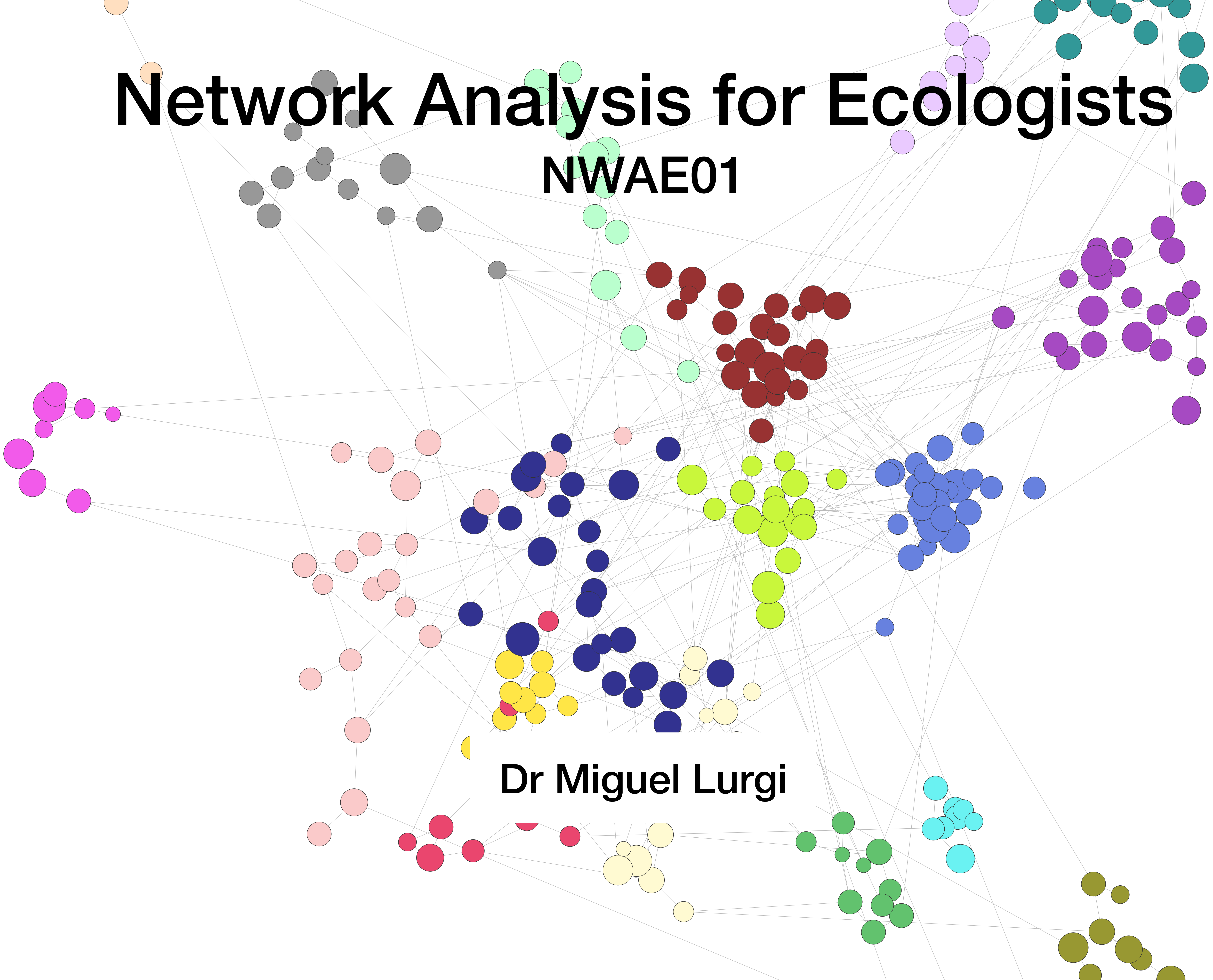


Network Analysis for Ecologists

NWAE01

Dr Miguel Lurgi

What will we learn today?

Part I : Introduction to networks

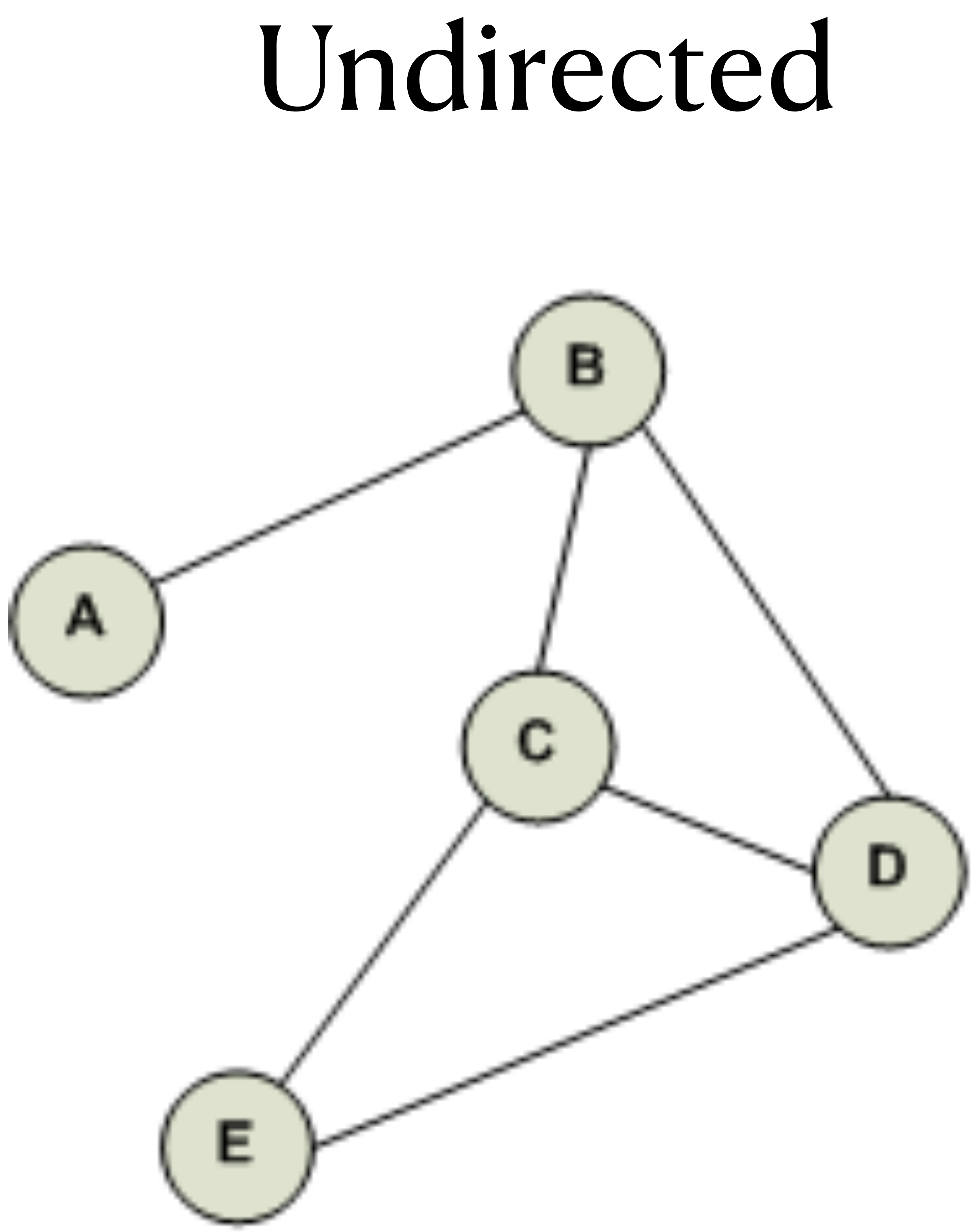
- What is a network? - Definition of a network and its constituent parts (vertices and edges)
- What analyses can be performed on networks? - Conceptual description of network metrics and specific descriptors used to analyse ecological networks.
- How can we use networks? - Description of their potential uses and their analysis.

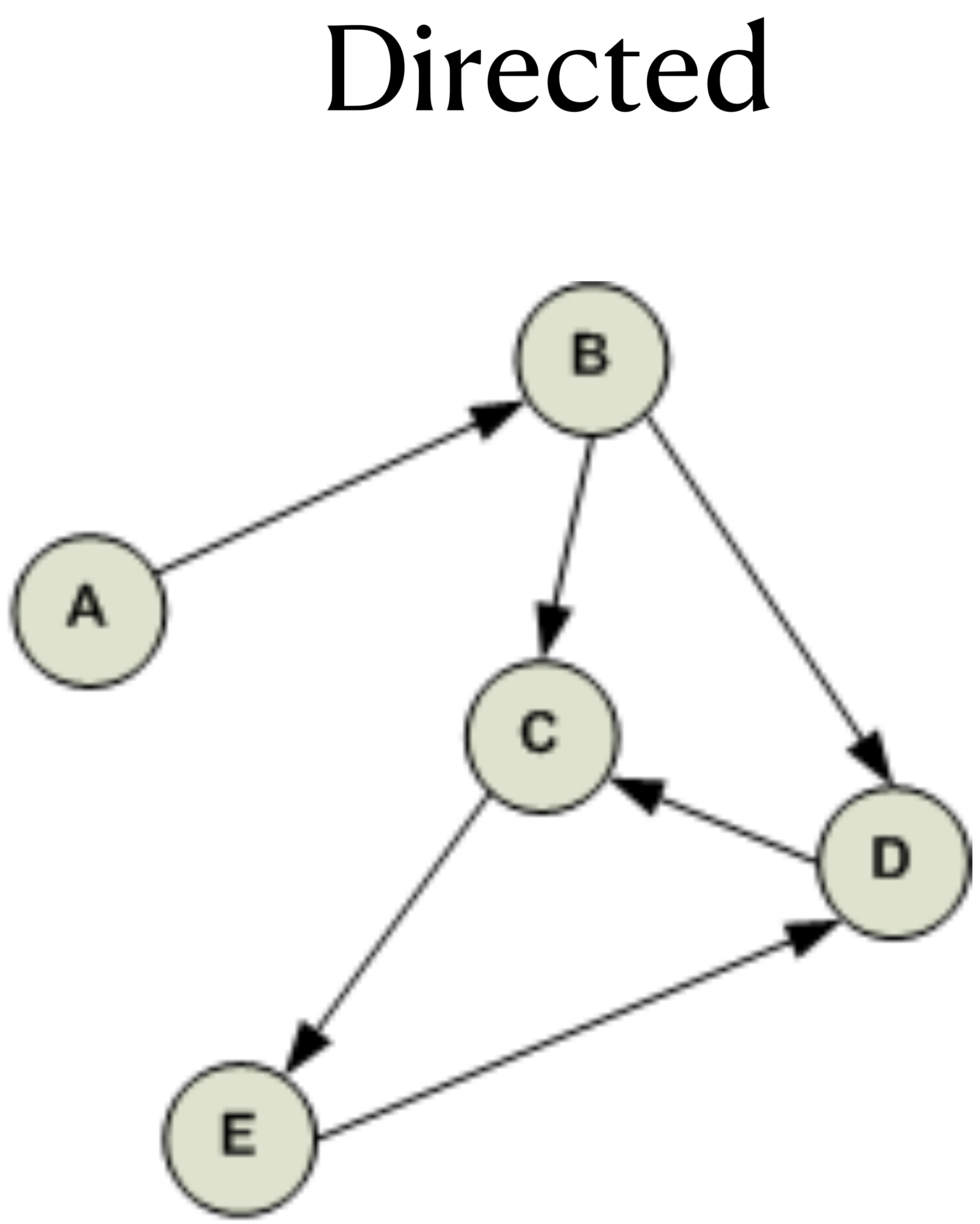
Part II : Methods for network analysis

- Understand in detail a suite of network metrics: Degree (number of interactions), degree distribution (heterogeneity of interaction number), modularity, nestedness, centrality

Part I: Introduction to Networks

What is a network?



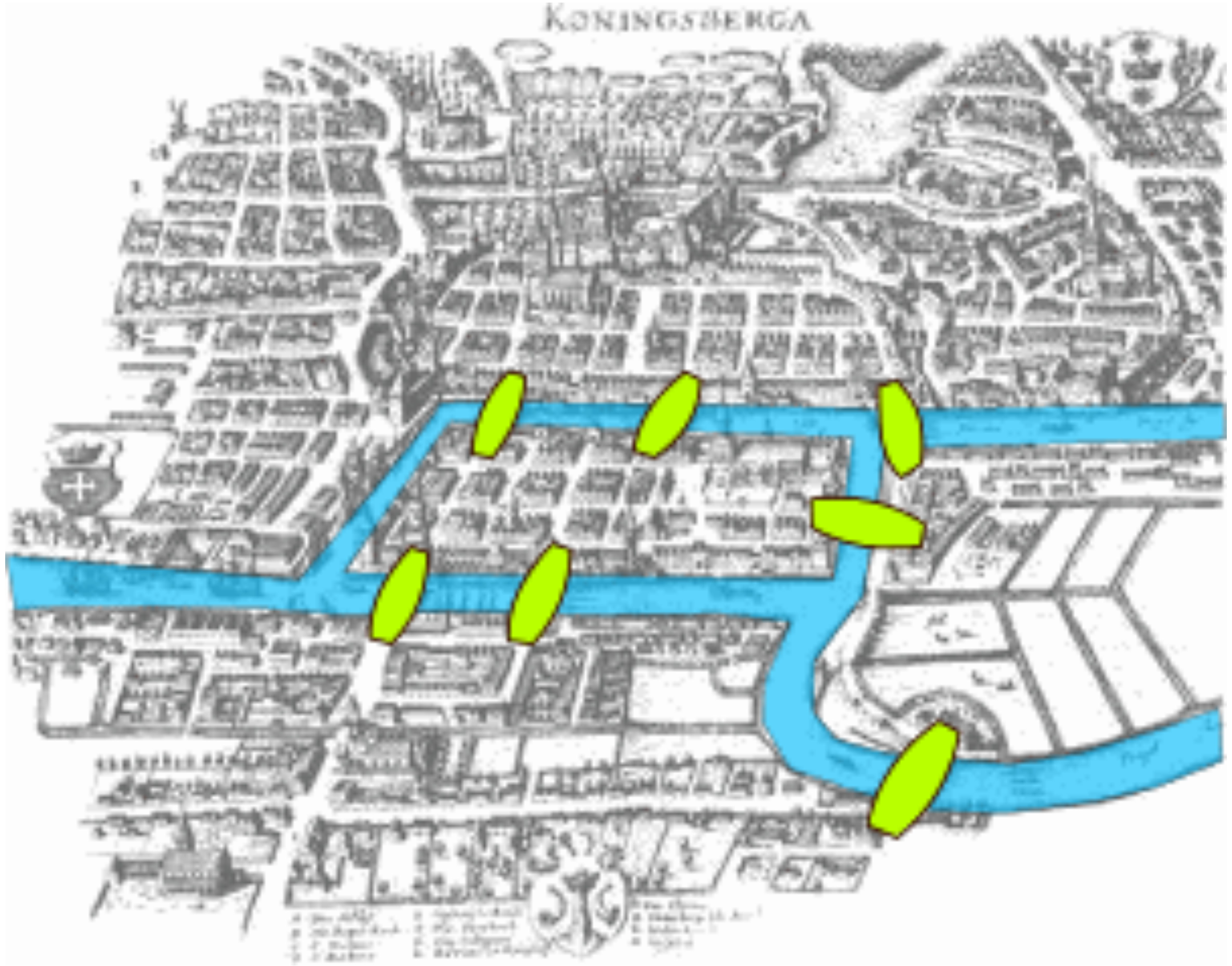


Nodes = vertices (e.g. species, people, computers)
Links = edges = interactions (e.g. trophic, social, information)

A bit of history…

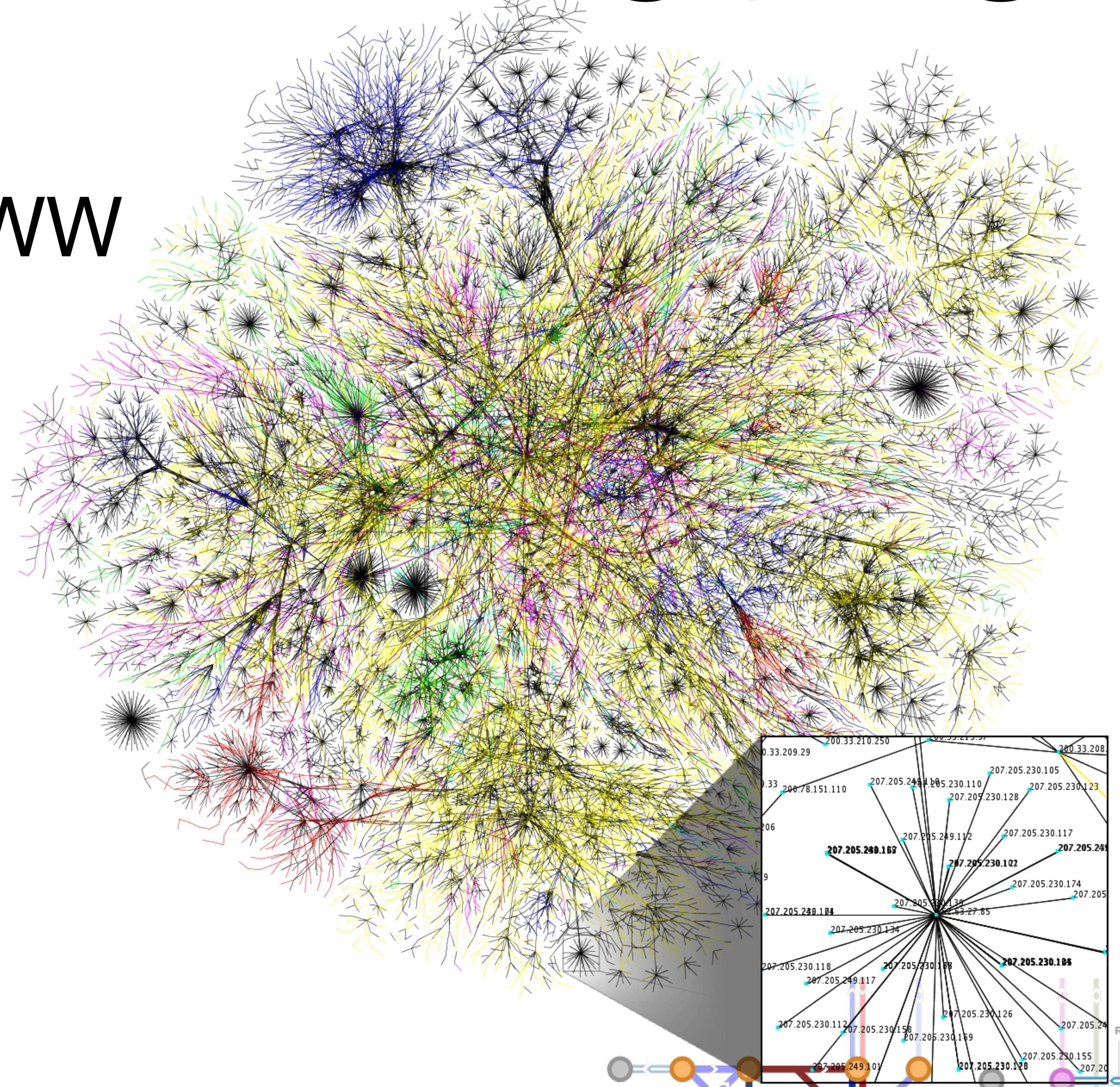
Leonhard Euler (1735)

Seven bridges of Königsberg

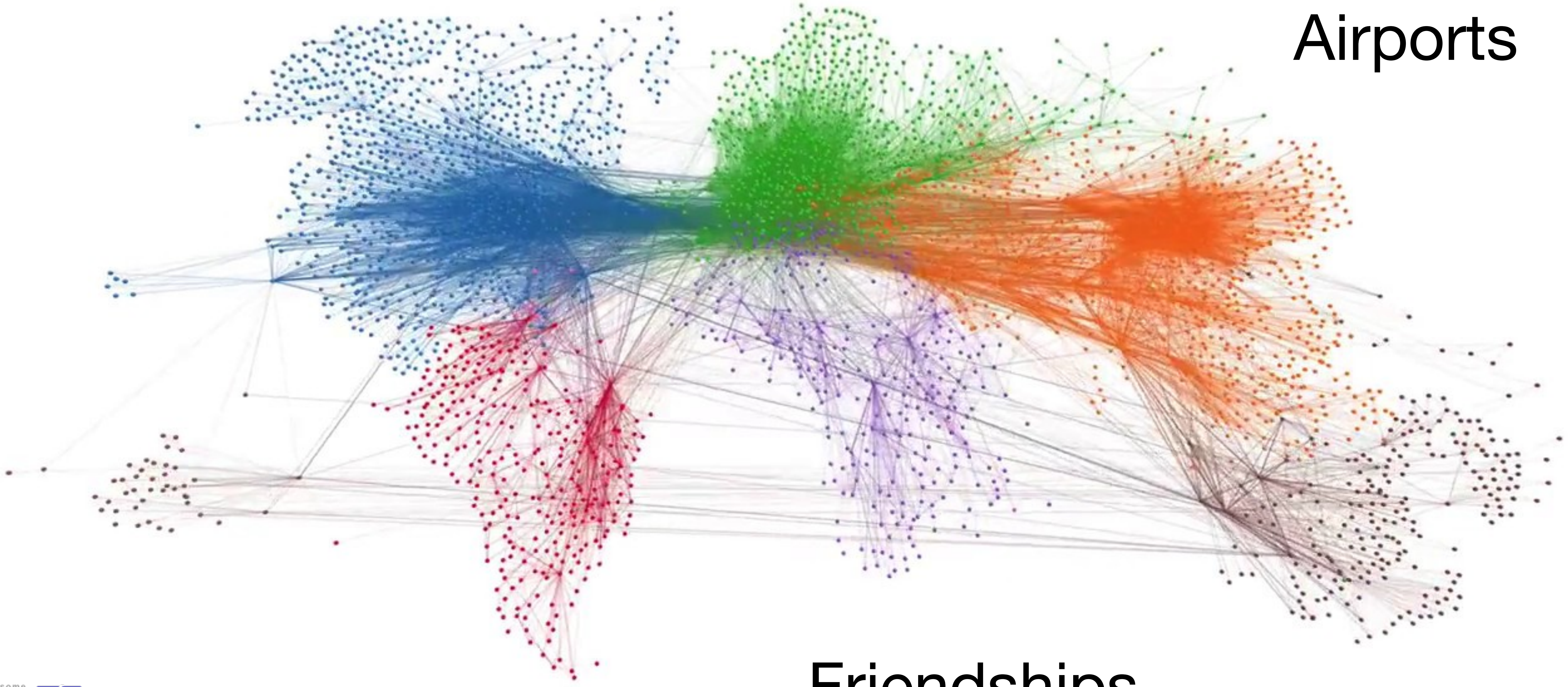


Networks all around us

WWW

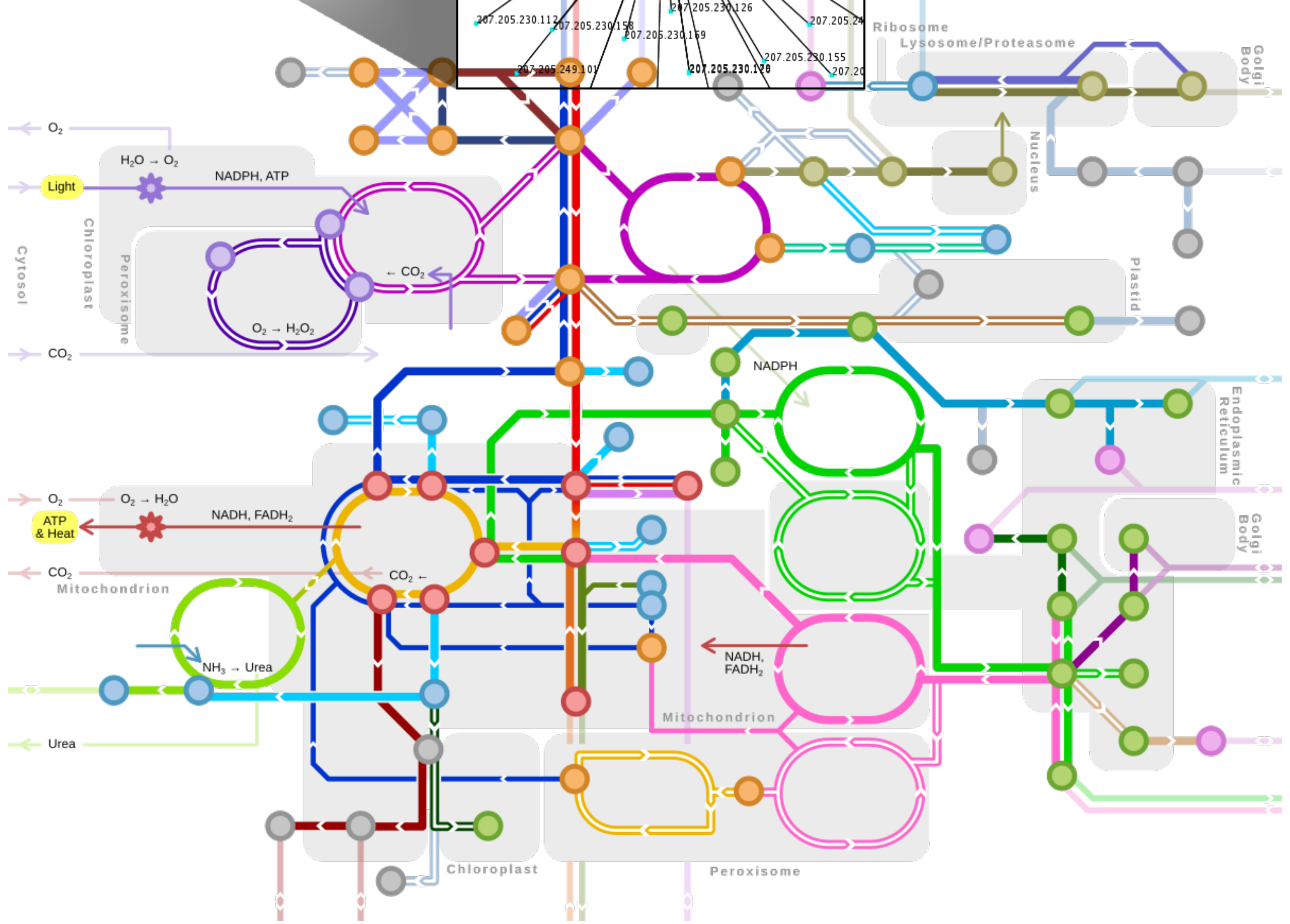


Airports

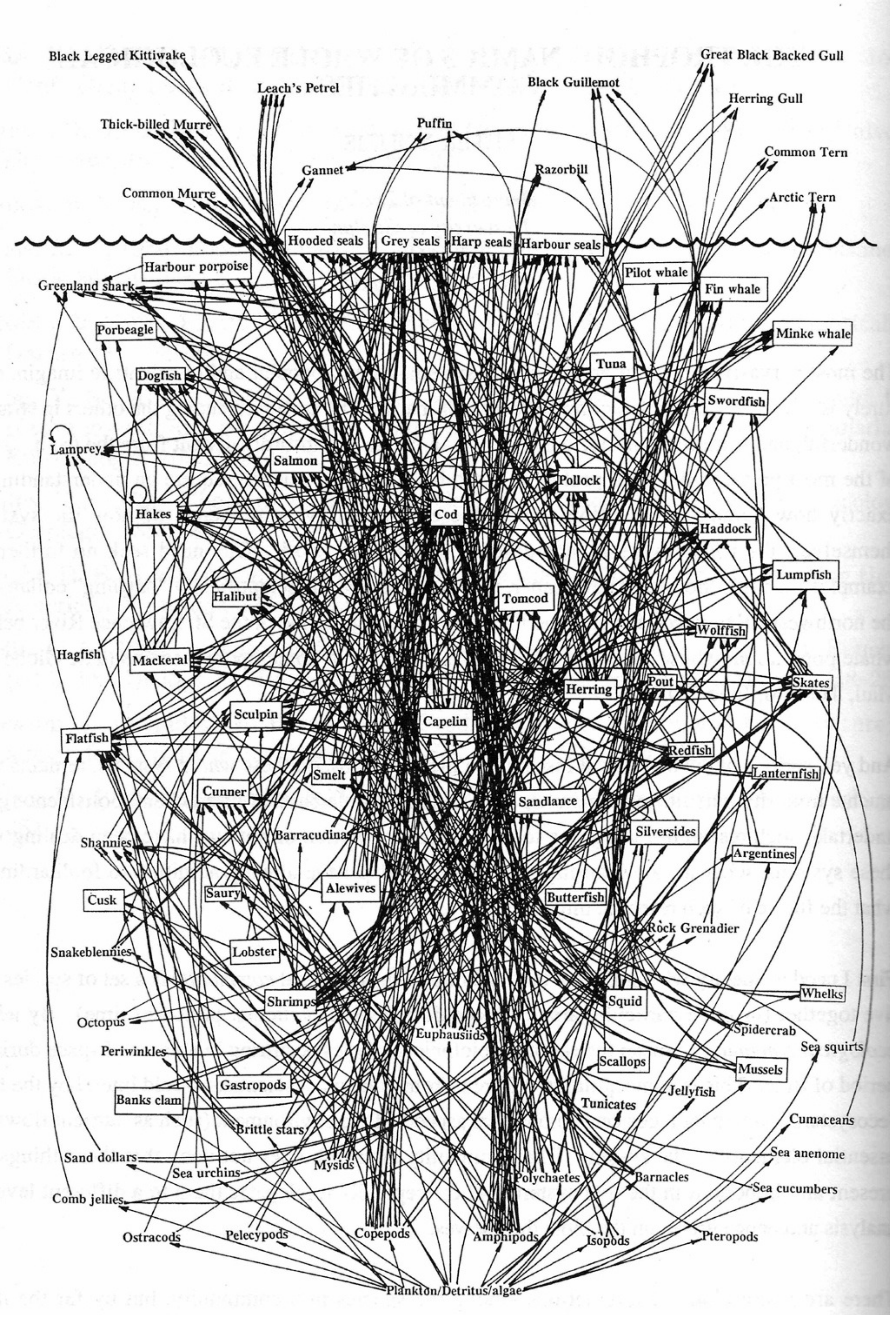


Friendships

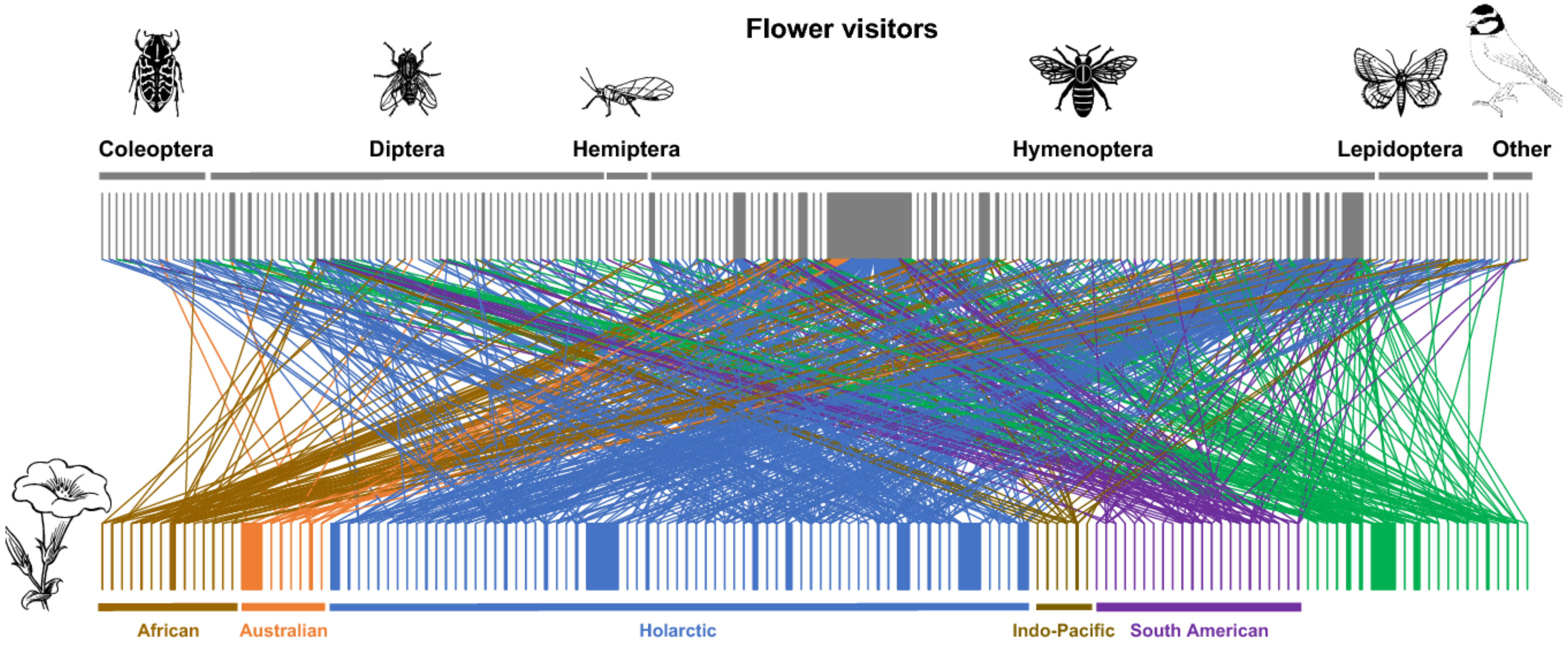
Metabolic



Ecological networks



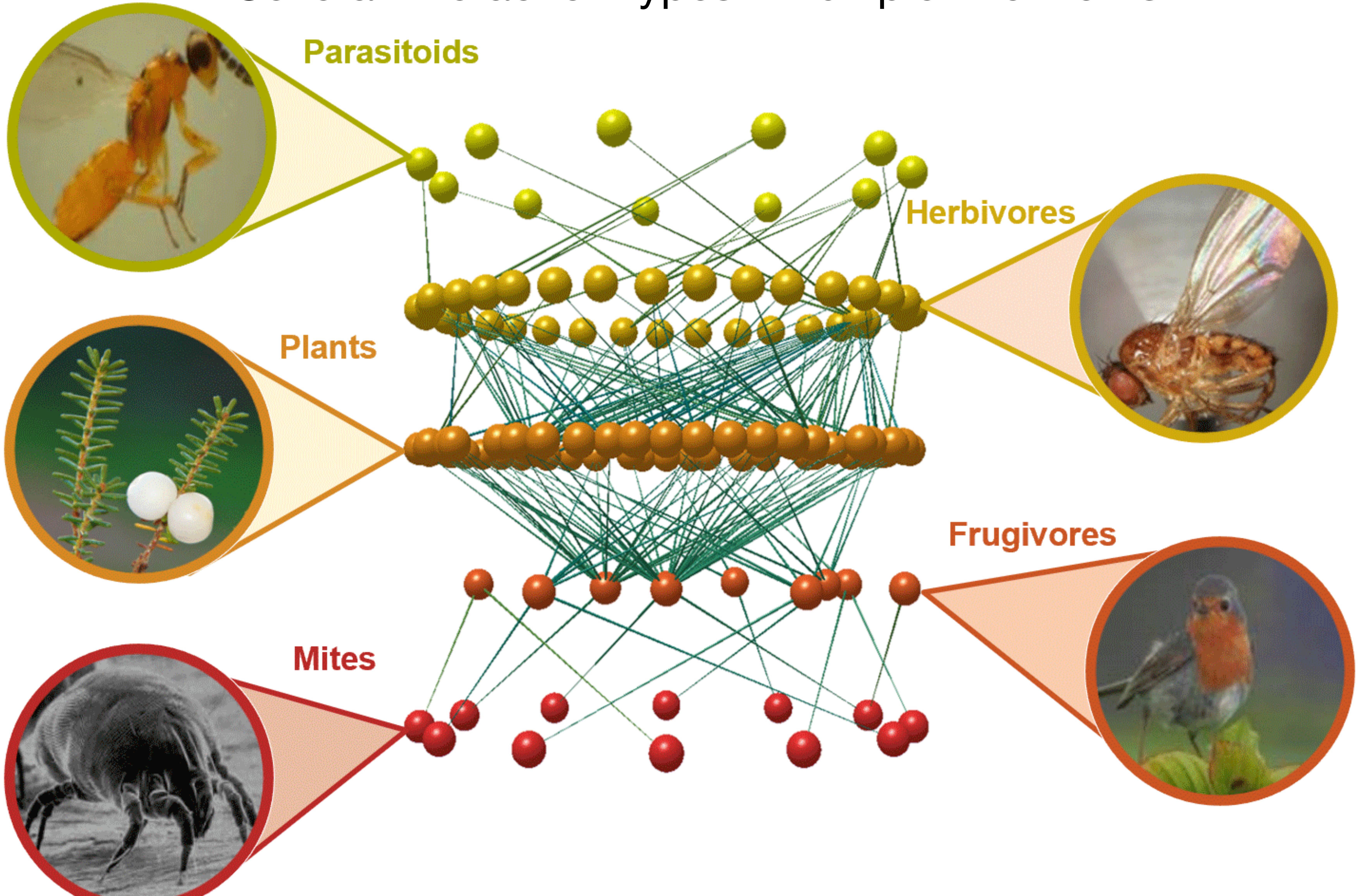
North-Atlantic Marine Food Web



European Terrestrial Plant-Pollination network

Ecological networks

Several interaction types - Multiplex networks

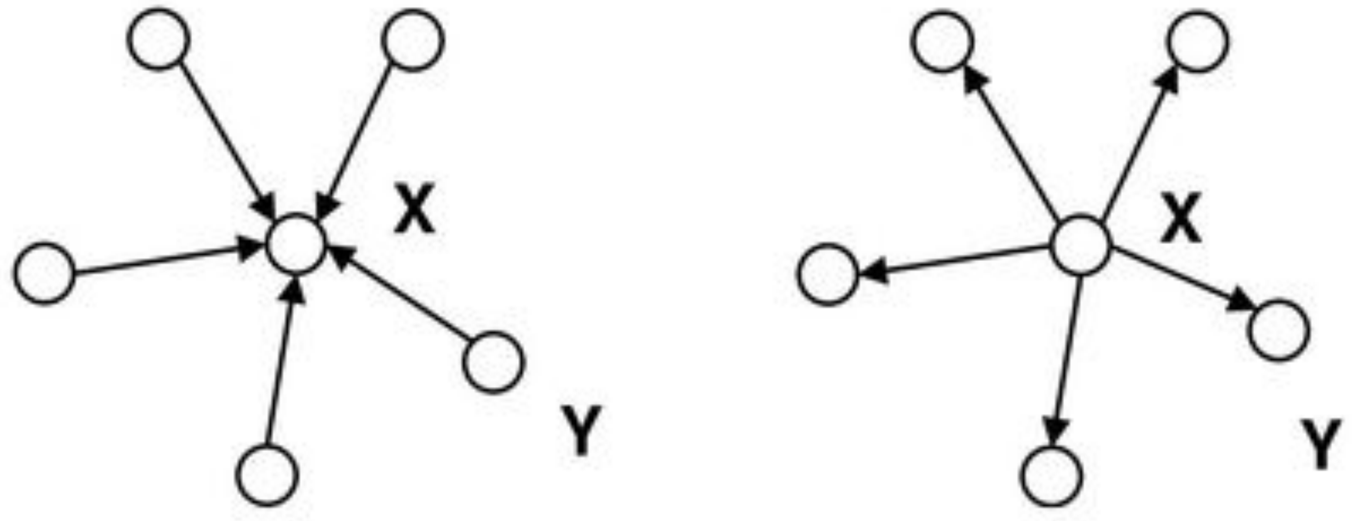


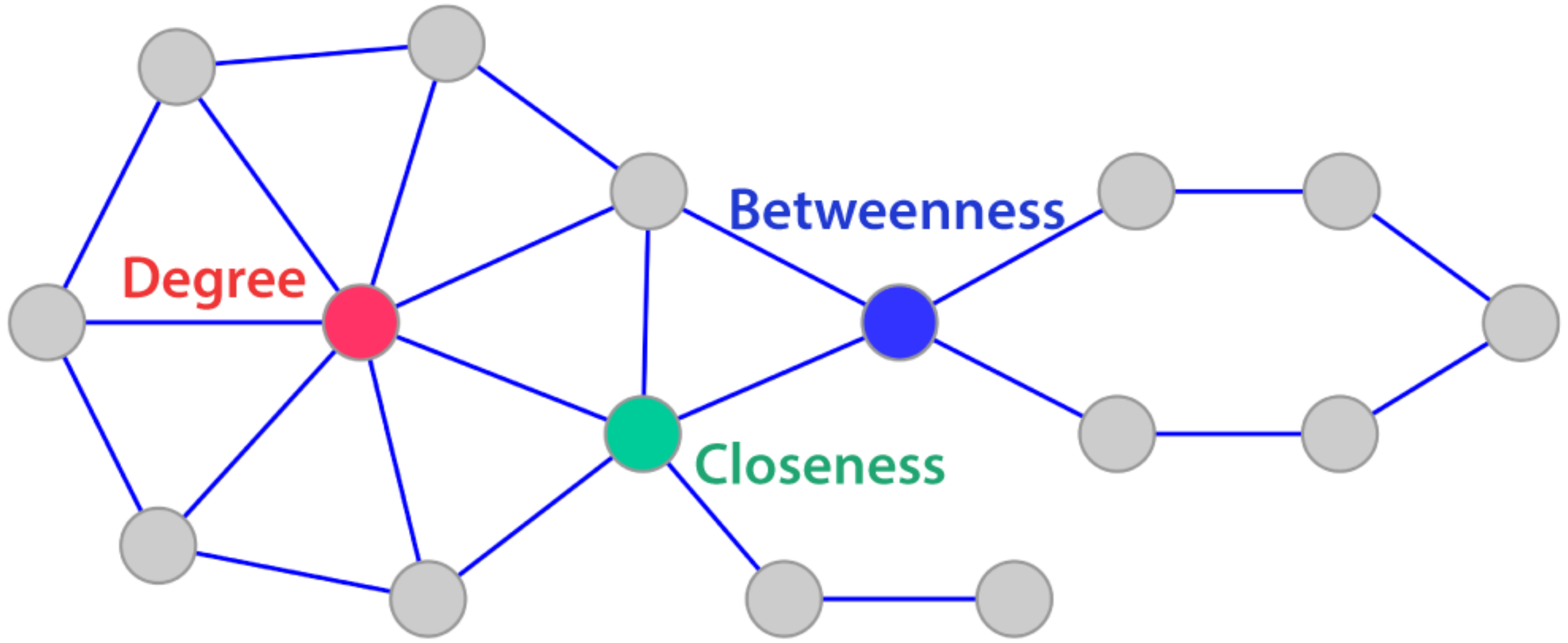
Why is a network useful?

- More synthetic representation of the data
- Analyse data quantitatively
    - Connectivity
    - Analysis of sub communities
    - Distributions of the links
    - Importance of vertices and links
- Identify key individuals / patterns of connectivity
- Propose mechanisms to explain observed patterns

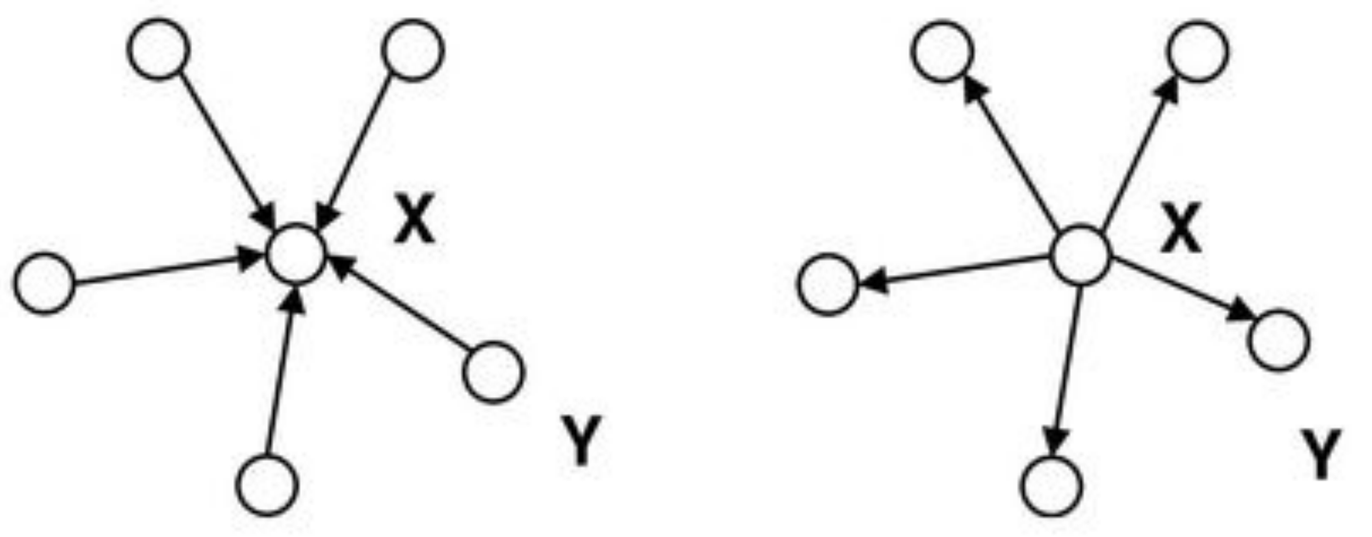
Analysing networks

- At the individual / node level
  - Degree (In / Out)
  - Centrality (degree, closeness, betweenness)





Analysing networks



- At the individual / node level
  - Degree (In / Out)
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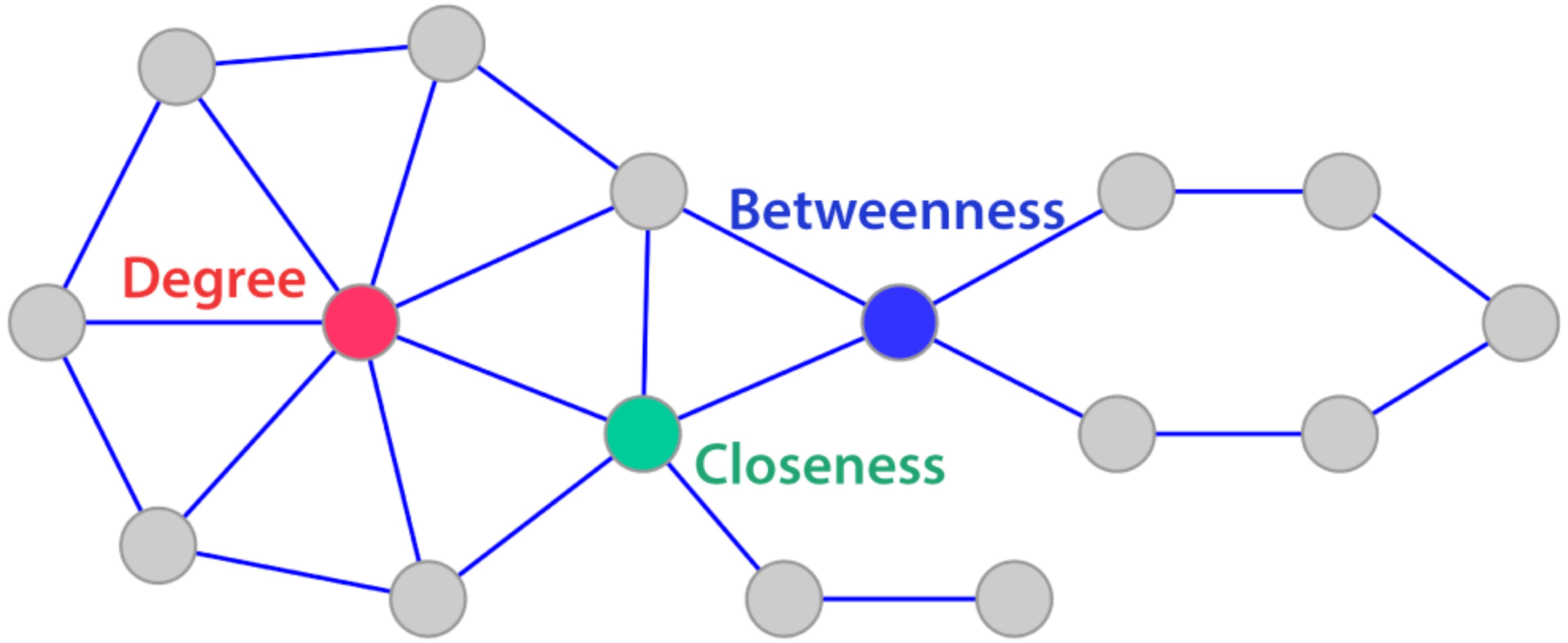
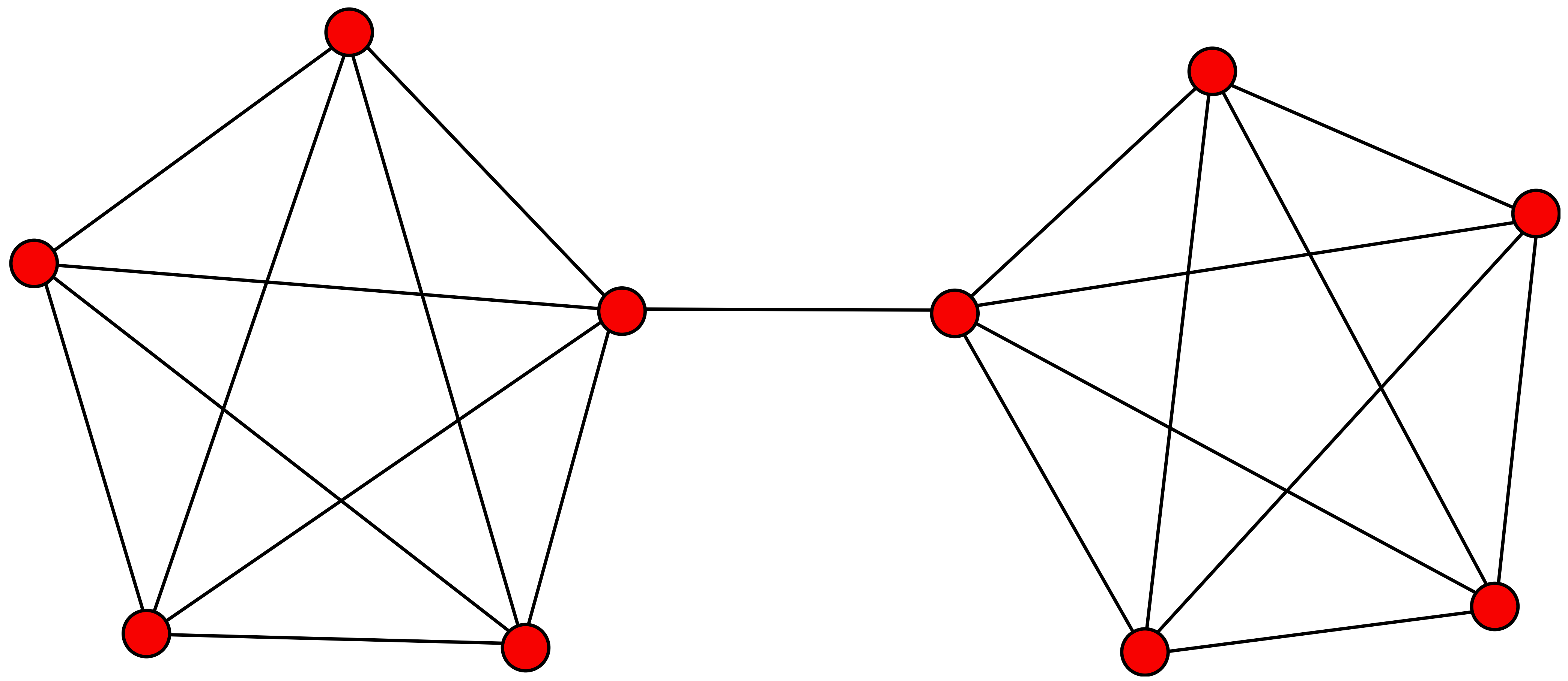
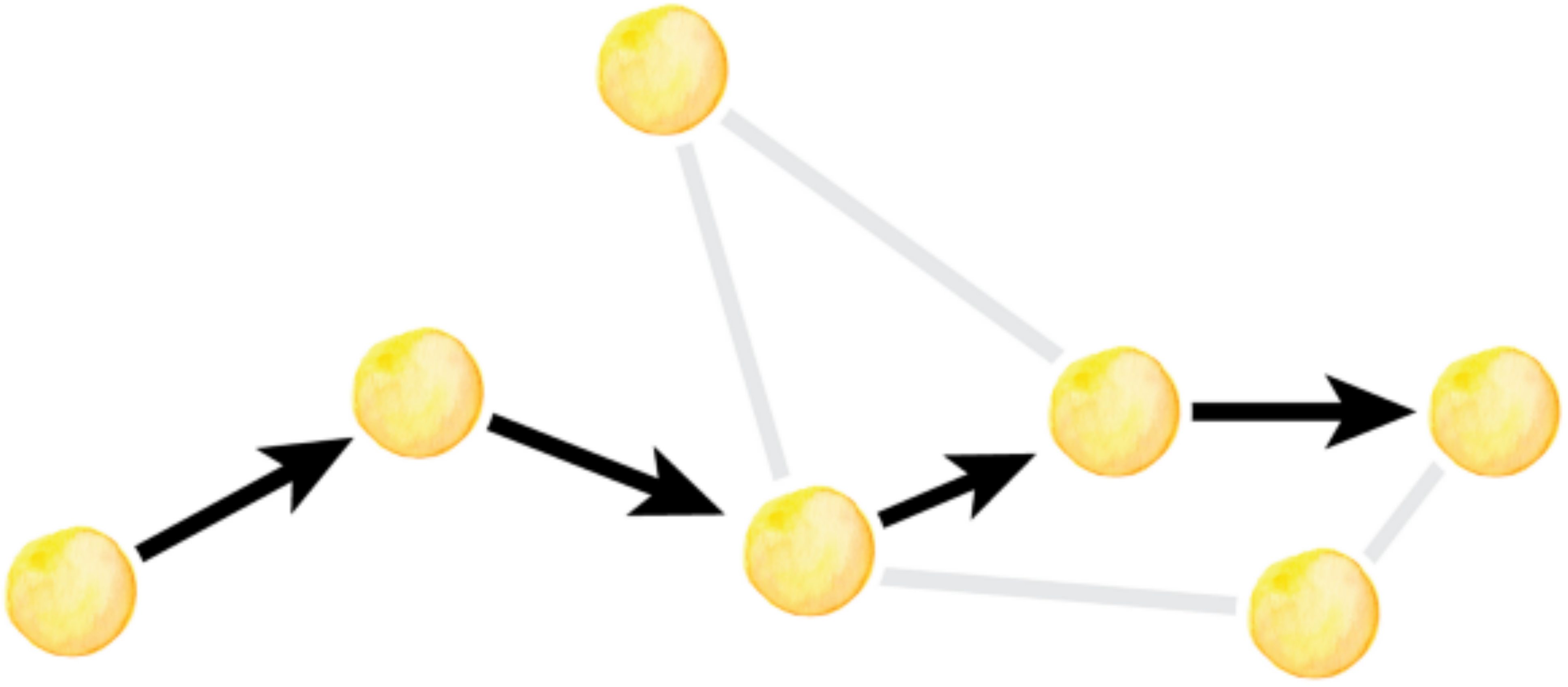


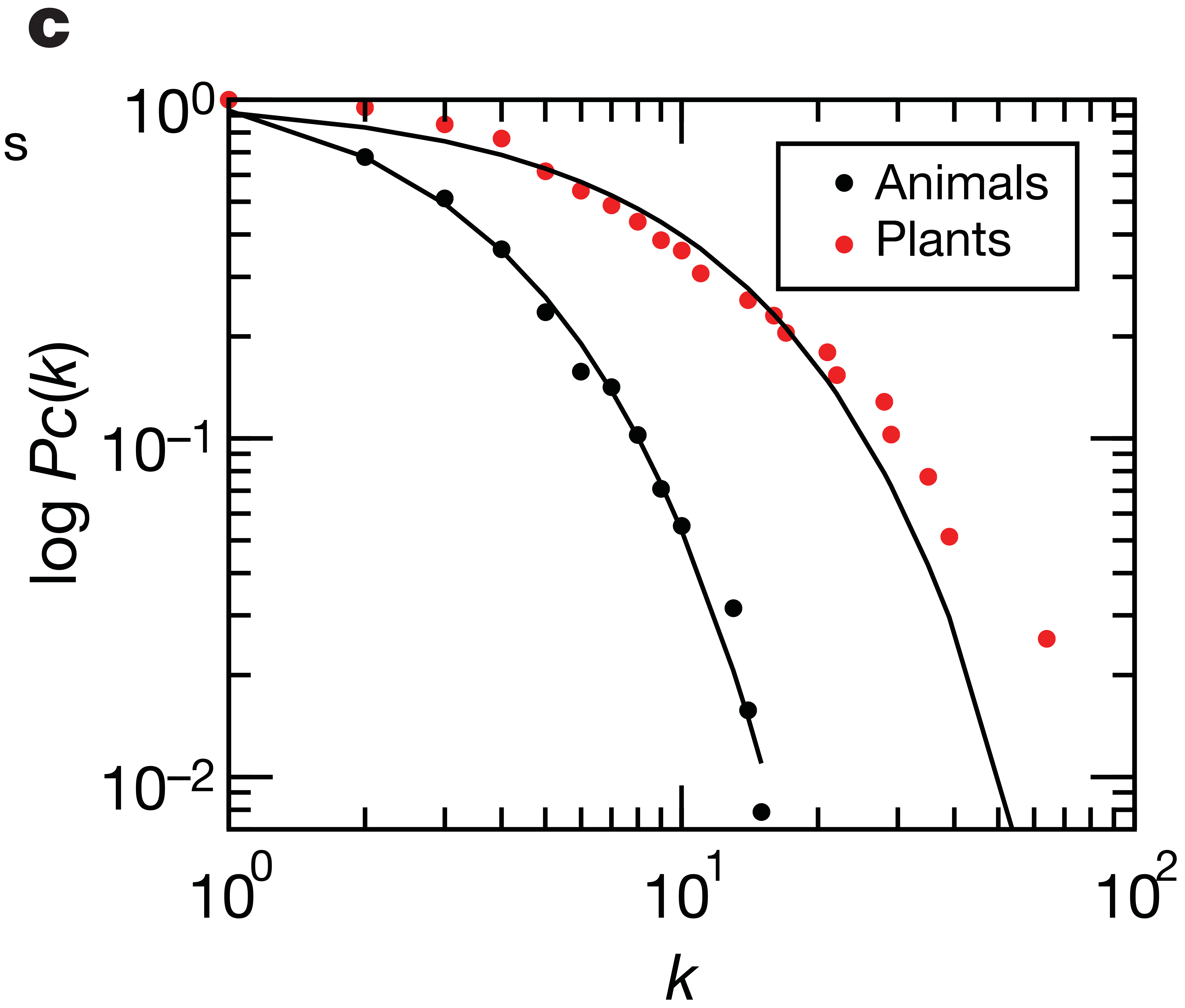
- At the intermediate level
  - Clustering coefficient



Analysing networks

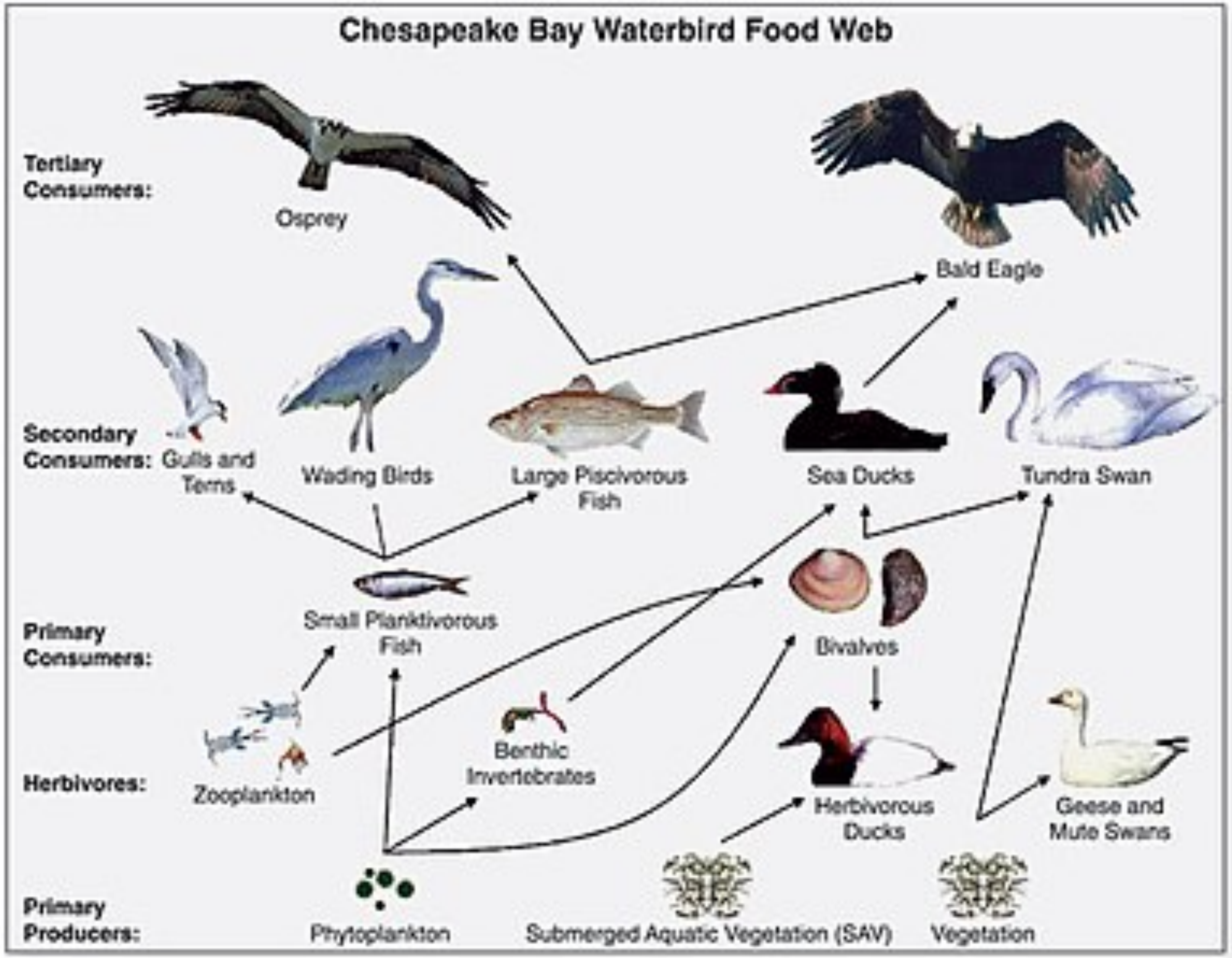
- At the network level
  - Longest, average, shortest path lengths
  - Connectivity / Connectance / Density
  - Degree distributions





Montoya et al. (2006) ***Nature***, 442: 259-264

Analysing networks



- Vertical complexity
  - Mean food chain length
  - Trophic level / position

Vol 442|20 July 2006|doi:10.1038/nature04927 nature

Analysing networks

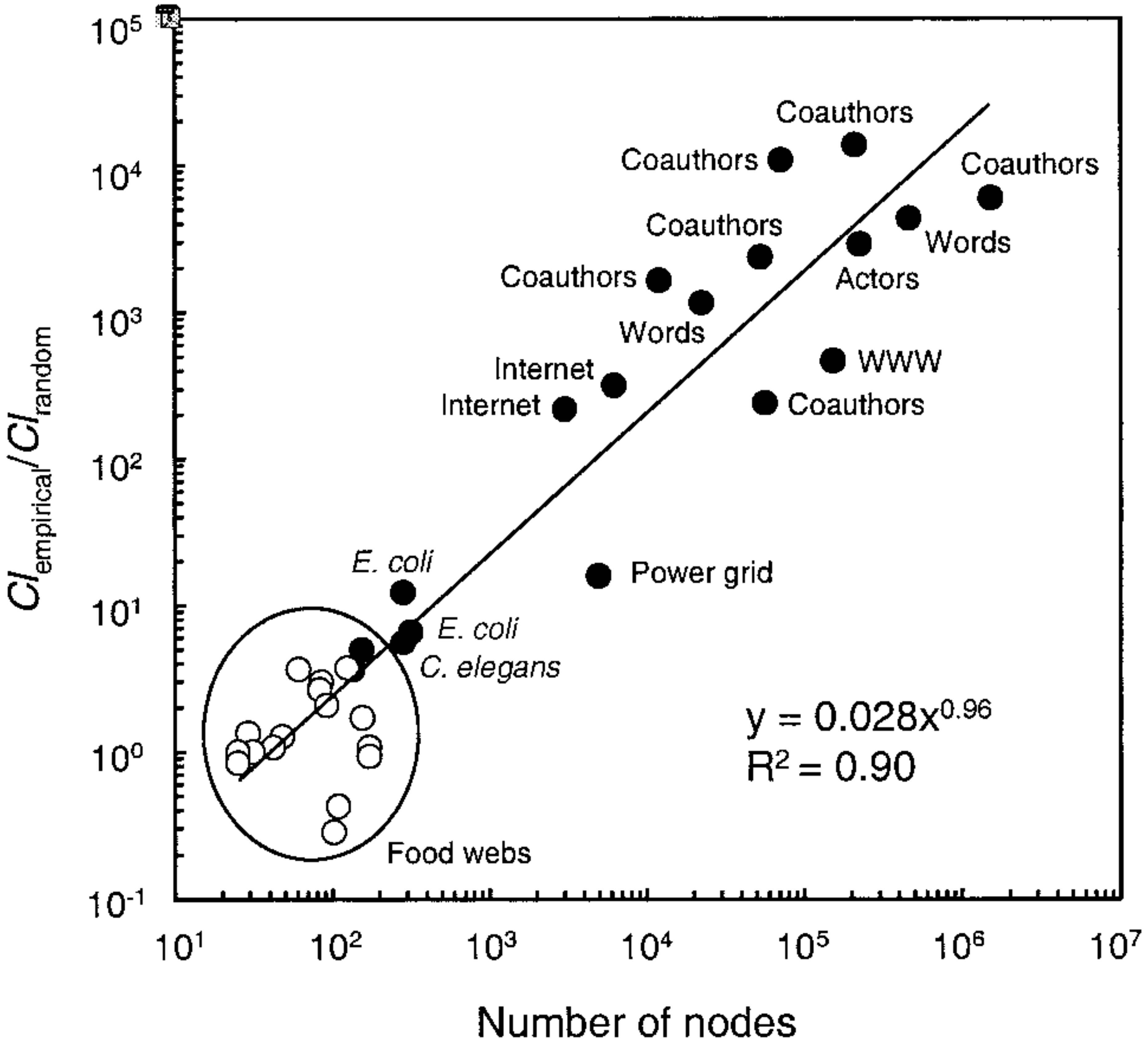
REVIEWS

Food-web structure and network theory: The role of connectance and size

Jennifer A. Dunne*[†‡], Richard J. Williams*, and Neo D. Martinez*

*Romberg Tiburon Center, San Francisco State University, 3152 Paradise Drive, Tiburon, CA 94920; and [†]Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501

Edited by Burton H. Singer, Princeton University, Princeton, NJ, and approved July 25, 2002 (received for review July 9, 2002)



Ecological networks and their fragility

José M. Montoya[1,2], Stuart L. Pimm[3] & Ricard V. Solé[2,4]

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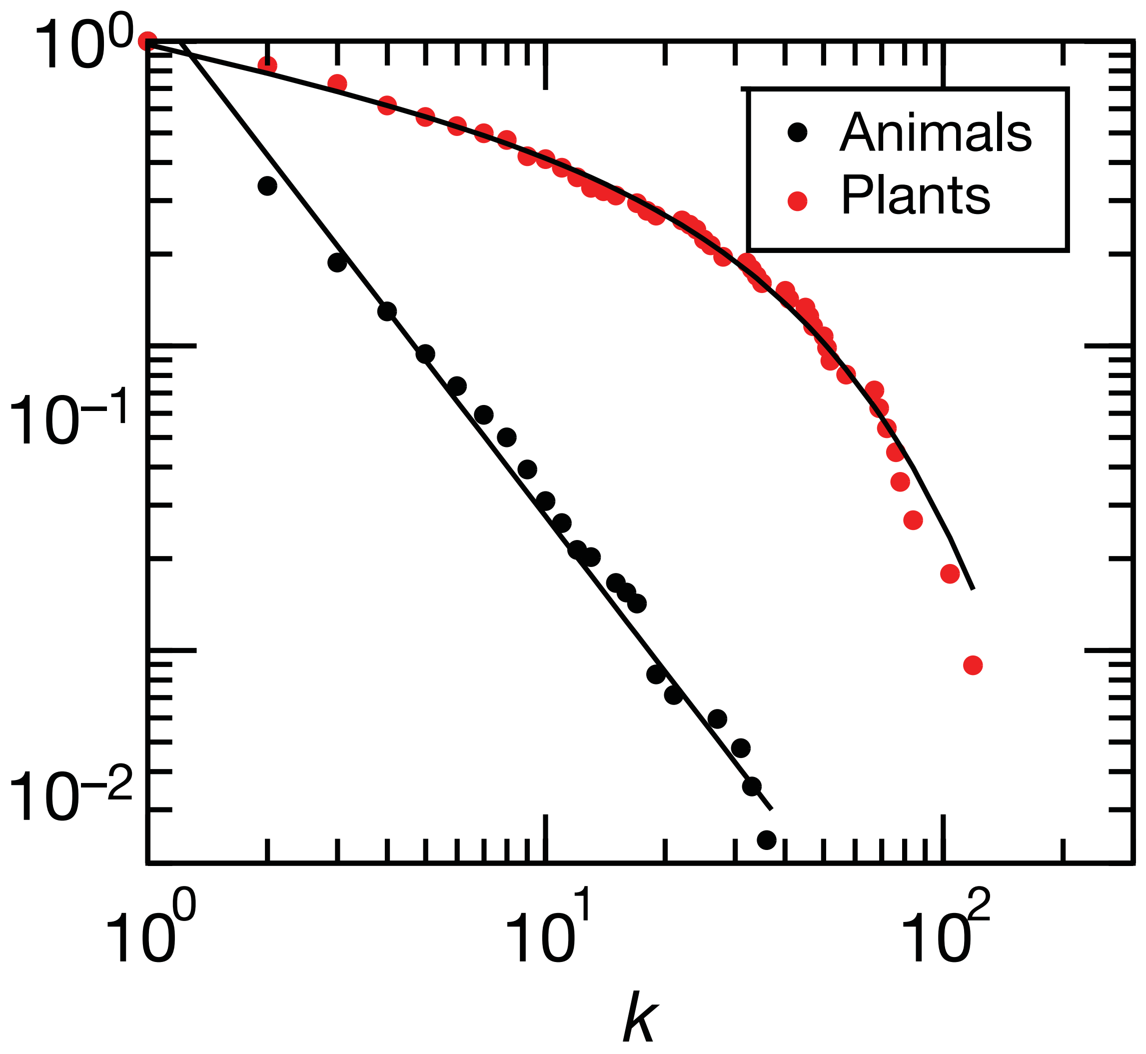

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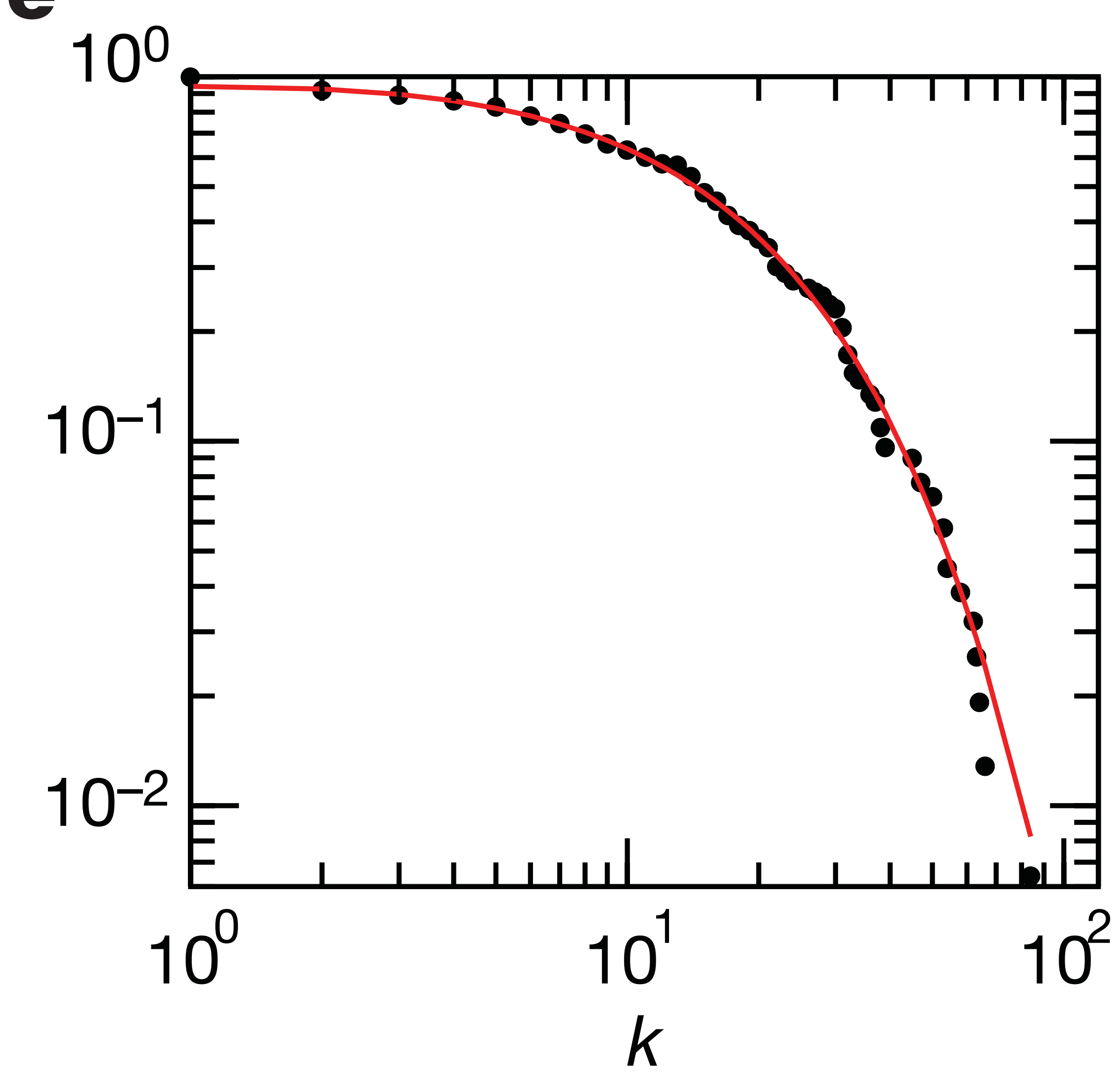

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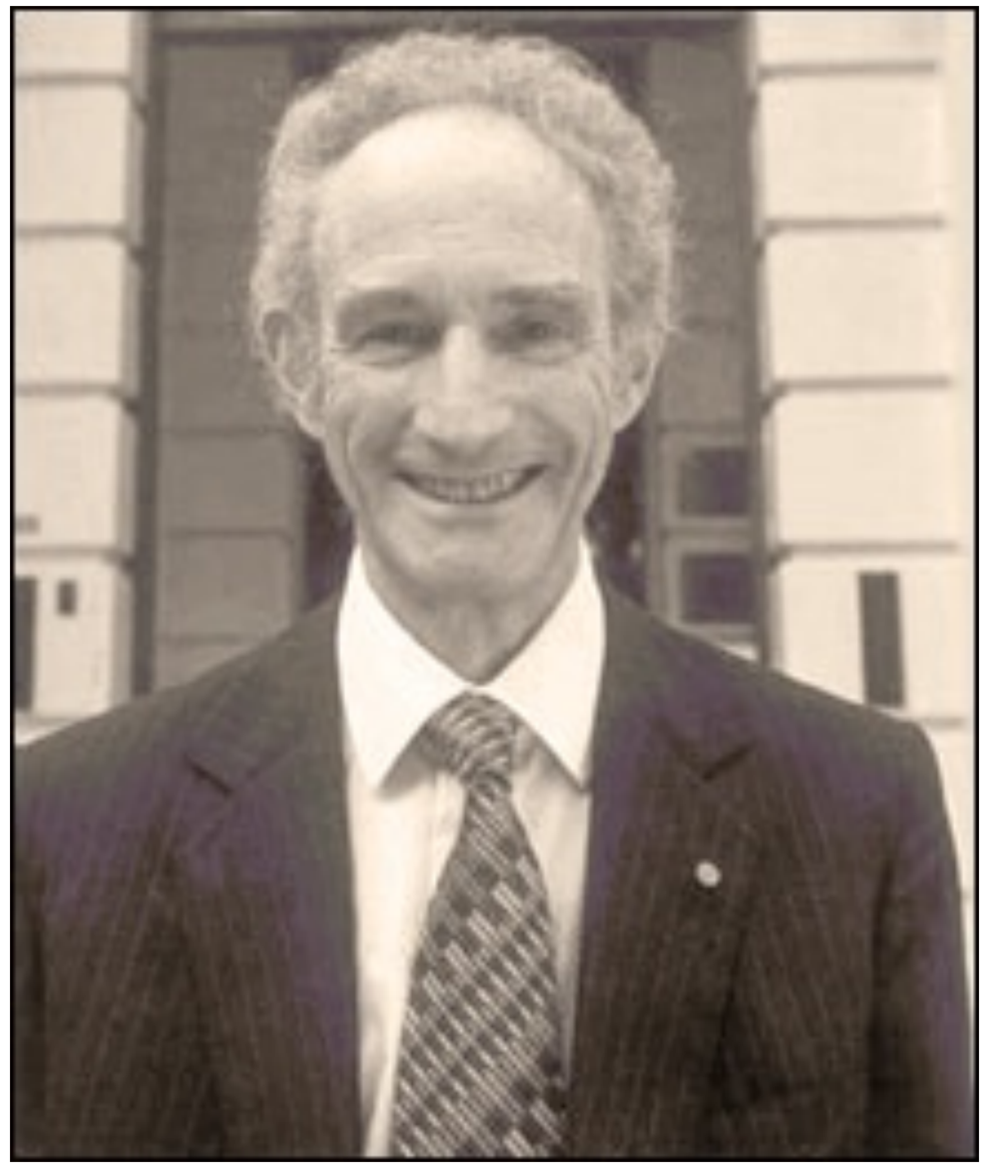
Relating networks to ecosystems properties

Complexity vs Stability

$$\frac{dx}{dt} = Ax$$

$$\mathbf{A}_a = \begin{bmatrix} - & + & + & + \\ - & - & 0 & 0 \\ - & 0 & - & 0 \\ - & 0 & 0 & - \end{bmatrix}$$



$$\alpha \sqrt{(SC)} < 1$$

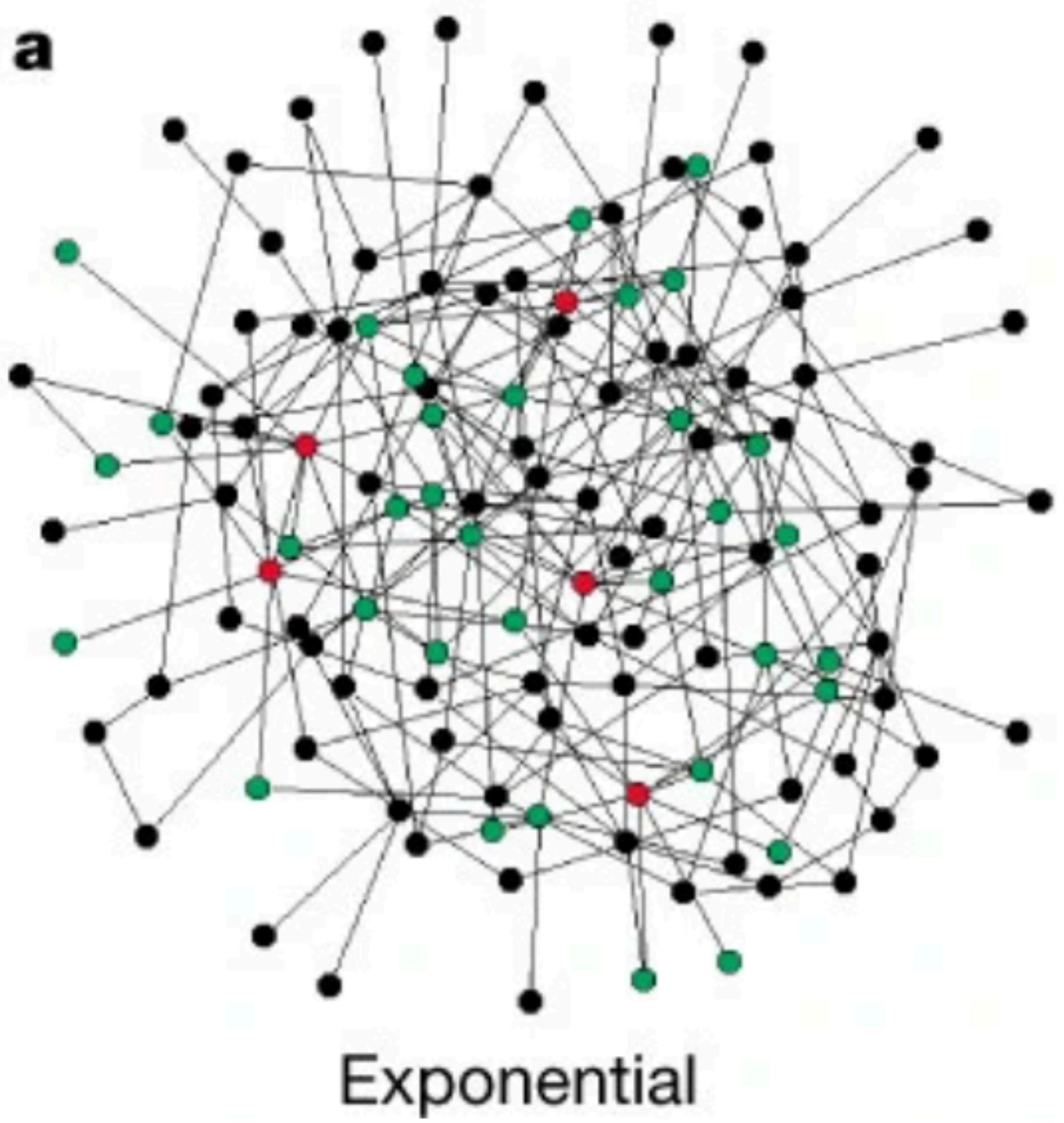
S: Species richness ; C: Connectivity ; α: Average interaction strength

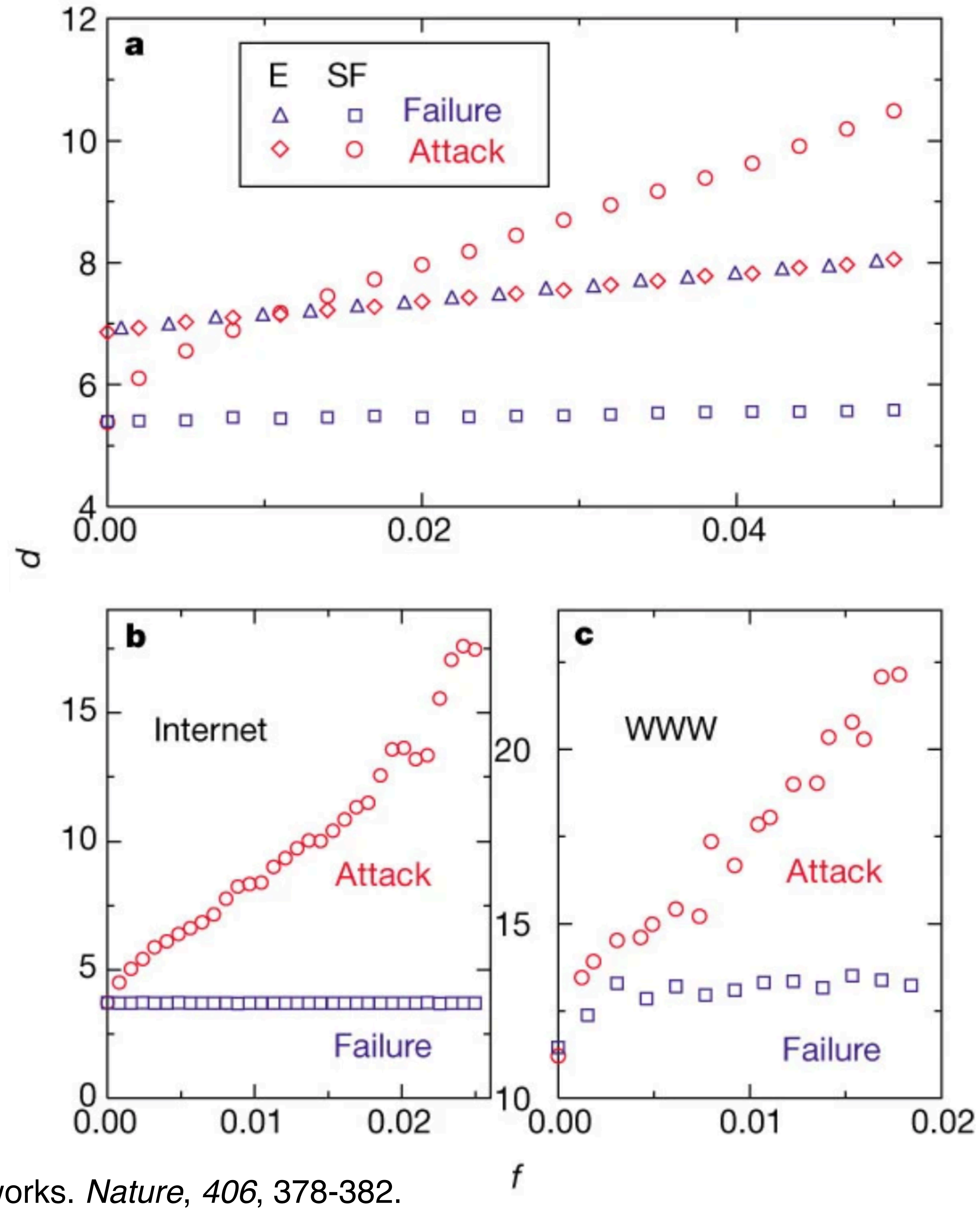
Challenge: To identify the devious strategies that a natural system uses to increase its species and connectivity capacity without sacrificing its stability and persistence

May, R. M. (1973). Stability and Complexity in Model Ecosystems. Princeton University Press.

Error Tolerance

Scale-free vs exponential networks





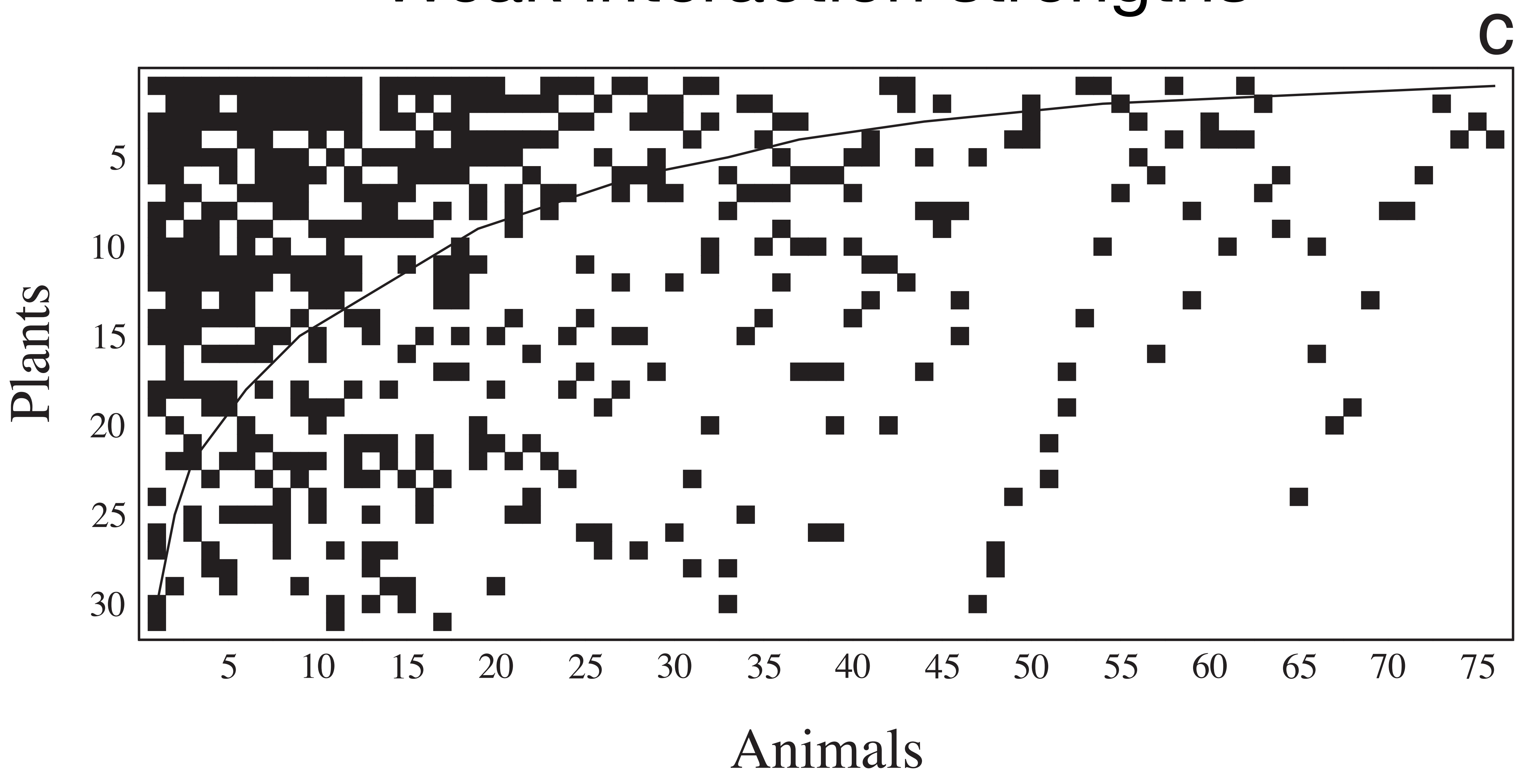
Albert R, Jeong H & Barabási A-L (2000). Error and attack tolerance of complex networks. *Nature*, *406*, 378-382.

Complexity vs Stability

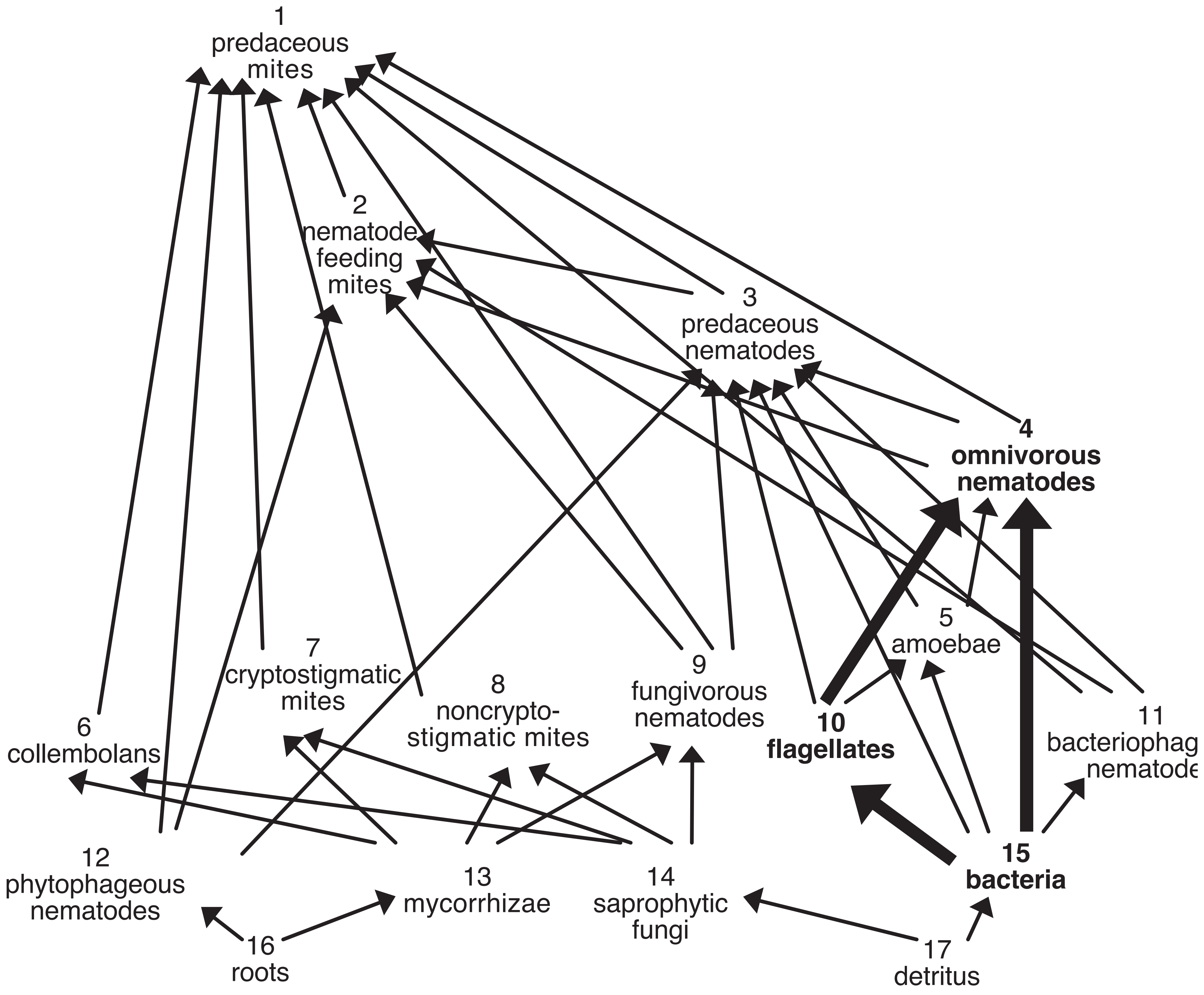
Challenge: To identify the devious strategies that a natural system uses to increase its species and connectivity capacity without sacrificing its stability and persistence

Devious strategies:

- Structure
- Weak interaction strengths



Bascompte et al. (2003) ***PNAS***, 100(16)



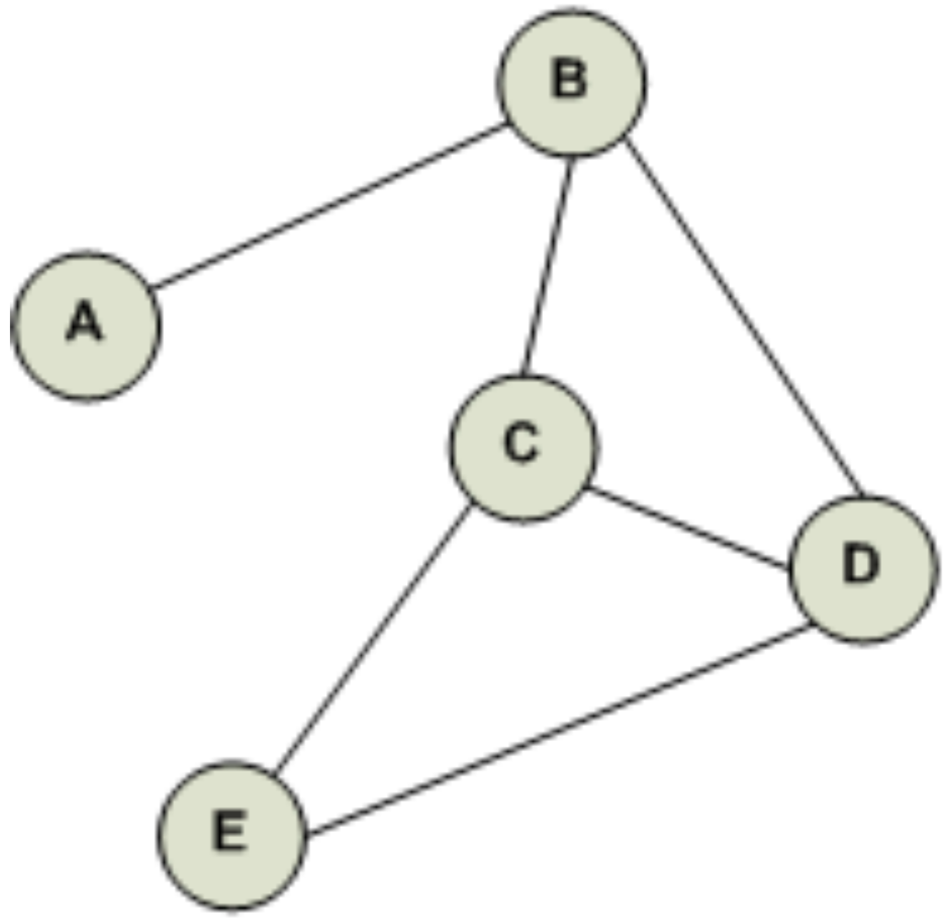
Neutel et al. (2002) ***Science***, 296(5570)

Part II: Methods for network analysis

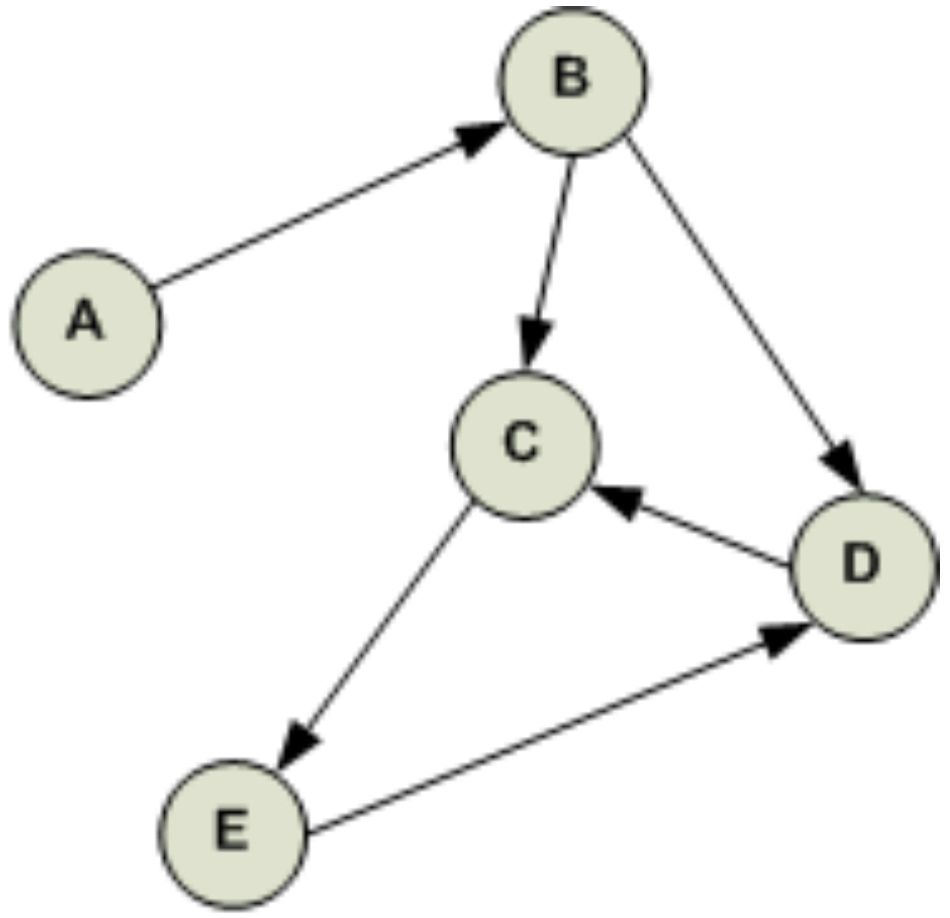
Matrix representation

Adjacency matrix

Undirected



Directed



Undirected

	A	B	C	D	E
A	0	1	0	0	0
B	1	0	1	1	0
C	0	1	0	1	1
D	0	1	1	0	1
E	0	0	1	1	0

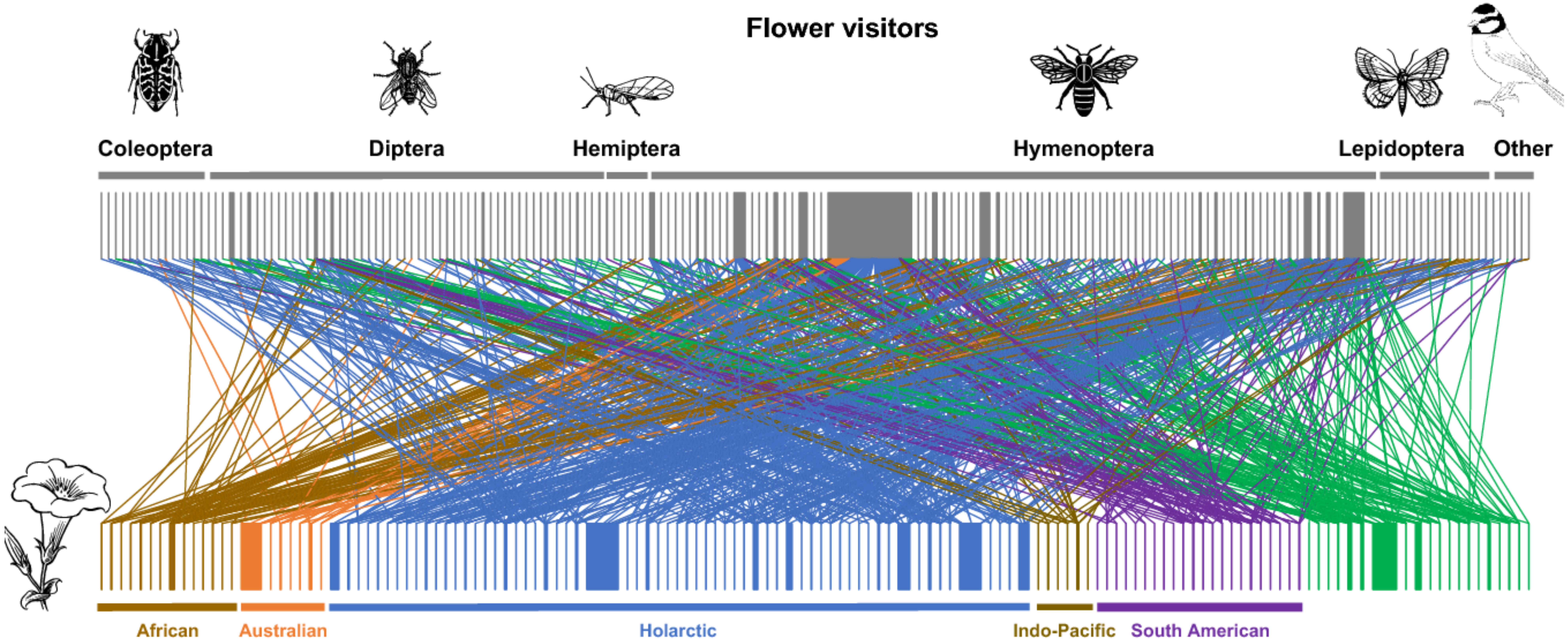
Directed

	A	B	C	D	E
A	0	1	0	0	0
B	0	0	1	1	0
C	0	0	0	0	1
D	0	0	1	0	0
E	0	0	0	1	0

Nodes = vertices (e.g. species, people, computers)
Links = edges = interactions (e.g. trophic, social, information)

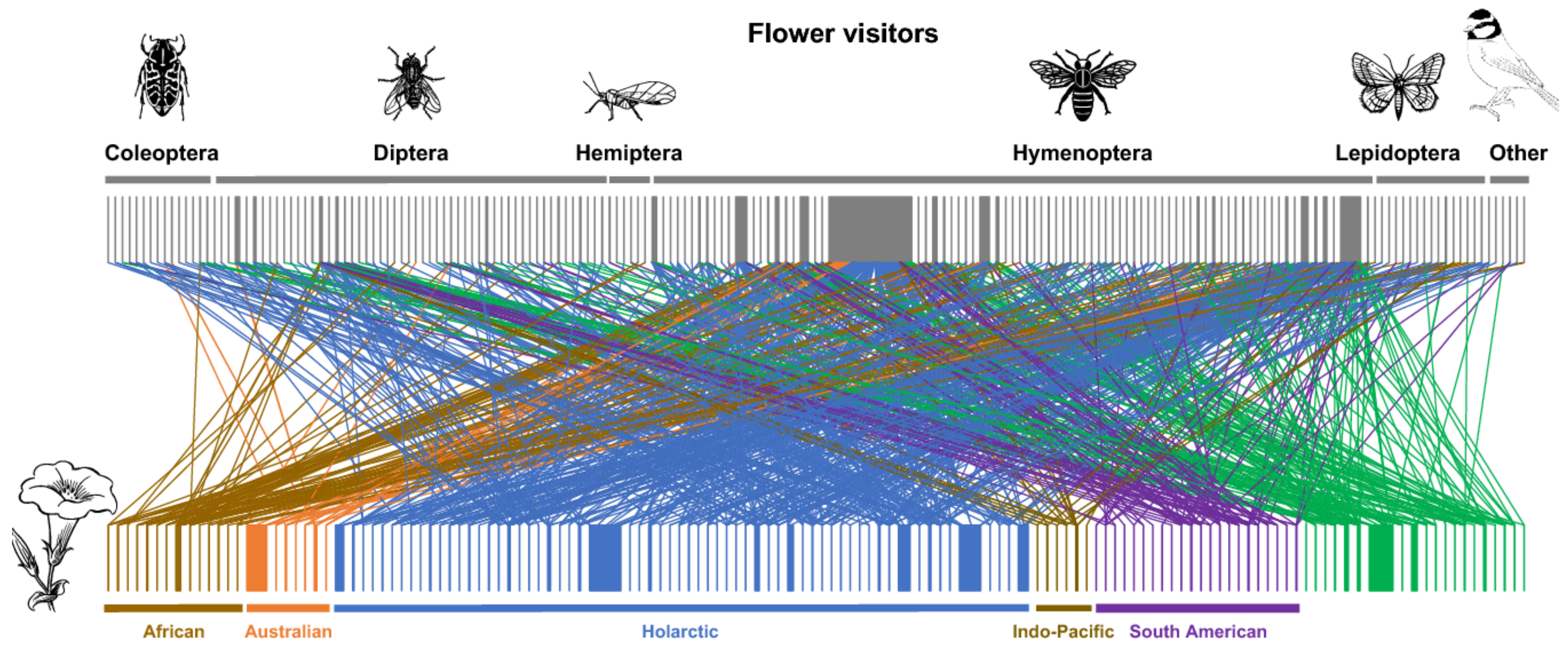
Matrix representation

Bipartite networks: Depict interactions between groups of species that do not interact within the groups

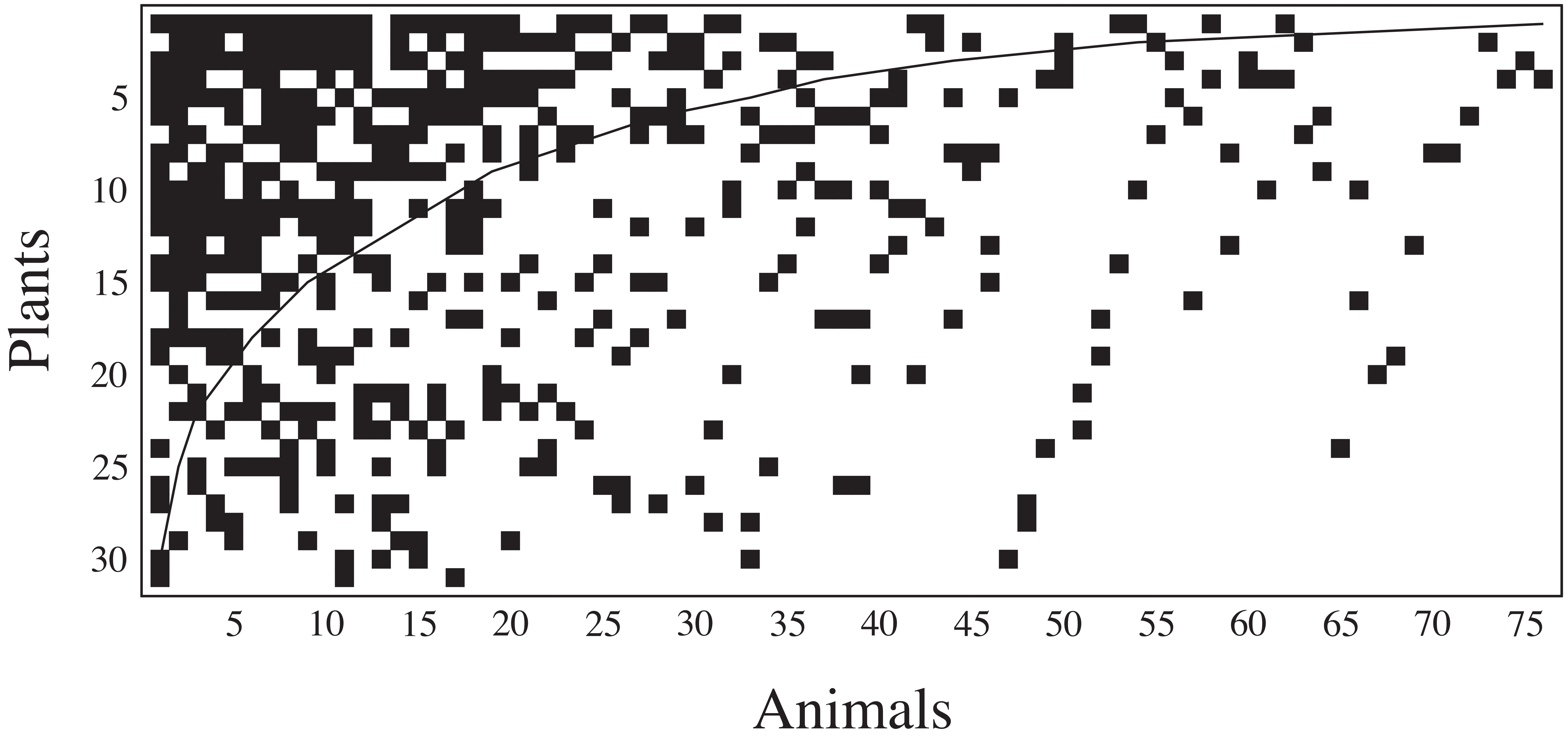


Matrix representation

Bipartite networks: Depict interactions between groups of species that do not interact within the groups



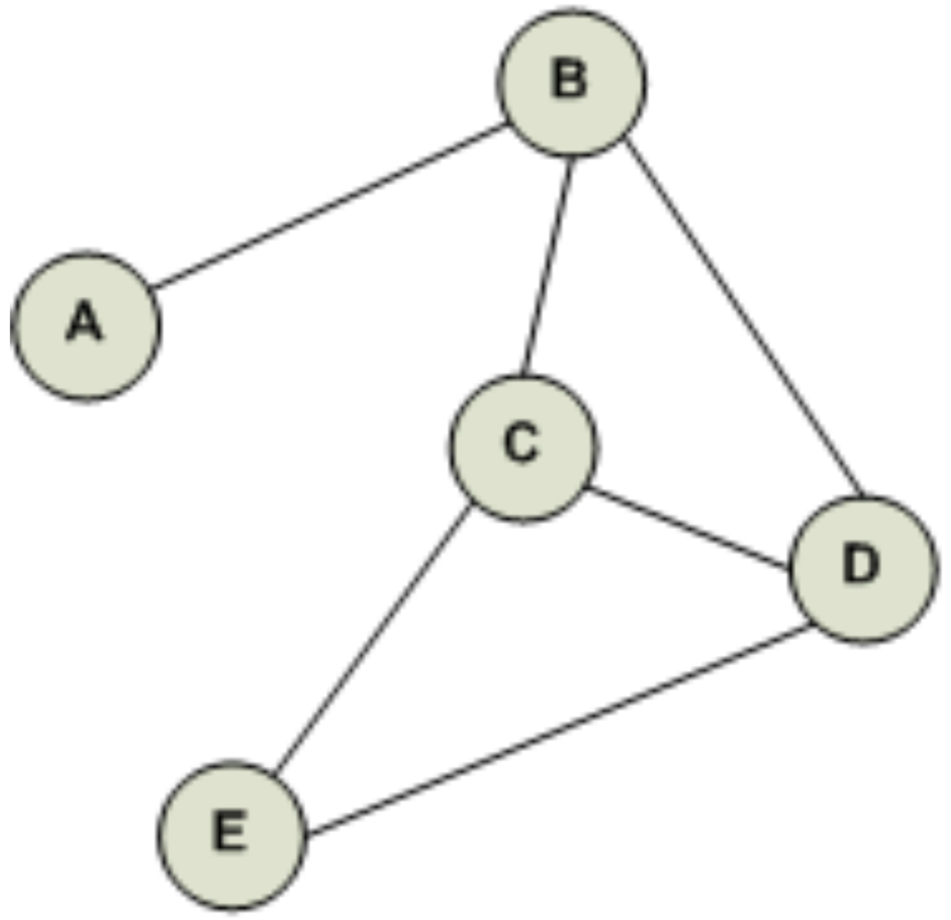
I = Incidence matrix



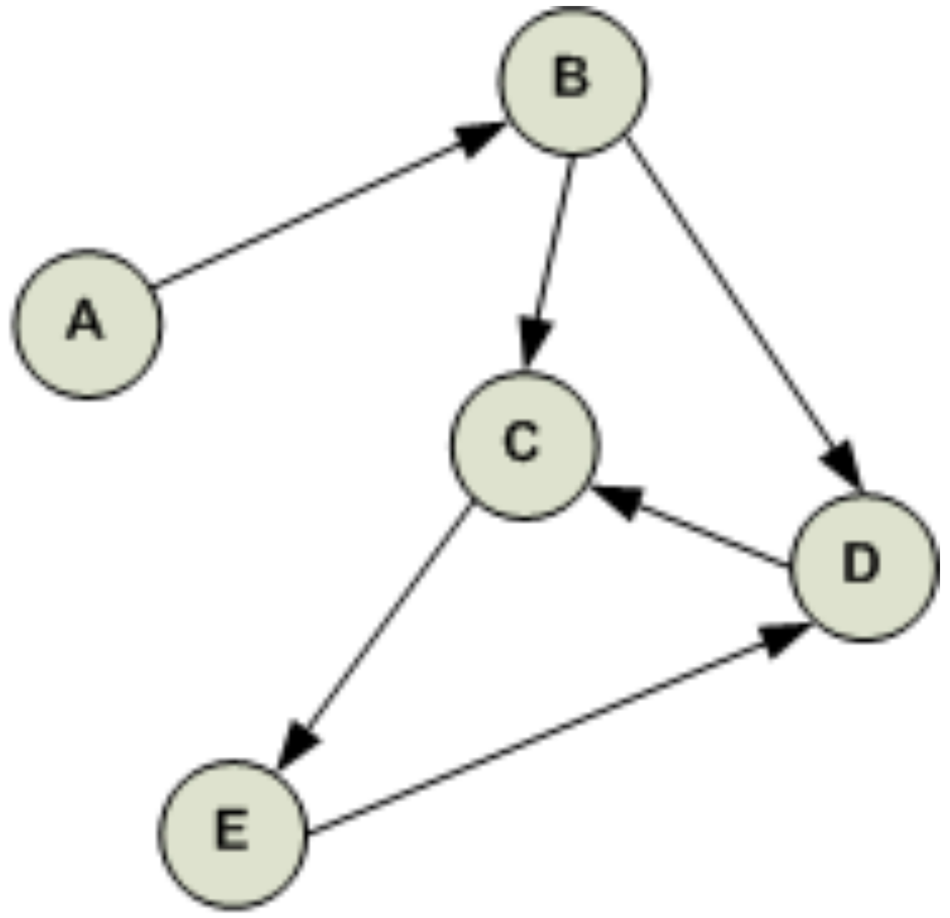
Matrix representation

A = Adjacency matrix

Undirected



Directed



Undirected

	A	B	C	D	E
A	0	1	0	0	0
B	1	0	1	1	0
C	0	1	0	1	1
D	0	1	1	0	1
E	0	0	1	1	0

Directed

	A	B	C	D	E
A	0	1	0	0	0
B	0	0	1	1	0
C	0	0	0	0	1
D	0	0	1	0	0
E	0	0	0	1	0

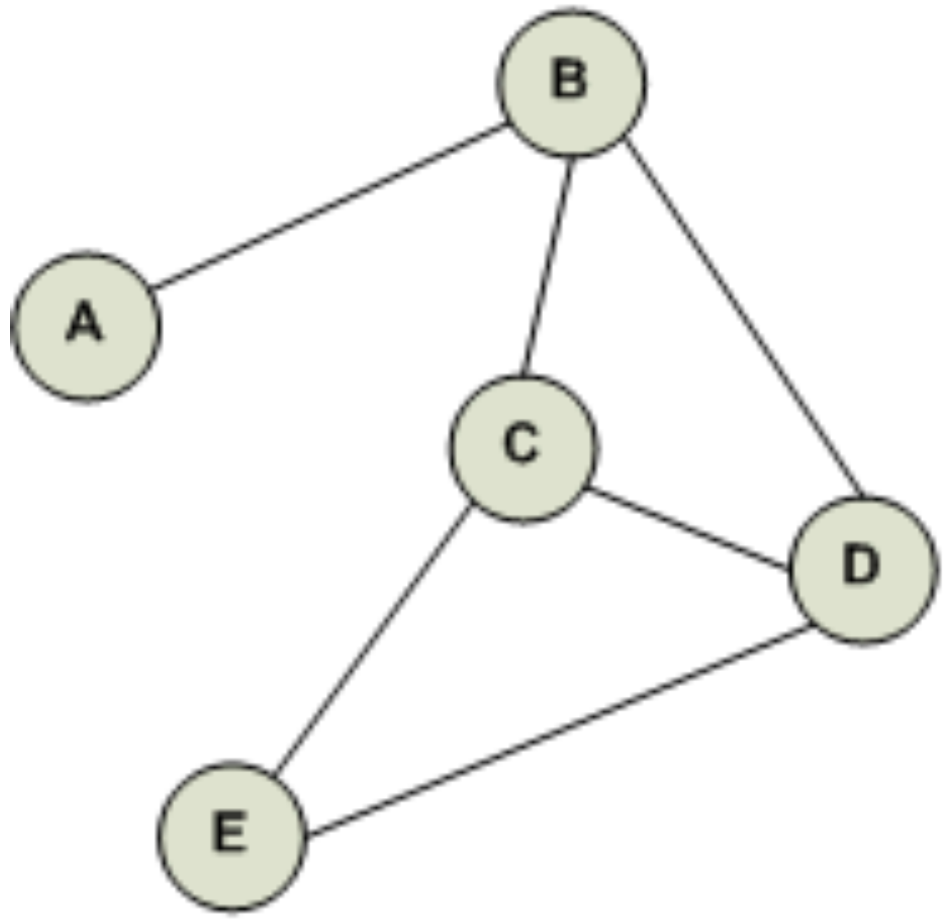
Number of Nodes = S = # rows = # columns

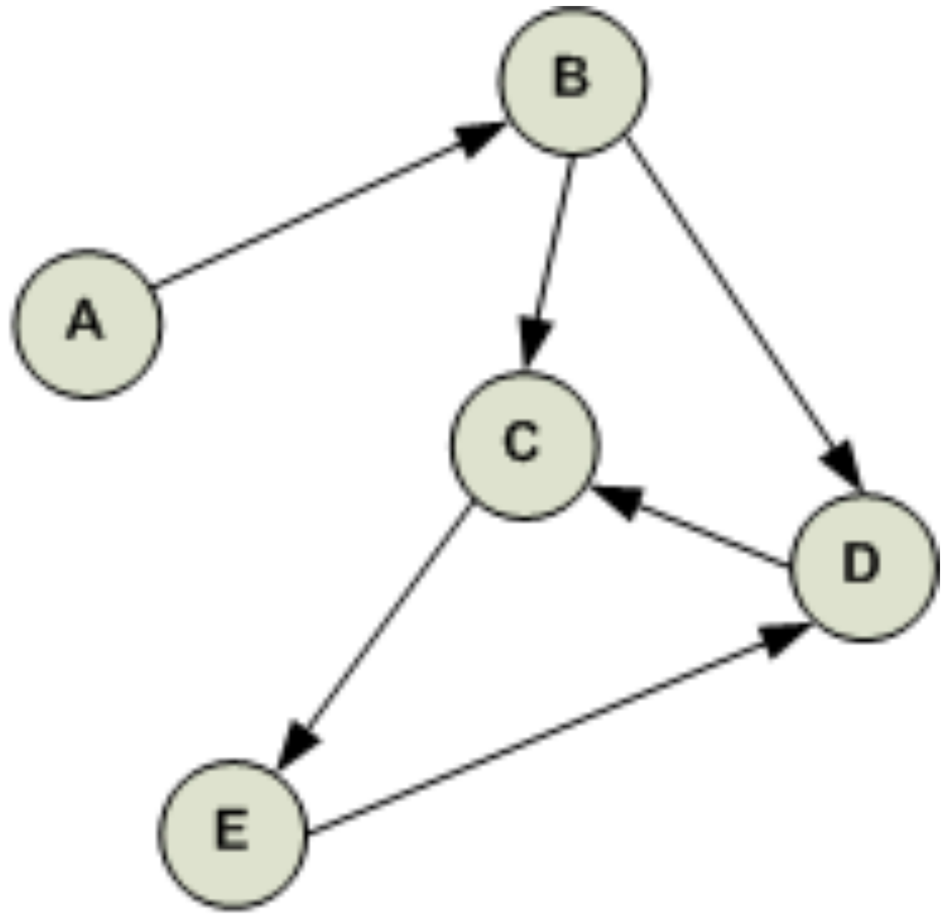
Number of Links = L = sum(A)

Degree

The number of links a node has

Undirected	Directed





Undirected

	A	B	C	D	E	d
A	0	1	0	0	0	1
B	1	0	1	1	0	3
C	0	1	0	1	1	3
D	0	1	1	0	1	3
E	0	0	1	1	0	2

Row Sum = Column Sum = Degree

Directed

	A	B	C	D	E	od
A	0	1	0	0	0	1
B	0	0	1	1	0	2
C	0	0	0	0	1	1
D	0	0	1	0	0	1
E	0	0	0	1	0	1
id	0	1	2	2	1	

Row Sum = Out-Degree
Column Sum = In-Degree

Node centrality

How 'important' a node is in the network - exact definition dependant on the interpretation of importance

Betweenness Centrality: Measure based on shortest paths - It measures how frequently a node appears on the shortest path between other nodes in the graph

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Where: σ_{st} is the number of shortest paths from *s* to *t*

and $\sigma_{st}(v)$ the number of those paths that pass through *v*

Clustering Coefficient

The extent to which neighbours of a node are also connected
between them - small-world networks

Graph

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

Neighbourhood of node i

$$N_i = \{v_j : e_{ij} \in E \vee e_{ji} \in E\}$$

$$k_i = |N_i|$$

Clustering Coefficient of node i

$$C_i = \frac{|\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\}|}{k_i(k_i - 1)}$$

Clustering Coefficient

The extent to which neighbours of a node are also connected between them - small-world networks

Using the adjacency matrix A to calculate C_i

$$C_i = \frac{1}{k_i(k_i - 1)} \sum_{j,k} A_{ij} A_{jk} A_{ki}$$

Where:

$$k_i = \sum_j A_{ij}$$

Network Average Clustering Coefficient

$$\overline{C} = \frac{1}{n} \sum_{i=1}^{n} C_i$$

Connectivity

Fraction of realised links

$$C = L/S^2$$ For directed networks

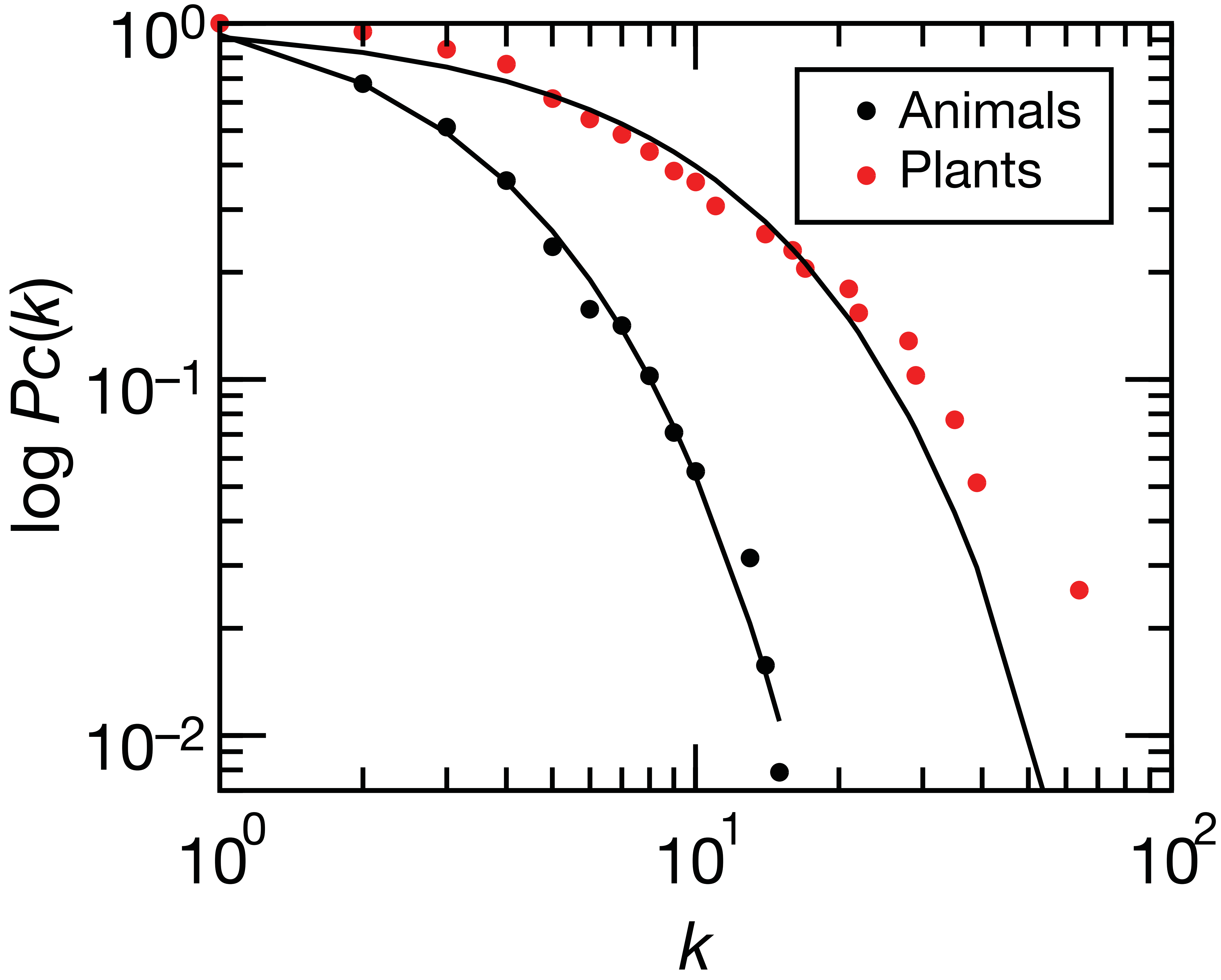
$$C = 2L/(S(S-1))$$ For undirected networks

Average number of links per species $= L/S$

Average generality / diet breadth (in-degree) and average vulnerability (out-degree)

Degree Distribution

Heterogeneity in the number of links



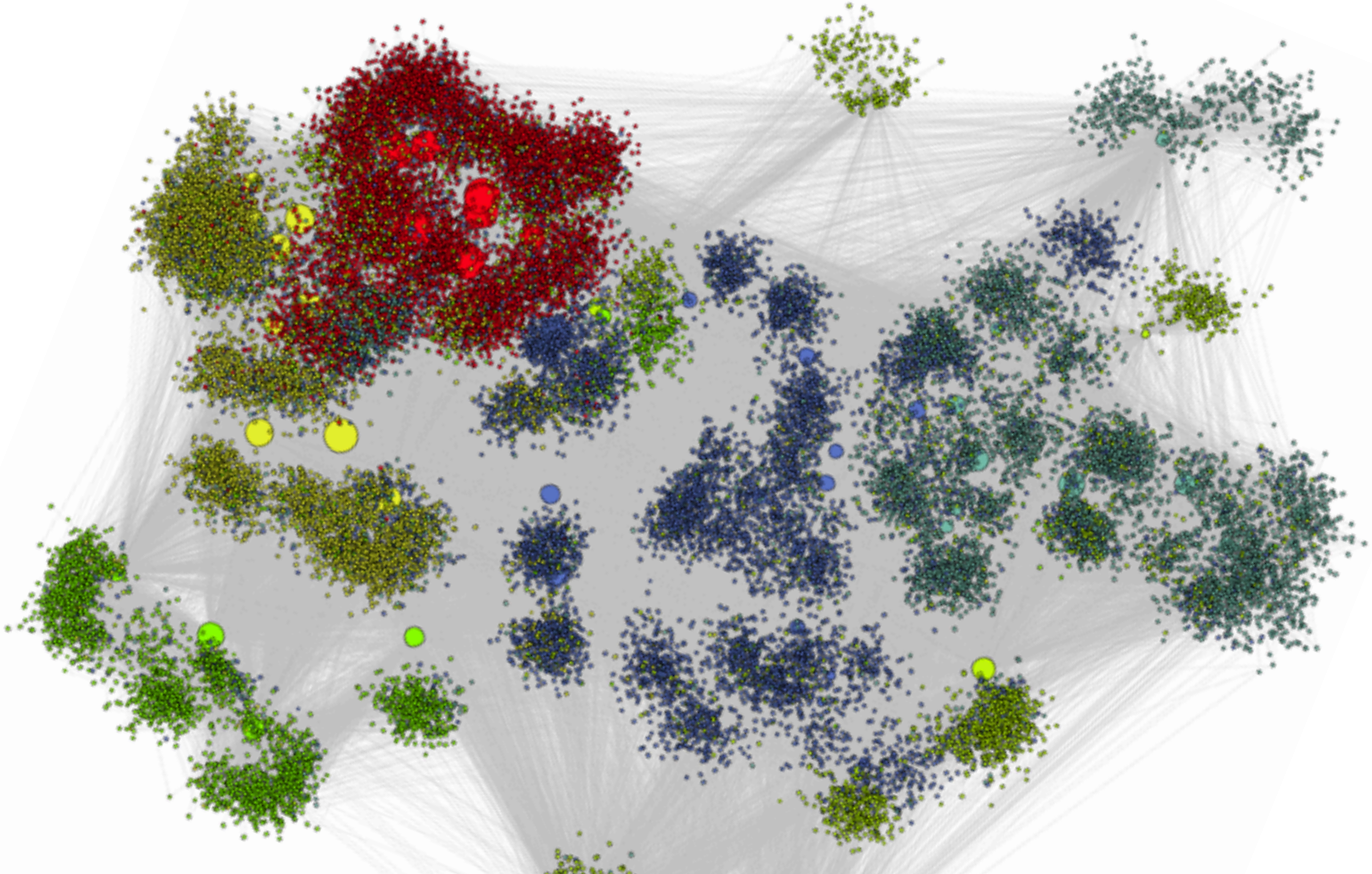
Modularity

Extent to which to which a network is organised into subcommunities within which their nodes are more connected amongst themselves than to the rest of the network

By doing this we obtain compartments / modules

$$M = \sum_{s=1}^{N_M} \left[\frac{l_s}{L} - \left(\frac{d_s}{2L} \right)^2 \right]$$

N_M = number of modules
L = # of links in the network
l_s = #of links between nodes in module s
d_s = sum of the degrees in module s



Nestedness

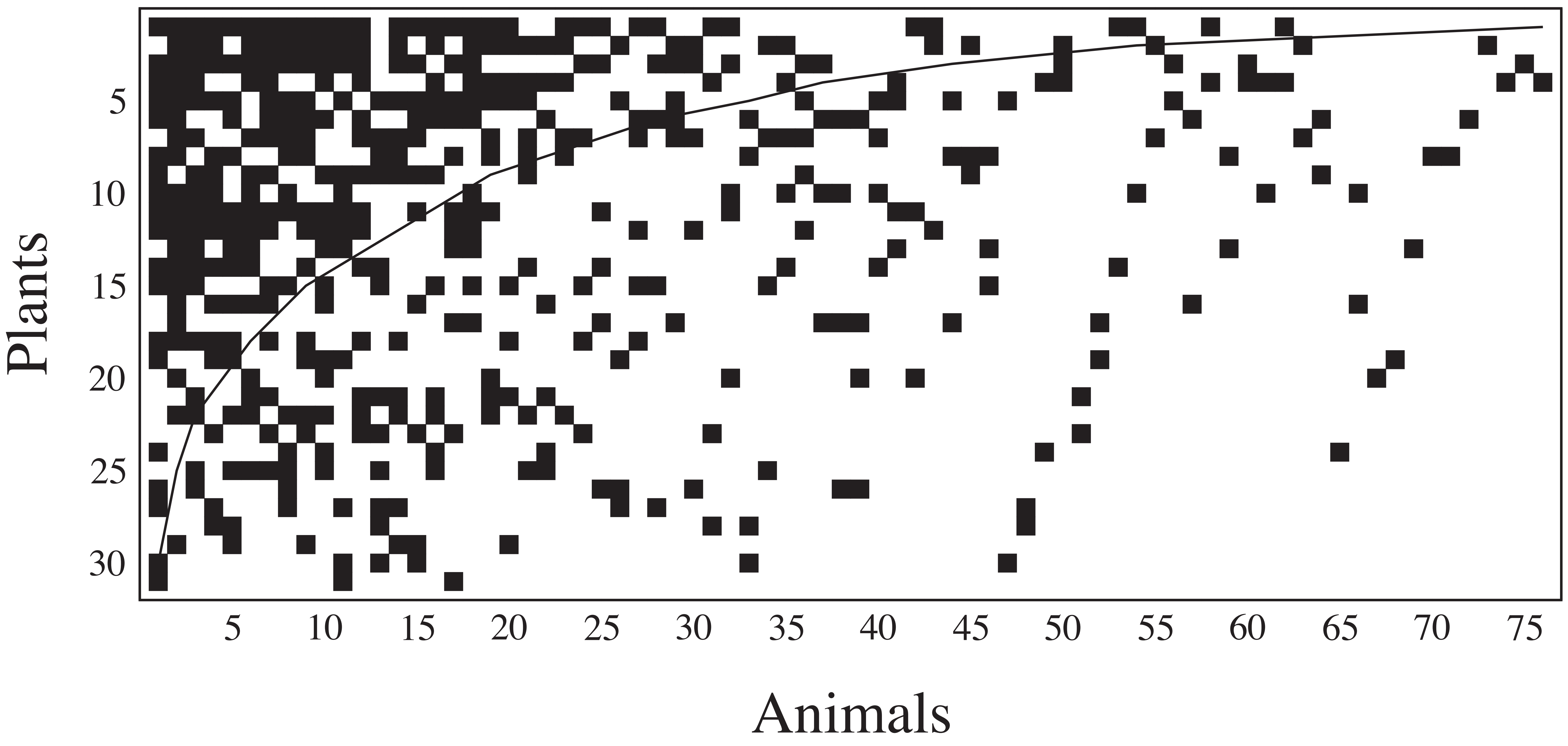
Exclusive to bipartite networks - Extent to which extent to which the sets of interaction partners more specialist species are proper subsets of the set of interacting partners of generalist species

$$NODF = \frac{\sum N_{paired}}{(\frac{n(n-1)}{2}) + (\frac{m(m-1)}{2})}$$

N_{paired} = score that quantifies the overlap between diets of contiguous rows and columns in I

n, m = # of rows and columns in I

I = Incidence matrix



Almeida-Neto M et al. (2008) A consistent metric for nestedness analysis in ecological systems: reconciling concept and measurement. ***Oikos***, 117, 1227-1239.

Summary

1. What is a network? - Nodes and links
2. Why use networks? - Quantitative analysis of complexity
3. What is an ecological network? - Species and biotic interactions
4. What are the implications of network structure for community stability? - Constraints on connectivity and links distribution
5. What are the properties commonly used to study networks and how to quantify them?
6. How can we use these tools to answer ecological questions?