EEC S6413: Information Networks

Thanks to Jure Leskovec, Stanford and Panayiotis Tsaparas, Univ. of Ioannina for slides

Agenda

- Characterizing/Measuring Networks
  - Network Properties
- Case Study: A Real World Network (MSN)

Network Properties: Characterizing/ Measuring Networks

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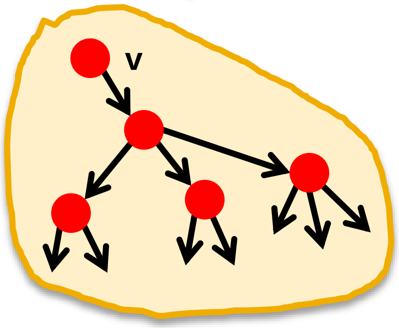
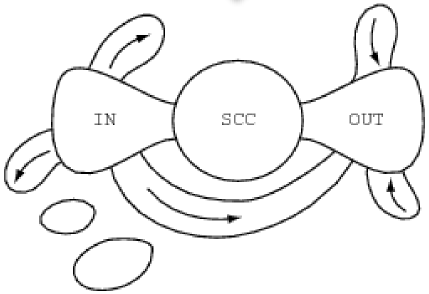
Structure of Networks

- **For example, last time we talked about Observations and Models for the Web graph:**
  - **1)** We took a real system: **the Web**
  - **2)** We represented it as a **directed graph**
  - **3)** We used the language of graph theory
    - **Strongly Connected Components**
  - **4)** We designed a **computational experiment:**
    - Find In- and Out-components of a given node v
  - **5) We learned something about the structure of the Web: BOWTIE!**



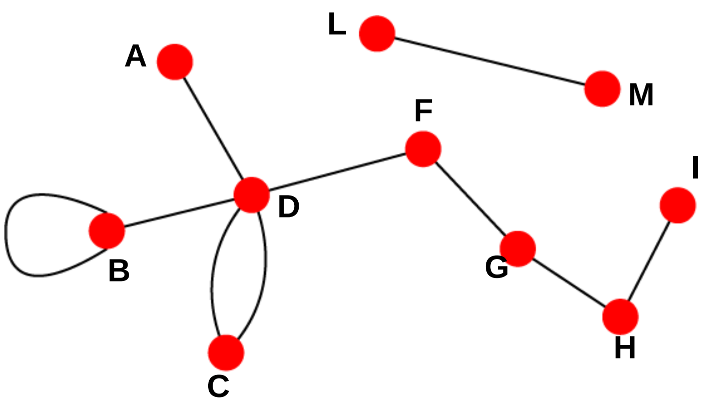
Out(v)



Undirected vs. Directed Networks

Undirected graphs

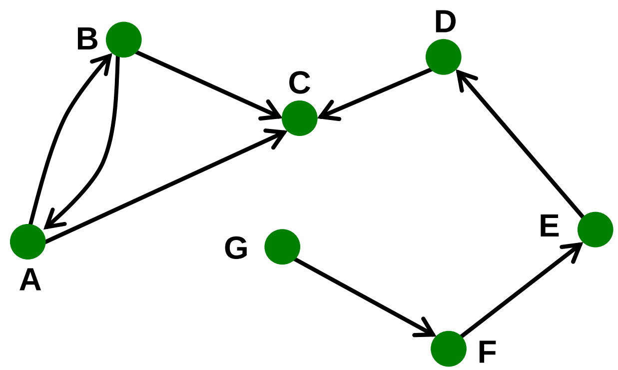
- **Links:** undirected (symmetrical, reciprocal relations)



- Undirected links:
  - Collaborations
  - Friendship on Facebook

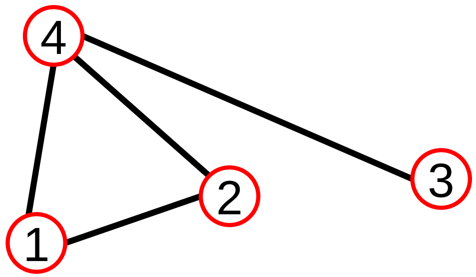
Directed graphs

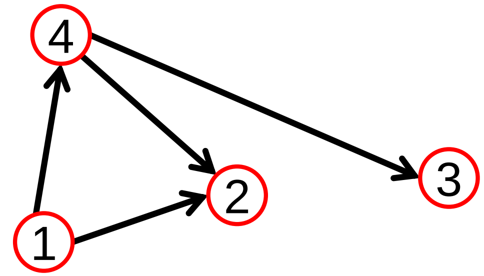
- **Links:** directed (asymmetrical relations)



- Directed links:
  - Phone calls
  - Following on Twitter

Adjacency Matrix





$A_{ij} = 1$ if there is a link from node ***i*** to node ***j***

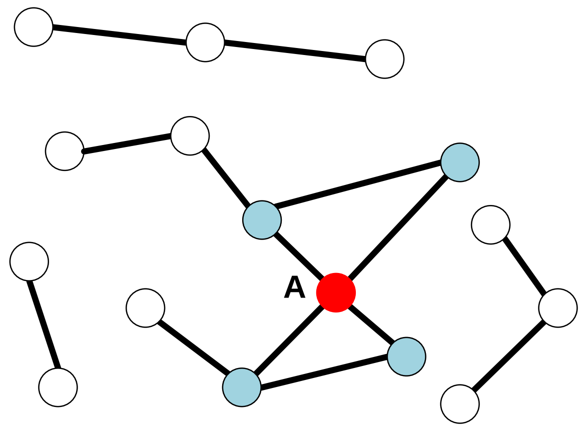
$A_{ij} = 0$ otherwise

$$A = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \qquad A = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

Note that for a directed graph (right) the matrix is not symmetric.

Node Degrees

Undirected

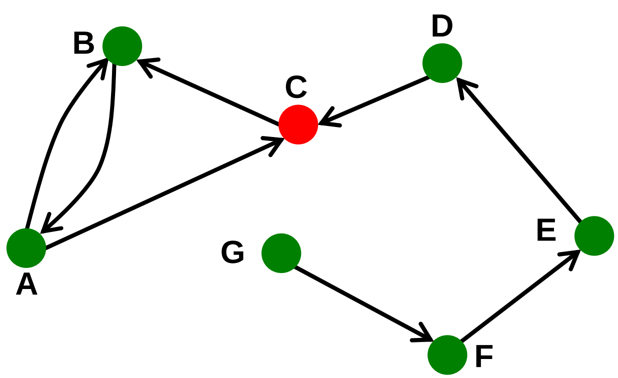


Node degree, k_i: the number of edges adjacent to node ***i***

$$k_A = 4$$

Avg. degree: $\bar{k} = \langle k \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i = \frac{2E}{N}$

Directed



In directed networks we define an **in-degree** and **out-degree.**

The (total) degree of a node is the sum of in- and out-degrees.

$$k_C^{in} = 2 \qquad k_C^{out} = 1 \qquad k_C = 3$$

$$\bar{k} = \frac{E}{N} \qquad \overline{k^{in}} = \overline{k^{out}}$$

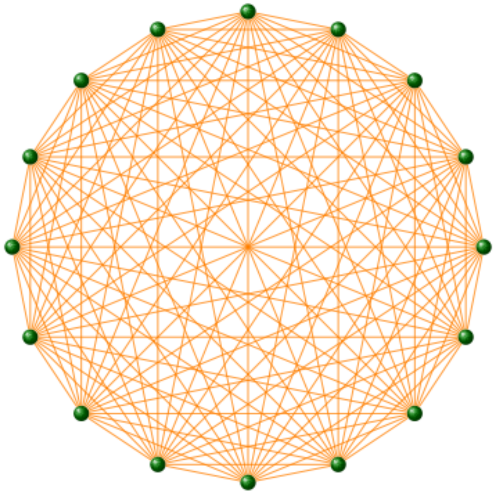
Source: Node with $k^{in} = 0$

Sink: Node with $k^{out} = 0$

Complete Graph

The **maximum number of edges** in an undirected graph on N nodes is

$$E_{\max} = \binom{N}{2} = \frac{N(N-1)}{2}$$



An undirected graph with the number of edges $E = E_{max}$ is called a **complete graph**, and its average degree is $N\text{-}1$

Networks are Sparse Graphs

Most real-world networks are sparse

$$E \ll E_{max} \quad (\text{or } \bar{k} \ll N-1)$$

WWW (Stanford-Berkeley):	N=319,717	$\langle k \rangle$=9.65
Social networks (LinkedIn):	N=6,946,668	$\langle k \rangle$=8.87
Communication (MSN IM):	N=242,720,596	$\langle k \rangle$=11.1
Coauthorships (DBLP):	N=317,080	$\langle k \rangle$=6.62
Internet (AS-Skitter):	N=1,719,037	$\langle k \rangle$=14.91
Roads (California):	N=1,957,027	$\langle k \rangle$=2.82
Proteins (S. Cerevisiae):	N=1,870	$\langle k \rangle$=2.39

(Source: *Leskovec et al., Internet Mathematics, 2009*)

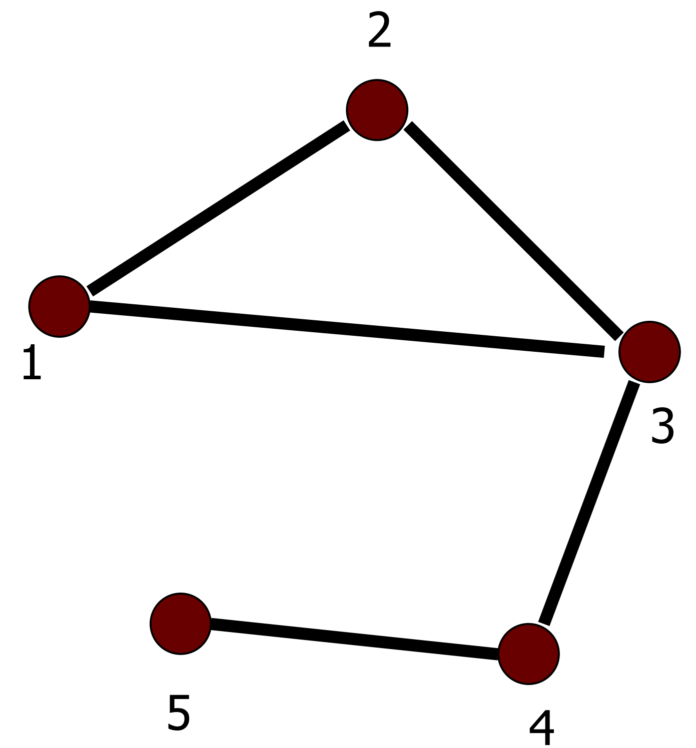
Consequence: Adjacency matrix is filled with zeros!

(**Density of the matrix (E/N^2):** WWW=1.51×10^{-5}, MSN IM = 2.27×10^{-8})

Graph Representation

- Adjacency Matrix
  - symmetric matrix for undirected graphs

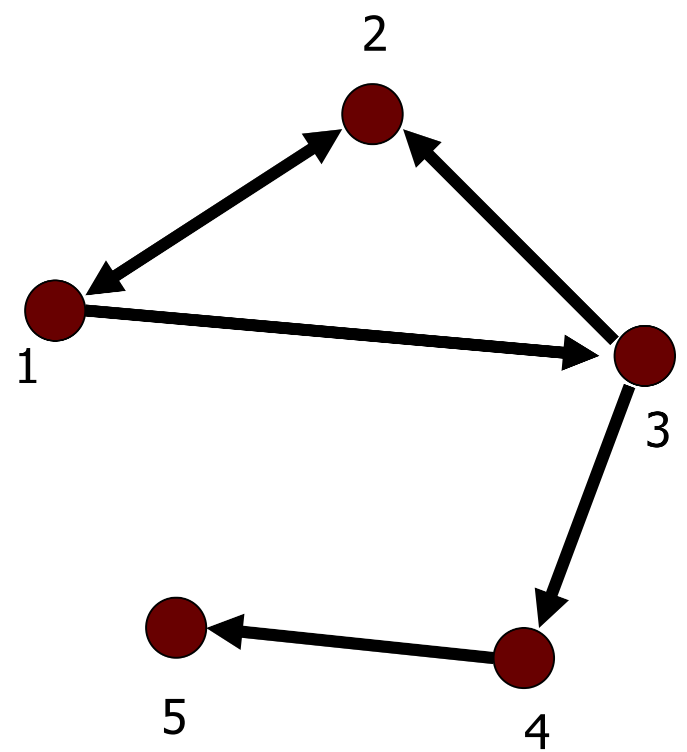
$$A = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$



Graph Representation

- Adjacency Matrix
  - unsymmetric matrix for undirected graphs

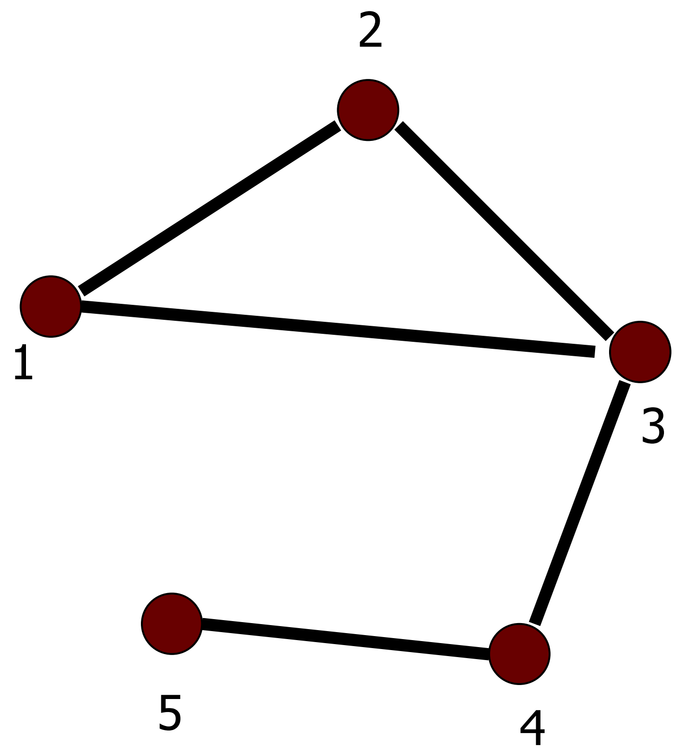
$$A = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$



Graph Representation

- Adjacency List
  - For each node keep a list with neighboring nodes

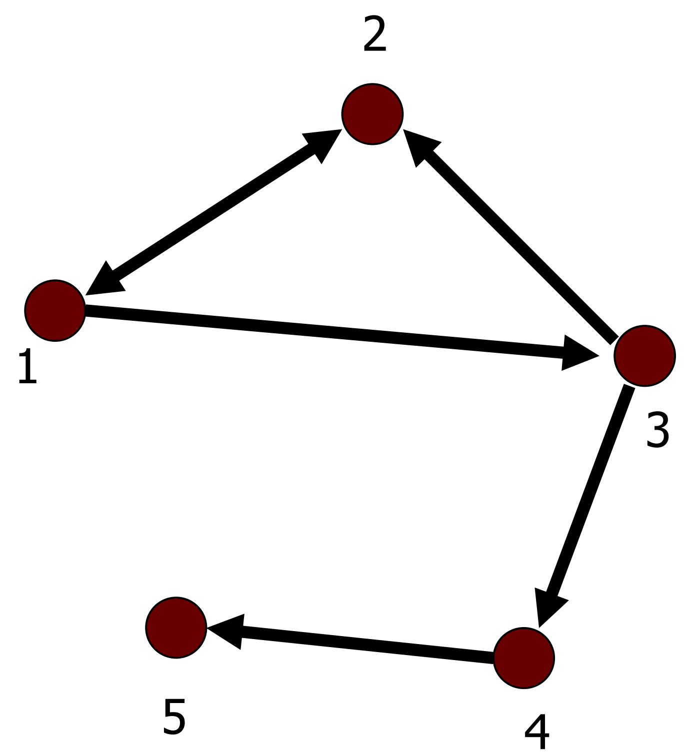
1: [2, 3]
2: [1, 3]
3: [1, 2, 4]
4: [3, 5]
5: [4]



Graph Representation

- Adjacency List
  - For each node keep a list of the nodes it points to

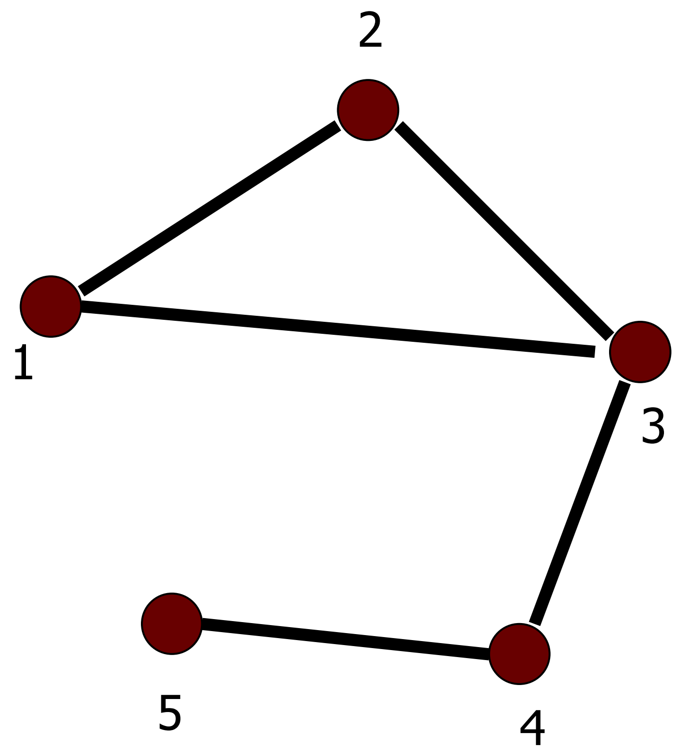
1: [2, 3]
2: [1]
3: [2, 4]
4: [5]
5: [null]



Graph Representation

- List of edges
  - Keep a list of all the edges in the graph

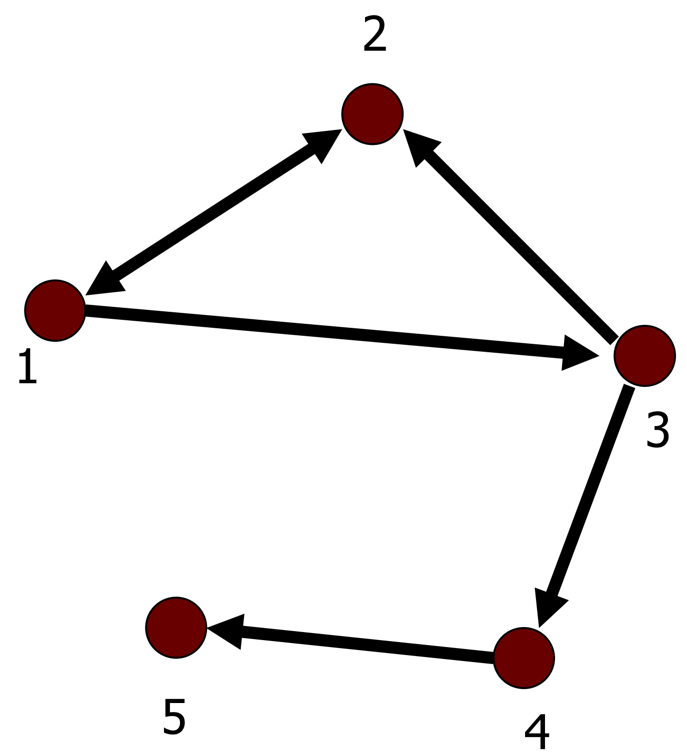
(1,2)
(2,3)
(1,3)
(3,4)
(4,5)



Graph Representation

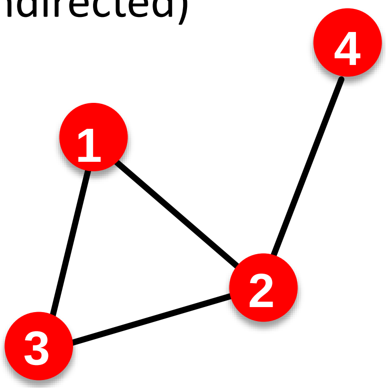
- List of edges
  - Keep a list of all the directed edges in the graph

(1,2)
(2,1)
(1,3)
(3,2)
(3,4)
(4,5)



More Types of Graphs:

- **Unweighted**
  (undirected)



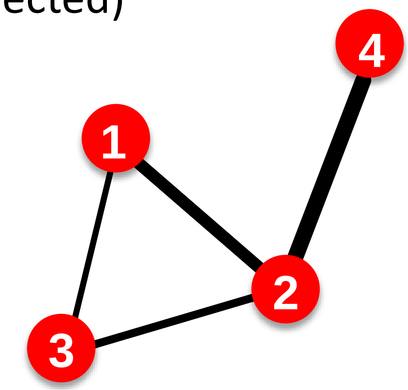
$$A_{ij} = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$A_{ii} = 0 \qquad A_{ij} = A_{ji}$$

$$E = \frac{1}{2}\sum_{i,j=1}^{N} A_{ij} \qquad \bar{k} = \frac{2E}{N}$$

Examples: Friendship, Hyperlink

- **Weighted**
  (undirected)



$$A_{ij} = \begin{pmatrix} 0 & 2 & 0.5 & 0 \\ 2 & 0 & 1 & 4 \\ 0.5 & 1 & 0 & 0 \\ 0 & 4 & 0 & 0 \end{pmatrix}$$

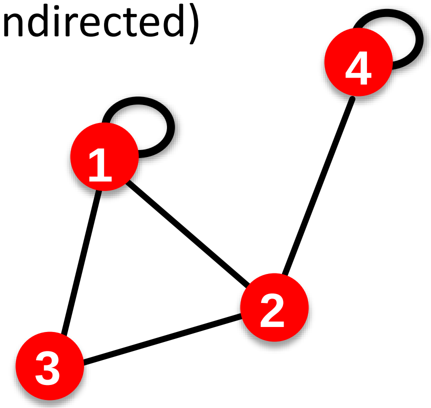
$$A_{ii} = 0 \qquad A_{ij} = A_{ji}$$

$$E = \frac{1}{2}\sum_{i,j=1}^{N} nonzero(A_{ij}) \qquad \bar{k} = \frac{2E}{N}$$

Examples: Collaboration, Internet, Roads

More Types of Graphs:

- **Self-edges (self-loops)**
  (undirected)



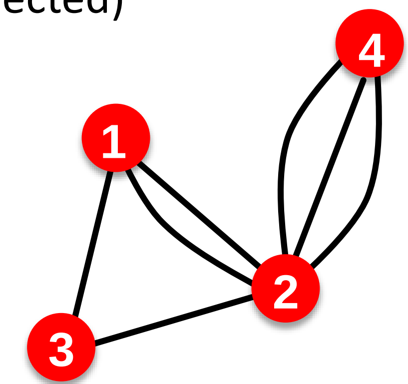
$$A_{ij} = \begin{pmatrix} 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

$$A_{ii} \neq 0 \qquad A_{ij} = A_{ji}$$

$$E = \frac{1}{2} \sum_{i,j=1, i \neq j}^{N} A_{ij} + \sum_{i=1}^{N} A_{ii}$$

Examples: Proteins, Hyperlinks

- **Multigraph**
  (undirected)



$$A_{ij} = \begin{pmatrix} 0 & 2 & 1 & 0 \\ 2 & 0 & 1 & 3 \\ 1 & 1 & 0 & 0 \\ 0 & 3 & 0 & 0 \end{pmatrix}$$

$$A_{ii} = 0 \qquad A_{ij} = A_{ji}$$

$$E = \frac{1}{2} \sum_{i,j=1}^{N} nonzero(A_{ij}) \qquad \bar{k} = \frac{2E}{N}$$

Examples: Communication, Collaboration

Network Representations

WWW >> directed multigraph with self-edges

Facebook friendships >> undirected, unweighted

Citation networks >> unweighted, directed, acyclic

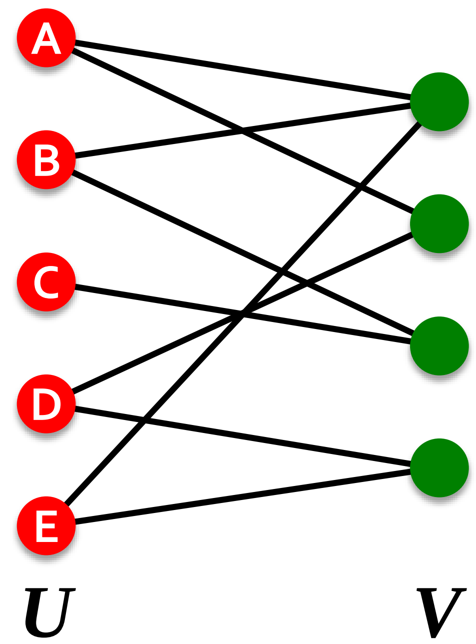
Collaboration networks >> undirected multigraph or weighted graph

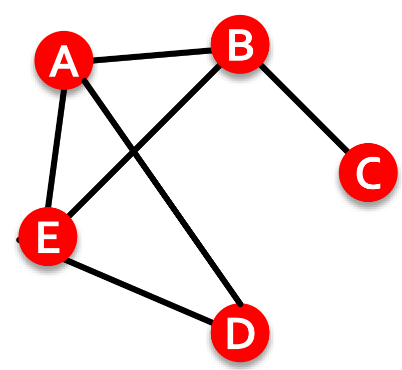
Mobile phone calls >> directed, (weighted?) multigraph

Protein Interactions >> undirected, unweighted with self-interactions

Bipartite Graph

- **Bipartite graph** is a graph whose nodes can be divided into two disjoint sets U and V such that every link connects a node in U to one in V; that is, U and V are **independent sets**
- **Examples:**
  - Authors-to-papers (they authored)
  - Actors-to-Movies (they appeared in)
  - Users-to-Movies (they rated)
- **"Folded" networks:**
  - Author collaboration networks
  - Movie co-rating networks

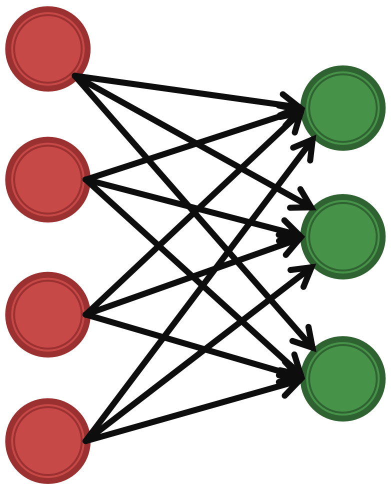




Folded version of the graph above

Web Cores

- Cores: Small complete bipartite graphs (of size 3x3, 4x3, 4x4)
  - Similar to the triangles in undirected graphs
- Found more frequently than expected on the Web graph
- Correspond to communities of enthusiasts (e.g., fans of japanese rock bands)



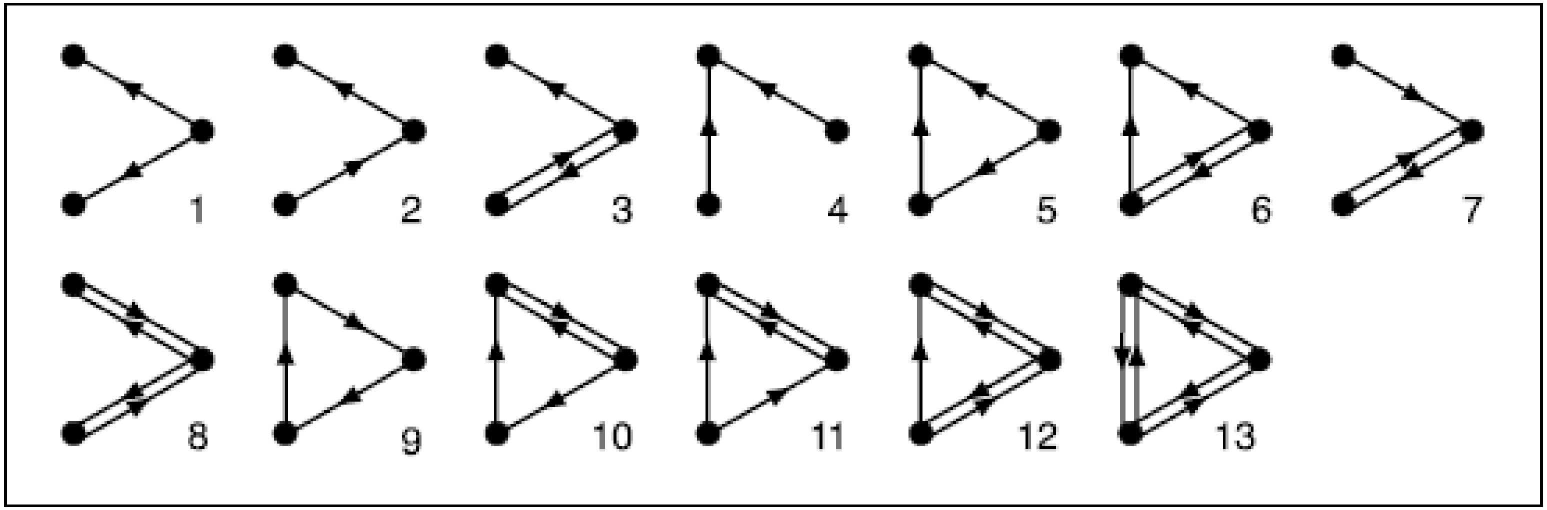
Motifs

- Most networks have the same characteristics with respect to global measurements
  - can we say something about the local structure of the networks?
- Motifs: Find small subgraphs that are over-represented in the network

Example

- Motifs of size 3 in a directed graph

B

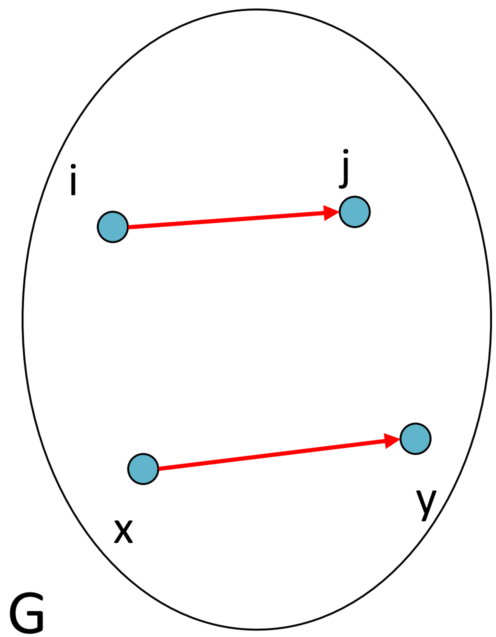


Finding Interesting Motifs

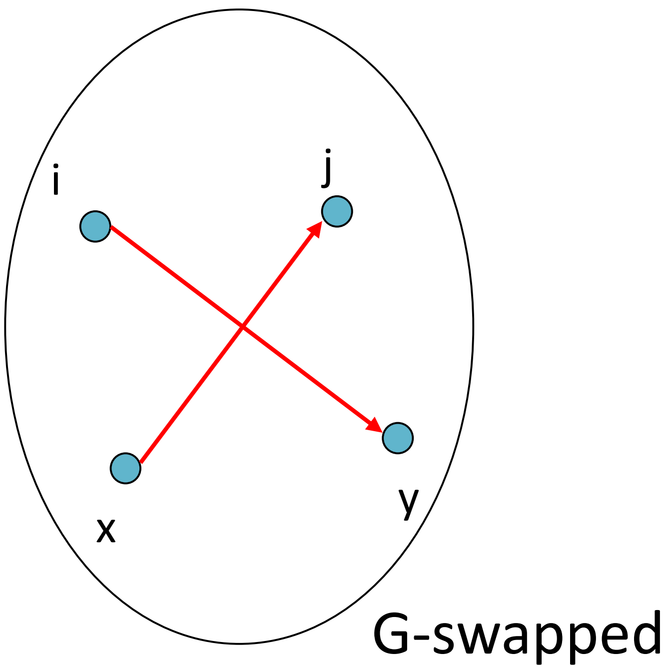
- Sample a part of the graph of size **S**
- Count the **frequency of the motifs** of interest
- Compare against the **frequency of the motif in a random graph** with the same number of nodes and the same degree distribution

Generating a Random Graph

- Find edges (i,j) and (x,y) such that edges (i,y) and (x,j) do not exist, and swap them
  - repeat for a large enough number of times



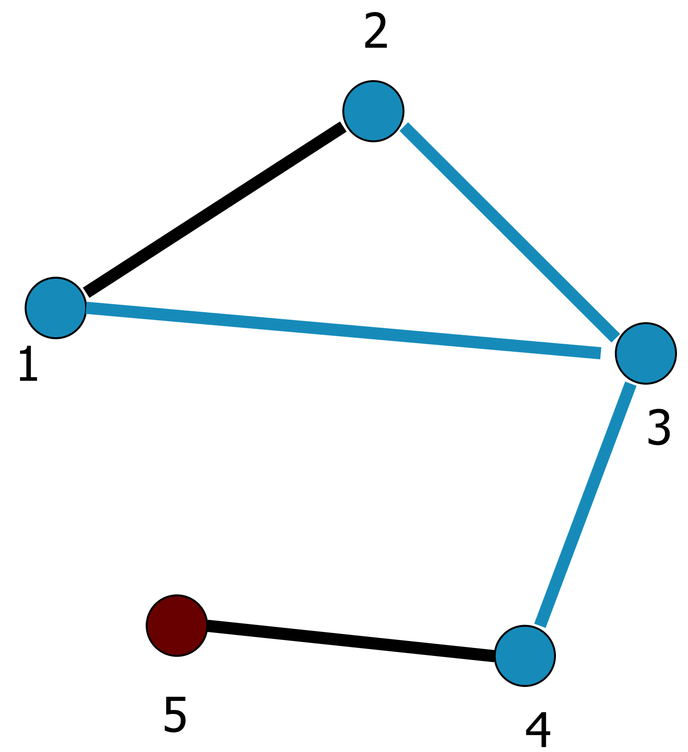
degrees of i,j,x,y are preserved



Subgraphs

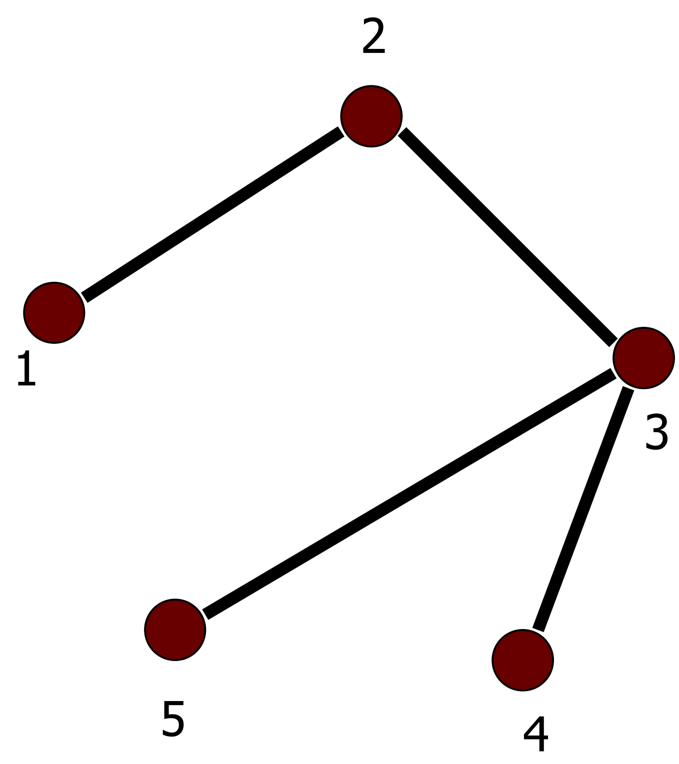
- Subgraph: Given $V' \subseteq V$, and $E' \subseteq E$, the graph $G'=(V',E')$ is a subgraph of G.

- Induced subgraph: Given $V' \subseteq V$, let $E' \subseteq E$ is the set of all edges between the nodes in V′. The graph $G'=(V',E')$, is an induced subgraph of G



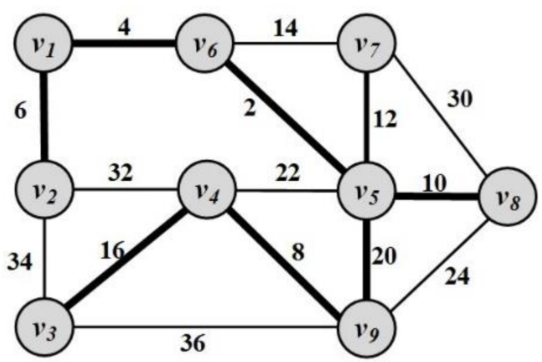
Trees

- Connected Undirected graphs without cycles

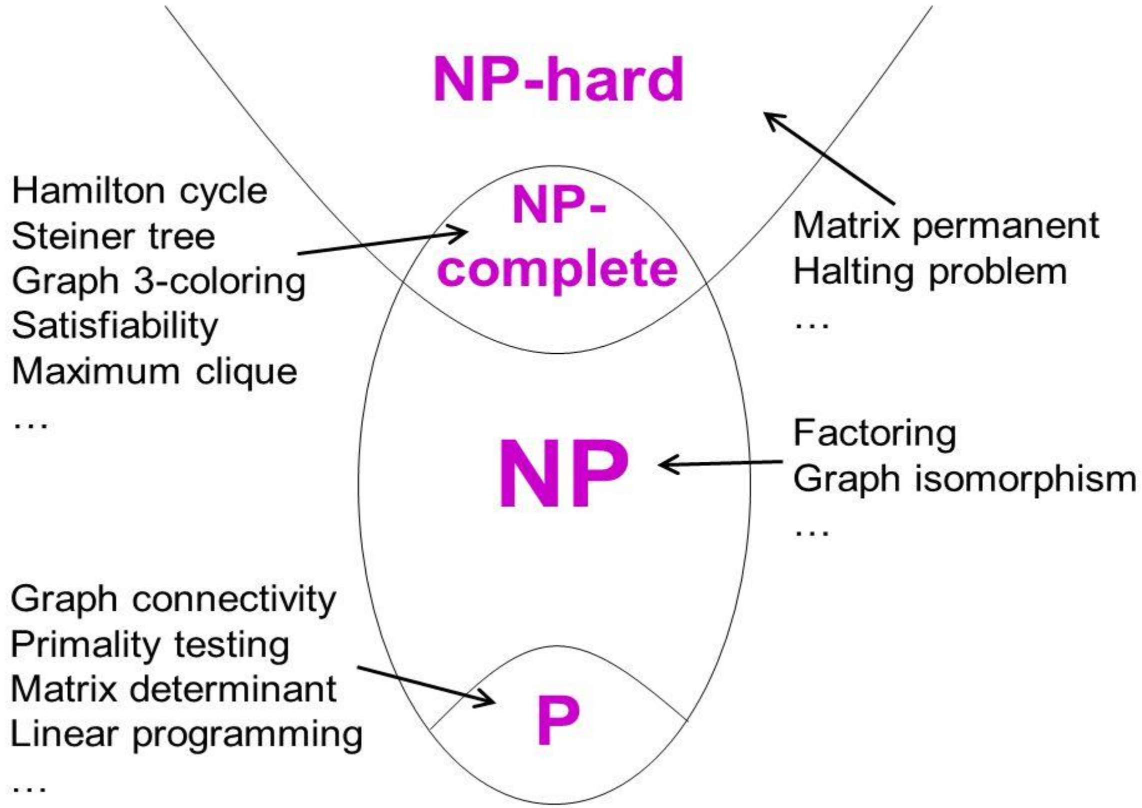


Spanning Tree

- For any connected graph, the spanning tree is a subgraph and a tree that includes all the nodes of the graph
- There may exist multiple spanning trees for a graph
- The weigh of a spanning tree (among multiple spanning trees) of a graph is the summation of the edge weights in that spanning tree
- Minimum Spanning Tree (MST): The spanning tree with the minimum weight



Classes of Complexity



P: Solvable in polynomial time

NP: Verified in polynomial time, but no known solution in polynomial time

NP-hard: At least as difficult as the hardest NP problems

NP-complete: The hardest of NP problems

More Network Properties…

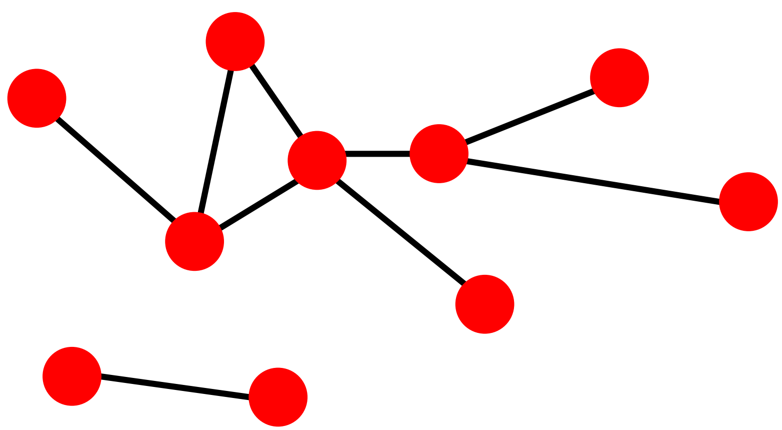
Degree Distribution

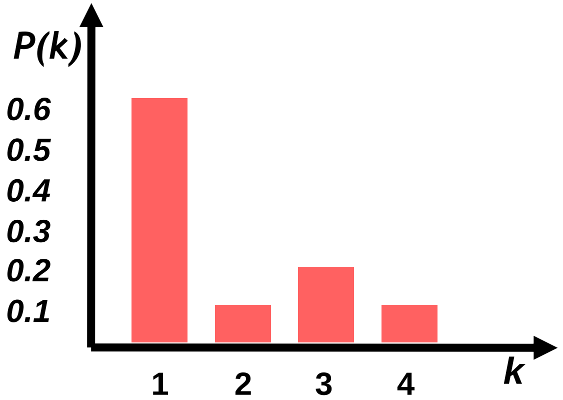
- **Degree distribution $P(k)$:** Probability that a randomly chosen node has degree k

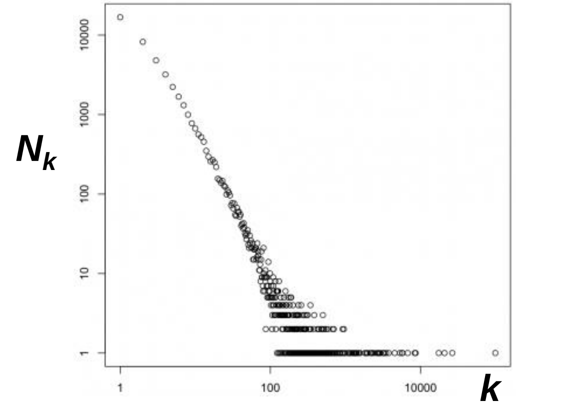
  N_k = # nodes with degree k

- Normalized histogram:

  $P(k) = N_k / N$ ➔ **plot**





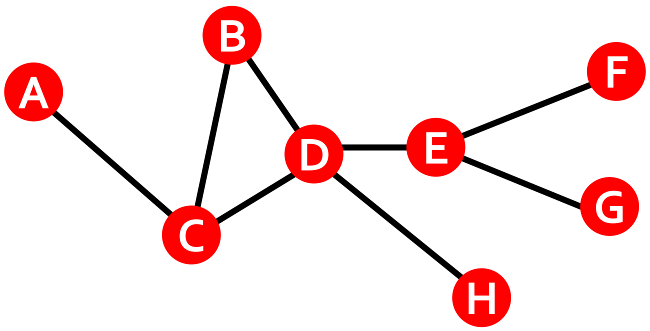


Paths in a Graph

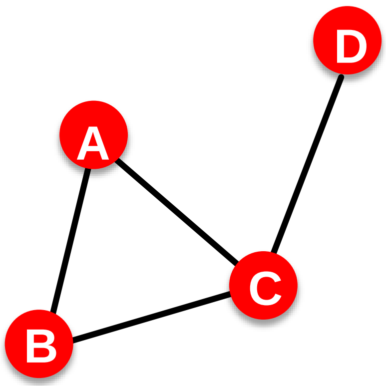
- A ***path*** is a sequence of nodes in which each node is linked to the next one

$$P_n = \{i_0, i_1, i_2, \ldots, i_n\} \qquad P_n = \{(i_0, i_1), (i_1, i_2), (i_2, i_3), \ldots, (i_{n-1}, i_n)\}$$

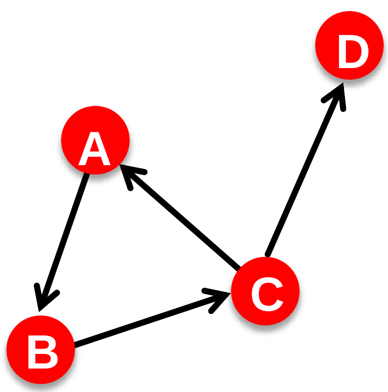
- Path can intersect itself and pass through the same edge multiple times
  - E.g.: ACBDCDEG
  - In a directed graph a path can only follow the direction of the "arrow"



Distance in a Graph



$h_{B,D} = 2$

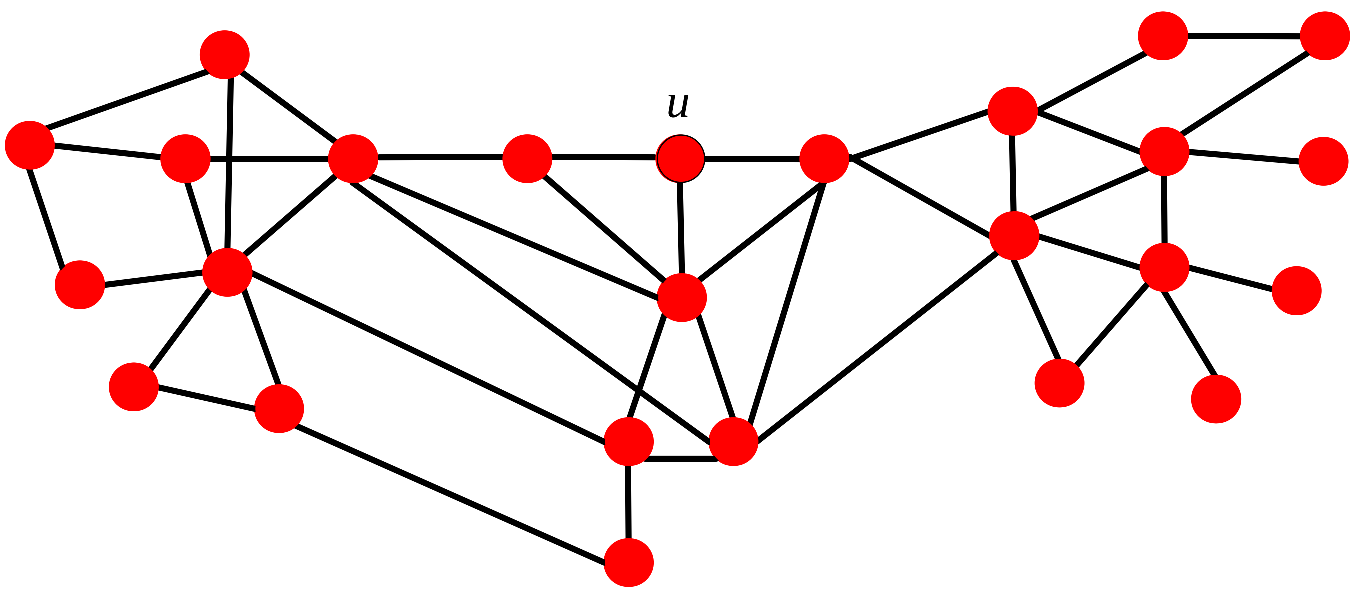


$h_{B,C} = 1$, $h_{C,B} = 2$

- **Distance (shortest path, geodesic)** between a pair of nodes is defined as the number of edges along the shortest path connecting the nodes
  - *If the two nodes are disconnected, the distance is usually defined as infinite
- In **directed graphs** paths need to follow the direction of the arrows
  - Consequence: Distance is **not symmetric**: $h_{A,C} \neq h_{C,A}$

Finding Shortest Paths

- **Breadth First Search:**
  - Start with node u, mark it to be at distance $h_u(u)=0$, add u to the queue
  - While the queue not empty:
    - Take node v off the queue, put its unmarked neighbors w into the queue and mark $h_u(w)=h_u(v)+1$



Shortest Paths on Weighted Graphs

- Shortest paths on weighted graphs are harder to construct
  - There are several well known algorithms for finding single-source, or all-pairs shortest paths
- Single-source Shortest Path (SSSP)
  - Dijkstra's algorithm (non-negative weights)
  - Bellman-Ford algorithm (allows negative weights)
- All-pairs Shortest Paths (APSP)
  - Floyd-Warshall algorithm (allows negative weights)
  - Johnson's algorithm (allows negative weights)

Network Diameter

- **Diameter:** the maximum (shortest path) distance between any pair of nodes in a graph

- **Average path length** for a connected graph (component) or a strongly connected (component of a) directed graph

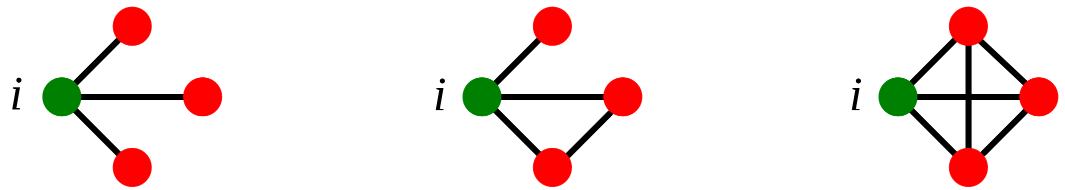
$$\bar{h} = \frac{1}{2E_{\max}} \sum_{i,j \neq i} h_{ij}$$

where h_{ij} is the distance from node i to node j

  - Many times we compute the average only over the connected pairs of nodes (that is, we ignore "infinite" length paths)

Clustering Coefficient

- **Clustering coefficient:**
  - What portion of ***i***'s neighbors are connected?
  - Node ***i*** with degree $\boldsymbol{k_i}$
  - $C_i \in [0,1]$
  - $$C_i = \frac{2e_i}{k_i(k_i-1)}$$ where e_i is the number of edges between the neighbors of node i



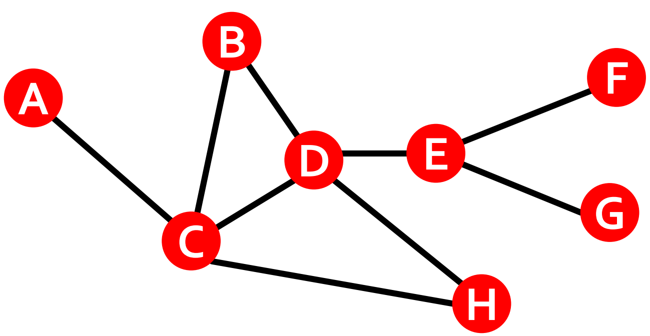
C_i=0 $\quad$ C_i=1/3 $\quad$ C_i=1

- **Average clustering coefficient:** $C = \frac{1}{N}\sum_{i}^{N} C_i$

Clustering Coefficient: Example

- **Clustering coefficient:**
  - What portion of ***i***'s neighbors are connected?
  - Node ***i*** with degree $\boldsymbol{k_i}$
  - $$C_i = \frac{2e_i}{k_i(k_i - 1)}$$

where e_i is the number of edges between the neighbors of node i



k_B=2, e_B=1, $\boldsymbol{C_B}$=2/2 = 1

k_D=4, e_D=2, $\boldsymbol{C_D}$=4/12 = 1/3

…

Key Network Properties

Degree distribution: $P(k)$

Path length: h

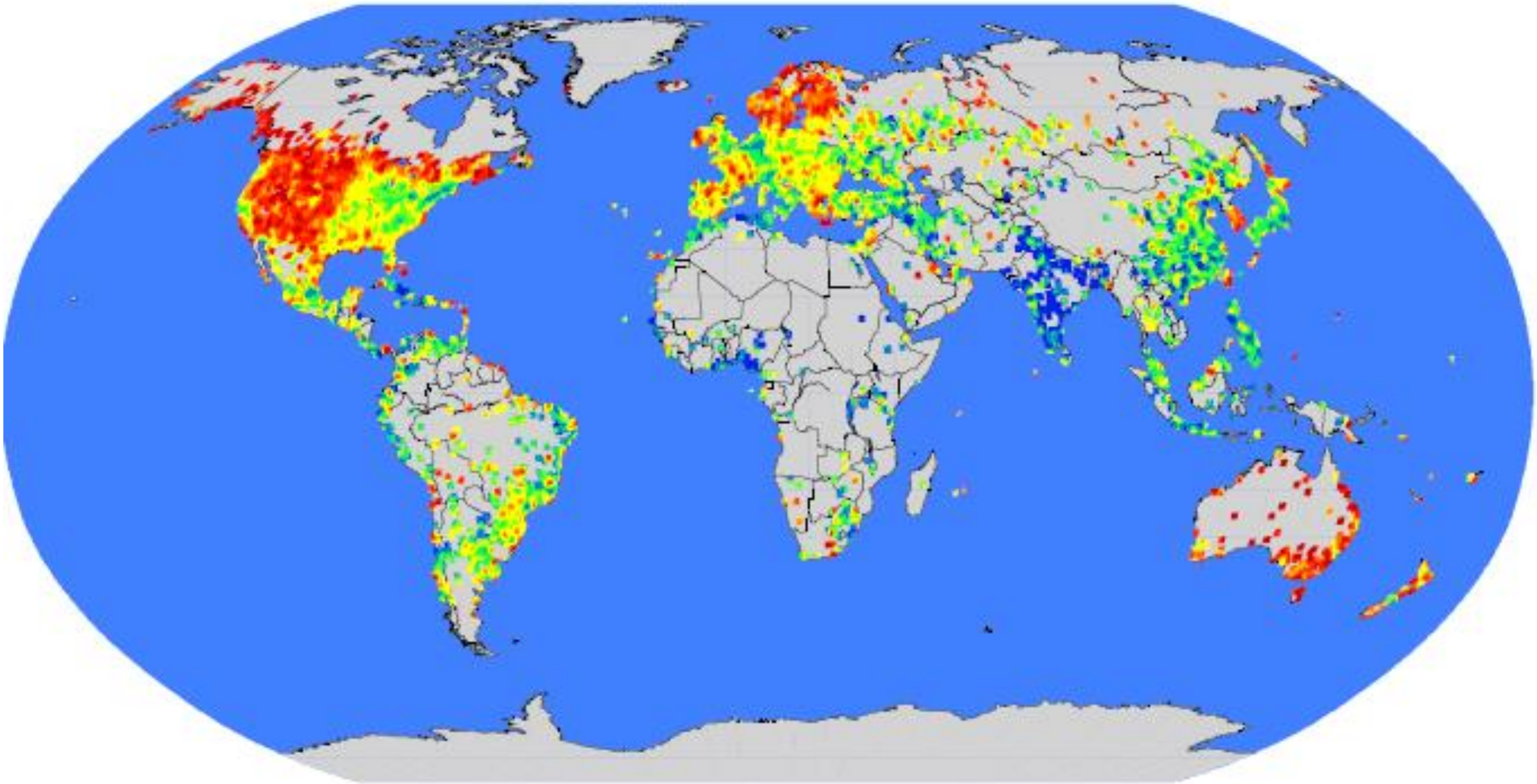
Clustering coefficient: C

Let's measure P(k), h and C on a real-world network!

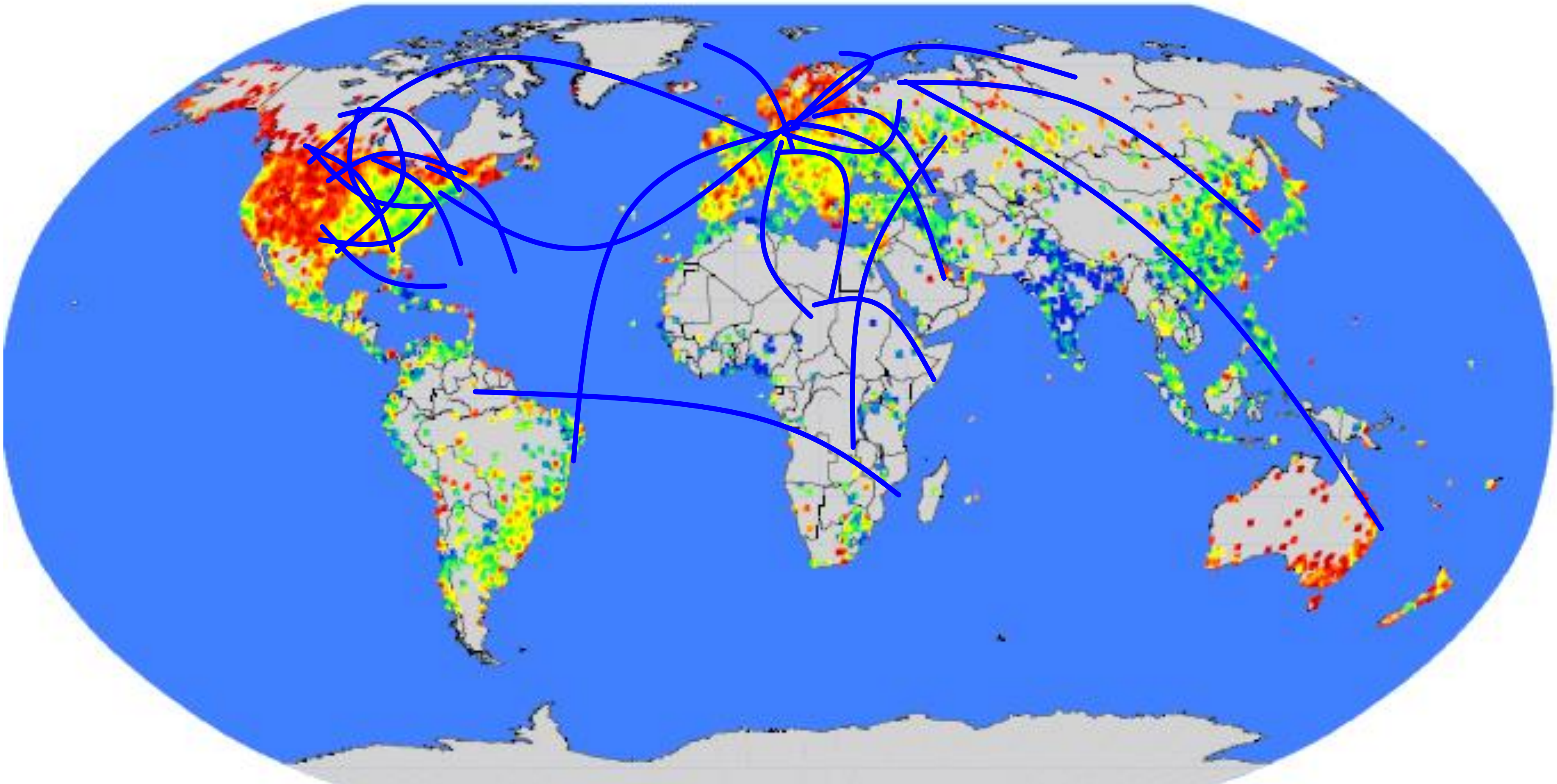
The MSN Messenger

- **MSN Messenger activity in June 2006:**
  - 245 million users logged in
  - 180 million users engaged in conversations
  - More than 30 billion conversations
  - More than 255 billion exchanged messages

Communication: Geography

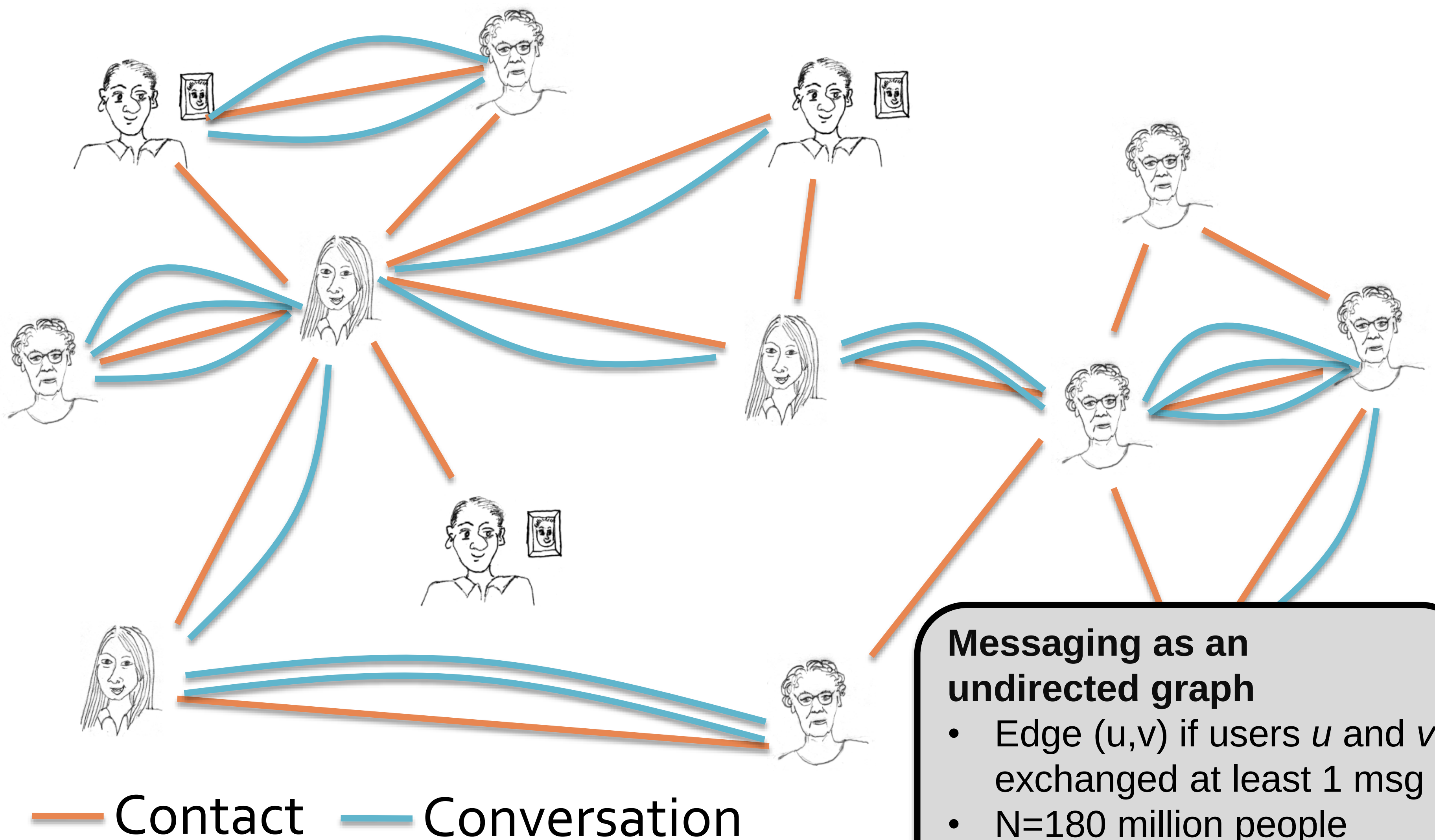


Communication network



Network: 180M people, 1.3B edges

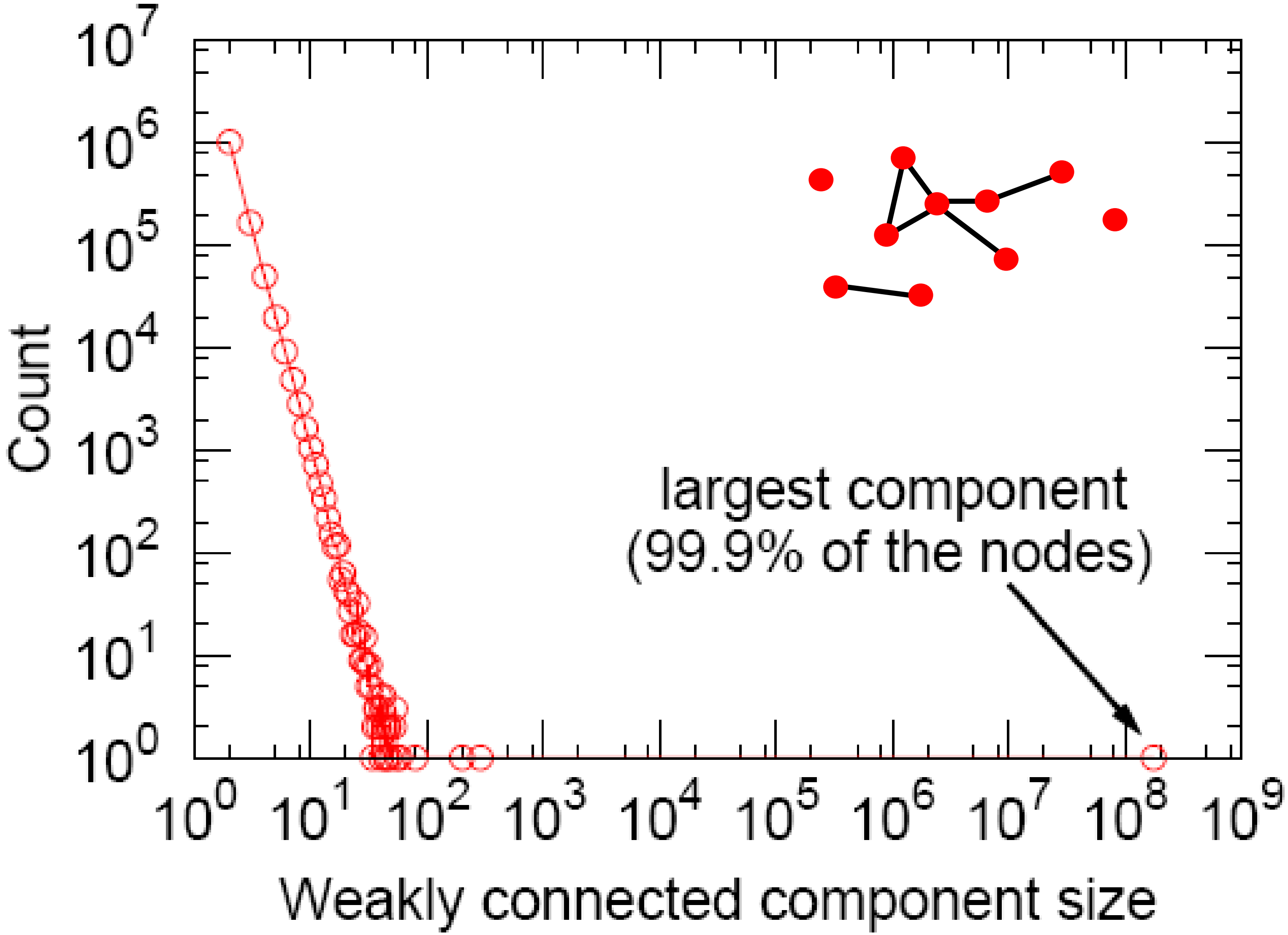
Messaging as a Multigraph



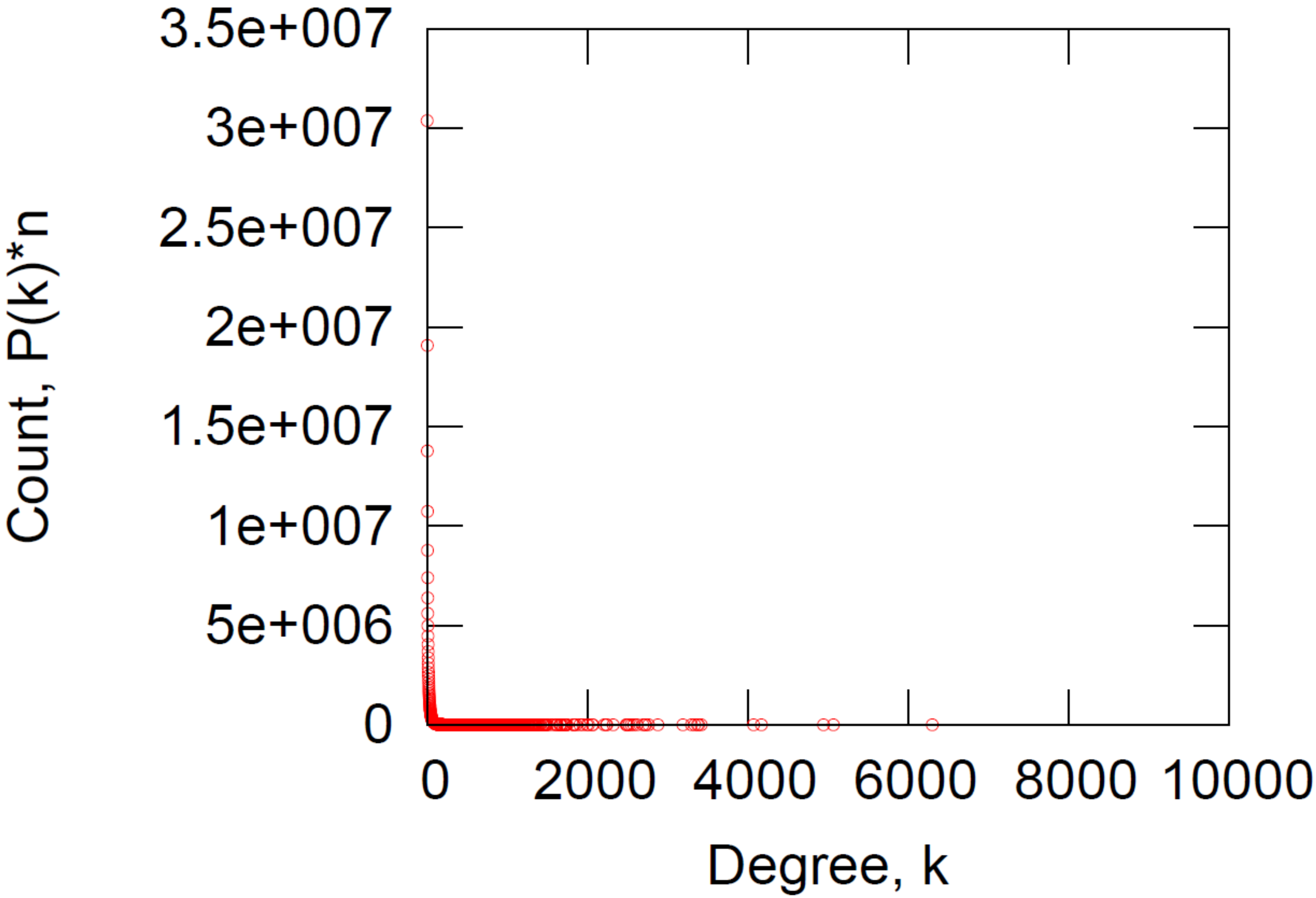
Messaging as an undirected graph

- Edge (u,v) if users *u* and *v* exchanged at least 1 msg
- N=180 million people
- E=1.3 billion edges

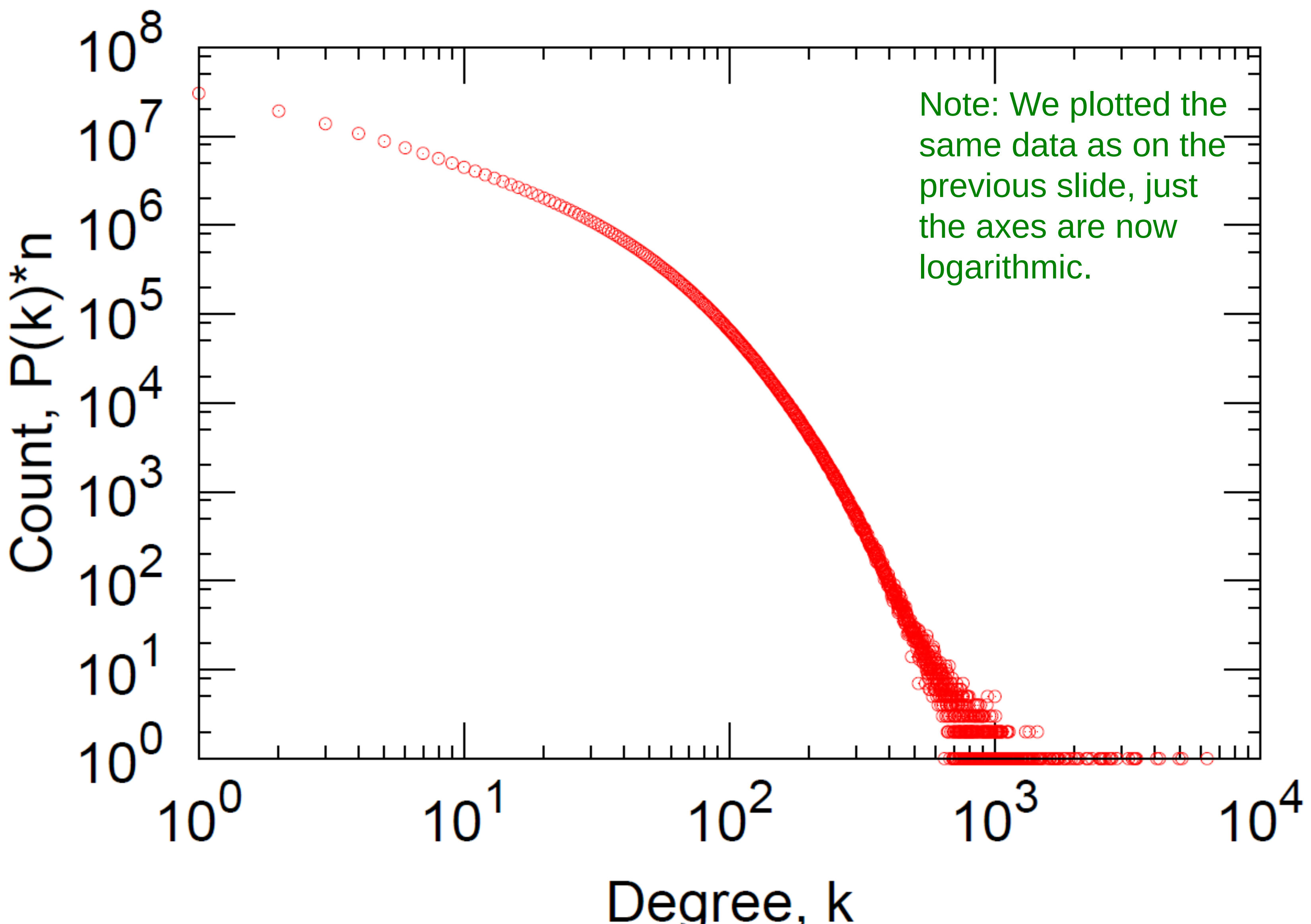
MSN Network: Connectivity



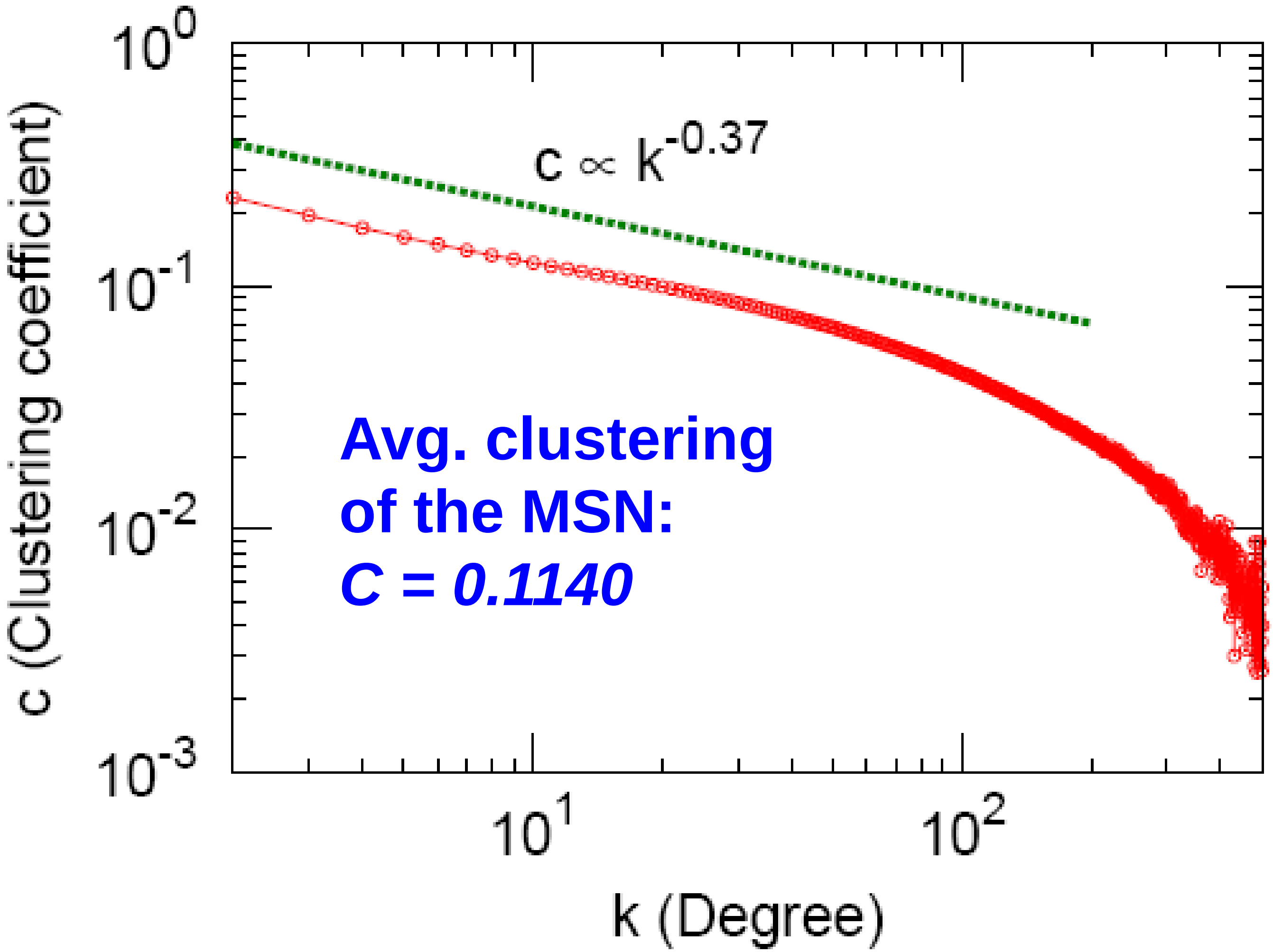
MSN: Degree Distribution



MSN: Log-Log Degree Distribution

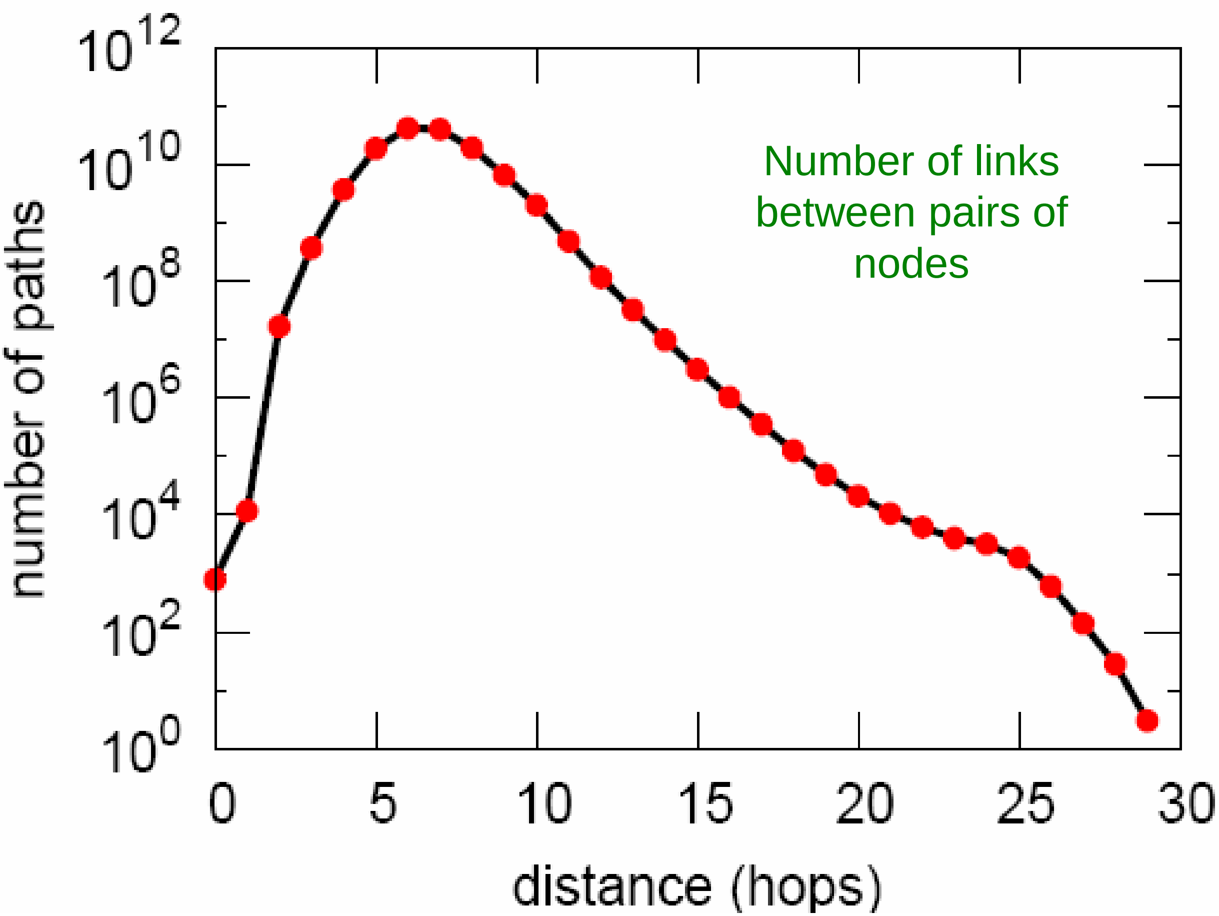


MSN: Clustering



C_k: average C_i of nodes i of degree k: $C_k = \frac{1}{N_k} \sum_{i:k_i=k} C_i$

MSN: Diameter



Avg. path length **6.6**

90% of the nodes can be reached in < 8 hops

nodes as we do BFS out of a random node

Steps	#Nodes
0	1
1	10
2	78
3	3,96
4	8,648
5	3,299,252
6	28,395,849
7	79,059,497
8	52,995,778
9	10,321,008
10	1,955,007
11	518,410
12	149,945
13	44,616
14	13,740
15	4,476
16	1,542
17	536
18	167
19	71
20	29
21	16
22	10
23	3
24	2
25	3

MSN: Key Network Properties

Degree distribution: *Heavily skewed*
avg. degree= 14.4

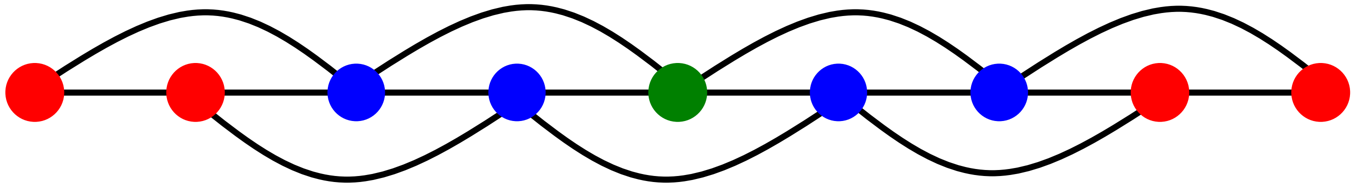
Path length: *6.6*

Clustering coefficient: *0.11*

Are these values "expected"?
Are they "surprising"?

To answer this we need a null-model!

Is MSN Network like a "chain"?



- $P(k) = \delta(k\text{-}4)$ $\quad k_i = 4$ for all nodes
- $C = \frac{1}{N}\left(\frac{1}{2}(N-4) + 2 + 2\frac{2}{3}\right) = ½$ as $N \rightarrow \infty$
- Path length: $h_{max} = \frac{N-1}{2} = O(N)$
  - Avg. shortest path-length: $\bar{h} < \frac{2}{N(N-1)} \frac{N-1}{2} \frac{N(N-1)}{2} = O(N)$
- So, we have: **Constant degree,**

  Constant avg. clustering coeff.

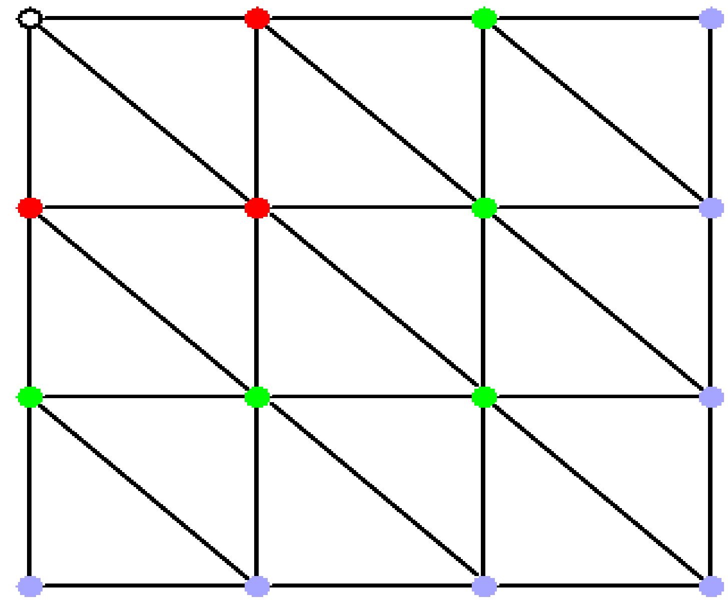
  Linear avg. path-length

Note about calculations:
We are interested in quantities as graphs get large (N→∞)

Is MSN Network like a “grid”?

- $P(k) = \delta(k\text{-}6)$
  - $k = 6$ for each inside node
- $C = 6/15$ for inside nodes
- **Path length:**

$$h_{max} = O(\sqrt{N})$$



- **In general, for lattices:**
  - Average path-length is $\bar{h} \approx N^{1/D}$ (D… lattice dimensionality)
  - Constant degree, constant clustering coefficient

What did we learn so far?

MSN Network is neither a chain nor a grid