Networks and hypernetworks 4

Hypernetworks

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Hypernetwork = Complex system with interactions represented by an Hypergraph

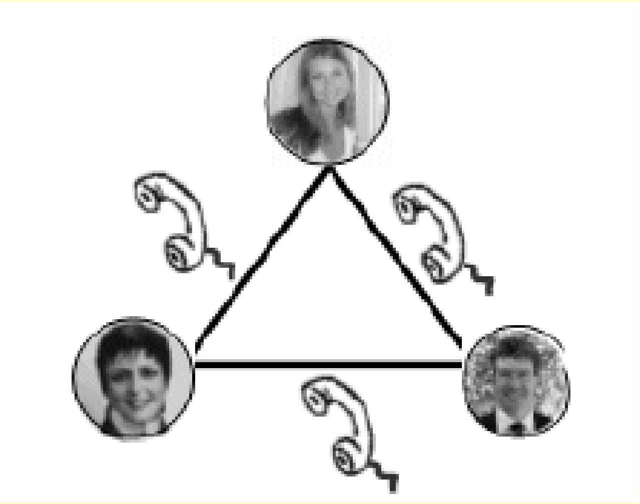
- Graphs, digraphs, competition networks and hypergraphs
- Degree, centrality, k-connection, path-length, clustering, etc.
- Homological notions
- Homology group calculations in hypergraphs
- Conclusion

Graphs, digraphs, competition networks and hypergraphs

- Graph = (V,E) = (Vertices, Edges)
- Digraph = a directed graph
- Graphs and digraphs represent **binary** relations between objects
- In Nature n-ary (n>2) relations are common and binary relations cannot adequately represent the interactions
- Example: 3 binary relations versus a conference call

Graphs, digraphs, competition networks and hypergraphs

- (mother,daughter)+(daughter,father) +(mother,father)
- Very different from (mother,daughter,father)



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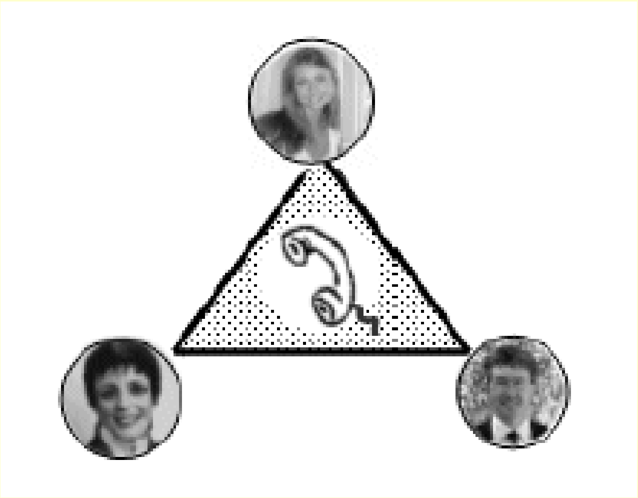
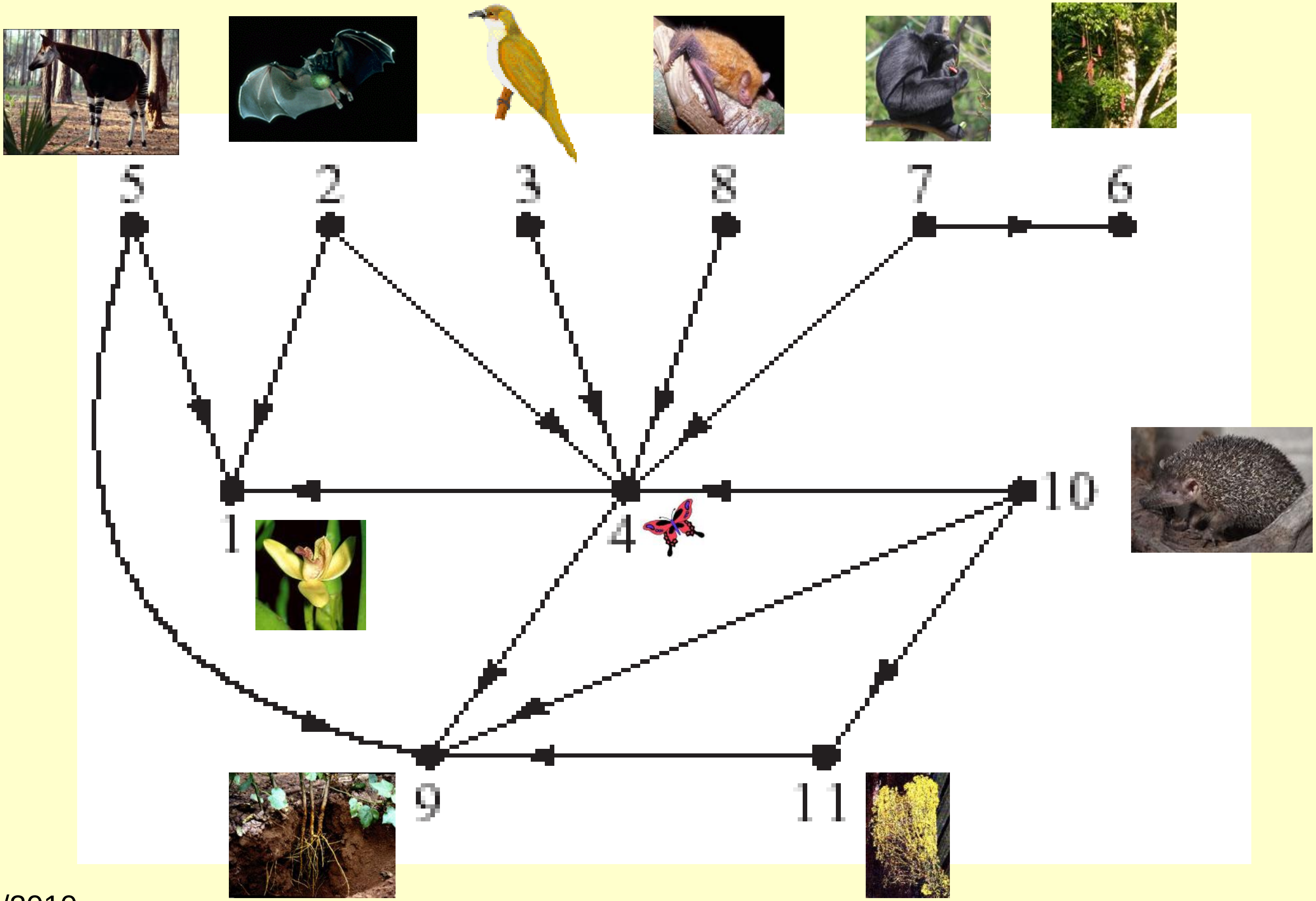


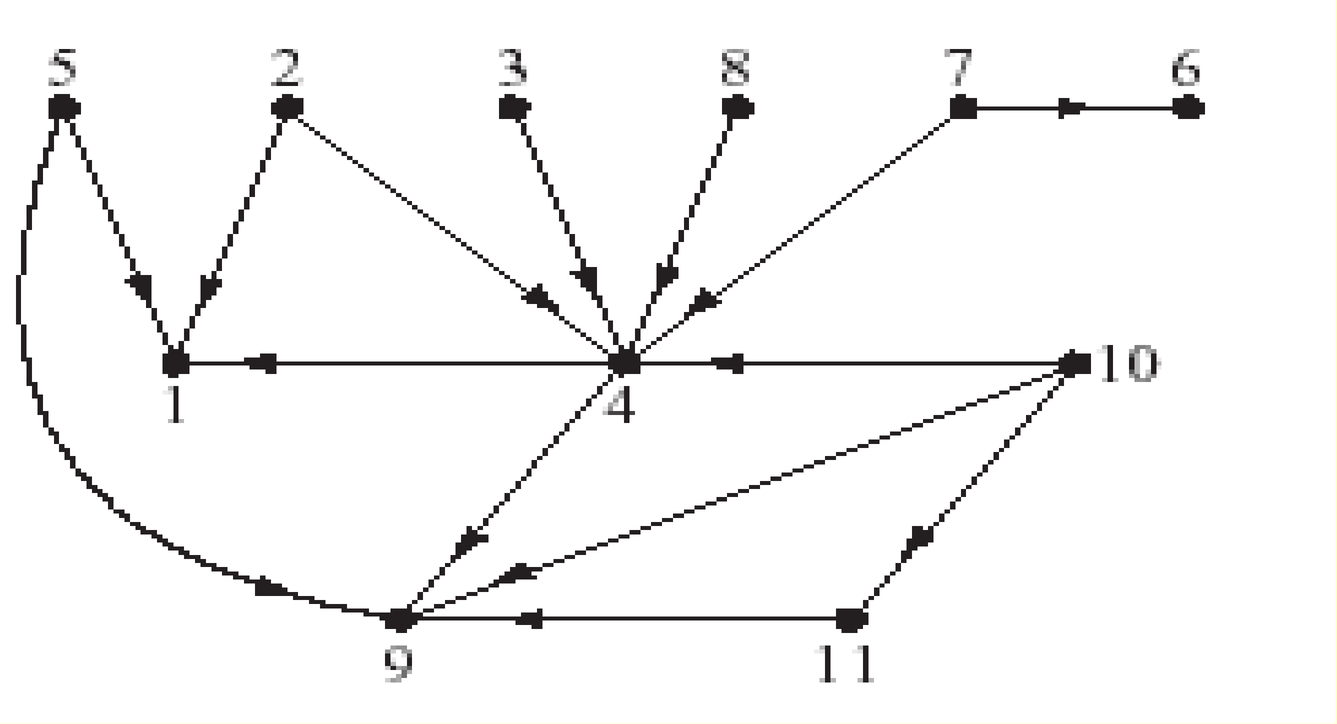
Food webs



Food webs and competition networks

- A food web is a digraph. The example: a food web of the Malaysian rain forest

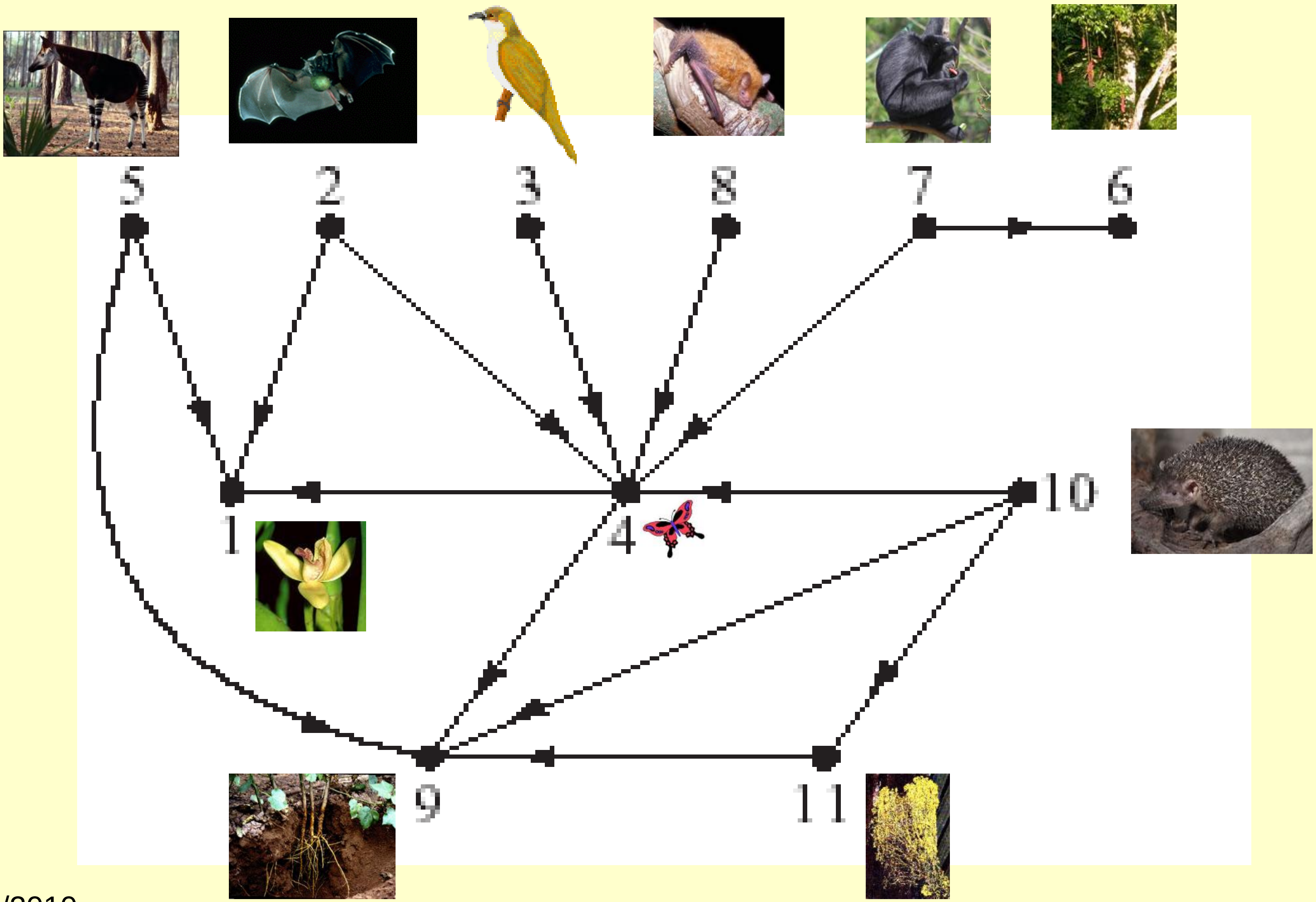
- D1



Food webs and competition networks

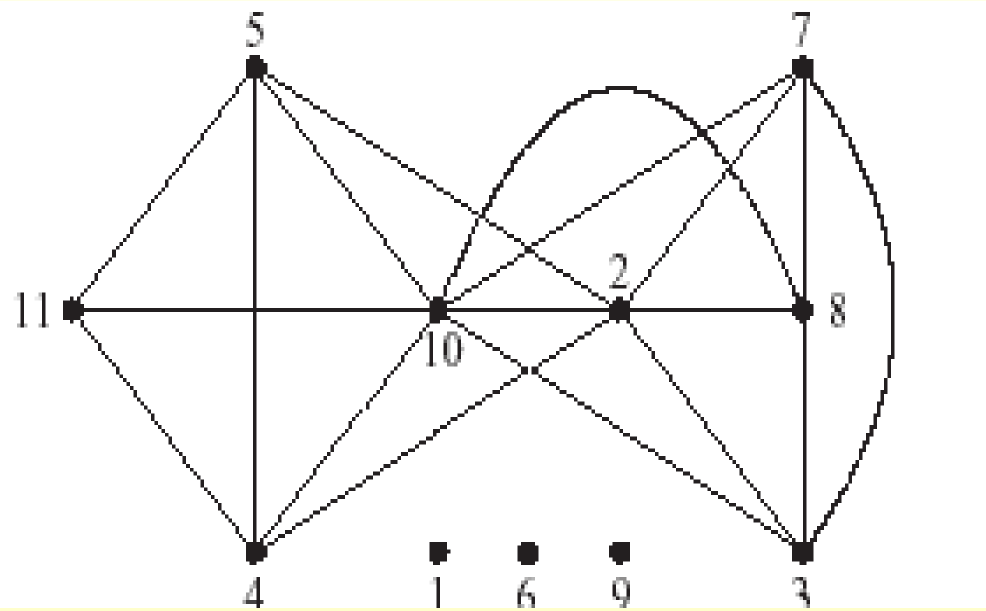
- 1. Canopy – leaves, fruits, flowers
- 2. Canopy animals – birds, fruit-bats …
- 3. Upper air animals – birds, bats (insectivorous)
- 4. Insects
- 5. Large ground animals – mammals, birds
- 6. Trunk, fruit, flowers
- 7. Middle zone animals – mammals in canopy and ground
- 8. Middle zone flying – birds, insectivorous bats
- 9. Ground – roots, fallen fruit, leaves, trunks
- 10. Small ground animals
- 11. Fungi

Food webs and competition networks



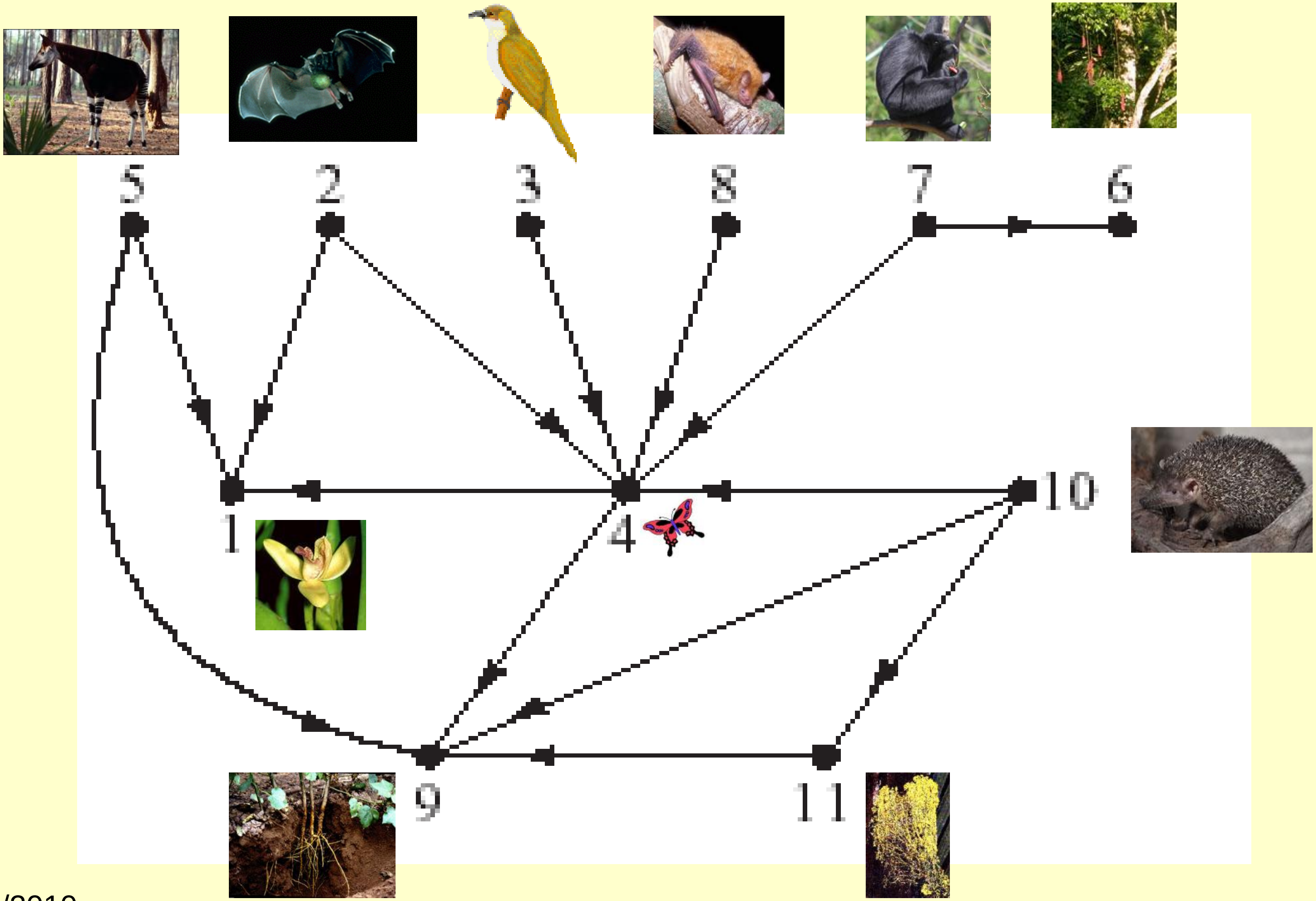
Food webs and competition networks

- The competition network C
- (v,w) in E(C) iff $\exists$ u : (v,u),(w,u) in E(D1)
- C(D1)



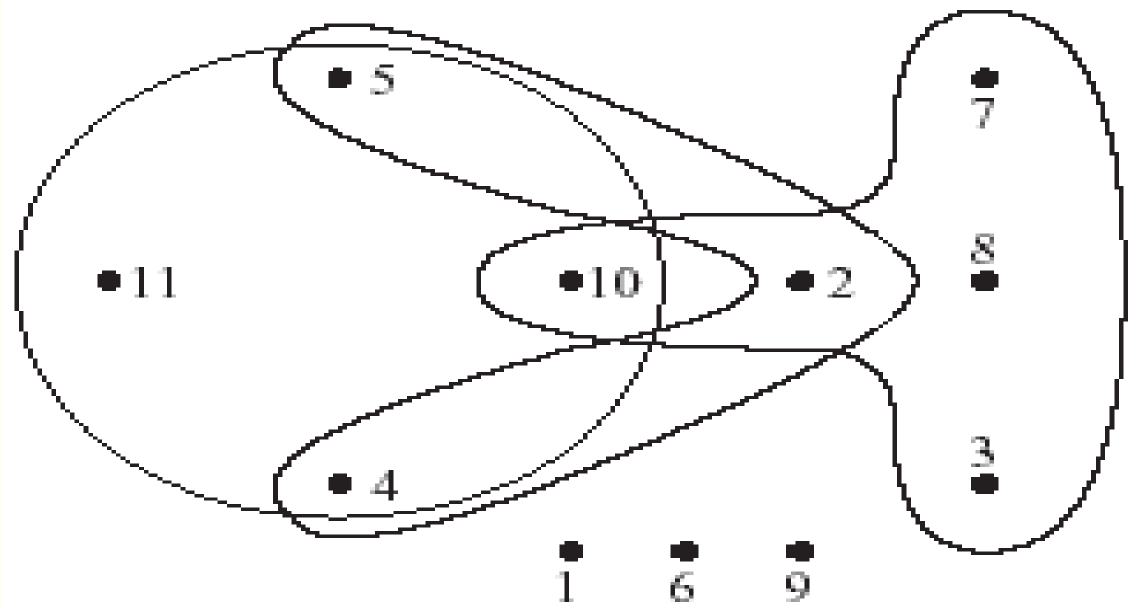
- Competition network=Competition graph=Niche overlap graph

Food webs and hypergraphs



Competition networks as hypergraphs

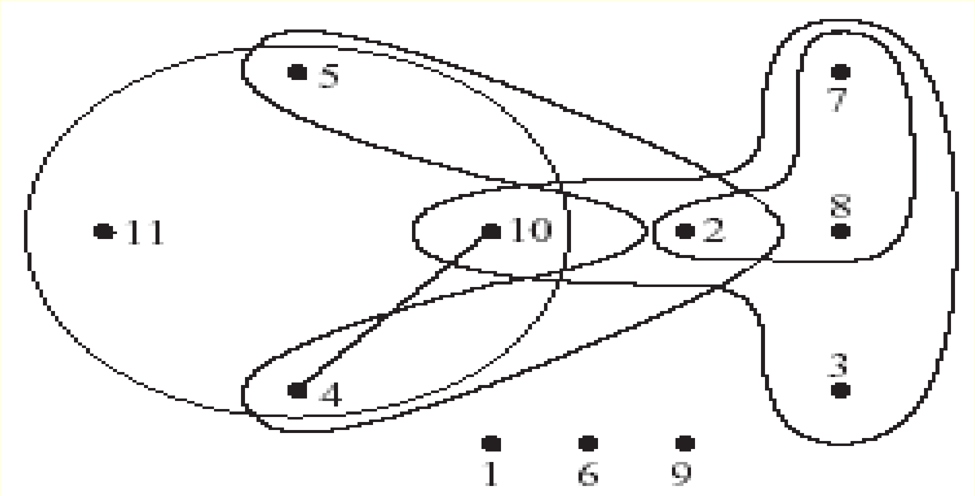
- (Sonntag-Teichert, 2004)
- H(D1)



- Hypergraph (V,E) E (hyper-edges) = family of subsets E_i of V such that $U_i\ E_i = V$

Competition networks as hypergraphs

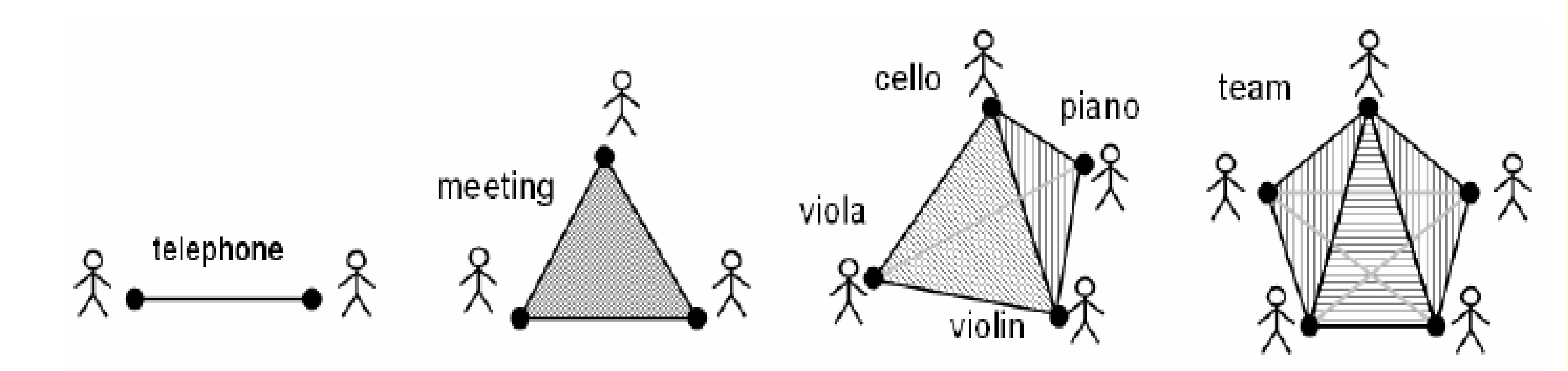
- Hypergraphs may contain more information than competition networks
- D2 = D1 + (2,6) + (8,6) + (4,11)
- The same competition network, but
- H(D2)



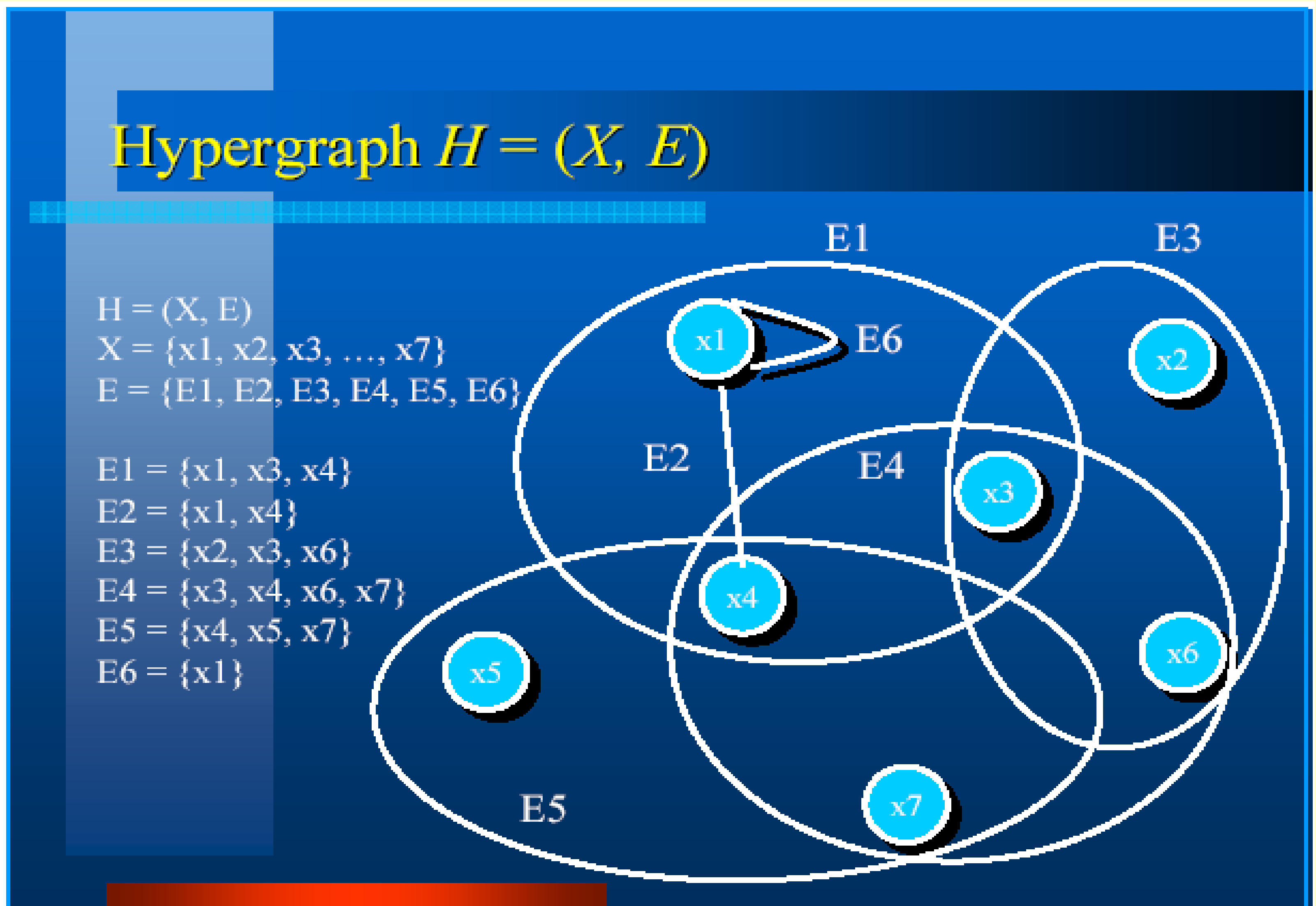
- However H(D2) is not a **simple** hypergraph

Hypergraphs

- Hypergraph (V,E)
- $\{E_i\}$ = hyper-edges
- Edges as simplexes



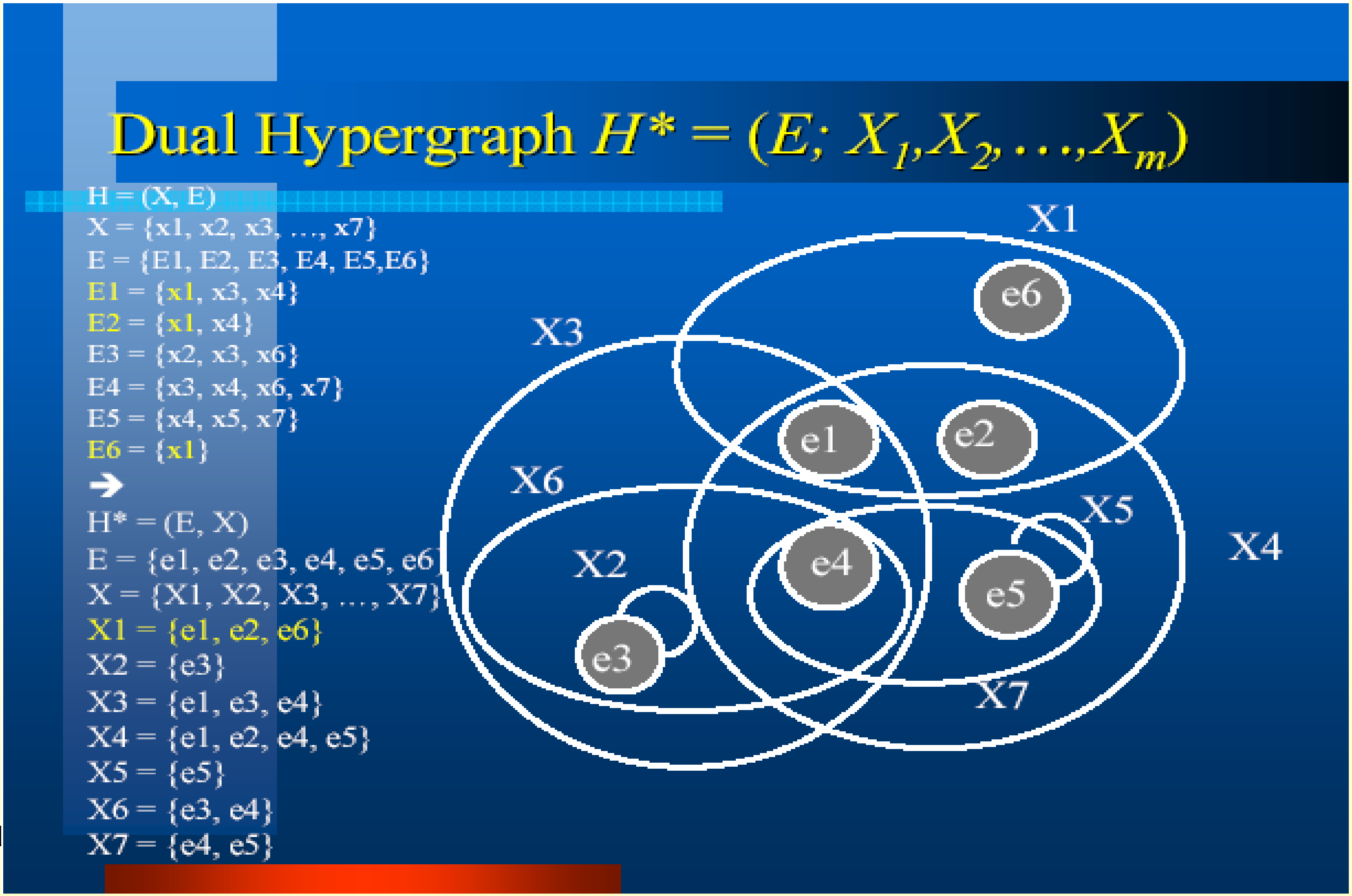
Hypergraphs, dual hypergraphs and incidence matrices



Hypergraphs, dual hypergraphs and incidence matrices

	x_1	x_2	x_3	x_4	x_5	x_6	x_7
E_1	1		1	1			
E_2	1			1			
E_3		1	1			1	
E_4			1	1		1	1
E_5				1	1		1
E_6	1						

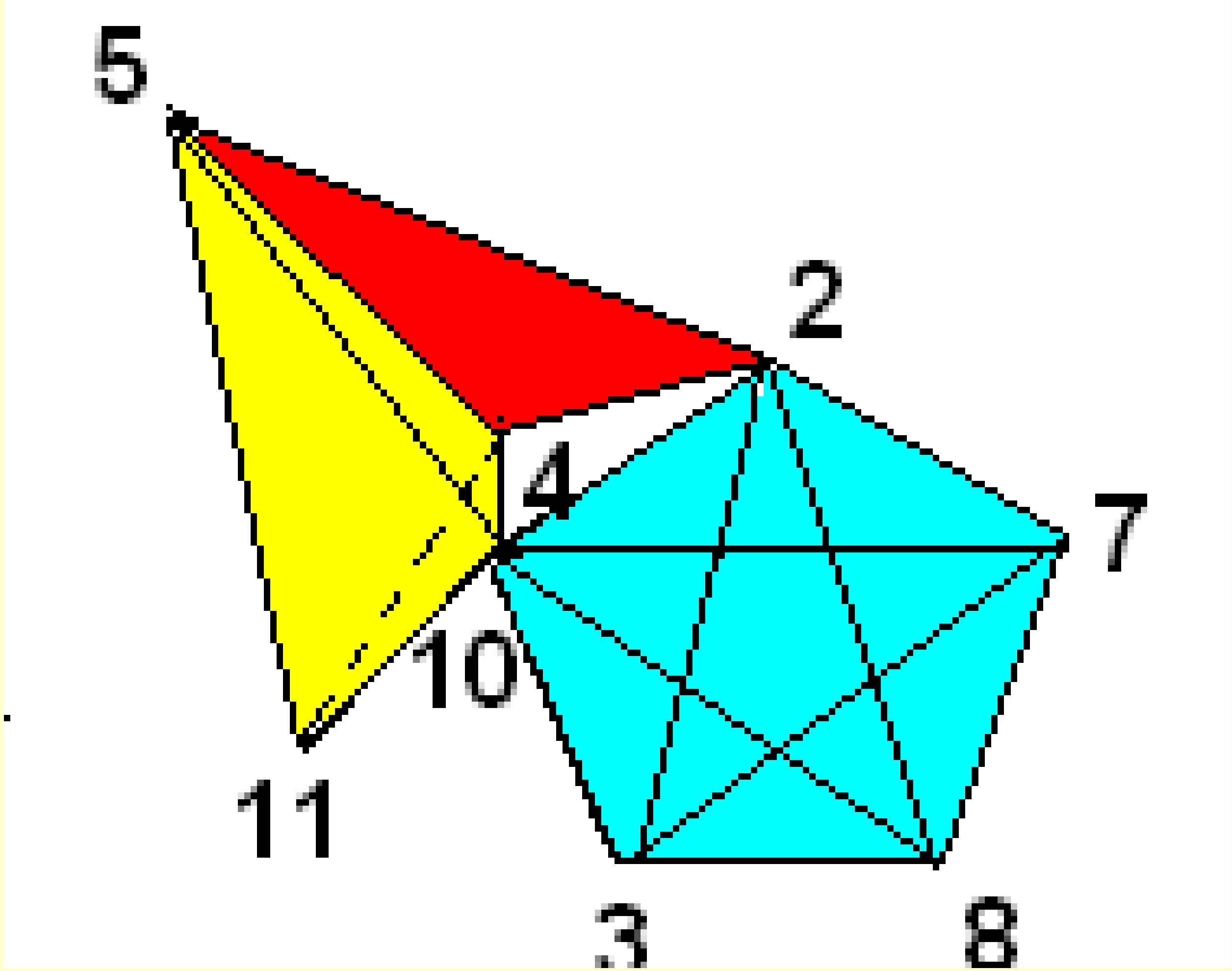
Hypergraphs, dual hypergraphs and incidence matrices



Hypergraphs, dual hypergraphs and incidence matrices

	e_1	e_2	e_3	e_4	e_5	e_6
X_1	1	1				1
X_2			1			
X_3	1		1	1		
X_4	1	1		1	1	
X_5					1	
X_6			1	1		
X_7				1	1	

The food web hypergraph as a simplicial complex



Topological parameters for hypergraphs

- **Degree** (D) of a vertex = no. of hyper-edges it belongs to
- **Adjacency matrix** (A(H)) (a_{ij} = no. of hyper-edges that contain both vertices i and j)
- $A(H) = E\,E^T - D$ (E = **incidence** matrix)
- **Associated graph of H** = graph with multiple links and the same A
- **Walks** $(v_1, v_2, \ldots, v_n)$**, paths** and **cycles**
- The no. of walks of length k is the (i,j) entry of A^k
- **Centrality** of a vertex i, $C(i)=\sum_k (A^k_{ii})/k!$
- **Centrality of the hypergraph** $C(H)=(\sum_i C(i))/N$

Topological parameters for hypergraphs

- **Transitivity: In graphs**

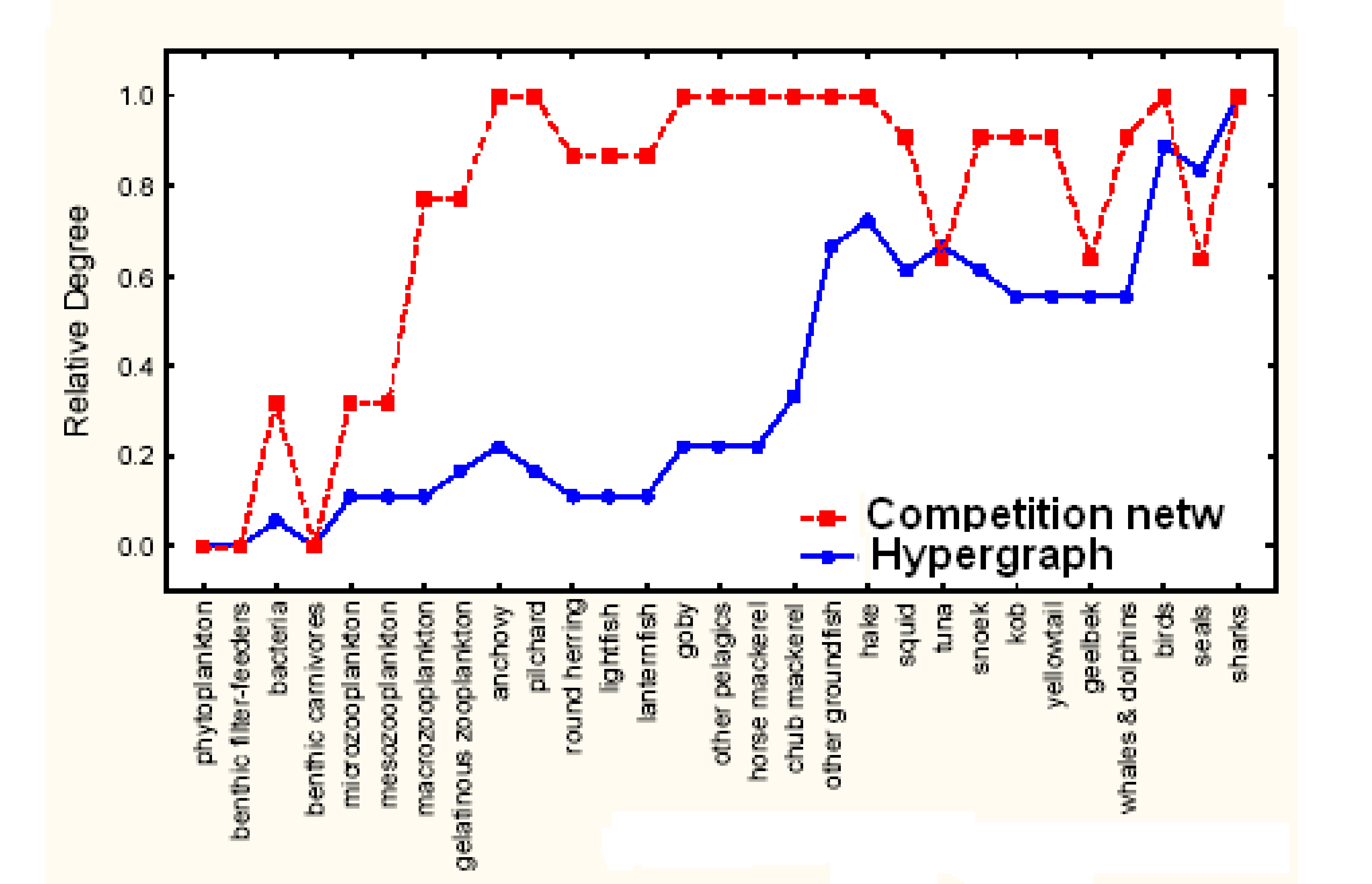
$$C(G) = \frac{6 \times number\ of\ triangles}{number\ of\ 2-paths}$$

- **In hypergraphs**

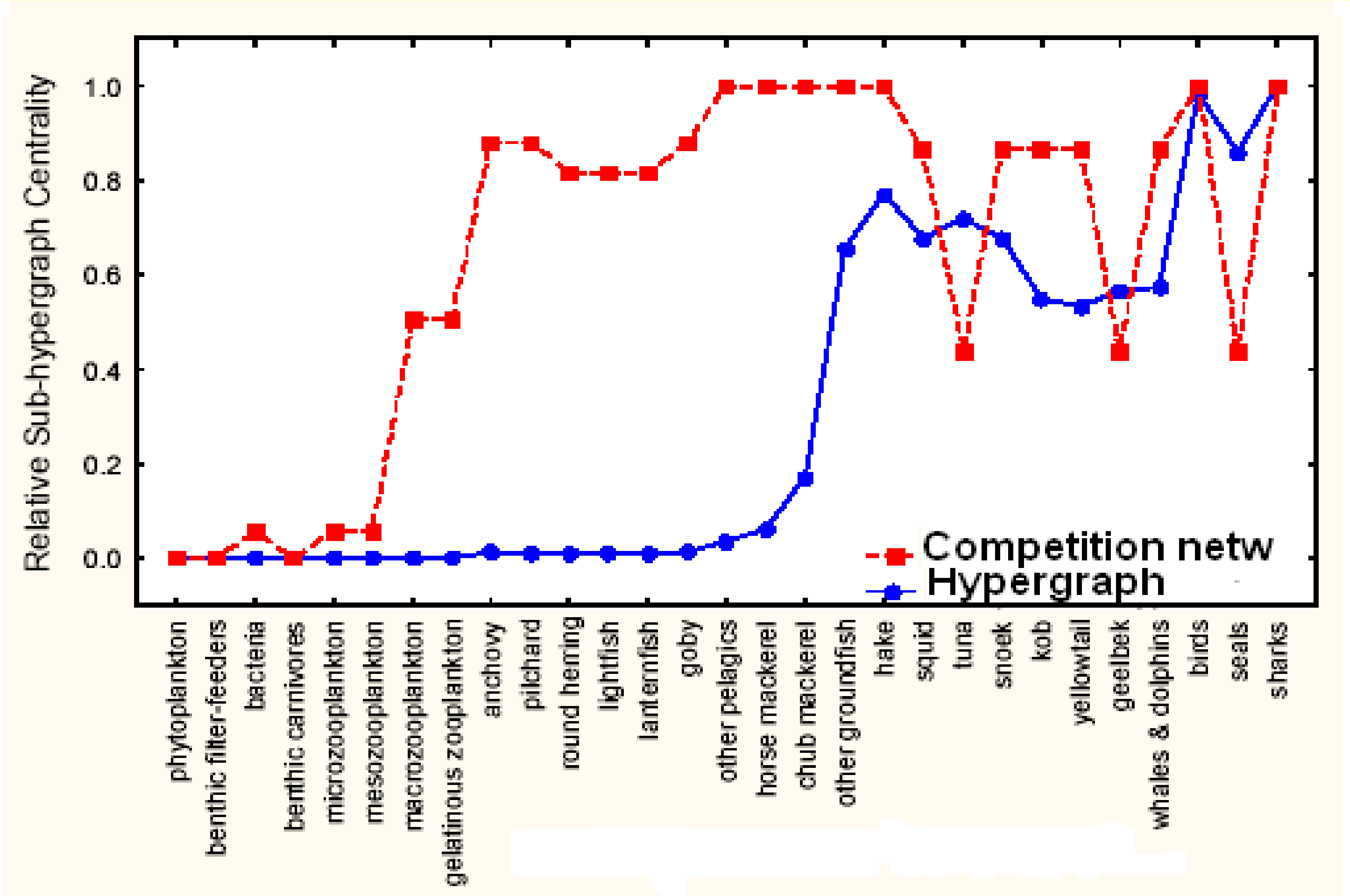
$$C(G) = \frac{6 \times number\ of\ hypertriangles}{number\ of\ 2-paths}$$

- **Hypertriangle = (v_i, E_p, v_j, E_q, v_k, E_r, v_i)**
- **2–path = (v_i, E_p, v_j, E_q, v_k)**

Competition network versus hypergraph for a marine food web



Competition network versus hypergraph for a marine food web



Competition network versus hypergraph for a marine food web

- Interpretation:
- In the competition network there are 10 species (anchovy, mackerel, sharks, birds, …) with degree 22, meaning that they compete for prey with 22 other species.
- However this does not tells us much about the competition groups each species participates in. It becomes clearer in the hypergraph parameters.
- Sharks in 18, birds in 16, whereas mackerel only in 4

Topological parameters for hypergraphs

- Two hyper-edges are *k–connected* if they share k vertices
- Construct a graph (hyper-edge graph) where the nodes are the hyper-edges and the links are weighed by the k-connections
- The weighted path length L_{ij}

Topological parameters for hypergraphs

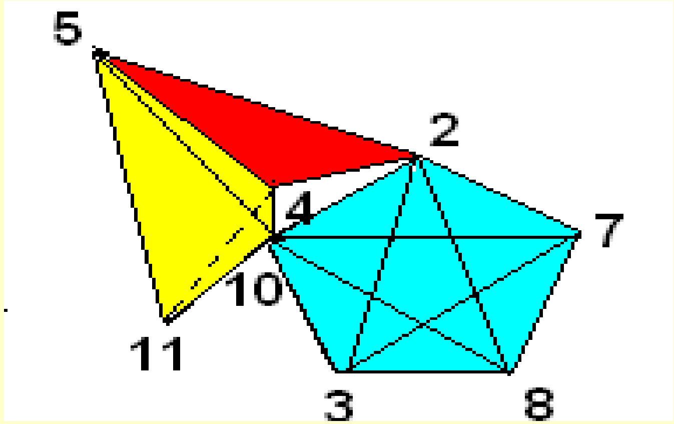
- Many other parameters:

- Metric
  Radius, diameter, eccentricity, unipolarity, centralization, dispersion, compactness
- Topological
  Wiener index, polarity, adjacency
- Informational
  Informational Wiener, autometricity

Topological parameters for hypergraphs

- **Homology approach:**
  1. Consider a (simple) hypergraph as the triangulation of an underlying manifold

  2. Use the tools of algebraic topology to characterize the structure of the hypergraph
- **Recall**



Homological notions

- n-dimensional oriented simplicial complex K = set of oriented simplexes up to dim. n
  $\sigma^p=[v_1, \ldots , v_{1p}]\,(-1)^P$
- $C_p(K)$ = p-chains of K = Free abelian group generated by the oriented p-simplexes of K
  $c_p = \sum_i f_i \sigma_i^p$ $\quad f_i$ in **Z**
- Boundary operator $\partial_p : C_p(K) \to C_{p-1}(K)$

$$\partial\left[v_0, \cdots, v_p\right] = \sum_{j=0}^{p} (-1)^j \left[v_0, \cdots, \hat{v}_j, \cdots, v_p \right]$$

- $\partial\partial = 0$

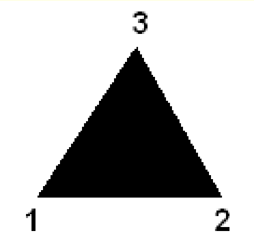
Homological notions

- p-cycle group $z_p \in Z_p(K): \quad \partial z_p = 0$
- p-boundary group
  $$b_p \in B_p(K): \quad \exists c_{p+1} \in C_{p+1}(K) \quad b_p = \partial c_{p+1}$$
- p-homology group $$H_p(K) = \frac{Z_p(K)}{B_p(K)}$$

- $H_p(K)$ is sensitive to the number of (p+1)-dimensional holes in the manifold
- If K is contractible $$H_p(K) = \begin{cases} \{0\} & p \neq 0 \\ Z & p = 0 \end{cases}$$
- $H_p(K) = G_p \oplus T_p$
  G_p = Z + Z+ ….. The rank of G_p is the number of p+1 dimensional holes (Betti number, β_p)
  T_p = Z_{i1}+Z_{i2}+ …. (the torsion group)

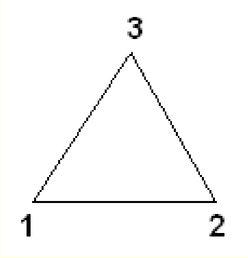
Homological notions

- A simple example: Three binary interactions versus a conference call



- {1,2,3}+ {1,2} + {2,3} + {3,1}+{1} + {2} + {3}
  $Z_0=Z^3$
  ∂ (a{1,2}+b {2,3}+c {3,1})=(c-a){1}+(a-b){2} +(b-c){3}
  $B_0=Z^2$ $\rightarrow$ $H_0=Z$
- ∂ (a{1,2}+b {2,3}+c {3,1})=0 $\rightarrow$ a=b=c $\rightarrow$ $Z_1=Z$
  ∂ {1,2,3}= {2,3} – {1,3} + {1,2} $\rightarrow$ $B_1=Z$
  $H_1=\{0\}$
- $Z_2=\{0\}$, $B_2=\{0\}$ $\rightarrow$ $H_2=\{0\}$

Homological notions

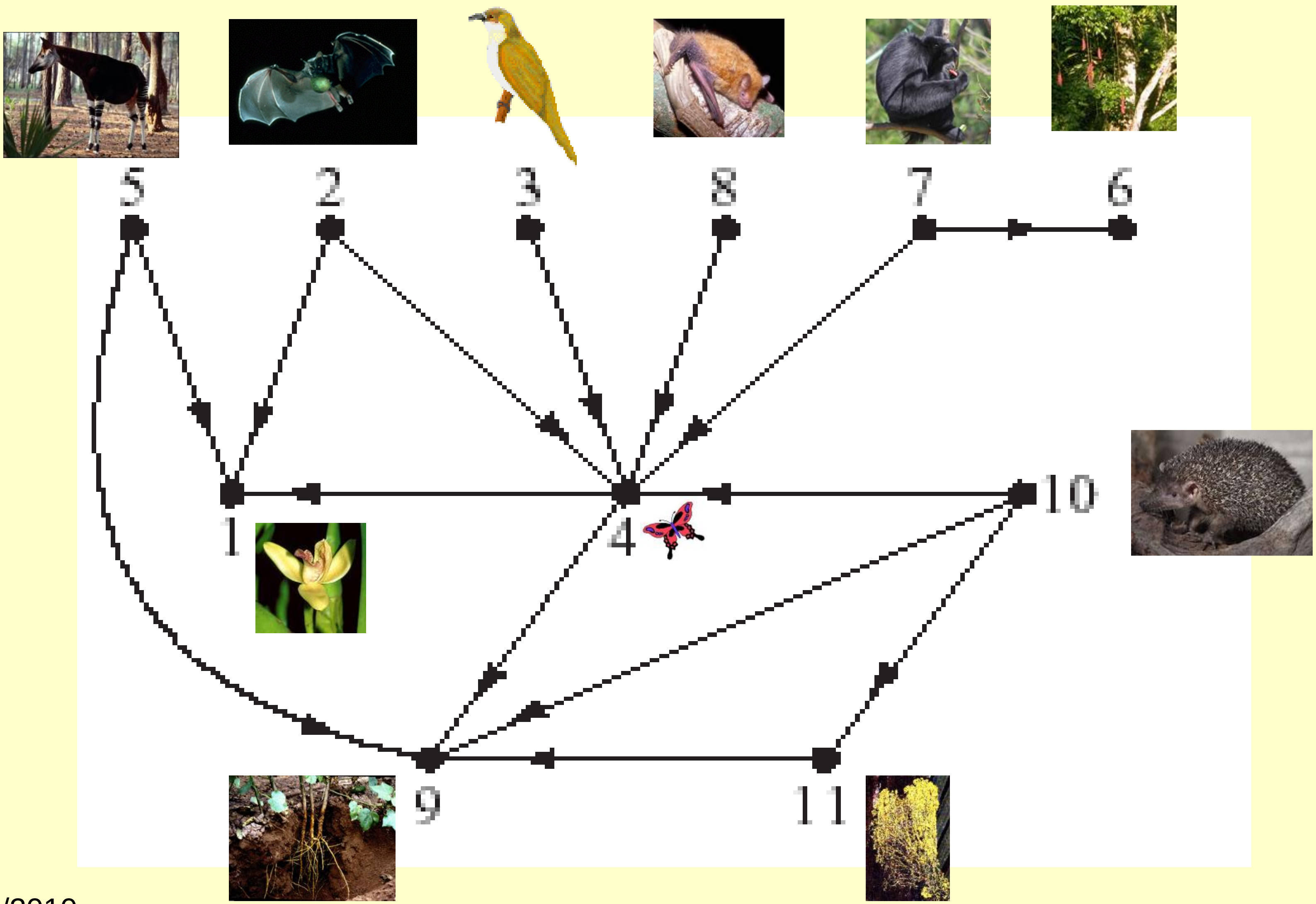


- $\{1,2\} + \{2,3\} + \{3,1\}+\{1\} + \{2\} + \{3\}$
  $Z_0=Z^3$
  $\partial\,(a\{1,2\}+b\,\{2,3\}+c\,\{3,1\})=(c-a)\{1\}+(a-b)\{2\} +(b-c)\{3\}$
  $B_0=Z^2 \quad \rightarrow \quad H_0=Z$
- $\partial\,(a\{1,2\}+b\,\{2,3\}+c\,\{3,1\})=0 \rightarrow a=b=c \rightarrow \quad Z_1=Z$
  $B_1=\{0\} \quad H_1=Z$
- $Z_2=\{0\}$, $B_2=\{0\} \quad \rightarrow \quad H_2=\{0\}$

Homological notions

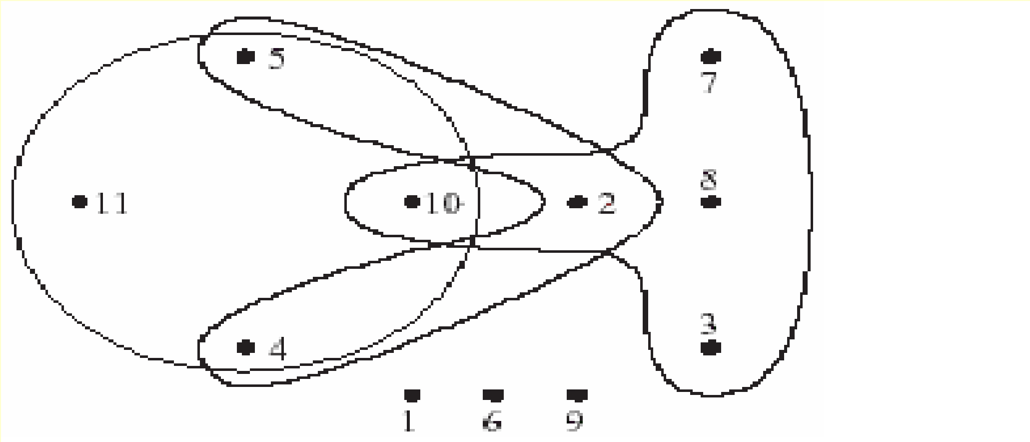
- Direct manual calculation of the homology groups is a hard job. Fortunately:
- PLEX (Calculations of Betti numbers) http://comptop.stanford.edu/programs/
- CHomP (Calculation of Betti numbers, homology groups and generators) http://chomp.rutgers.edu/
- GAP http://www.linalg.org/gap.html

The rain forest food web

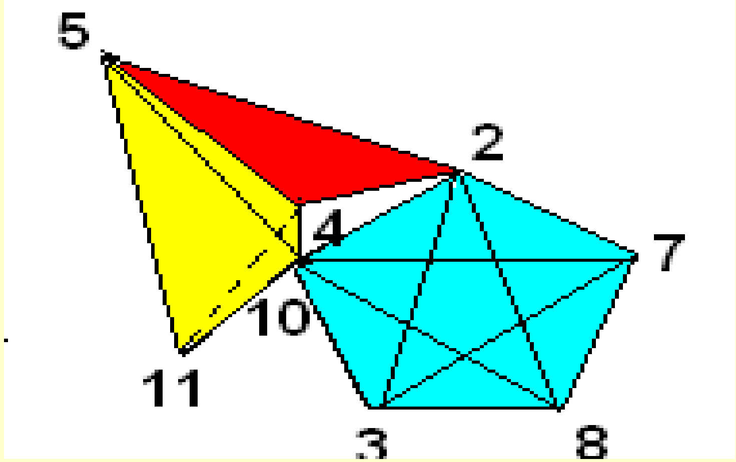


Homological notions

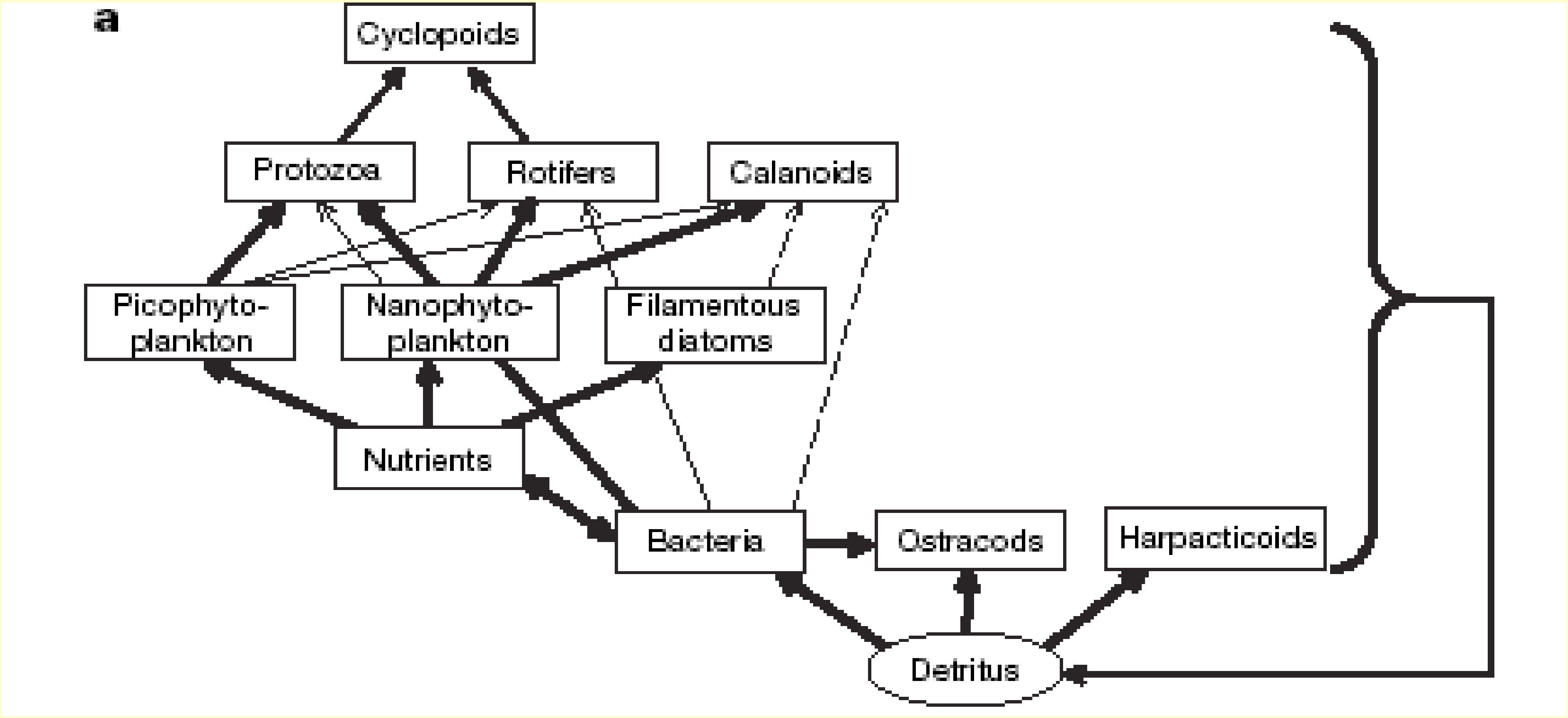
- The rain forest food web
  {2,3,7,8,10}
  {4,5,10,11}
  {2,4,5}
  {1}
  {6}
  {9}



- $H_0 = Z^4$
  Generators = {1} , {6} , {8} , {9}
- $H_1 = Z$
  Generator =
  {10,8}+{2,5}+{8,2}+{5,10}
- $H_p = 0 \quad p \geq 2$



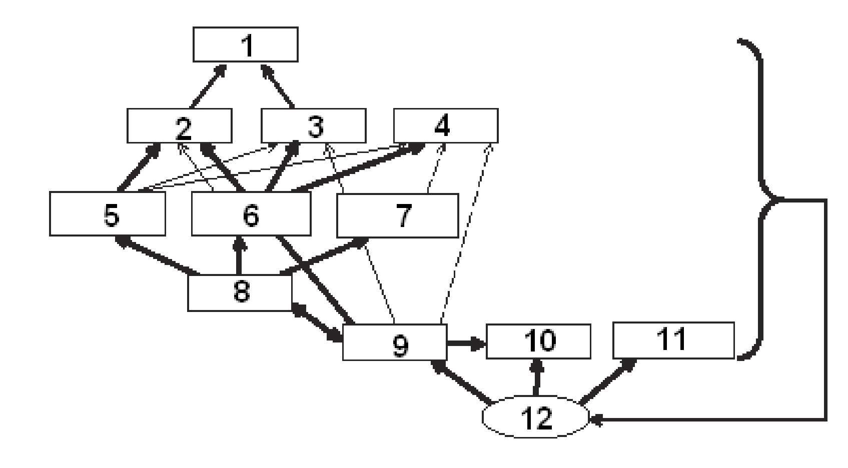
Food web of a plankton community
(Nature 451 (2008) 822-825)



- (For the arrows the opposite convention is used here)

Homological notions

- The plankton food web
  {2,3,4,8,10,12}
  {5,6,7,9,12}
  {2,3,4,12}
  {9,10,11}
  {3,4,12}
  {1}

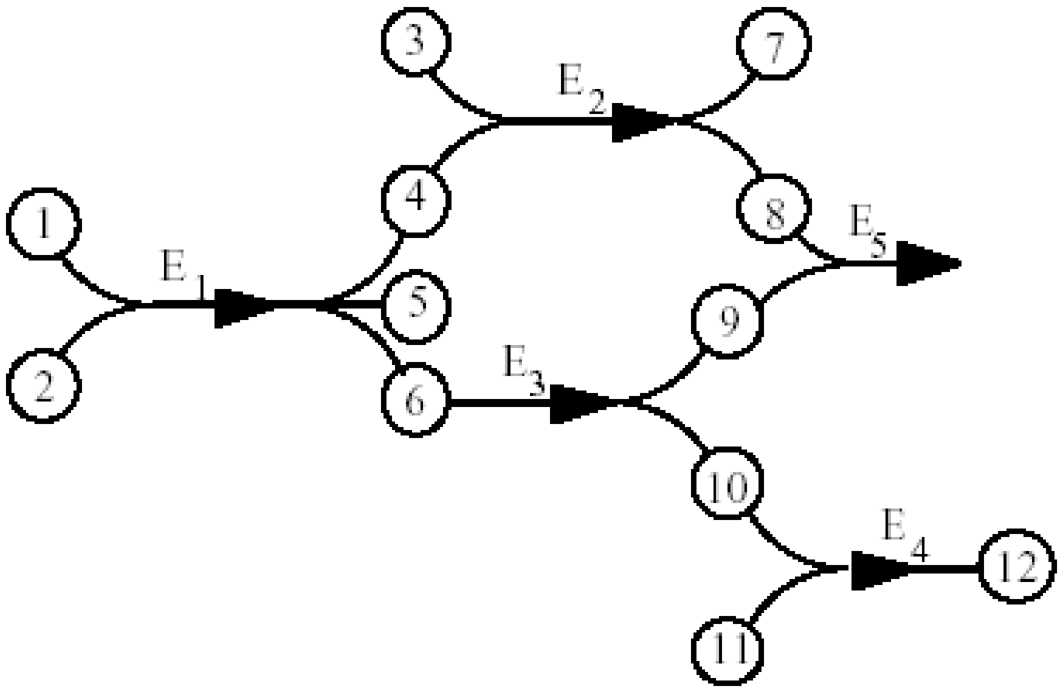


- $H_0 = Z^2$
  Generators = {1} , {9}
- $H_1 = Z$
  Generator = {6,5}+{5,9}+{9,10}+{10,12}+{12,6}
- $H_p = 0$ $p \geq 2$

Homological notions

- Projective plane
  {1,4,5}
  {1,2,5}
  {1,2,6}
  {1,3,6}
  {5,2,3}
  {3,2,4}
  {2,4,6}
  {4,5,6}
  {3,5,6}
  {1,3,4}
- $H_0 = Z$
  Generator = {3}
- $H_1 = Z_2$
  Generator = {3,5}+{5,6}+{6,4}+{4,3}
- $H_p = 0$ $p \geq 2$

Also directed hypergraphs



	E_1	E_2	E_3	E_4	E_5
1	-1	0	0	0	0
2	-1	0	0	0	0
3	0	-1	0	0	0
4	1	-1	0	0	0
5	1	0	0	0	0
6	1	0	-1	0	0
7	0	1	0	0	0
8	0	1	0	0	-1
9	0	0	1	0	-1
10	0	0	1	-1	0
11	0	0	0	-1	0
12	0	0	0	1	0

- A one-to-one correspondence between directed hypergraphs and (-1,0,1) matrices

Some real world applications of hypernetworks

- Food webs
- Collaboration networks
  (Estrada, Velazquez, arXiv:physics/0505137)
  different ranking for authors in networks and hypernetworks
- Linguistics
  (Zhang, Park, Proc. W. Acad. Sci. Eng. Tech. 27 (2008) 134)
- Economics: breeding environment, virtual entreprises
  (Volpentesta, Eur. J. Op. Res. 188 (2008) 390)

Some real world applications of hypernetworks

- Proteomics (Ramadan, Tarafdar, Pothen, Proc. IEEE Workshop High Perfor. Comp. Bio. 2004)
- Chemistry of molecules with polycentric bonds (Konstantinova, Skorobogatov, Discr. Math. 235 (2001) 365)