Find my presentations here:

http://db.tt/9PdUuOrq

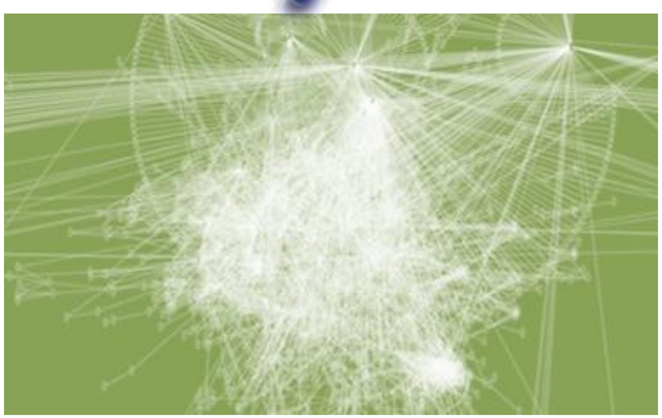
Introduction to Networks

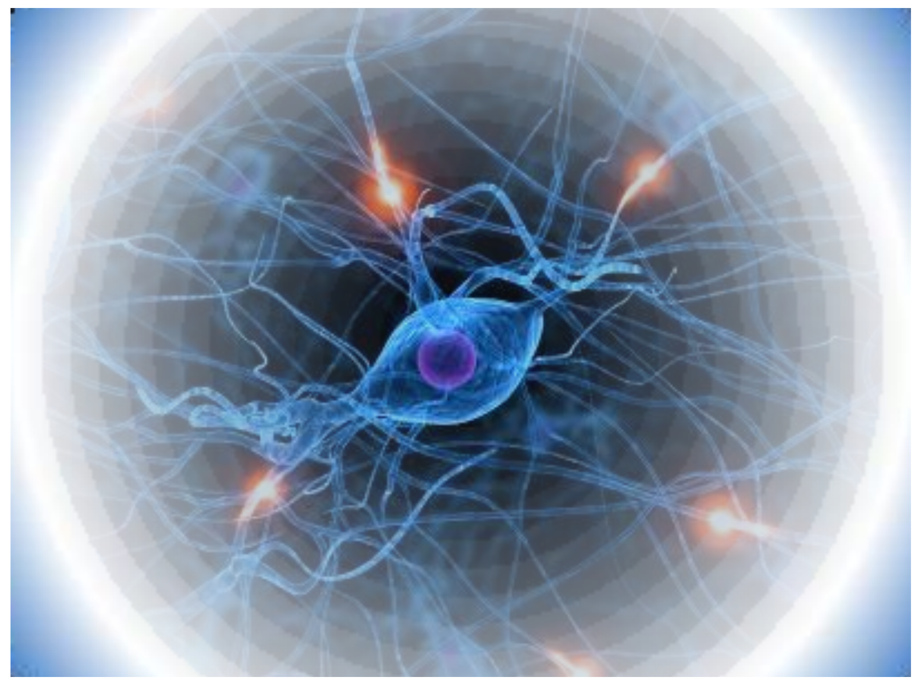
European Territorial Cooperation Programme
Greece-Bulgaria 2007-2013
INVESTING IN OUR FUTURE

Blagoevgrad 2013

European Territorial Cooperation Progamme
Greece - Bulgaria 2007 - 2013
This Project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria

A small review to complexity





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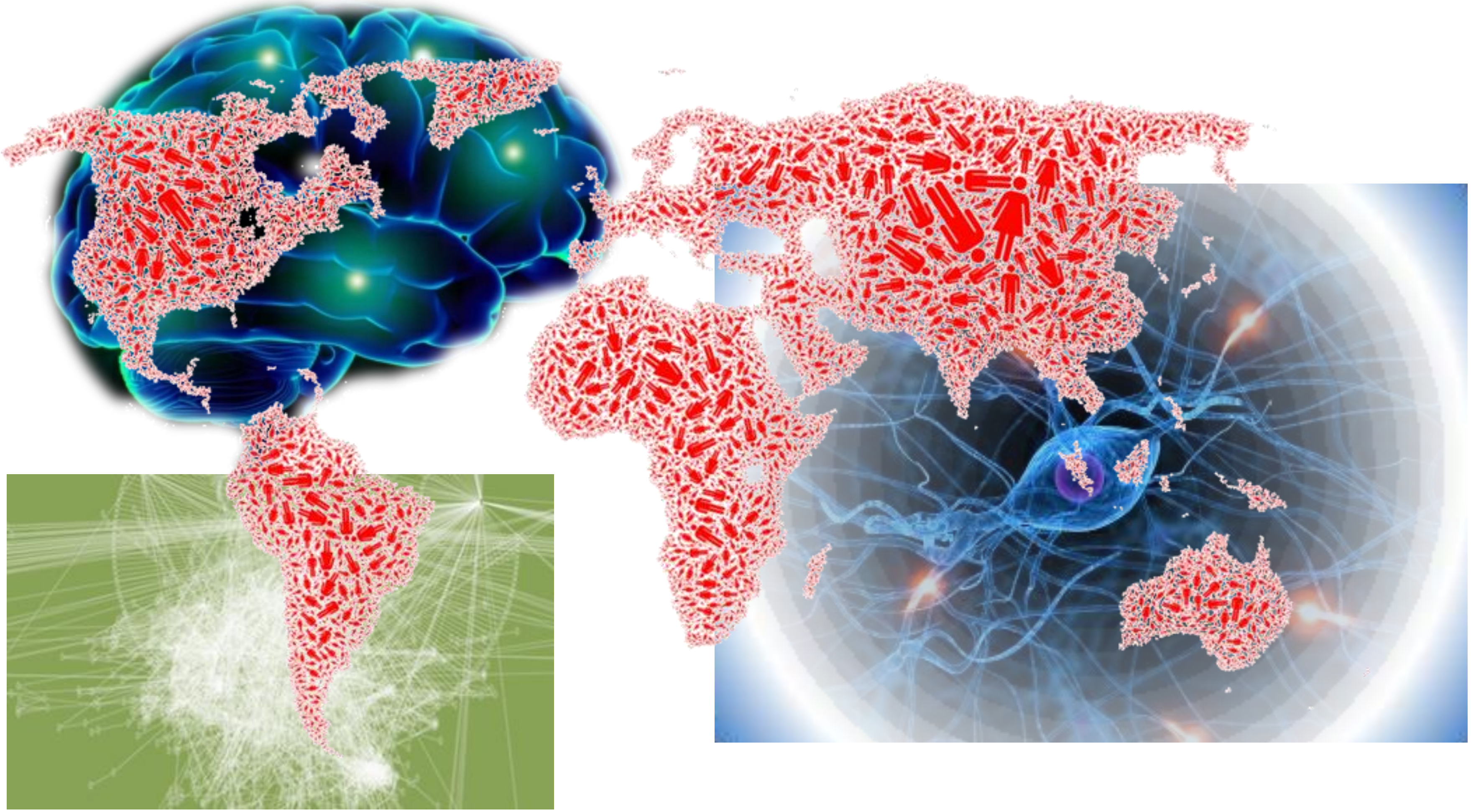

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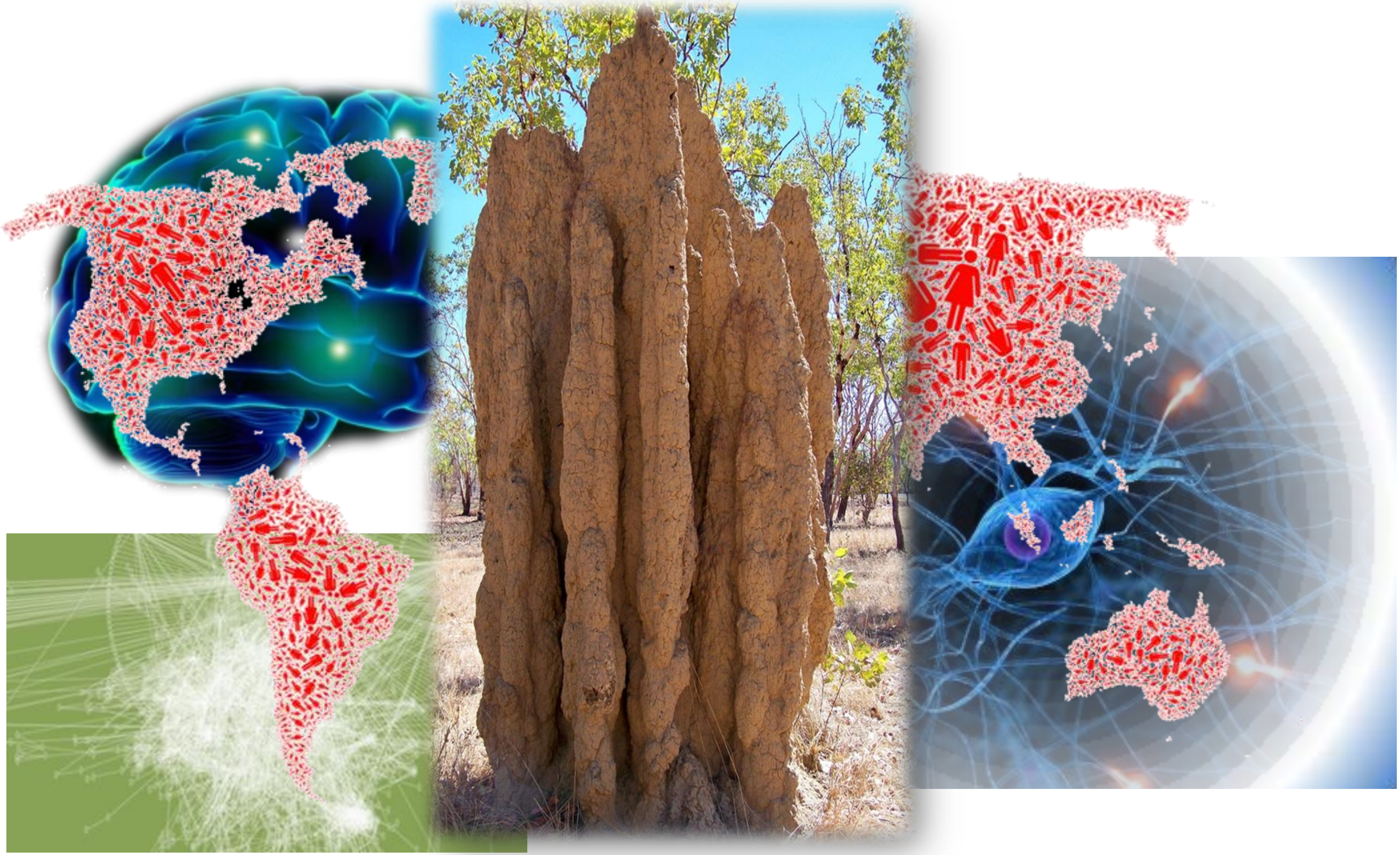
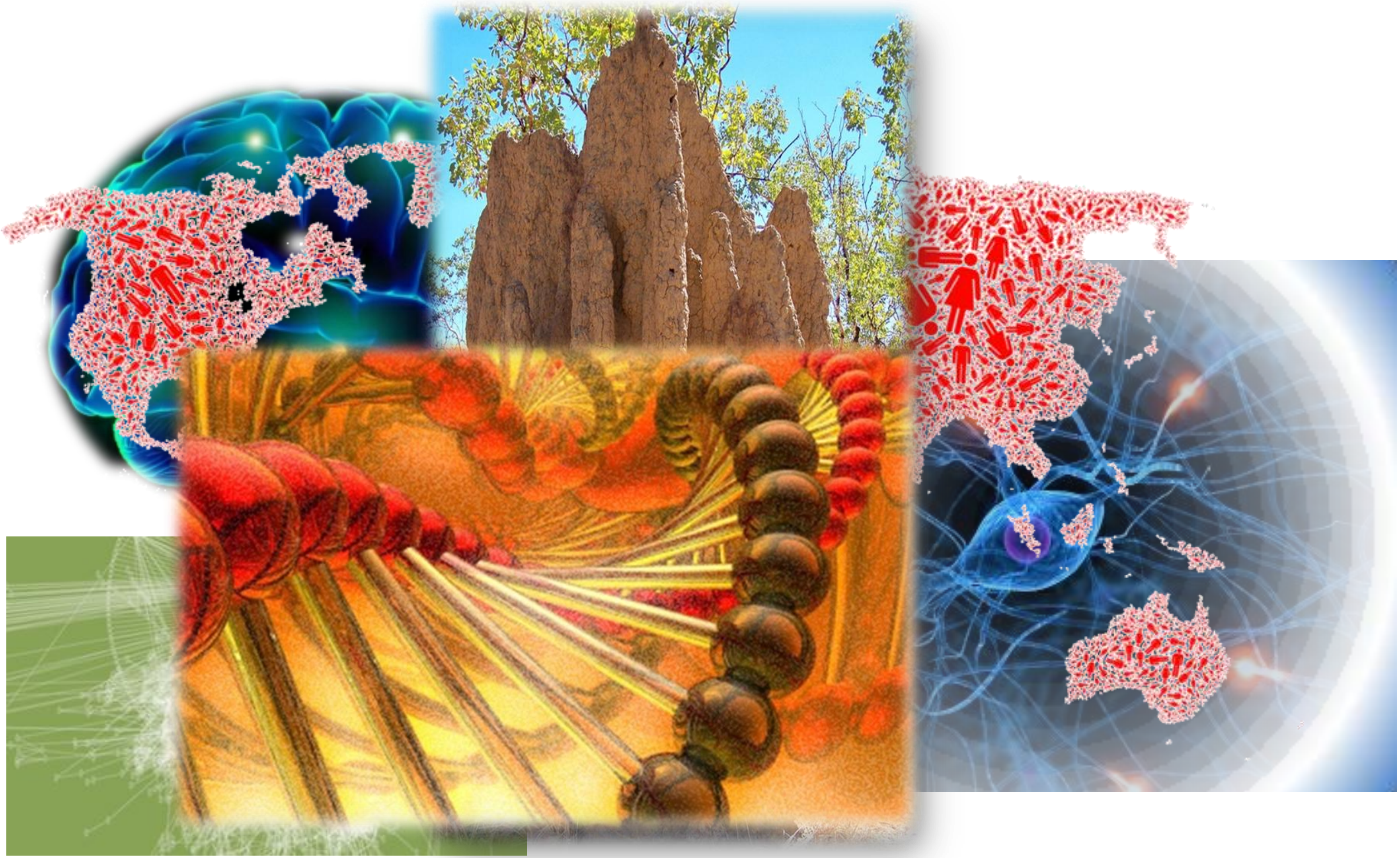


A small review to complexity



Modeling with Random Numbers

CPU

↓

Random number Generator

↓

Random number

↓

Independent variable of the problem.

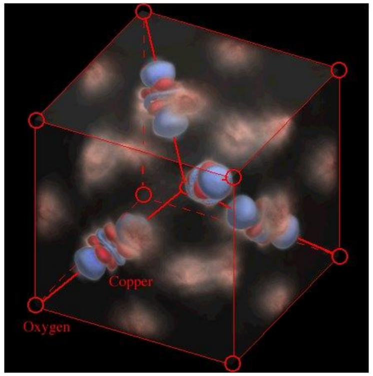
The truth is that we can NOT have absolutely random numbers!!

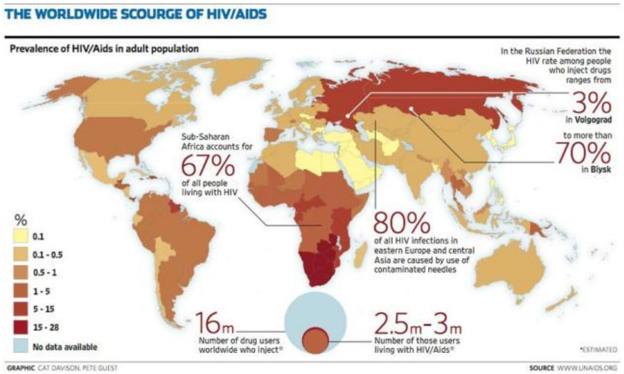
…But WHY modeling?

A simulation is a procedure that takes place virtually in a machine.

Even because the ***timeframe / space*** of the experiment is to small or large! NOT in human observable size!

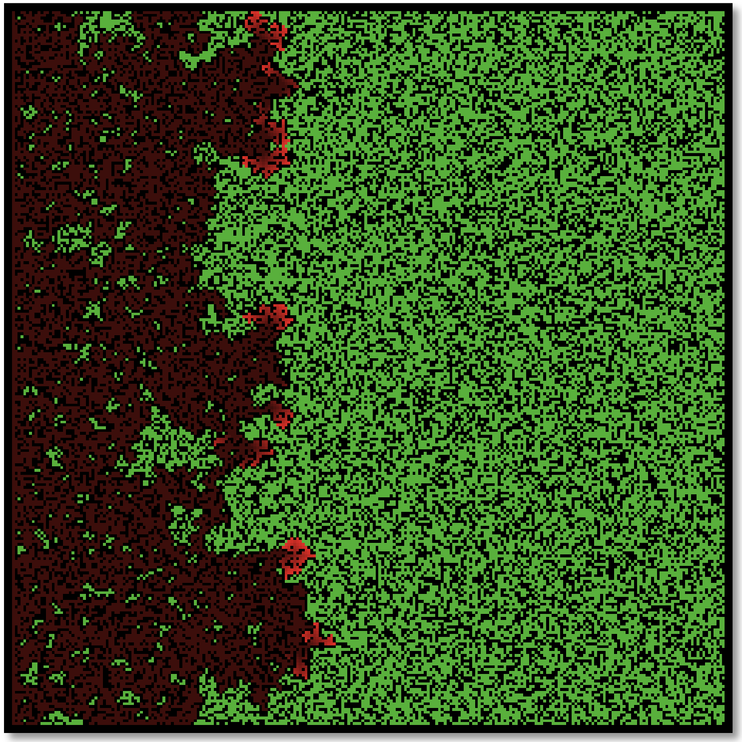
Even because the experiment has ***not*** a human observable parameters.





Percolation

in real life

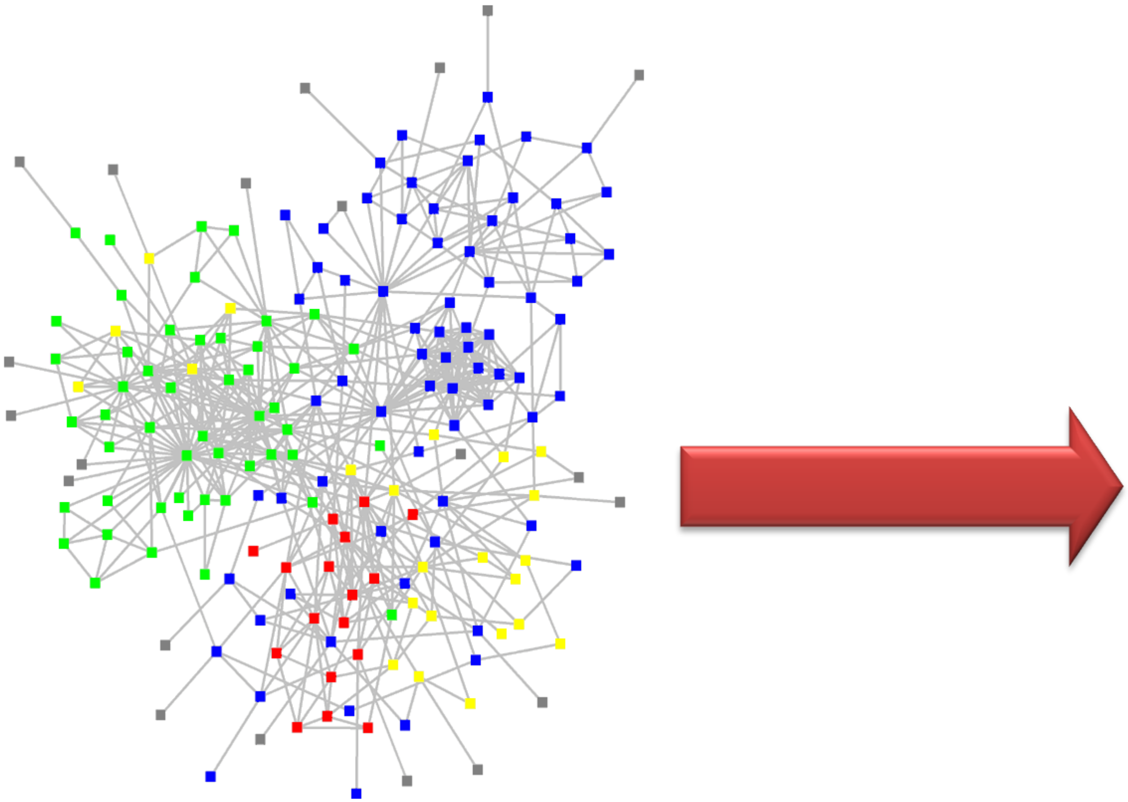


Forest fire

Oil in a porous material

Percolation

in real life



Spread of a disease

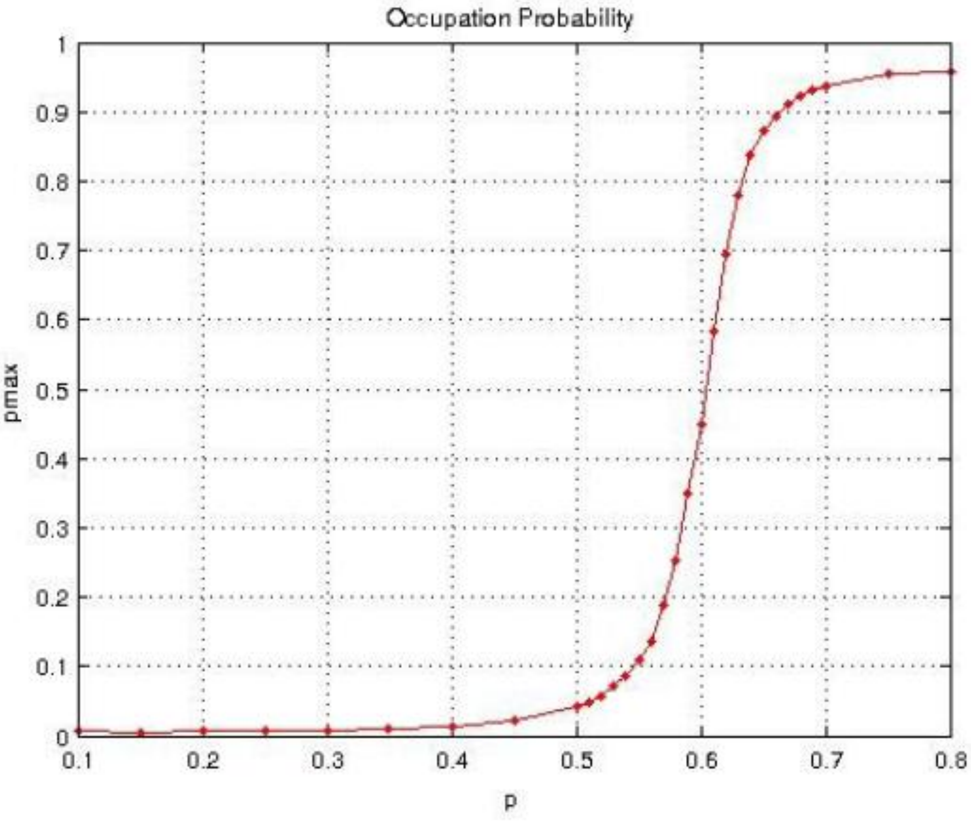
or

information

Percolation

in the computer!

Plot of the probability of one site to belong to the spanning cluster



A small review to complexity

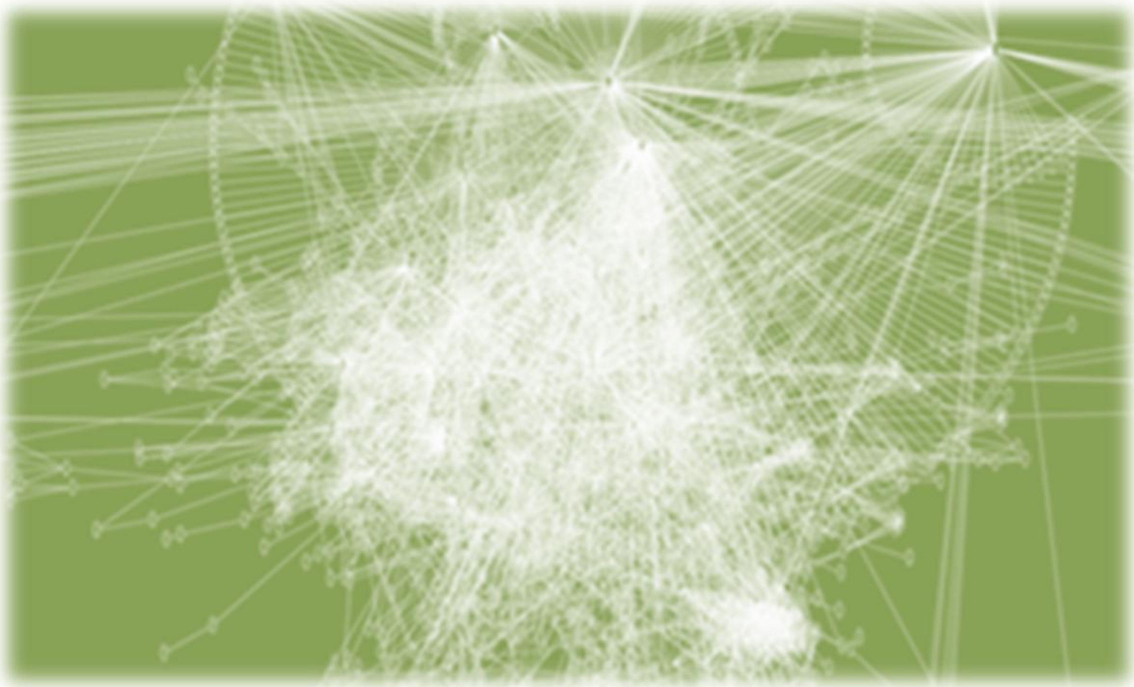
No blueprint or master-mind

Self-organization

Evolution

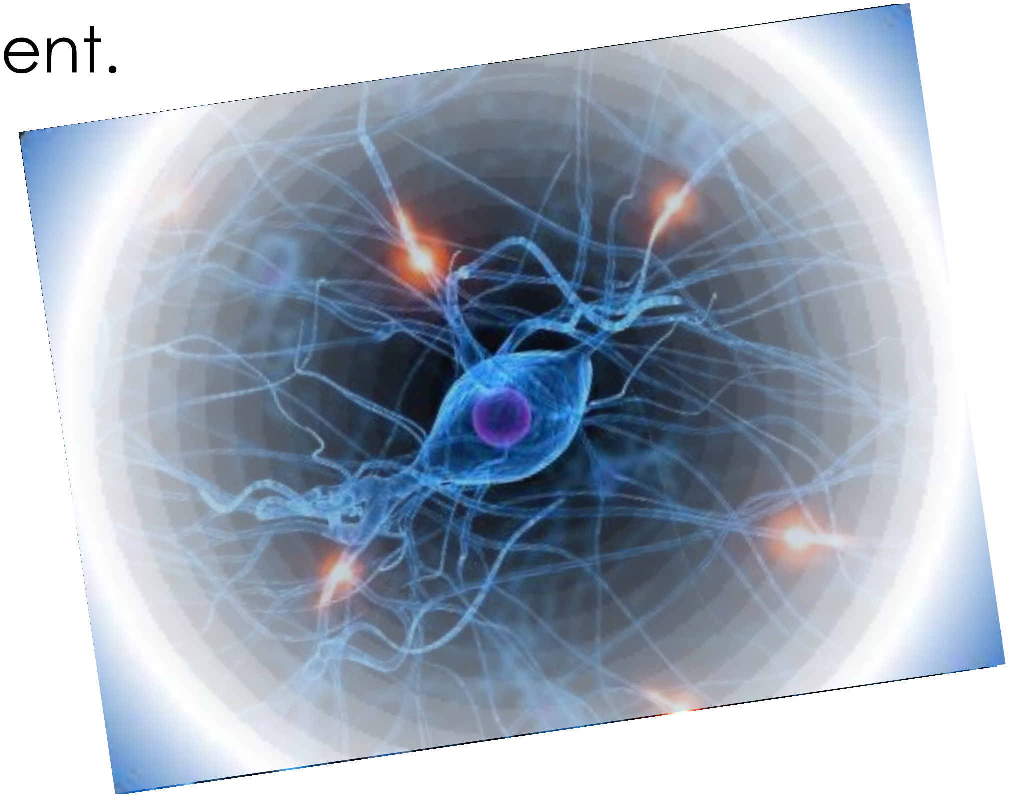
Adaptation

Emergence

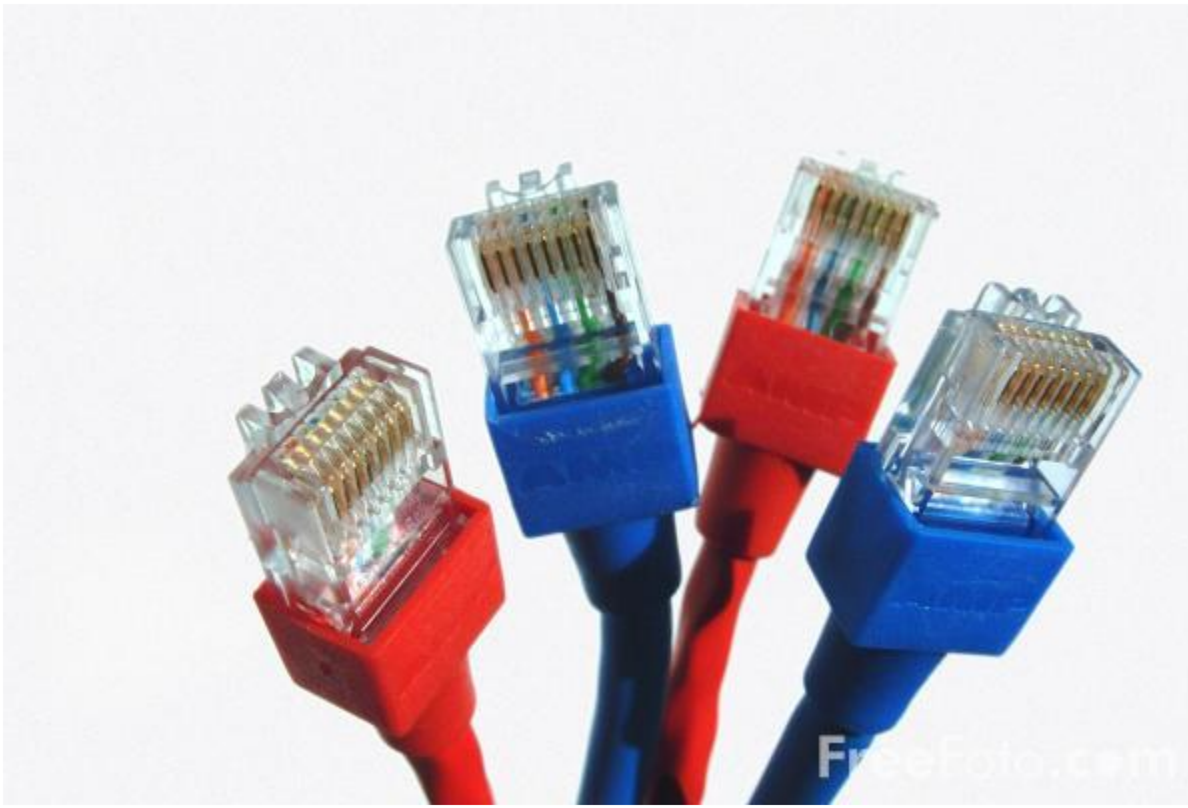


A small review to complexity

Behind each complex system there is a network, that defines the interactions between the component.

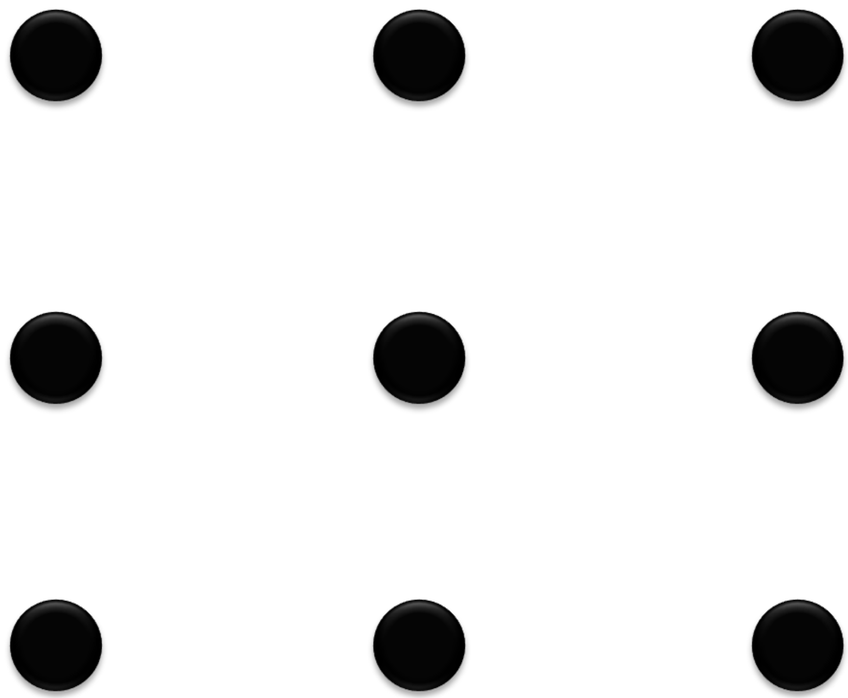


What is a network ?



Let's play a game!

Connect all the dots with 4 continuous straight lines.



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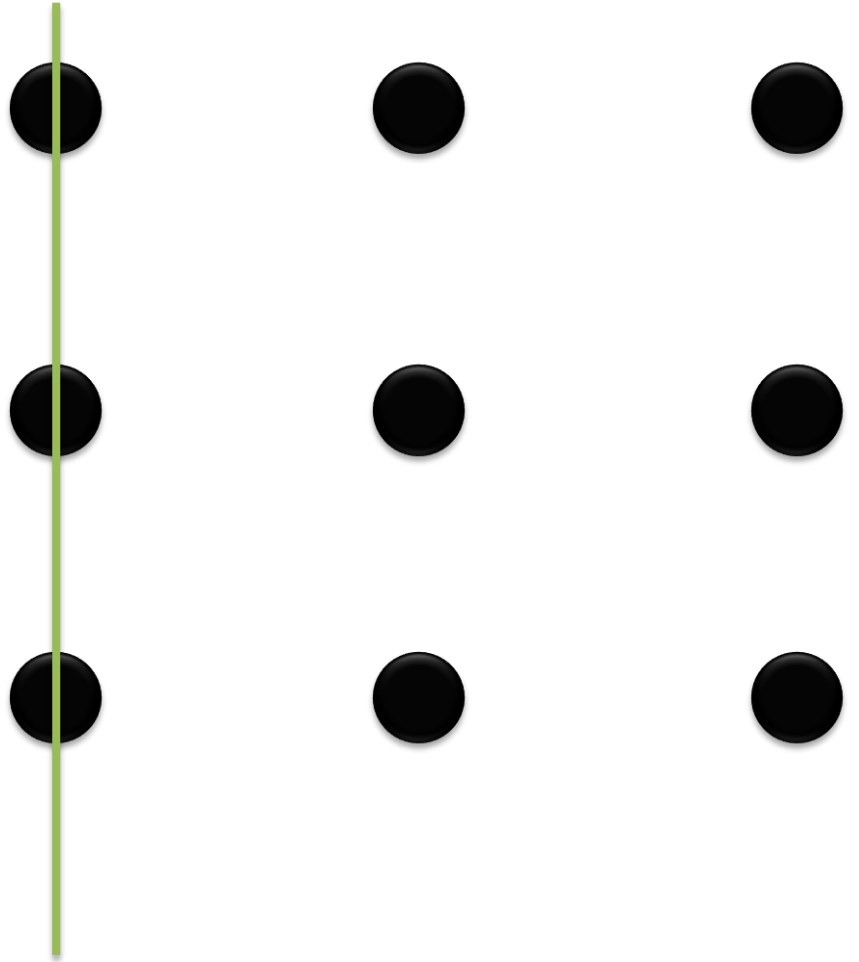

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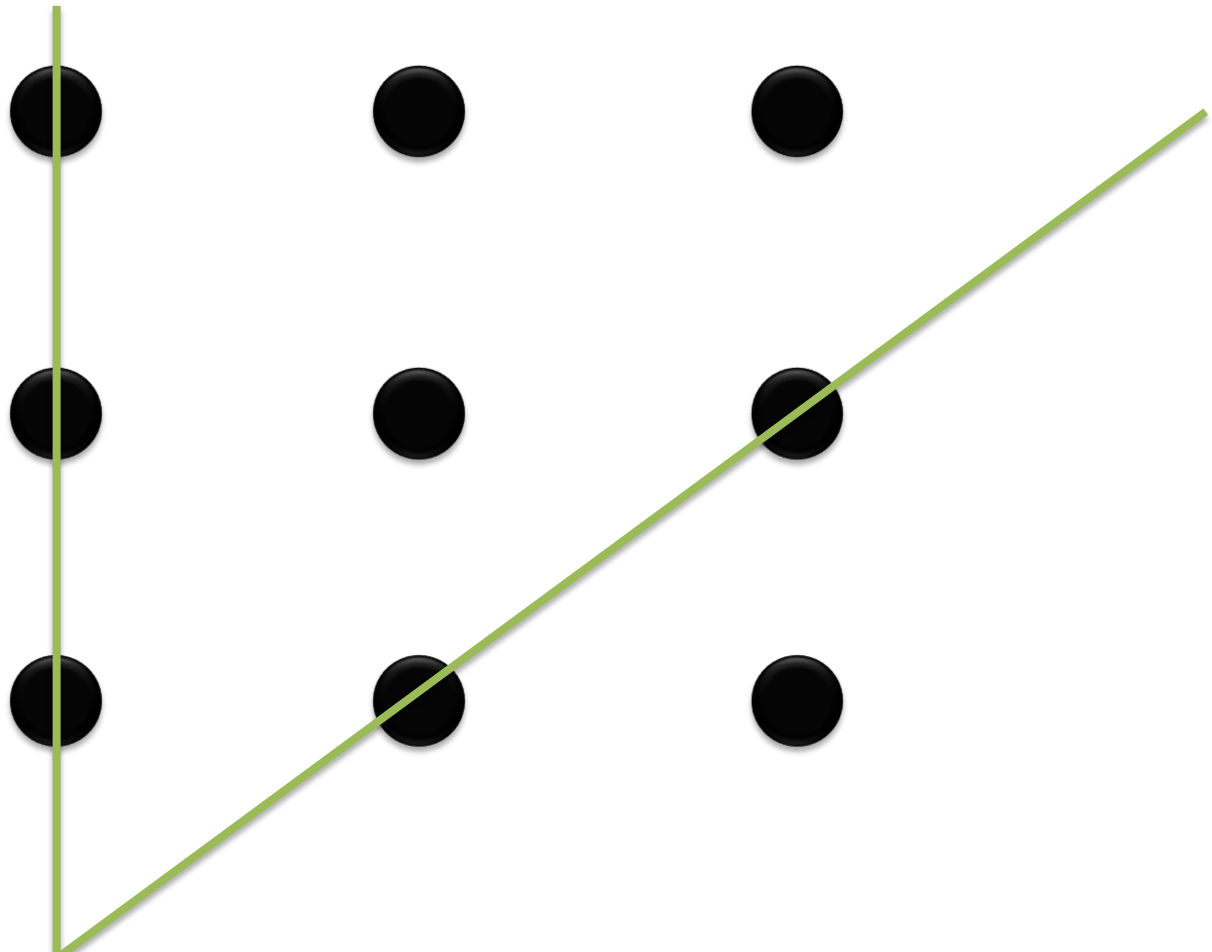

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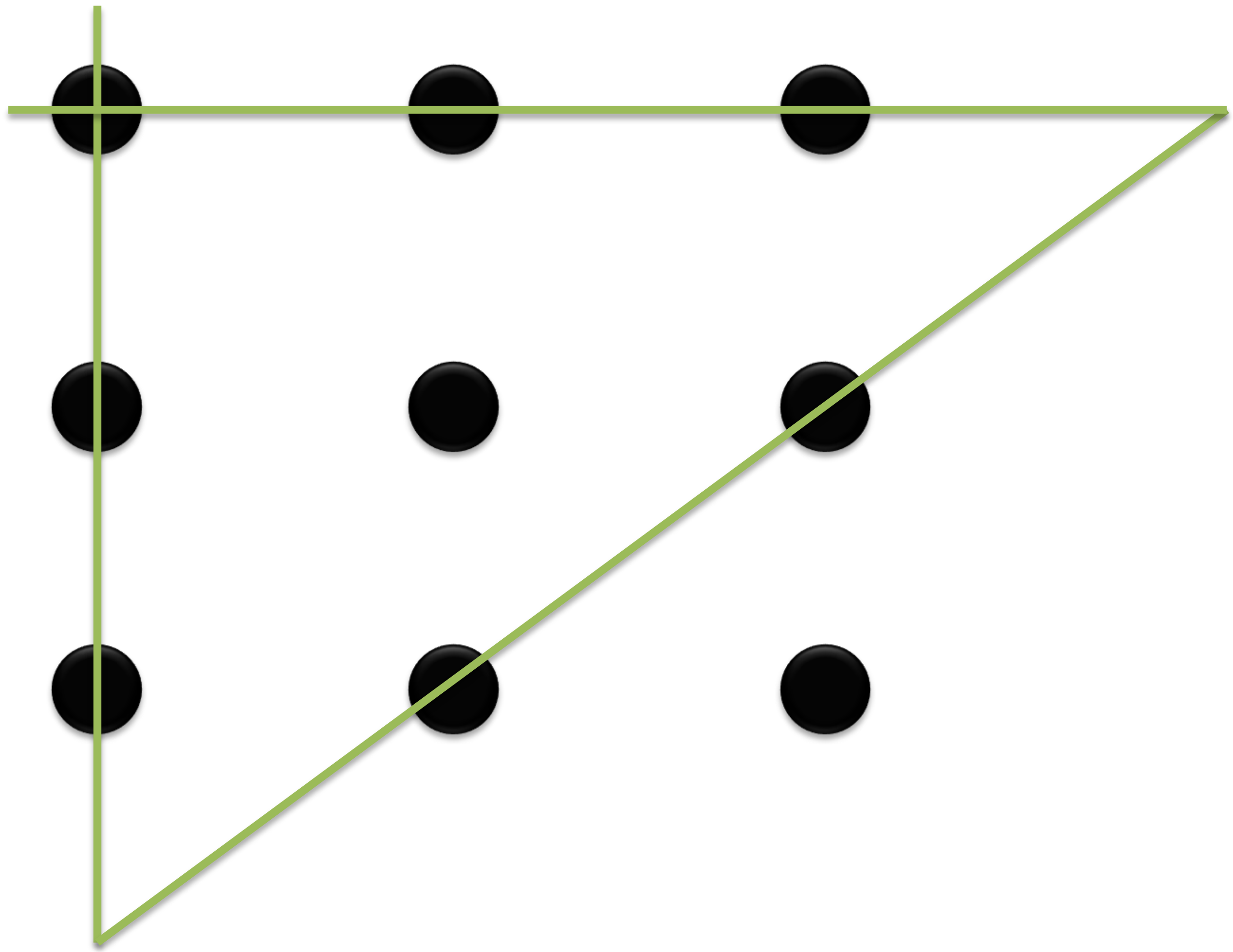

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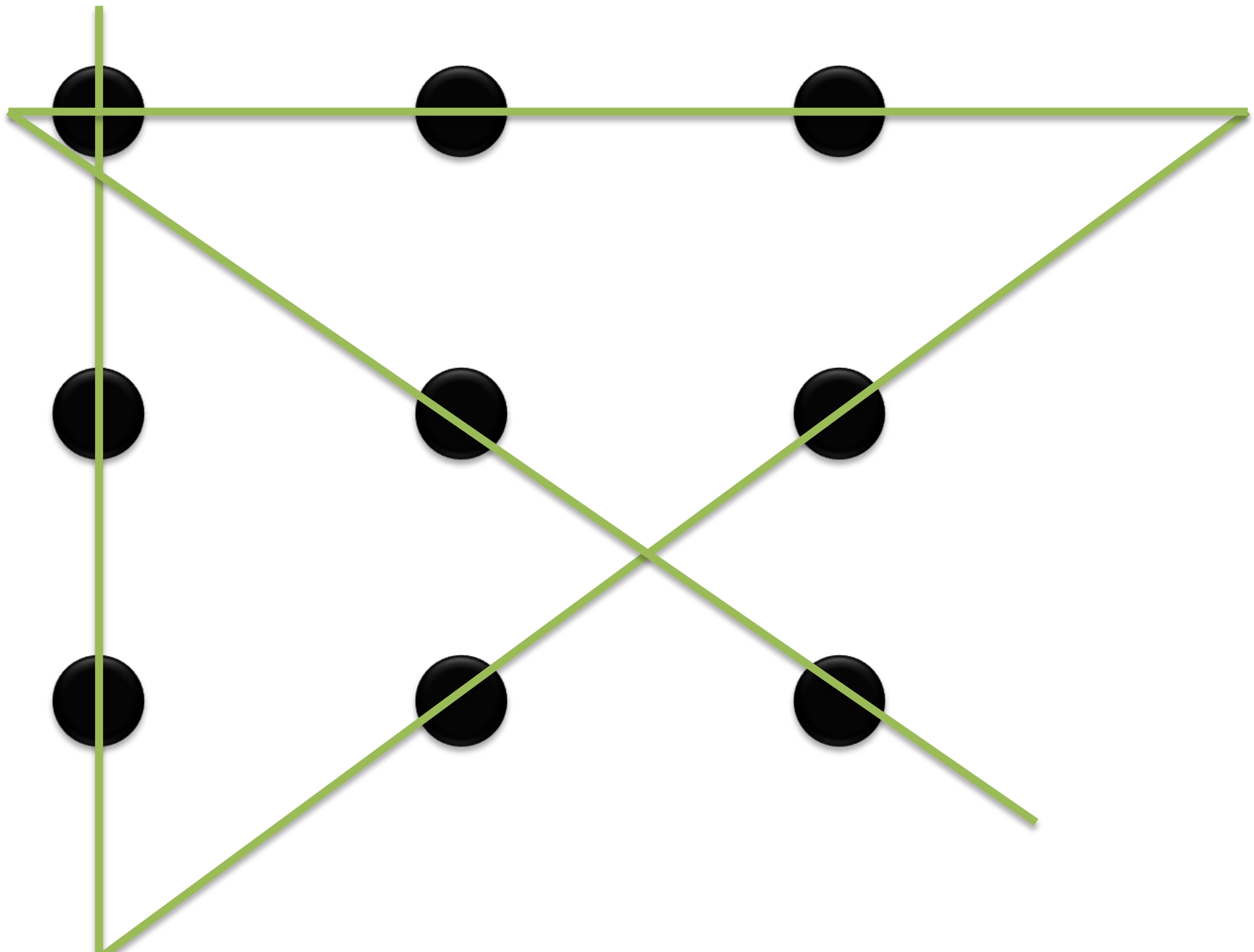

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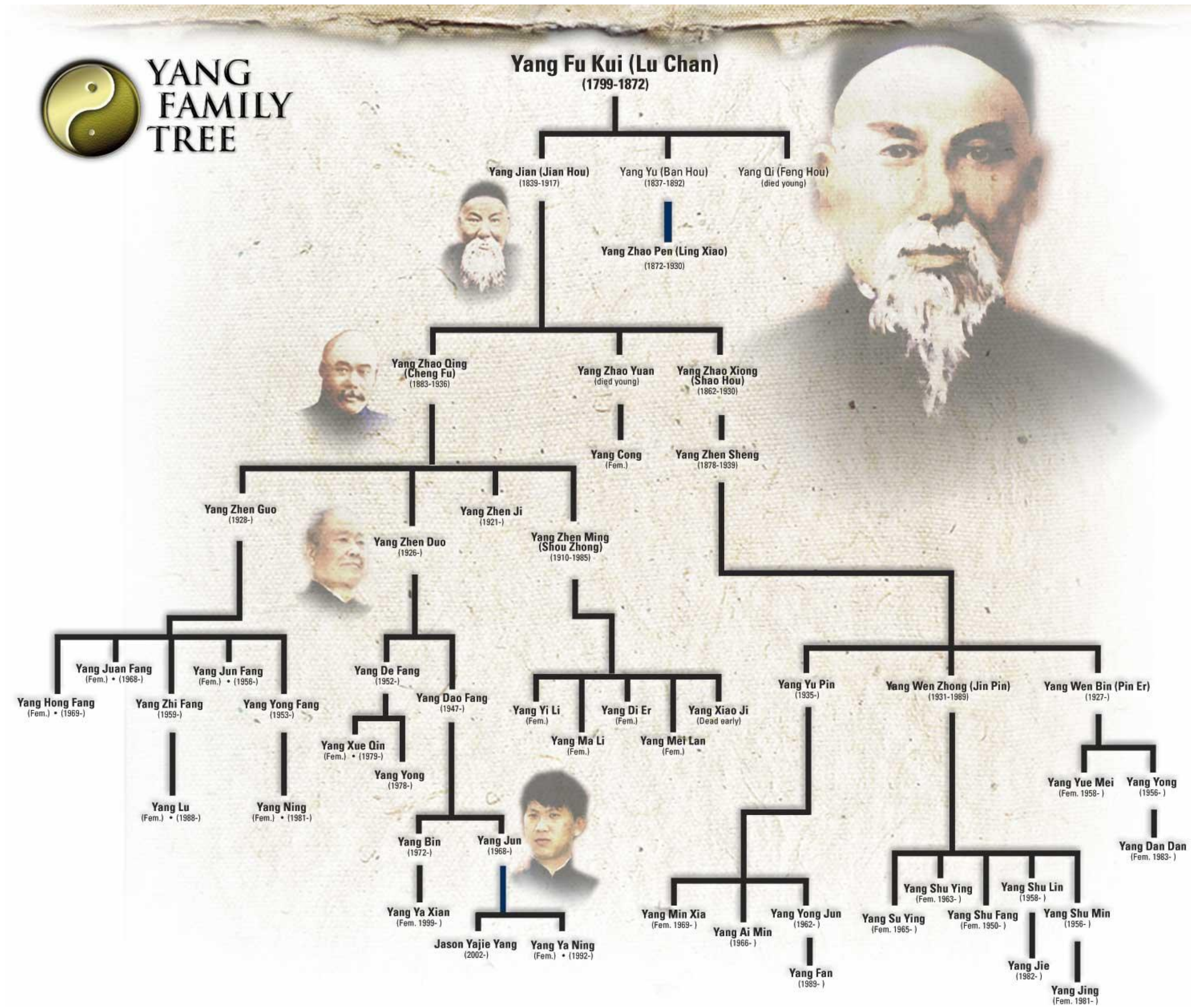
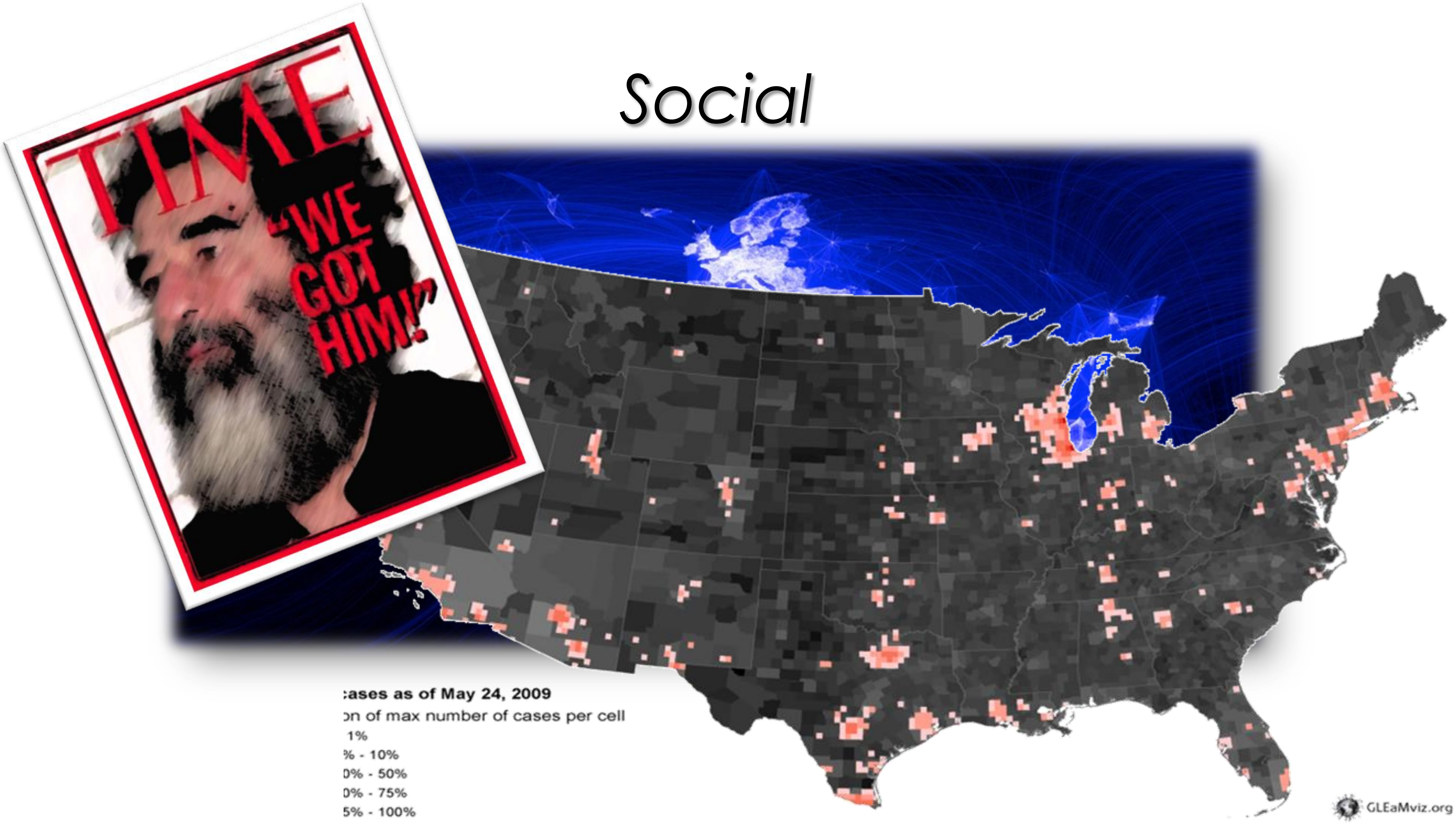


Networks

Social

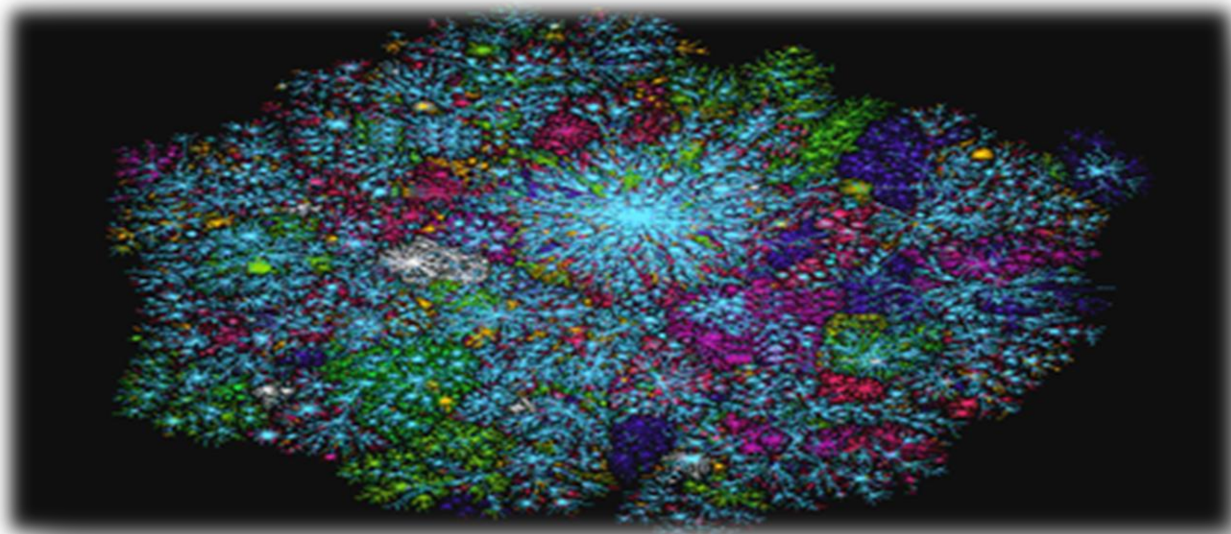
Networks

Social



Networks

technological



Networks

technological

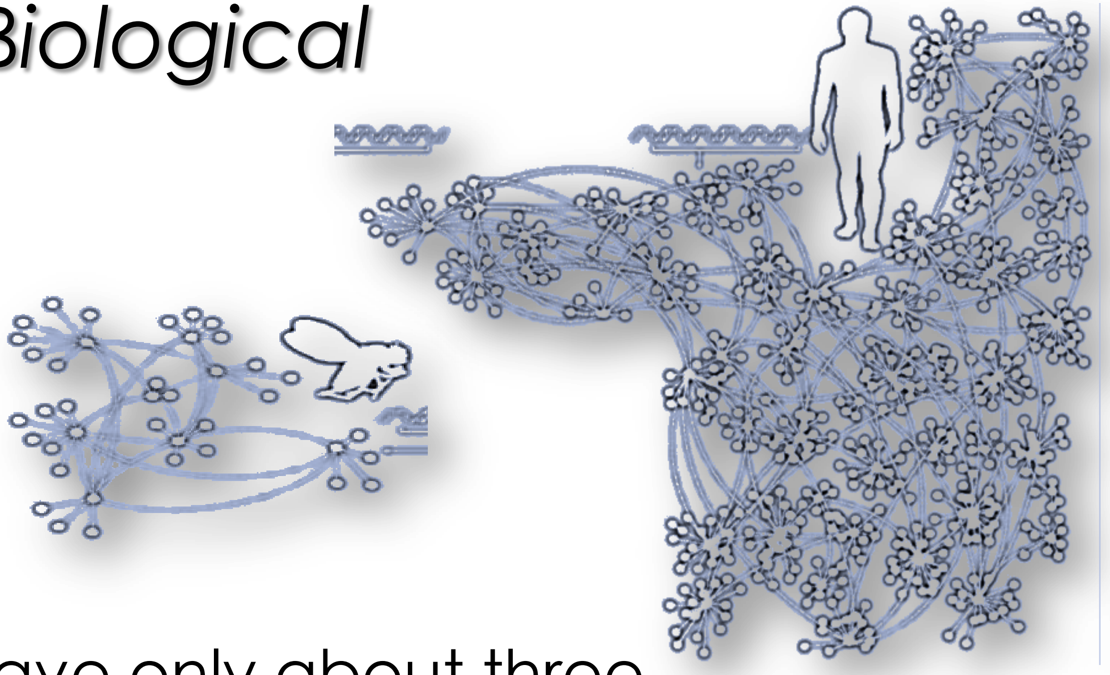
Networks

Biological

Humans have only about three times as many genes as the fly

Networks

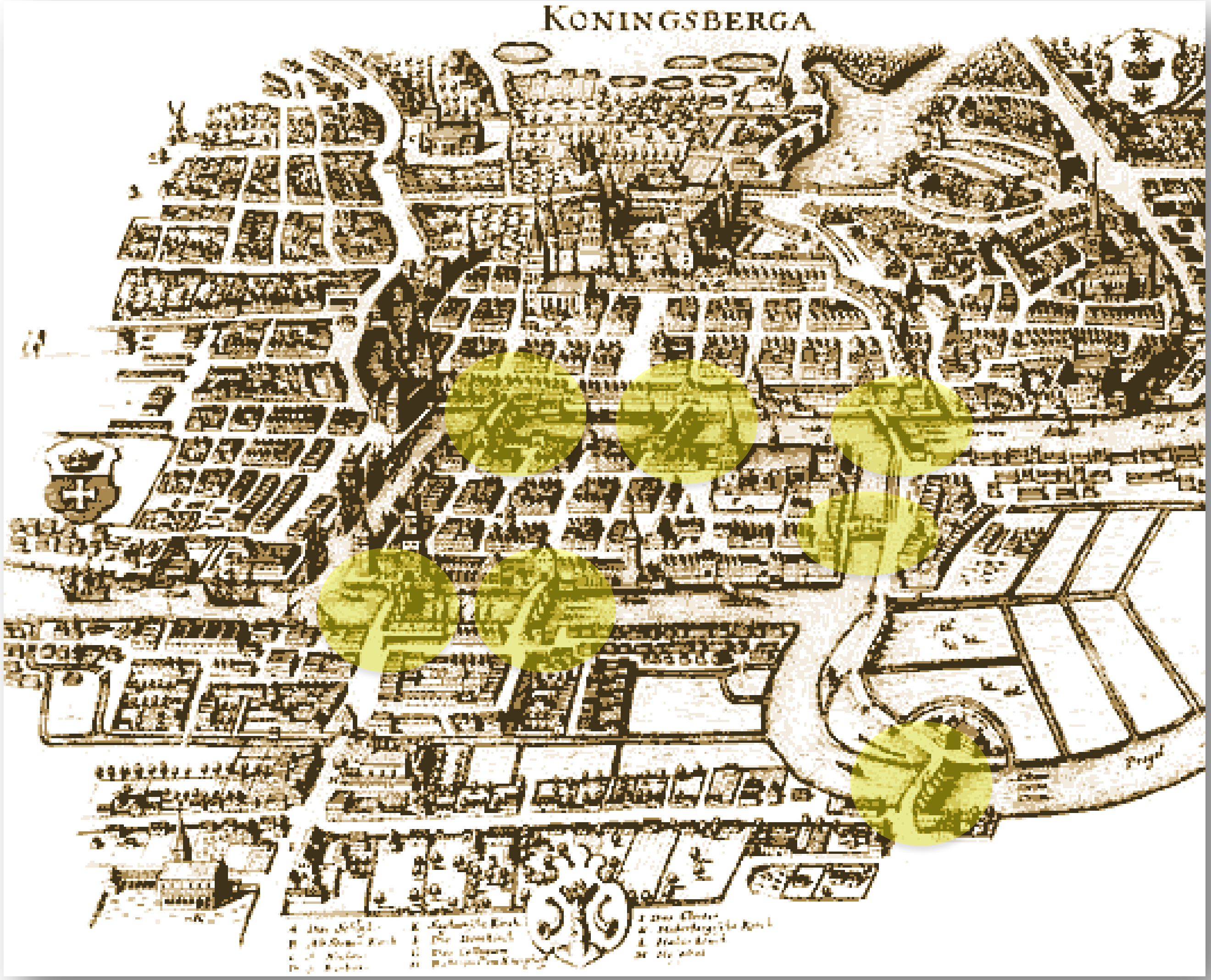
Biological



Humans have only about three times as many genes as the fly

Where it All Began – Back to 1735

Can one walk across the seven bridges and never cross the same bridge twice?



Where it All Began – Back to 1735

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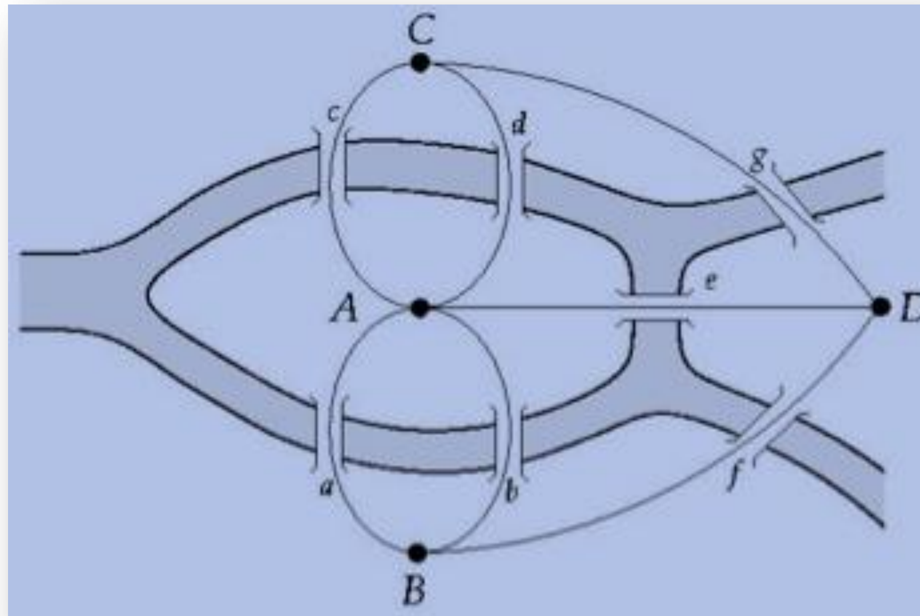
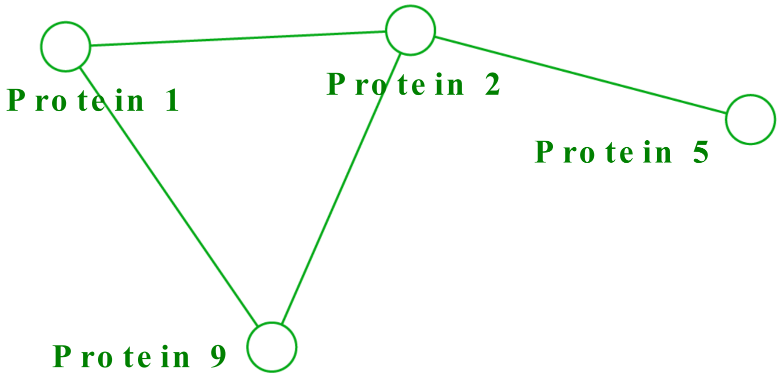
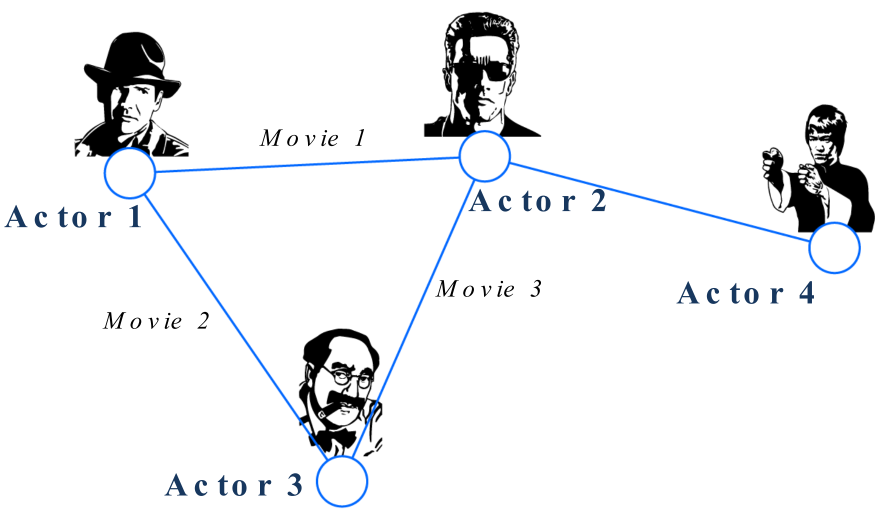


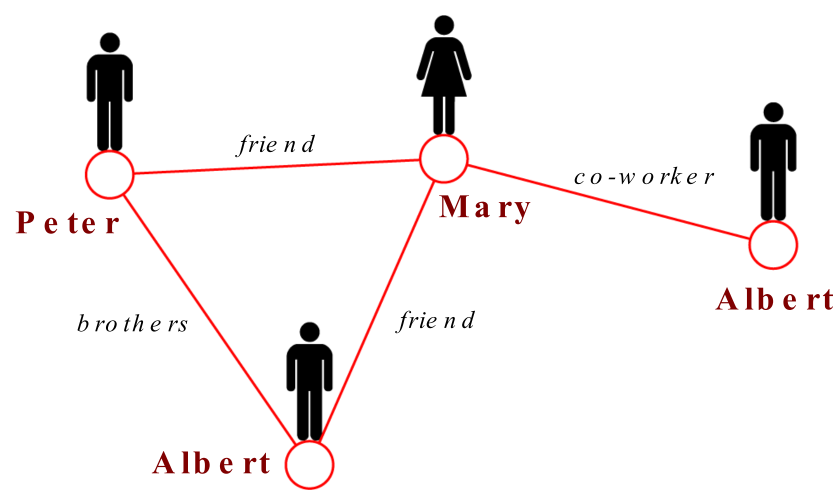
Abstracting the problem into a graph allows to develop a universal language

Networks

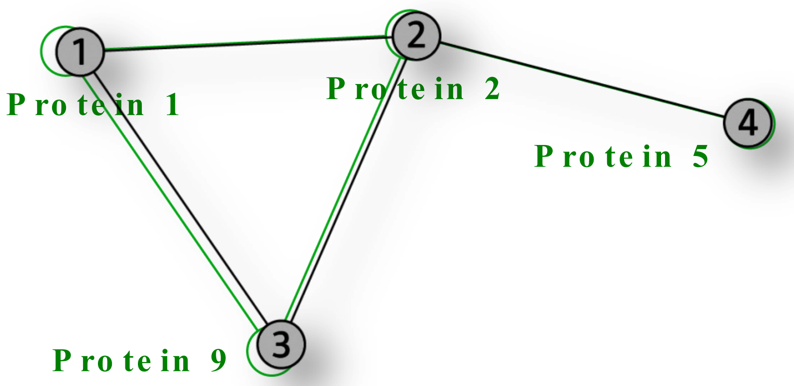


Abstracting the problem into a graph allows to develop a universal language

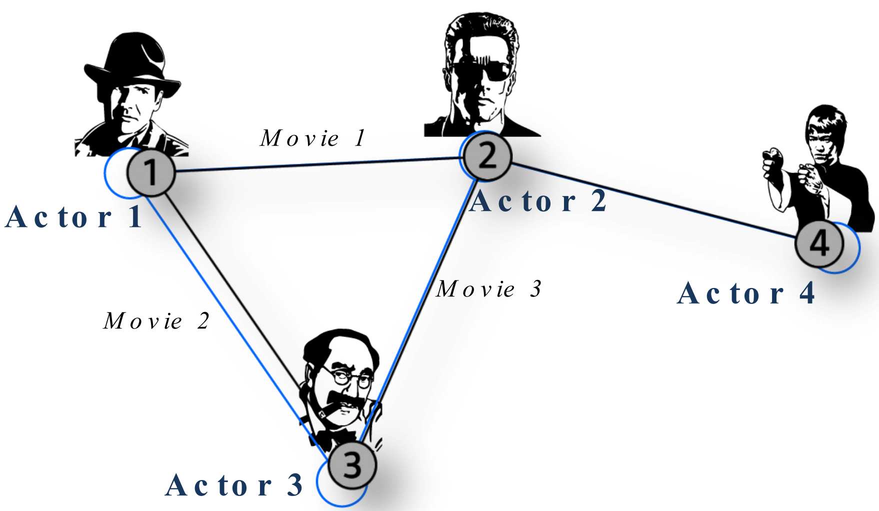


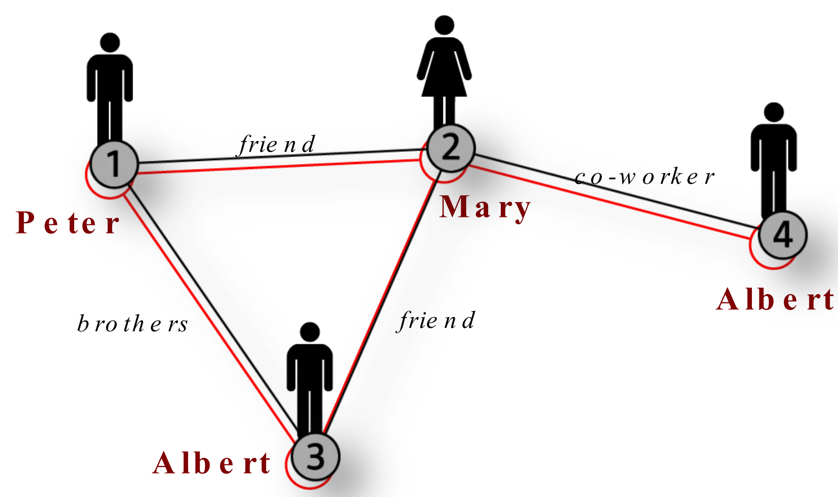


Networks

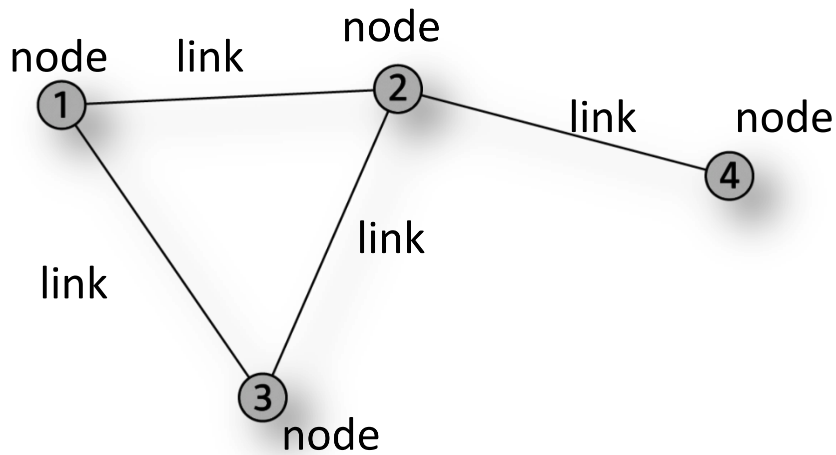


Abstracting the problem into a graph allows to develop a universal language





Networks



Networks & randomness

We extract a random number

This random number represents a single random node

Networks & randomness

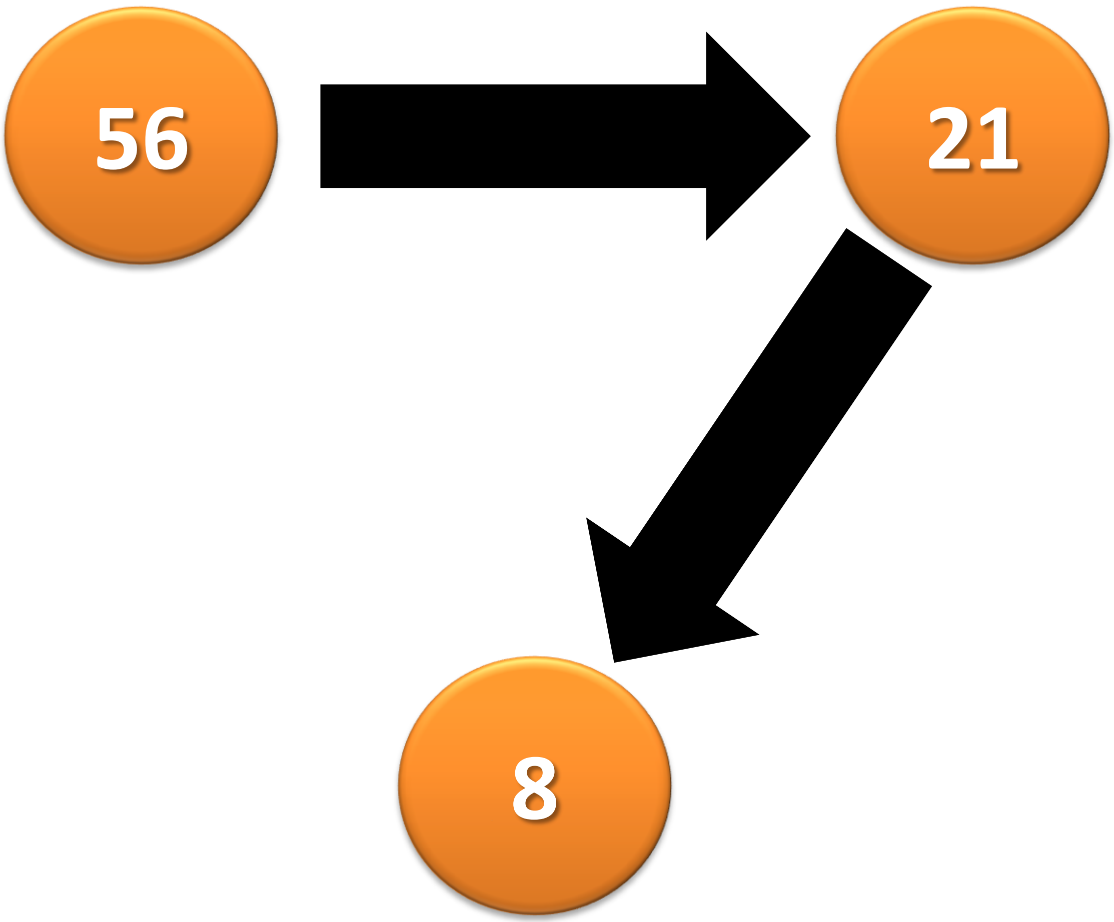
We extract a random number AGAIN

This random number represents the second single random node

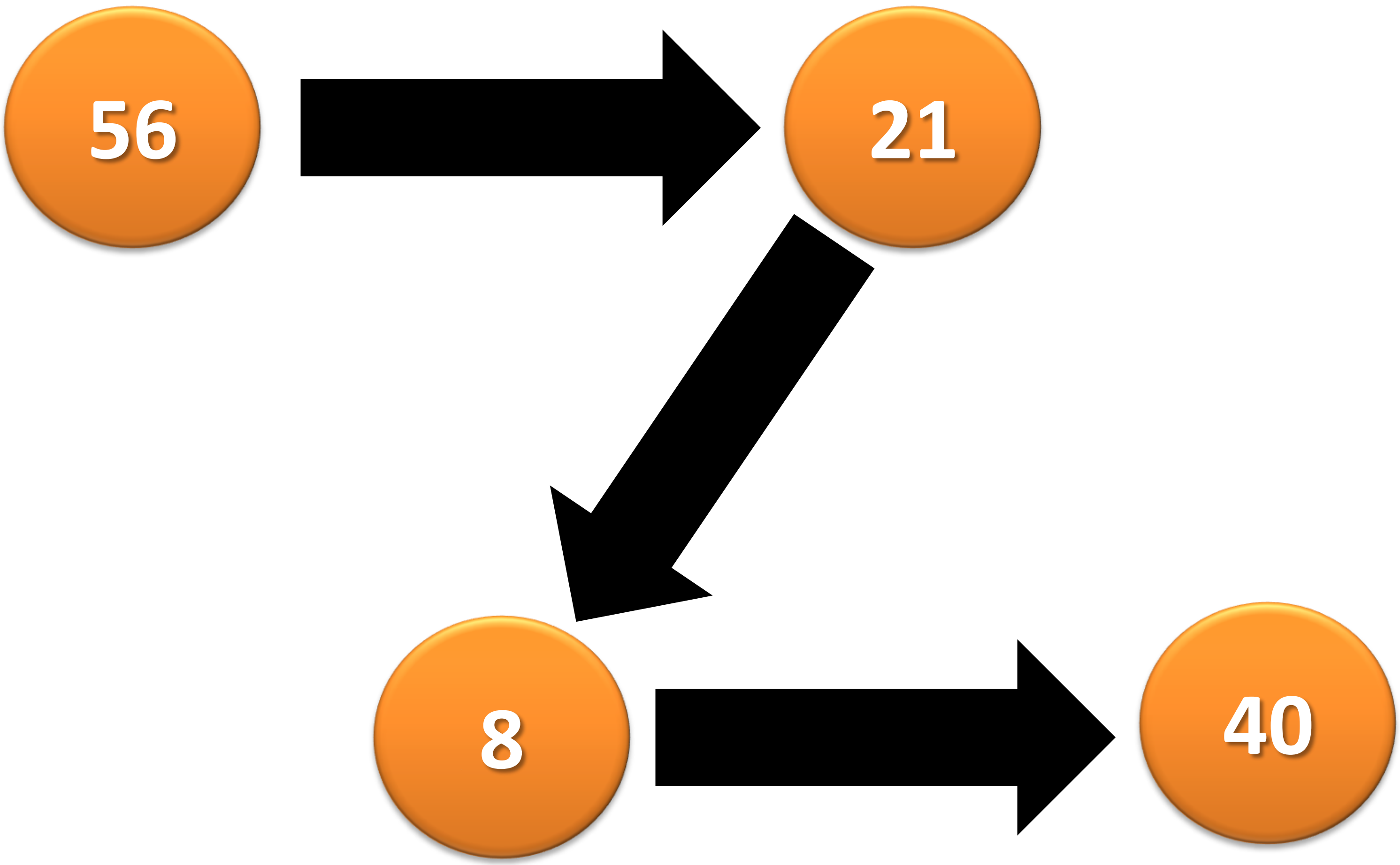
21

Networks & randomness

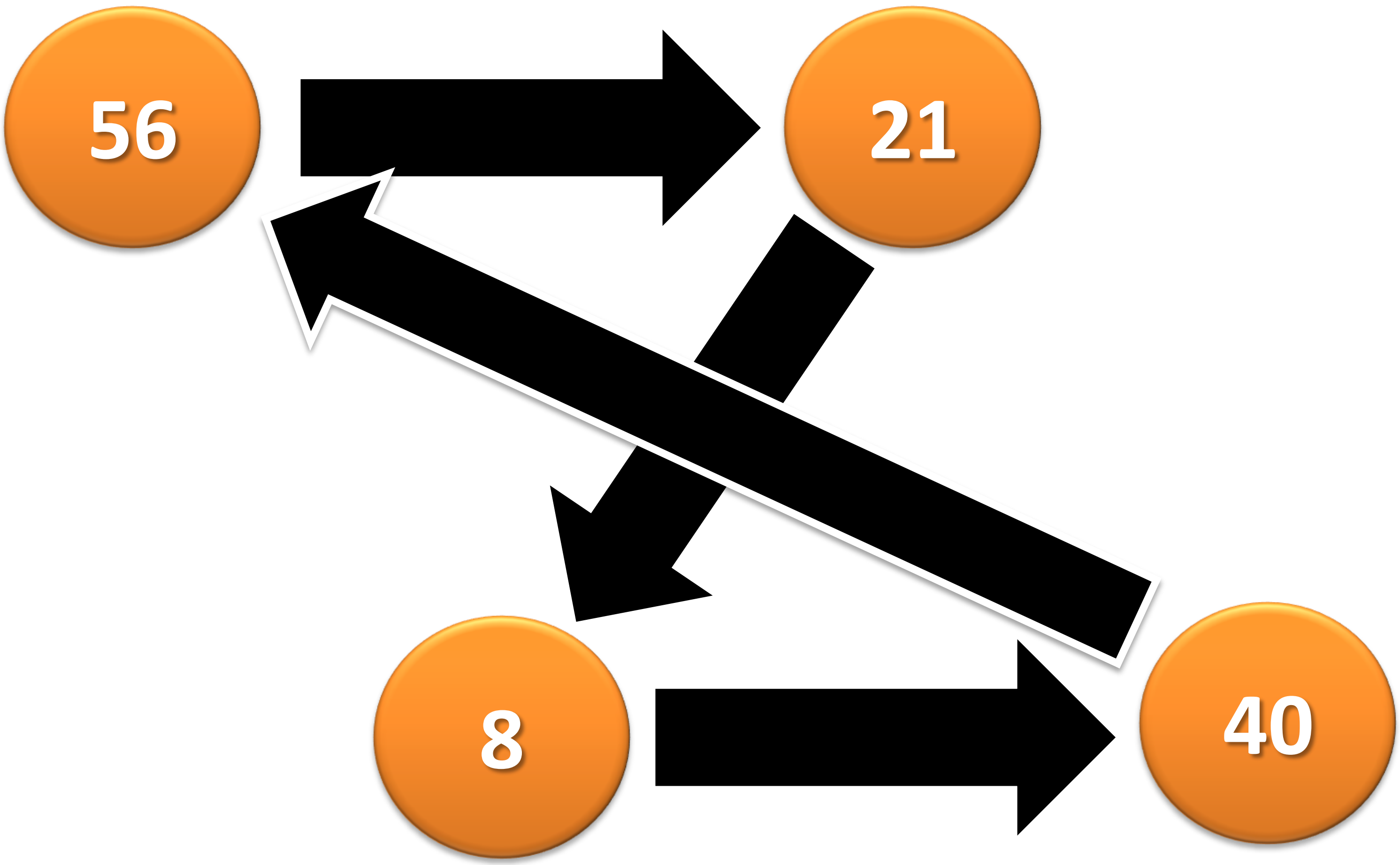
Networks & randomness



Networks & randomness



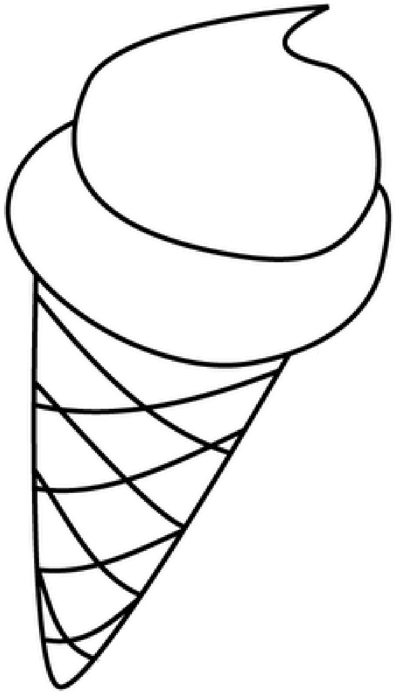
Networks & randomness



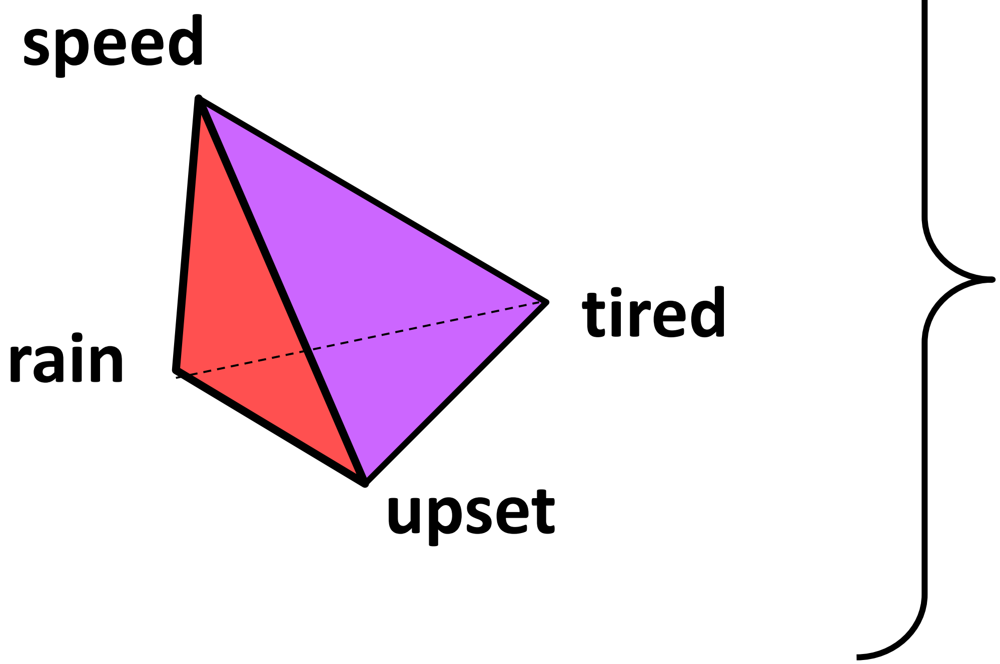
How can we generate a network?

Vanilla Ice Cream ≠ cold + yellow + soft + sweet + vanilla

We need a method to combine all the ingredients

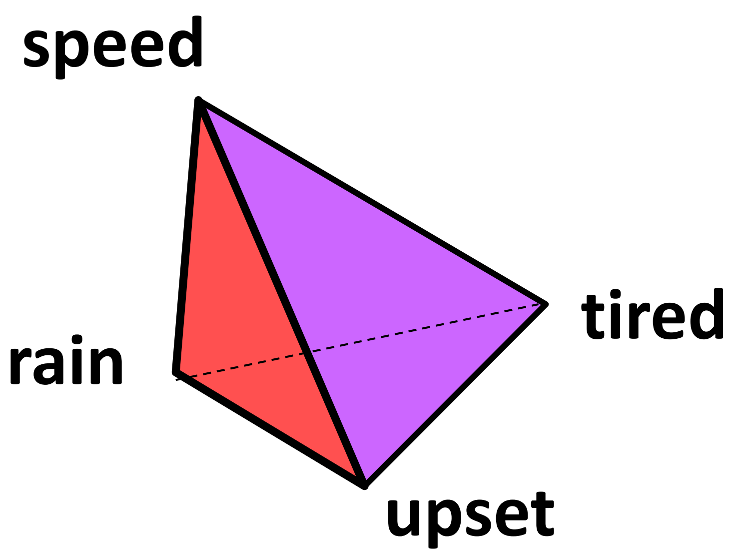


Example: Road Accidents



The accident is a ***whole***

Example: Road Accidents



The accident is a ***whole***

the individual ***parts*** may not cause an accident

The coffee break is not far ..

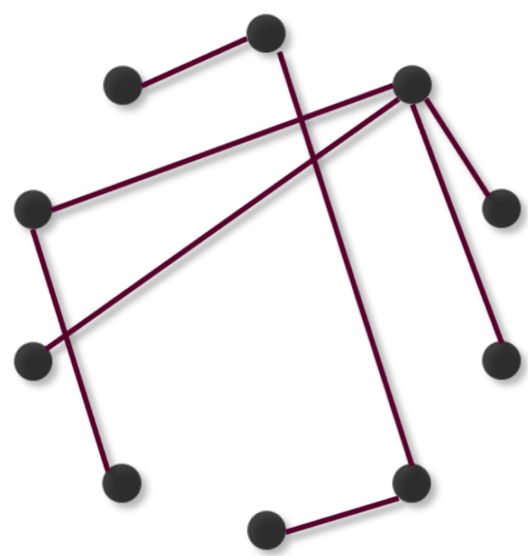
Let’s see what a network means

- Try to combine the different ingredients of a set in a way that you want.

The Erdős-Rényi Random Graph

- *Start with N nodes*
- *Connect each pair with probability p*
- *Obtain L links*

$L_{max} = N(N-1) / 2$



$N = 10$

$p = 1/6$

$L = 8$

The Erdős-Rényi Random Graph

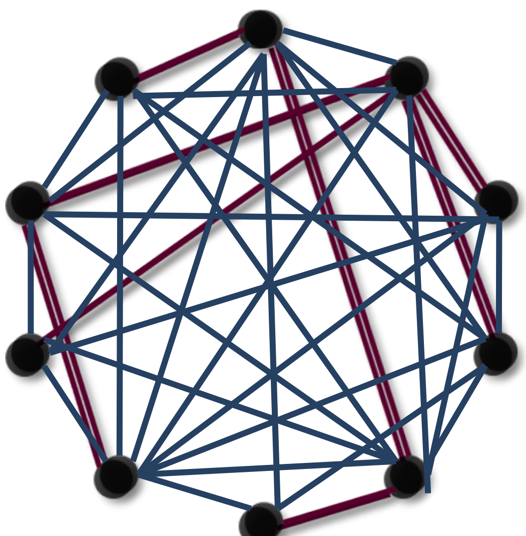
- ***Start with N nodes***
- ***Connect each pair with probability p***
- ***Obtain L links***

1/6 = 0.166

S = 8 / 45 = 0.177

L_{max} = N(N-1) / 2

$S = L / L_{max}$



N = 10

p = 1/6

L = 8

The Erdős-Rényi Random Graph

Density vs. Sparseness –

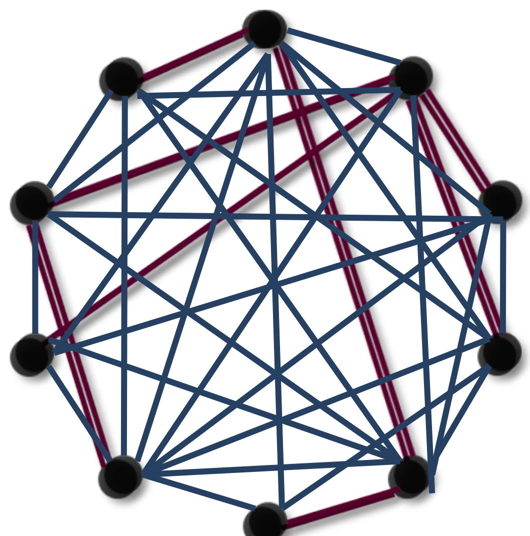
How many links are present vs. how many could there potentially be

1/6 = 0.166

$S = 8 / 45 = 0.177$

$L_{max} = N(N-1) / 2$

$S = L / L_{max}$



$N = 10$

$p = 1/6$

$L = 8$

The Erdős-Rényi Random Graph

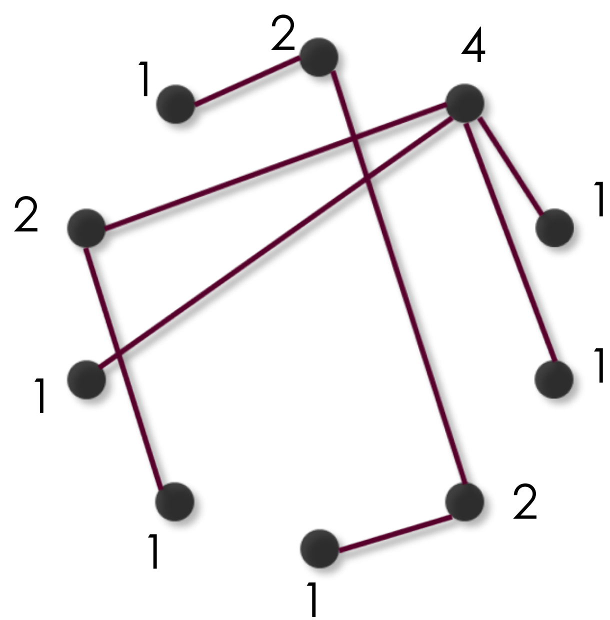
Degree –

The number of links of a node

$$\langle k \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i = \frac{2L}{N}$$

$$\langle k \rangle_{ER} = p(N-1)$$

→ <k> = 1.5



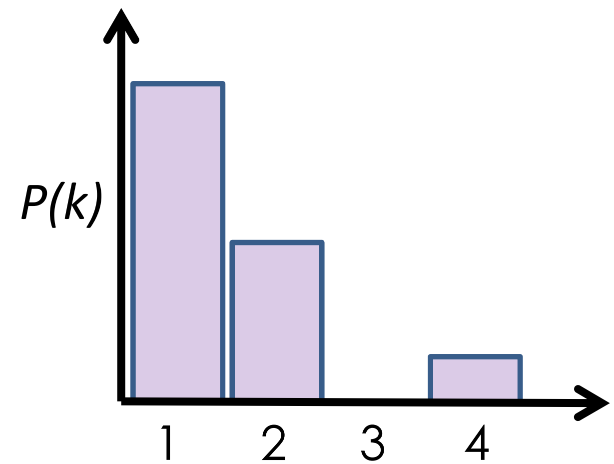
The Erdős-Rényi Random Graph

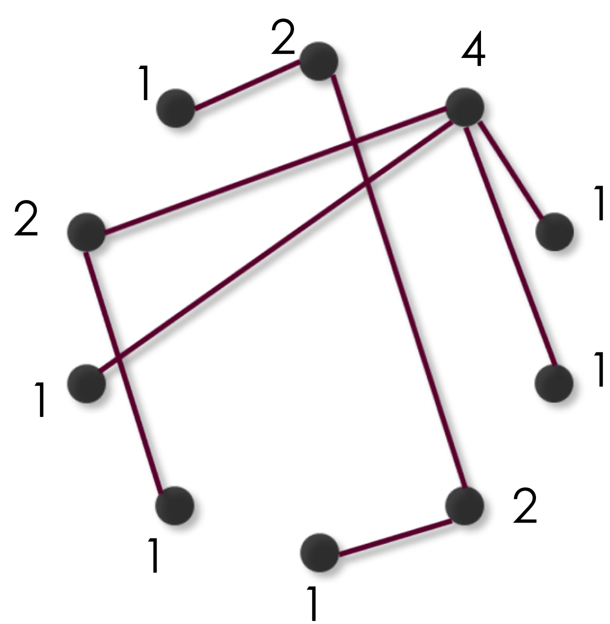
Degree Distribution -

The probability for a random node to have degree *k*.

$$\langle k \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i = \frac{2L}{N}$$

$$\langle k \rangle_{ER} = p(N-1)$$





The Erdős-Rényi Random Graph

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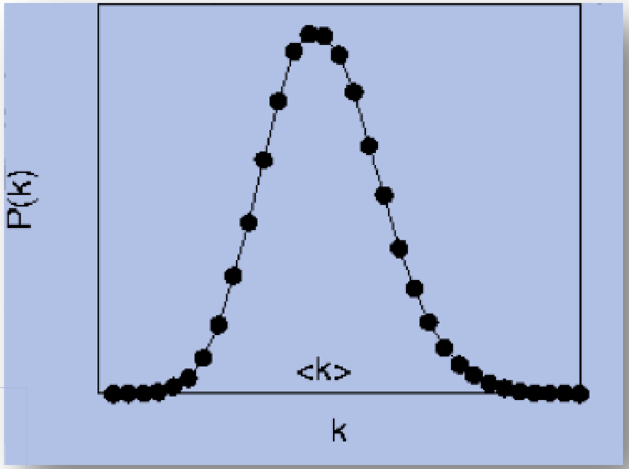
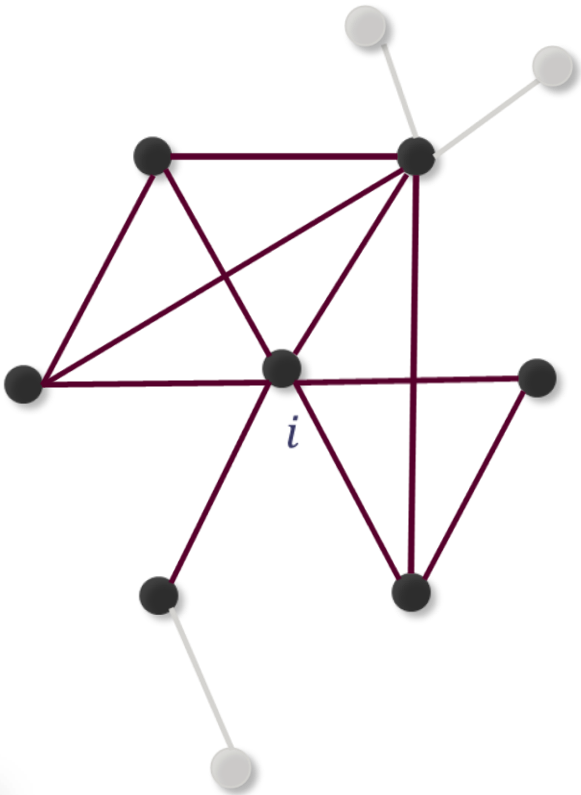


Clustering

Clustering Coefficient –

Characterizes the

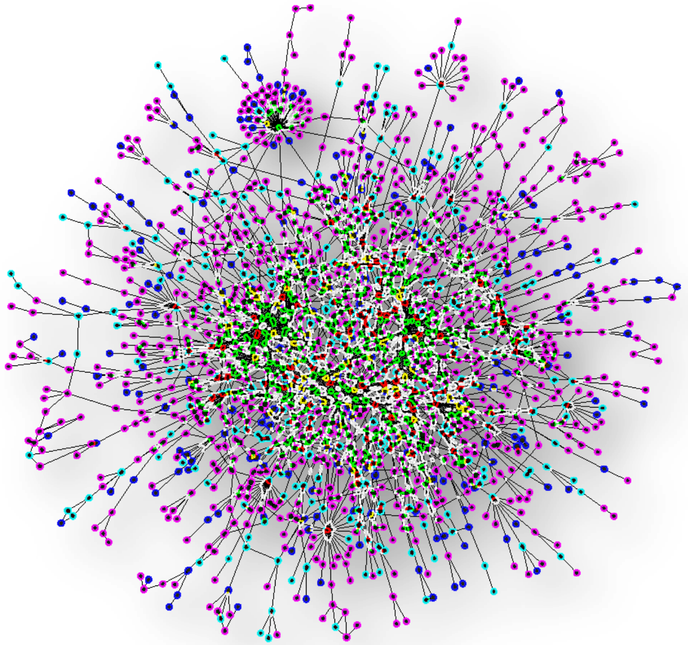
tendency to form triangles

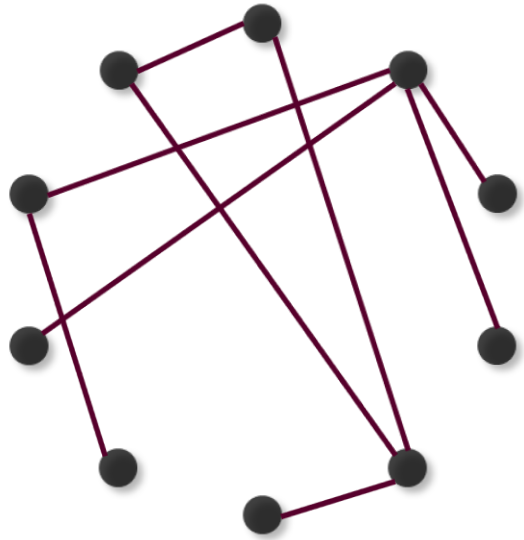


Types of Graphs

<u>**Undirected**</u>

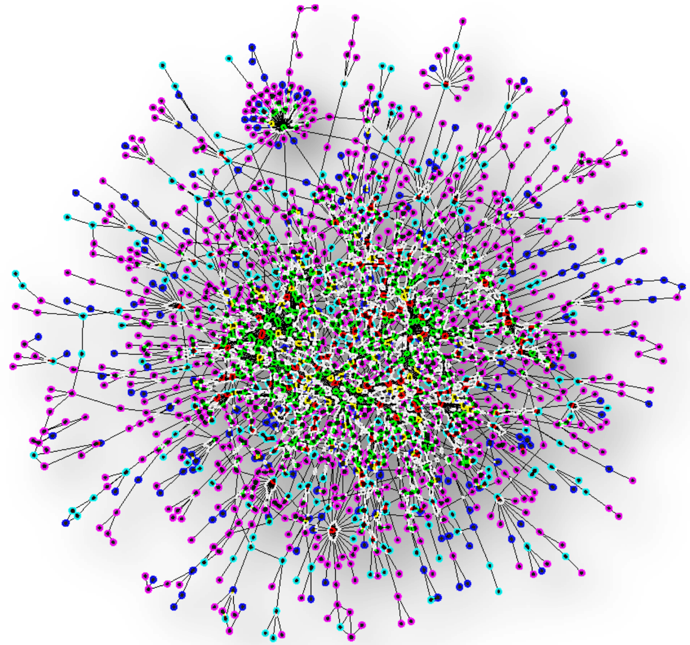
- Protein interaction networks
- Collaboration networks
- Actor co-stardom networks
- Internet





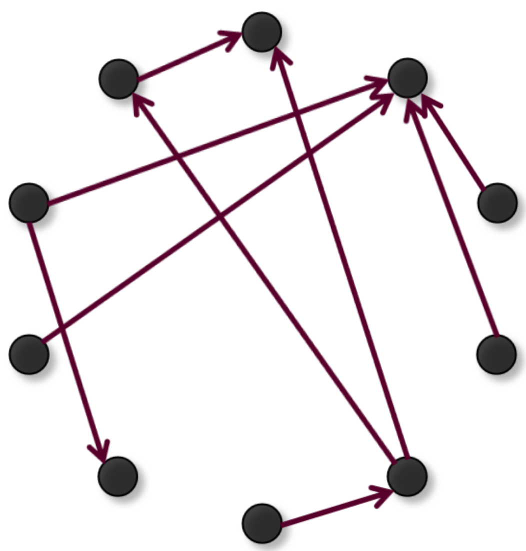
$$A_{ij} = \begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Types of Graphs



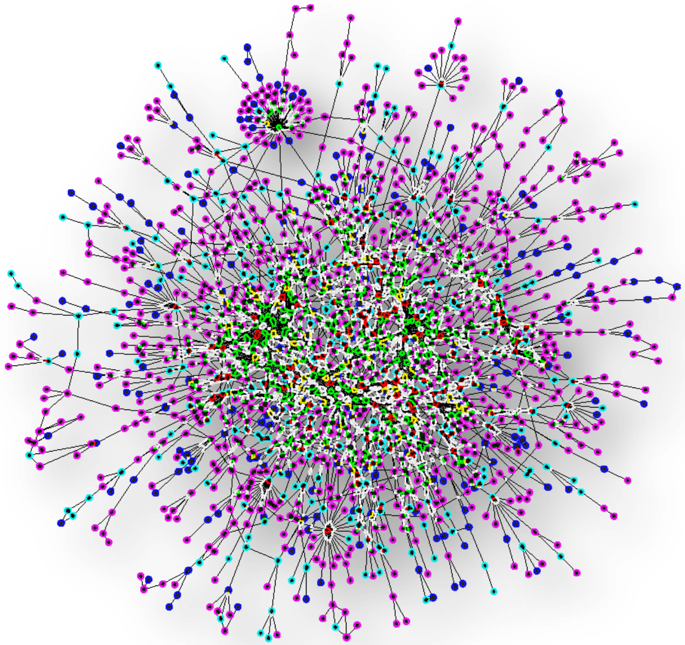
Directed

- Metabolic
- Citation networks
- World Wide Web



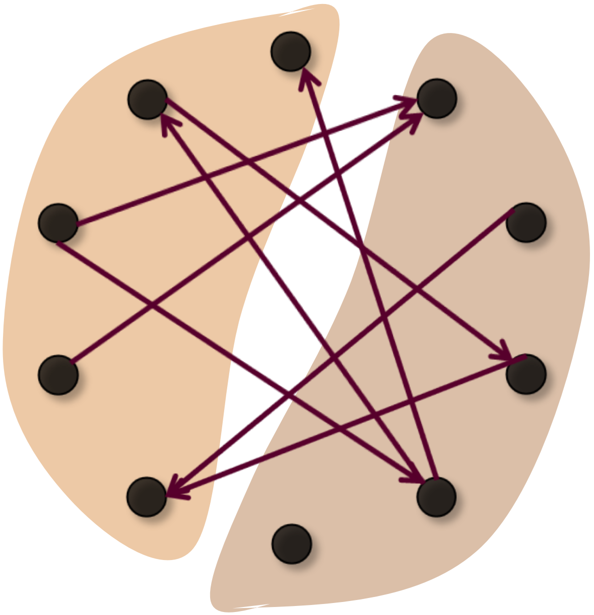
$$A_{ij} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Types of Graphs



Bipartite

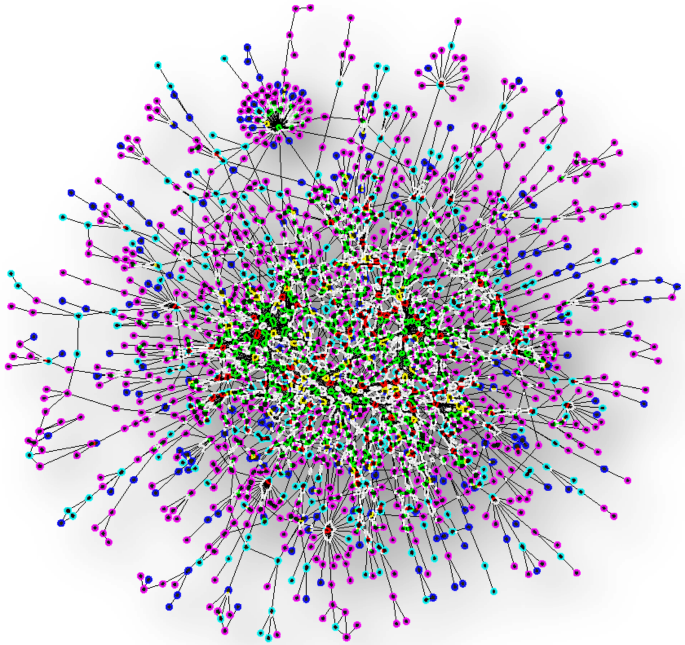
- Collaboration networks
- Actor co-stardom network
- Disease network

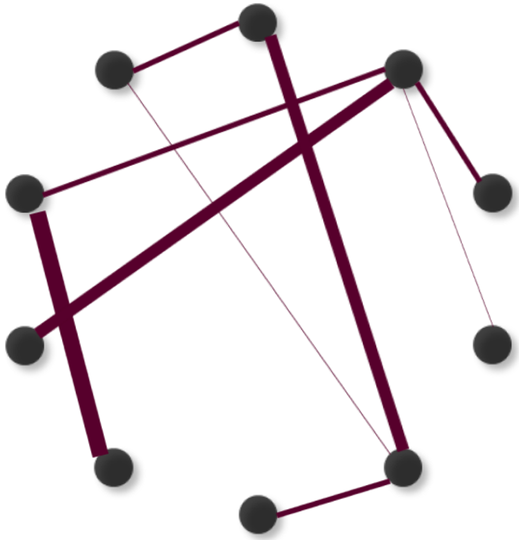


Types of Graphs

Weighted

- Metabolic networks
- Collaboration networks
- Actor co-stardom networks
- Social networks





$$A_{ij} = \begin{pmatrix} 0 & 0.8 & 0 & 0 & 0.1 & 0 \\ 0.1 & 0 & 0.3 & 0.4 & 0 & 0.6 \\ 0 & 0 & 0 & 0.8 & 0.9 & 0 \\ 0 & 0.3 & 0.5 & 0 & 0.3 & 0 \\ 0.2 & 0 & 0.7 & 0.2 & 0 & 0.2 \\ 0 & 0 & 0 & 0 & 0.6 & 0 \end{pmatrix}$$

A paradigm

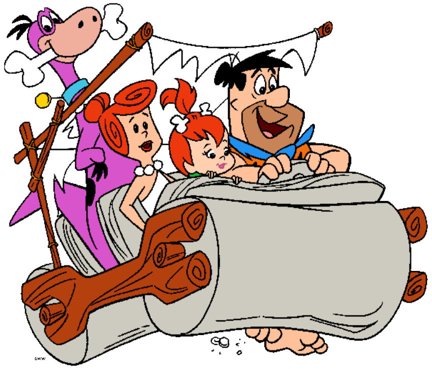
What kind of networks are the following ones:

Facebook

Twitter

Name	Market Price	OV / UN Valued	VE Rating	Last 12-M Return(%)	Forecast 1-Yr Return(%)	P/E Ratios	Industry	Value Level	Pivot	Risky Level
BROCADE COMM SY	$5.53	15.3	3	0.5	4.4	10.8	NETWORKS	5.23 Q		6.08 A
DIGI INTL INC	$9.75	7.4	3	11.5	1.5	36.3	NETWORKS	9.08 W		12.37 S
EMULEX CORP	$6.32	43.6	3	15.5	4.5	9.6	NETWORKS	5.76 S	6.49 Q	6.66 W
EMAGIN CORP	$3.27	45.1	3	17.4	0.0	44.6	PERIPHERAL EQUIPMENT	3.15 W		3.85 M
EXTREME NETWRKS	$3.61	13.2	3	19.9	1.1	20.1	NETWORKS	3.18 M	3.68 W	5.06 A
INTERMEC INC	$7.98	16.7	3	8.6	0.3	72.6	PERIPHERAL EQUIPMENT	5.04 M		8.08 W
INFINERA CORP	$5.79	26.9	3	15.4	3.0	N/A	NETWORKS	5.01 W		6.87 S
KEY TRONIC	$9.87	21.3	3	105.6	2.5	7.5	PERIPHERAL EQUIPMENT	7.49 Q	9.94 W	10.37 M
LOGITECH INTL	$7.52	31.7	3	3.2	2.8	14.0	PERIPHERAL EQUIPMENT	6.12 W		9.87 M
MITEK SYSTEMS	$3.45	106.8	3	58.4	0.1	N/A	OPTICAL RECOGNITION	3.01 A	3.24 A	5.57 S
NOVATEL WIRELES	$1.31	18.5	2	56.5	9.6	N/A	PERIPHERAL EQUIPMENT	1.09 W		3.67 Q
PLANAR SYSTEMS	$1.19	49.5	2	40.2	9.1	N/A	PERIPHERAL EQUIPMENT	1.05 S	1.18 W	1.78 Q
QLOGIC CORP	$8.83	49.1	3	41.3	4.1	11.4	NETWORKS	7.57 A	8.60 W	12.02 Q
SIERRA WIRELESS	$7.95	26.0	3	14.9	3.1	12.0	PERIPHERAL EQUIPMENT	7.53 A	8.14 Q	9.17 M
TRANSACT TECH	$7.43	9.6	3	12.2	1.1	16.2	PERIPHERAL EQUIPMENT	6.74 S	7.53 M	7.72 W

stocks



Family

internet

Transportation

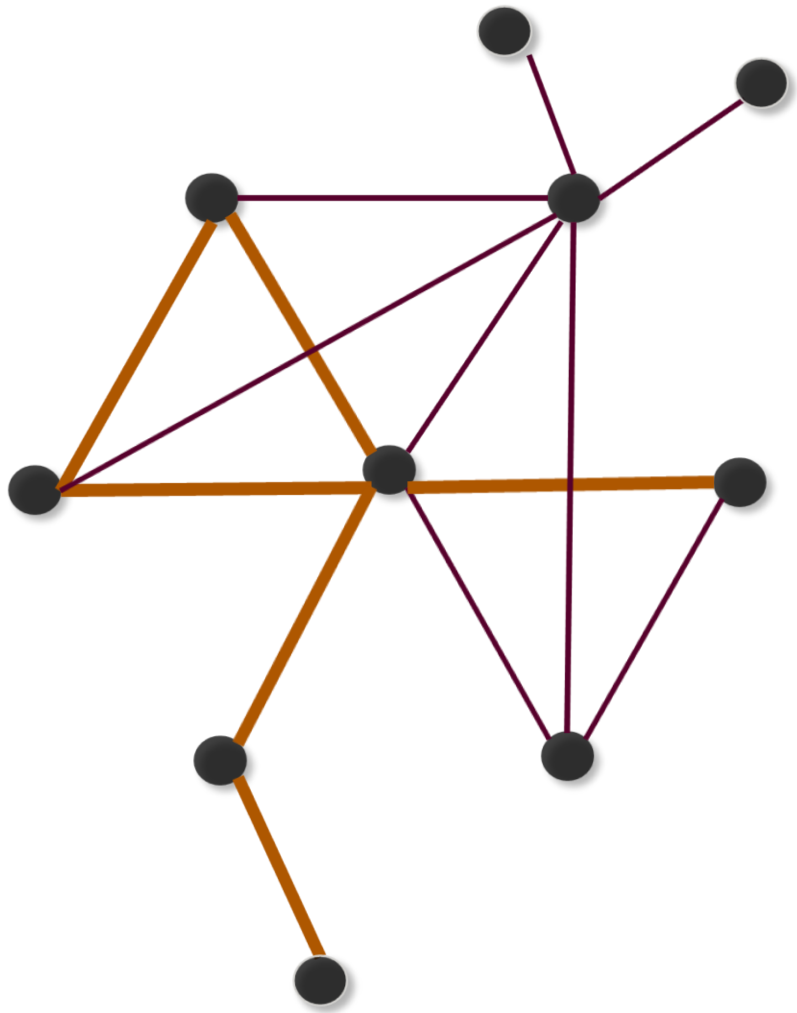
The metric of paths

Network Distance –

the minimum number of edges

between a pair of nodes

$D_{ij} = 3$



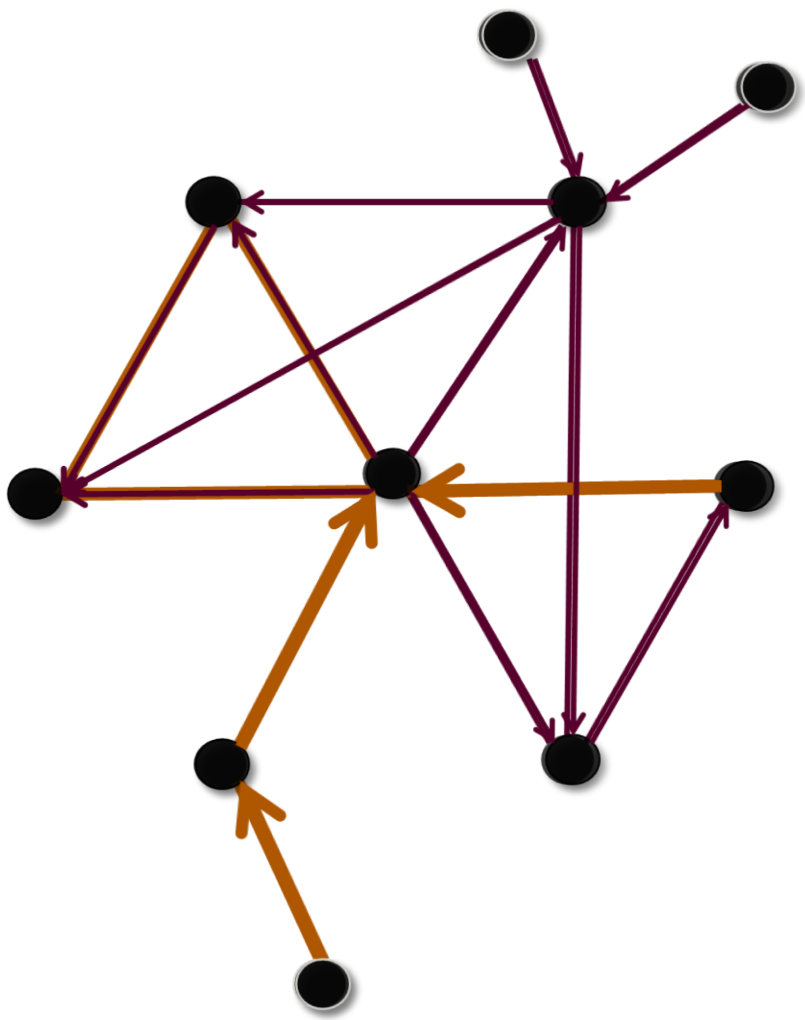
The metric of paths

Network Distance –

the minimum number of edges

between a pair of nodes

$D_{ij} = 4$



The metric of paths

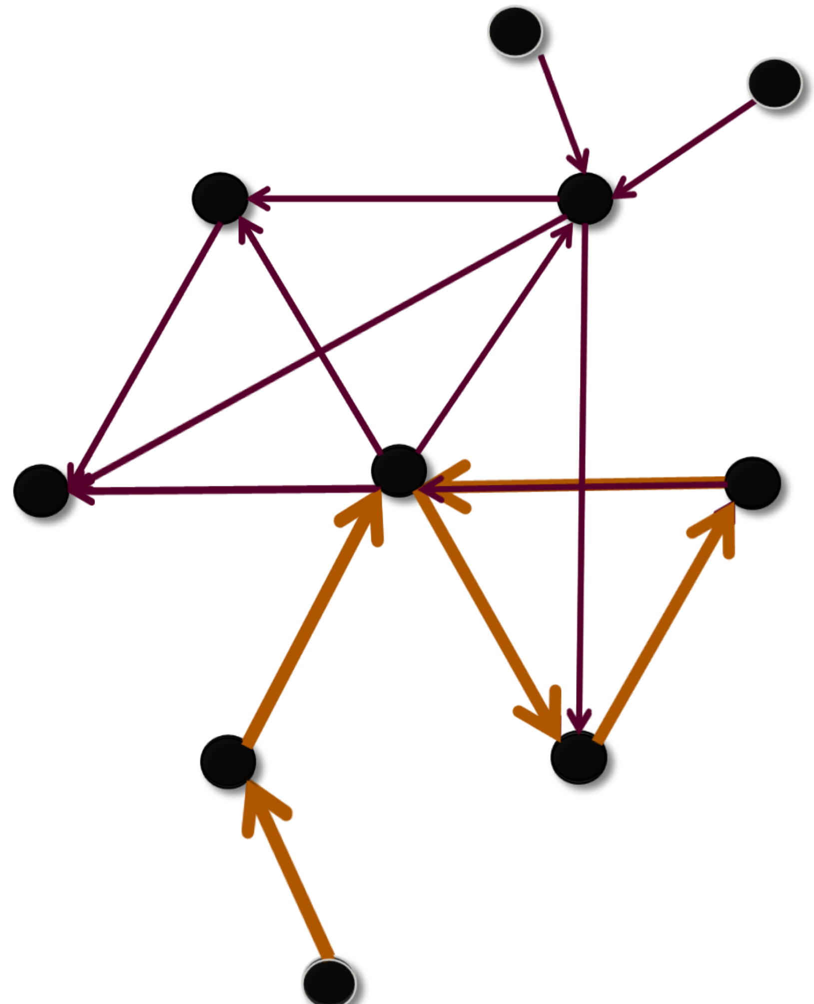
Network Distance –

the minimum number of edges

between a pair of nodes

$D_{ji} = \infty$

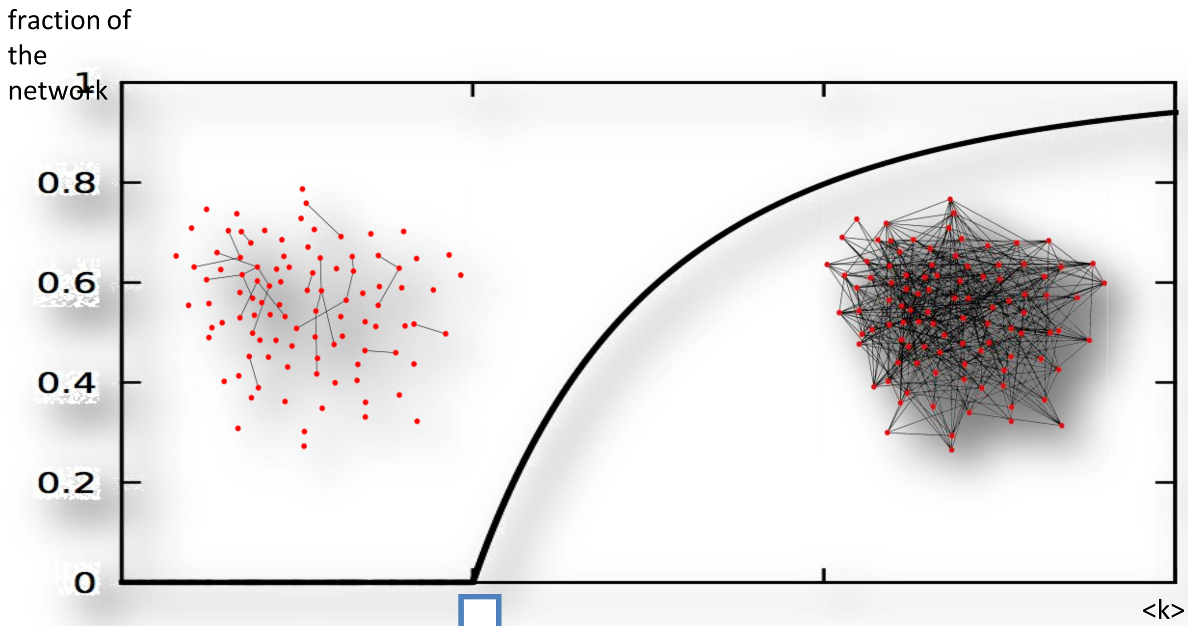
$D_{ij} = 4$



Giant Component

Component –

A group of nodes that can be reached by finite paths from one another



$$\langle k \rangle_{crit.} = 1$$

Giant Component

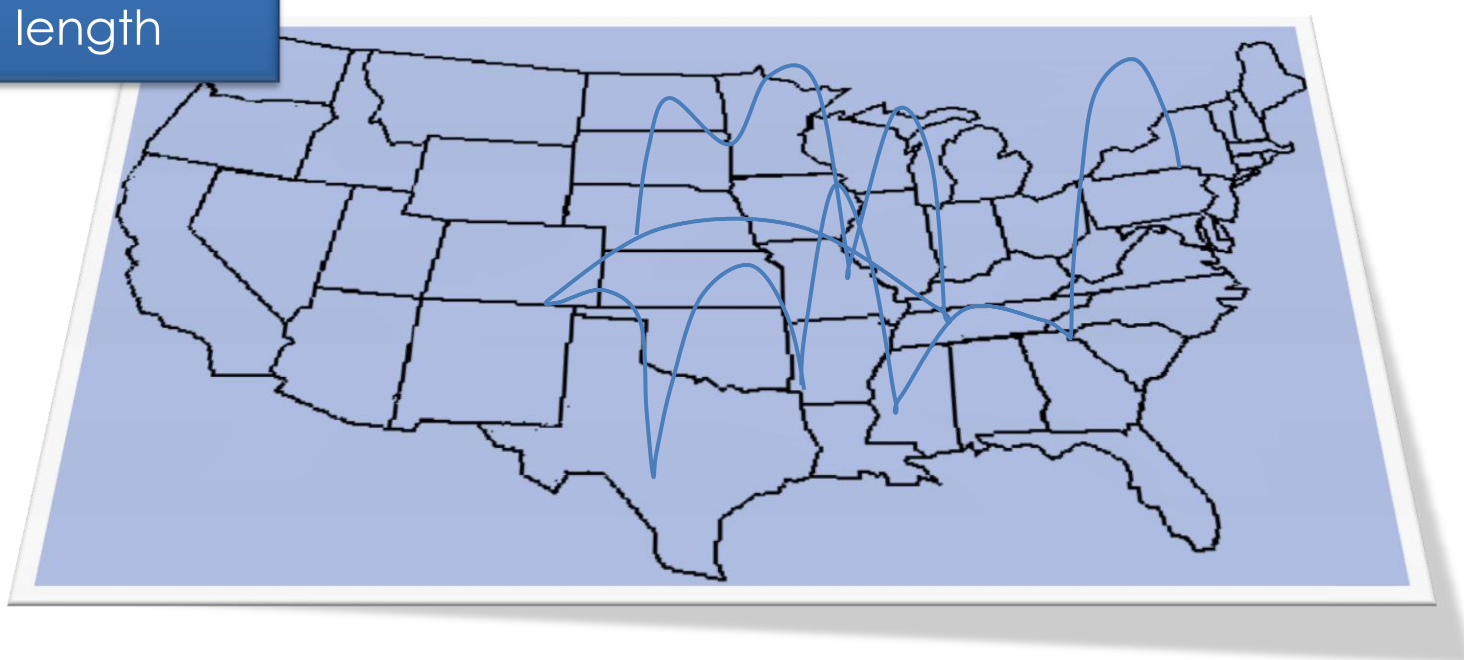
Radius –

Average path length

Diameter –

Maximum path length

HOMEWORK 1 :
Search for ..
"Milgram's Experiment -
Six Degrees of Separation"



A Paradigm

ROMANIA
VIDIN
SILISTRA
ROUSSE
MONTANA
PLEVEN
RAZGRAD
DOBRICH
VRATSA
SHUMEN
SERBIA
VELIKO TARNOVO
TARGOVISHTE
VARNA
LOVECH
GABROVO
SOFIA
SOFIA REGION
SLIVEN
BLACK SEA
PERNIK
STARA ZAGORA
BURGAS
YAMBOL
КЮСТЕНДИЛ
PAZARDZHIK
PLOVDIV
HASKOVO
BLAGOEVGRAD
MACEDONIA
TURKEY
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KARDZHALI
GREECE

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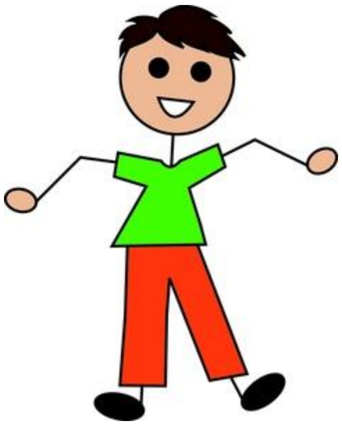
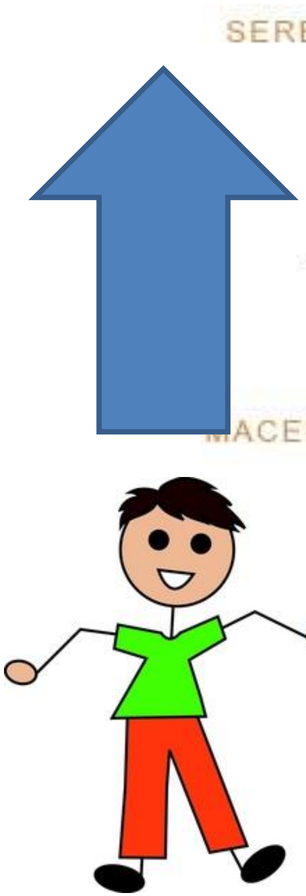


A Paradigm

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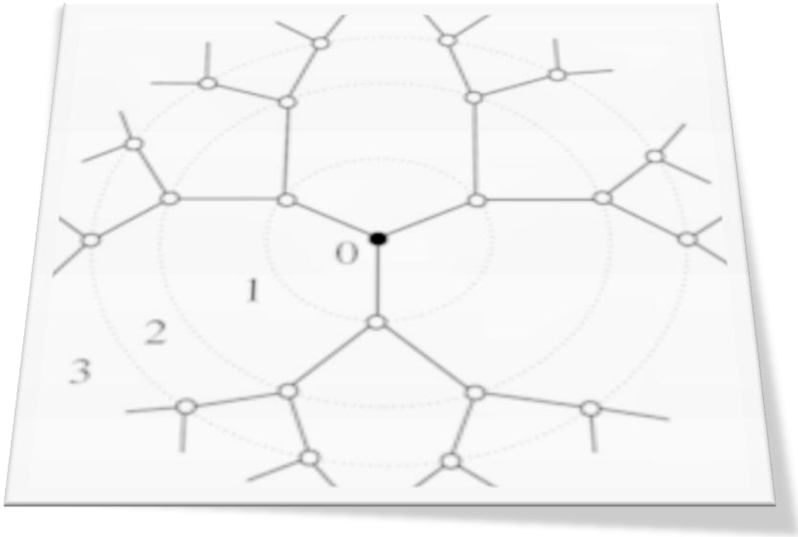
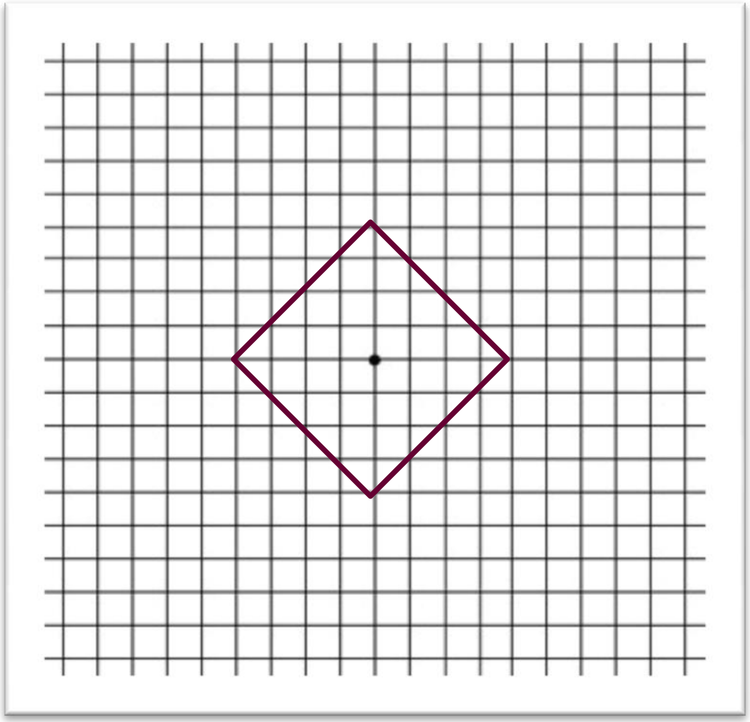
KARDZHALI
GREECE

The exploding volume of networks

The secret behind the small world effect – Looking at the network volume

$S(d) = 4d$

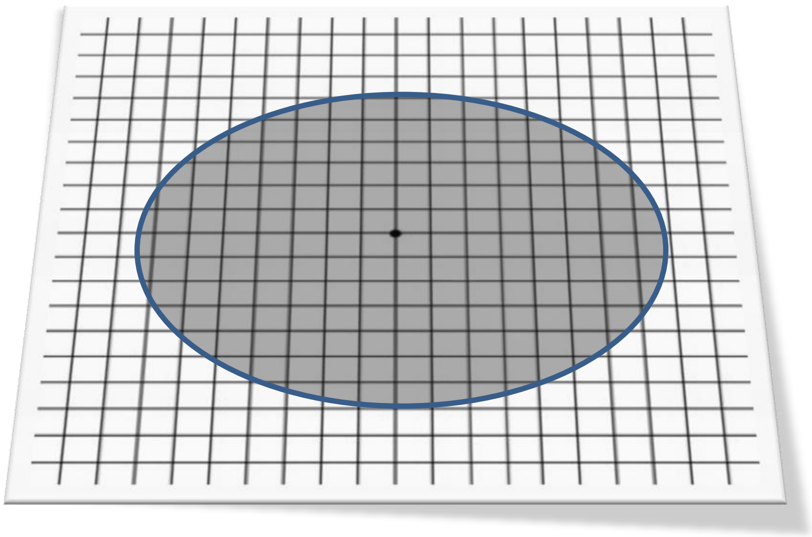




The exploding volume of networks

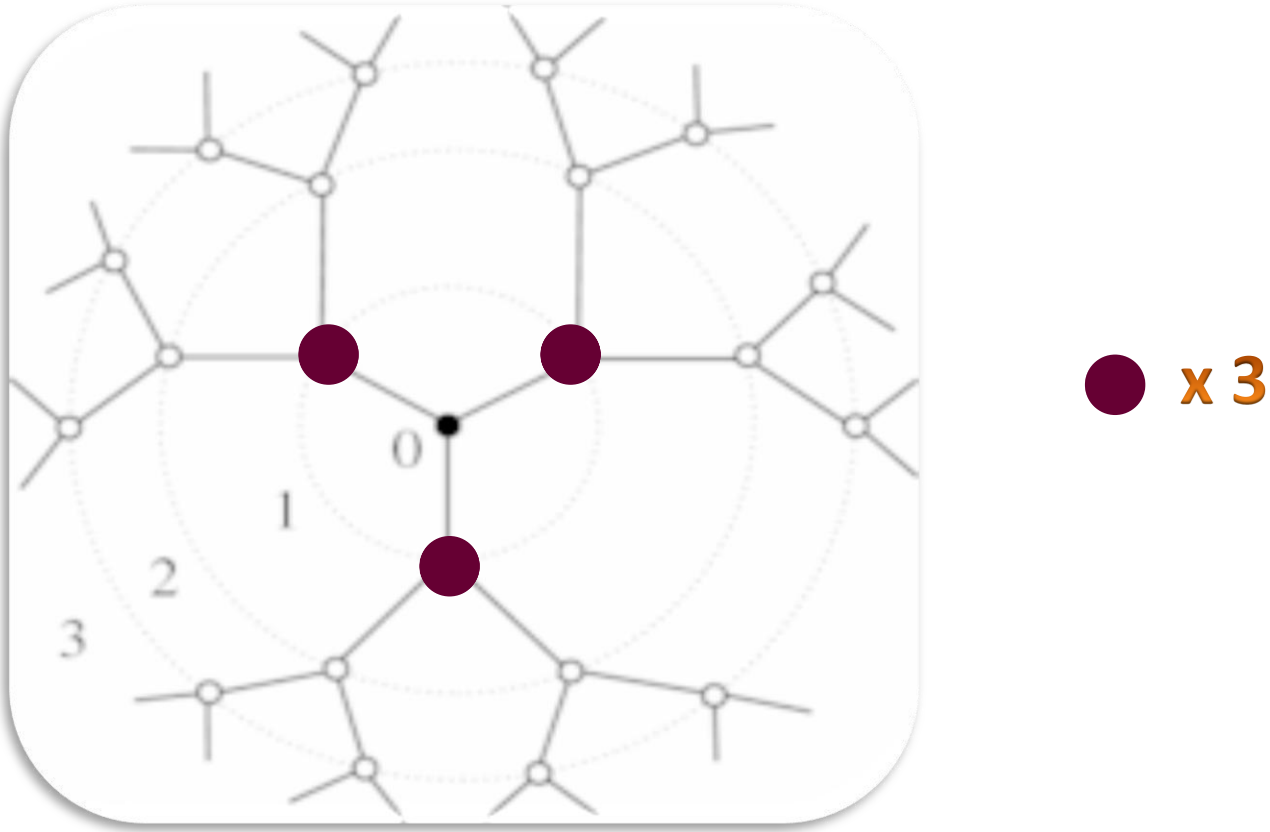
The secret behind the small world effect –
Looking at the network volume

$$N(d) = \sum_{x=1}^{d} 4x = 2d(d+1) \sim d^2$$



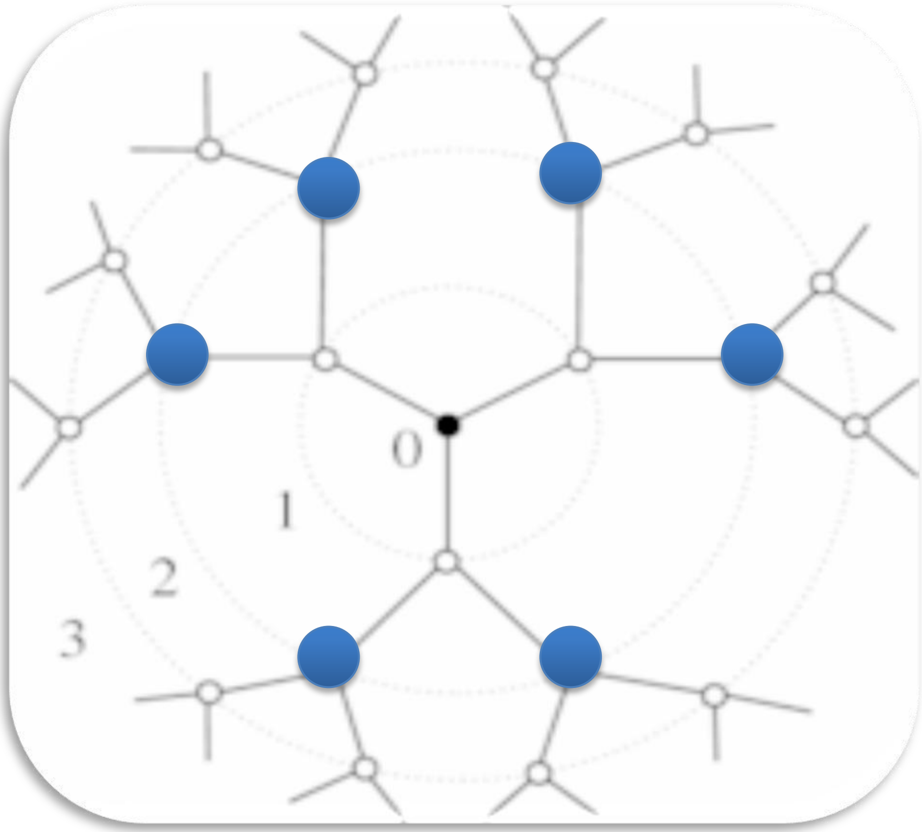
The exploding volume of networks

First Neighborhood



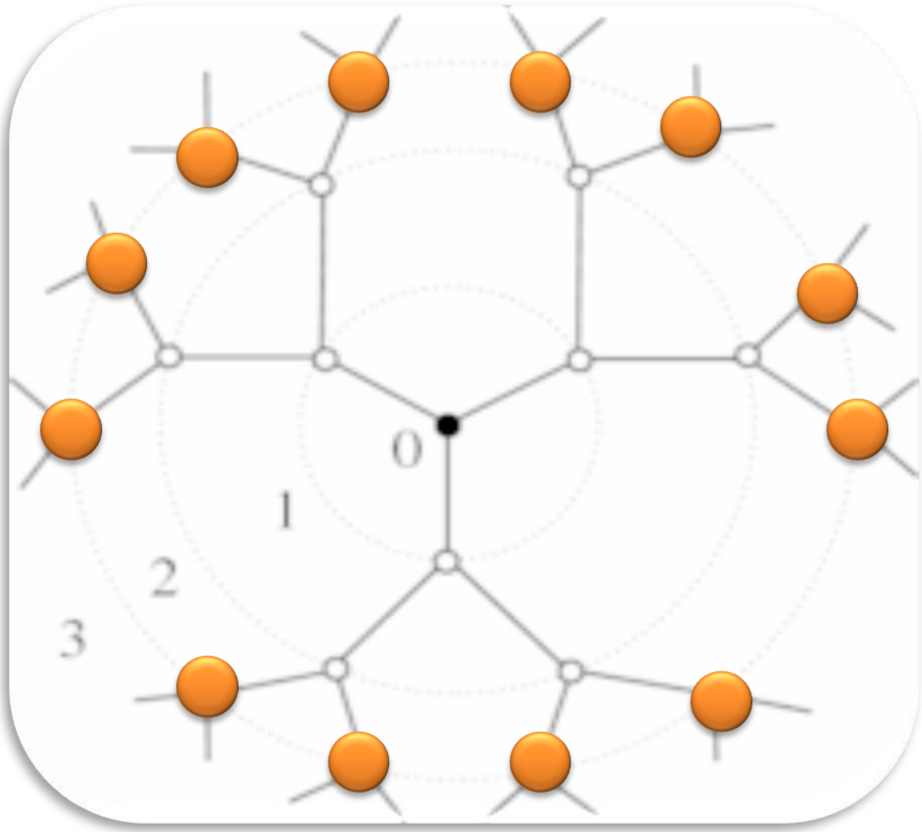
The exploding volume of networks

Second Neighborhood



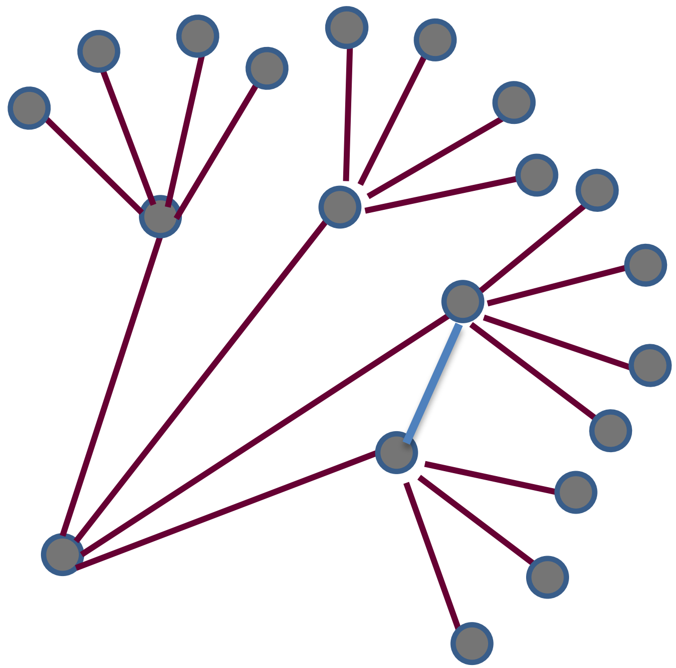
The exploding volume of networks

Third Neighborhood



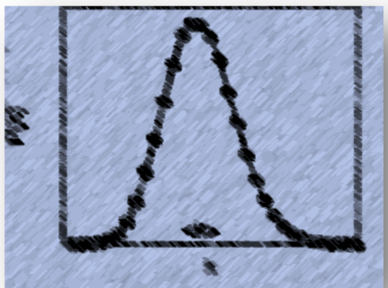
TREES ?

Random Graphs are NOT trees.

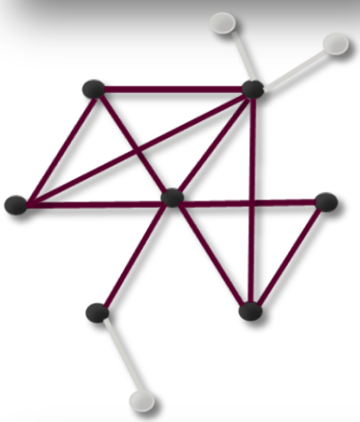


Some of your neighbor's neighbors are also your own

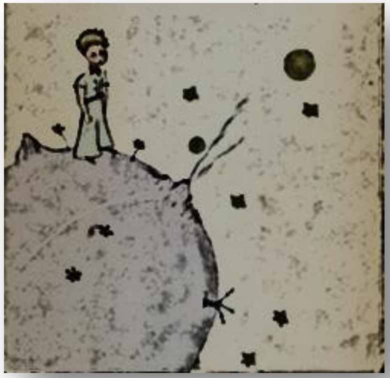
The Erdős-Rényi Random Graph



Poisson



Clustering



Small world
radius scales logarithmically with volume

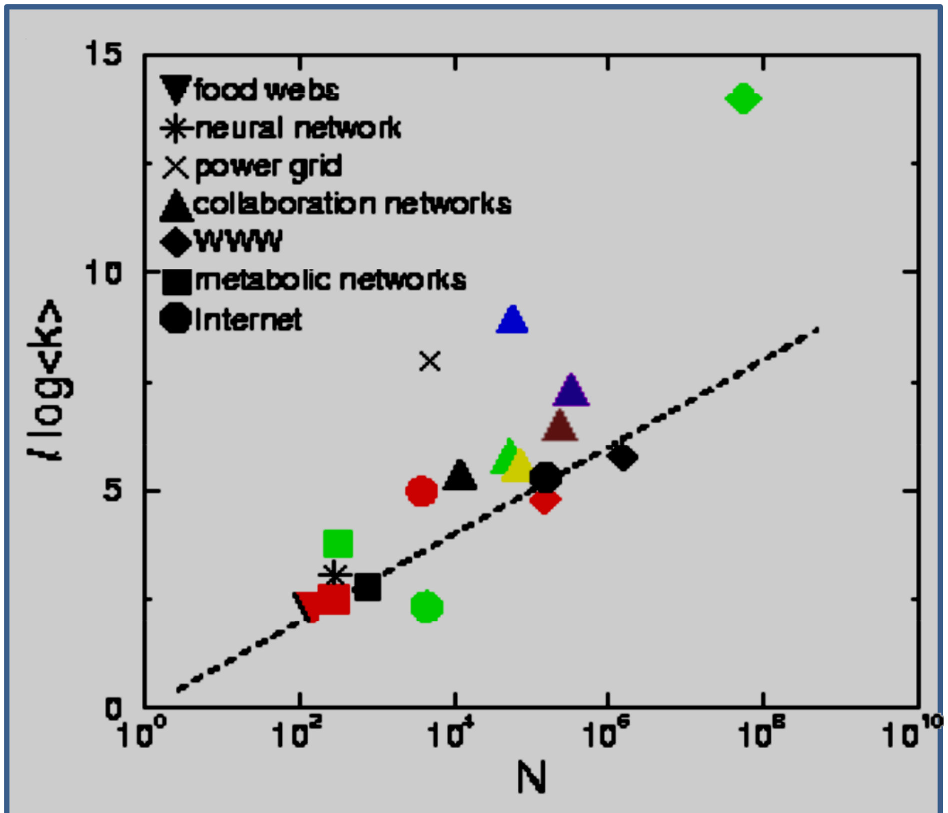
Exercise 1

Random Network

Create a network with N nodes.
Use N=10000 and N=100000 for a Random distribution of connections.
Use the rule that for every possible connection between two (2) nodes there is a probability of 1/6.

Find the k of every node, where k is its number of connections.
Make the distribution of P(k) and plot P(k) vs k on a graph.
The data will be the average of 100 runs.

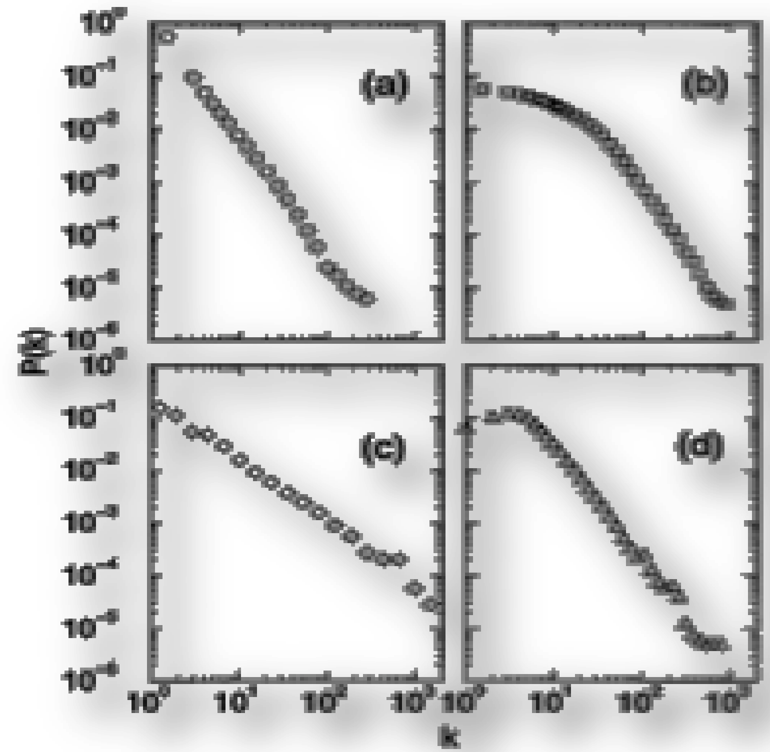
The Erdős-Rényi Model can be used in Real Networks ❓



The Erdős-Rényi Model and Real Networks

It is the reference model – a standard candle

It will help us calculate many quantities, that can then be compared to the real data, understanding to what degree is a particular property the result of some random process.

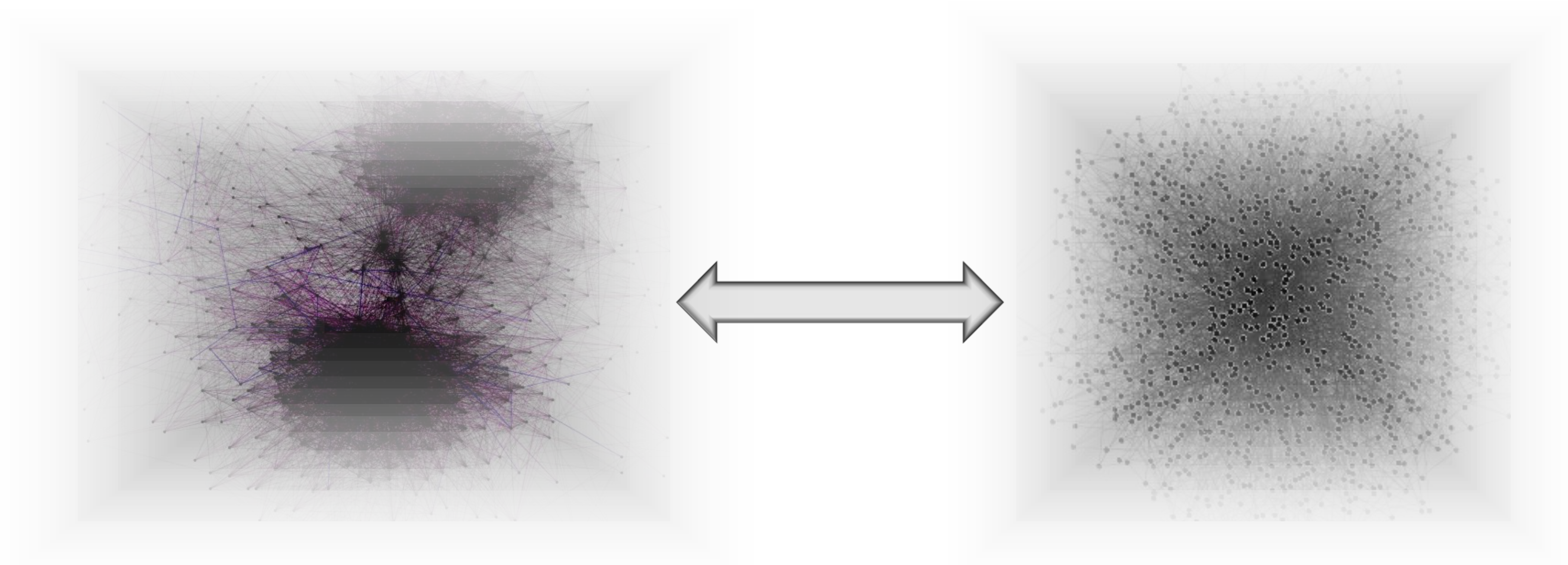


Which is the type of Real Networks in Nature ?

Scale-free Networks

Scale-free Networks

Where should we place the social network?



Clustered | Random

Scale-free Networks

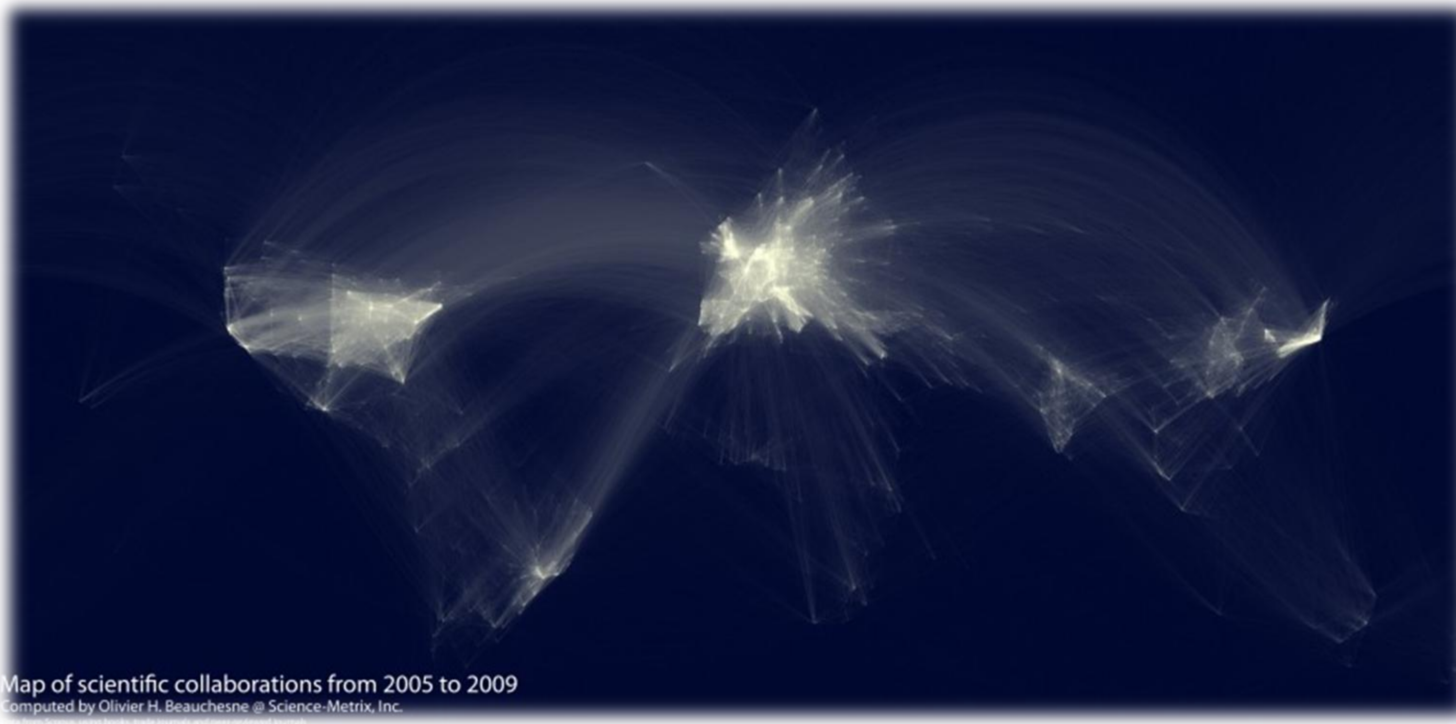
Could a network which is so strongly locally structured be at the same time a small world?

Scale-free Networks

Could a network which is so strongly locally structured be at the same time a small world?

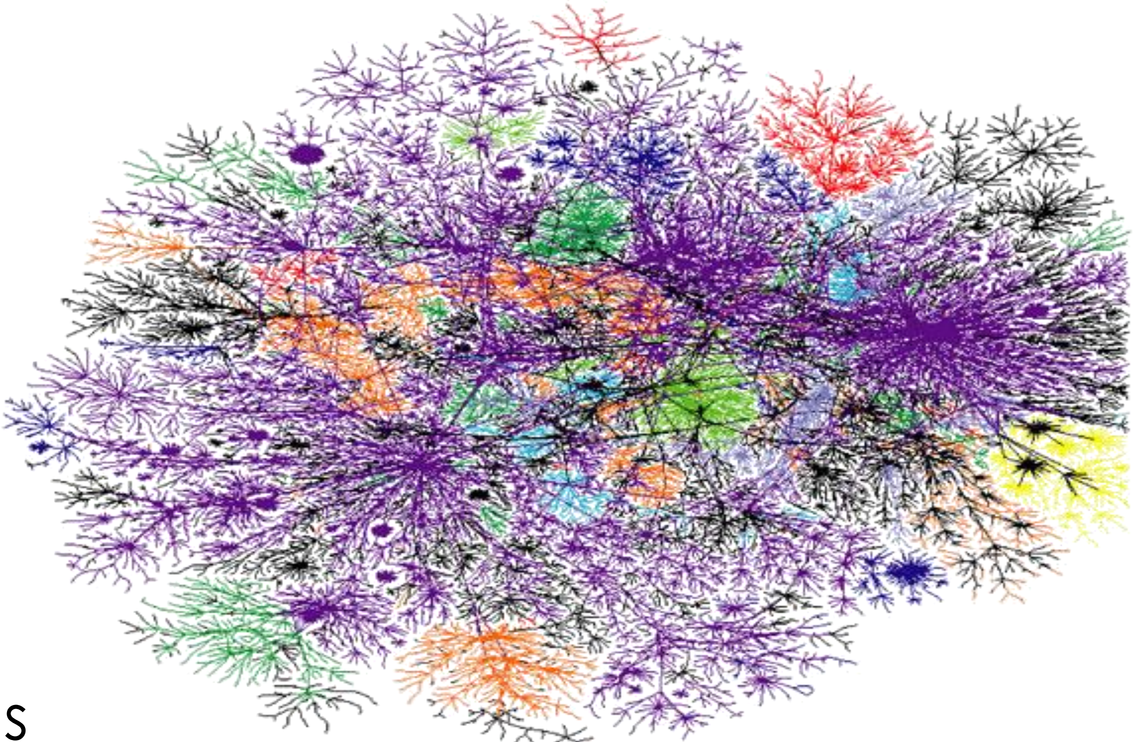
Yes. You don't need more than a few random links.

Map of Scientific Collaborations



The Internet-based experiment

- 60000 start nodes
- 18 targets
- 384 completed chains
- Average path length between 5 to 7.



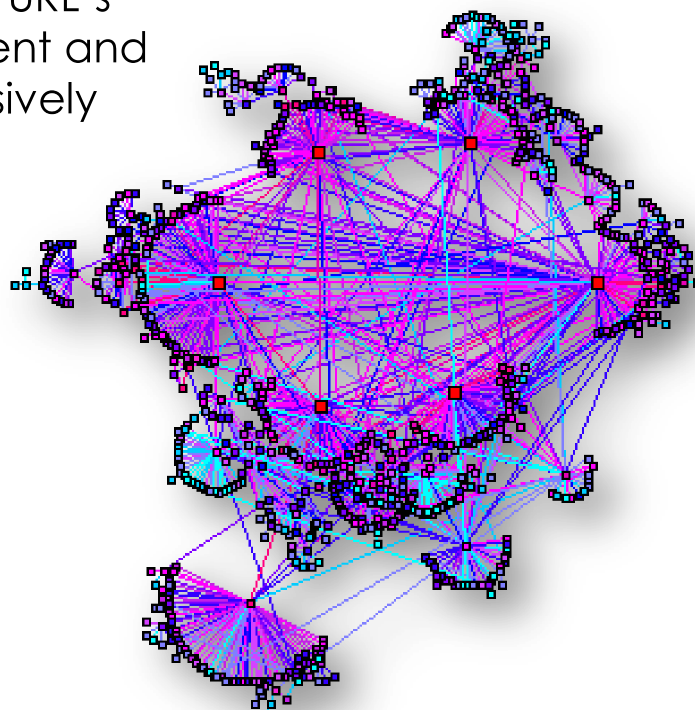
Dodds, Muhamad and Watts, Science **301**,827 (2003

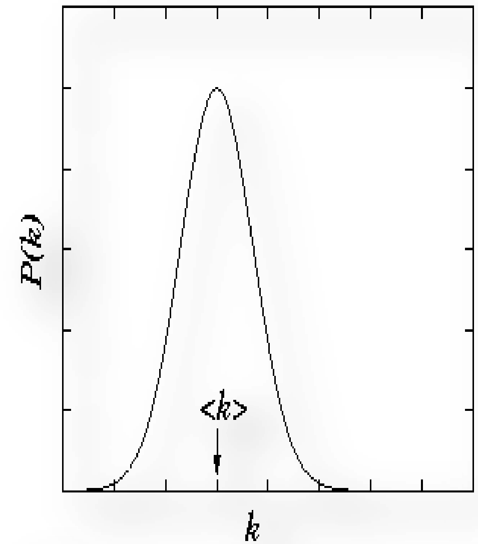
How it All Started

Nodes: WWW documents
Links: URL links

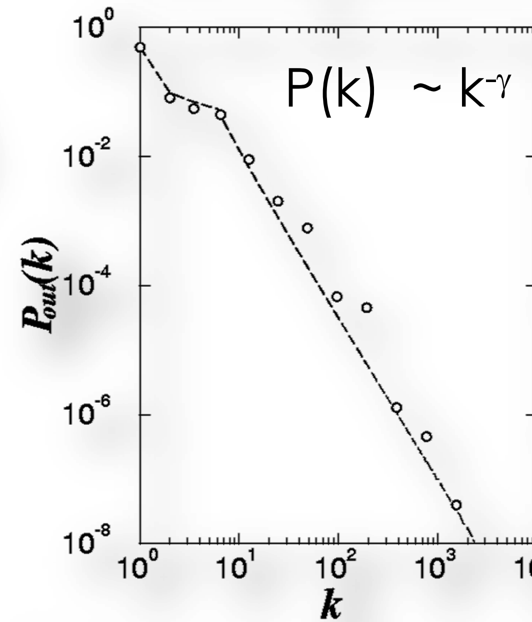
Over 3 billion documents

ROBOT: collects all URL's found in a document and follows them recursively



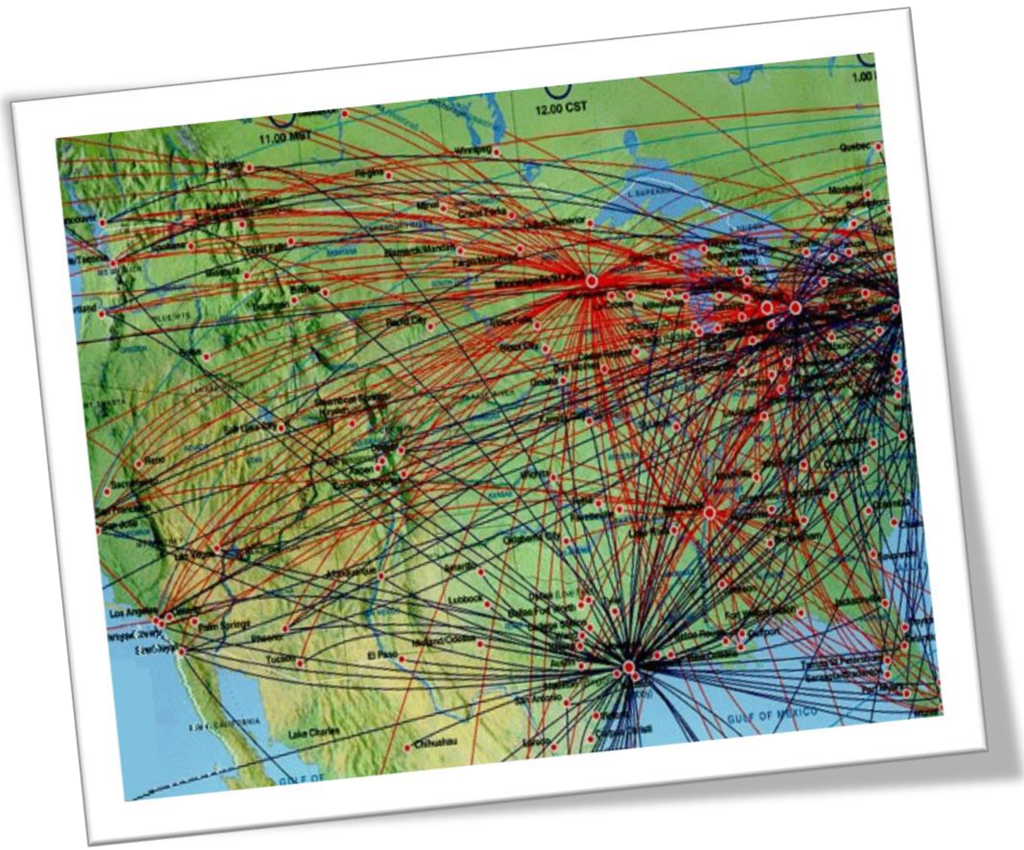


Expected



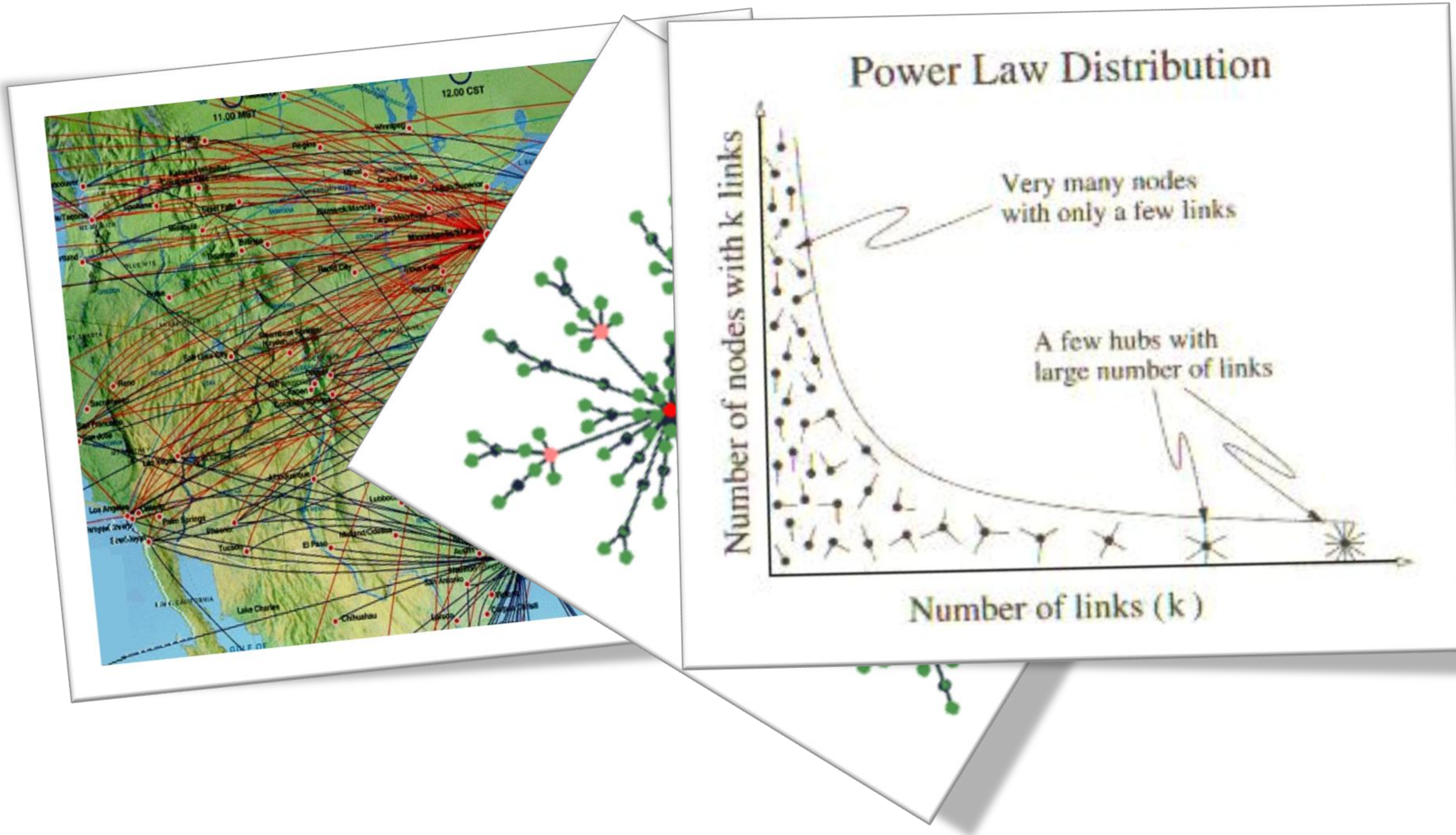
Found

Scale-free network

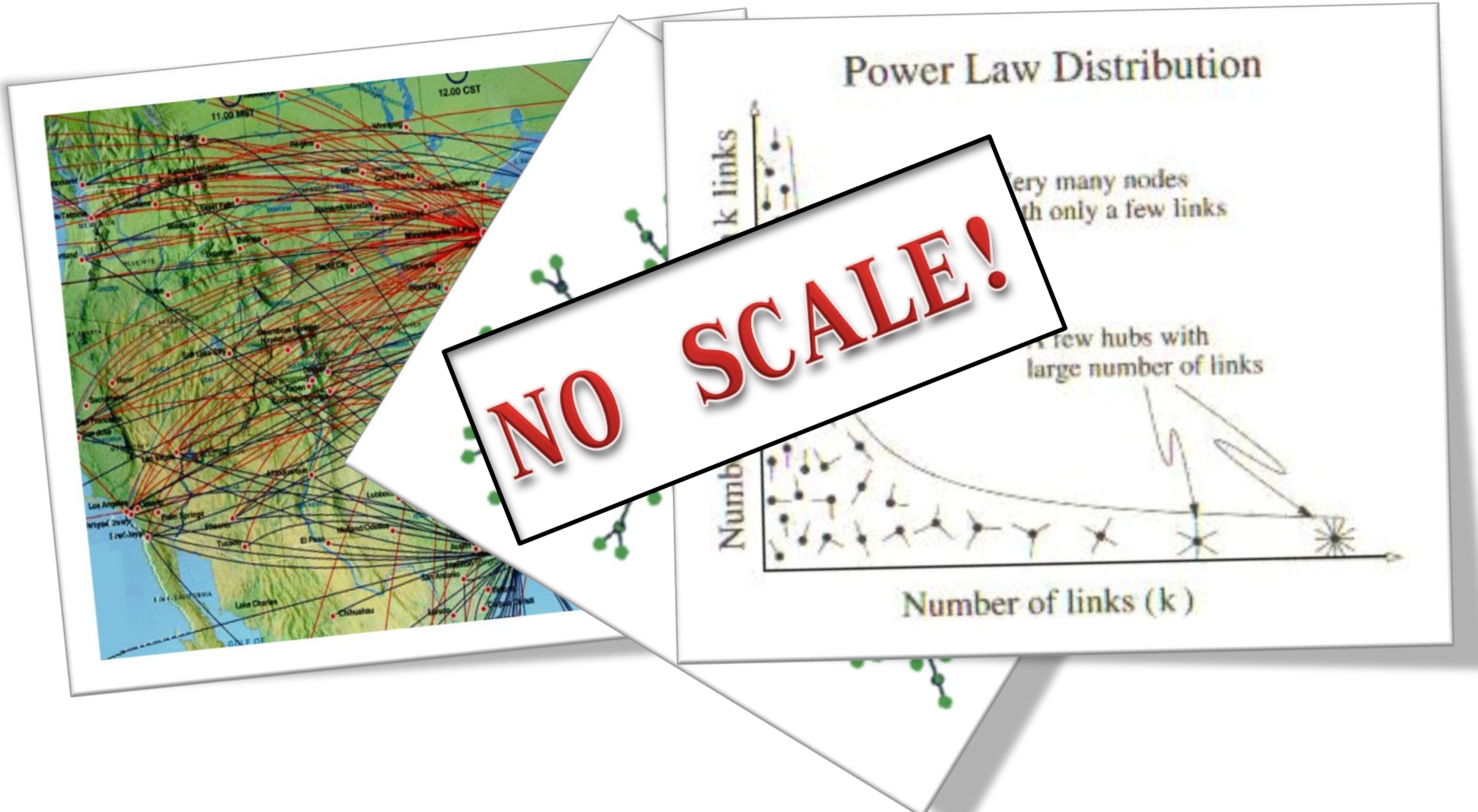


Scale-free network

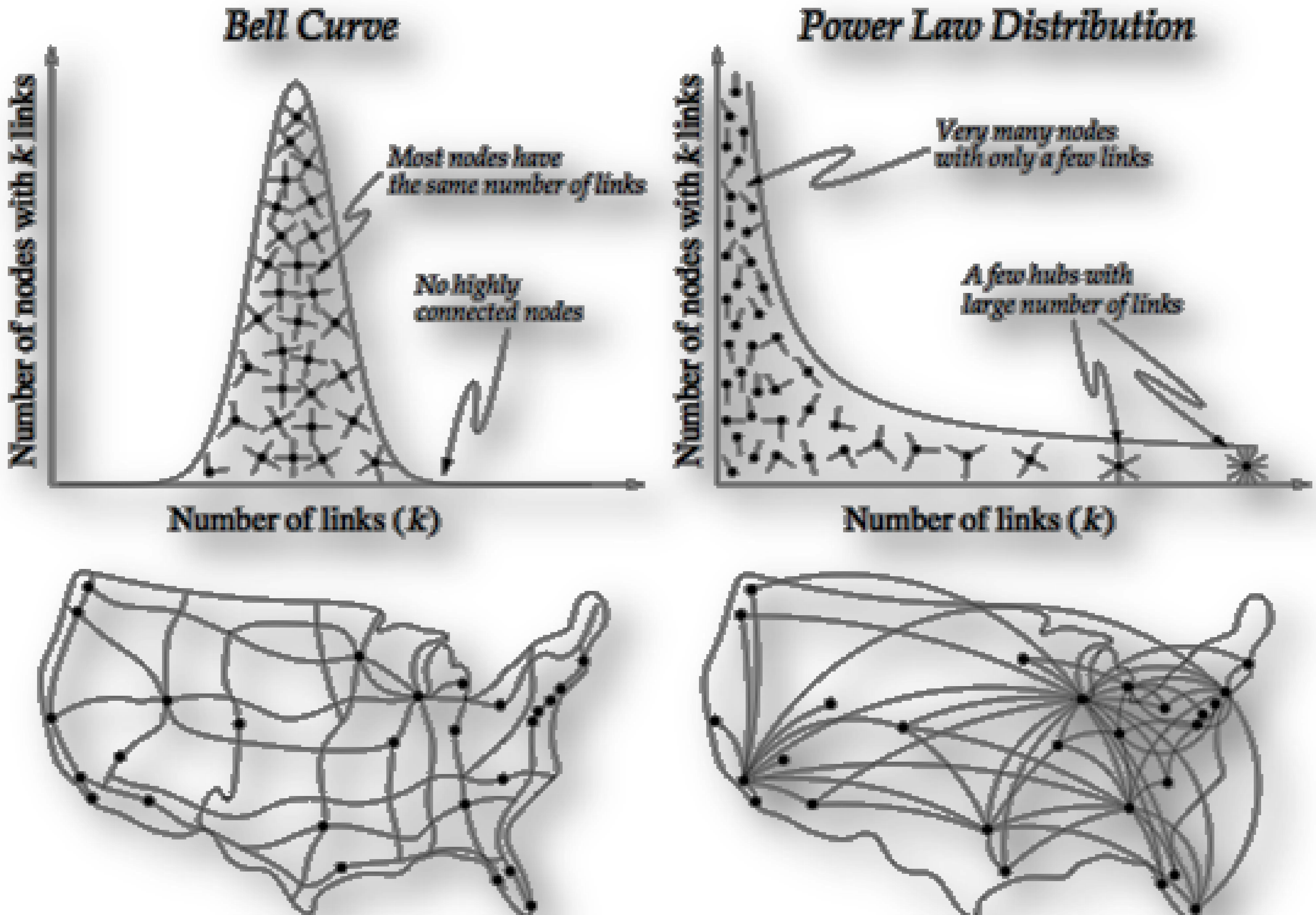
Scale-free network



Scale-free network

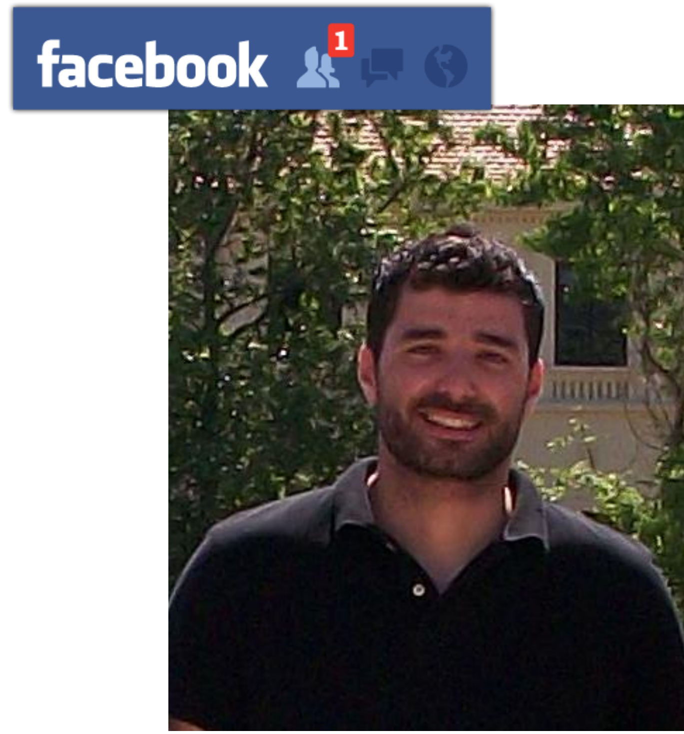


Scale-free network



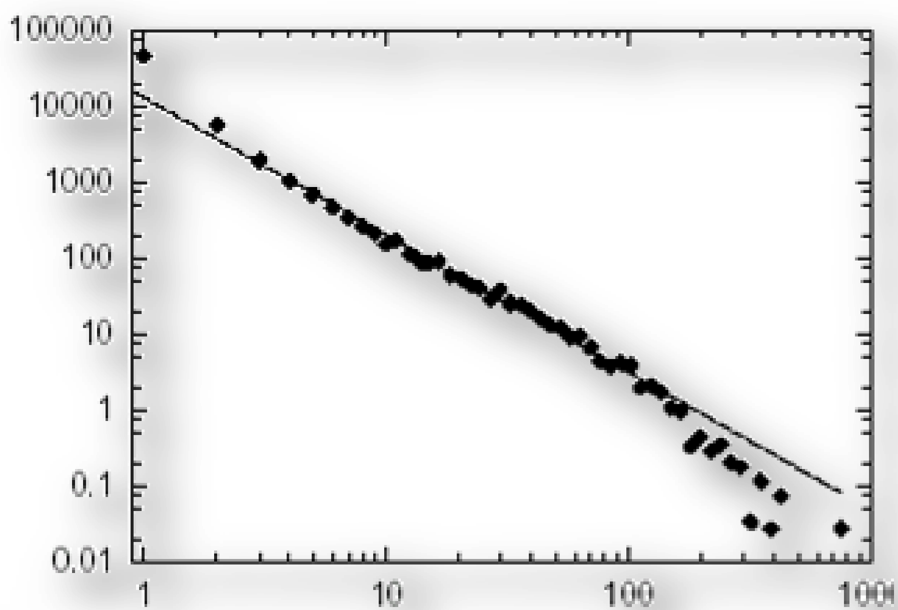
Scale-free network

There are few nodes with a lot of connections..

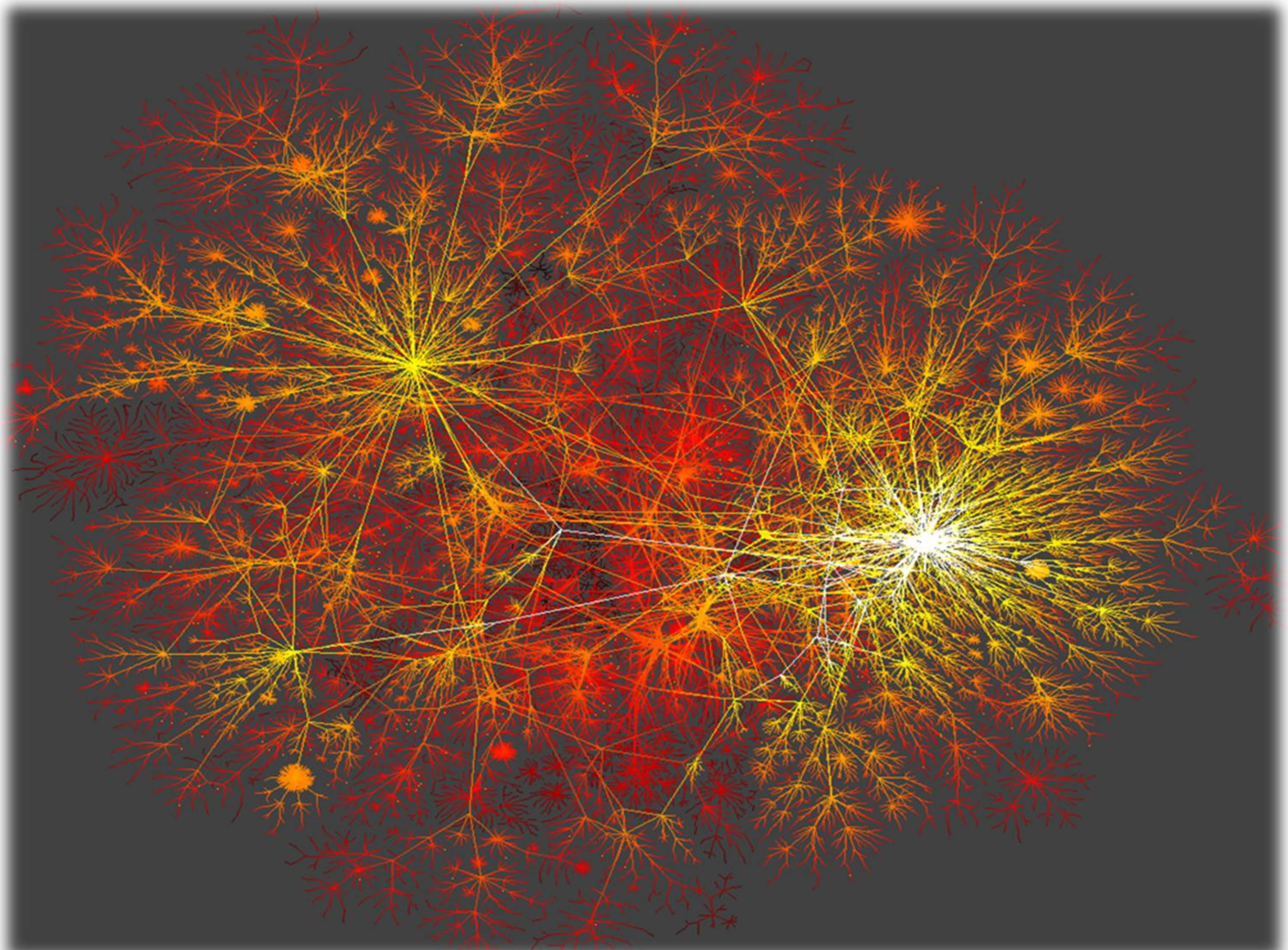


.. and the majority of the nodes have very few connections

What it Means to Be a Power-Law

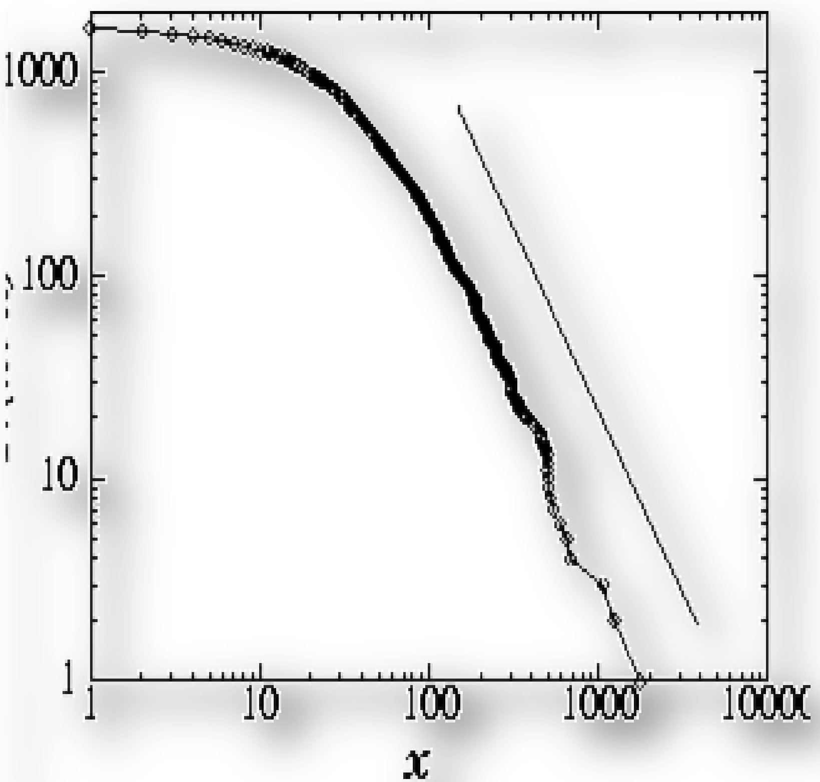


What it Means to Be a Power-Law



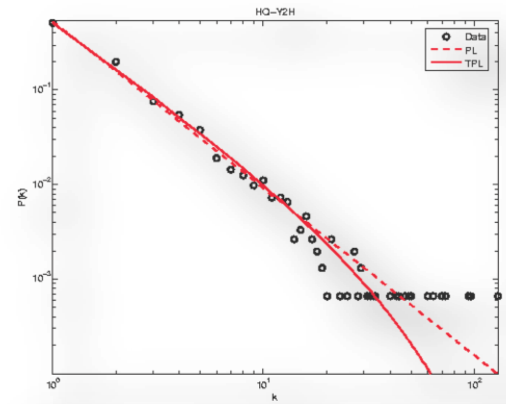
Power Law Distributions

in Biology



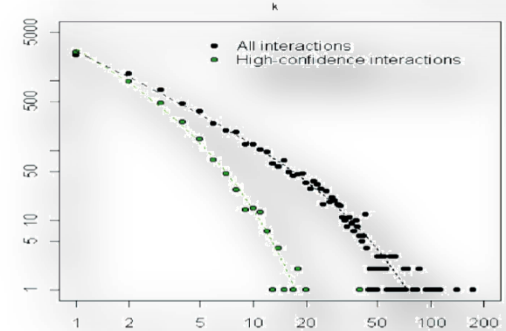
GENOME

protein-gene interactions



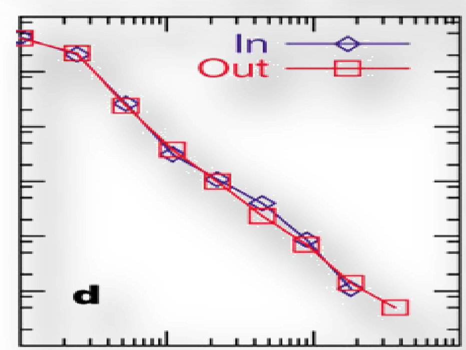
PROTEOME

protein-protein interactions

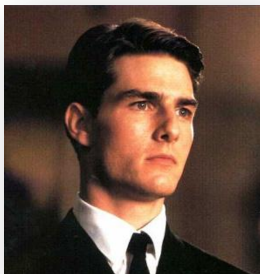


METABOLISM

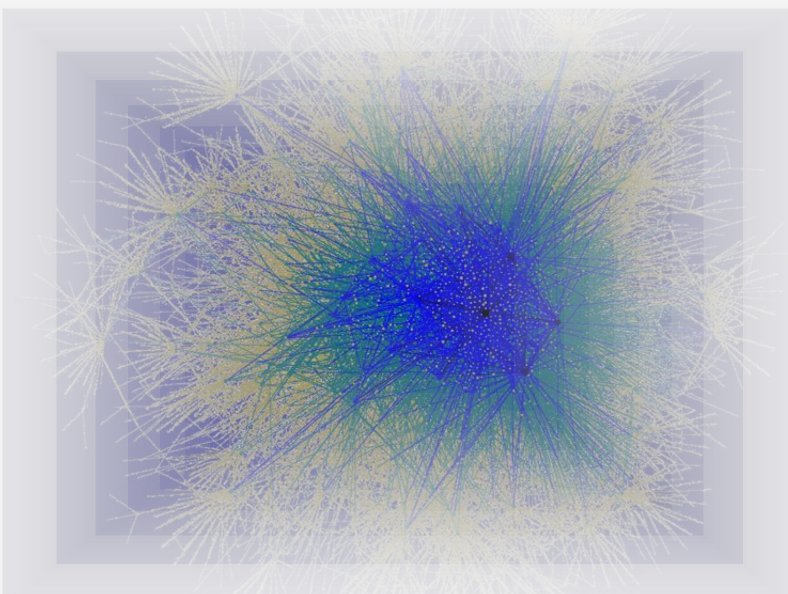
Bio-chemical reactions

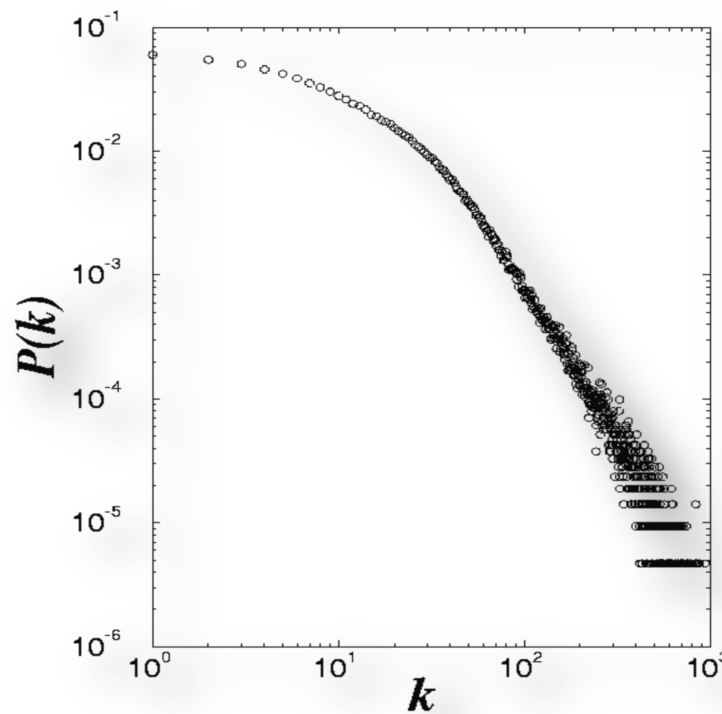


Internet Movie Database - IMDB



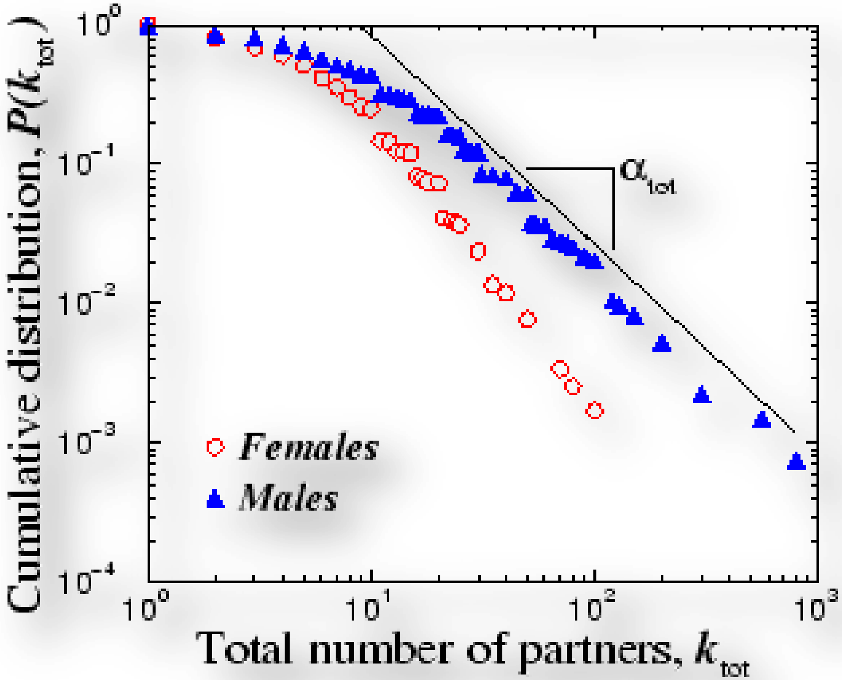
Days of Thunder (1990)
Far and Away (1992)
Eyes Wide Shut (1999)





Sexual Partnership

Nodes: people (Females; Males)
Links: sexual relationships



Liljeros et al. Nature 2001

How to .. Power-Law

An easy way to have a power-law distribution

1. Generate a random number ***x*** between [0,1]
2. Give to constant ***γ*** a standard value
3. Let $y_{max} = N$ (if you have a Scale-free network of N nodes)
4. Let $y_{min} = 1$ (because everyone must be connected to someone!)
5. Use the following equation:

$$y = [(y_{max}^{1-\gamma} - y_{min}^{1-\gamma})x + y_{min}^{1-\gamma}]^{\frac{1}{1-\gamma}}$$

6. Finally ***y*** is the degree of each node of your network
7. Make the distribution of ***p(k)*** in dependence of ***k***
8. Congratulations! You have a Power-Law distribution!

Power-Law in a computer

Node	degree (k)
1	2
2	1
3	1
4	3
5	2
6	8
7	1
8	2
9	6
10	1

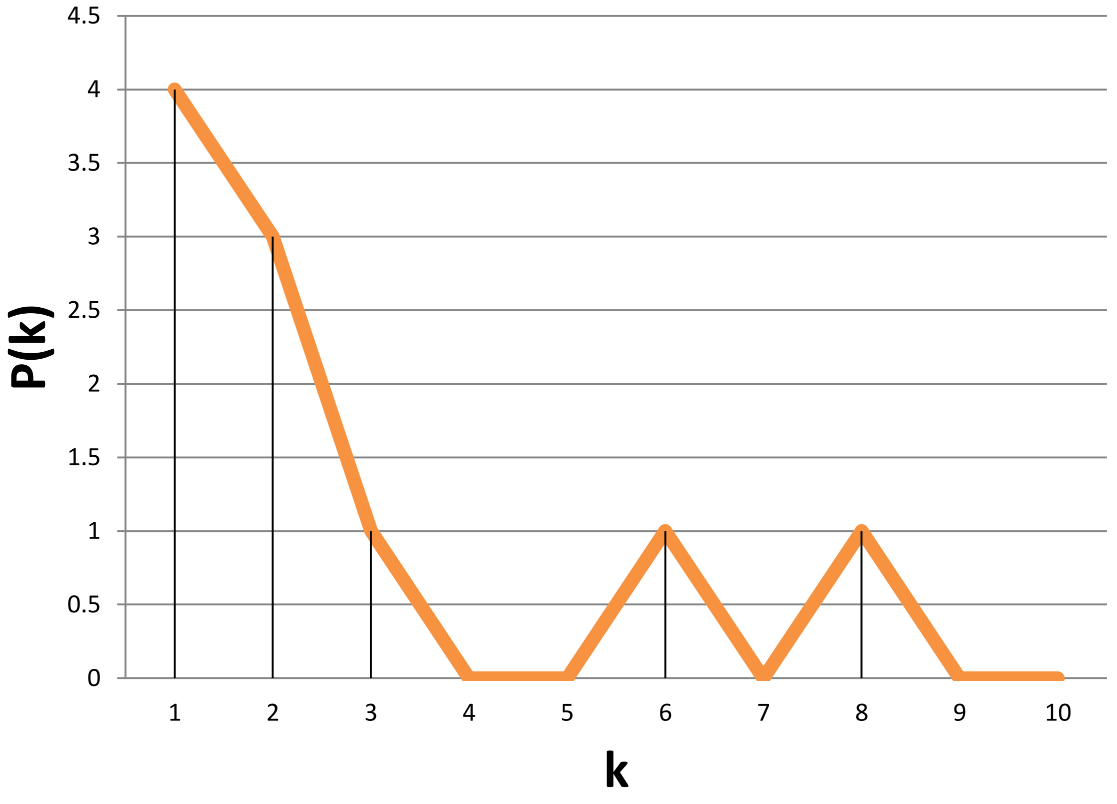
$$y = k$$

$$y_{max} = k_{max}$$

$$y_{min} = k_{min}$$

P(k)	degree (k)
4	1
3	2
1	3
0	4
0	5
1	6
0	7
1	8
0	9
0	10

Power-Law in a computer



Exercise 2

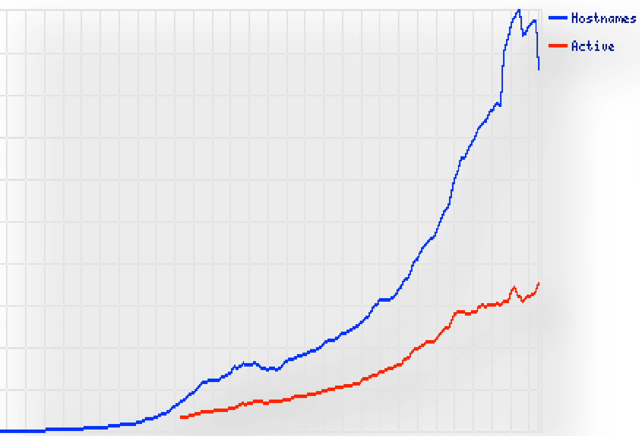
Scale-Free Network

Create a network with N nodes.
Use N=10000 and N=100000 for a Power law distribution which results in a scale-free network.
Use the distribution $P(k) \sim k^{-\gamma}$, where γ is constant.
Here use k=2, 2.5, 3.
Use the values $k_{min}=1$ and $k_{max}=N$.
On a graph (with logarithmic axes) create the distributions P(k) vs k for the three values of γ.
The data will be the average of 100 runs. .

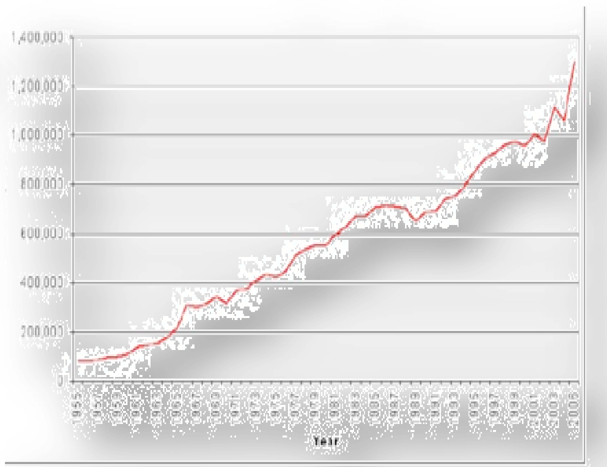
$$y = [(y_{max}^{1-\gamma} - y_{min}^{1-\gamma})x + y_{min}^{1-\gamma}]^{\frac{1}{1-\gamma}}$$

BA Model –
Networks are Not Static

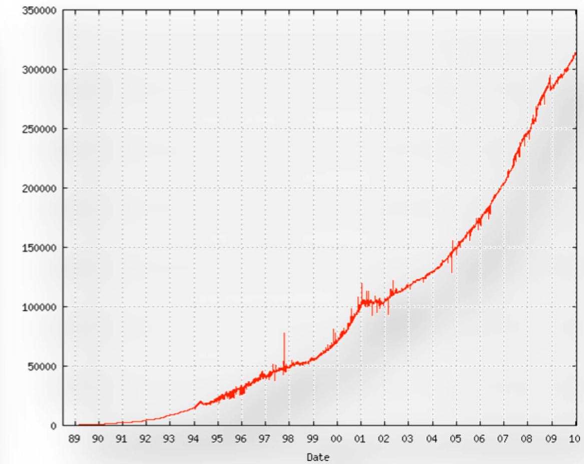
Real networks continuously expand by the addition of new nodes



WWW



Citations

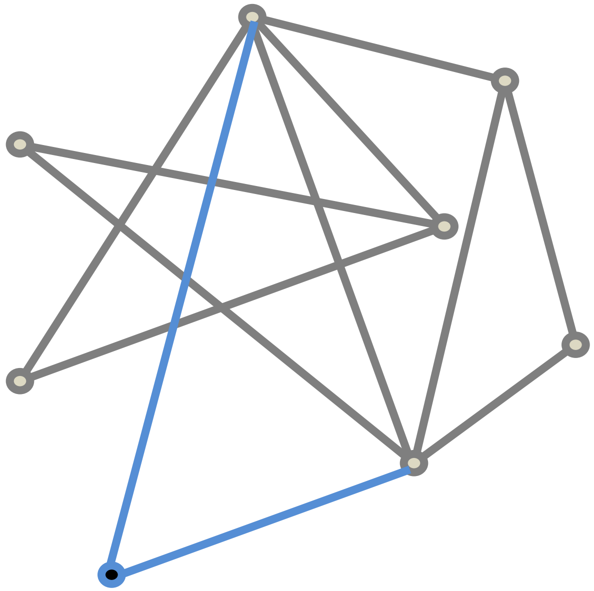


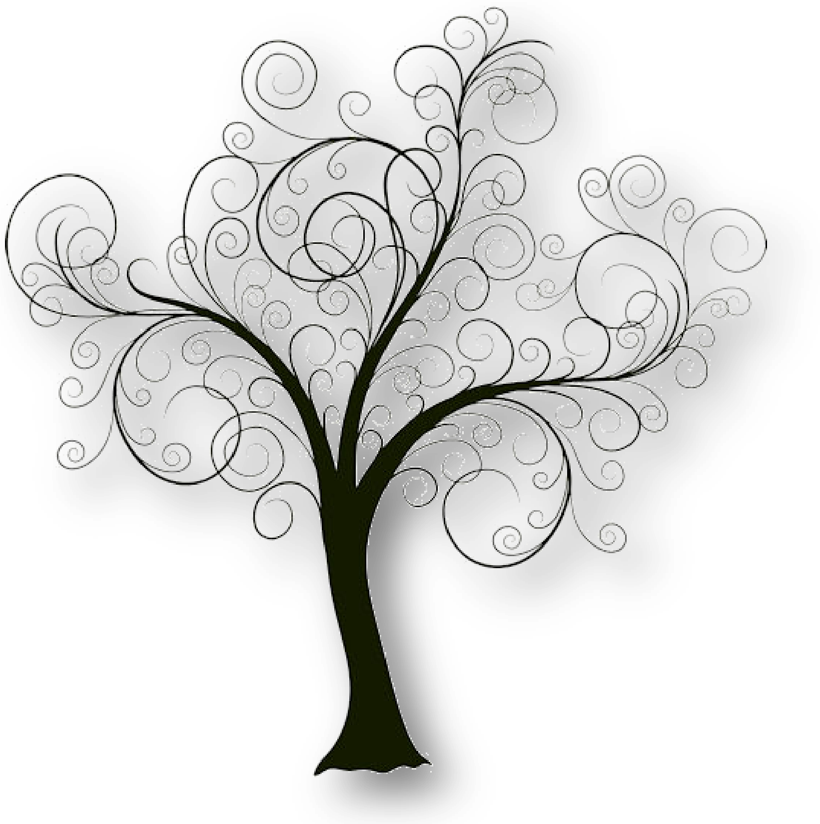
Internet

BA model – Growth

Networks continuously expand by the addition of new nodes

Add a new node with m links



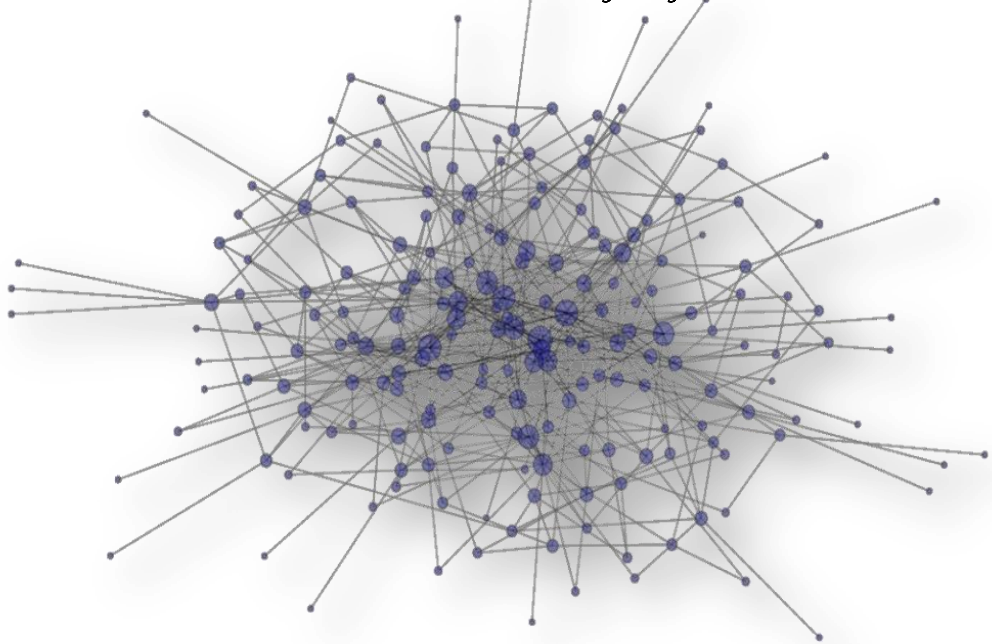


Barabási & Albert, *Science* **286,** 509 (1999)

Preferential attachment

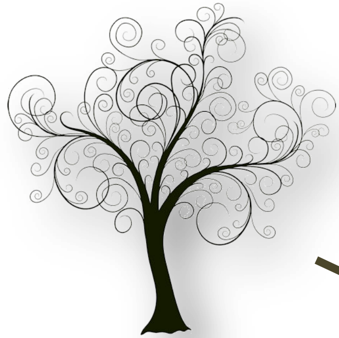
The probability that a node connects to a node with *k* links is proportional to *k*.

$$\Pi(k_i) = \frac{k_i}{\Sigma_j k_j}$$

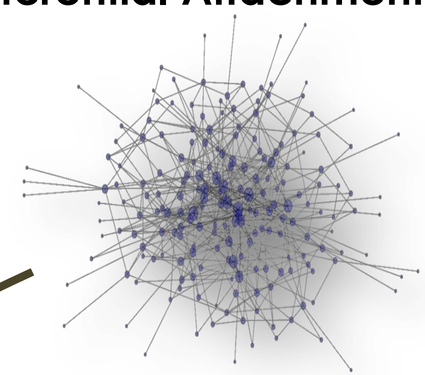


BA Growth / preferential attachment

Growth



Preferential Attachment

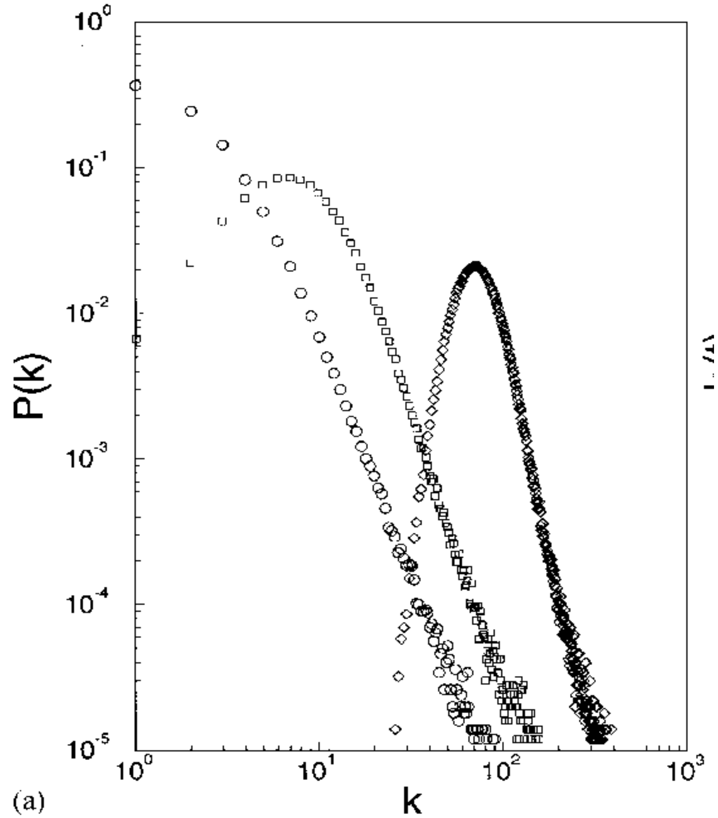


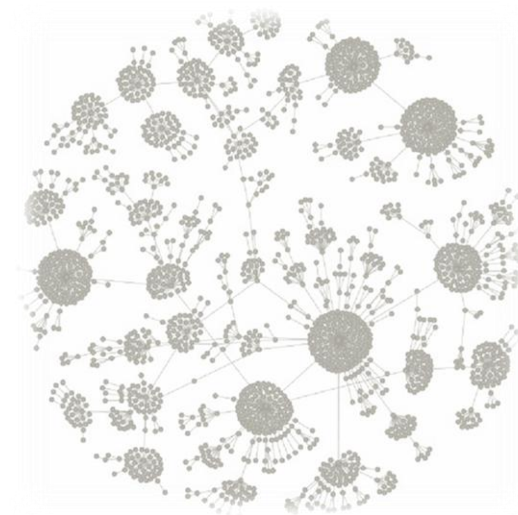
Richer nodes accumulate links more rapidly

Degree Heterogeneity

Power Law

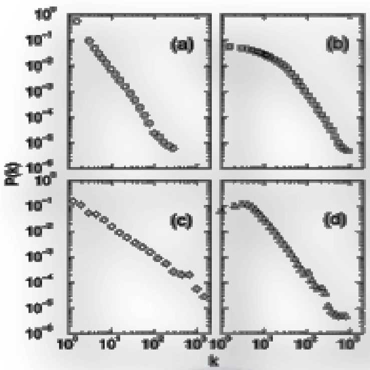
$$P(k) = k^{\gamma}$$



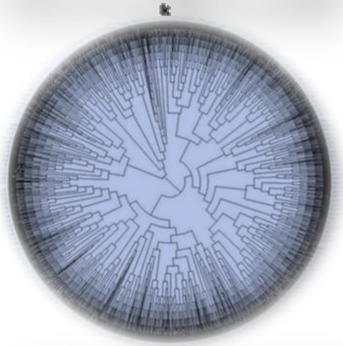


As the power-law describes systems of rather different ages and sizes, it is expected that a correct model should provide a time-independent degree distribution. Indeed, asymptotically the degree distribution of the BA model is independent of time (and of the system size N) - the network reaches a stationary scale-free state.

Universality of Networks



Power law degree distribution



High clustering and community structure

Small world topology

Despite the diversity in scale, purpose and functionality, the topological characteristics of networks exhibit a high degree of universality

Universality of Networks

Universality - The observation that there are properties for a large class of systems that are independent of the dynamical details of the system

- *Diverse phenomena explained by the same fundamental principles*
- *Unified set of analytical and empirical tools*
- *Limiting the number of relevant observables*

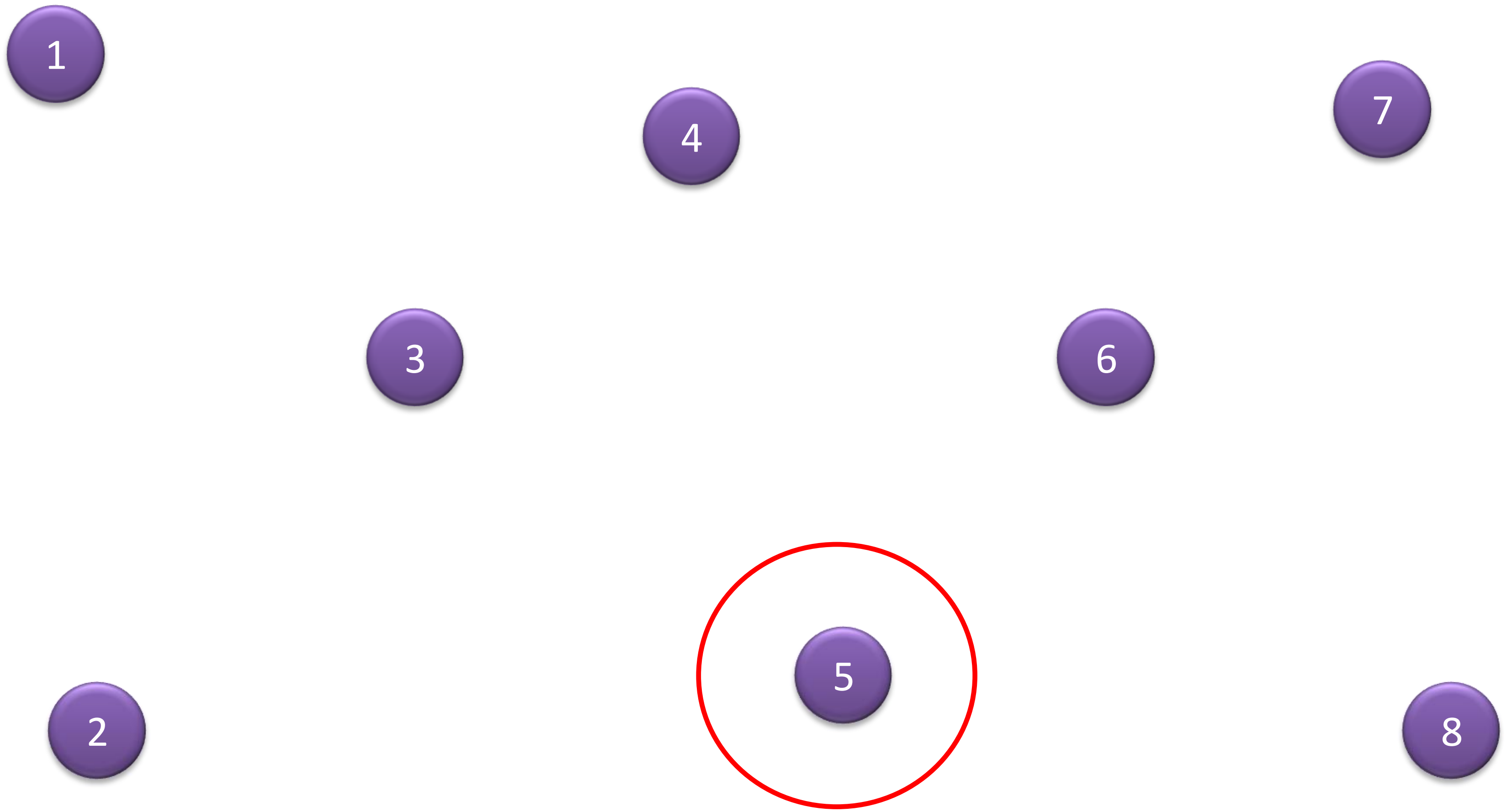
Some simulation techniques

```
  nblocks = (gidsetsize + NGROUPS_PER_BLOCK - 1) / NGROUPS_PER_BLOCK;
/* Make sure we always allocate at least one indirect block pointer */
nblocks = nblocks ? : 1;
group_info = kmalloc(sizeof(*group_info) + nblocks*sizeof(gid_t *), GFP_USER);
if (!group_info)
 return NULL;
group_info->ngroups = gidsetsize;
group_info->nblocks = nblocks;
atomic_set(&group_info->usage, 1);

if (gidsetsize <= NGROUPS_SMALL)
 group_info->blocks[0] = group_info->small_block;
else {
 for (i = 0; i < nblocks; i++) {
  gid_t *b;
    b = (void *)__get_free_page(GFP_USER);
  if (!b)
     goto out_undo_partial_alloc;
    group_info->blocks[i] = b;
```

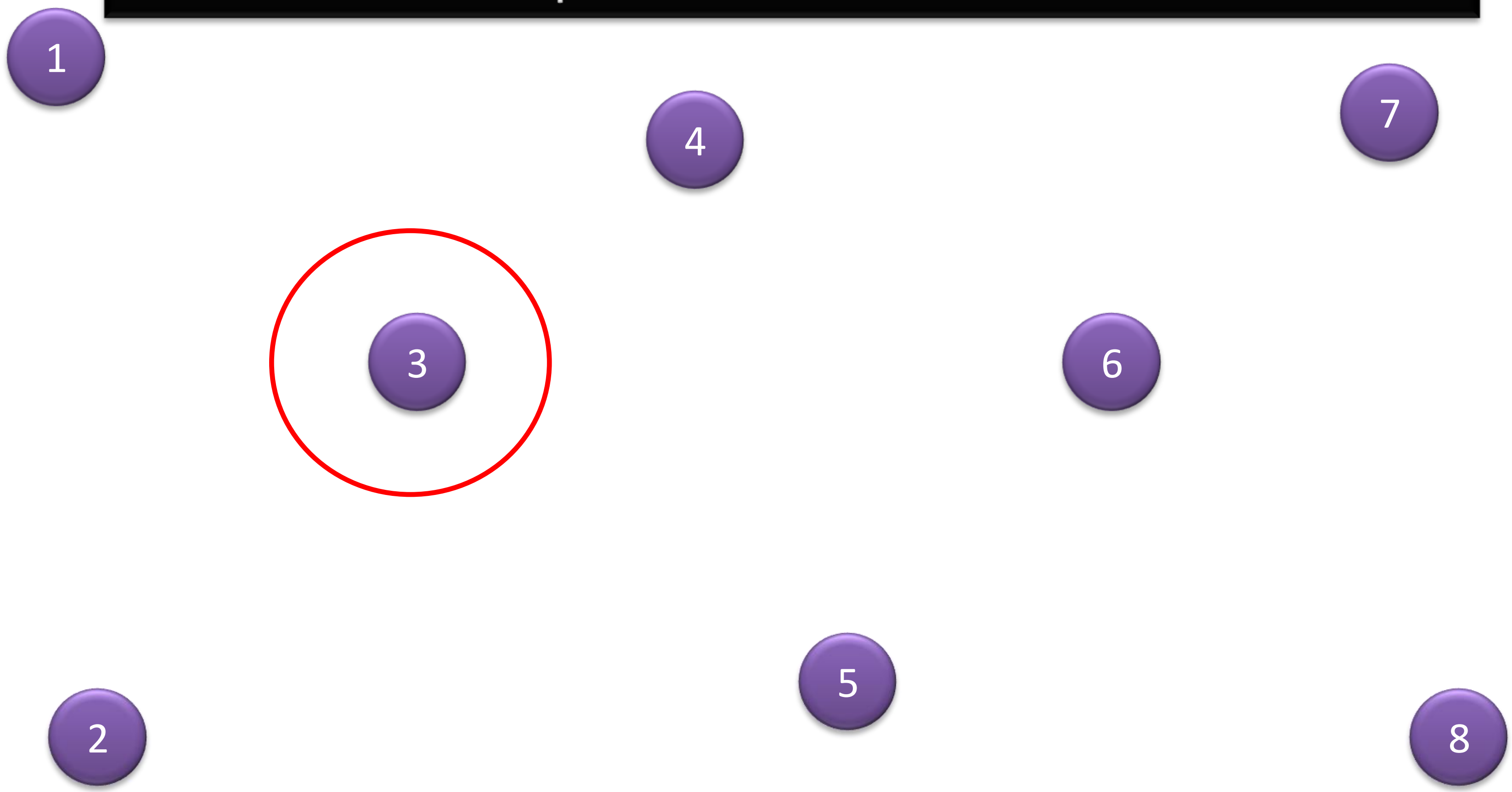
Some simulation techniques

Step 1:
We generate a random number *x* between [1,8], representing the node of the network which is to be connected.



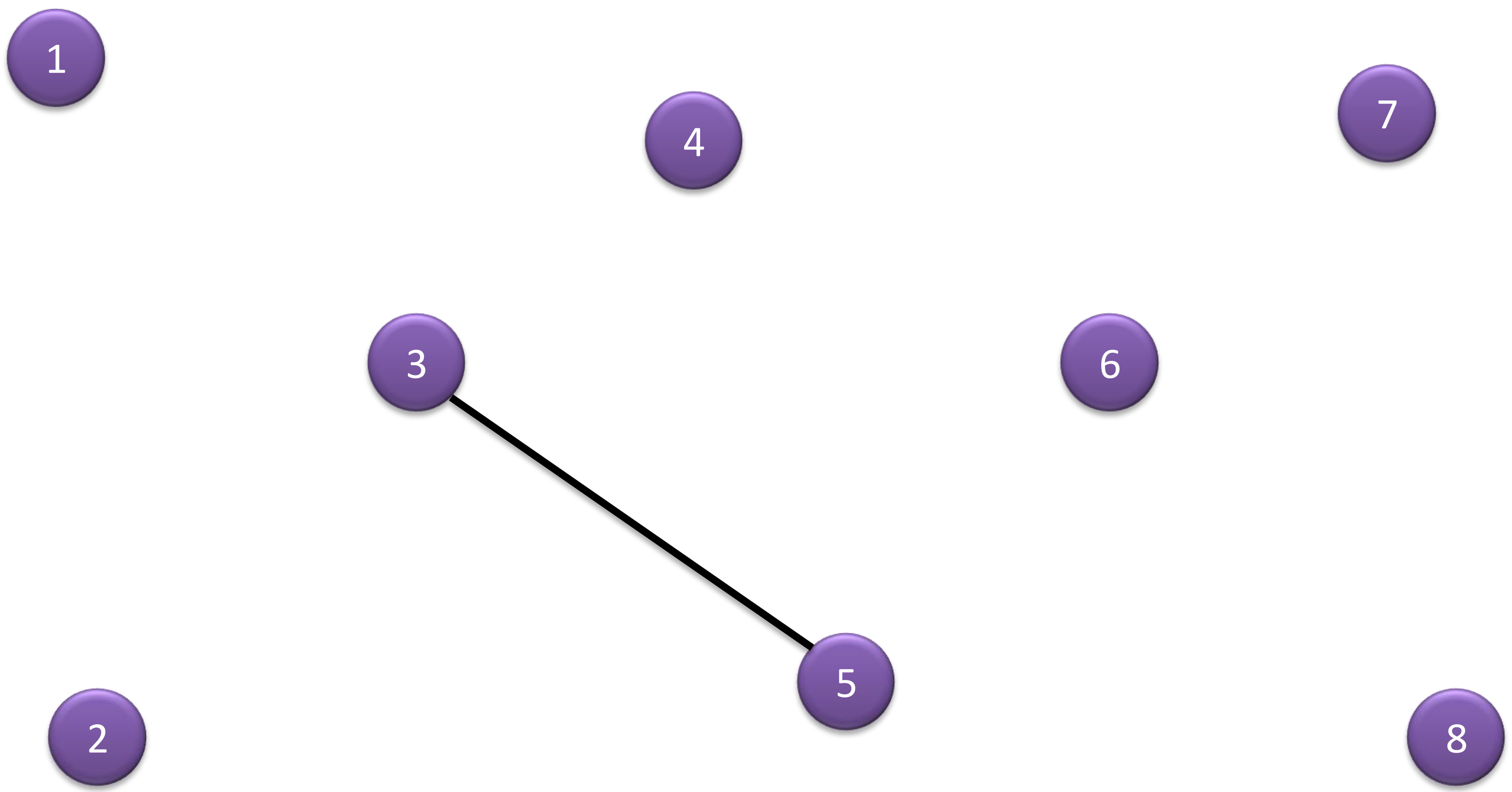
Some simulation techniques

Step 2:
We generate then a random number *x2* between [1,8], representing the node of the network which is to be connected with the previous one.



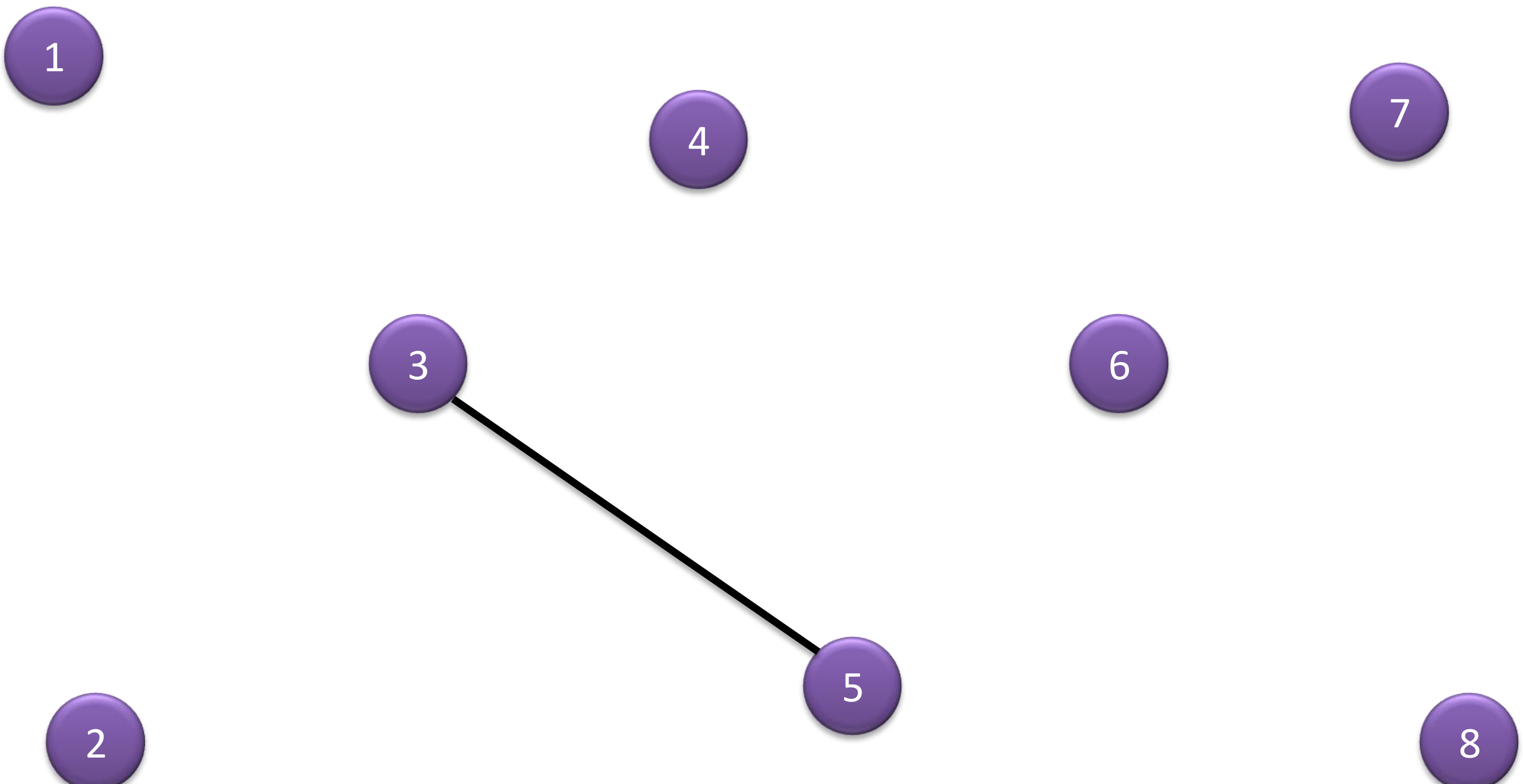
Some simulation techniques

Step 3:
We consider the two nodes as connected (we put the link).



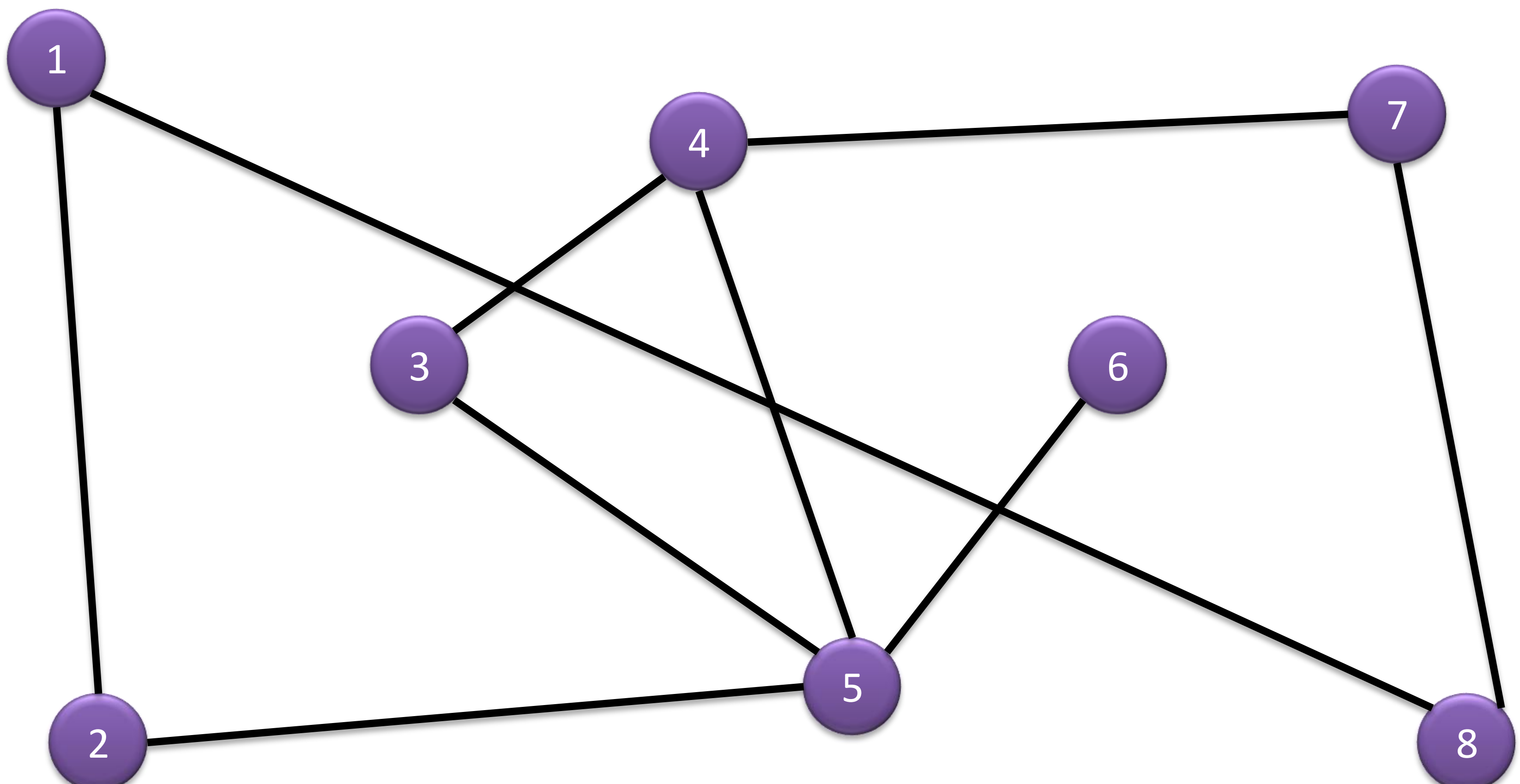
Some simulation techniques

Step 4:
We repeat the previous 3 steps as much as we want..



Some simulation techniques

Simulating a network



Some simulation techniques

Simulating a network all we need is a two-dimensional array

nodes	1	2	3	4	5	6	7	8
1	*0*	*1*	*0*	*0*	*0*	*0*	*0*	*1*
2	*1*	*0*	*0*	*0*	*1*	*0*	*0*	*0*
3	*0*	*0*	*0*	*1*	*1*	*0*	*0*	*0*
4	*0*	*0*	*1*	*0*	*1*	*0*	*1*	*0*
5	*0*	*1*	*1*	*1*	*0*	*1*	*0*	*0*
6	*0*	*0*	*0*	*0*	*1*	*0*	*0*	*0*
7	*0*	*0*	*0*	*1*	*0*	*0*	*0*	*1*
8	*1*	*0*	*0*	*0*	*0*	*0*	*1*	*0*

Some simulation techniques

OR you can use another two-dimensional array

connections	1	2	3	4	5	6	7	8
1	*2*	*8*	*0*	*0*	*0*	*0*	*0*	*0*
2	*1*	*5*	*0*	*0*	*0*	*0*	*0*	*0*
3	*4*	*5*	*0*	*0*	*0*	*0*	*0*	*0*
4	*3*	*5*	*7*	*0*	*0*	*0*	*0*	*0*
5	*2*	*3*	*4*	*6*	*0*	*0*	*0*	*0*
6	*5*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
7	*4*	*8*	*0*	*0*	*0*	*0*	*0*	*0*
8	*1*	*7*	*0*	*0*	*0*	*0*	*0*	*0*

nodes

for more information…

- *visit:*

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- *or e-mail:*

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for more information…

- *Or search for .. :*

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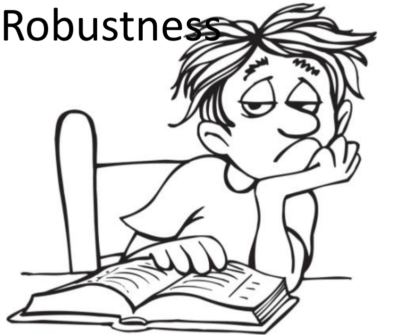

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Thank you for your attention!!