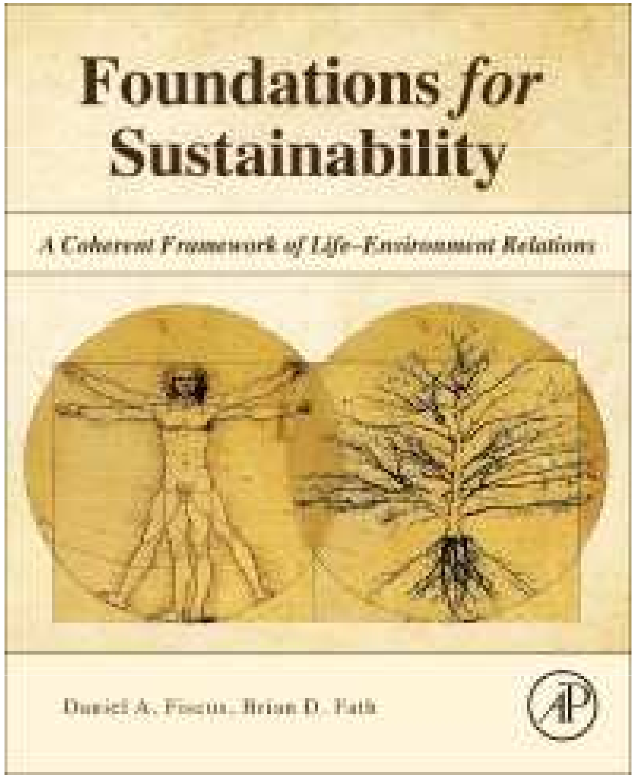


Foundations *for* Sustainability

Brian D. Fath & Dan Fiscus

Fulbright Distinguished Chair, Masaryk University, Brno, Czech Republic

Professor, Towson University, Maryland, USA

Senior Research Scholar, International Institute for Applied Systems Analysis, Austria

Chapter 6: Life science lessons from ecological networks and systems ecology

Your reaction

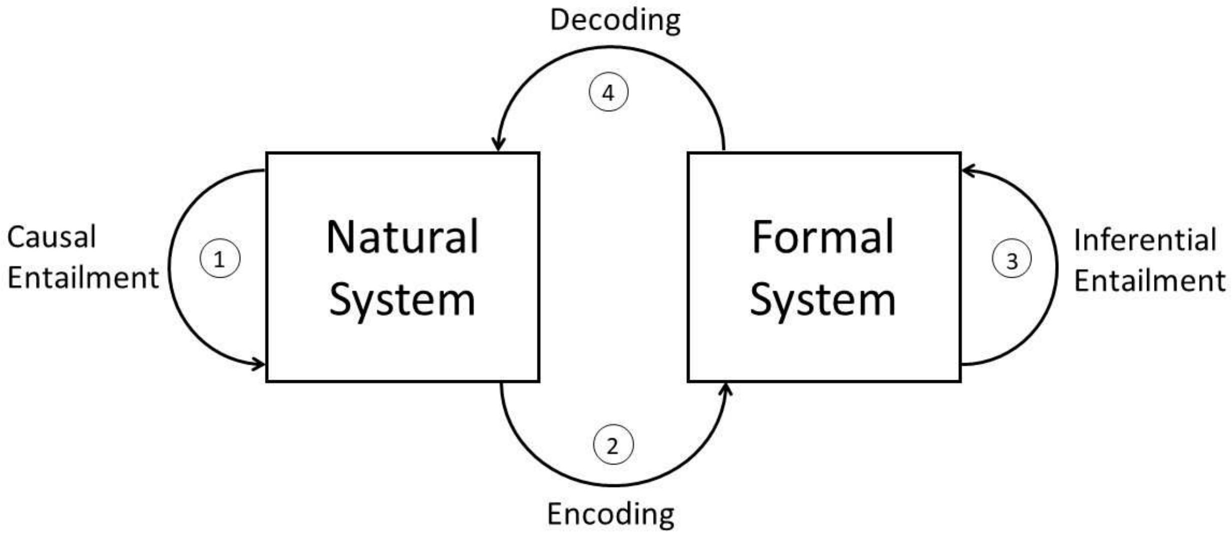
1) What do you think is a main conclusion from using network analysis? Why?

2) What questions do you have?

Ecological Network Analysis provides holistic tools

1) Discrete versus sustained life
2) Developmental tendencies of ecosystems are complementary
3) Indirect impacts are often greater than direct ones
4) All Life is connected—via ENA, we can quantify the connections
5) Ecosystems show mutualism between species
6) Ecosystems and networks naturally balance order and flexibility
7) A hypothetical new formalism prohibits fragmentation of life from environment and of life from life

Knowing what we know

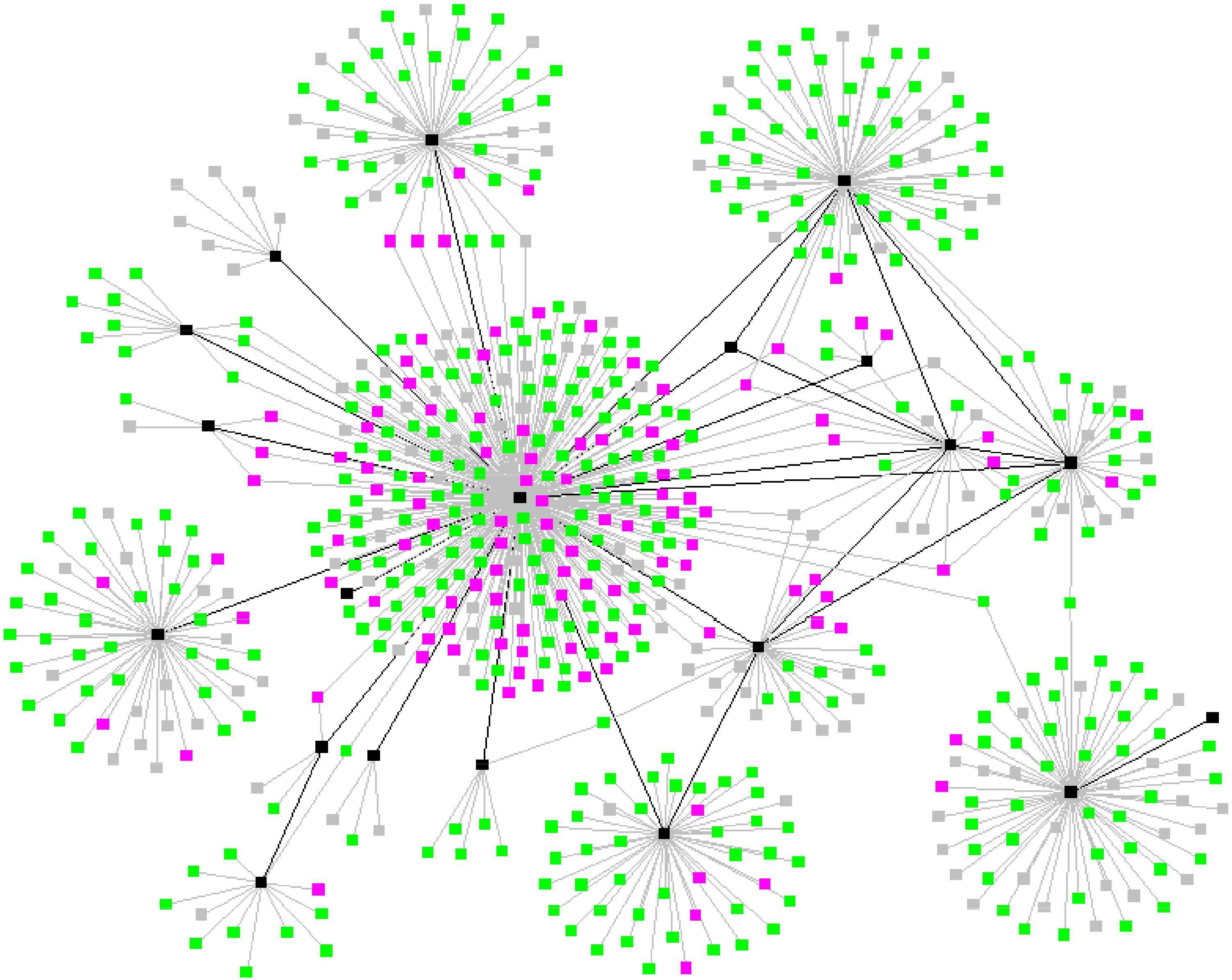


Rosen’s (1991) modeling relation: An elegant representation of the scientific process as heavily entangled with the real world it seeks to understand

Life’s great advance as a complex adaptive system was to emerge as differentiations from and using the stuff of the background and simultaneously develop ways to interact and make sense of this background.

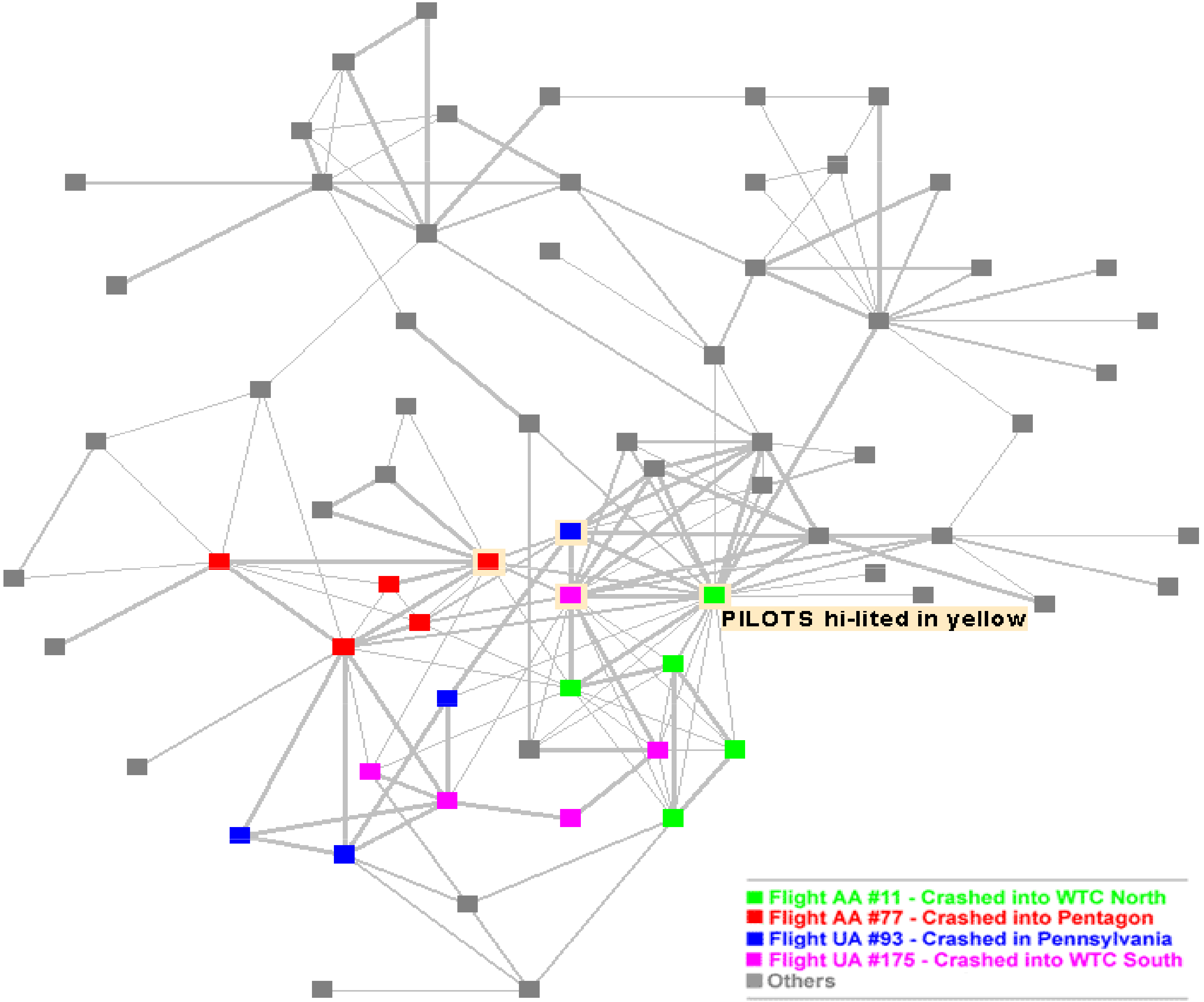
Network Primer

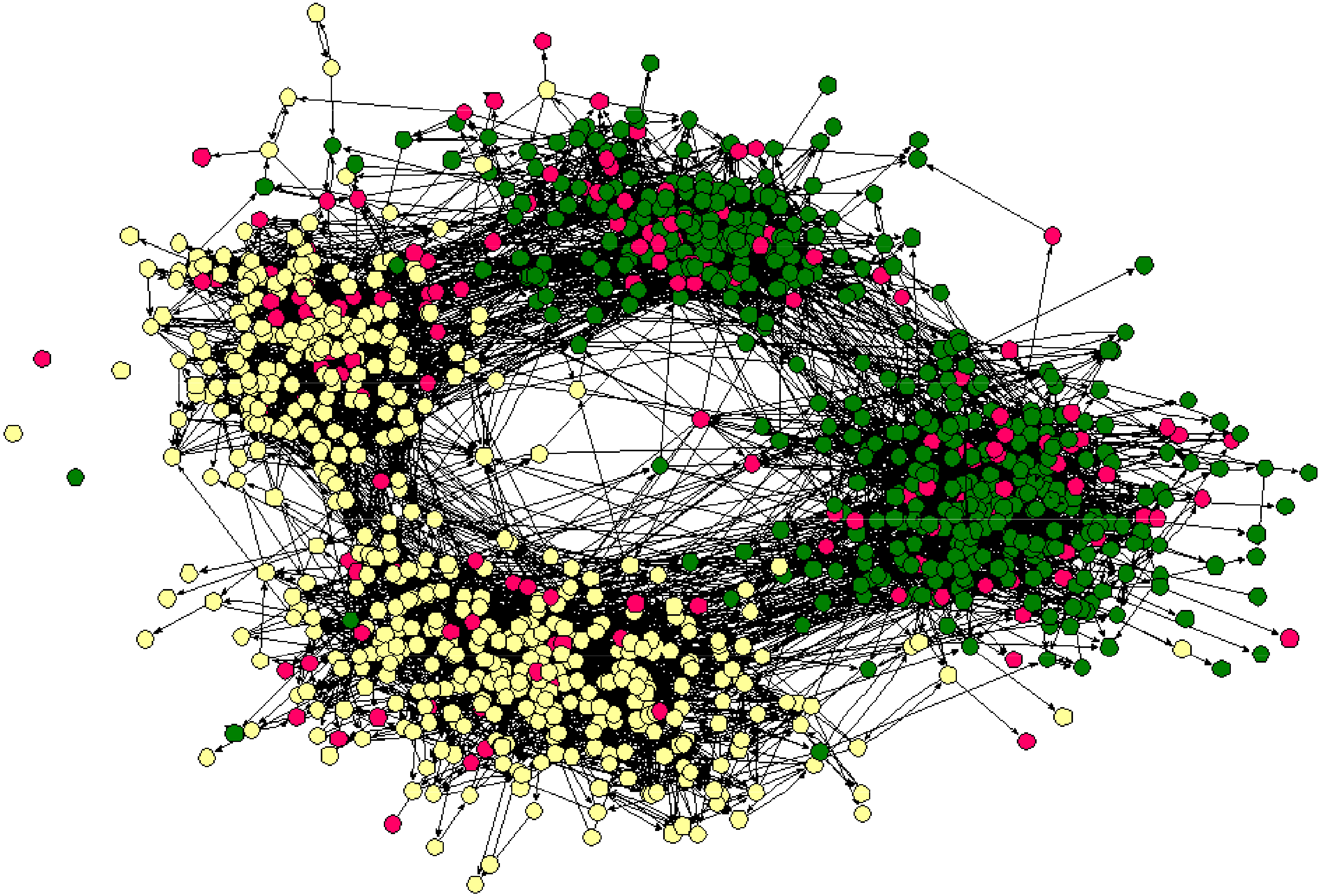
Networks are everywhere!



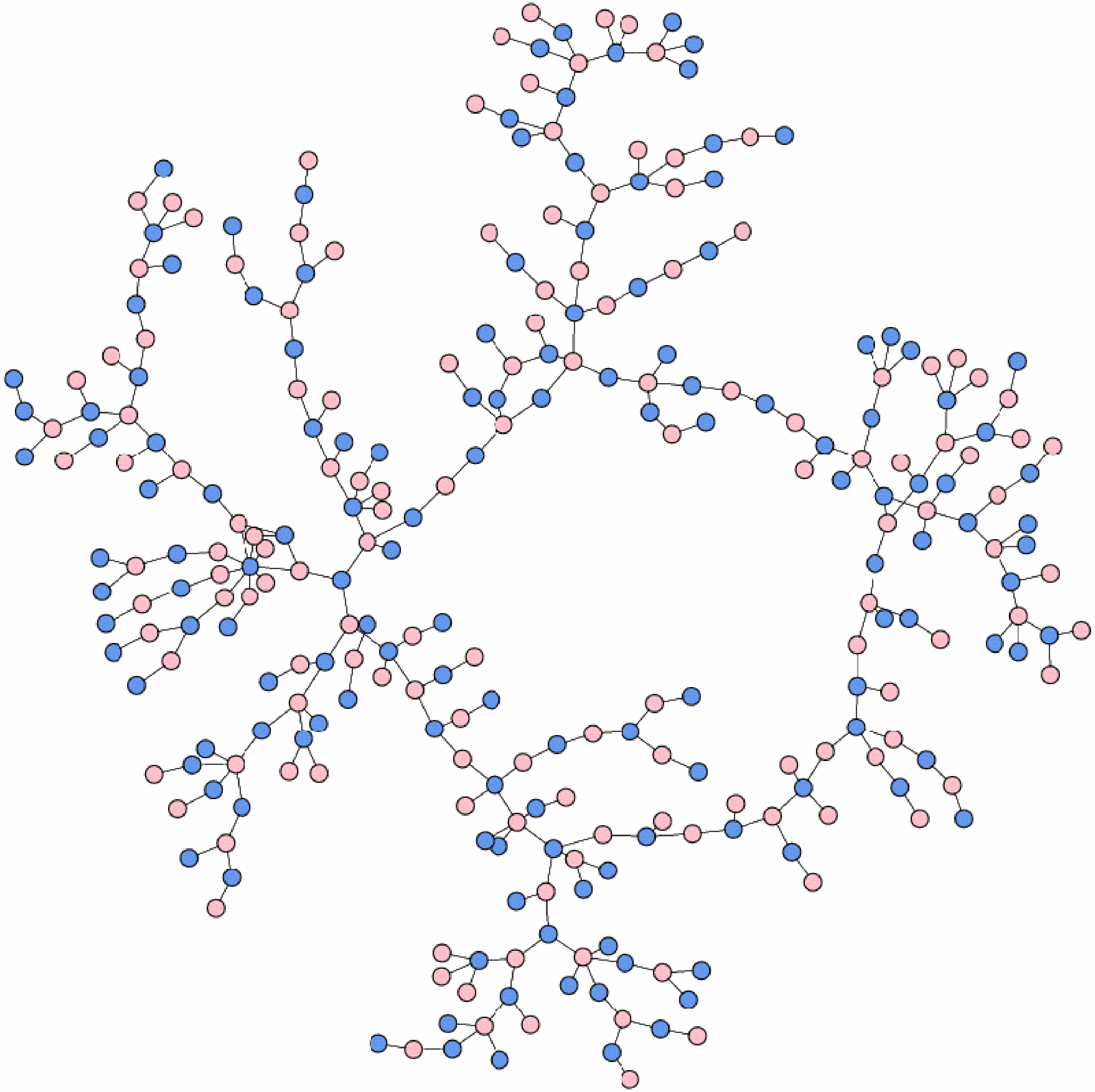
Communicable disease

Terrorism network

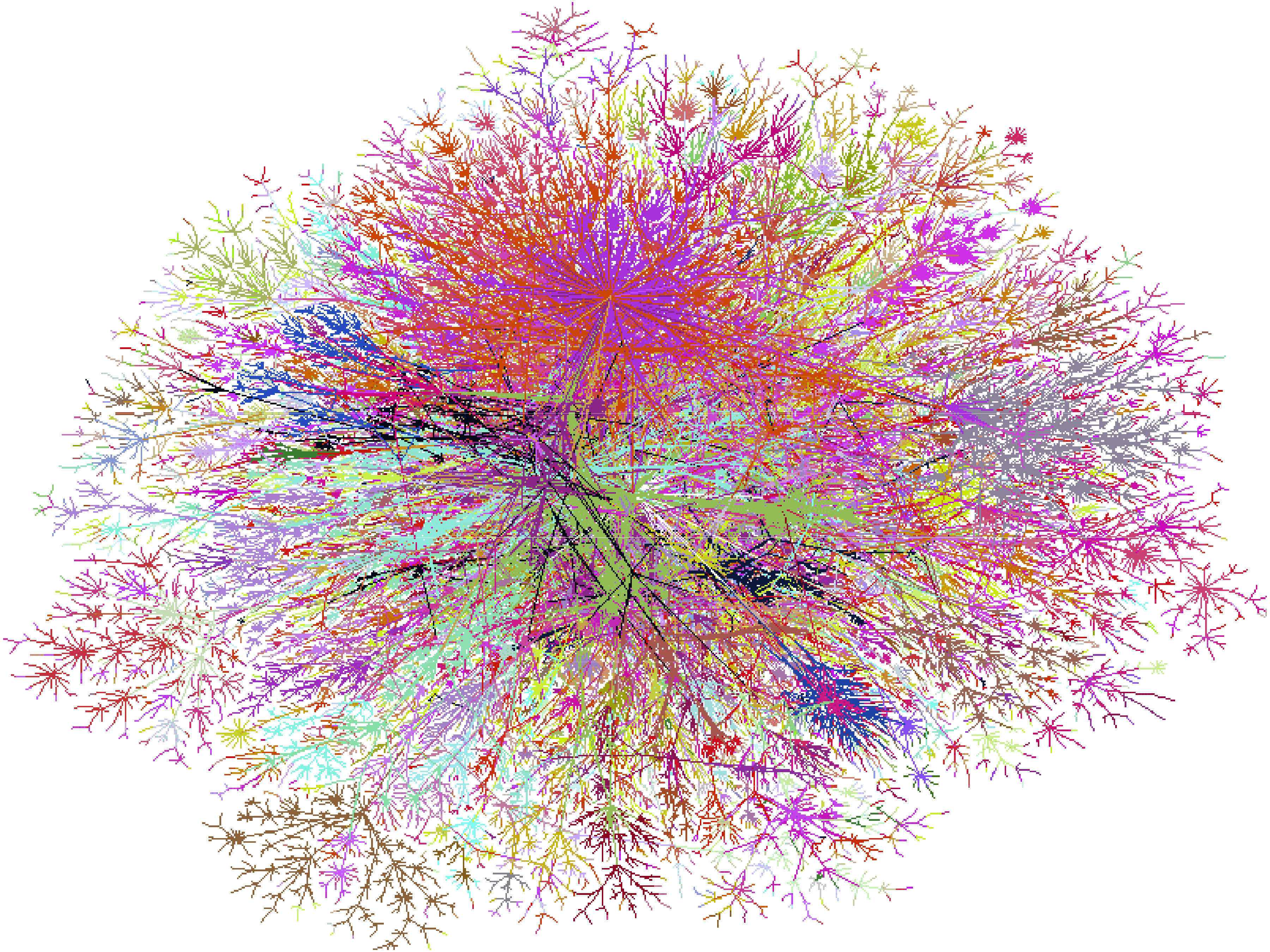




High School Friendship

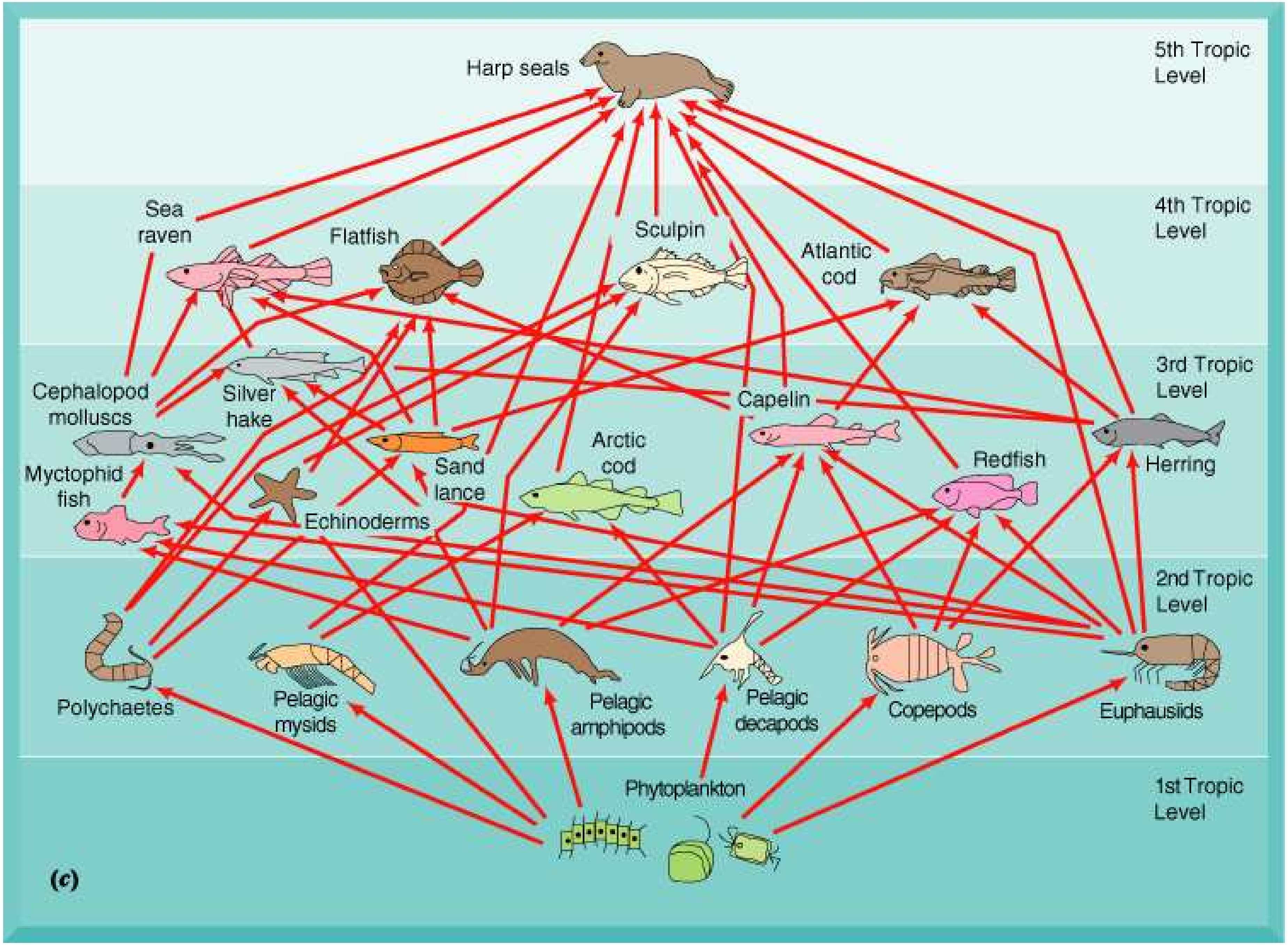


High School Dating

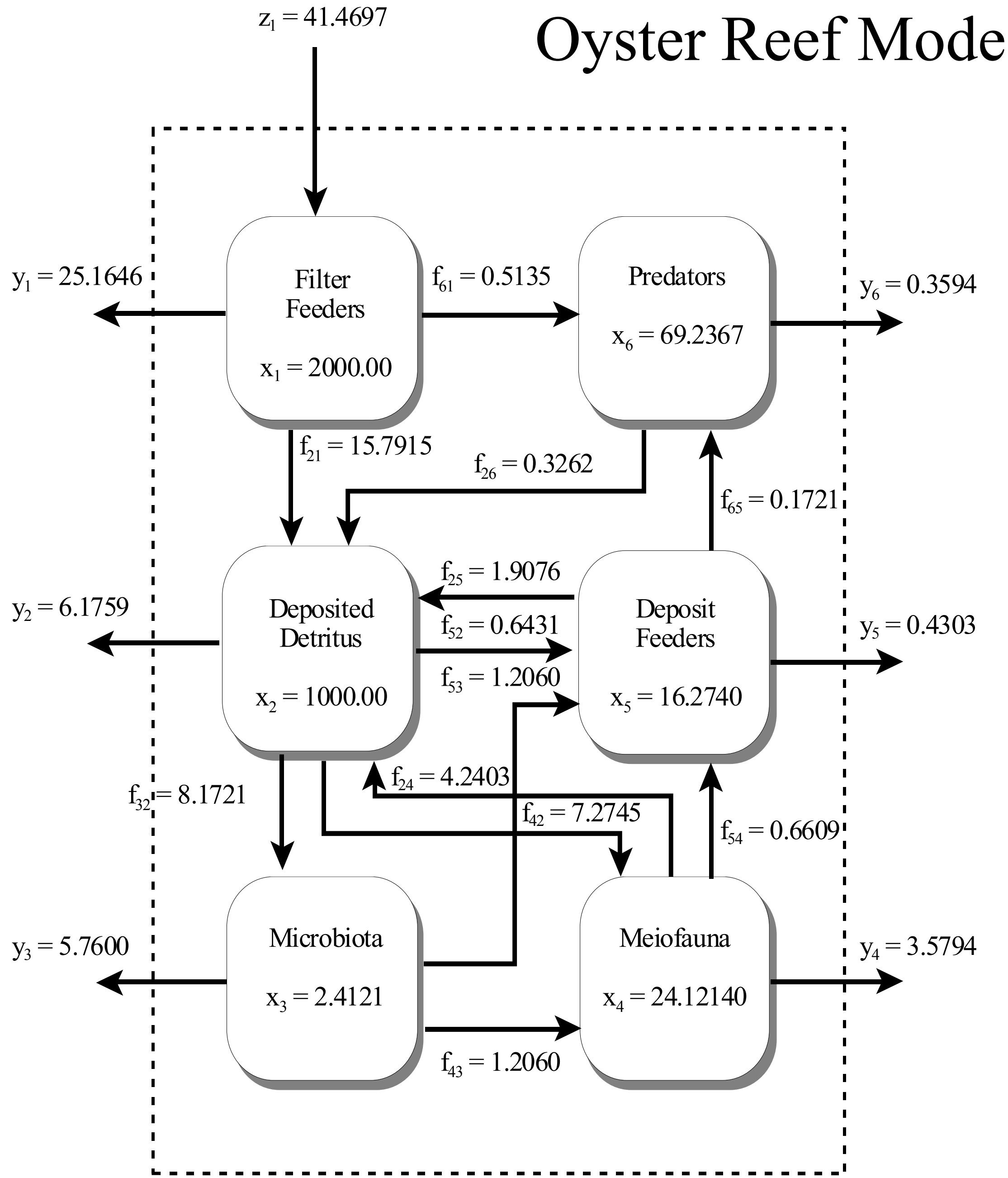


The Internet

Ecological Food Web



Oyster Reef Model



$z_1 = 41.4697$

Filter Feeders

$x_1 = 2000.00$

$y_1 = 25.1646$

$f_{61} = 0.5135$

Predators

$x_6 = 69.2367$

$y_6 = 0.3594$

$f_{21} = 15.7915$

$f_{26} = 0.3262$

$f_{65} = 0.1721$

Deposited Detritus

$x_2 = 1000.00$

$y_2 = 6.1759$

$f_{25} = 1.9076$

$f_{52} = 0.6431$

$f_{53} = 1.2060$

Deposit Feeders

$x_5 = 16.2740$

$y_5 = 0.4303$

$f_{32} = 8.1721$

$f_{24} = 4.2403$

$f_{42} = 7.2745$

$f_{54} = 0.6609$

Microbiota

$x_3 = 2.4121$

$y_3 = 5.7600$

Meiofauna

$x_4 = 24.12140$

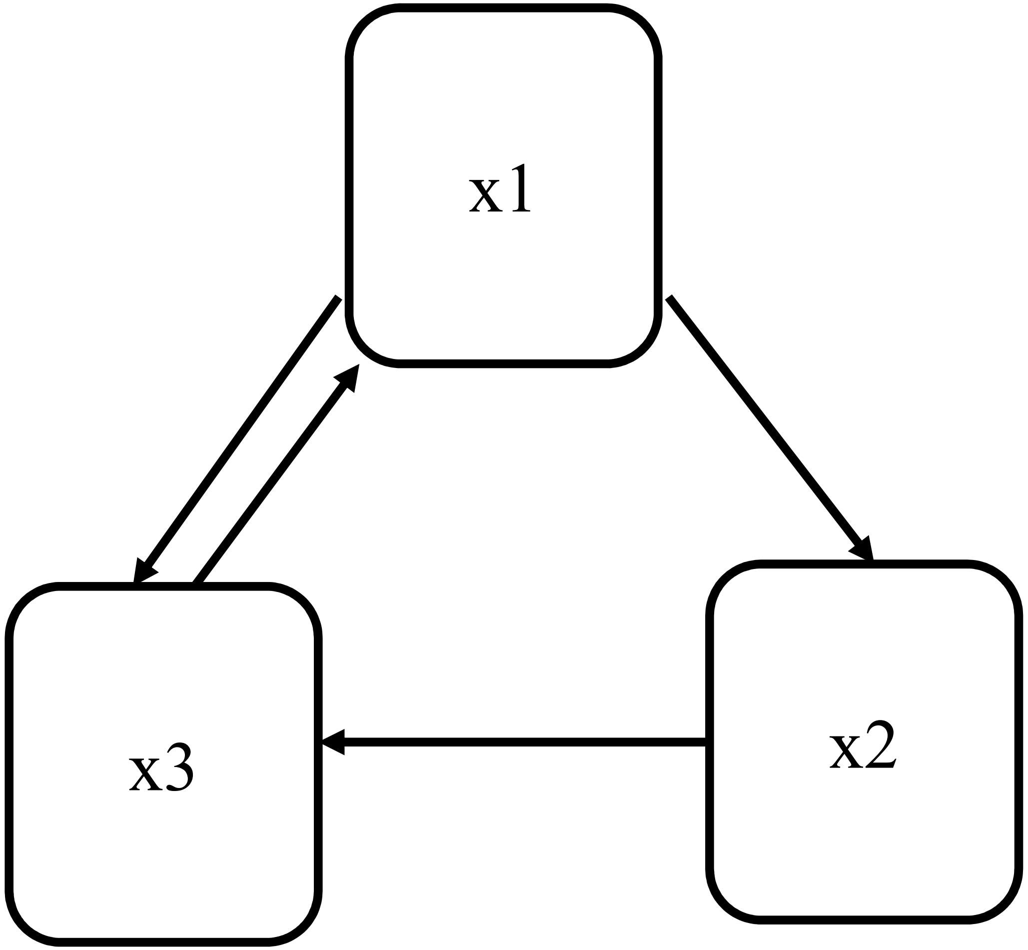
$y_4 = 3.5794$

$f_{43} = 1.2060$

Dame and Patten 1981 – flow is in kcal/(day m^2), storage in kcal/m^2

How to measure structure and indirectness

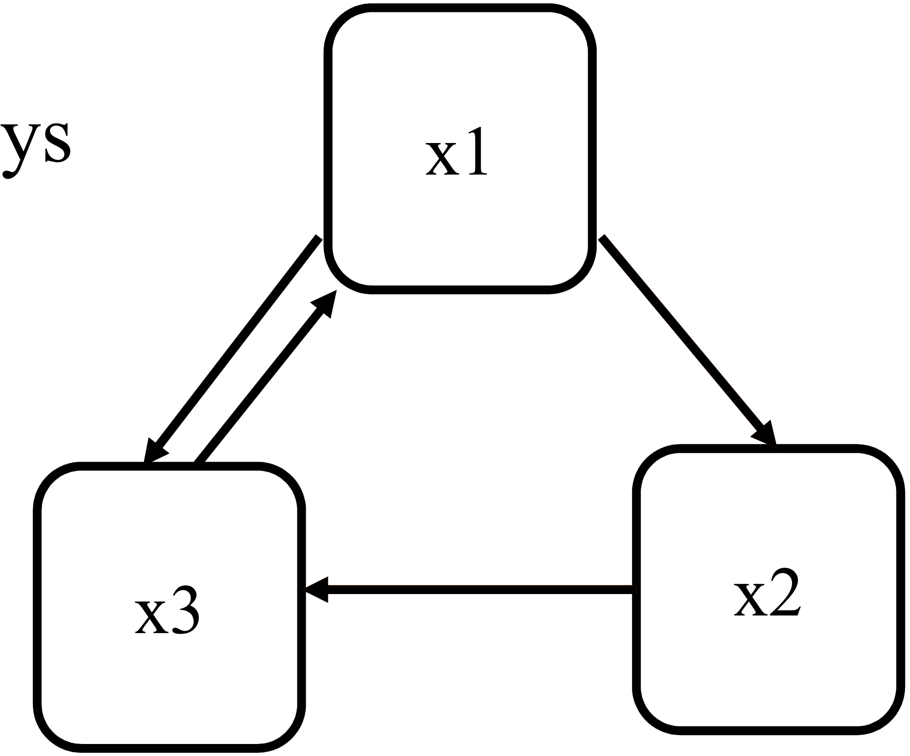
Example – digraph to adjacency matrix



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

Matrix multiplication gives Higher Order (Indirect) Pathways

A^m, where m > 1



$$A^2 = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \end{bmatrix} \quad A^4 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 2 & 1 & 1 \end{bmatrix}$$

$$A^3 = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad A^5 = \begin{bmatrix} 2 & 1 & 1 \\ 1 & 1 & 1 \\ 2 & 1 & 2 \end{bmatrix}$$

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

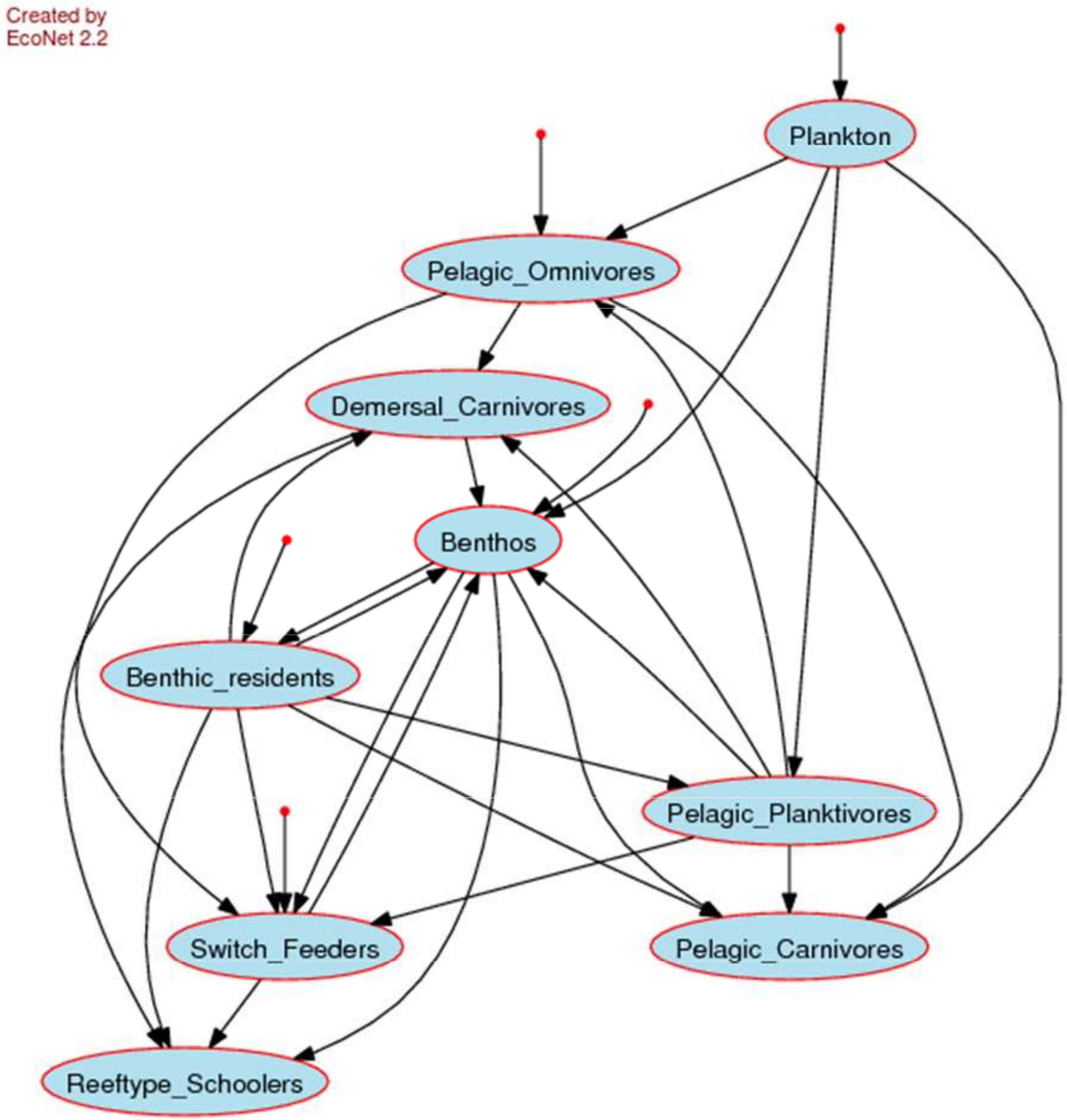
Powers of a matrix!!

The matrix A^m gives exactly the number of paths between two nodes of length m.

A^1 are the direct paths.
A^2 are the paths that take two steps
A^3 are the paths that take three steps, etc.

Notice that some elements which were zero originally get filled in.

In other words we have a way to identify the indirect, i.e., $m>1$, walks in the matrix, and hence in the graph.



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

$$A^2 = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 2 & 0 & 2 & 1 \\ 2 & 1 & 0 & 0 & 0 & 1 & 0 & 3 & 0 \\ 4 & 2 & 1 & 1 & 1 & 4 & 0 & 5 & 3 \\ 3 & 2 & 0 & 2 & 0 & 3 & 0 & 2 & 1 \\ 5 & 3 & 0 & 3 & 2 & 5 & 0 & 3 & 3 \\ 2 & 1 & 0 & 2 & 1 & 3 & 0 & 1 & 2 \\ 3 & 2 & 0 & 4 & 3 & 5 & 1 & 1 & 4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 3 & 1 & 0 & 2 & 2 & 4 & 0 & 3 & 3 \end{bmatrix}$$

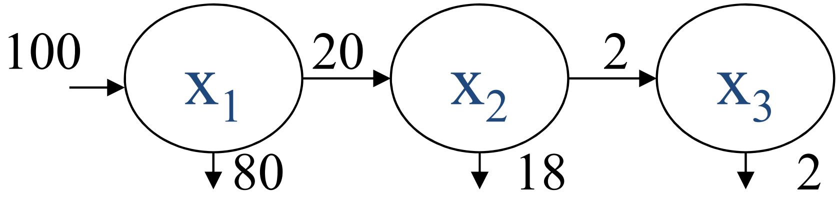
Food web model Gulf of Mexico ecosystem

Very many pathways as path length increases

$$A^{10} = \begin{bmatrix} 13263 & 6193 & 0 & 9397 & 4260 & 16467 & 0 & 13083 & 9397 \\ 6014 & 2810 & 0 & 4260 & 1933 & 7464 & 0 & 5927 & 4260 \\ 41273 & 19276 & 1 & 29238 & 13271 & 51236 & 0 & 40696 & 29248 \\ 21998 & 10274 & 0 & 15591 & 7069 & 27315 & 0 & 21696 & 15590 \\ 51245 & 23931 & 0 & 36317 & 16467 & 63631 & 0 & 50548 & 36317 \\ 29247 & 13657 & 0 & 20727 & 9397 & 36317 & 0 & 28852 & 20727 \\ 65743 & 30698 & 0 & 46590 & 21122 & 81635 & 1 & 64860 & 46590 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 42510 & 19850 & 0 & 30123 & 13658 & 52783 & 0 & 41935 & 30124 \end{bmatrix}$$

As m increases, the number of paths typically increases greatly

Flow Analysis



Adjacency matrix

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

Inter-compartmental flows

$$F = \begin{bmatrix} 0 & 0 & 0 \\ 20 & 0 & 0 \\ 0 & 2 & 0 \end{bmatrix}$$

inputs

$$z = \begin{bmatrix} 100 \\ 0 \\ 0 \end{bmatrix}$$

outputs

$$y = \begin{bmatrix} 80 & 18 & 2 \end{bmatrix}$$

Total flow through each compartment

$$T = \begin{bmatrix} 100 \\ 20 \\ 2 \end{bmatrix}$$

The outflow (time forward, input driven) fractions are given by g_{ij} where

$$g_{ij} = \frac{f_{ij}}{T_j}$$

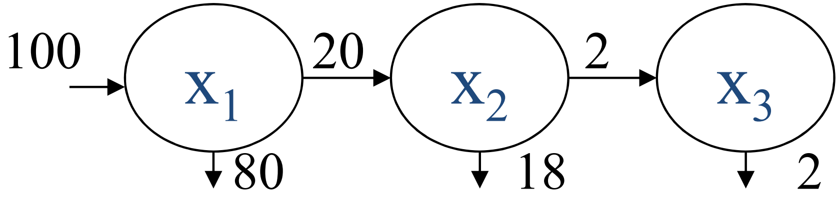
$$G = \begin{bmatrix} 0 & 0 & 0 \\ 0.2 & 0 & 0 \\ 0 & 0.1 & 0 \end{bmatrix}$$

Just as powers of A gave higher order pathways,
Powers of G give flow transfers along higher order pathways.

$$G = \begin{bmatrix} 0 & 0 & 0 \\ 0.2 & 0 & 0 \\ 0 & 0.1 & 0 \end{bmatrix}$$

G^2 gives the fraction of flow leaving j that took 2 steps to reach i.

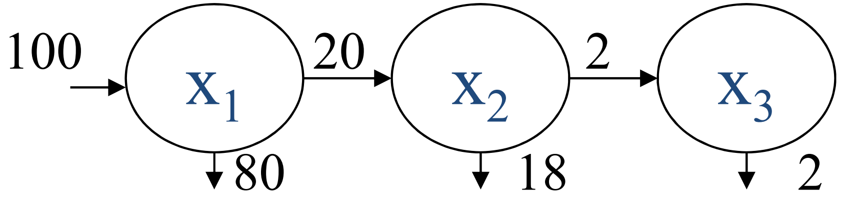
$$G^2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.02 & 0 & 0 \end{bmatrix}$$



Continuing:

G^3 gives the fraction of flow leaving j that took 3 steps to reach i.

$$G^3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



Summarizing:

G^2 gives transfers over pathways of length 2
G^3 gives transfers over pathways of length 3, etc., i.e.,

G^m gives transfers over pathways of length m

Summing over m=1→∞ gives powers over all pathways

$\sum_{m=0}^{\infty} G^m$ where $\sum_{m=2}^{\infty} G^m$ represent indirect transfers

Unlike like powers of A, powers of G get smaller and the series converges

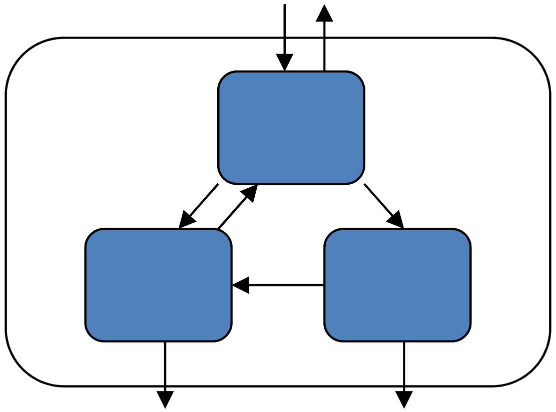
$$N = \sum_{m=0}^{\infty} G^m \equiv (I - G)^{-1}$$

N is the INTEGRAL output flow matrix since it includes direct and all indirect flows

Propagation of network indirect effects

$$\text{Flow:}\qquad \mathbf{N} = \mathbf{I} + \mathbf{G} + \underbrace{\mathbf{G}^2 + \mathbf{G}^3 + \mathbf{G}^4 + \ldots}$$

integral = *initial input* + *direct* + *indirect*

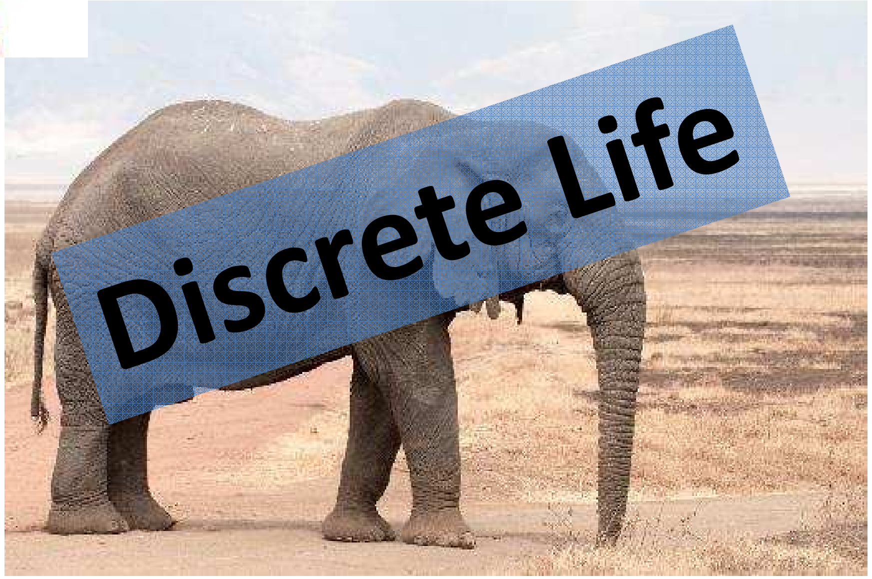


Key findings:

- Quantify input and output flow
- Indirect flows > direct flows
- Flows are well mixed
- Mutualistic relations dominate

L1: Coupled Complementary Life has Discrete and Sustained Aspects

Environment and ecological interactions



Discrete Life

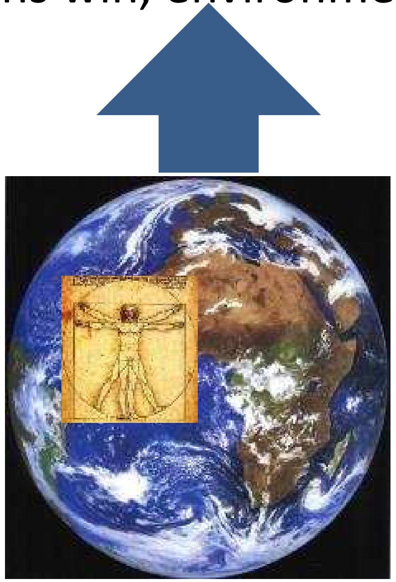
A single organism possesses all the necessary aspects to be alive

Interacting ecological community and its environment is an ecosystem

An ecosystem possesses all the necessary aspects to sustain life

Life and environment are best understood and modeled as unified as a single “life–environment” system.

Bounty of the Commons
Humans win, environment improves



Fiscus D, Fath BD, Goerner S. 2012. E:CO 14(3), 44–88.

Evolution of an undifferentiated whole

“Biologists have rather been in the habit of reflecting upon the evolution of individual species. This point of view does not bear the promise of success, if our aim is to find expression for the fundamental law of evolution. We shall probably fare better if we constantly recall that the physical object before us is an undivided system, that the divisions we make therein are more or less arbitrary importations, psychological rather than physical, and as such, are likely to introduce complications into the expression of natural laws operating upon the system as a whole.” (Lotka p. 158)

And later:

“. . . the concept of evolution, to serve us in its full utility, must be applied, not to an individual species, but to groups of species which evolve in mutual interdependence; and further to the system as a whole, of which such groups form inseparable part.” (Lotka p. 277)

L2: Complementarity of Ecological Goal Functions

- **Quo vadis ecosystem?**
- **Ecological Goal Functions** are assumed to measure given properties or tendencies of ecosystems, emerging as a result of self-organization processes in their development (Marques 1998).

Examples of Goal functions from the literature

1 ***Minimize specific entropy production*** (Prigogine 1947).
Decrease in the respiration to biomass ratio.

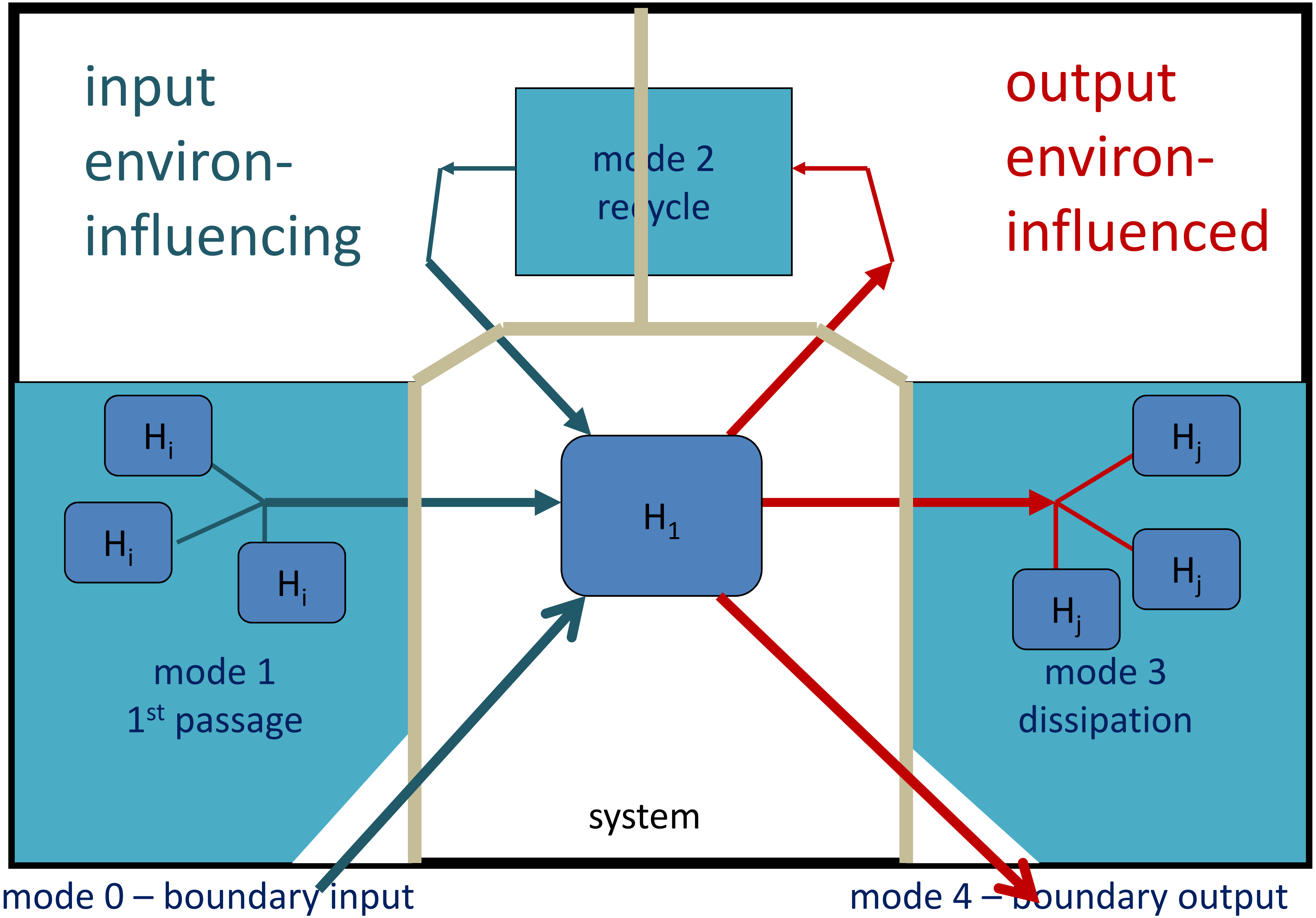
2 ***Maximize energy throughflow*** *(Odum 1983).*
Increase in the internal energy flow.

3 ***Maximize exergy degradation*** *(Kay 1984).* As the amount of exergy captured increases, so does the amount dissipated.

4 ***Maximize exergy storage*** *(Jørgensen & Mejer 1977).* Exergy storage (biomass) and information increase due to shift to more complex species composition.

5 ***Maximize retention time*** *(Cheslak & Lamarra 1981).* Biological components develop mechanisms to increase time lags to maintain the energy stores longer.

Environs form a partition of the system.



Network representation of flow and storage partitioning for any (i,j) pair in the system.

	FLOW pair-wise interactions	**STORAGE** pair-wise interactions
mode 1 (first passage)	$f_{ij}^{(1)} = \left(\frac{n_{ij}}{n_{ii}} - \delta_{ij} \right) z_j$	$x_{ij}^{(1)} = \left(\frac{q_{ij}}{q_{ii}} - \delta_{ij} \right) z_j \Delta t$
mode 2 (cyclic)	$f_{ij}^{(2)} = \frac{n_{ij}}{n_{ii}} (n_{ii} - 1) z_j$	$x_{ij}^{(2)} = \frac{q_{ij}}{q_{ii}} (q_{ii} - 1) z_j \Delta t$
mode 3 (dissipative)	$f_{ij}^{(3)} = \left(\frac{n_{ij}}{n_{ii}} - \delta_{ij} \right) z_j$	$x_{ij}^{(3)} = \left(\frac{q_{ij}}{q_{ii}} - \delta_{ij} \right) z_j \Delta t$

Goal Function	Ecological Representation	Network Parameter	Network Analysis Formulation
max power	max(TST)	$TST = f^{(1)} + f^{(2)}$	$TST = \sum\sum (n_{ij})z_j$
max exergy storage	max(TSS)	$TSS = x^{(1)}+x^{(2)}$	$TSS = \sum\sum\tau_i(n_{ij})z_j$
max dissipation	max(TSE)	$TSE = f^{(3)}$	$TSE = \sum \sum (n_{ij}/n_{ii})z_j$
max cycling	max(TSC)	$TSC = f^{(2)}$	$TSC = \sum \sum (n_{ij}/n_{ii})(n_{ii}-1)z_j$
min specific dissipation	min(TSE/TSS)	$TSE/TSS = f^{(3)}/(x^{(1)}+x^{(2)})$	$TSE/TSS = \sum \sum ((n_{ij}/n_{ii})z_j)/x_{ij}$ $= \sum\sum 1/(\tau_i n_{ii})$
max residence time	max(TSRT)	$TSRT = \tau$	$TSRT = \sum\sum x_i/(n_{ij})z_j$ $= \sum\tau_i$

Conclusion

Ecosystem tendencies are consistent and mutually implicating

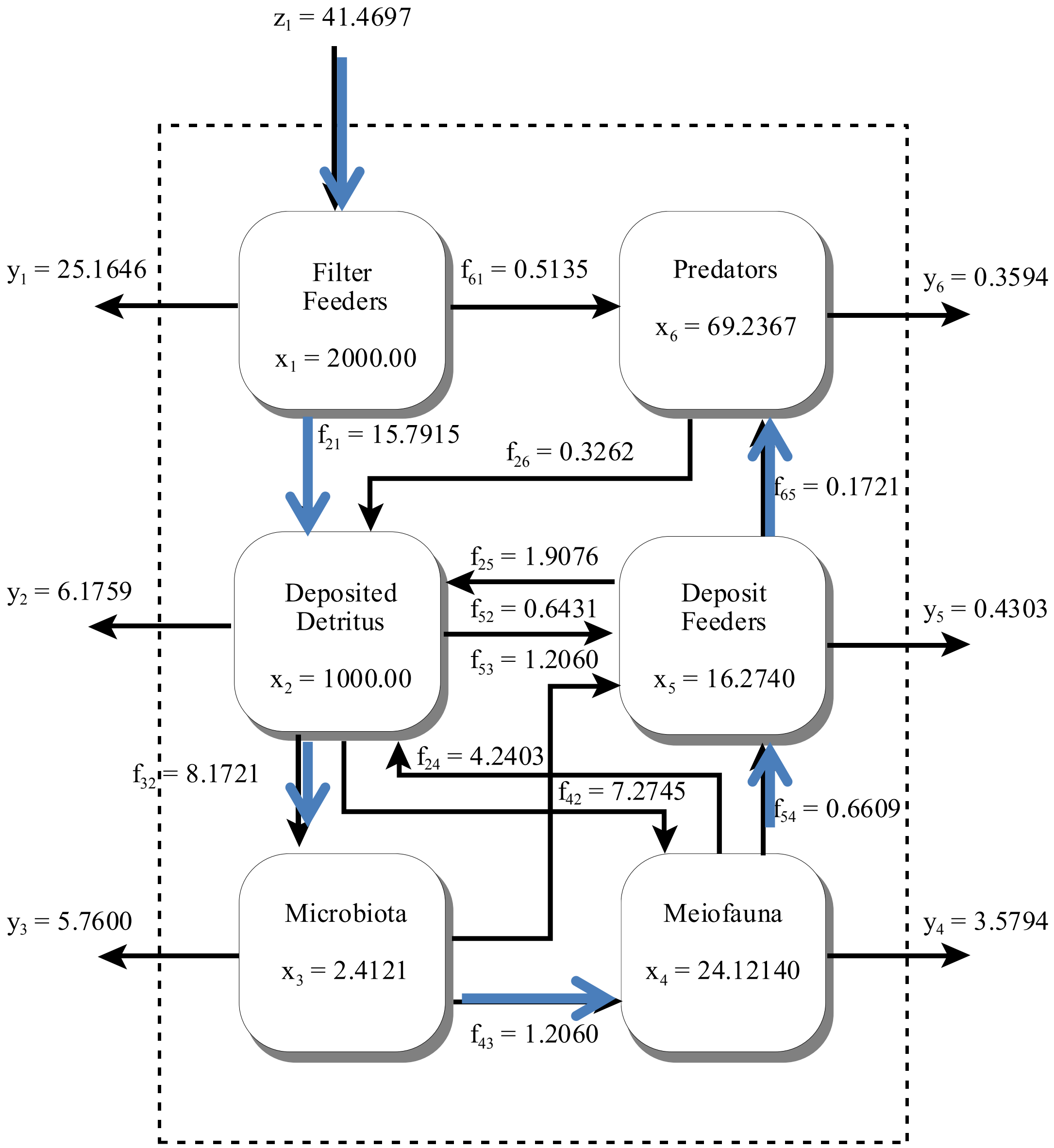
Three common properties:

1) **First passage flow**
2) **Cycling**
3) **Retention time**

Get as much as it can (maximize first passage flow);
Hold on to it for as long as it can (maximize retention time);
and
If it must let it go, then try to get it back (maximize cycling).

L3: Dominance of Indirect Effects

Measuring indirect flows



$$F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 15.79 & 0 & 0 & 4.24 & 1.91 & 0.33 \\ 0 & 8.17 & 0 & 0 & 0 & 0 \\ 0 & 7.27 & 1.21 & 0 & 0 & 0 \\ 0 & 0.64 & 1.21 & 0.66 & 0 & 0 \\ 0.51 & 0 & 0 & 0 & 0.17 & 0 \end{bmatrix}$$

$$G = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0.38 & 0 & 0 & 0.5 & 0.76 & 0.48 \\ 0 & 0.37 & 0 & 0 & 0 & 0 \\ 0 & 0.33 & 0.15 & 0 & 0 & 0 \\ 0 & 0.29 & 0.15 & 0.08 & 0 & 0 \\ 0.01 & 0 & 0 & 0 & 0.07 & 0 \end{bmatrix}$$

Flow: $\mathbf{N} = \mathbf{I} + \mathbf{G} + \mathbf{G}^2 + \mathbf{G}^3 + \mathbf{G}^4 + \ldots$

integral = *initial input* + *direct* + *indirect*

G =

```
      0        0         0         0         0         0
 0.3808        0         0    0.5000    0.7600    0.4758
      0   0.3670         0         0         0         0
      0   0.3267    0.1476         0         0         0
      0   0.0289    0.1476    0.0779         0         0
 0.0124        0         0         0    0.0686         0
```

DIRECT FLOWS

$G^2 =$

```
      0         0         0         0         0         0
 0.0059    0.1853    0.1859    0.0592    0.0326         0
 0.1398         0         0    0.1835    0.2789    0.1746
 0.1244    0.0542         0    0.1634    0.2483    0.1554
 0.0110    0.0796    0.0115    0.0144    0.0220    0.0137
      0    0.0020    0.0101    0.0053         0         0
```

$G^3 =$

```
      0         0         0         0         0         0
 0.0706    0.0885    0.0136    0.0952    0.1408    0.0882
 0.0022    0.0680    0.0682    0.0217    0.0120         0
 0.0226    0.0605    0.0608    0.0464    0.0518    0.0258
 0.0305    0.0096    0.0054    0.0415    0.0615    0.0379
 0.0008    0.0055    0.0008    0.0010    0.0015    0.0009
```

$G^4 =$

```
      0         0         0         0         0         0
 0.0348    0.0401    0.0348    0.0552    0.0733    0.0421
 0.0259    0.0325    0.0050    0.0349    0.0517    0.0324
 0.0234    0.0390    0.0145    0.0343    0.0478    0.0288
 0.0041    0.0173    0.0152    0.0096    0.0099    0.0046
 0.0021    0.0007    0.0004    0.0028    0.0042    0.0026
```

N =

```
 1.0000         0         0         0         0         0
 0.5369    1.3885    0.2775    0.7800    1.1006    0.6606
 0.1971    0.5096    1.1019    0.2863    0.4039    0.2425
 0.2045    0.5288    0.2533    1.2971    0.4192    0.2516
 0.0605    0.1565    0.1904    0.1659    1.1241    0.0745
 0.0165    0.0107    0.0131    0.0114    0.0771    1.0051
```

INTEGRAL FLOWS

N-I-G =

```
      0         0         0         0         0         0
 0.1561    0.3885    0.2775    0.2800    0.3406    0.1848
 0.1971    0.1426    0.1019    0.2863    0.4039    0.2425
 0.2045    0.2021    0.1057    0.2971    0.4192    0.2516
 0.0605    0.1276    0.0428    0.0879    0.1241    0.0745
 0.0042    0.0107    0.0131    0.0114    0.0085    0.0051
```

TOTAL INDIRECT FLOWS

Indirect/direct=
sum(sum(N–I–G))/sum(sum(G)) =

$$\frac{5.0523}{3.2932} = \mathbf{1.5341}$$

Dominance of Indirectness occurs when indirect contribution is greater than direct. This occurs in the majority of food web models studied so far and is one of the key results of ecological network analysis and insights into understanding the role of networks on system organization.

Indirectness increases with increasing:

- connectivity
- cycling
- system order
- direct effects

Make the direct observation, but analyze the whole system. Direct observations give less than half the story.

L4: All Life is Physically and Relationally Connected

Relation – qualitative, value-oriented, direct or indirect interaction types. Nine possible interaction types

Transaction – transfer of energy or matter between two directly connected components

$$\begin{array}{cccc} & + & 0 & - \\ + & (+,+) & (+,0) & (+,-) \\ 0 & (0,+) & (0,0) & (0,-) \\ - & (-,+) & (-,0) & (-,-) \end{array}$$

Utility Analysis

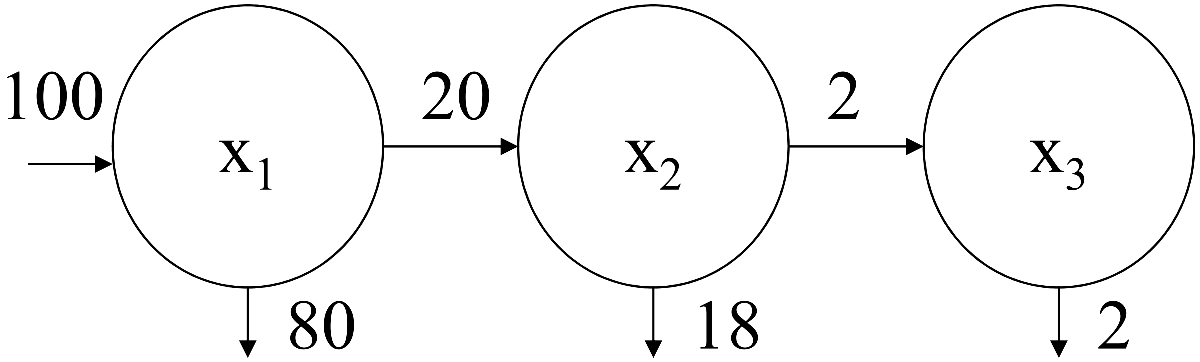
- determines relationship types
- demonstrates network synergism and mutualism

Let

$$d_{ij} = \frac{\left(f_{ij} - f_{ji}\right)}{T_i}$$

- Normalized net flow between components

Three compartment food chain



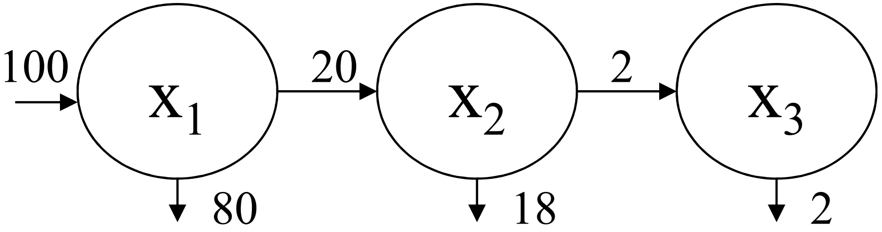
$$A = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$F = \begin{bmatrix} 0 & 0 & 0 \\ 20 & 0 & 0 \\ 0 & 2 & 0 \end{bmatrix}$$

$$T = \begin{bmatrix} 100 \\ 20 \\ 2 \end{bmatrix}$$

Network utility analysis uses net flow between components

$$d_{ij} = \frac{f_{ij} - f_{ji}}{T_i} \qquad D = \begin{bmatrix} 0 & -20/100 & 0 \\ 1 & 0 & -2/20 \\ 0 & 1 & 0 \end{bmatrix}$$



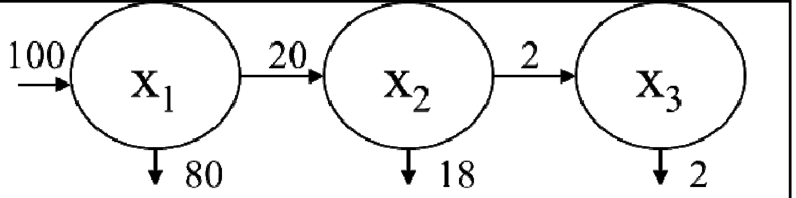
Direct Sign Matrix

$$D = \begin{bmatrix} 0 & -{}^{20}\!/_{100} & 0 \\ 1 & 0 & -{}^{2}\!/_{20} \\ 0 & 1 & 0 \end{bmatrix} \qquad \operatorname{sgn}(D) = \begin{bmatrix} 0 & - & 0 \\ + & 0 & - \\ 0 & + & 0 \end{bmatrix}$$

Direct relations – from comparing terms across the main diagonal:

$$(sd_{21}, sd_{12}) = (+, -) \rightarrow \text{predation}$$
$$(sd_{32}, sd_{23}) = (+, -) \rightarrow \text{predation}$$
$$(sd_{31}, sd_{13}) = (0, 0) \rightarrow \text{neutralism}$$

Integral Utility:



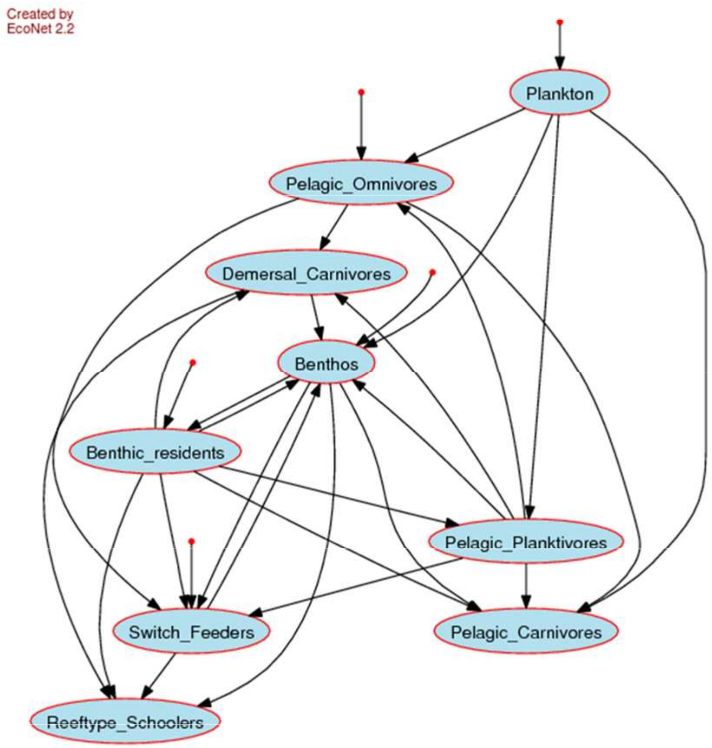
Utility: $U = I + D + D^2 + D^3 + D^4 + \ldots$

integral = *initial input* + *direct* + *indirect*

$$U = \begin{bmatrix} 0.846 & -0.154 & 0.015 \\ 0.769 & 0.769 & -0.077 \\ 0.769 & 0.769 & 0.923 \end{bmatrix}$$

All terms are non-zero indicating relational connectivity

Direct interaction matrix, shows null (0,0) relations



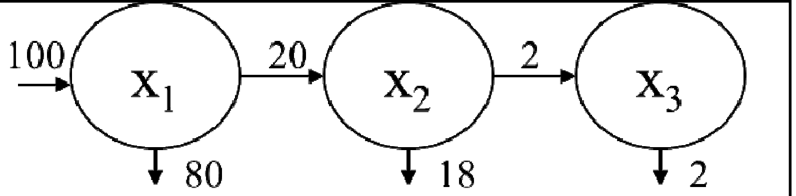
$$D * 100 = \begin{bmatrix} 0 & -2.9000 & -1.2 & -0.2000 & -0.5 & 7.0637 & 0 & 92.9363 & -0.9 \\ 0.1236 & 0 & -2.1 & -0.1000 & -0.4 & 0 & 0 & 0.8909 & 0 \\ 1.7935 & 73.6704 & 0 & 0 & 0 & 10.5572 & 0 & 10.4176 & 3.5613 \\ 1.0510 & 12.3349 & 0 & 0 & -1.2 & 85.7141 & -0.4 & 0 & 0 \\ 0.0213 & 0.4003 & 0 & 0.0097 & 0 & 0.3012 & -0.3 & 0 & -0.8968 \\ -0.3 & 0 & -0.3 & -0.6927 & -0.3 & 0 & -0.2 & 0 & 0.7156 \\ 0 & 0 & 0 & 0.4589 & 42.4193 & 28.3905 & 0 & 0 & 28.7313 \\ -4.0 & -0.9 & -0.3 & 0 & 0 & 0 & 0 & 0 & -0.8 \\ 0.0378 & 0 & -0.1 & 0 & 0.8827 & -0.7071 & -0.2 & 0.7801 & 0 \end{bmatrix}$$

Integral (direct + indirect) relations are all non-zero, indicating everything affects everything, at least indirectly

$$U * 100 = \begin{bmatrix} 96.373 & -4.621 & -1.345 & -0.233 & -0.497 & 6.473 & -0.007 & 89.372 & -1.582 \\ 0.056 & 98.45 & -2.069 & -0.097 & -0.392 & -0.297 & 0.002 & 0.713 & -0.078 \\ 1.336 & 72.32 & 98.394 & -0.147 & -0.306 & 10.324 & -0.0216 & 12.164 & 3.464 \\ 0.764 & 11.844 & -0.516 & 99.395 & -1.734 & 85.027 & -0.563 & 0.765 & 0.431 \\ 0.020 & 0.394 & -0.008 & 0.006 & 99.862 & 0.229 & -0.298 & 0.014 & -0.980 \\ -0.298 & -0.287 & -0.288 & -0.688 & -0.364 & 99.298 & -0.196 & -0.305 & 0.652 \\ -0.071 & 0.118 & -0.116 & 0.265 & 42.479 & 28.458 & 99.758 & 0.146 & 28.49 \\ -3.86 & -0.918 & -0.222 & 0.011 & 0.018 & -0.281 & 0.002 & 96.38 & -0.746 \\ 0.0074 & -0.076 & -0.098 & 0.005 & 0.799 & -0.767 & -0.201 & 0.775 & 99.92 \end{bmatrix}$$

L5: Mutualism is Common and Crucial

Integral Utility:



Utility: $U = I + D + D^2 + D^3 + D^4 + \ldots$

integral = *initial input* + *direct* + *indirect*

$$\mathrm{sgn}(D) = \begin{bmatrix} 0 & - & 0 \\ + & 0 & - \\ 0 & + & 0 \end{bmatrix}$$

What is indirect relation between X1 and X3?

$$\mathrm{sgn}(U) = \begin{bmatrix} + & - & + \\ + & + & - \\ + & + & + \end{bmatrix}$$

$(sd_{21}, sd_{12}) = (+, -) \rightarrow$ predation

$(sd_{32}, sd_{23}) = (+, -) \rightarrow$ predation

$(sd_{31}, sd_{13}) = (+, +) \rightarrow$ **mutualism**

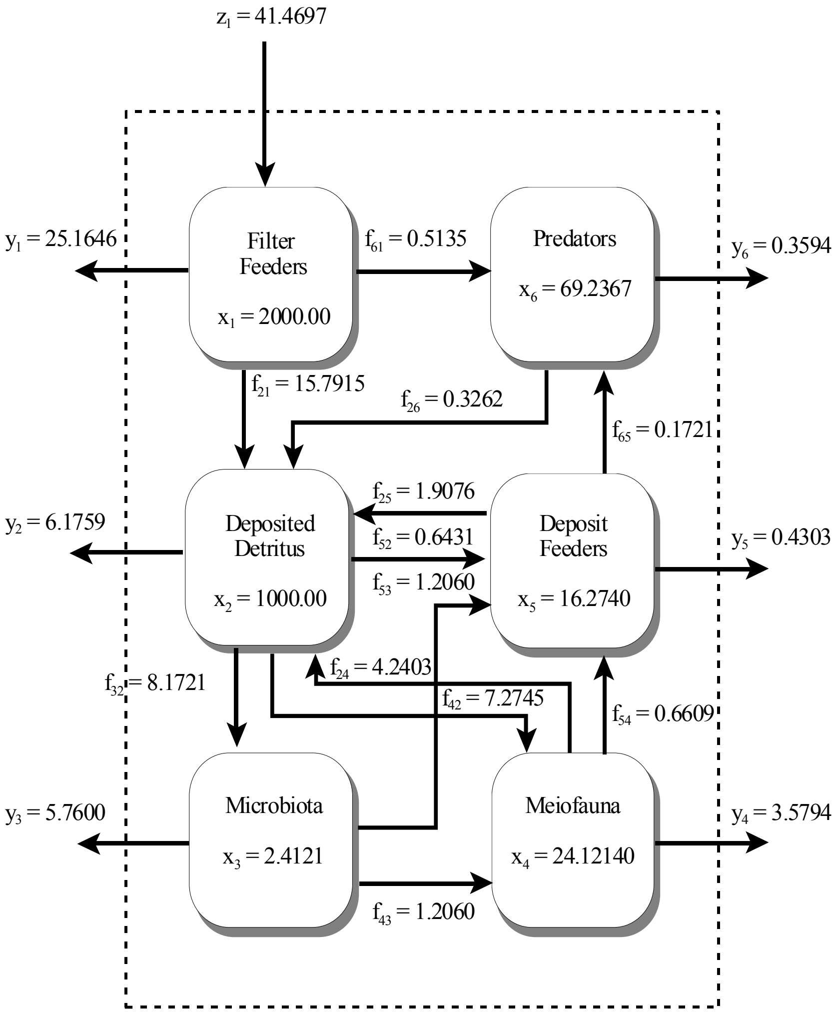
Community-level relations are more positive than the direct relations that produced them: **This is network mutualism**.

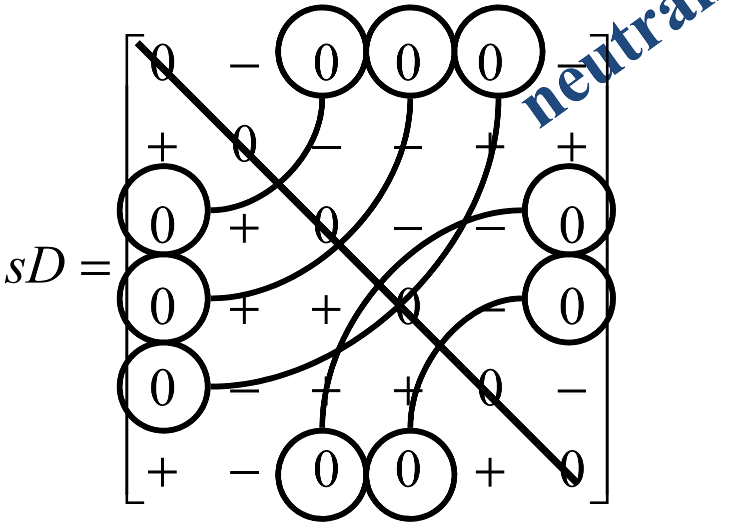
$$U * 100 = \begin{bmatrix} 96.373 & -4.621 & -1.345 & -0.233 & -0.497 & 6.473 & -0.007 & 89.372 & -1.582 \\ 0.056 & 98.45 & -2.069 & -0.097 & -0.392 & -0.297 & 0.002 & 0.713 & -0.078 \\ 1.336 & 72.32 & 98.394 & -0.147 & -0.306 & 10.324 & -0.0216 & 12.164 & 3.464 \\ 0.764 & 11.844 & -0.516 & 99.395 & -1.734 & 85.027 & -0.563 & 0.765 & 0.431 \\ 0.020 & 0.394 & -0.008 & 0.006 & 99.862 & 0.229 & -0.298 & 0.014 & -0.980 \\ -0.298 & -0.287 & -0.288 & -0.688 & -0.364 & 99.298 & -0.196 & -0.305 & 0.652 \\ -0.071 & 0.118 & -0.116 & 0.265 & 42.479 & 28.458 & 99.758 & 0.146 & 28.49 \\ -3.86 & -0.918 & -0.222 & 0.011 & 0.018 & -0.281 & 0.002 & 96.38 & -0.746 \\ 0.0074 & -0.076 & -0.098 & 0.005 & 0.799 & -0.767 & -0.201 & 0.775 & 99.92 \end{bmatrix}$$

$$sign(U) = \begin{bmatrix} + & - & - & - & - & + & - & + & - \\ + & + & - & - & - & - & + & + & - \\ + & + & + & - & - & + & - & + & + \\ + & + & - & + & - & + & - & + & + \\ + & + & - & + & + & + & - & + & - \\ - & - & - & - & - & + & - & - & + \\ - & + & - & + & + & + & + & + & + \\ - & - & - & + & + & - & + & + & - \\ + & - & - & + & + & - & - & + & + \end{bmatrix}$$

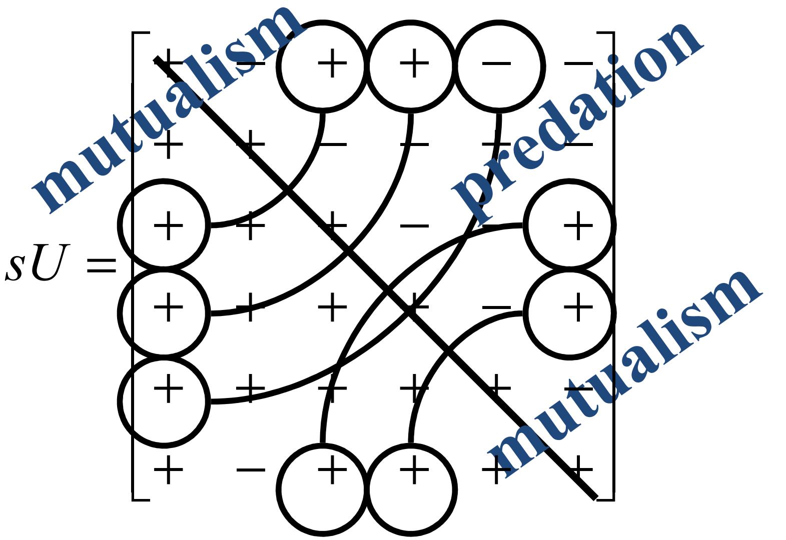
43 are positive and 38 are negative

Oyster Reef Model



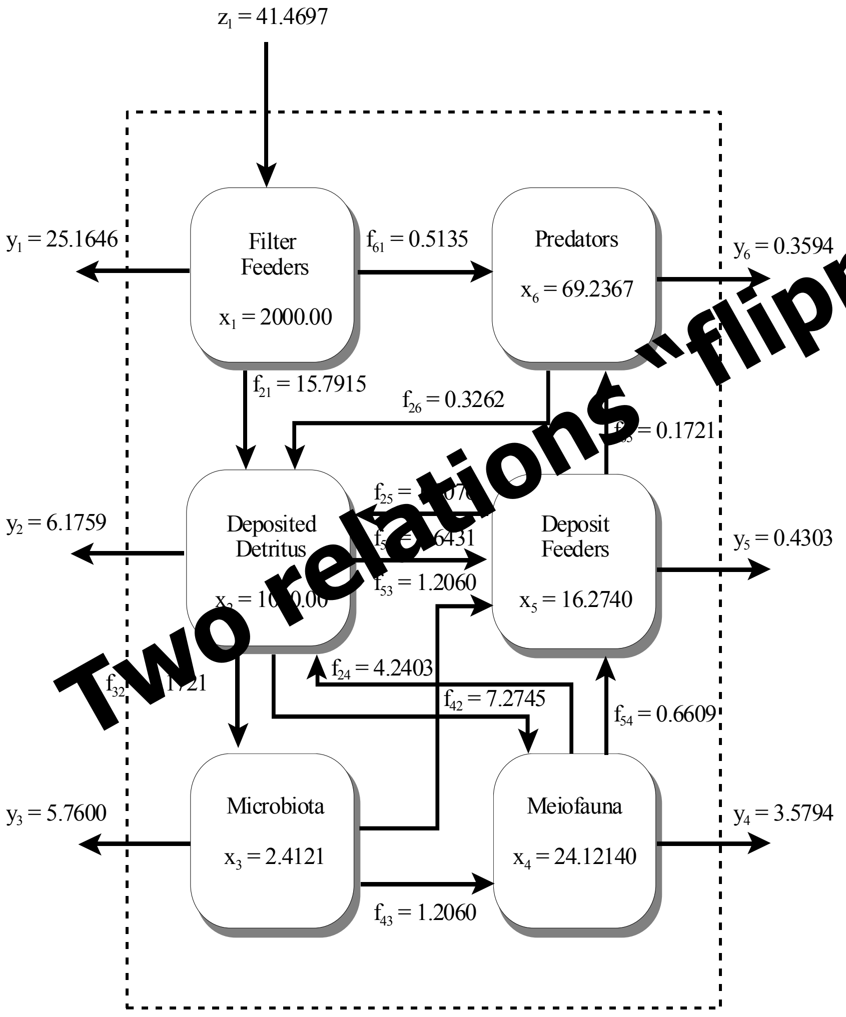


$$sD = \begin{bmatrix} 0 & - & 0 & 0 & 0 & - \\ + & 0 & - & - & + & + \\ 0 & + & 0 & - & - & 0 \\ 0 & + & + & 0 & - & 0 \\ 0 & - & + & + & 0 & - \\ + & - & 0 & 0 & + & 0 \end{bmatrix}$$

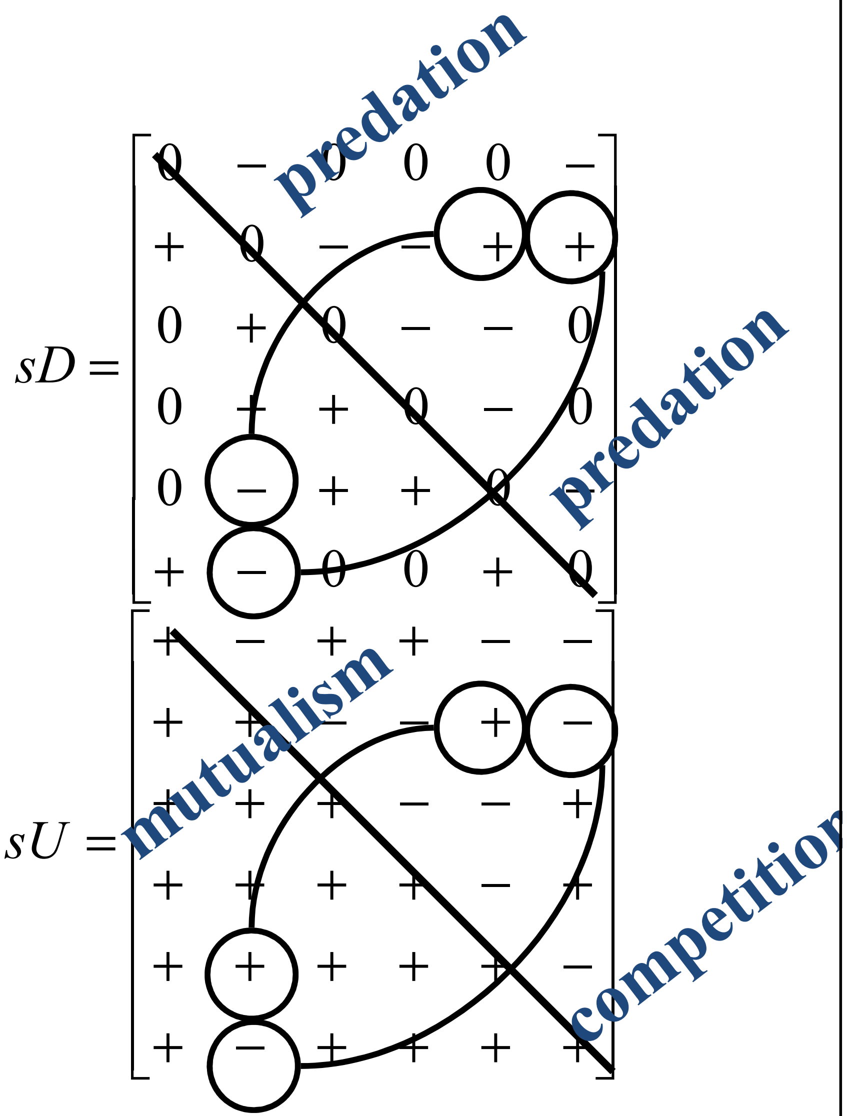


$$sU = \begin{bmatrix} + & - & + & + & - & - \\ + & + & - & - & + & - \\ + & + & + & - & + & + \\ + & + & + & + & - & + \\ + & + & + & + & + & + \\ + & - & + & + & + & + \end{bmatrix}$$

Oyster Reef Model



Two relations “flipped”



$$sD = \begin{bmatrix} 0 & - & 0 & 0 & 0 & - \\ + & 0 & - & - & \textcircled{+} & \textcircled{+} \\ 0 & + & 0 & - & - & 0 \\ 0 & + & + & 0 & - & 0 \\ 0 & \textcircled{-} & + & + & 0 & - \\ + & \textcircled{-} & 0 & 0 & + & 0 \end{bmatrix}$$

$$sU = \begin{bmatrix} + & - & + & + & - & - \\ + & + & - & - & \textcircled{+} & \textcircled{-} \\ + & + & + & - & - & + \\ + & + & + & + & - & + \\ + & \textcircled{+} & + & + & + & - \\ + & \textcircled{-} & + & + & + & + \end{bmatrix}$$

predation

predation

mutualism

competition

L6: Ecosystems Balance Efficiency and Adaptability

Information-based Ecological Network Analysis

Robustness as a trade-off between efficiency and diversity

Total system capacity

$$H = -k \sum_{i,j} \left(\frac{f_{ij}}{f_{..}}\right) log \left(\frac{f_{ij}}{f_{..}}\right)$$

$$= AMI + H_c$$

Efficiency

$$AMI = -k \sum_{i,j} \left(\frac{f_{ij}}{f_{..}}\right) log \left(\frac{f_{ij} f_{..}}{f_{i.} f_{.j}}\right)$$

Diversity

$$H_c = -k \sum_{i,j} \left(\frac{f_{ij}}{f_{..}}\right) log \left(\frac{f_{ij}^2}{f_{i.} f_{.j}}\right)$$

Degree of order

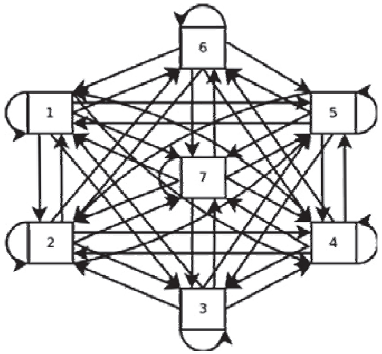
$$a = \frac{AMI}{(AMI + H_c)}$$

Robustness

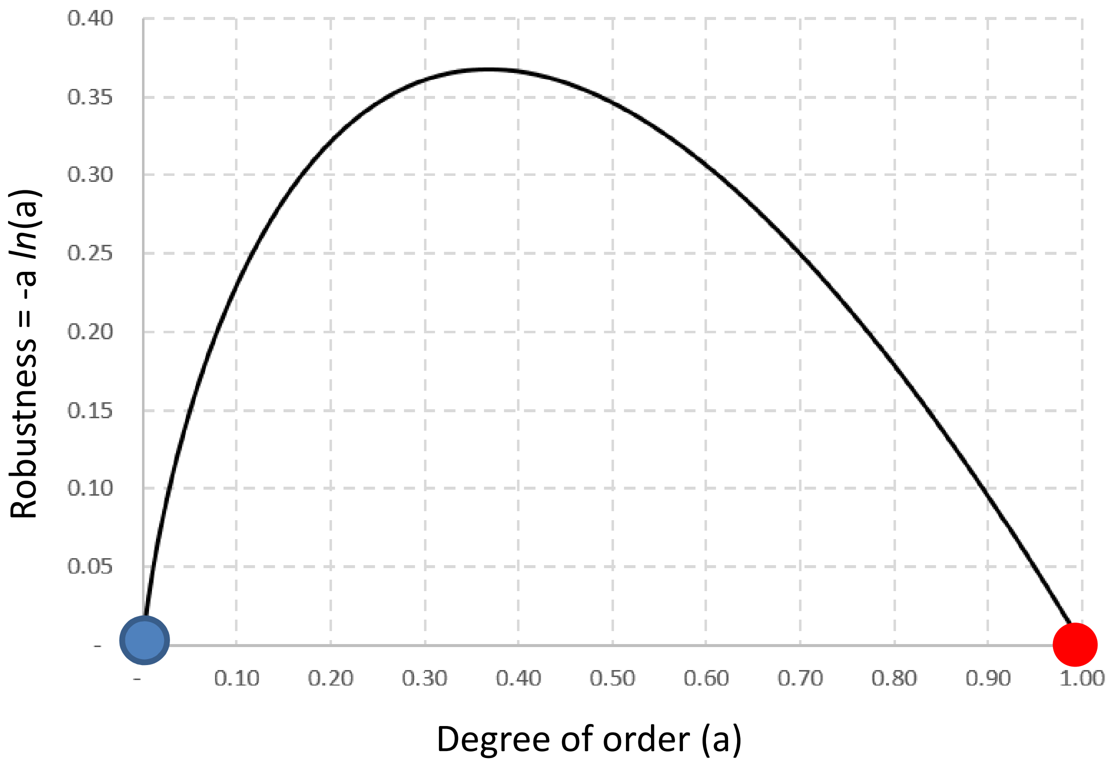
$$R = -a \ln(a)$$

Two example networks

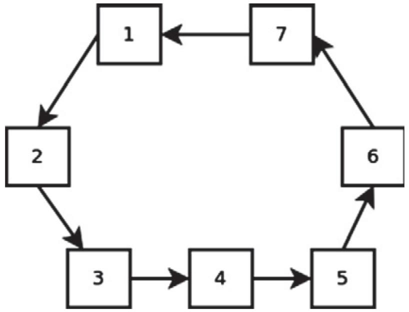
Fully connected



$$a = \frac{AMI}{AMI + H_c} = \mathbf{0}$$

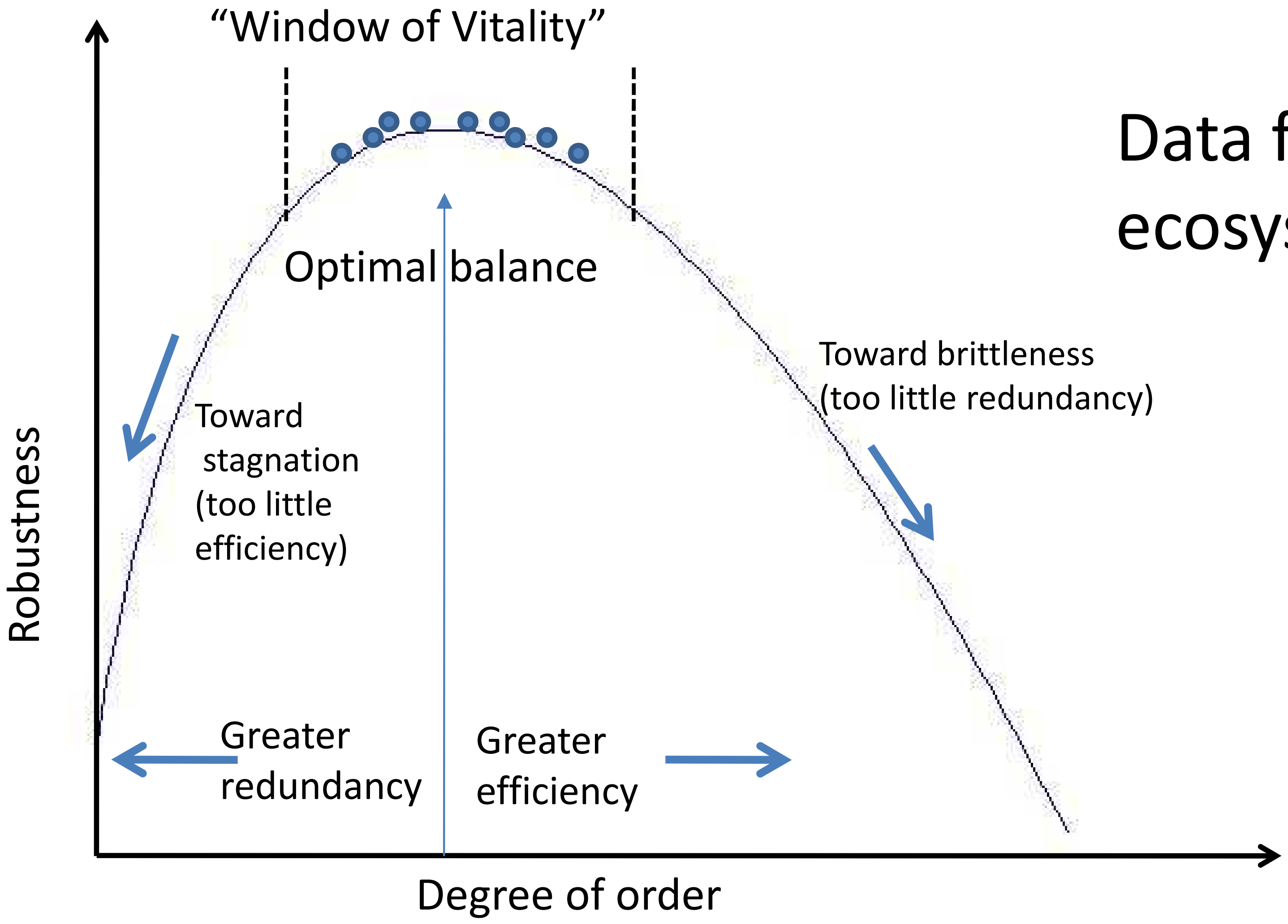


Minimally connected



$$a = \frac{AMI}{AMI + H_c} = \mathbf{1}$$

Robustness combines both efficiency and redundancy



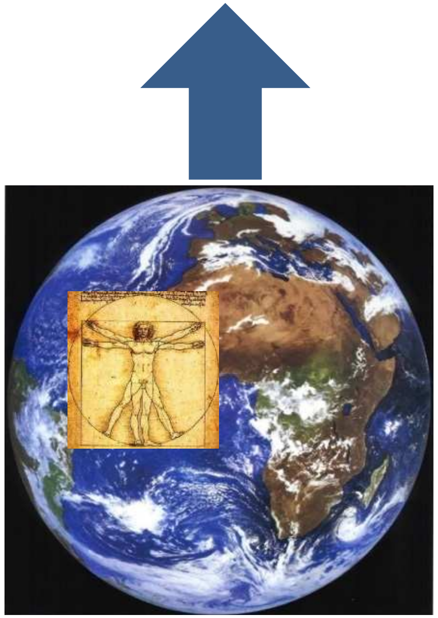
Data from ecosystems

Ulanowicz 2009 A Third Window

L7: A Hyperset Formalism of Life Prohibits Fragmentation of Life from Environment

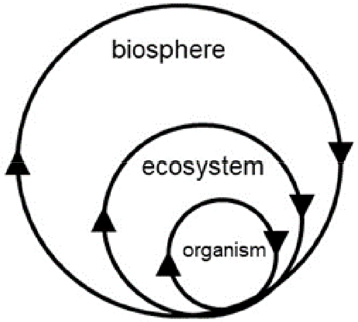
Recursive nature of nature

Bounty of the Commons
Humans win, environment improves



1) A hyperset equation explicitly and formally *prohibits fragmentation of life from environment*

Three holons and Life unit-models



$$\text{life–environment} = \{\text{environment}\{\text{ecosystems}\{\text{organisms}\{\text{environment}\}\}\}\}$$

Fiscus D, Fath BD, Goerner S. 2012. E:CO 14(3), 44–88.

Summary of the six principles

- Network insight and tools can give new understanding and contribute to a new holistic, interconnected, reflective science
- “With an eco-mind, we move from ‘fixing something’ outside ourselves to realigning our relationships within our ecological home.” (Lappe 2011, p. 16)

Discussion questions

- could a plant exist alone with a “very slow working cycle”
- What if all organisms incorporated chloroplast cells? Is it sufficient?

Discussion questions

- How can the hyperset formulation help us think like an ecosystem?
  - Practical implementations of it?