A basic introduction to Complex Networks, using python

Marcelo Ponce

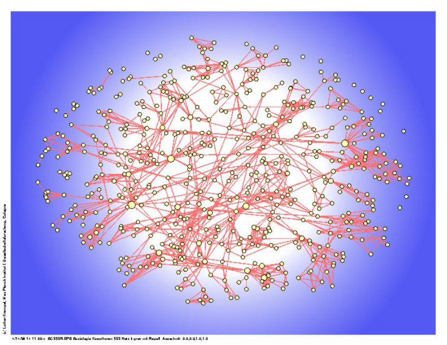
May 14th, 2015

Outline

1. Introduction
   - Motivation & Examples
2. Basic Elements
   - Python Packages
   - Building your own CN: **NetworkX**
   - Networks
   - Several types of graphs/networks in **NetworkX**
   - Basic Network Analysis
3. Real-life applications
   - Twitter relationships
   - SciNet GPC cluster
4. Simulating CNs
   - PyCX
5. References

Examples of Complex Networks

A system composed of many nonlinear interacting units often forms a complex system with new emergent properties that are not held by the individual units.


(c) Lothar Krempel, Max Planck Institut f. Gesellschaftsforschung, Cologne

▲ Co-Authorship Network By Lothar Krempel

http://www.mpi-fg-koeln.mpg.de/~lk/netvis/Huge.html

Examples:

- circadian rhythms,
- electrochemical reactions,
- laser arrays,
- neuron networks,
- populations of fireflies,
- Josephson junction arrays..., etc.

http://www.nd.edu/~networks/Image␣Gallery/gallery.htm

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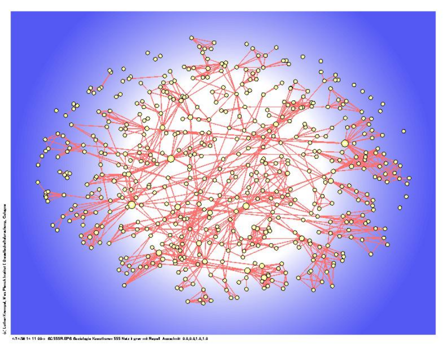

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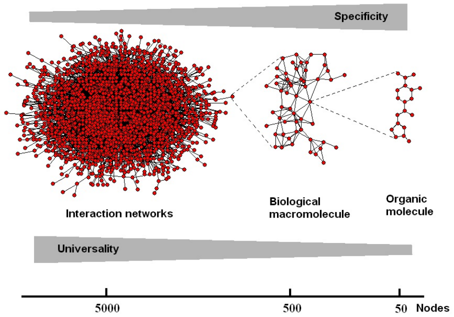
Examples of Complex Networks

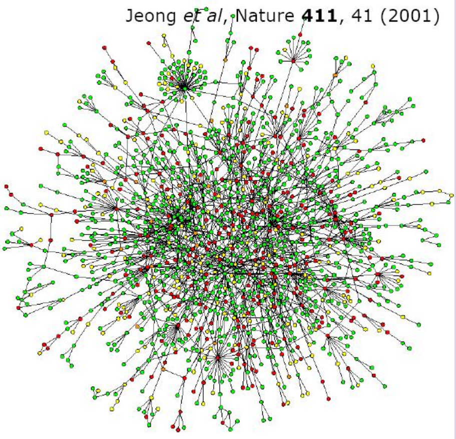
Biological networks...

- Proteins, molecules, chemical reactions...



Map of protein-protein interactions. The colour of a node signifies the phenotypic effect of removing the corresponding protein (lethal; non-lethal; slow growth; unknown). ▸

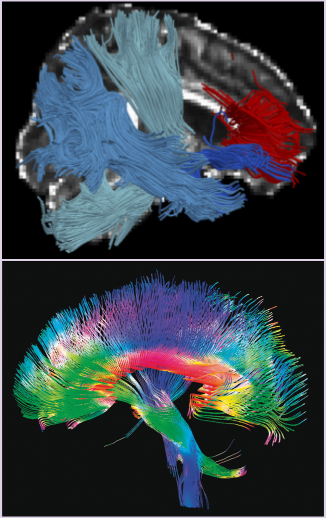
- Genes, proteins, ...


Jeong et al, Nature **411**, 41 (2001)

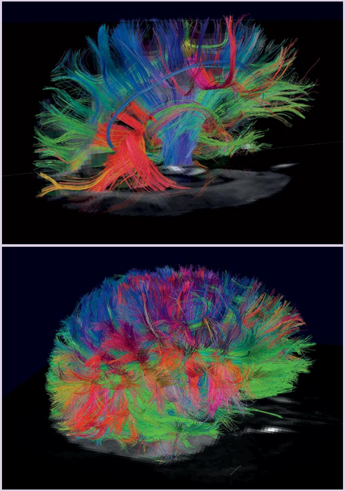
Examples of Complex Networks

Brain networks...

- Physiological networks



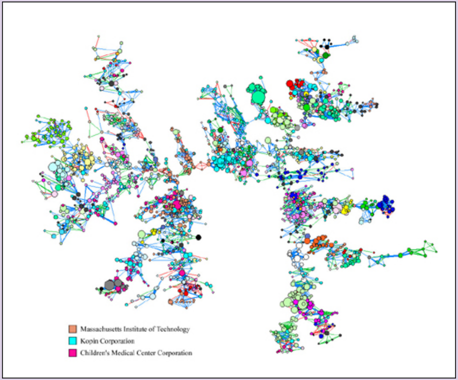
- Neurological pathways



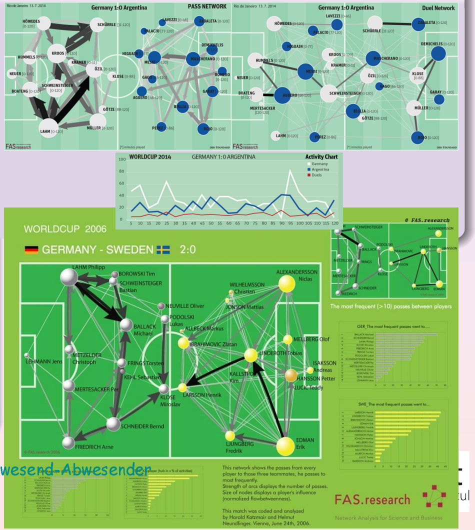
Examples of Complex Networks

Social networks...

▾ Boston Inventor Networks mid-1990s


Massachusetts Institute of Technology
Kopin Corporation
Children's Medical Center Corporation

▾ Sports: Futbol - world cup...

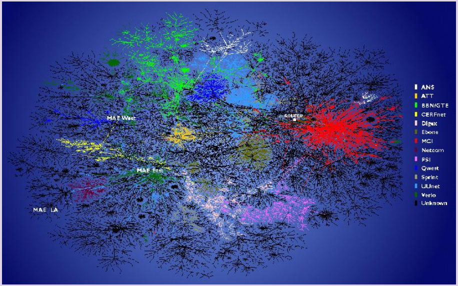

Rio de Janeiro 13.7.2014
Germany 1:0 Argentina
PASS NETWORK
Duel Network
FAS research
DER STANDARD
WORLDCUP 2014
GERMANY 1:0 ARGENTINA
Activity Chart
Germany
Argentina
Duels
WORLDCUP 2006
GERMANY - SWEDEN 2:0
FAS.research
The most frequent (>10) passes between players
GER_The most frequent passes went to...
SWE_The most frequent passes went to...
This network shows the passes from every player to those three teammates, he passes to most frequently.
Strength of arcs displays the number of passes.
Size of nodes displays a player's influence (normalized flowbetweenness).
This match was coded and analyzed by Harald Katzmair and Helmut Neundlinger. Vienna, June 24th, 2006.
Network Analysis for Science and Business

http://derstandard.at/2000002589338/Messi-glaenzt-als-anwesend-Abwesender

Examples of Complex Networks

Internet

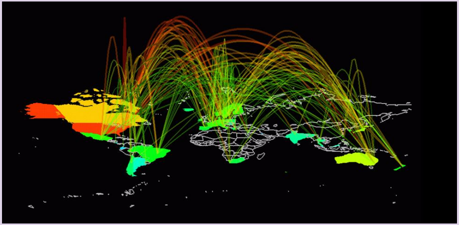
- Internet connectivity,



with selected backbone ISPs (Internet Service Provider)

colored separately

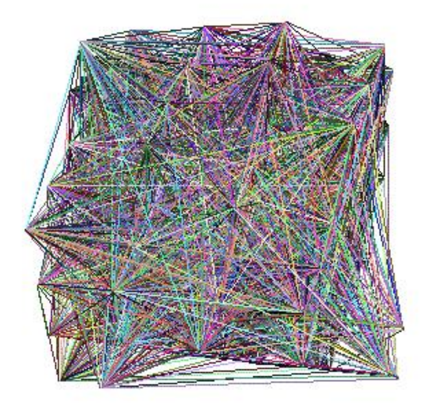
- Arc map showing the world-wide internet traffic



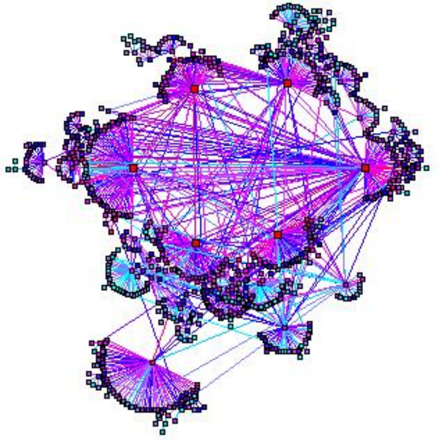
Examples of Complex Networks

Internet

- Mapping the internet: tracing domain routes



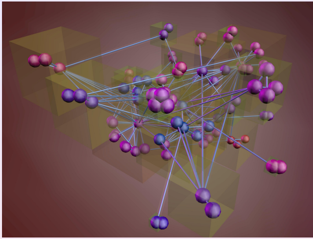
- Hierarchical topology of the international web cache



nodes, network, maps...

A network is a set of nodes interconnected via links.

1. [nodes]: ensemble of N oscillators
2. [dynamics+network]: each oscillator evolves according to its own intrinsic dynamics [map (fn)] + a coupling term [network].
3. The coupling term is defined by:
   - coupling strength
   - coupling topology (all-to-all, n-n, etc)



- Nodes and Links can be anything depending on the **context**

from the previous examples:

- Internet: Nodes ⇝ routers & Links ⇝ optical fibers.
- WWW: Nodes ⇝ document files & Links ⇝ hyperlinks.
- The Scientific Citation Network: Nodes ⇝ papers & Links ⇝ citations.
- Social Networks: Nodes ⇝ individuals & Links ⇝ relations.

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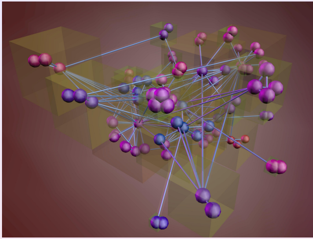

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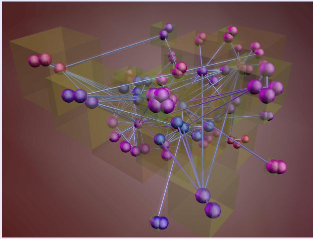

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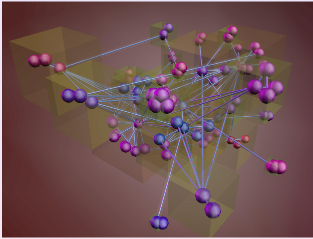

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CN: several packages & tools available in Python

- **networkX**: http://networkx.lanl.gov/
- **PyCX** Project: http://pycx.sf.net/
- ComplexNetworkSim
- SimPy
- graph-tool [http://graph-tool.skewed.de/]
- pyGraphViz (GraphViz) [http://www.graphviz.org/]
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Required Packages

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www.scipy.org

NumPy

www.numpy.org

matplotlib

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- NetworkX

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Defining a graph

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import networkx as nx

g = nx.Graph()

g.add_edge('a','b',weight=0.1)
g.add_edge('b','c',weight=1.5)
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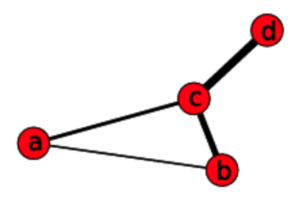

Some basic props. of the graph

```
g.number_of_nodes()   # also g.order()
4
g.order()   # also g.size()
4
```

```
g.nodes()
['a', 'c', 'b', 'd']
g.edges()
[('a', 'c'), ('a', 'b'), ('c', 'b'), ('c', 'd')]

g.edges('b')
[('b', 'a'), ('b', 'c')]
```

```
g.degree('a')
2
g.neighbors('c')
['a', 'b', 'd']
```

```
print nx.shortest_path(g,'b','d')
['b', 'c', 'd']

print nx.shortest_path(g,'b','d',weight='weig
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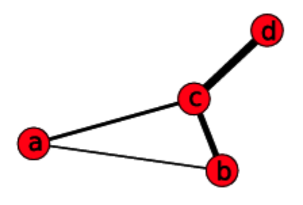

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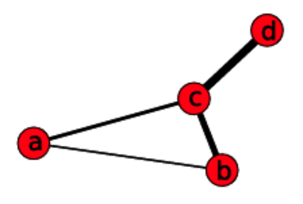

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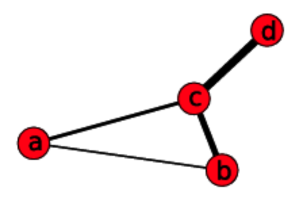

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g.edges(’b’)
[(’b’, ’a’), (’b’, ’c’)]
```

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2
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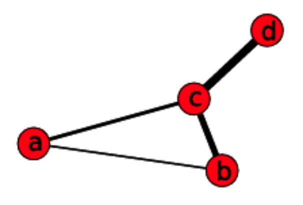

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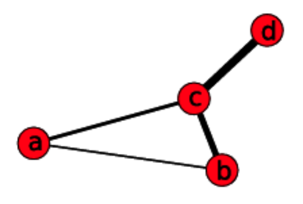

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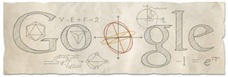
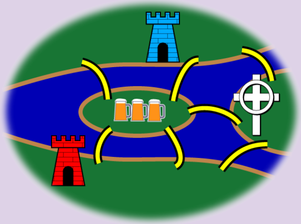
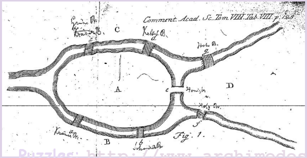
Network Topology

Graph Theory

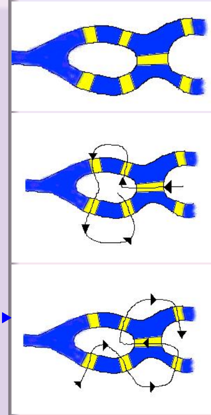
- 7 bridges of Königsberg [Euler, 1736]



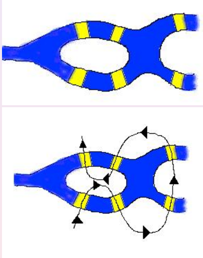


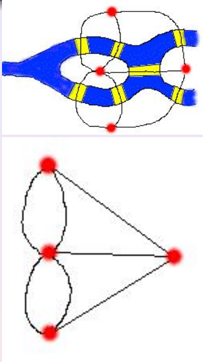


- 7 bridges



- 6 bridges





> “If a network has more than **two odd** vertices, it does NOT have an Euler path.”

- NO soln!!!

Puzzles: http://www.archimedes-lab.org/How_to_Solve/Water_gas.html
http://www.mathsisfun.com/activity/seven-bridges-konigsberg.html

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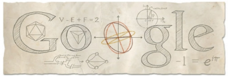

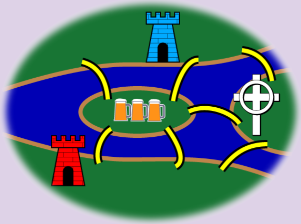

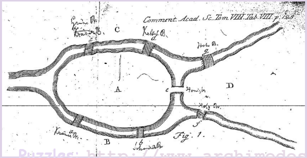

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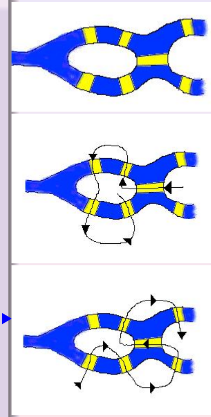

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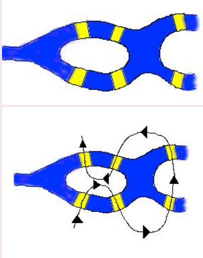

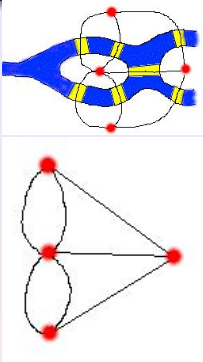

“If a network has more than two odd vertices, it does NOT have an Euler path.”

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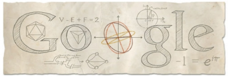
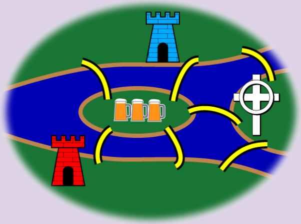
http://www.mathsisfun.com/activity/seven-bridges-konigsberg.html

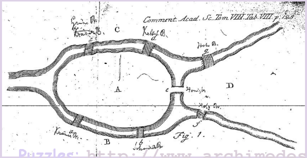
Network Topology

Graph Theory

- 7 bridges of Königsberg [Euler, 1736]







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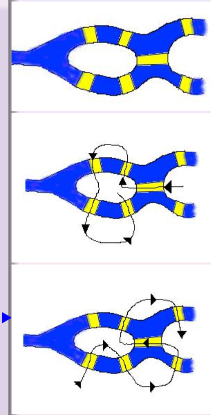

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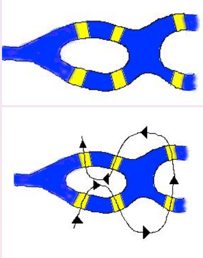

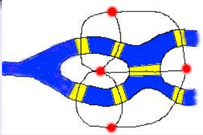

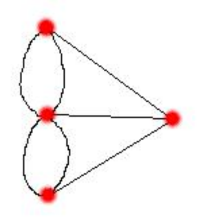

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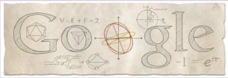

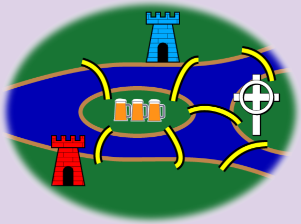

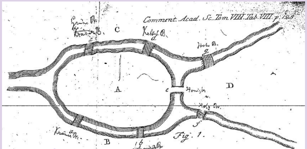

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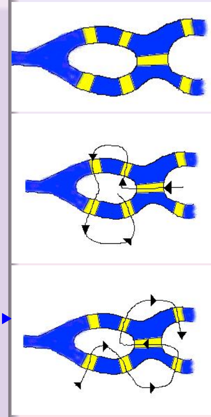

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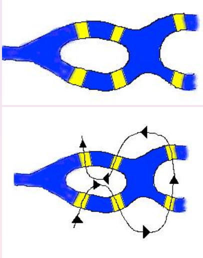

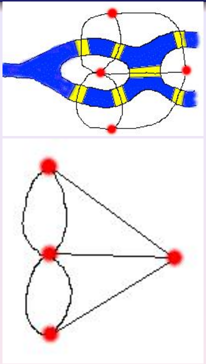

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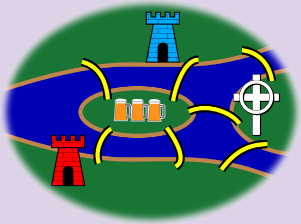

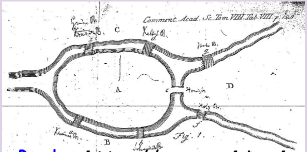

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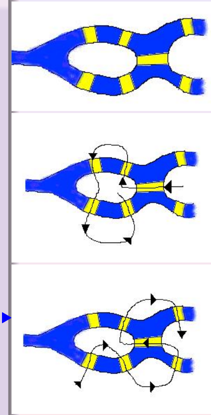

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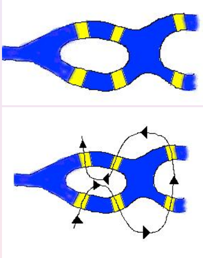

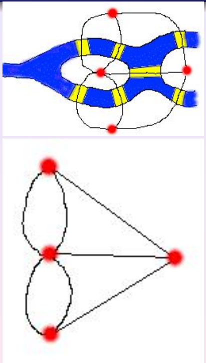

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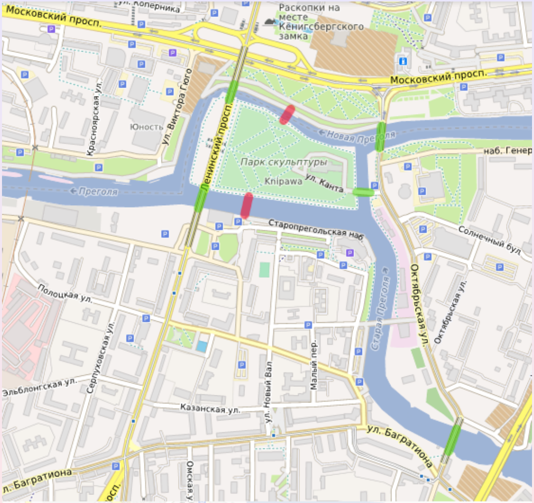
Present state of the seven bridges of Königsberg



Leaflet | Map data © OpenStreetMap contributors, rendering GIScience Research Group @ Heidelberg University

Src: `http://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg`

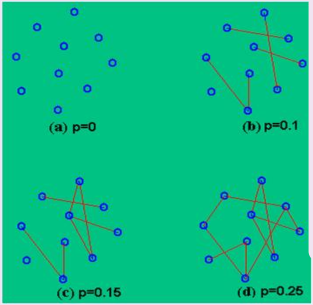
Network Topology

how nodes are connected

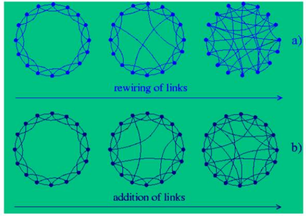
- According to the topology is possible to "classify" the networks.

Distribution of links $P(k)$ (degree distrib), avg. nbr. of links $\langle k \rangle$, clustering coeff, avg. length $\langle \ell \rangle$ (diam),...

- random networks
  - Erdös-Rényi (1960)



- regular or uniform
  - globally coupling, nearest-neighbors, ...



- irregular or heterog.
  - non-uniform distrib. (star), ...

e.g. airlines routes

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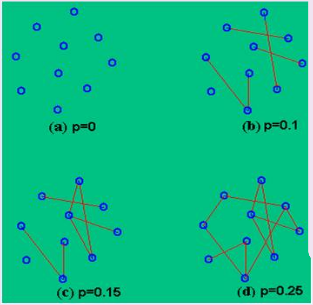

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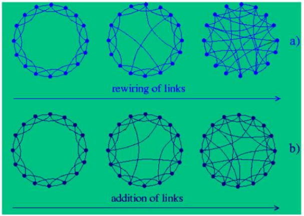

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ATLANTIC OCEAN

e.g. airlines routes

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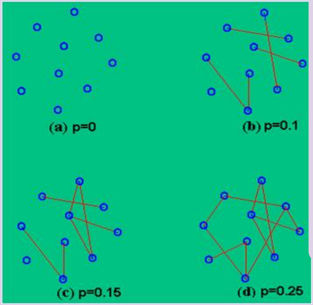

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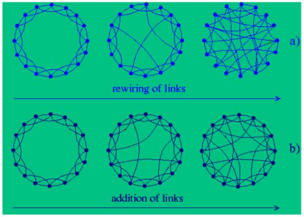

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ATLANTIC OCEAN

e.g. airlines routes▲

Complex Networks I

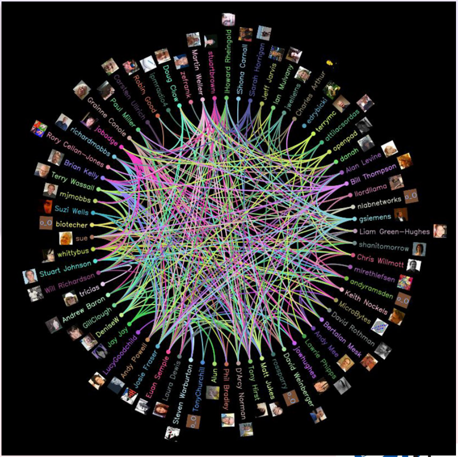
Properties of «REAL» networks

Small-World [Watts and Strogatz, Nature, 1998]

most nodes can be reached by a small number of steps («6 dof»!)

- Connectivity distribution: uniform but decays exponentially
- Homogeneous nature: each node has roughly the same number of links

facebook
December 2010



Complex Networks II

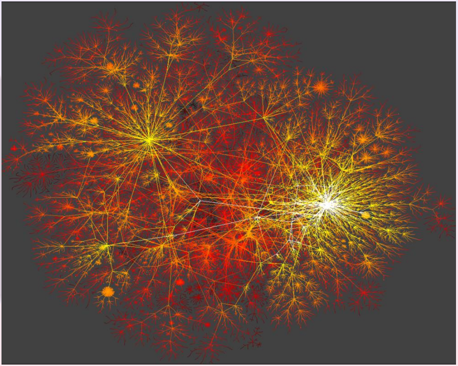
Properties of «REAL» networks

- Scale-Free [Barabási and Albert, Science, 1999]

some nodes act as "highly connected hubs", and most nodes are of low degree distribution:

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

$2 \leqslant \gamma \leqslant 3$ (power law)



MultiGraph: multiple edges

```
mg = nx.MultiGraph()
mg.add_weighted_edges_from([(1,2, .5), (1,2, .75), (2,3, .5)])
mg.degree()
{1: 2, 2: 3, 3: 1}
mg.degree(weight='weight')
{1: 1.25, 2: 1.75, 3: 0.5}
```

DiGraph: directed graphs

```
dg = nx.DiGraph()
dg.add_weighted_edges_from([(1,4,0.5), (3,1,0.75)])
dg.degree(1,weight='weight')
1.25
dg.successors(1)
[4]
dg.predecessors(1)
[3]
```

More graphs generators

```
K_5=nx.complete_graph(5)
nx.draw(K_5)

K_3_5=nx.complete_bipartite_graph(3,5)
nx.draw(K_3_5)

barbell=nx.barbell_graph(10,10)
nx.draw(barbell)

lollipop=nx.lollipop_graph(10,20)
nx.draw(lollipop)
```

Random graphs generators

```
er=nx.erdos_renyi_graph(100,0.15)
nx.draw(er)

ws=nx.watts_strogatz_graph(30,3,0.1)
nx.draw(ws)

ba=nx.barabasi_albert_graph(100,5)
nx.draw(ba)

red=nx.random_lobster(100,0.9,0.9)
nx.draw(red)
```

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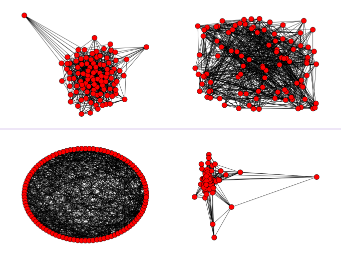
Visualization & Graph properties...

Visualization

```
import networkx as nx
import pylab as plt
g = nx.erdos_renyi_graph(100,0.15)
nx.draw(g)
nx.draw_random(g)
nx.draw_circular(g)
nx.draw_spectral(g)
plt.savefig('graph.png')
```



Graph properties

```
N,K = g.order(), g.size()
avg_deg = float(K)/N
print "Nodes:␣", N
print "Edges:␣", K
print "Average␣degree:␣", avg_deg
```

Degree distribution

```
g.in_degrees()
```

```
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
AttributeError: 'Graph' object has no attribute 'in_degrees'
```

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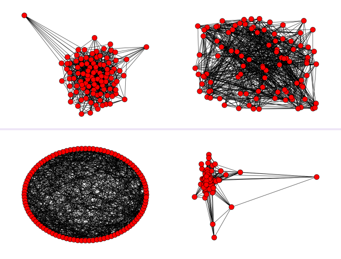

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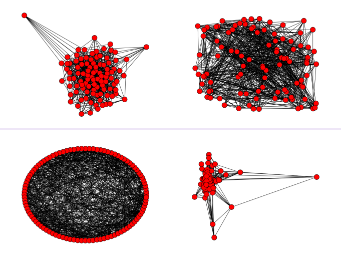

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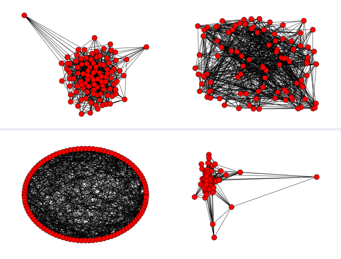

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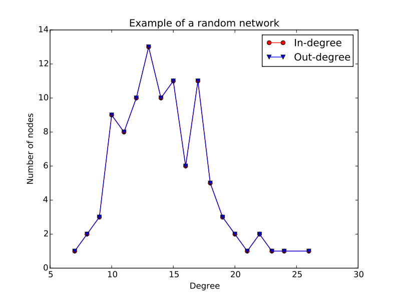
```

Graph properties: degree distribution ...

Degree distribution

```
diG=nx.DiGraph(g) #create a directed graph
# account for in/out-going connections...
in_degrees = diG.in_degree() # dictionary node:degree
out_degrees = diG.out_degree() # dictionary node:degree
in_values = sorted(set(in_degrees.values()))
out_values = sorted(set(out_degrees.values()))
# put data in histogram-form
in_hist = [in_degrees.values().count(x) for x in in_values]
out_hist = [out_degrees.values().count(x) for x in out_values]

# plot
plt.figure()
plt.plot(in_values,in_hist,'ro-') # in-degree
plt.plot(out_values,out_hist,'bv-') # out-degree
plt.legend(['In-degree','Out-degree'])
plt.xlabel('Degree')
plt.ylabel('Number␣of␣nodes')
plt.title('Example␣of␣a␣random␣network')
plt.savefig('network_degree_distribution.pdf')
plt.close()
```

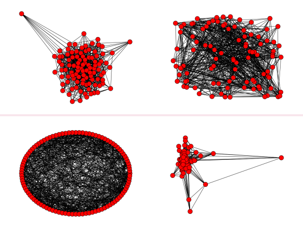


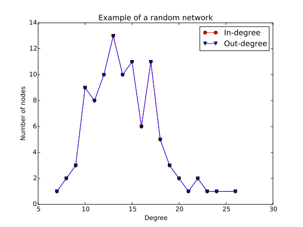
Graph properties: connectivity properties ...

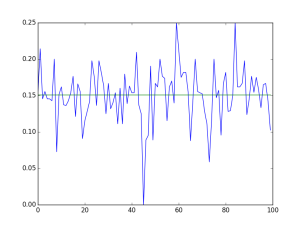
Clustering Coefficient

```
import numpy as np
g_ud = diG.to_undirected()
# Clustering coefficient of node 0
print nx.clustering(g_ud, 0)
# Clustering coefficient of all nodes (in a dictionary)
clust_coefficients = nx.clustering(g_ud)
# Average clustering coefficient
ccs = nx.clustering(g_ud)
avg_clust = sum(ccs.values()) / len(ccs)

plt.plot(ccs.keys(),ccs.values())
plt.plot(ccs.keys(),np.ones(len(ccs))*avg_clust)
```







Modeling Twitter Relationships I

"Following"

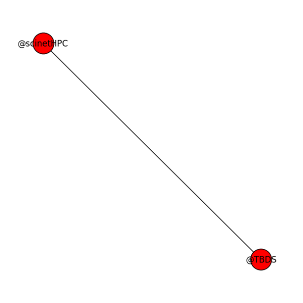
```
import networkx as nx
import pylab as plt

g = nx.Graph()  #nx.DiGraph()
g.add_node(0, {"handle": "@scinetHPC"})
g.add_node(1, {"handle": "@TBDS"})
g.add_edge(0, 1)

node_labels = nx.get_node_attributes(g,'handle')

plt.figure(figsize=(6,6))
plt.ion()

pos = nx.spring_layout(g)
nx.draw(g, pos, arrows=True, node_size=900)
nx.draw_networkx_labels(g, pos, labels = node_labels)
```



Modeling Twitter Relationships II

“Re-Tweets”

```
g = nx.DiGraph()
g.add_node(0, {"id": "@scinetHPC", "color": "r"})
g.add_node(1, {"id": "@TBDS", "color": "r"})
g.add_node(2, {"id": "Tweet␣#530038648860065793", "color": "orange"})
g.add_edge(0, 1, {"type": "follows"})
g.add_edge(0, 2, {"type": "tweeted"})

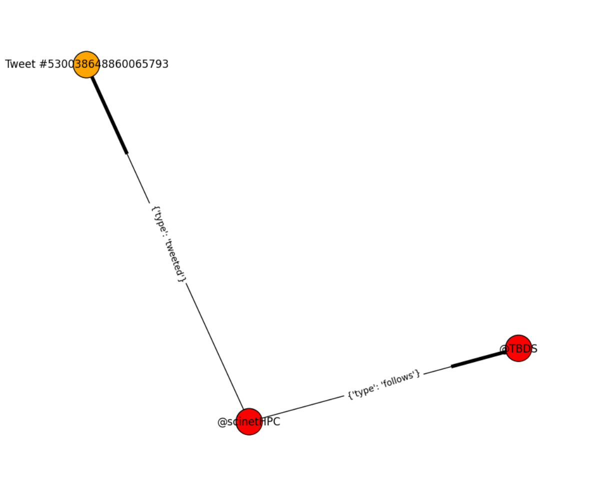
node_labels = nx.get_node_attributes(g,’id’)
edge_labels = nx.get_edge_attributes(g,’type’)
colors = nx.get_node_attributes(g, ’color’)

plt.figure(figsize=(6,6))

pos = nx.spring_layout(g)
nx.draw(g, pos, arrows=True, node_size=900, node_color=colors.values())
nx.draw_networkx_labels(g, pos, labels = node_labels)
nx.draw_networkx_edge_labels(g, pos, labels = edge_labels)
```

Modeling Twitter Relationships III

A model for the Twitter network



Modeling the I/O-ops @ SciNet I

Data

```
tcs-f06n01  tcs-f06n01  0.013554078
tcs-f06n01  tcs-f06n01  0.004655432
tcs-f07n02  gpc-f119n017  0.002597279
tcs-f07n02  tcs-f07n02  0.000283613
tcs-f06n02  tcs-f06n02  0.000703586
tcs-f06n02  tcs-f06n02  0.001286946
tcs-f07n01  tcs-f07n01  0.025607990
tcs-f07n01  tcs-f07n01  0.018086633
tcs-f07n01  tcs-f07n01  0.003623529
tcs-f06n04  tcs-f06n04  0.012281074
tcs-f06n04  tcs-f06n04  0.012600201
tcs-f06n03  tcs-f06n03  0.006405814
tcs-f06n03  tcs-f06n03  0.024002783
tcs-f06n03  tcs-f06n03  0.019571064
tcs-f07n04  tcs-f07n04  0.034180323
tcs-f07n04  tcs-f07n04  0.100195957
```

449 records

- networkX.read_edgelist(...)

```
 g =
nx.read_format("path/to/file.txt",...options..

nx.write_format(g,"path/to/file.txt",...option
```

- Read and write edge lists

```
g = nx.read_edgelist(path,comments='#',
    create_using=None,
    delimiter=' ',nodetype=None,
    data=True,edgetype=None,
    encoding='utf-8')

nx.write_edgelist(g,path,comments='#',
    delimiter=' ',data=True,

    encoding='utf-8')
```

Modeling the I/O-ops @ SciNet II

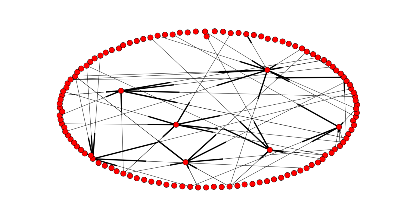
Importing and plotting the data

```
import networkx as nx
import pylab as plt

scinetG = nx.read_edgelist("scinet_data.txt",
        comments='#',
        create_using=nx.MultiDiGraph(),
        delimiter='␣␣',
        nodetype=str,data=(('weight',float),) )

plt.ion()
nx.draw(scinetG)


plt.figure()
```



Modeling the I/O-ops @ SciNet III

“Massaging” the network (data)

```
plt.figure()
plt.axis(’off’)

cutOff=0.001
elarge=[(u,v) for (u,v,d) in scinetG.edges(data=True) if d[’weight’] > cutOff]
esmall=[(u,v) for (u,v,d) in scinetG.edges(data=True) if d[’weight’] <= cutOff]

#try different ones from the ones below...
#pos=nx.spring_layout(scinetG) # positions for all nodes
pos=nx.graphviz_layout(scinetG)
#pos=nx.shell_layout(scinetG)
#pos=nx.random_layout(scinetG)
#pos=nx.spectral_layout(scinetG)

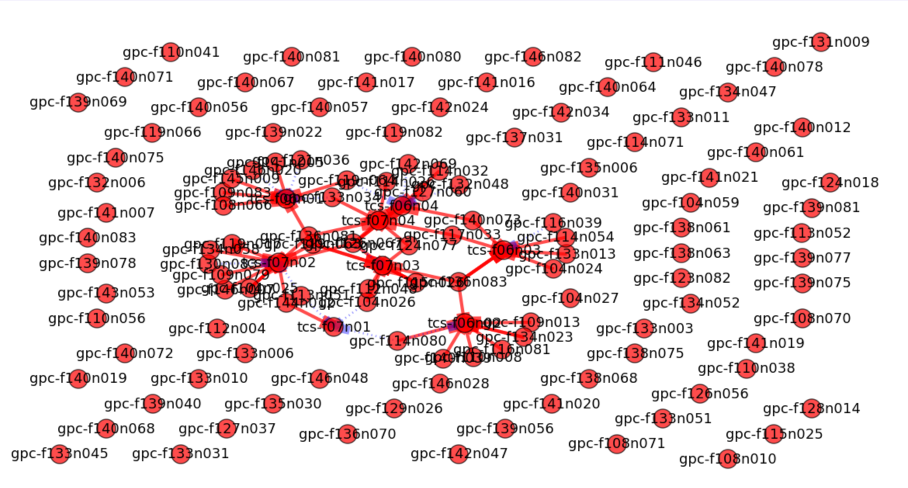
# nodes
nx.draw_networkx_nodes(scinetG,pos,
#                 node_color=nodeType.values(),
#                 node_size=tmW.values(),
                cmap=plt.cm.Reds, alpha=0.7)

# edges
color_edges=range(scinetG.number_of_edges())
nx.draw_networkx_edges(scinetG,pos,edgelist=elarge,
                    width=3,alpha=0.7,edge_color=’r’,
                    with_labels=’True’,edge_cmap=plt.cm.Blues)
nx.draw_networkx_edges(scinetG,pos,edgelist=esmall,
                    width=2,alpha=0.4,edge_color=’b’,style=’dotted’)
```

Modeling the I/O-ops @ SciNet IV

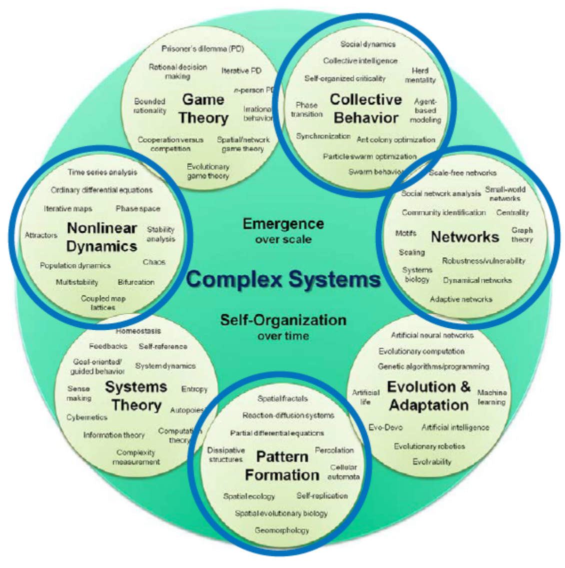
```
# labels
try:
        nx.draw_networkx_labels(scinetG,pos,labels,font_size=13,
                font_family='sans-serif', font_color='Indigo')
except:
        nx.draw_networkx_labels(scinetG,pos,font_size=13,font_family='sans-serif')
```

Modeling the I/O-ops @ SciNet V



PyCX: Python-based CompleX systems simulations

Online repository: http://pycx.sf.net/



Further Resources & Examples

- NetworkX: Network Analysis with Python, Salvatore Scellato
  http://www.cl.cam.ac.uk/~cm542/teaching/2011/stna-pdfs/stna-lecture11.pdf
- Graph Theory, including modelling of relationships, tweets, how to build a NetworkX graph from Twitter crawl results ...
  http://nbviewer.ipython.org/github/jquacinella/IS609_Group/blob/master/GraphTheory/Graph%20Theory%20-%20Social%20Networking.ipynb
- Graph and Network Analysis
  http://mlg.ucd.ie/files/summer/tutorial.pdf
- Social Network Analysis in Python
  https://ep2013.europython.eu/media/conference/slides/social-network-analysis-in-python.pdf
- Tutorial on PyCX
  http://pycx.sourceforge.net/PyCX-ECAL2013-tutorial.pdf

More about Complex Networks

NECSI:

http://necsi.edu/ http://www.necsi.edu/publications/dcs/index.html

http://www.necsi.edu/events/vidlib/ http://www.necsi.edu/research/overview.php

Some other good references:

http://www-personal.umich.edu/~mejn/courses/2004/cscs535/review.pdf

http://www.ifr.ac.uk/netsci08/Download/Invited/ws1_Caldarelli.pdf

http://barabasilab.neu.edu/courses/phys5116/

SantaFe Institute:

http://www.santafe.edu/education/schools/complex-systems-summer-schools/2015-program-info/