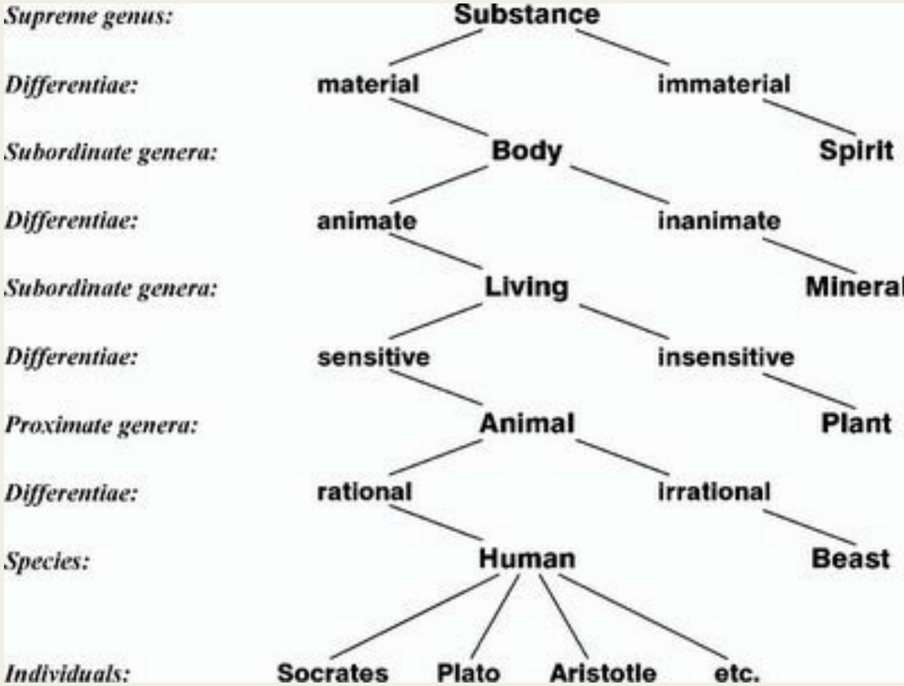


Networks are Everywhere

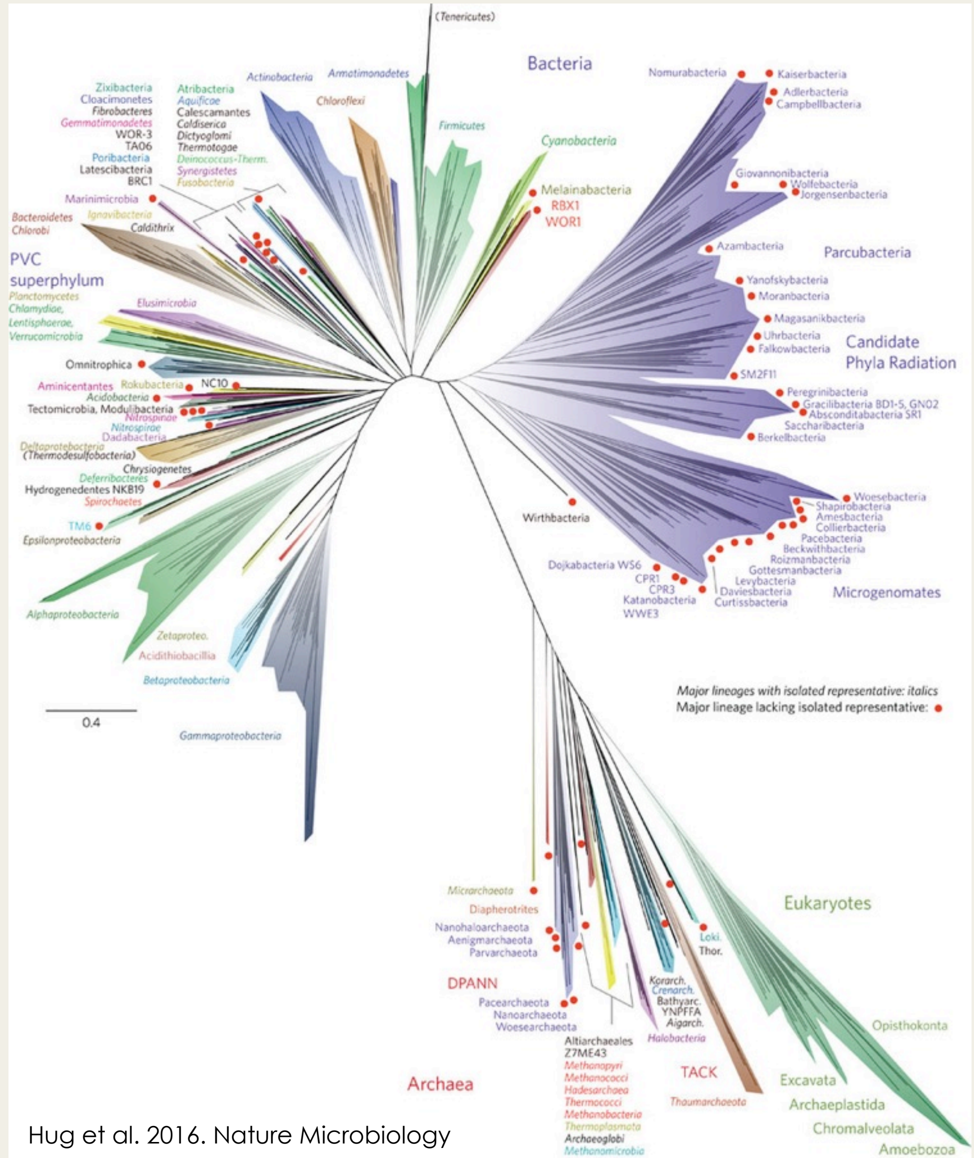
Manuel Lima
2011

Example Networks: Classification Trees

Porphyrian Classification Tree



Tree of Life: Cladogram

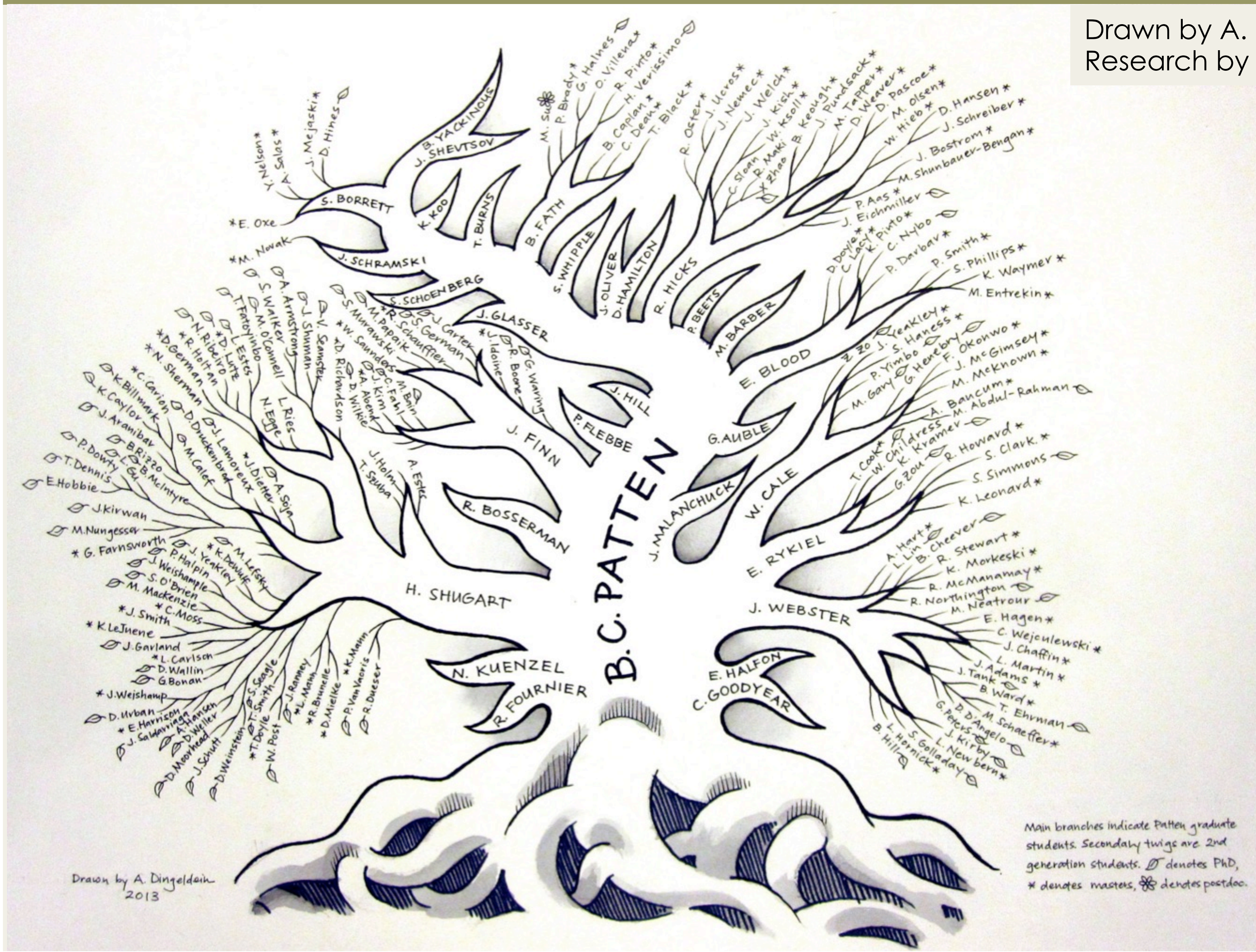


Hug et al. 2016. Nature Microbiology

Tree = no cycles

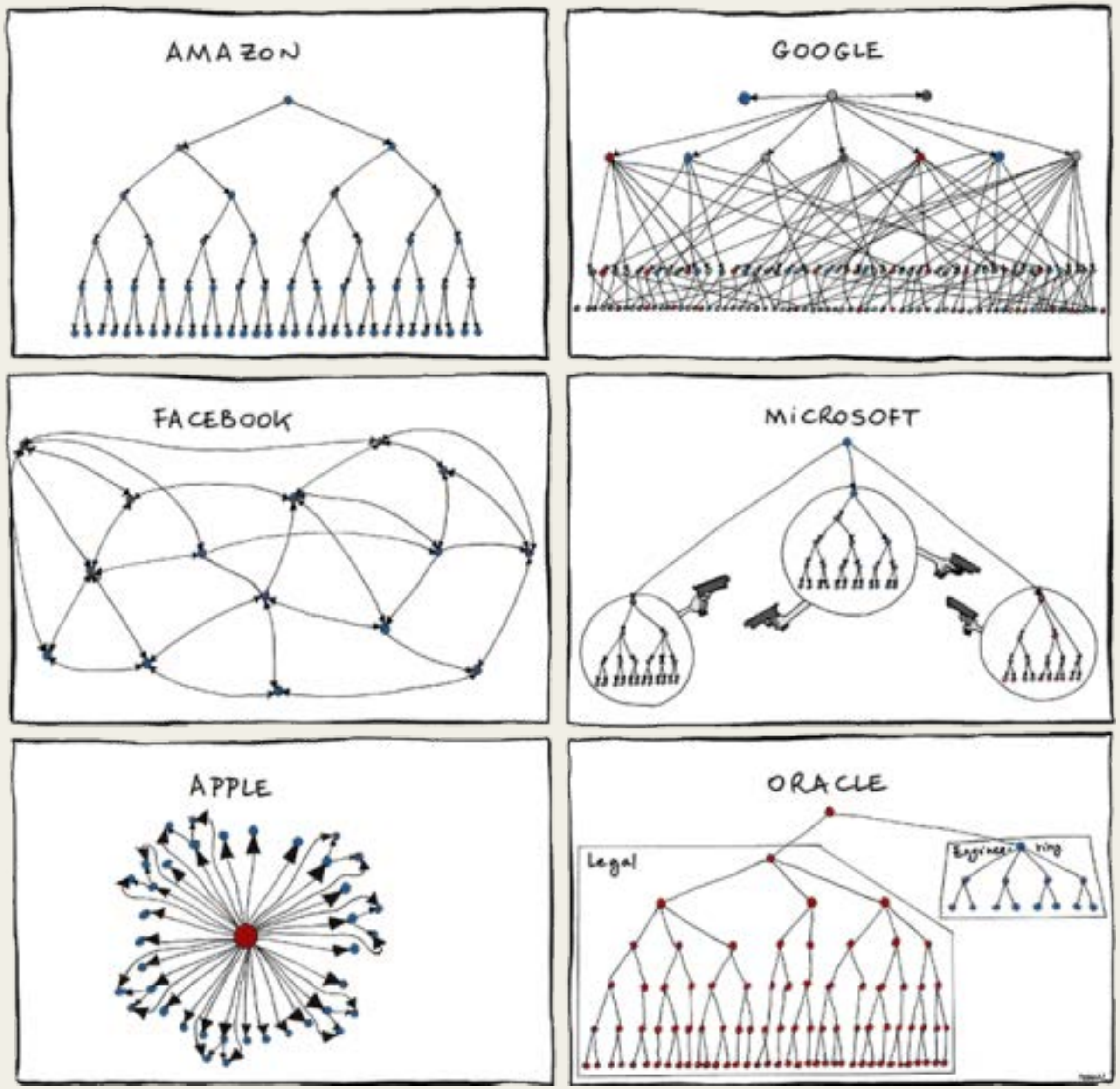
Example Networks: Family Tree

Drawn by A. Dingeldein
Research by D.E. Hines



Example Networks: Organization Charts

Comparison of tech companies



What does the modeler (cartoonist) want you to know about each company?

Charts from http://foxhugh.com/charts/describe-organizational-chart/

Example Networks: Social Networks

Friendship Locality, 2010

https://www.facebook.com

The world map emerges from the network drawing

Connectivity is Transformative

In ***complete*** graphs,
the number of connections increases faster than the number of nodes

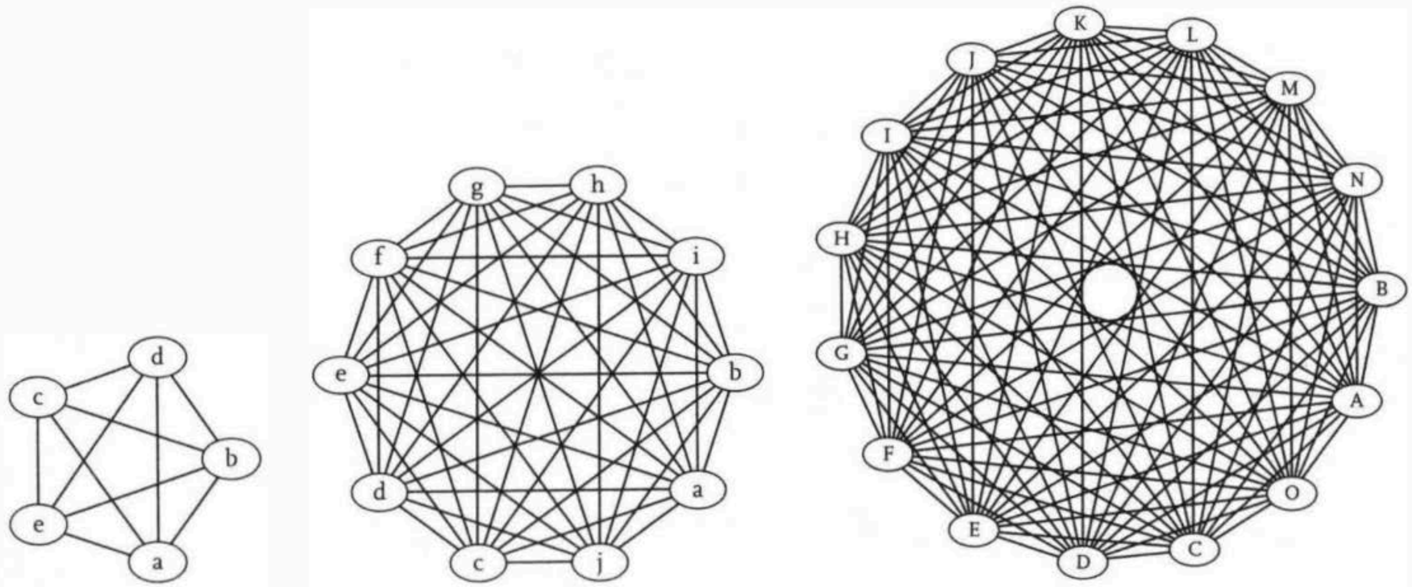


Figure 2-1: Three clusters, with all connections drawn. The small cluster has 5 members and 10 connections; the middle one has 10 members and 45 connections; and the large one has 15 and 105. A group's complexity grows faster than its size.

Shirkey 2008

Transaction Cost Constraint

Reduce costs?

1. Lower transaction cost
2. Reduce connections

1. Network Elements
2. Network Ecology
3. Context

1

Network Elements

a Relational Model

Network are one type of model

What is a model?

Model

A model is an abstract (perhaps idealized), non-unique, description of a natural system that captures its features essential for addressing the modeling objectives.

Patten, pers. Com.

Ahl & Allen 1996

Formal Modeling Relation: Mapping

Q: What does the model tell you about the natural system?

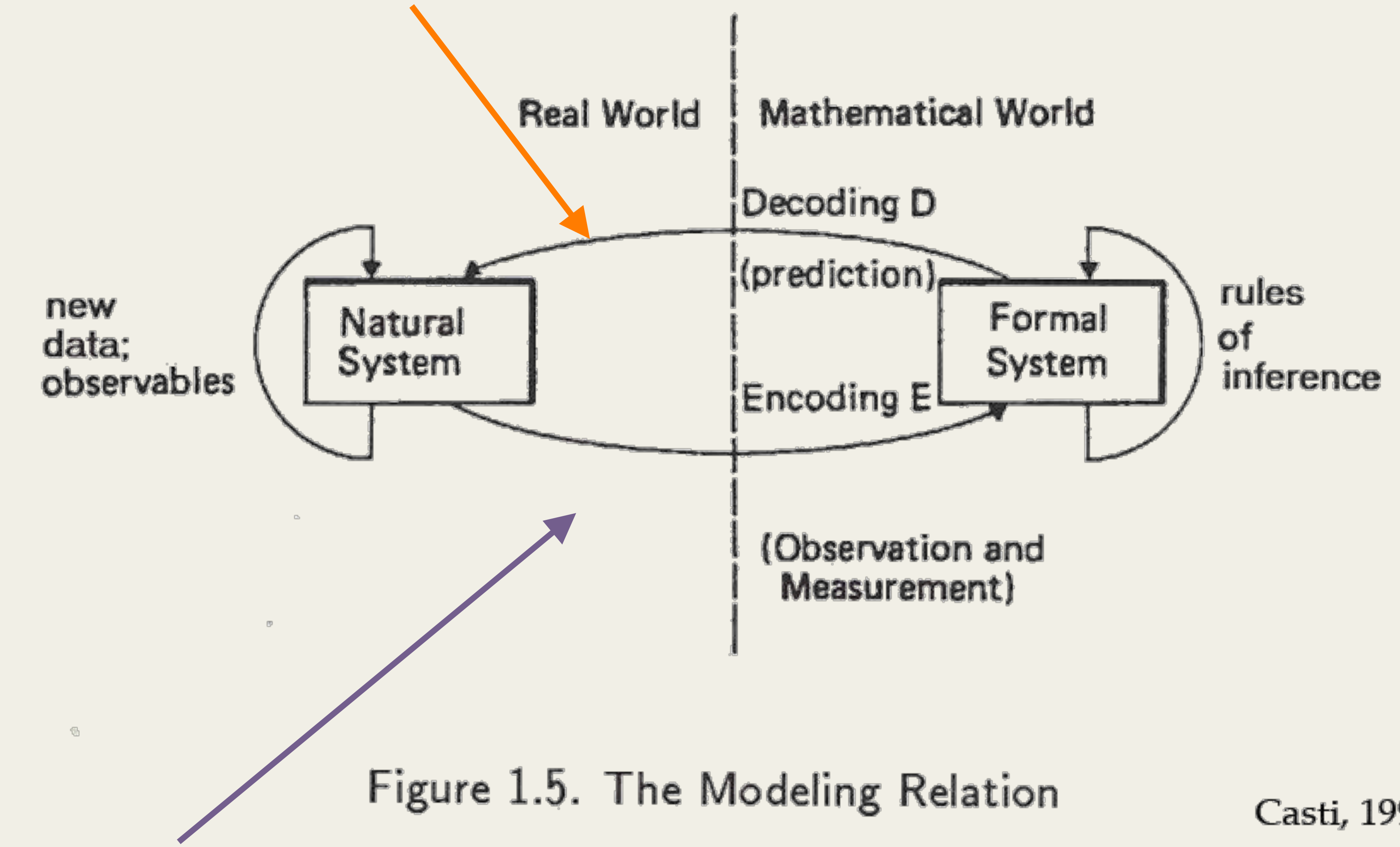


Figure 1.5. The Modeling Relation

Casti, 1992

This abstraction process is key to model making.

Q: What do you include in the model and how do you formally represent it?

All Models are wrong, some are useful

George Box, 1979

How do we know if our model is sufficient?

Network Models

Network models map relationships between objects

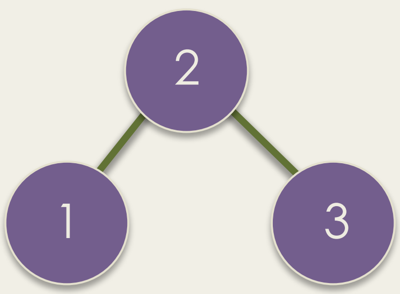
Networks are Graphs

G = {N, E}

N = nodes → objects

E = edges → relationship

Graph



Matrix

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Graph Theory

Linear Algebra

Adjacency

Two nodes (*i, j*) are adjacent if there is an edge between them

Adjacency Matrix

$$A = (a_{ij}) = \begin{cases} a_{ij} = 1 & \text{if i, j adjacent,} \\ a_{ij} = 0 & \text{otherwise} \end{cases}$$

Another common Data Structure

Edge List

From, to

1, 2

2, 1

2, 3

3, 2

Network Models

Network models map relationships between objects

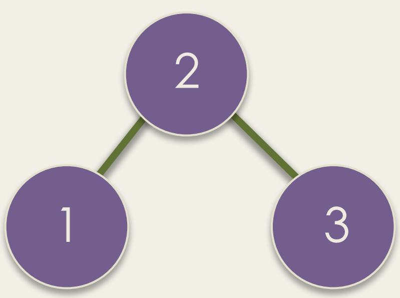
Networks are Graphs

$G = \{N, E\}$

N = nodes → objects

E = edges → relationship

Graph



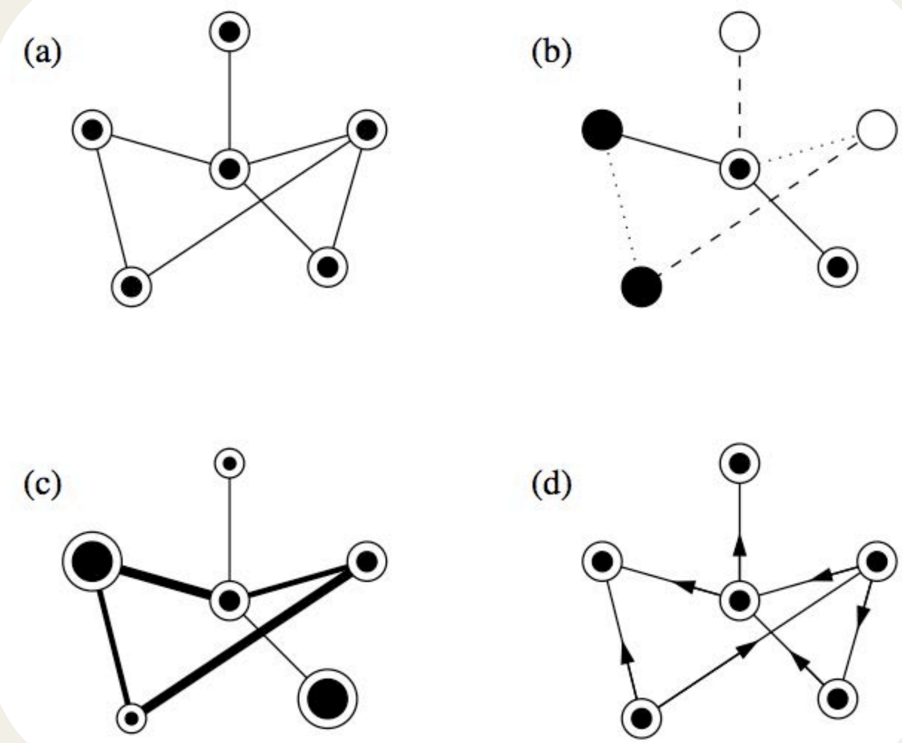
Matrix

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Graph Theory

Linear Algebra

Graph Variations

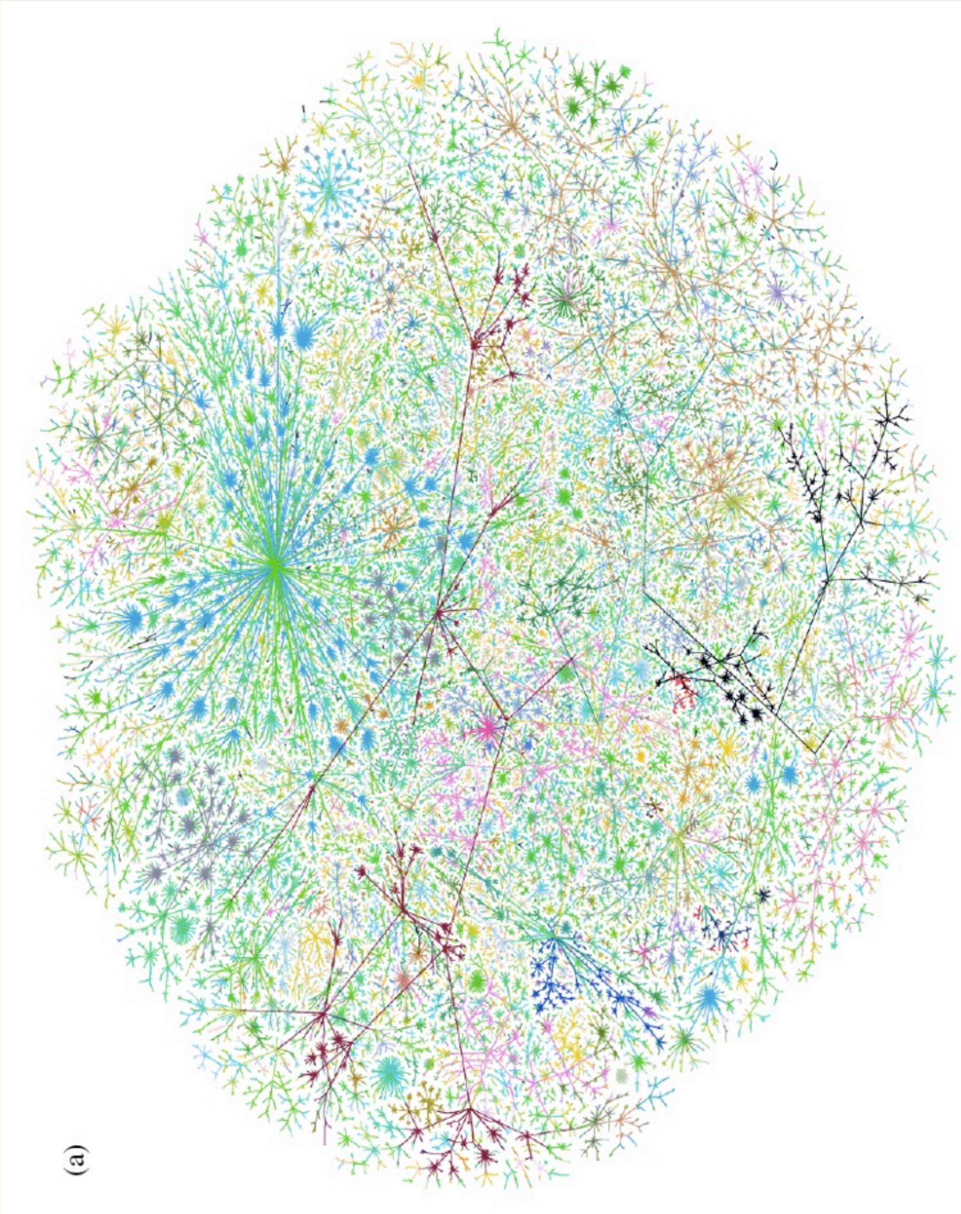


Newman 2003 SIAM

Typically Simple Graphs

One edge to/from each node, no loops

Internet



G = {N, E}

Nodes

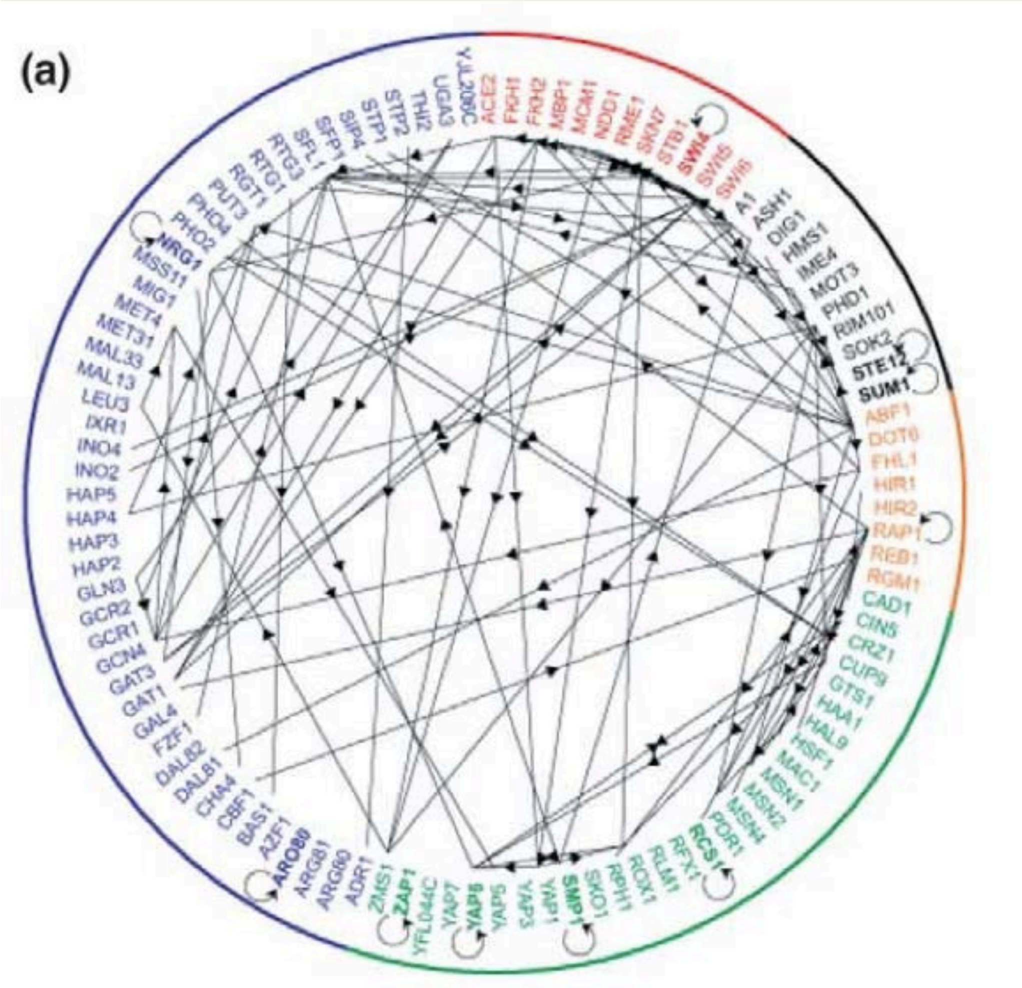
Autonomous systems (computer groups)

Edges

Physical Internet connection

"…at the level of "autonomous systems"—local groups of computers each representing hundreds or thousands of machines. Picture by Hal Burch and Bill Cheswick, courtesy of Lumeta Corporation. " Newman 2003

Gene Regulatory Network



G = {N, E}

Nodes

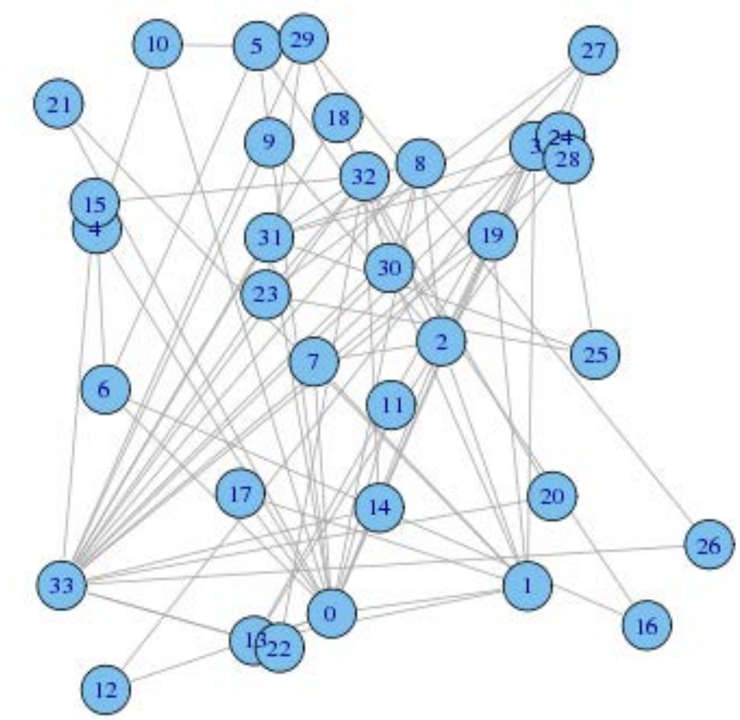
Genes

Edges

Directed regulation of transcription of other genes

As in Proloux et al. 2005. [Network thinking in ecology and evolution]

Zachary's Karate Club



Zachary 1977

G = {N, E}

Nodes

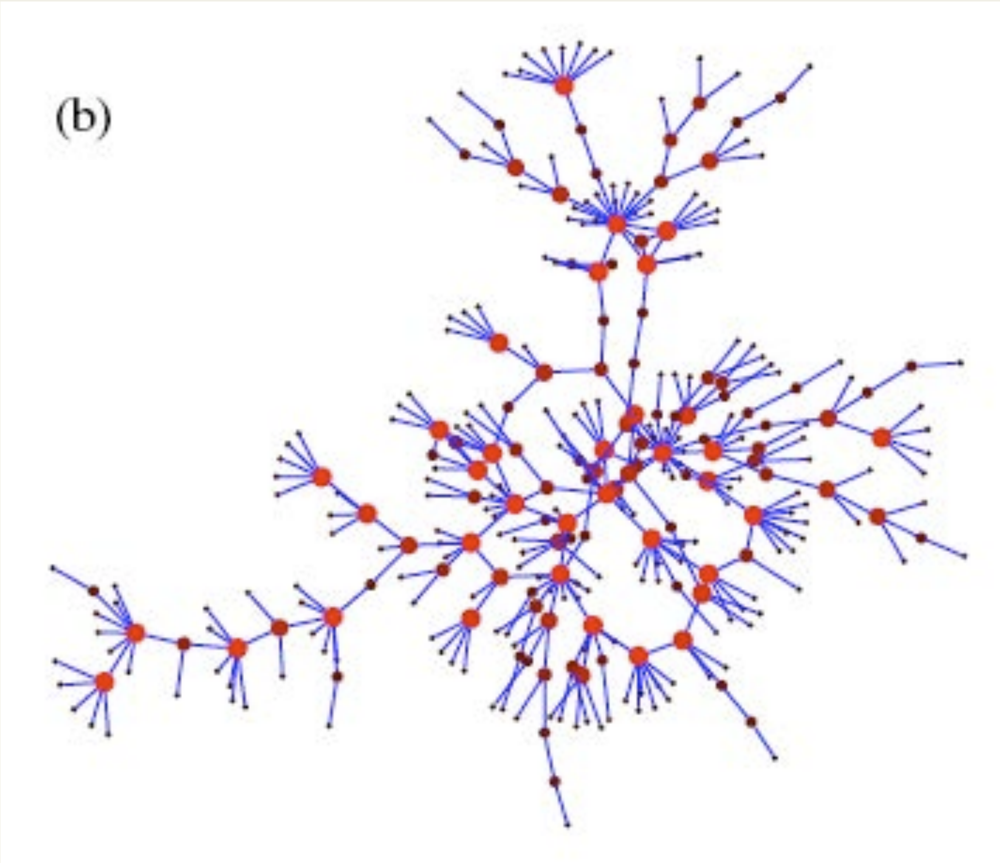
Individual people

Edges

Friendships

(note as drawn its undirected and thus assumes friendships are necessarily reciprocal)

Sexual Contacts - HIV



Potterat et al. 2002, as in Newman 2003

$G = \{N, E\}$

Nodes

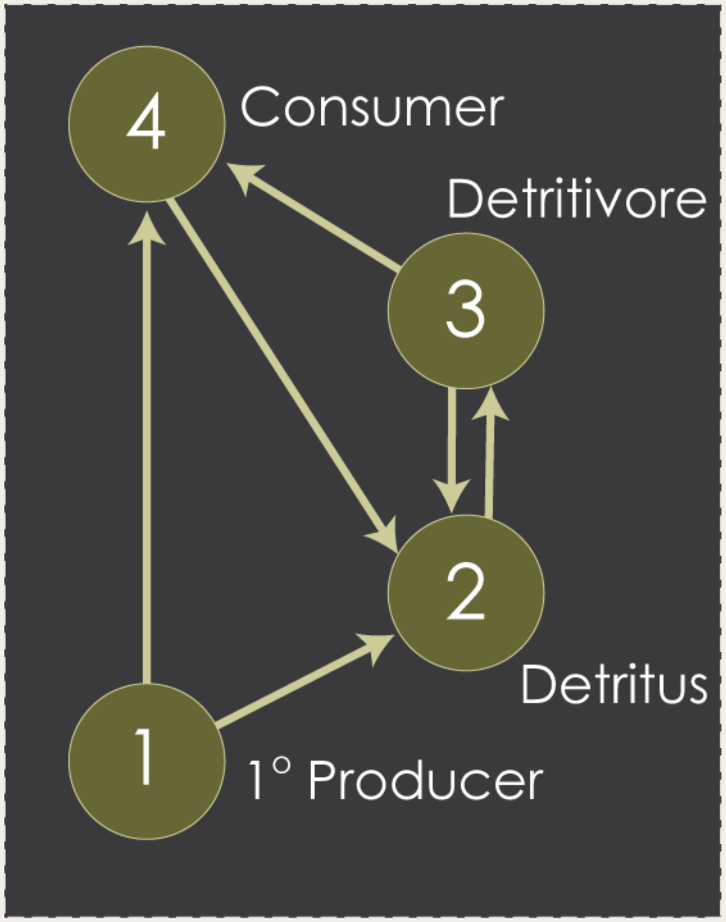
Individual people

Edges

Sexual Intercourse

How do the scientists get the data for this kind of model? How reliable is the data?

Describing a Network



$$G = \{N, E\}$$

N = ???; E = ????

Type of Graph → Simple, Directed

Number of Nodes (Vertices) $n = 4$

Number of Edges (Links) $L = 6$

Connectance or Density

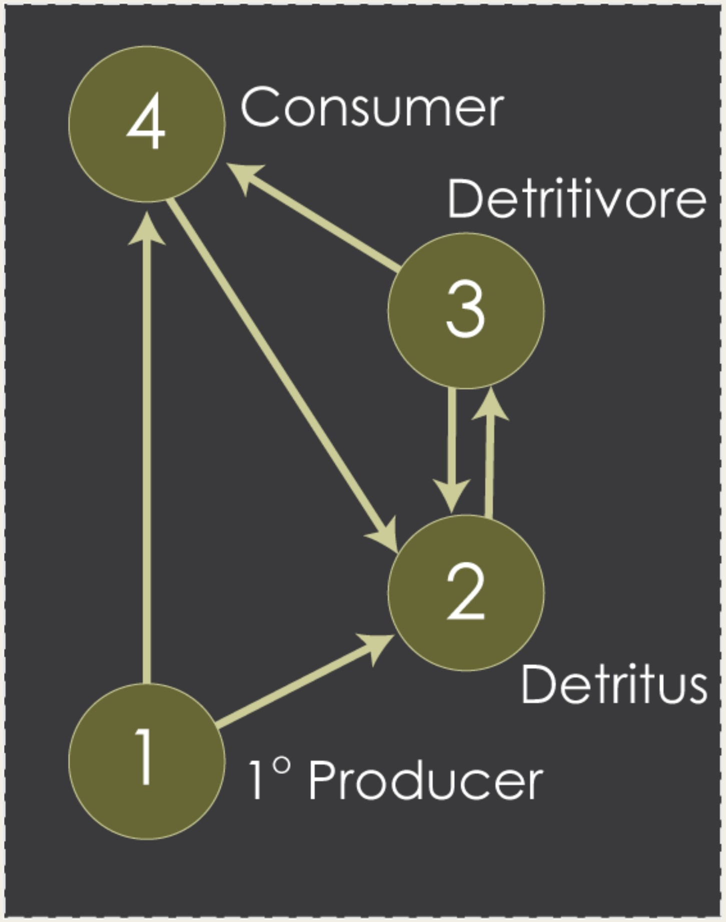
$$C = \frac{L}{n^2} = \frac{6}{16} = 0.375$$ With loops

$$C = \frac{L}{n(n-1)} = \frac{6}{12} = 0.5$$ No loops

Loop (aka self loop)
Edge from a node to itself

Have not described patterns of connections

Describing a Network: Pathways



Pathway: a sequence of edges

$$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 2 \rightarrow 3$$

Pathway length: the number of edges in the sequence (5 in example)

Distance (Geodesic): the minimum path length required to get from one node to another.

$$\mathbf{D} = \begin{bmatrix} 0 & 1 & 2 & 1 \\ \infty & 0 & 1 & 2 \\ \infty & 1 & 0 & 1 \\ \infty & 1 & 2 & 0 \end{bmatrix}$$

Row-to-Col

Reachability

Diameter: the *mean* or *maximum* distance

Cycle: pathway that starts and stops at the same node

$$2 \rightarrow 3 \rightarrow 2 \quad \textit{or} \quad 2 \rightarrow 3 \rightarrow 4 \rightarrow 2$$

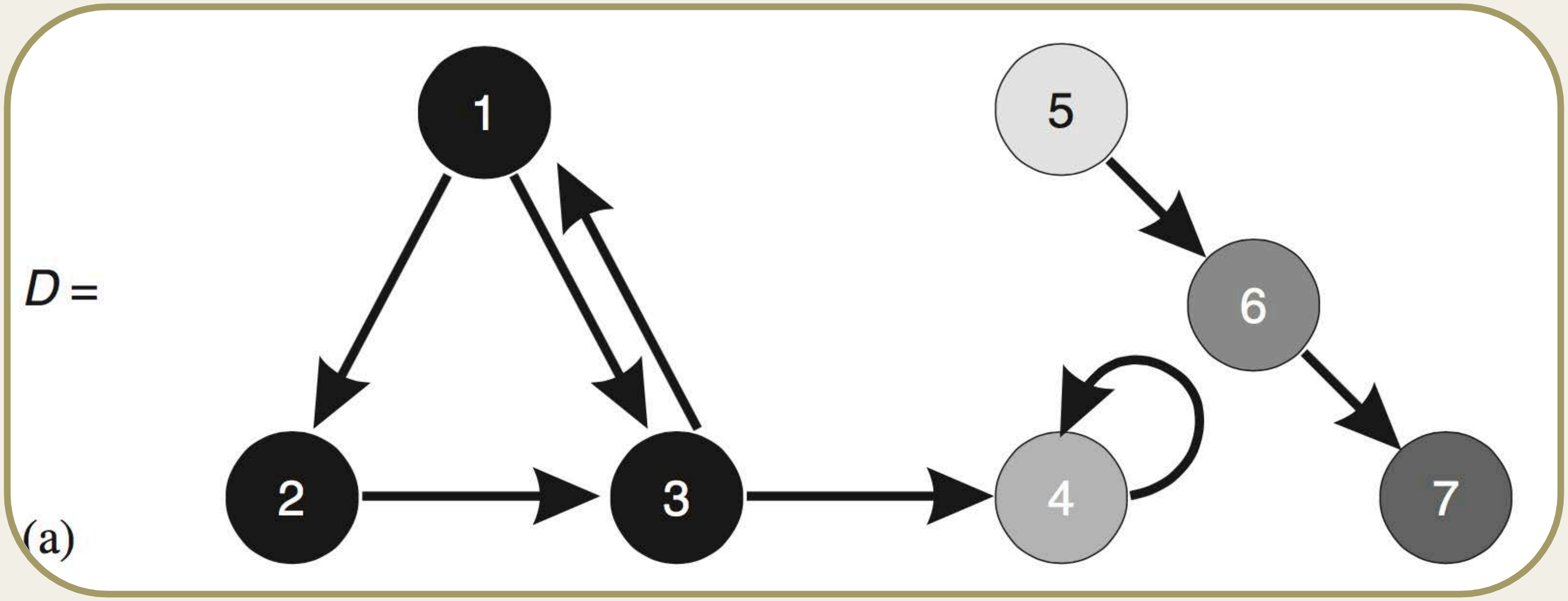
Components

Component
the nodes are reachable across a pathway ignoring direction

"maximally induced subgraph"

Strongly Connected Component
(SCC) possible to move from any node to any node over a pathway of some length following directions.

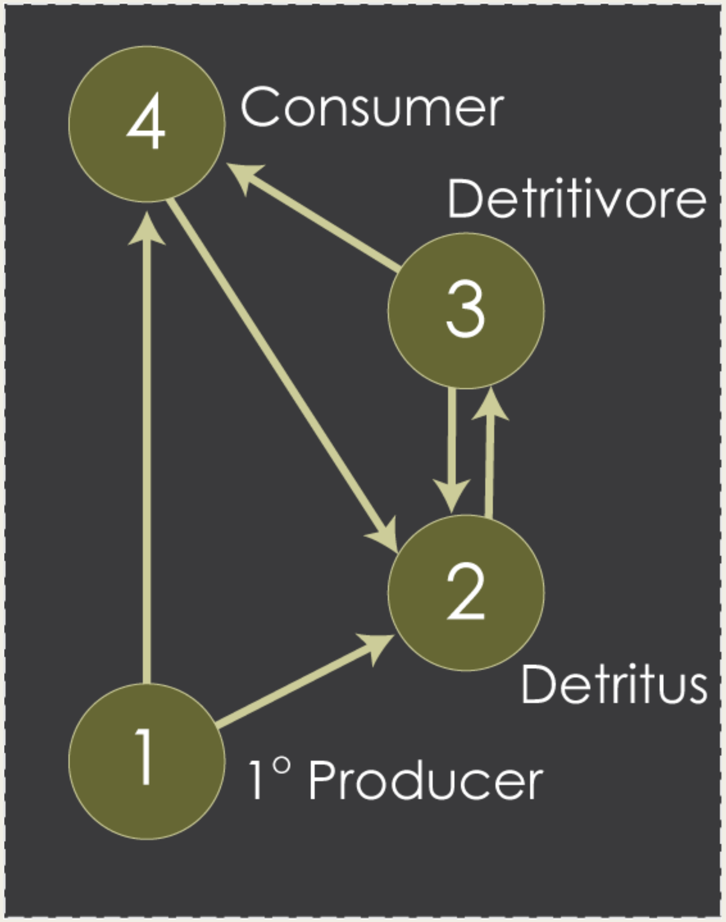
Example Digraph with 2 Components and 5 SCC



What are the Components? SCC's?

Borrett et al 2007

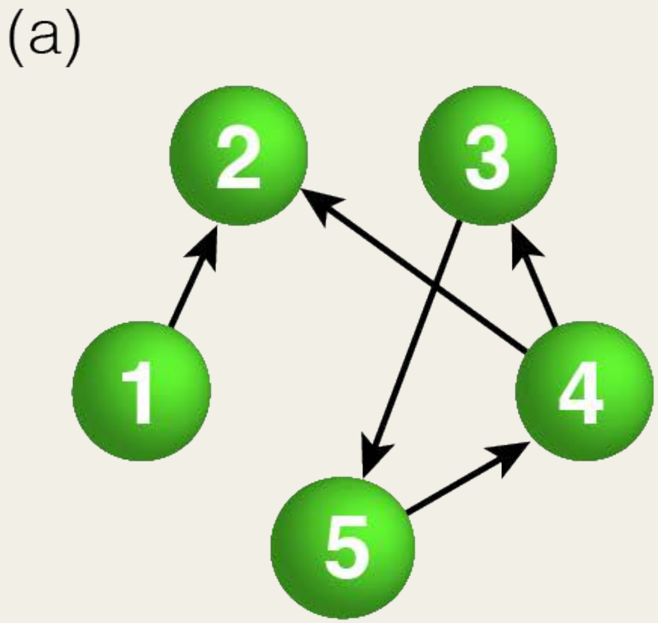
Degree

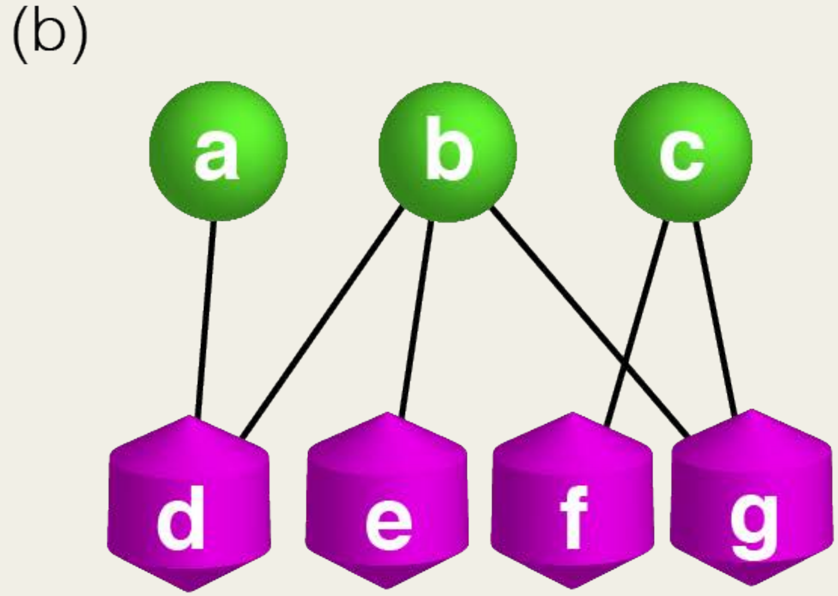


Node degree
number of edges incident to a node

What are the node degrees?

Try It





Find the Adjacency matrix for (a) and (b)

Find the degree of nodes 2, 4, b, d

How many components are in (a)? SCCs?

THINK

① What example networks can you identify? $G = \{N, E\}$

② Why networks?

2

Network Ecology

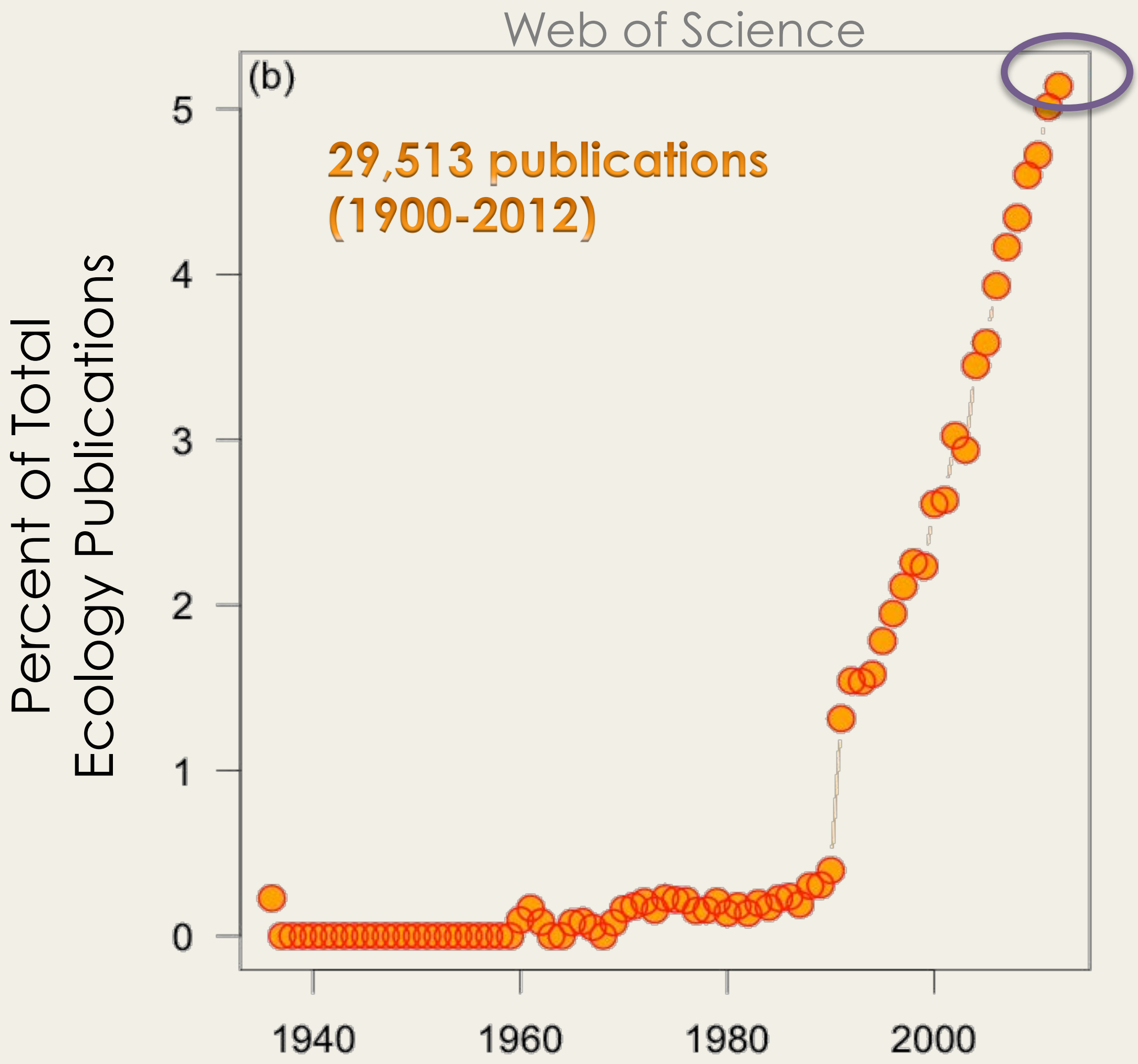
Study of ecological systems using network models and analysis to characterize their structure, function, and evolution.

Borrett, Christian, Ulanowicz 2012
Encyclopedia of Environmetrics

Network Ecology

Duke Network Analysis Center
DUKE UNIVERSITY

Study of ecological systems using network models and analysis to characterize the their structure, function, and evolution

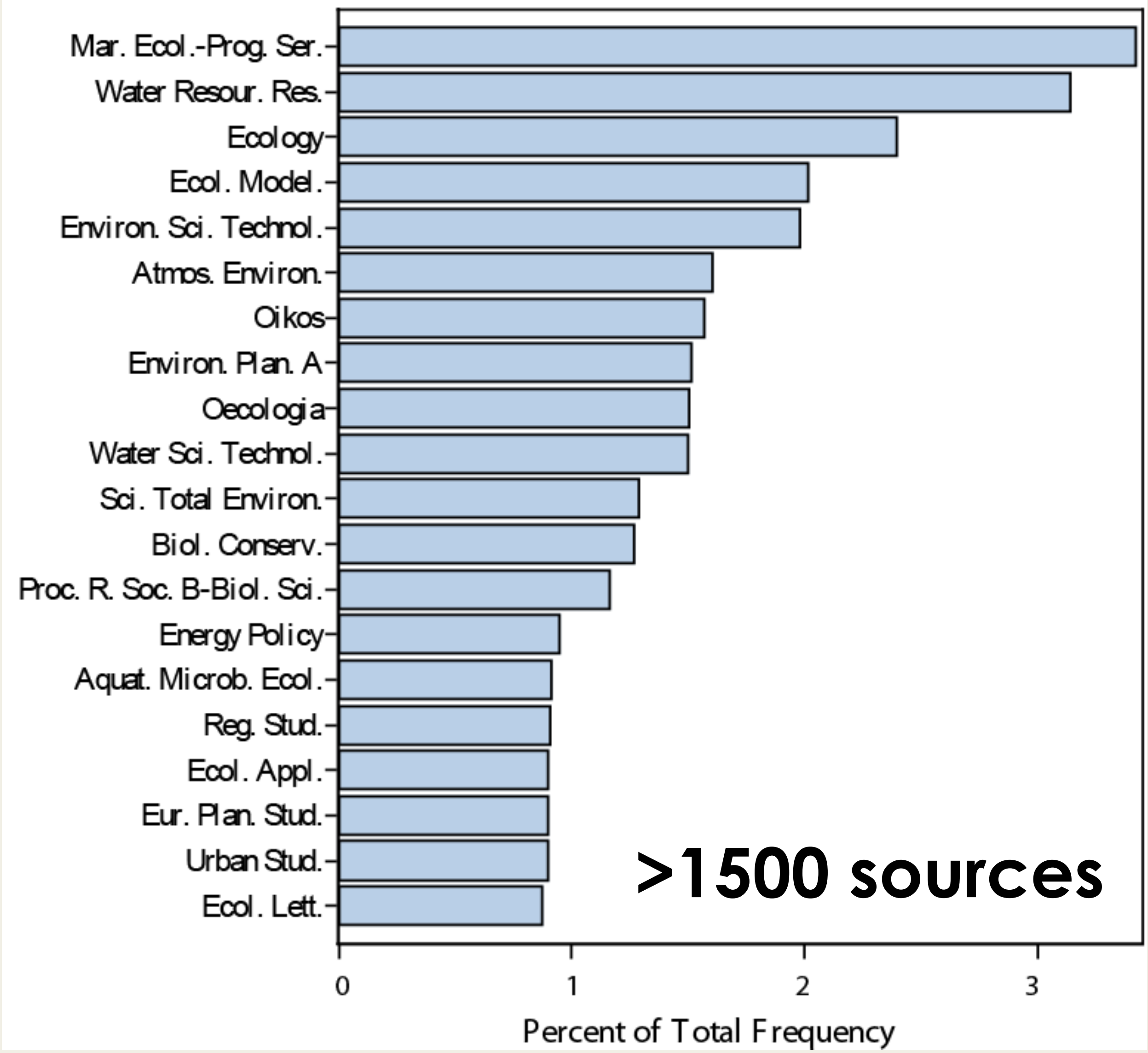


Network Ecology is a large, and rapidly growing domain

Borrett, et al. 2014, Ecol Model

Where is Network Ecology Published?

Journals (sources)



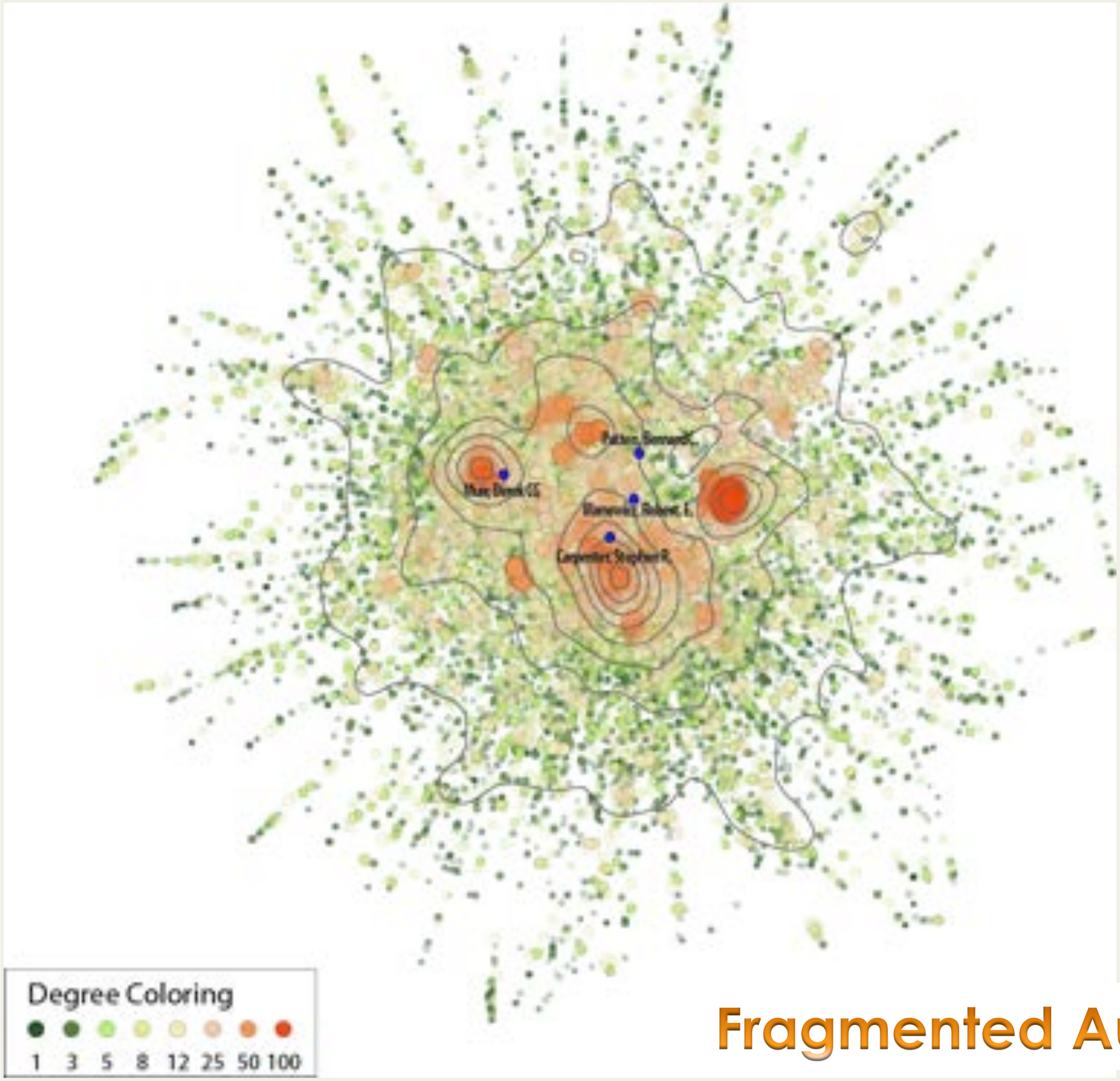
Network Ecology publications are broadly dispersed

Borrett et al. 2014 Ecol. Model.

Fragmented CoAuthorship

Borrett et al. 2014

Co-Author Network



G = {N,E}
N: author
E: co-authorship

69,564 Total Authors

Largest Component -
46% of authors

149 Clusters

(Louvian community detection algorithm)

Cluster Size

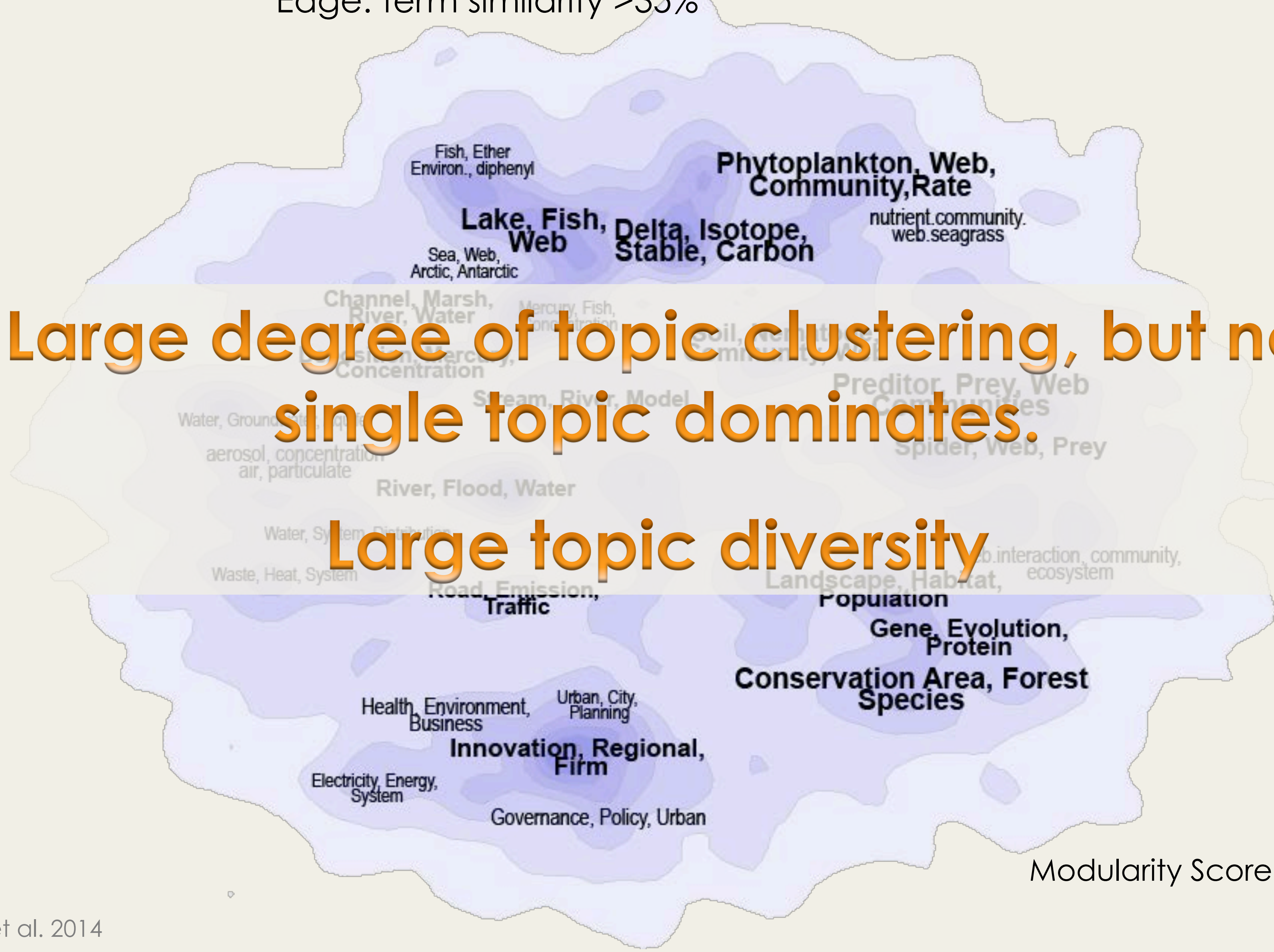
6 – 1,618 authors

Fragmented Author Communities

Diverse Topics

Topic Network

Node: paper
Edge: term similarity >35%



Large degree of topic clustering, but no single topic dominates.

Large topic diversity

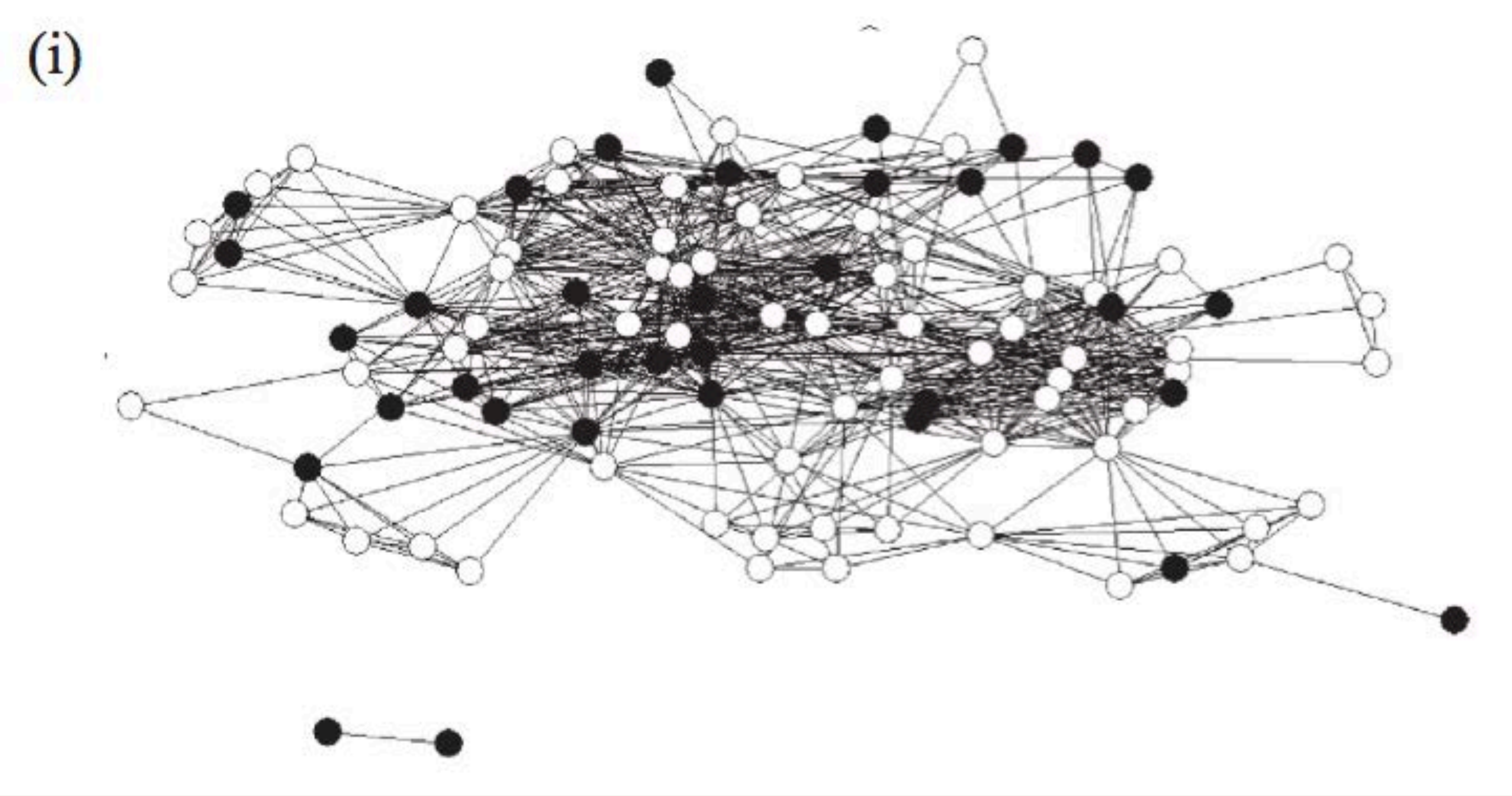
Modularity Score = 0.927

Borrett et al. 2014

Population

Animal Behavioral Network

Social Network of Guppy Fish

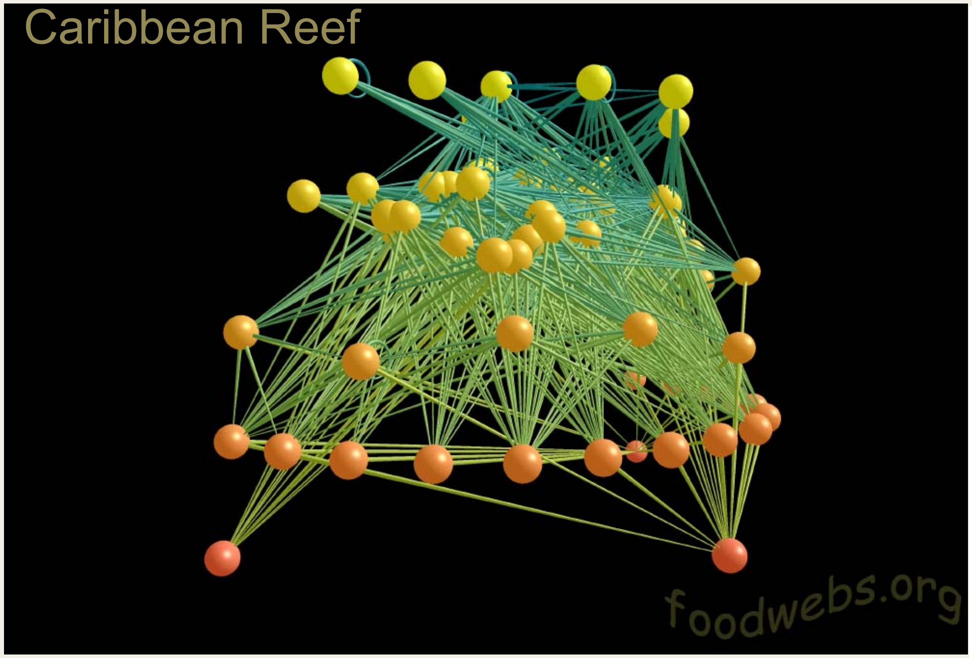


Node = individual Guppy Fish *Poecilia reticulata* (male, filled; female, open)
Edge = individual co-occurance in shoal

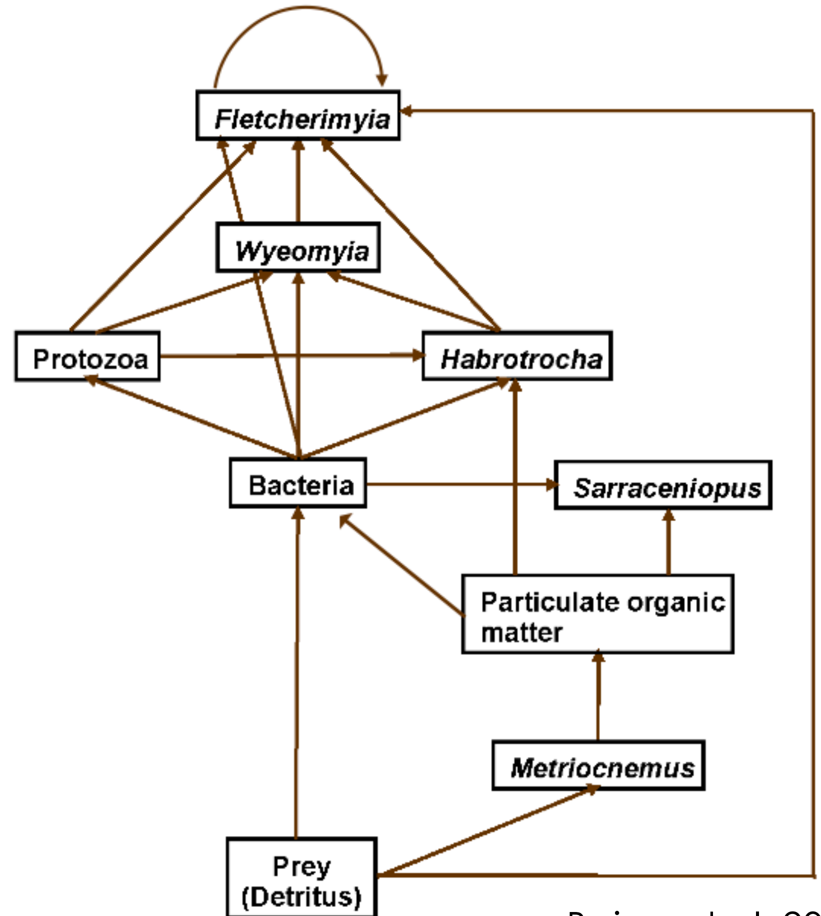
Conclude: Highly structured social system

Croft et al. 2004

Food Webs



http://foodwebs.org



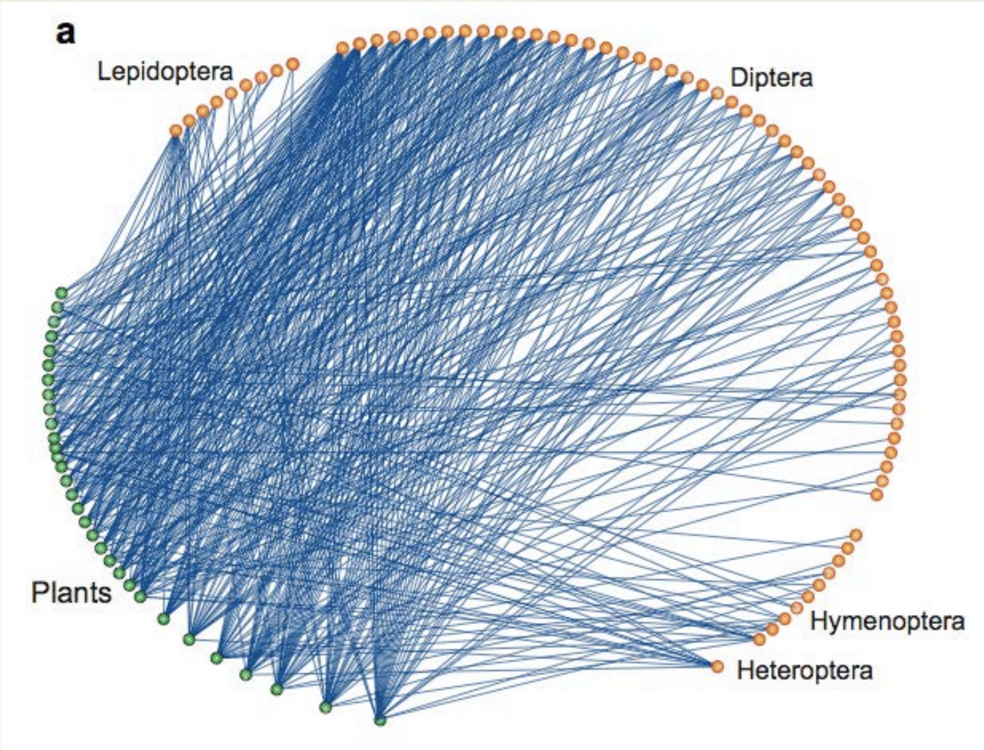
Baiser et al. 2011

Nodes: Species, Trophospecies, Functional Group, or NL Resource

Edges: classically who **eats** whom

Mutualistic Networks

Plant-Animal Interactions



Bascompte & Jordano 2007

$G = \{N, E\}$

Nodes

(a) Plant species

(b) Animal species

Edges

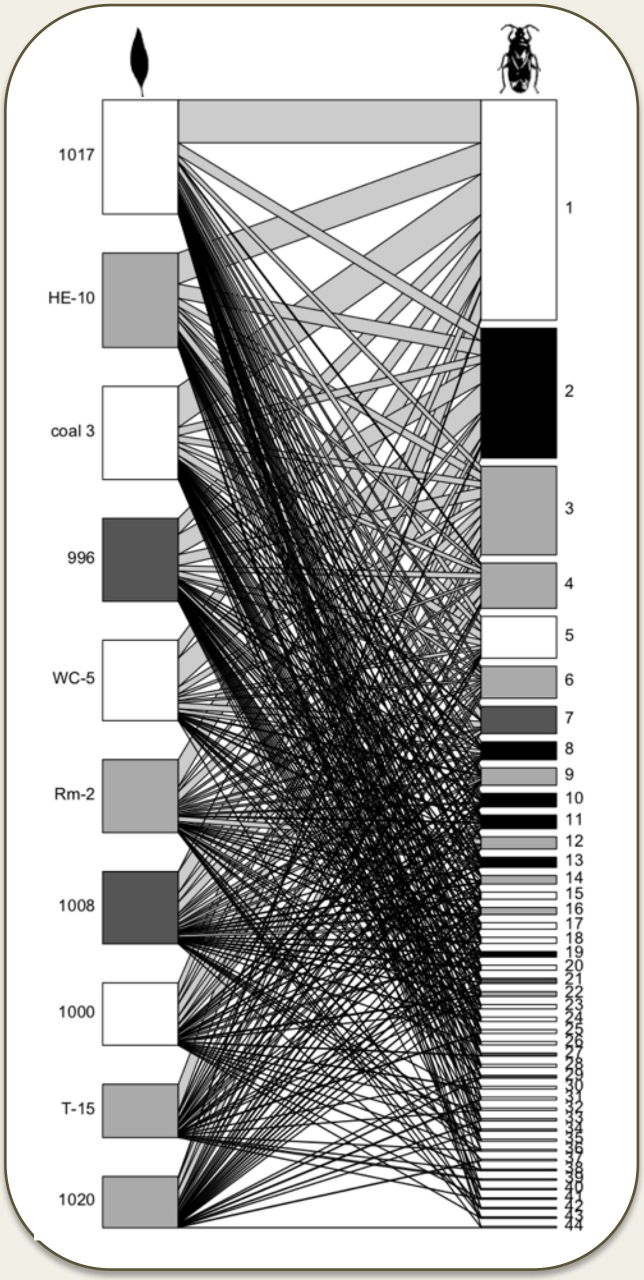
Pollination visit

Bipartite Graph

Discovered re-occurring **nested** pattern
What causes this pattern? Consequences?

Community

Genotype-Community



$G = \{N, E\}$

Nodes – Two Types

A: Tree Genotypes

B: Insect Species

Edges

Co-occurrence

Bipartite Graph

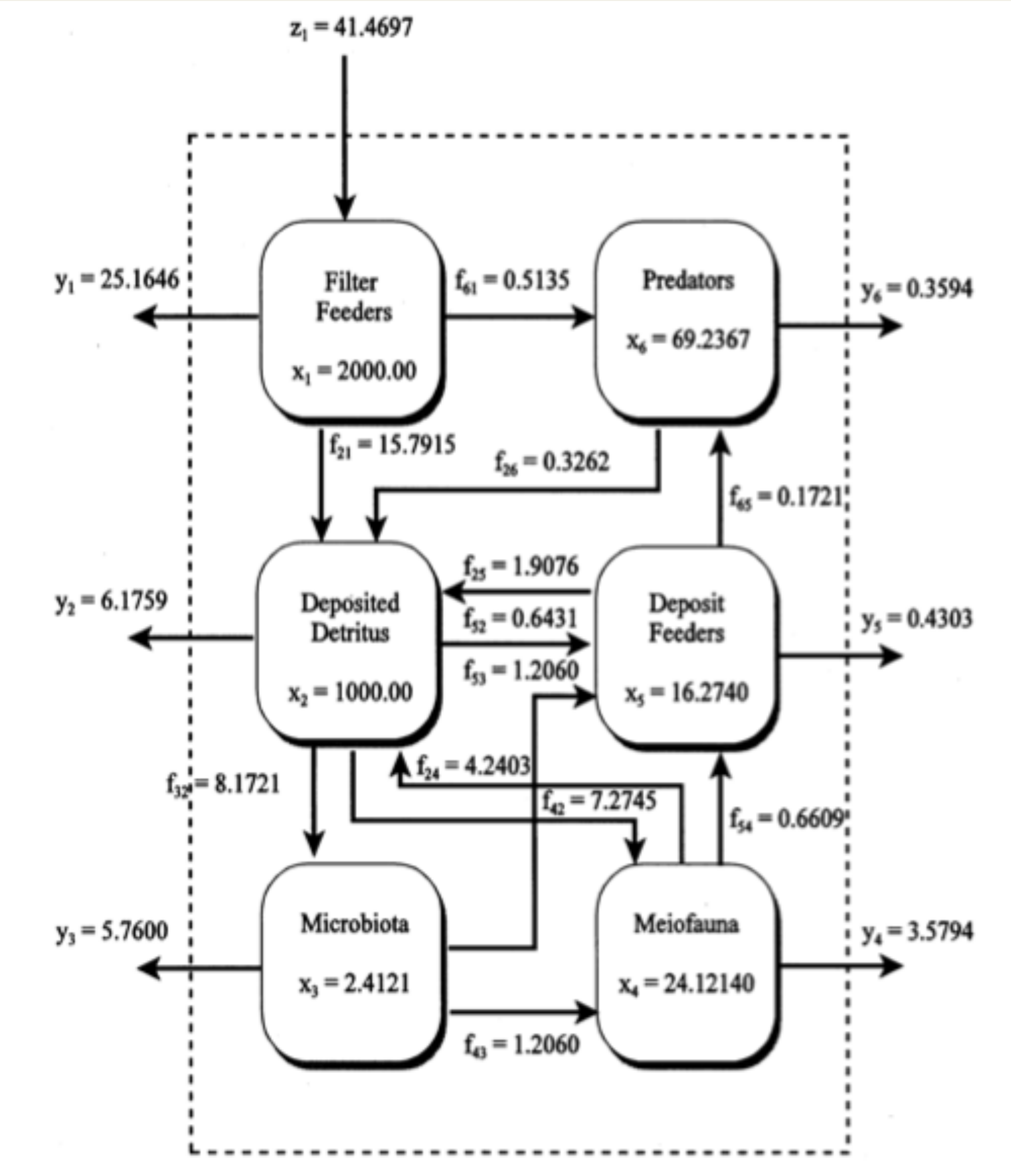
Clear effect of tree *genotype* on insect community composition

Lau et al. 2016

Trophic Ecosystem Model

SC Oyster Reef Ecosystem (Dame and Patten 1981)

"Compartment Models"



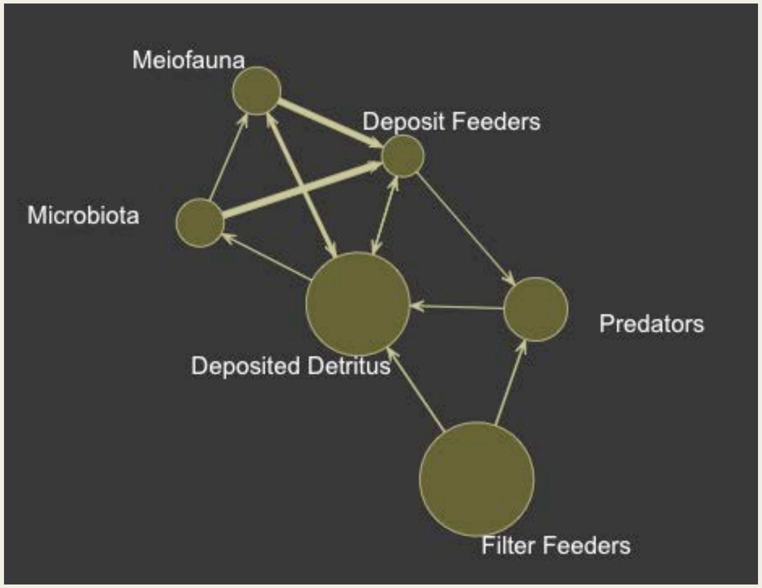
$G = \{N, E\}$

Nodes

Species, Functional Groups

Edges

Flux of energy kcal m^{-2} yr^{-1}



Urban Water Metabolism

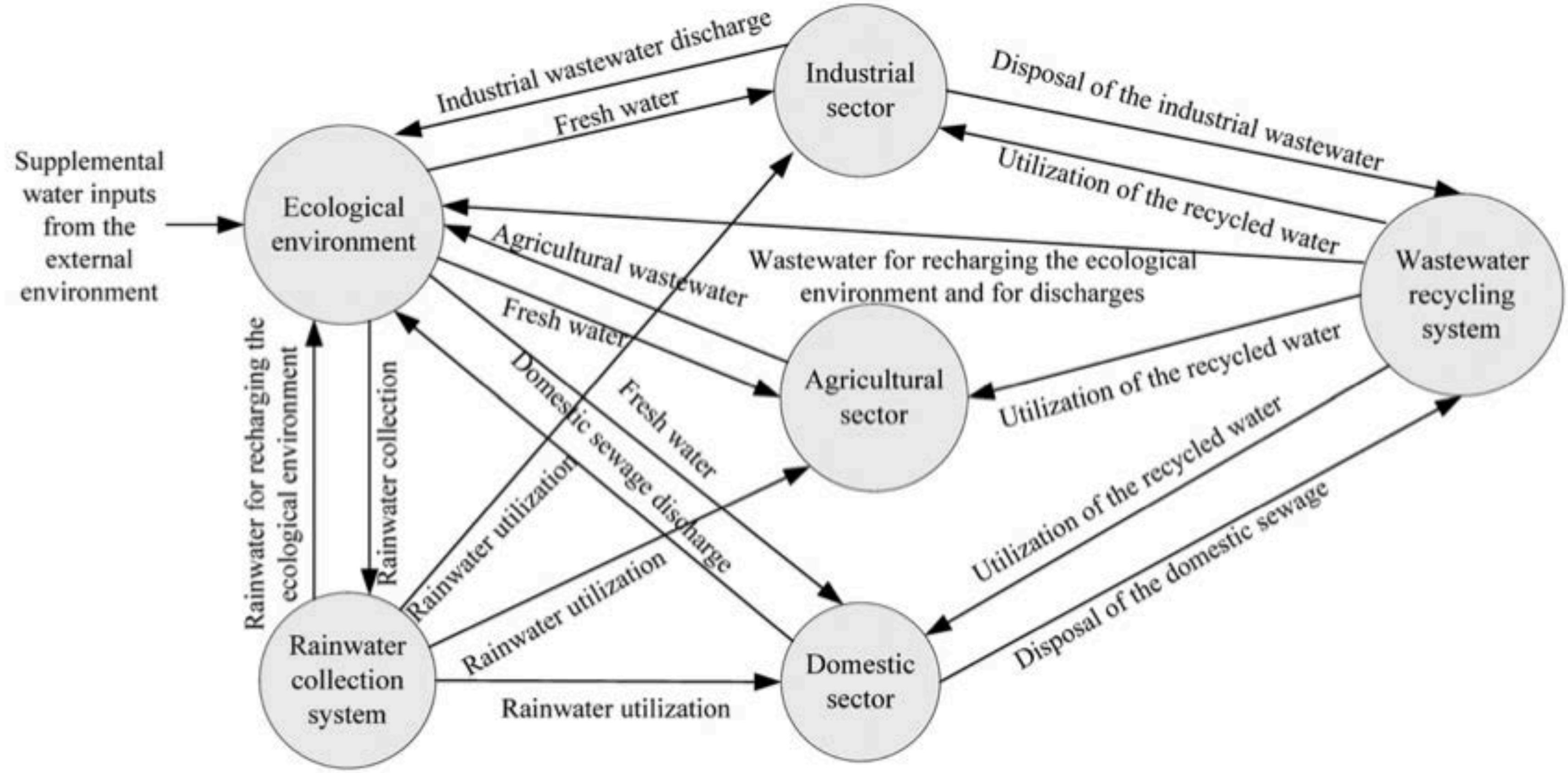


Fig. 1. A conceptual model of the water flows in the urban water metabolism.

G = {N, E}

Nodes: Economic Sector

Edges: Flux of water $m^3\ yr^{-1}$ (not certain of time unit)

Zhang et al. 2010

Habitat Networks

Animal movement across the landscape

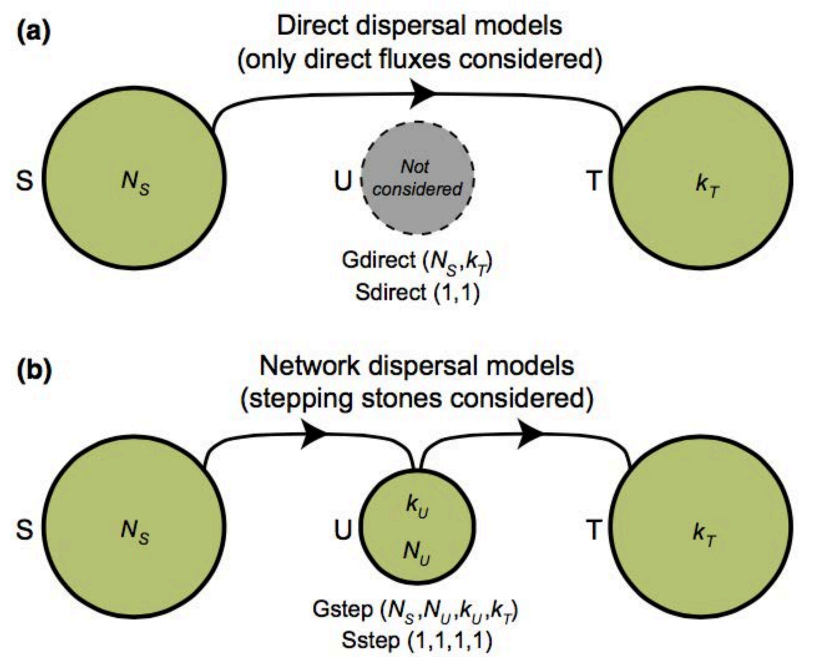
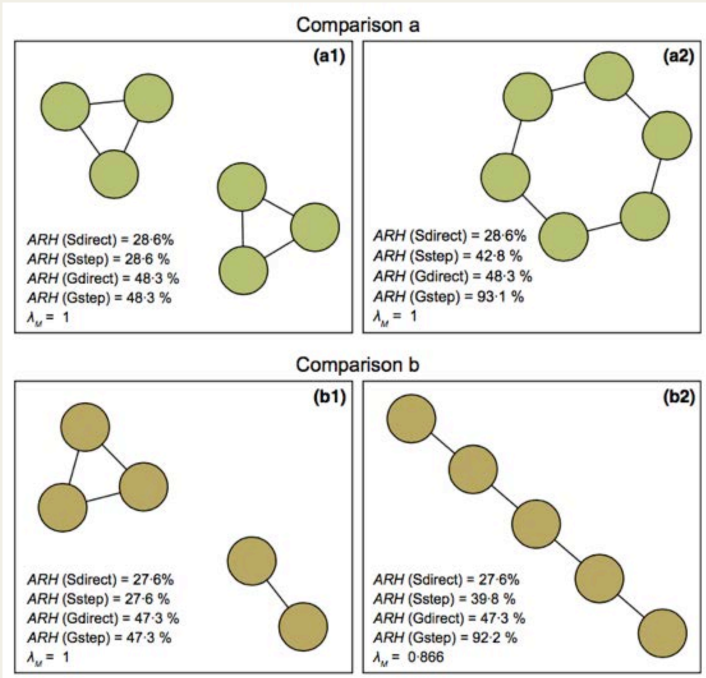


Fig. 1. Illustration of the assumptions and implications of the different connectivity models in a three-patch system. The system consists of a source patch S, a destination (target) patch T and a patch U that may act as a stepping stone facilitating dispersal from S to T. Patch S is fully occupied up to its carrying capacity by the focal species (with N_S individuals dispersing from S), whereas U and T are initially vacant. The species may get established in U or T if at least k_U or k_T individuals are able to colonize the patch, respectively. Many connectivity models (Sdirect, Gdirect) do not consider the potential role of U in facilitating the colonization of T (a), which is accounted for in models Sstep and Gstep through network analysis (b).

$G = \{N, E\}$

Nodes: Habitat Patches

Edges: Species movement (dispersal)



Spatial arrangement, patch quality

"Stepping Stones"

Saura et al. 2014

Trophic Cascades & Pollination

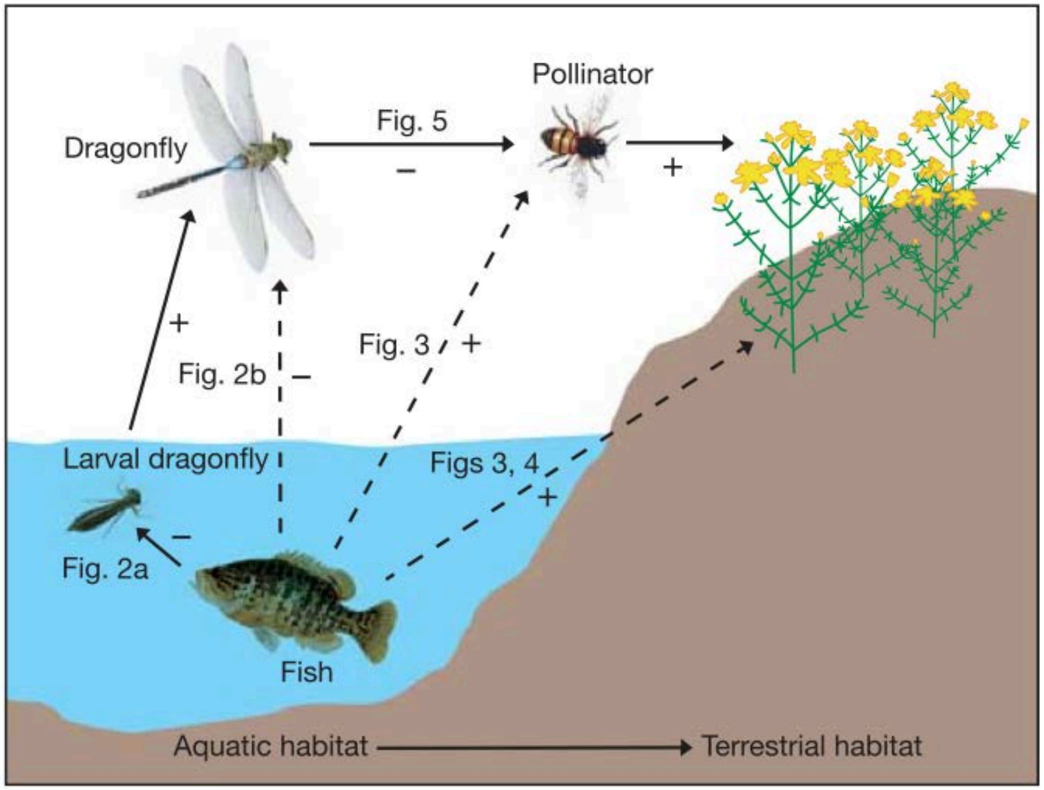


Figure 1 | Interaction web showing the pathway by which fish facilitate plant reproduction. Solid arrows indicate direct interactions; dashed arrows denote indirect interactions. The sign refers to the expected direction of the direct or indirect effect (see the text). Figure numbers indicate which figure presents data supporting each of the predicted effects. (Figure created by S. White and C. Stierwalt.)

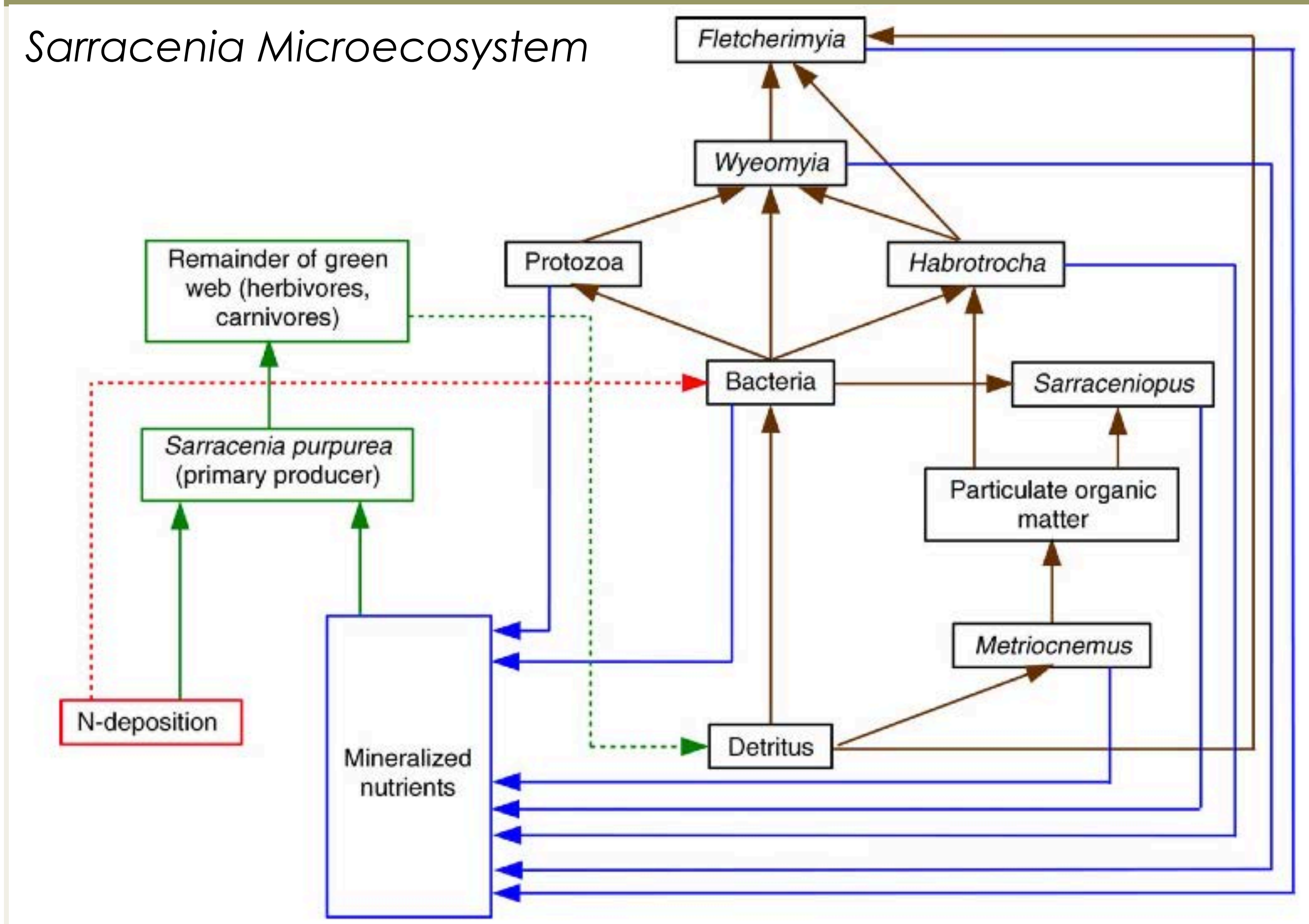
Presence of fish in ponds decreases the fitness of nearby plants

Linked food web and pollination network

Knight et al. 2005

Combination

Food web, biogeochemistry, …



Stuart Borrett @ Flickr

Stuart Borrett

Butler et al 2008 Ecology

G = {N, E}

Nodes: Species/Groups, Resource Pools (N, Det), Plant parts

Edges: Flux of stuff (biomass, N, etc) – Mixed Units Problem

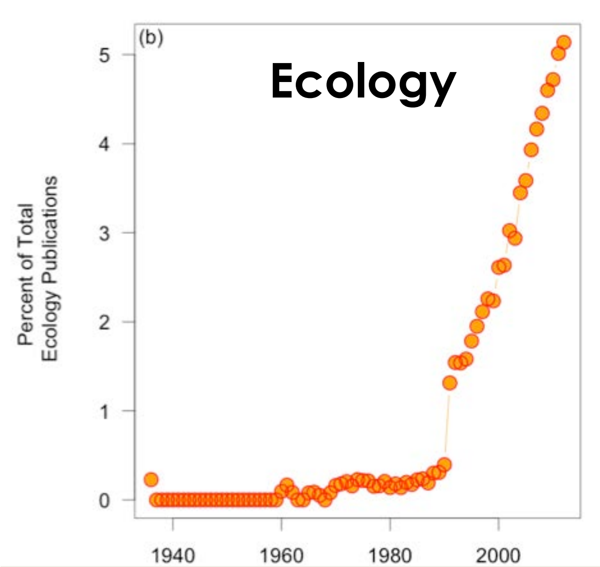
1. Network Elements
2. Network Ecology
3. Context

3 Parting Thoughts

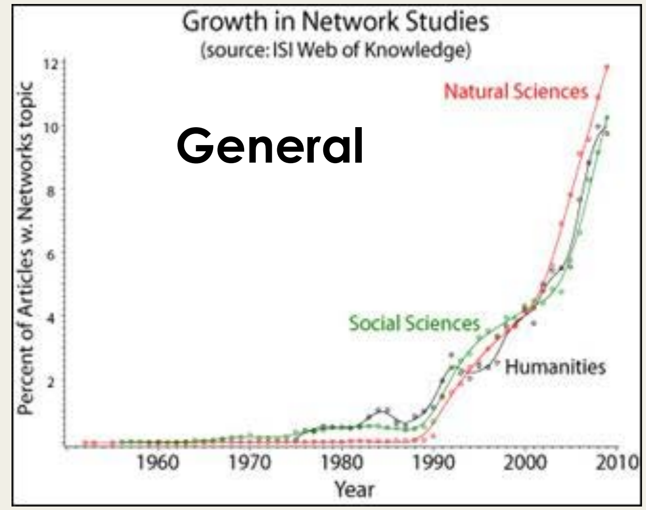
Ensnared

Clarified

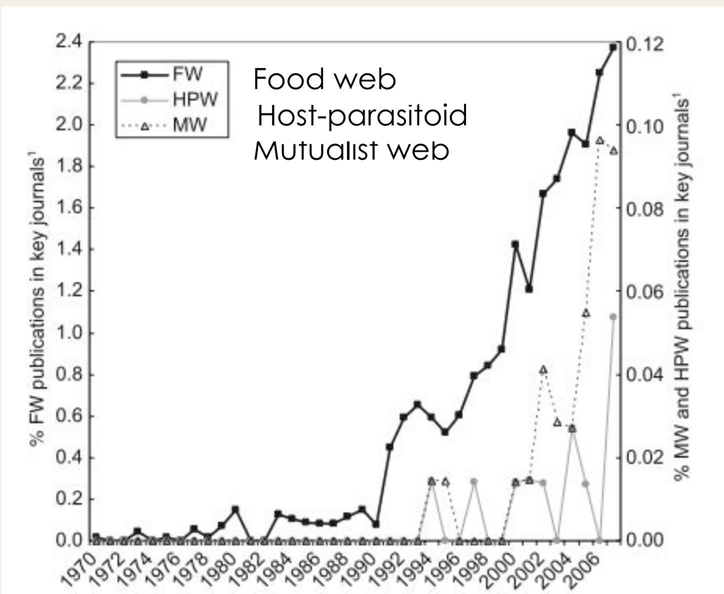
Rise of Network Ecology



A common pattern



Duke Network Analysis Center



Ings et al. 2009

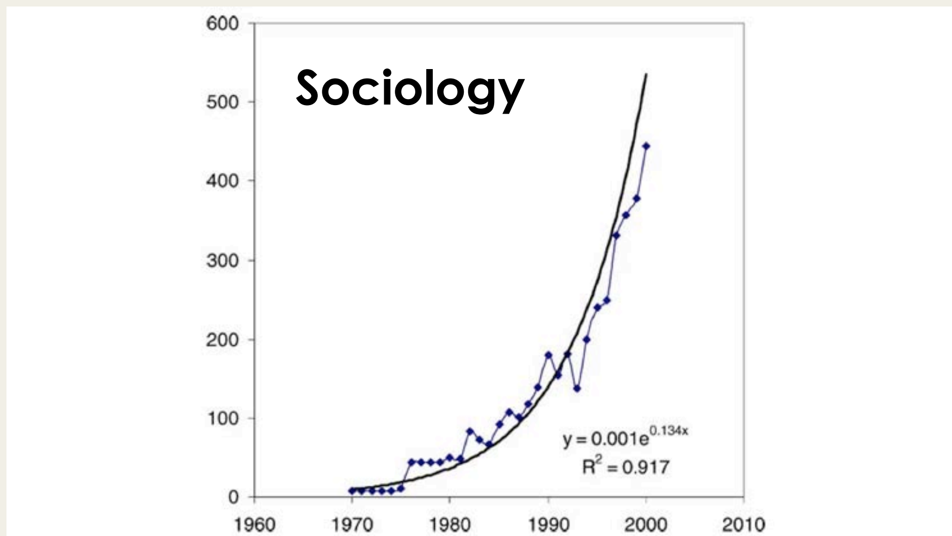


Figure 1. Exponential growth of publications indexed by Sociological Abstracts containing "social network" in the abstract or title.

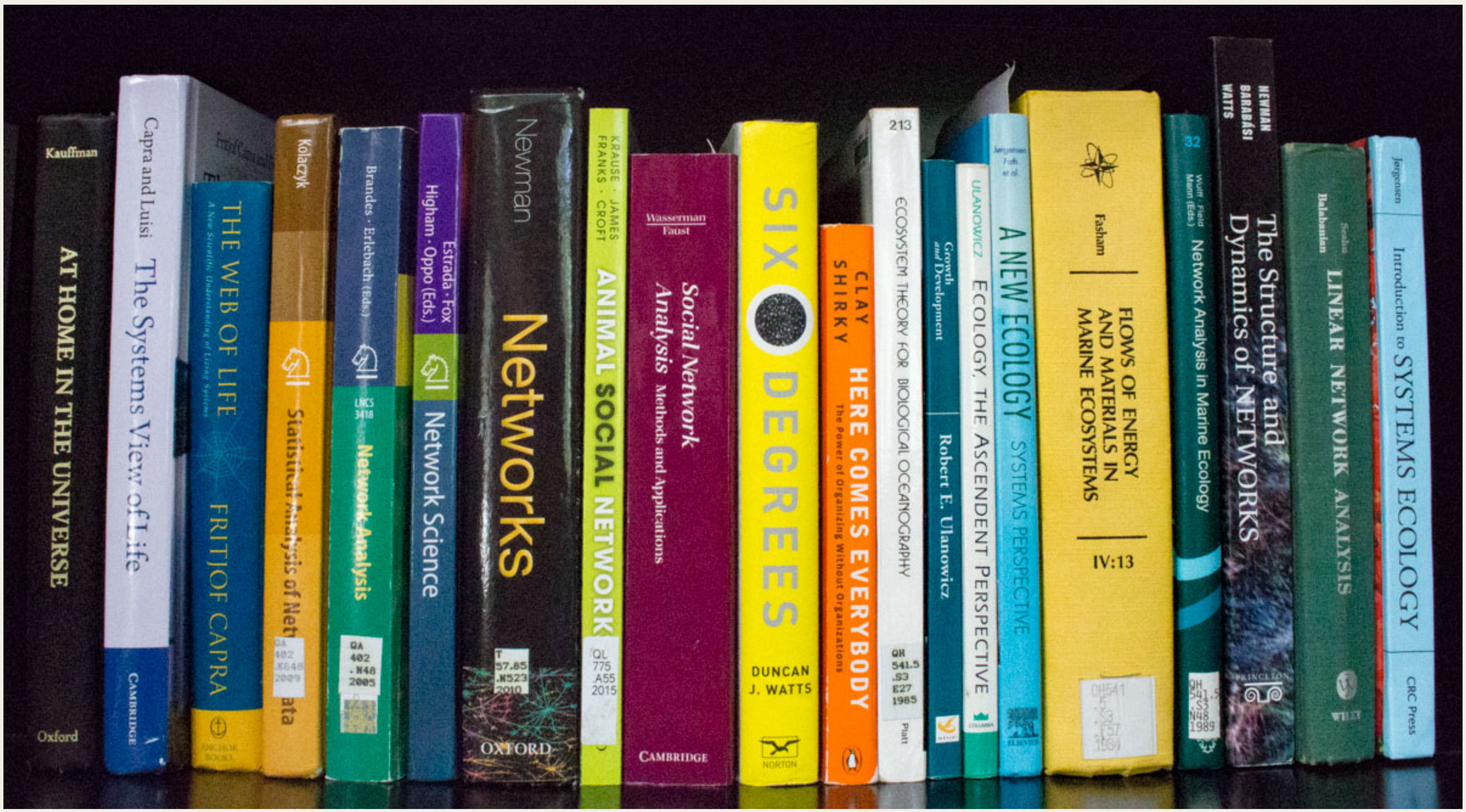
Borgatti and Foster 2003

Network Science

"The study of the collection, management, analysis, interpretation, and presentation of relational data"

"the study of network models"

Brandes et al. 2013 Network Science



Network Science

"The study of the collection, management, analysis, interpretation, and presentation of relational data"

"the study of network models"

Brandes et al. 2013 Network Science

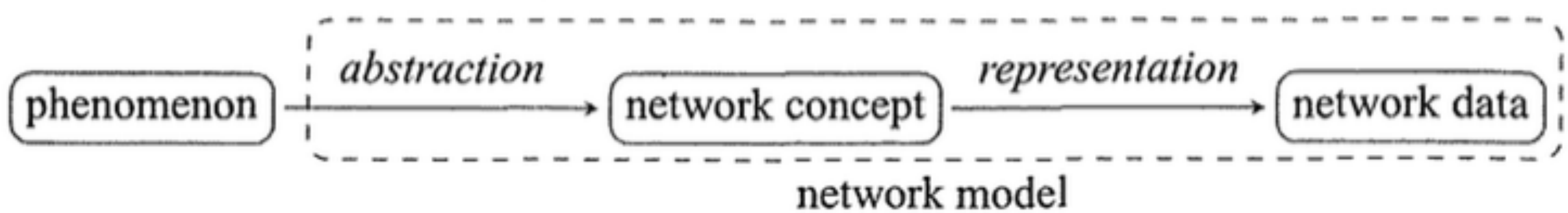


Fig. 1. The elements of network models.

Network Science

"The study of the collection, management, analysis, interpretation, and presentation of relational data"

"the study of network models"

Brandes et al. 2013 Network Science

Network Statics

How do we describe the network?

Dynamics ON Networks

Disease, information transmission
Traffic or Energy Flow

Dynamics OF Networks

How do networks change through time/space?

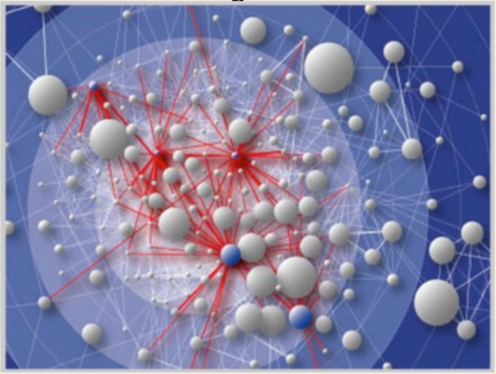
SAMSI Opening Workshop 2010; Porter et al 2014

Discussion

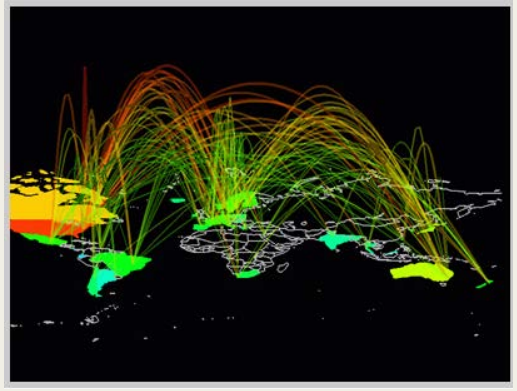
Forces Shaping the Rise of Networks (Ecology)

- Fundamentally a useful approach

  Relational model & analysis for a fundamentally relational science



- Critical Mass
  - Number of practitioners/problems
  - Arrival of the physicists
  - Maturation of techniques



- Data availability data explosion
- Swing toward synthetic science
  - Limits of reductionism in many domains (Barabasi 2012)
- All of the above

Frontiers of Network Ecology

Applications of techniques to new areas/problems

- Physiological Networks (Cohen et al. 2012)
- Urban Metabolism (Zhang et al. 2010, Layton et al. 2012)

Applied Questions (networks as tools, Memmott 2009)

- Effect of Sea Level Rise (Hines et al. 2012, 2015, 2016)

Tools and Methods

- Model construction
- Sensitivity/Uncertainty analysis
- Network statistics – statistical inference
- Software

Combining network models (Fontaine et al. 2011)

- Trophic cascades across ecosystems (Knight et al. 2005)
- Evolution on population network structure (Malcom 2012)
- Multilayer network framework (Kivela et al. 2014)

Online Resources

Network Science | Matthias Scholz

http://www.network-science.org

Statistical Analysis of Network Data | Eric D. Kolacyk

http://www.samsi.info/sites/default/files/Kolaczyk-CN.pdf

Visual Complexity | Manuel Lima

http://www.visualcomplexity.com/vc/

Simplifying Complexity | Eric Berlow

http://www.ted.com/talks/eric_berlow_how_complexity_leads_to_simplicity

Introduction to Networks

1. Network Elements
2. Network Ecology
3. Context

S.R. Borrett