Global Networks: Understanding an Interconnected World

Pietro Battiston

VII Festa di Scienza e Filosofia
Foligno, 29/04/2016

What is a network?

What is a network?

Main ingredients

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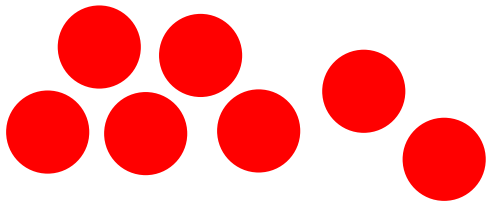

Things

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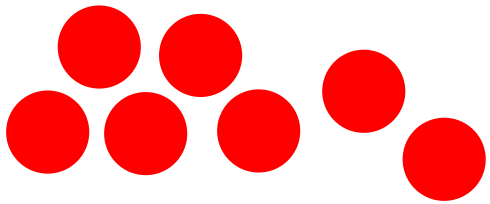

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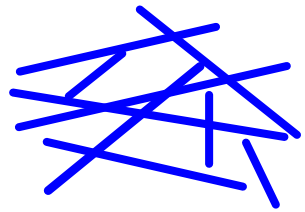

Connections

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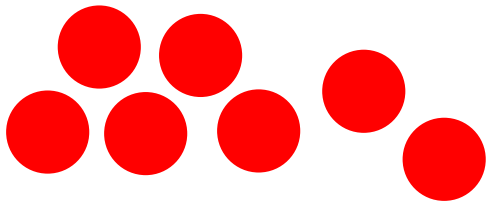

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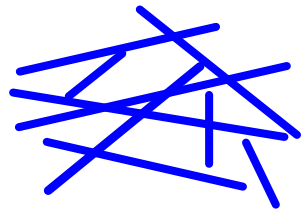

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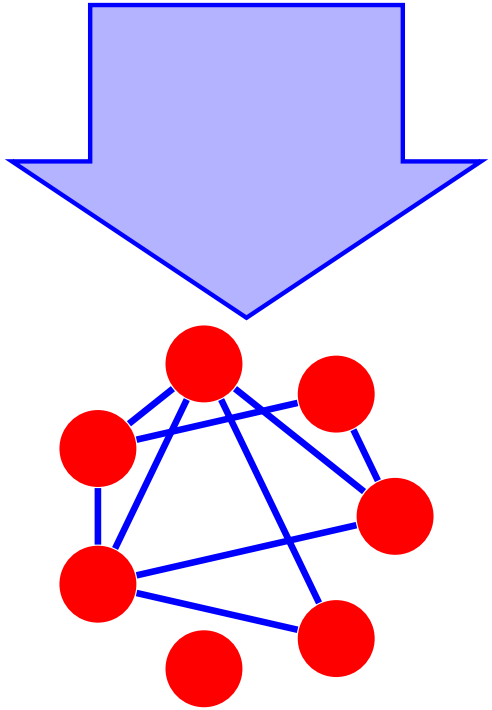

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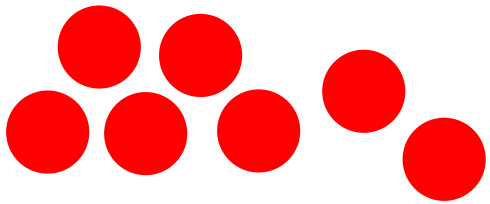

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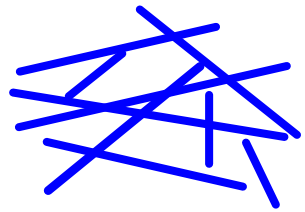
Nodes



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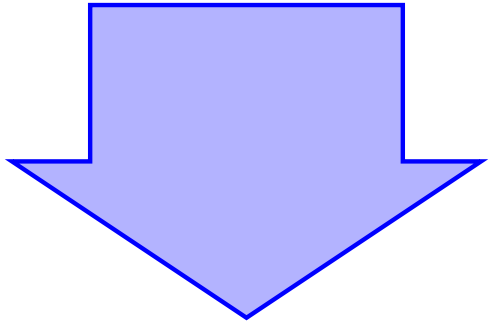

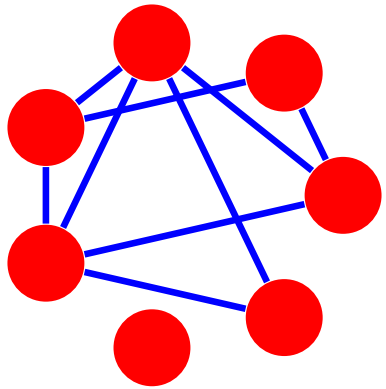

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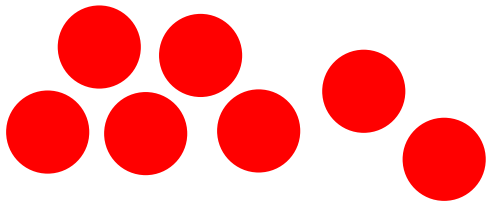

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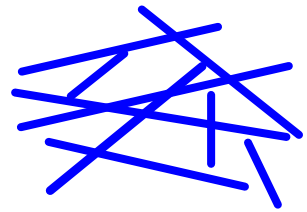
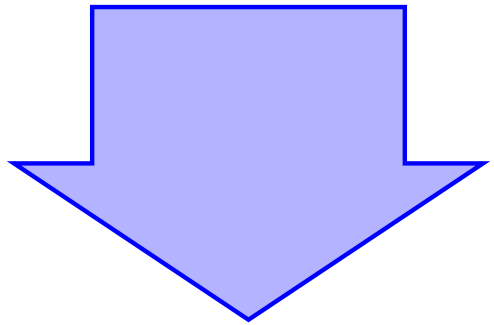
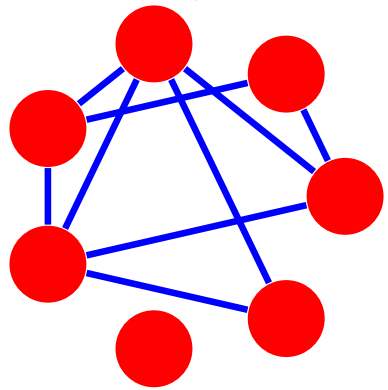


~~Connections~~

Edges





A couple of examples

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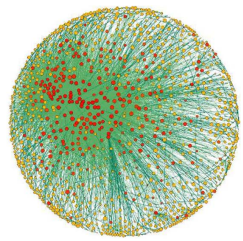
Nodes

Edges



A couple of examples

Nodes banks

Edges

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Nodes banks

Edges loans

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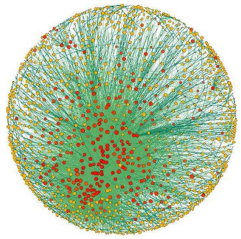
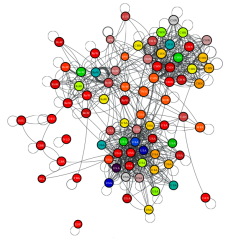
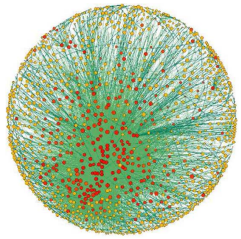


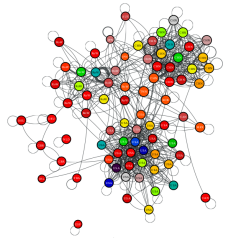


Nodes banks

Edges loans

A couple of examples





Nodes	banks	industrial sectors
Edges	loans	

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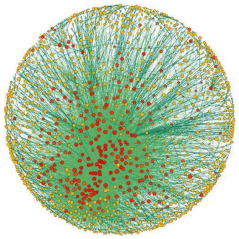

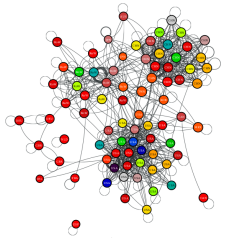

Nodes	banks	industrial sectors
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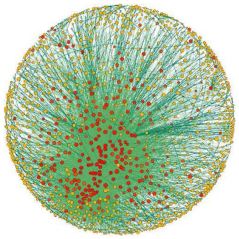

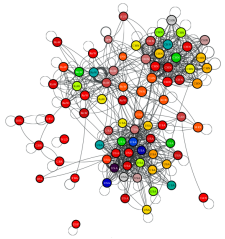

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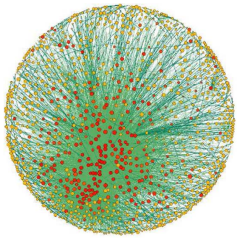

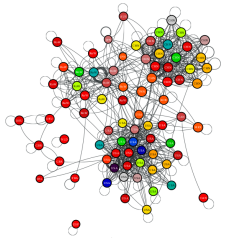

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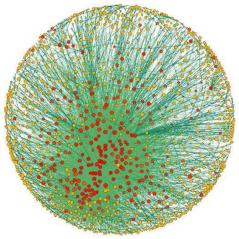

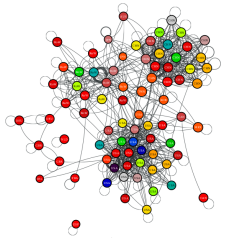

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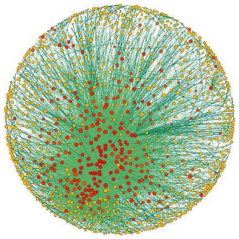
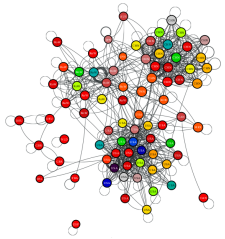

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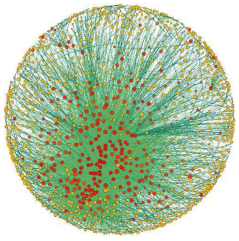
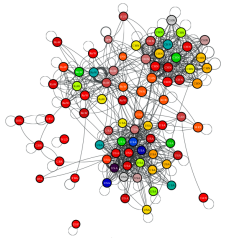

Nodes	banks	industrial sectors	web pages	twitter accounts
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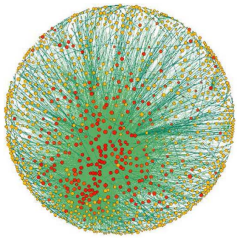
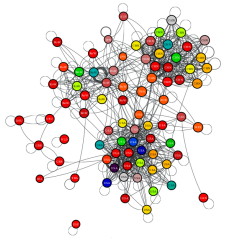

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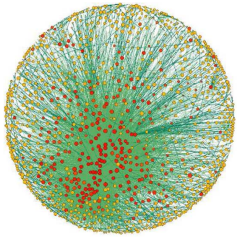
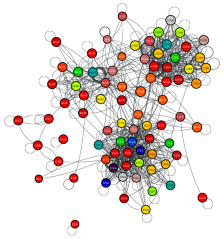

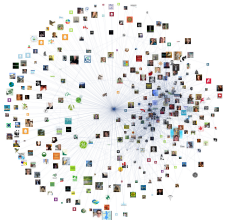

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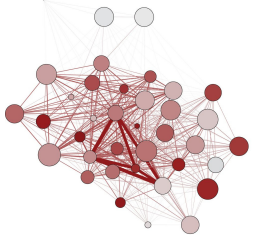

Nodes

Edges

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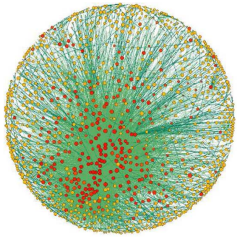
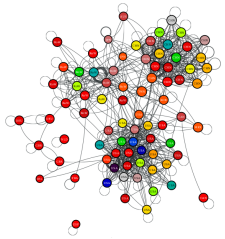

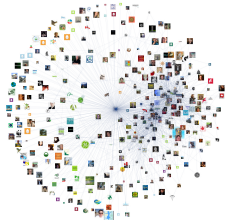

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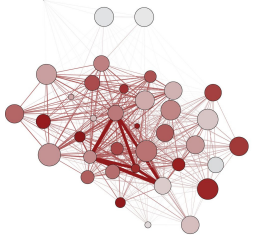
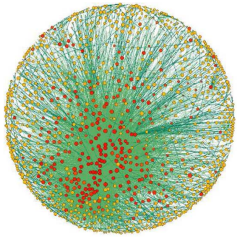


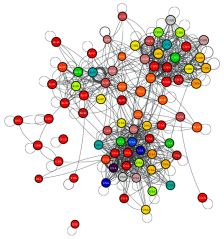
Nodes	sharks
Edges	

A couple of examples



Nodes banks

Edges loans

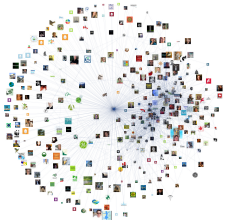


Nodes industrial sectors

Edges trade

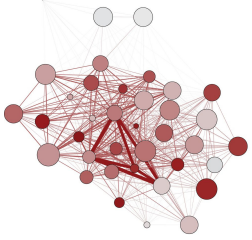
Nodes web pages

Edges links



Nodes twitter accounts

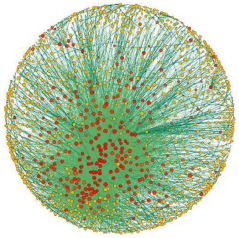
Edges followers

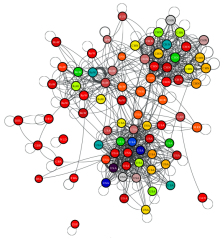


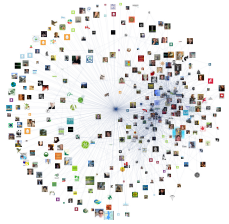
Nodes sharks

Edges hanging out

A couple of examples







Nodes	banks	industrial sectors	web pages	twitter accounts
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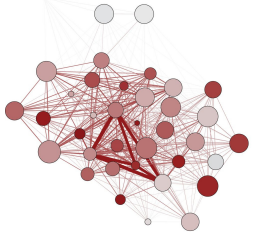

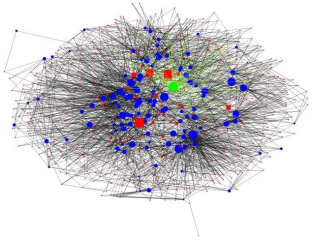

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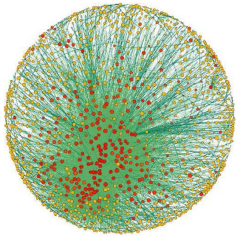
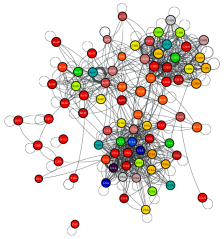

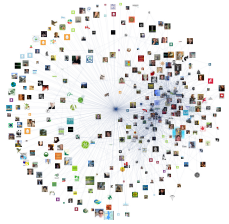

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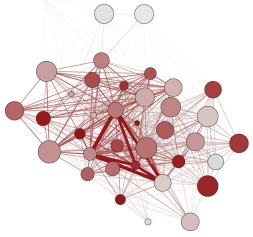
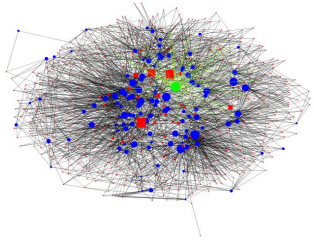

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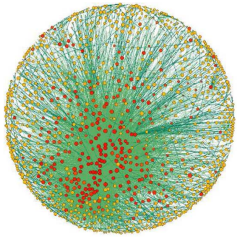
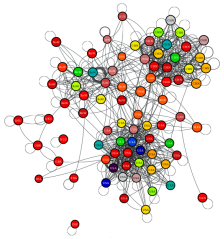
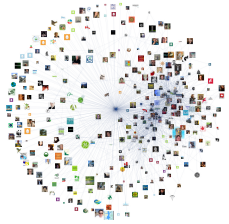
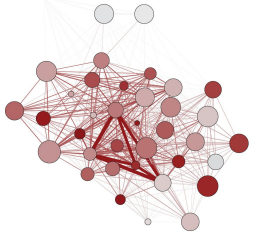
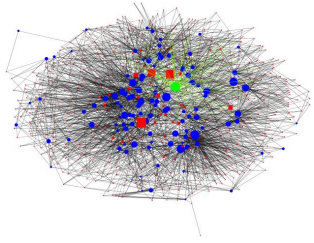
A couple of examples

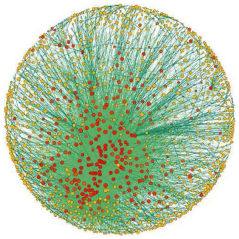
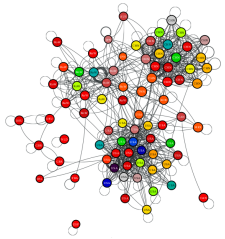
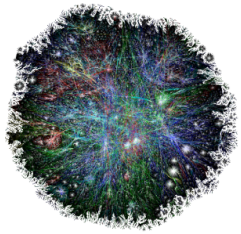
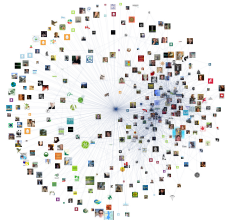


Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

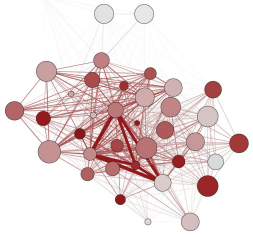
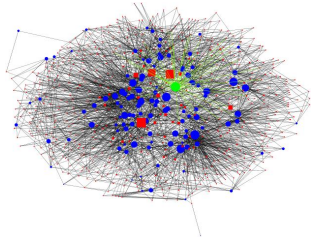
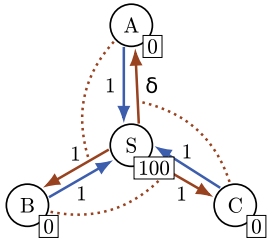



Nodes	sharks	actors
Edges	hanging out	collaboration

A couple of examples

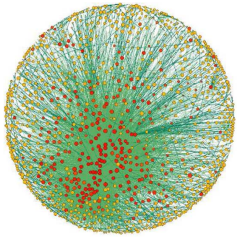
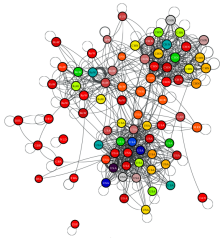





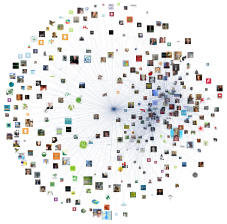
Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

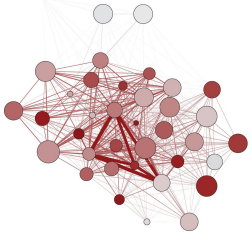
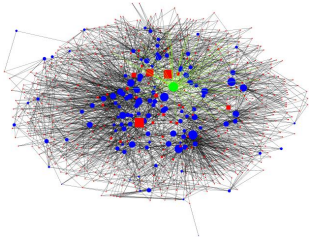
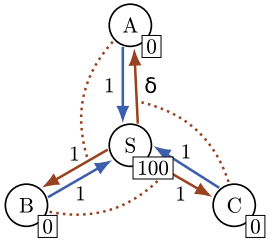
Nodes	sharks	actors
Edges	hanging out	collaboration

A couple of examples

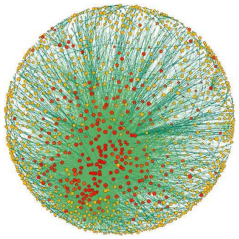
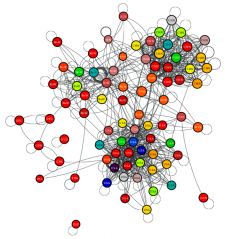
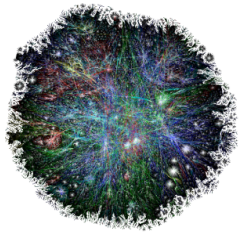
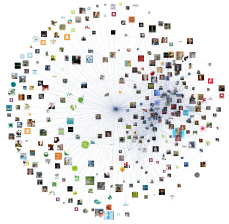


Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

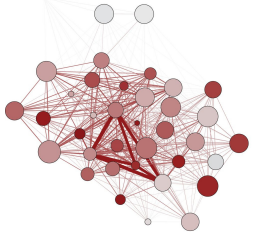
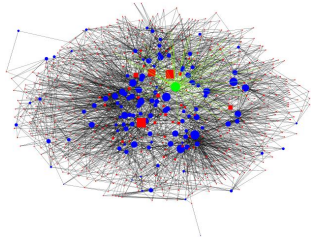
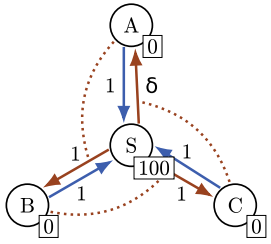




Nodes	sharks	actors	traders
Edges	hanging out	collaboration	

A couple of examples

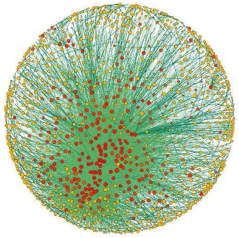
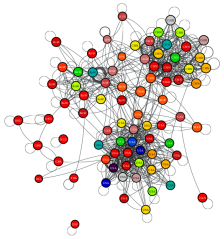





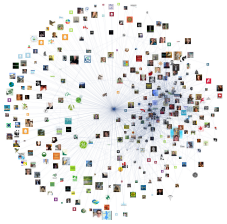
Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

Nodes	sharks	actors	traders
Edges	hanging out	collaboration	derivatives

A couple of examples



Nodes	banks	industrial sectors	web pages	twitter accounts
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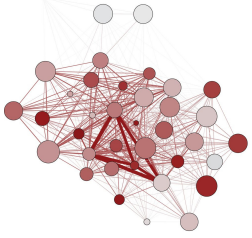
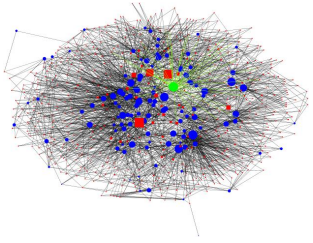
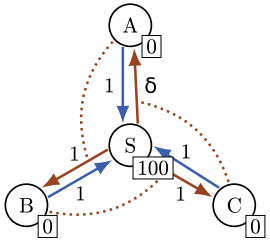
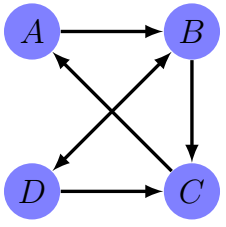
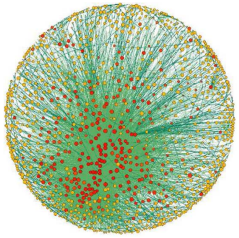
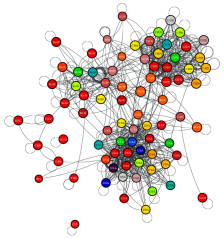




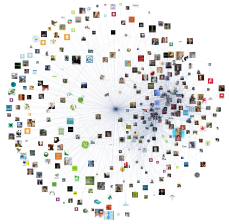


Nodes	sharks	actors	traders
Edges	hanging out	collaboration	derivatives

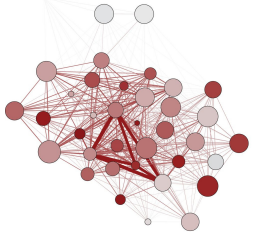
A couple of examples

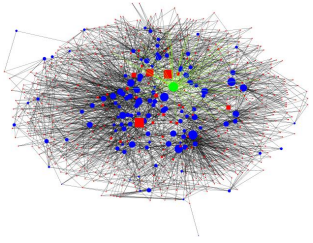


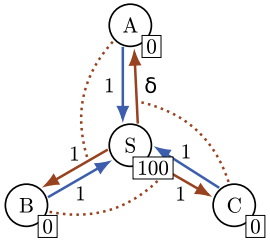


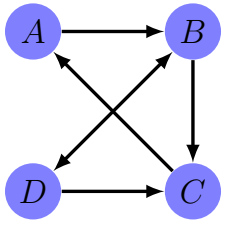


Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers



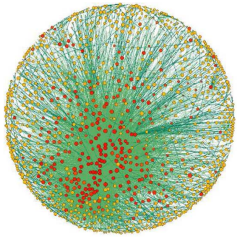
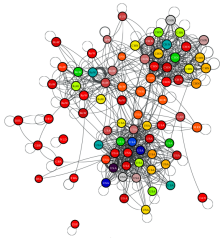


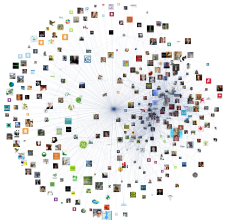




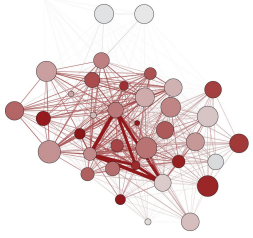
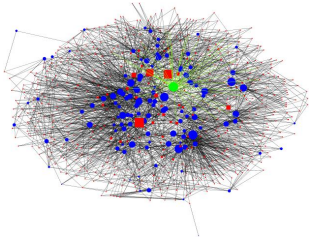
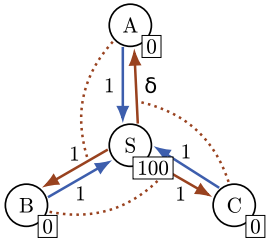
Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	

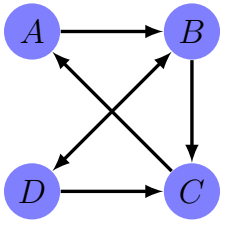
A couple of examples



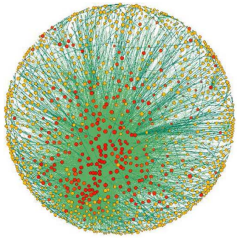
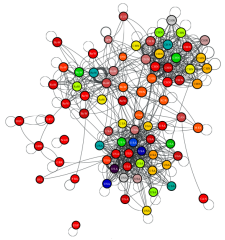
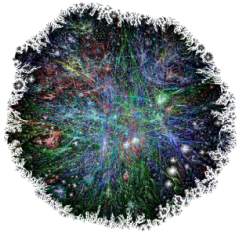
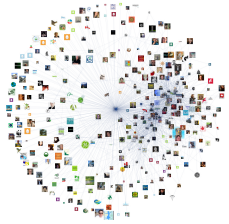
Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

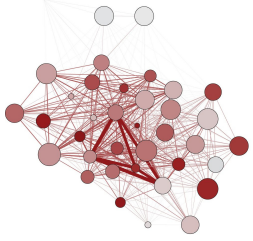
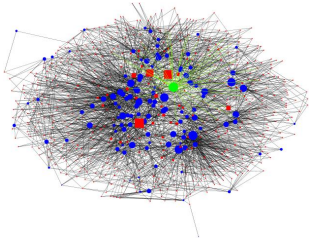
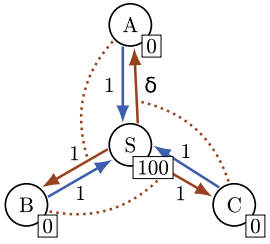


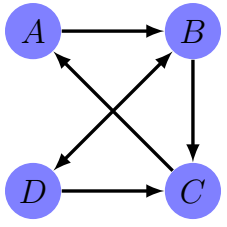
Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

A couple of examples

Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

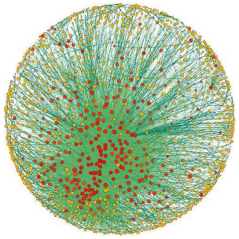
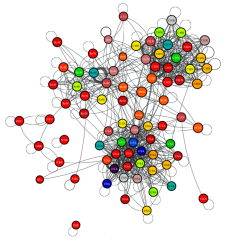
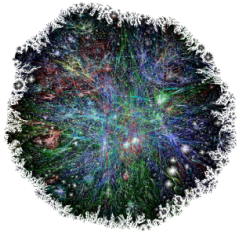
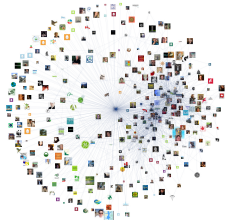






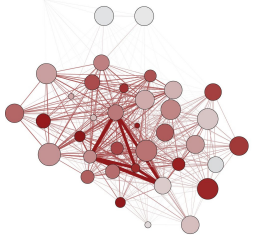
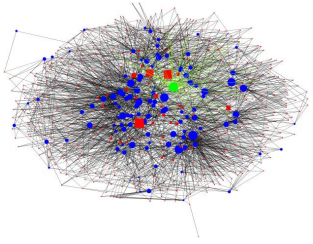
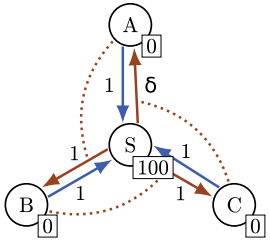
Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

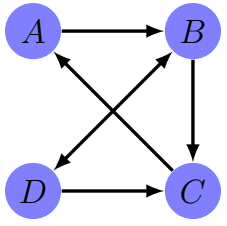
Nodes	
Edges	

A couple of examples

Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

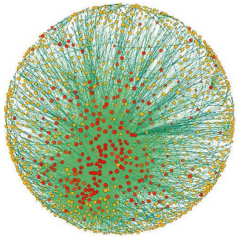
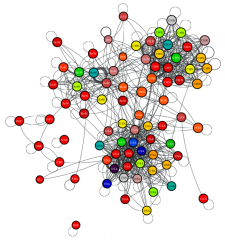
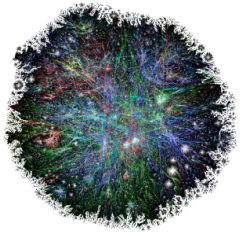
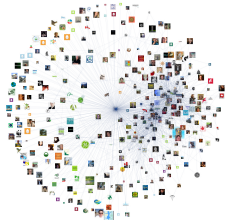






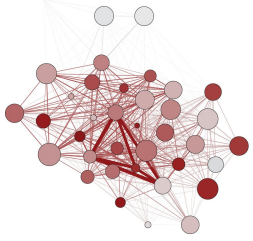
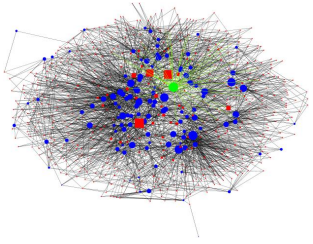
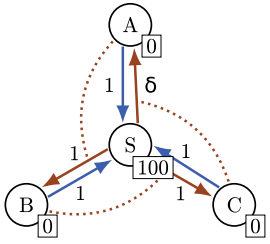
Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

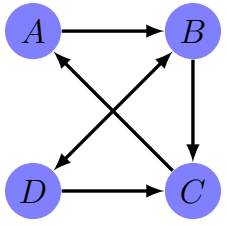
Nodes	cities
Edges	

A couple of examples

Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

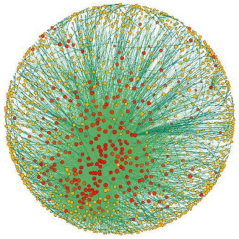
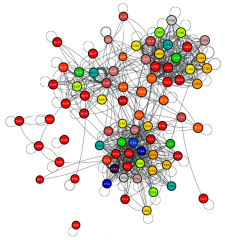
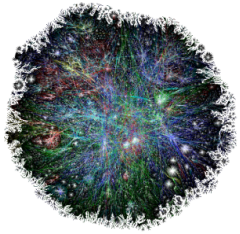
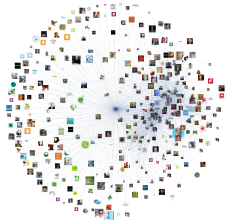






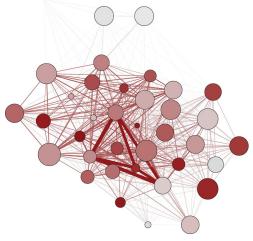
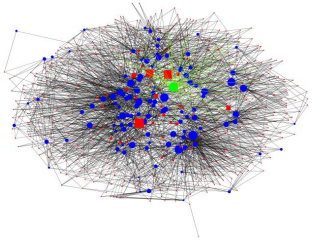
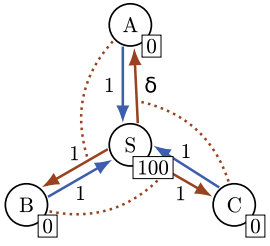
Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

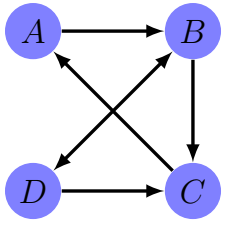
Nodes	cities
Edges	migration

A couple of examples

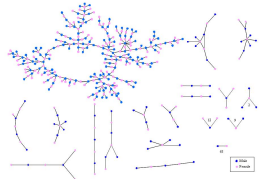





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

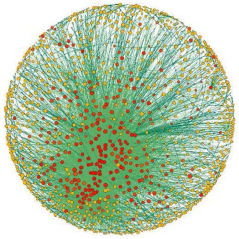
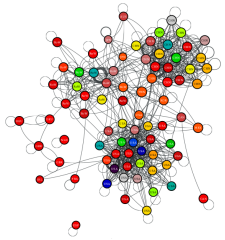
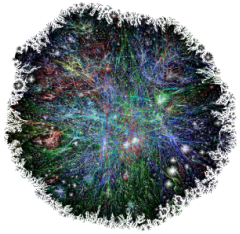
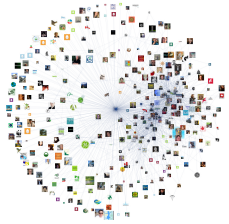


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

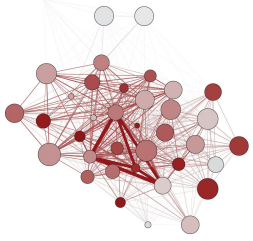
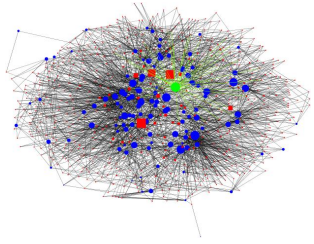
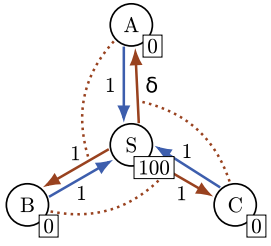



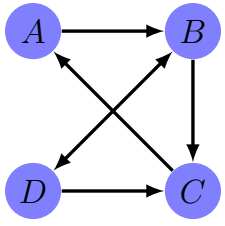
Nodes	cities
Edges	migration

A couple of examples

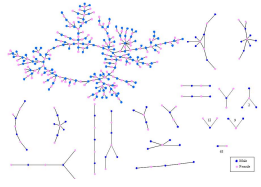





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

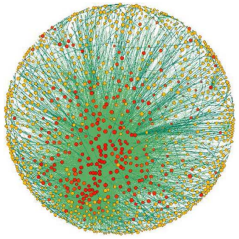
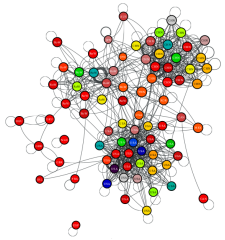
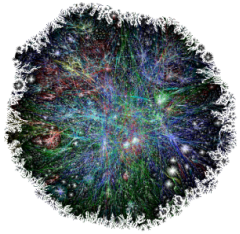
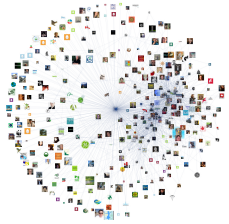


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

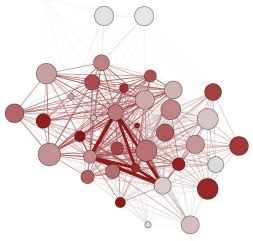
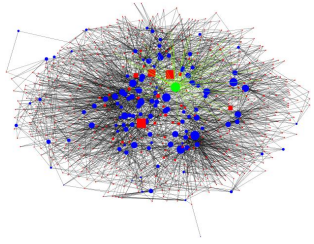
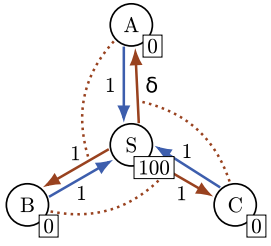



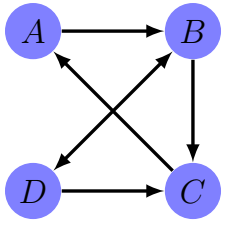
Nodes	cities	students
Edges	migration	

A couple of examples

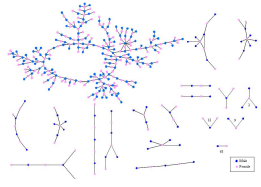





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

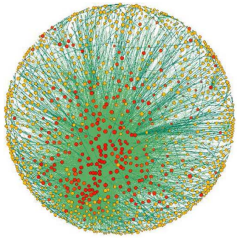
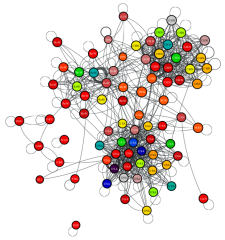
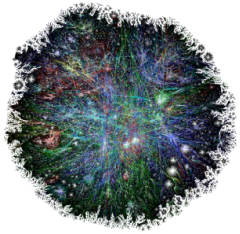
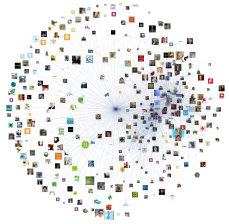


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

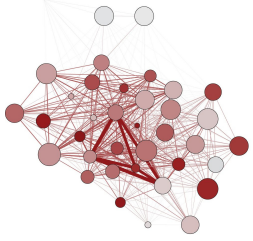
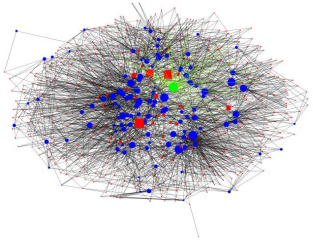
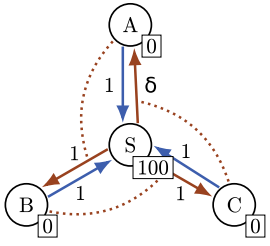



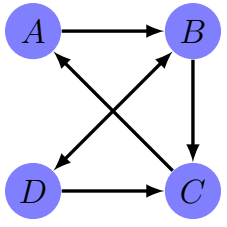
Nodes	cities	students
Edges	migration	relationship

A couple of examples

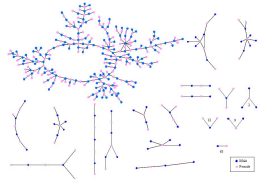
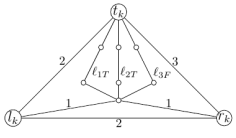





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

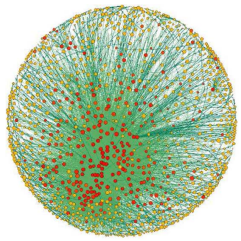
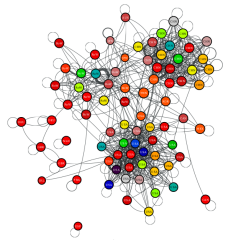
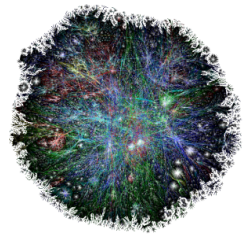


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

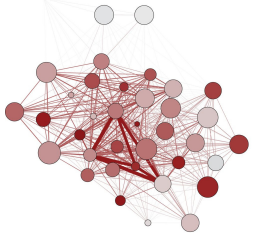
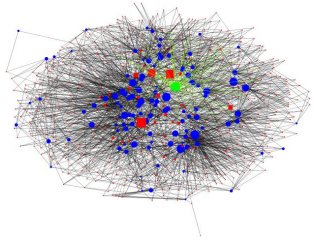
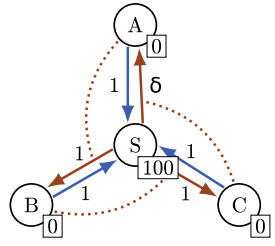




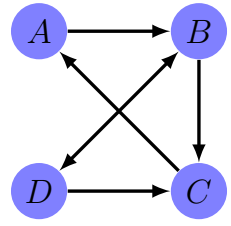
Nodes	cities	students
Edges	migration	relationship

A couple of examples

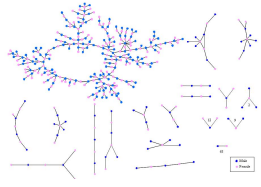
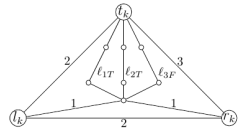





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

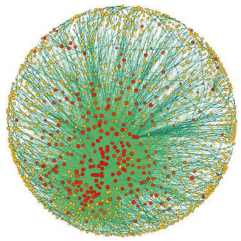
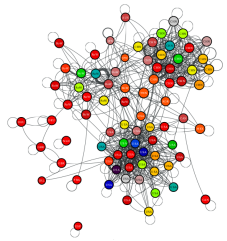
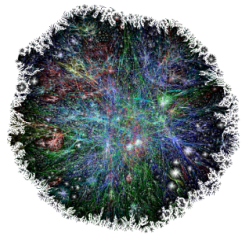
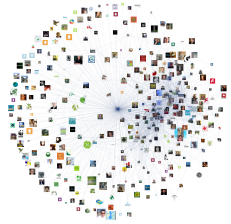


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

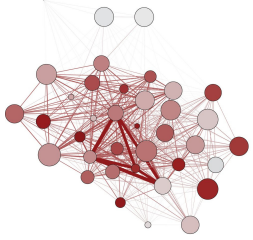
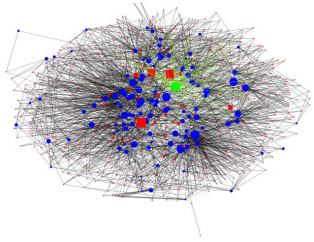
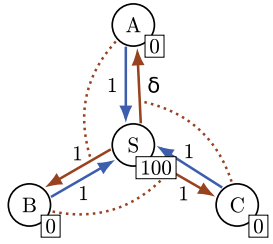




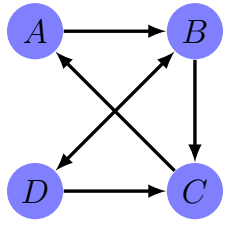
Nodes	cities	students	logic variables
Edges	migration	relationship	

A couple of examples

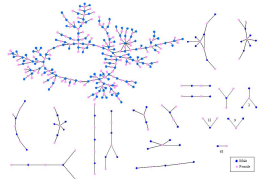
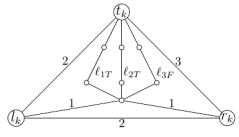





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

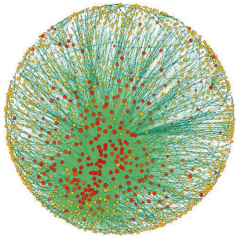
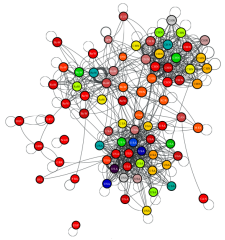
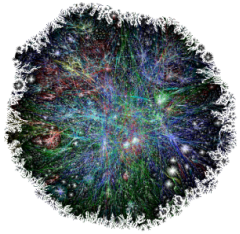


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

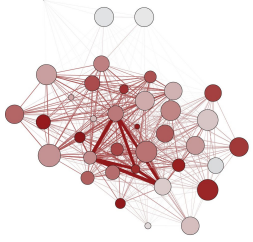
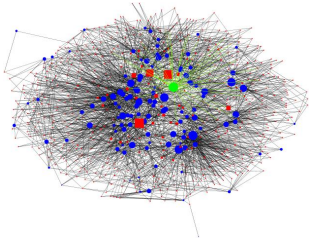
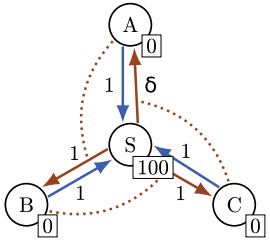




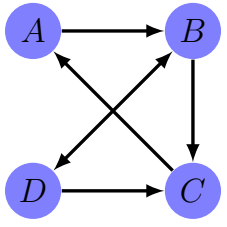
Nodes	cities	students	logic variables
Edges	migration	relationship	connectors

A couple of examples

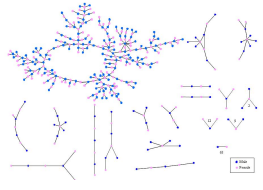
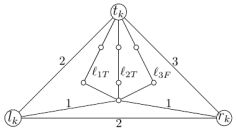
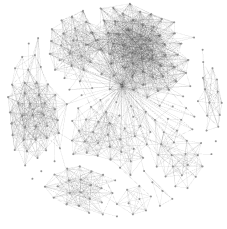





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

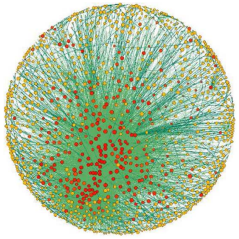
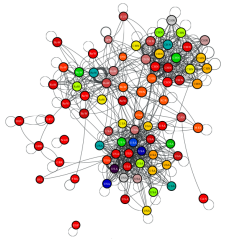
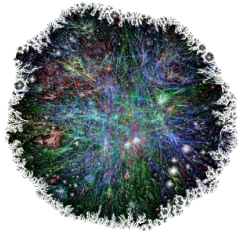


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

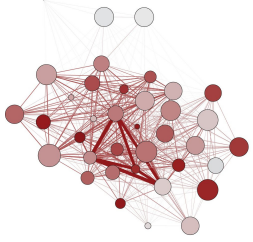
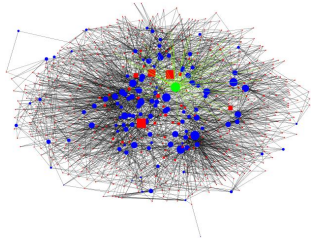
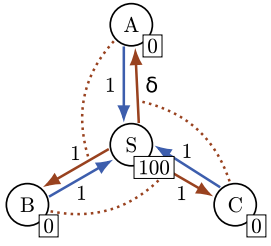





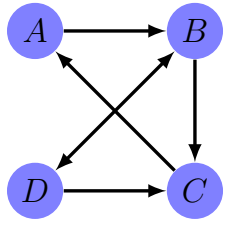
Nodes	cities	students	logic variables	
Edges	migration	relationship	connectors	

A couple of examples

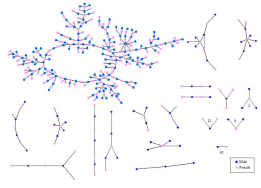
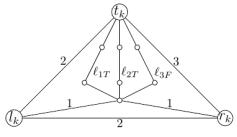
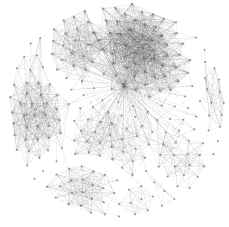





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers

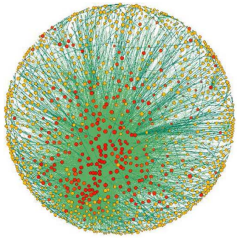
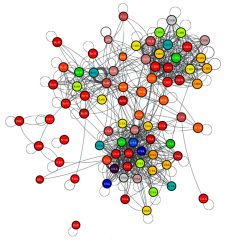
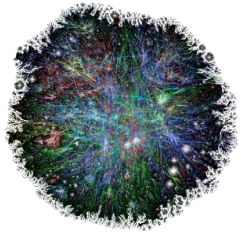


Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

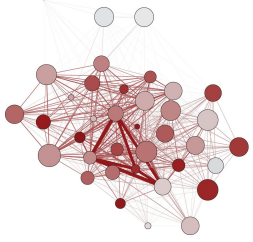
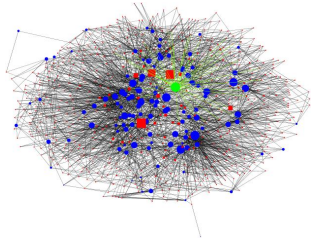
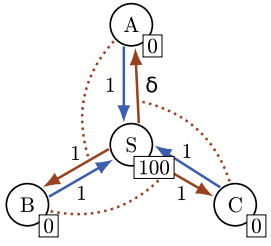





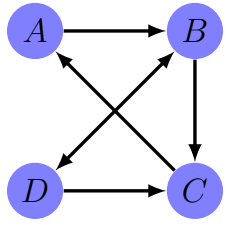
Nodes	cities	students	logic variables	facebook profiles
Edges	migration	relationship	connectors	

A couple of examples

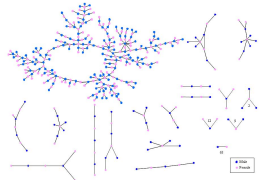
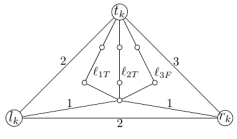
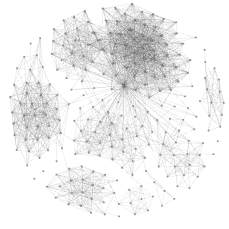





Nodes	banks	industrial sectors	web pages	twitter accounts
Edges	loans	trade	links	followers



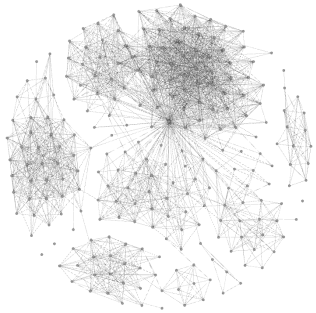
Nodes	sharks	actors	traders	individuals
Edges	hanging out	collaboration	derivatives	communication

Nodes	cities	students	logic variables	facebook profiles
Edges	migration	relationship	connectors	friendship

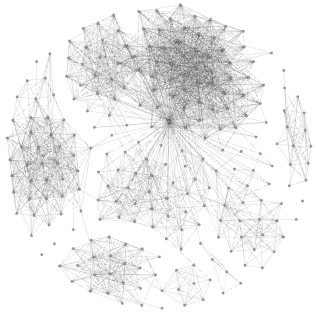
Additional ingredients - 1/3: edge properties

Additional ingredients - 1/3: edge properties

Difference between  and  ?

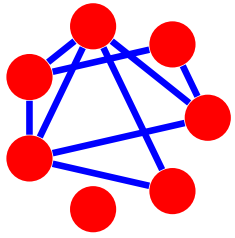
(facebook) (twitter)

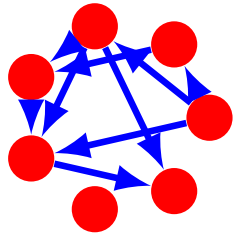
Additional ingredients - 1/3: edge properties

Difference between  and  ?

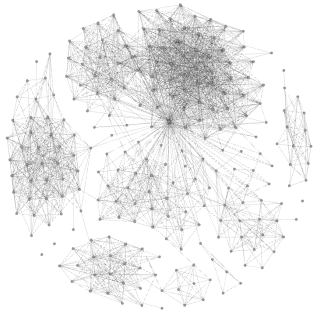
(facebook) (twitter)

Direction



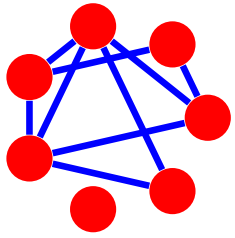


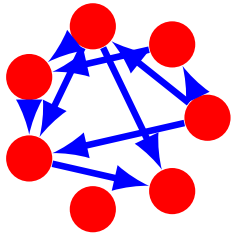
Additional ingredients - 1/3: edge properties

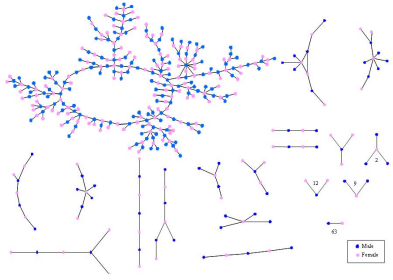
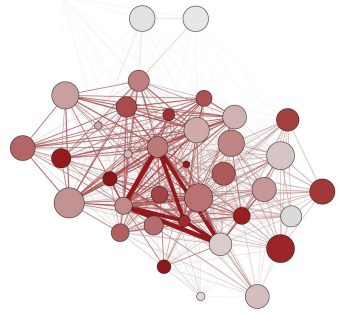
Difference between  and  ?

(facebook) (twitter)

Direction

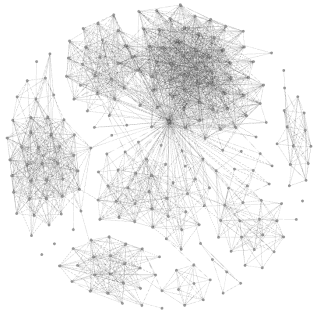




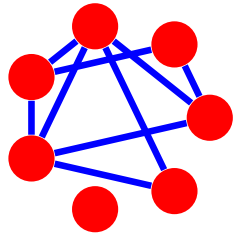
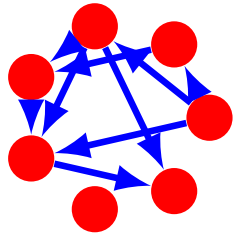
Difference between  and  ?

(students) (sharks)

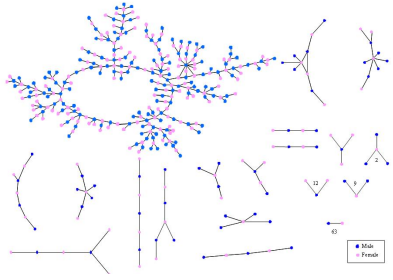
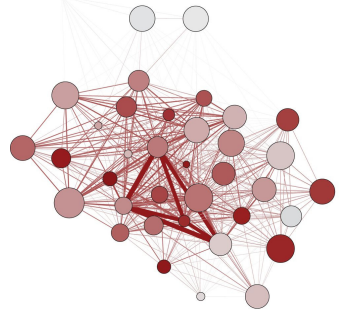
Additional ingredients - 1/3: edge properties

Difference between  and  ?

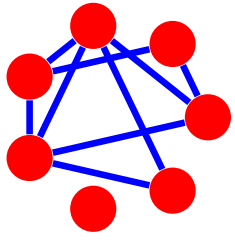
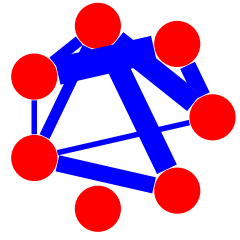
(facebook) (twitter)

Direction

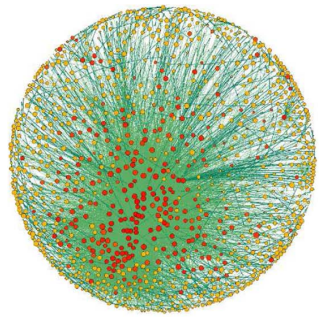
Difference between  and  ?

(students) (sharks)

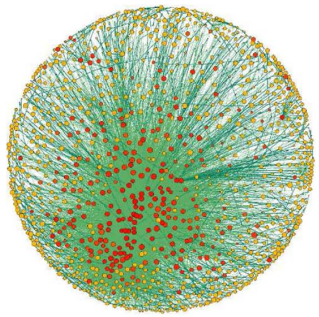
Importance/weight

Additional ingredients - 2/3: node properties

Difference between  and  ?

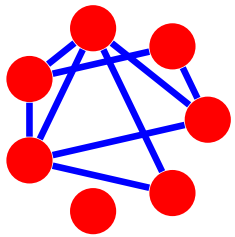
(twitter accounts) (banks)

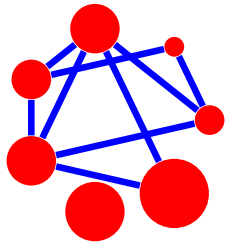
Additional ingredients - 2/3: node properties

Difference between  and  ?

(twitter accounts) (banks)

Importance/size





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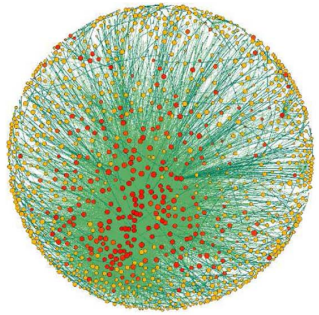
Difference between  and  ?

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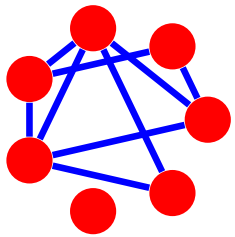
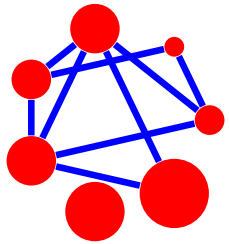
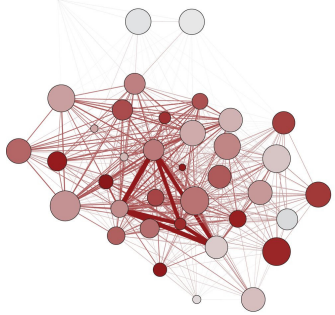


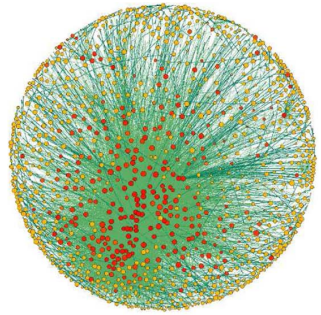


Importance/size

Difference between  and  ?

(sharks) (cities)

Additional ingredients - 2/3: node properties

Difference between  and  ?

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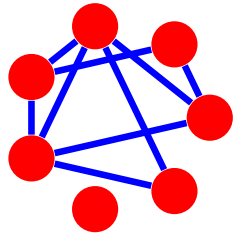

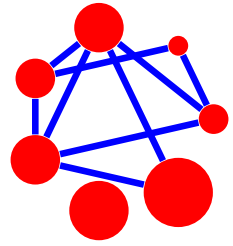

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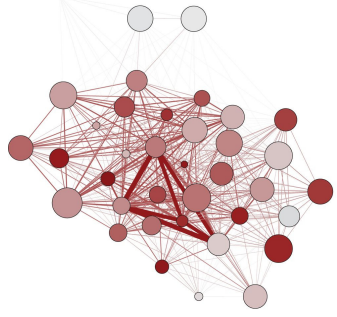
Difference between  and  ?

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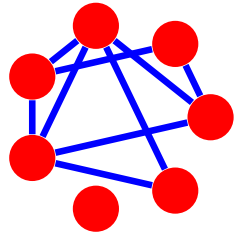

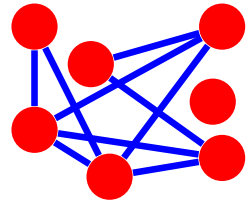

Position in space

Additional ingredients - 3/3: time

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On nodes:

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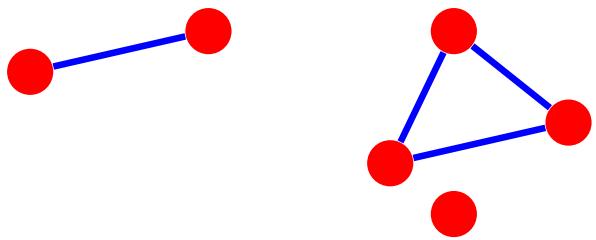

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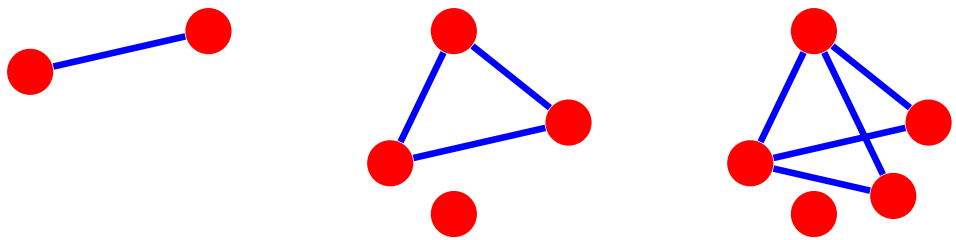

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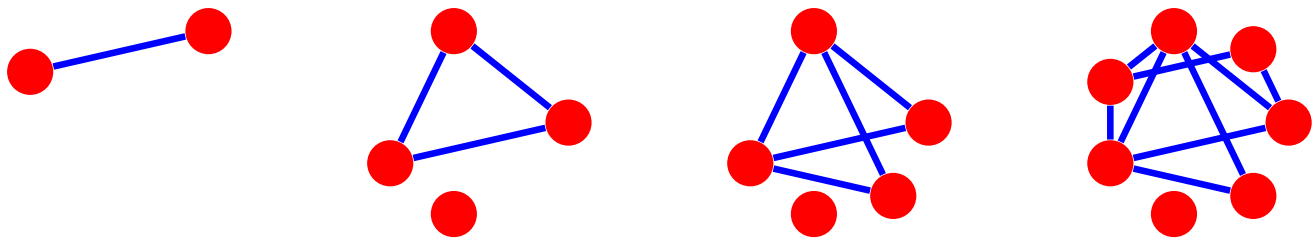

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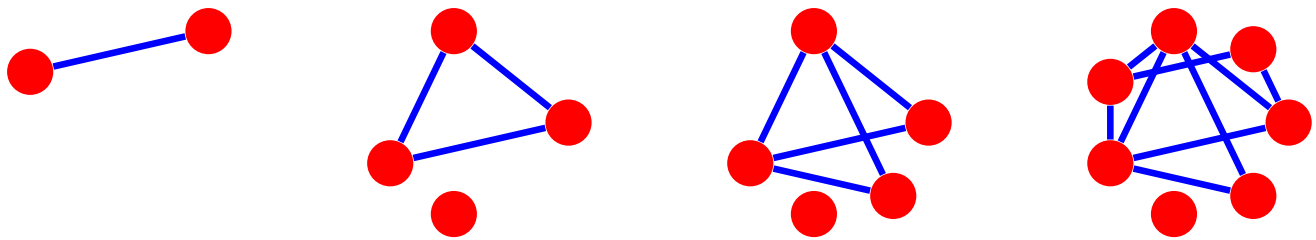

On edges:

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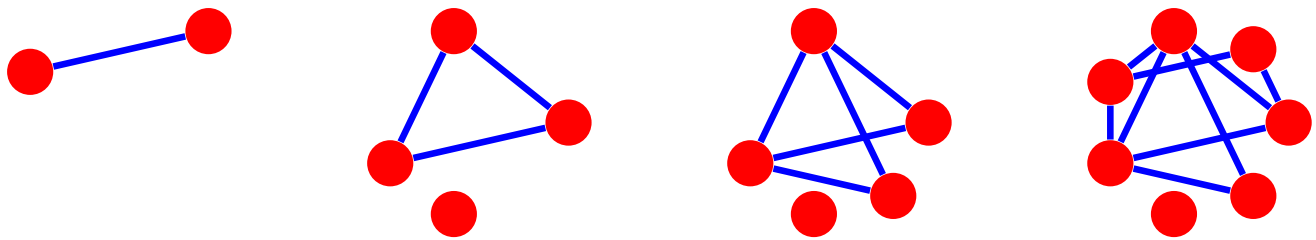

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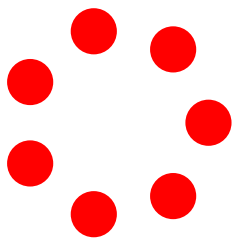

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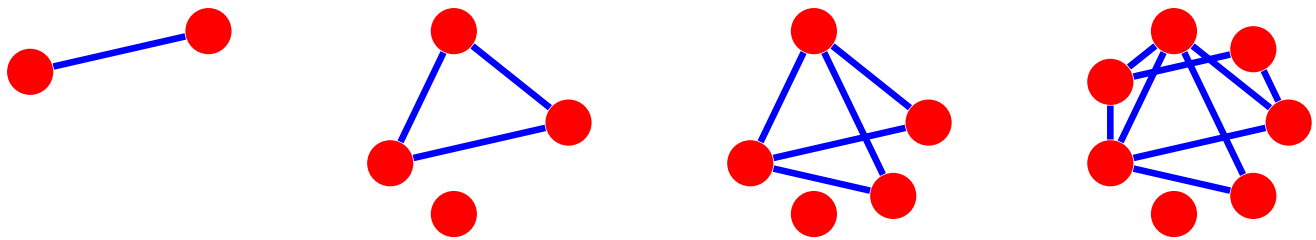

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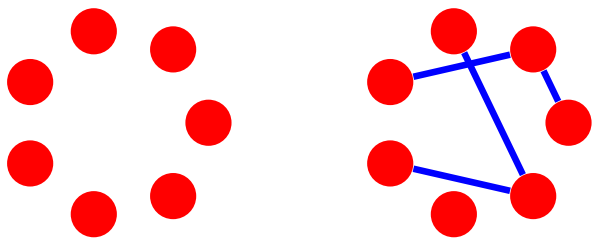

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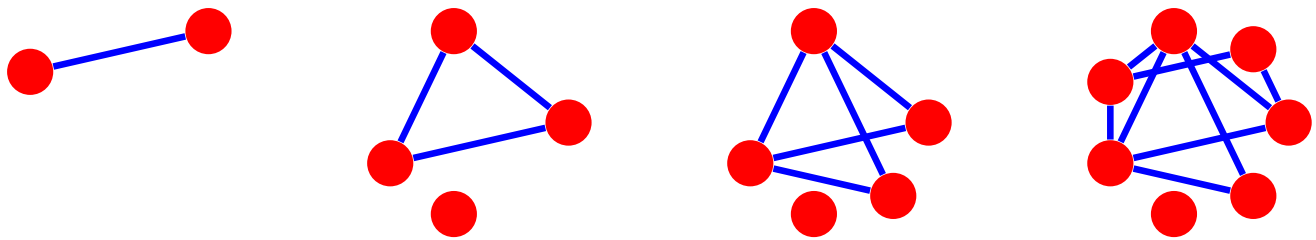

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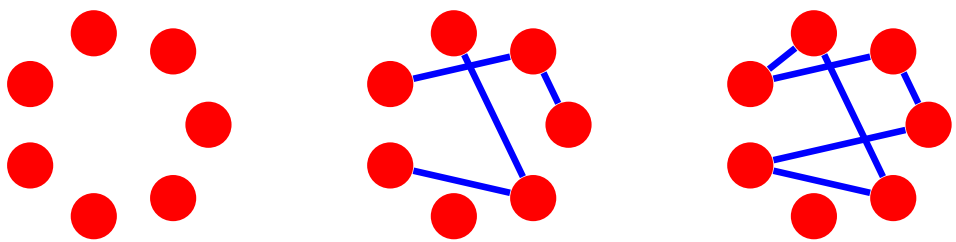

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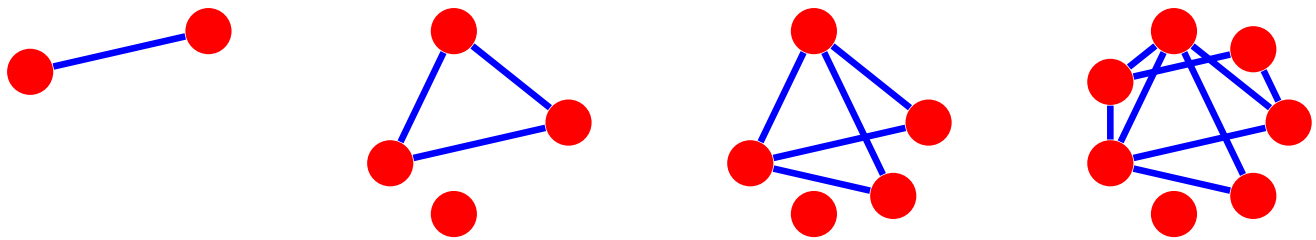

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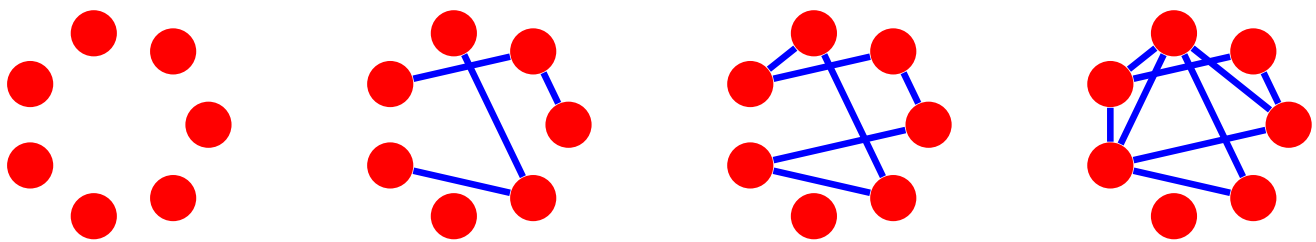

Application 1: The network of international trade

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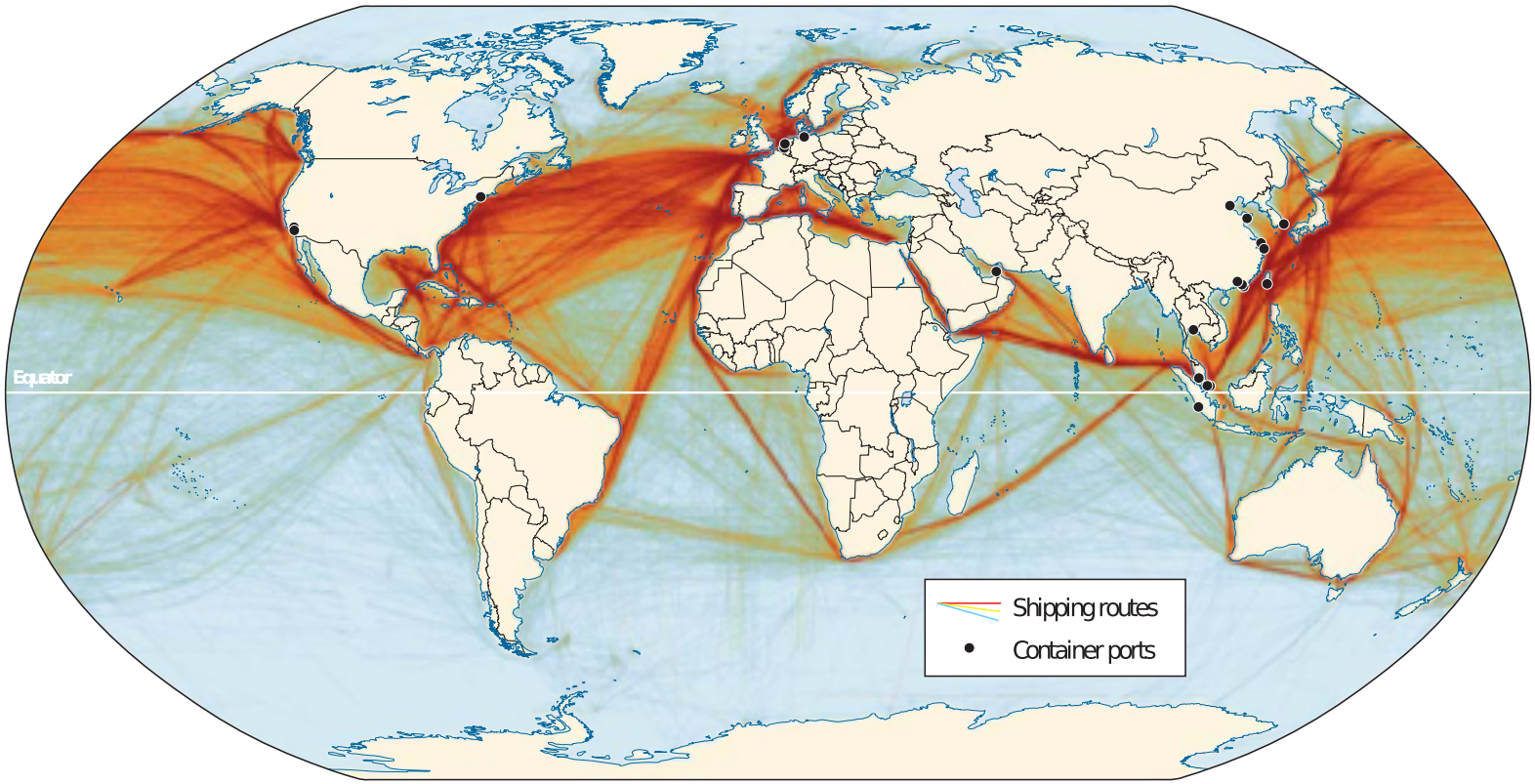

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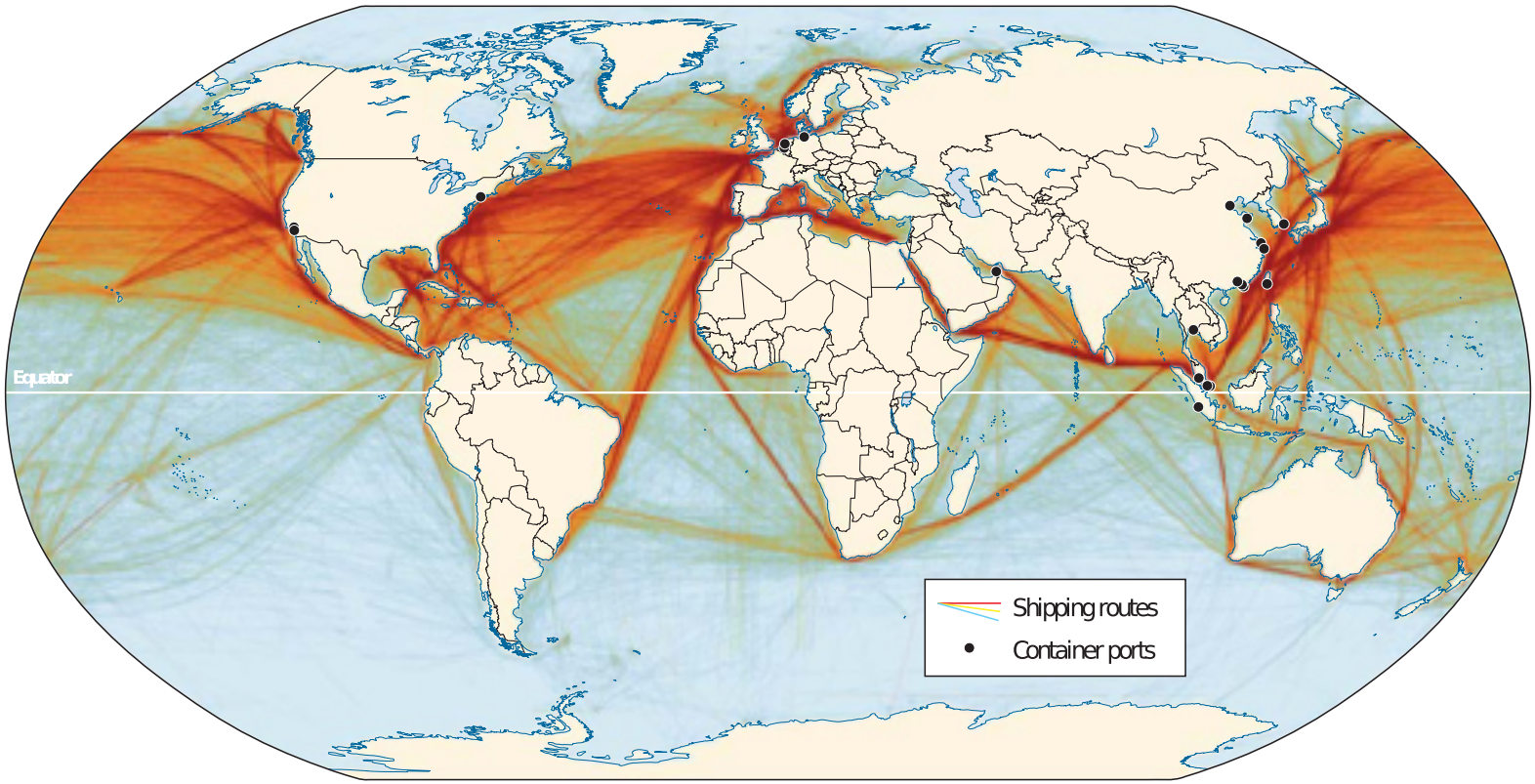

Opportunity for growth

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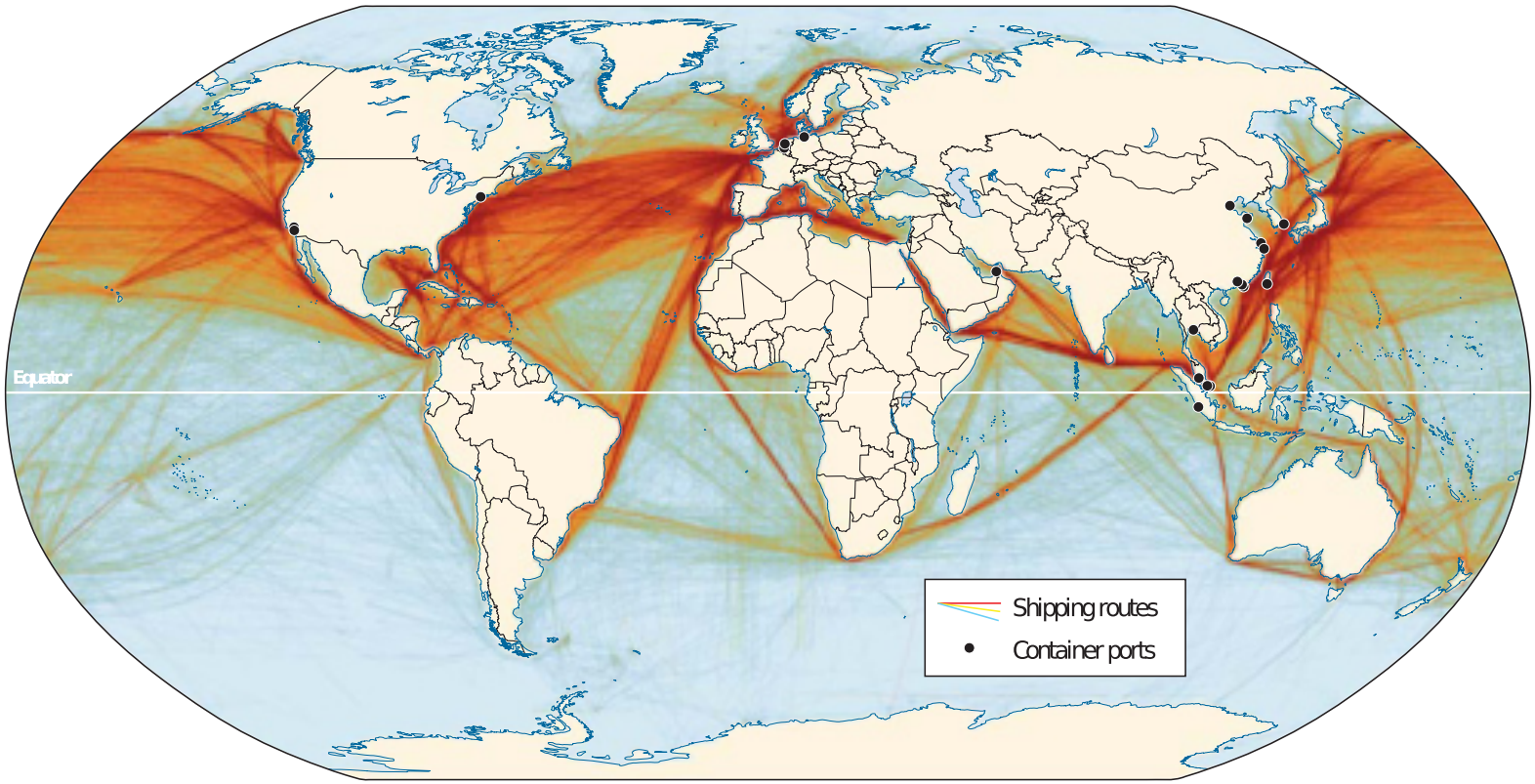

Opportunity for growth. . . but also for predatory competition concerning:

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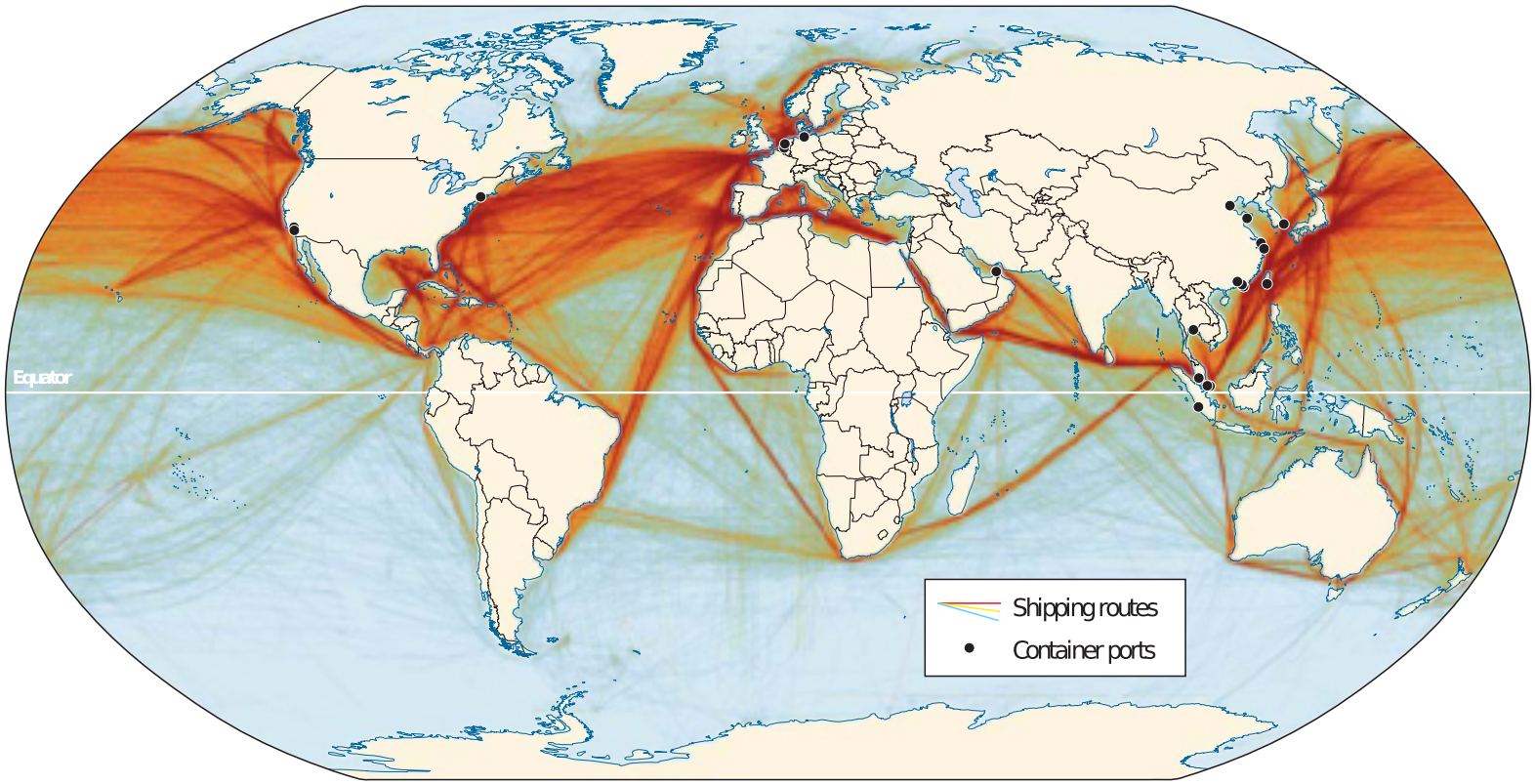

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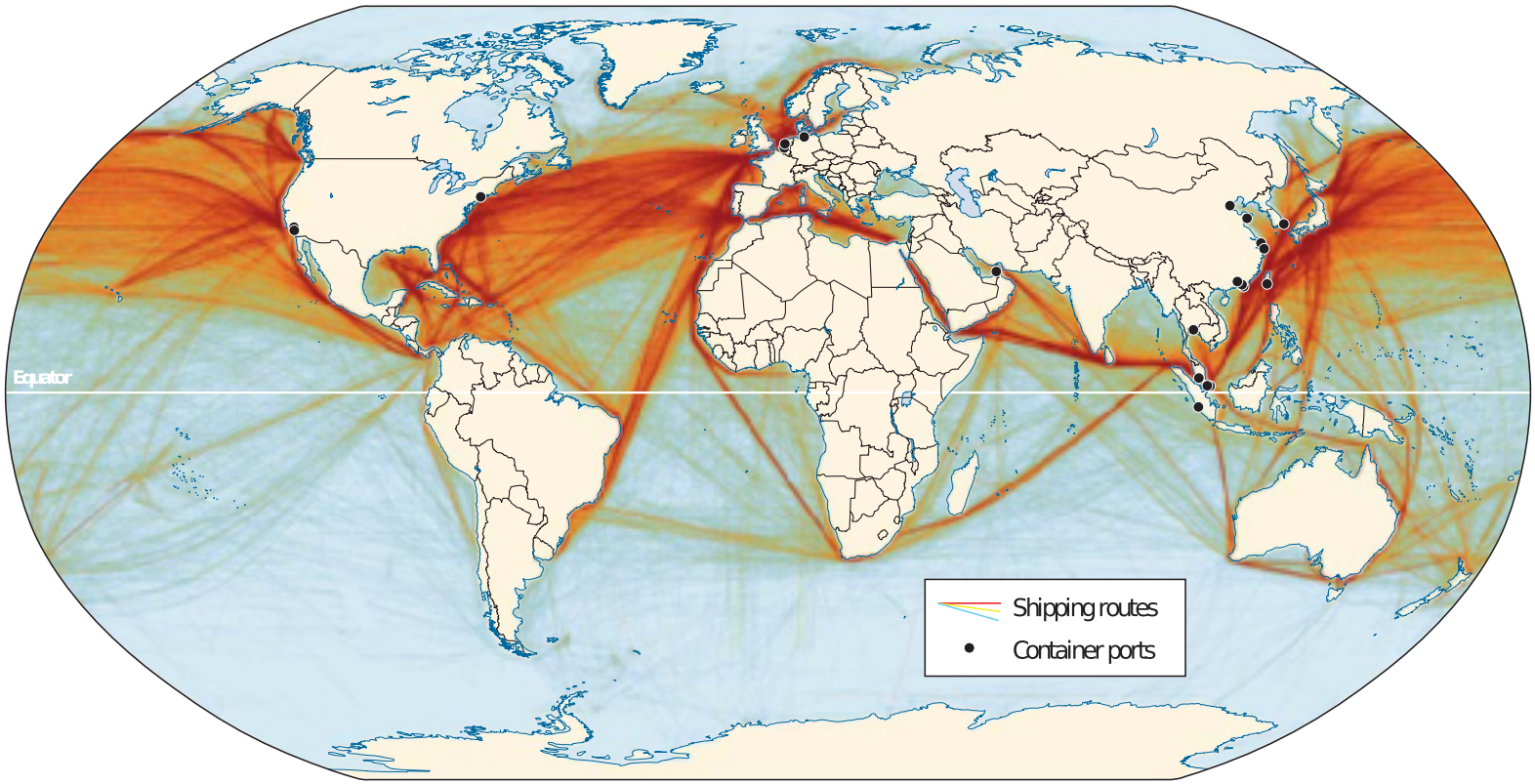

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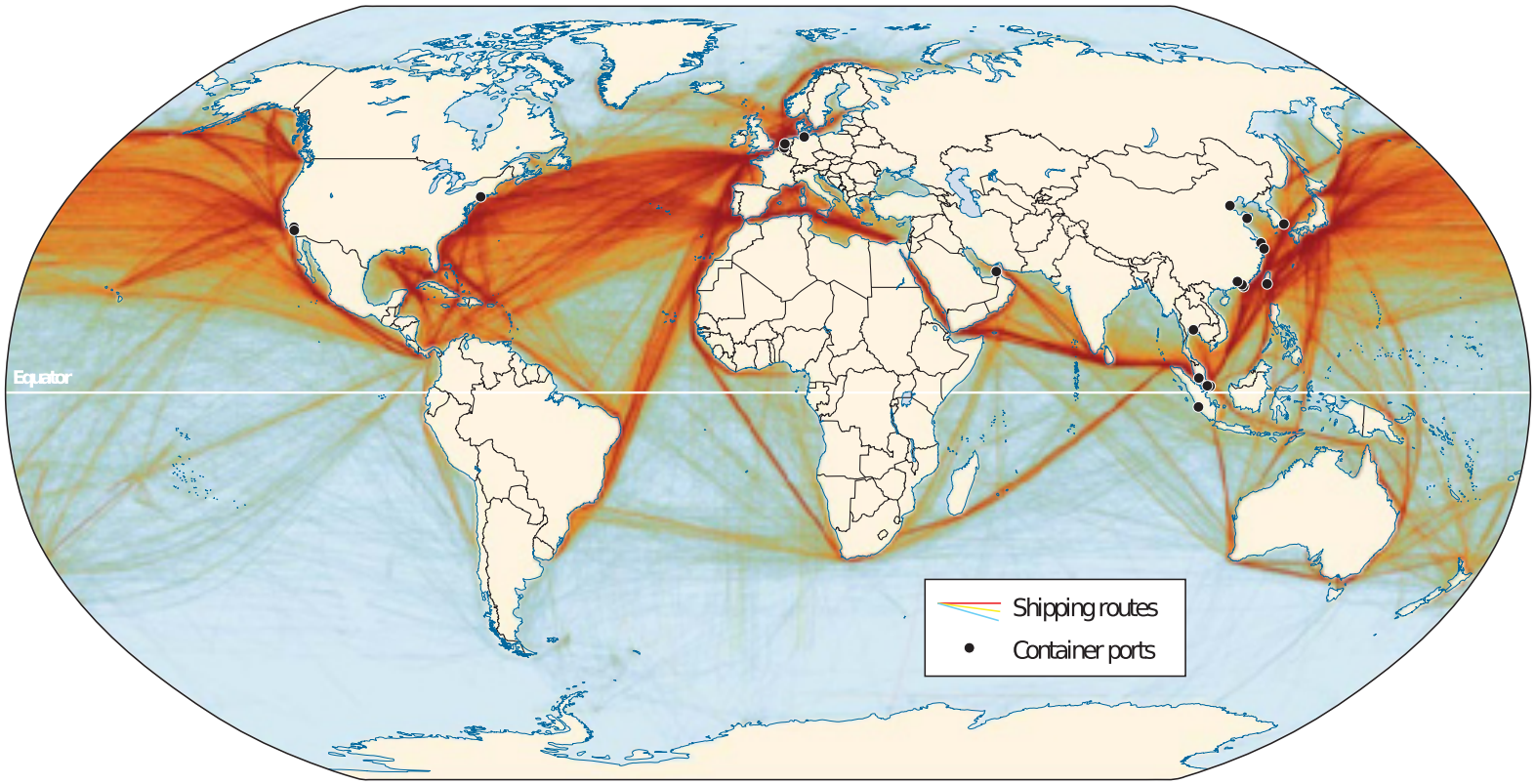

Opportunity for growth. . . but also for predatory competition concerning:

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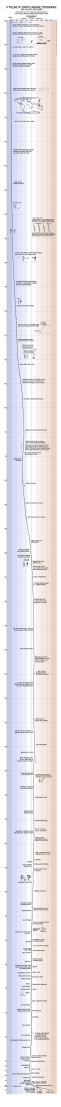
. . . about environmental regulation



(https://xkcd.com/1732)

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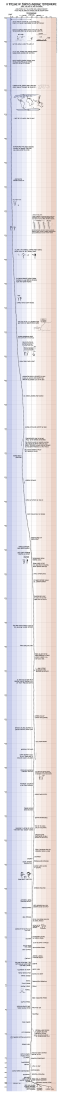

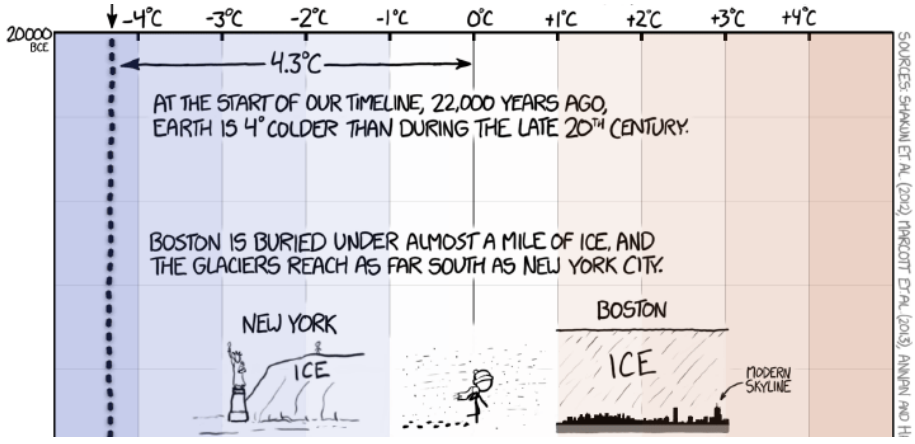

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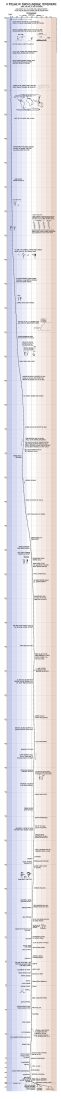

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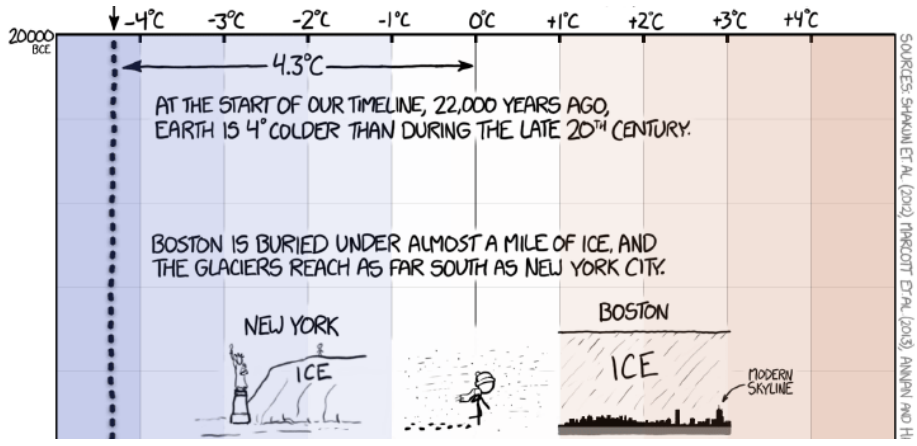
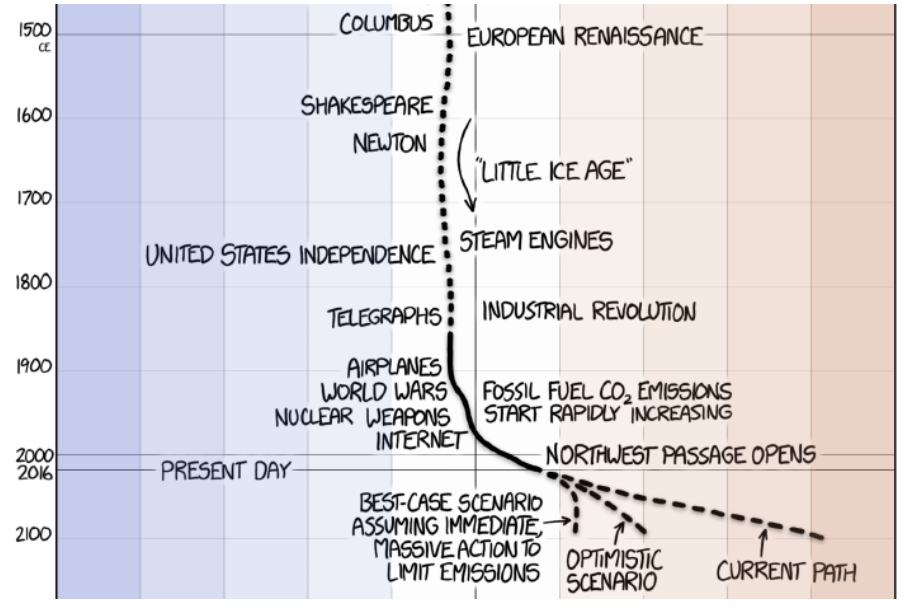


Zoom on the last 500 years:



The problem with CO2 emissions

A *global* problem with *local* causes.

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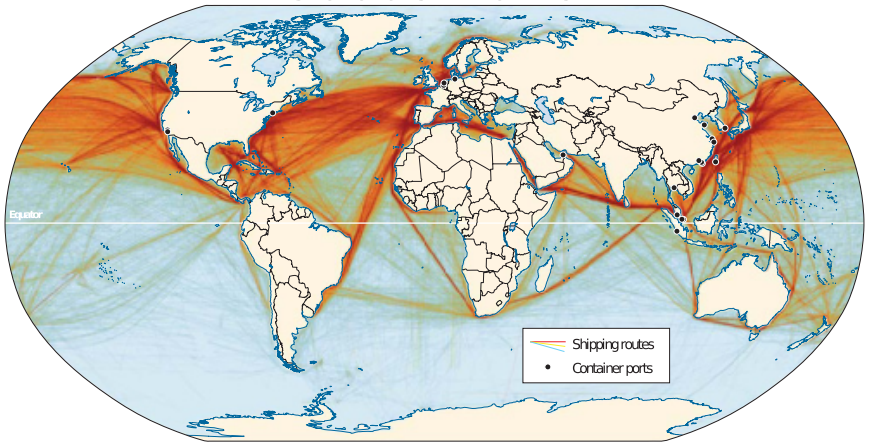
Goods flows:



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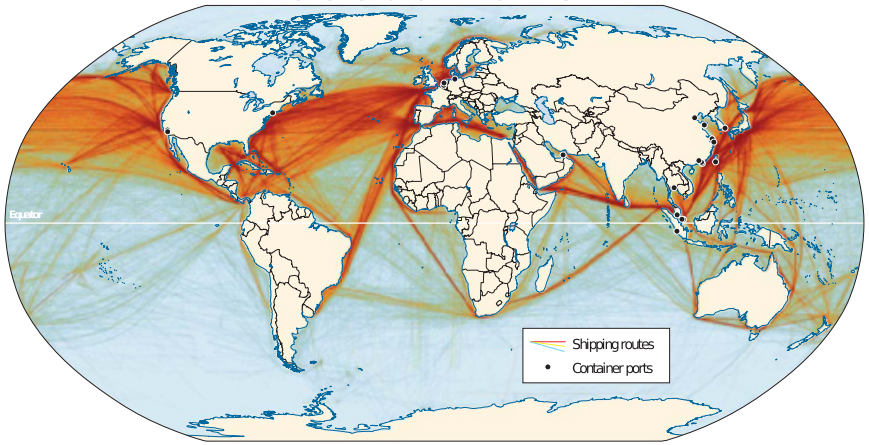

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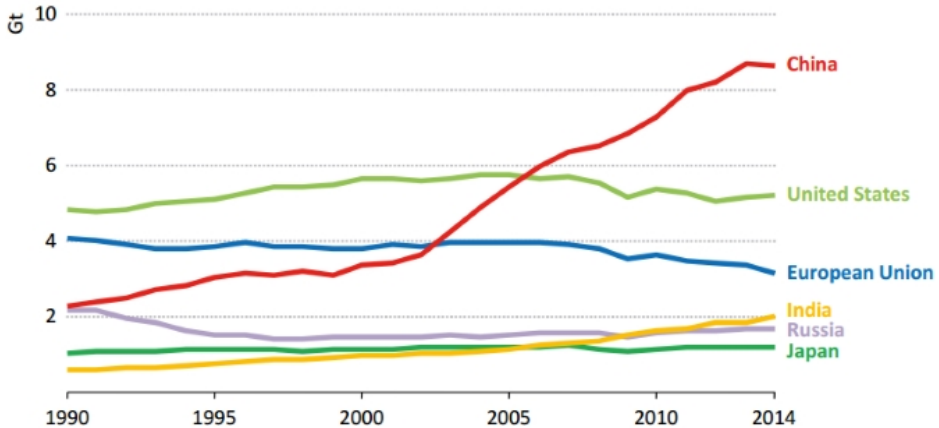

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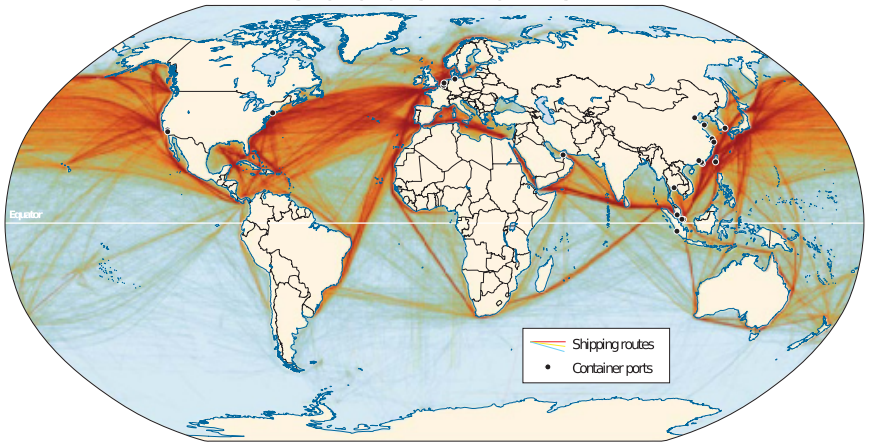

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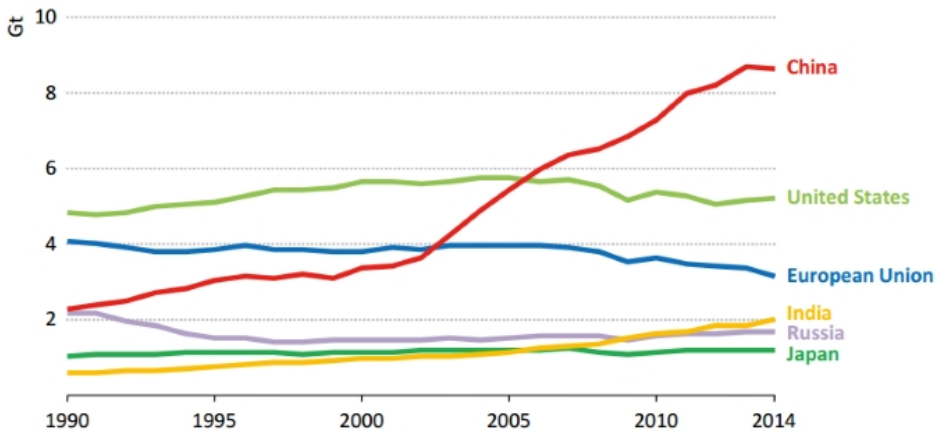
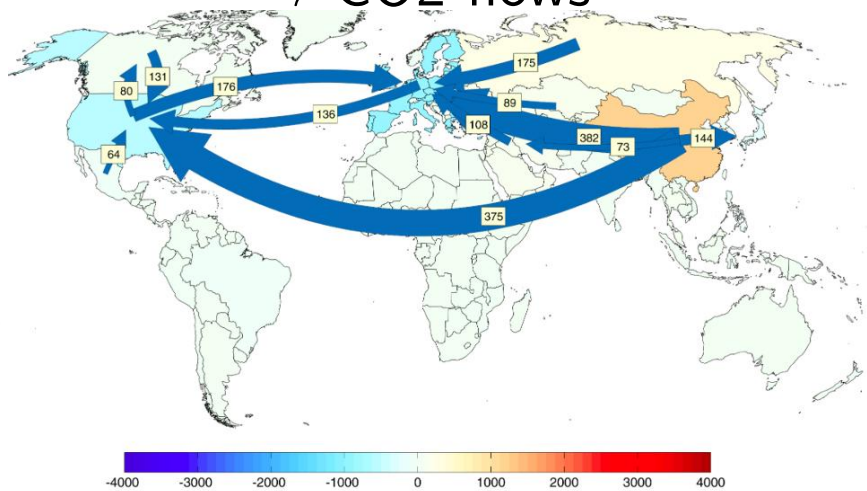


→ CO2 flows



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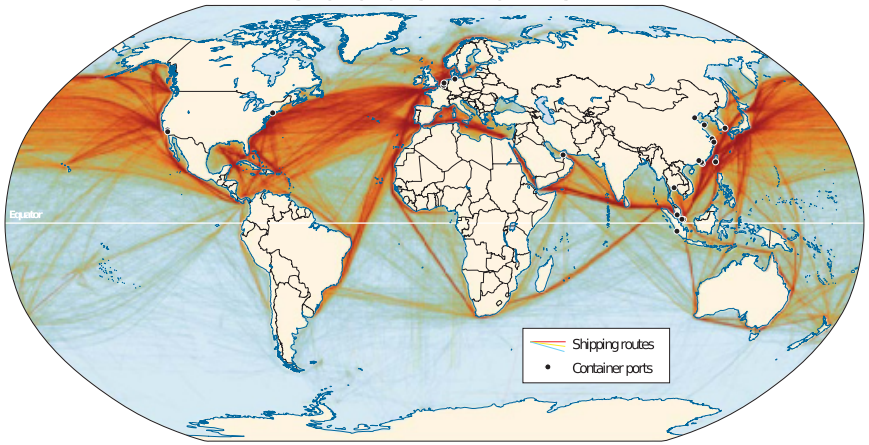

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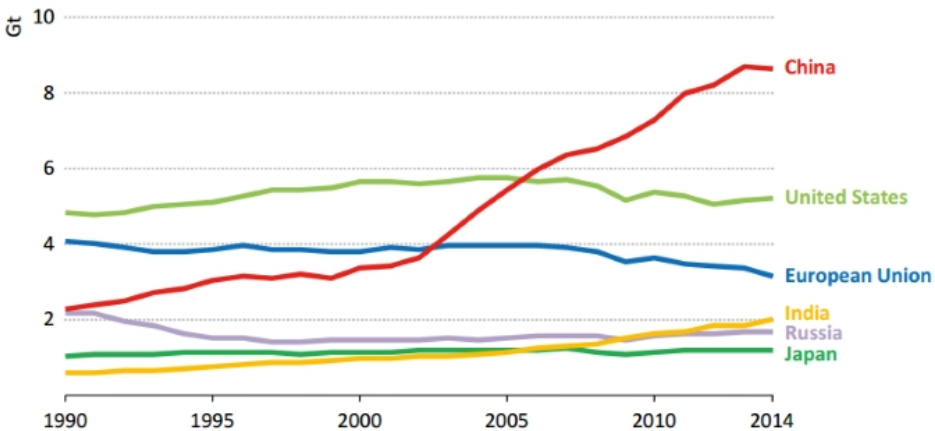

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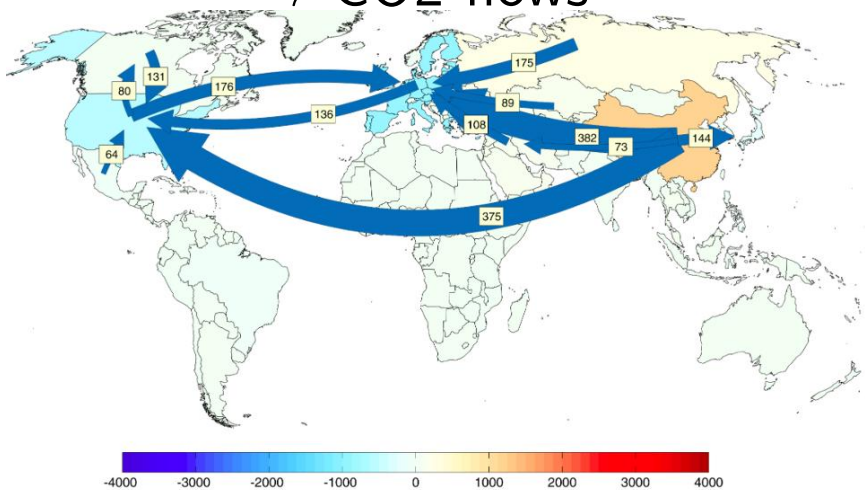
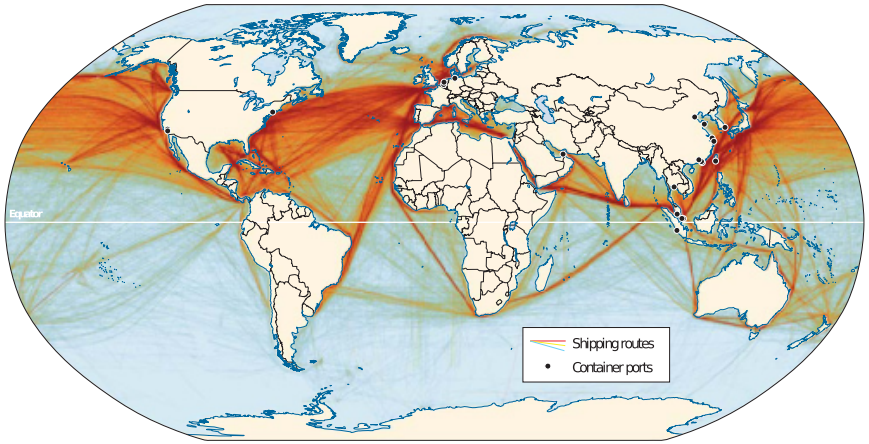


"Carbon leakages"

A possible solution



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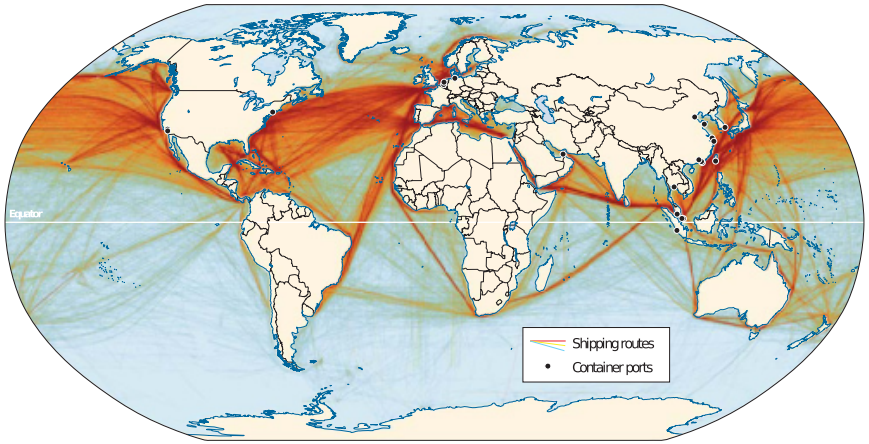
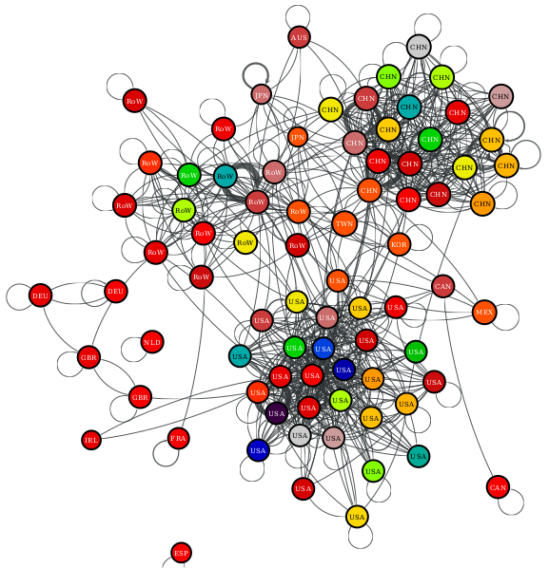


From countries...

to sectors/products (WIOD database):



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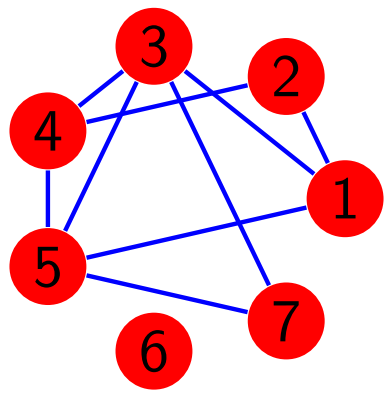

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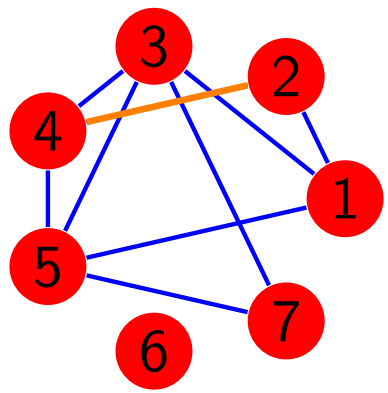

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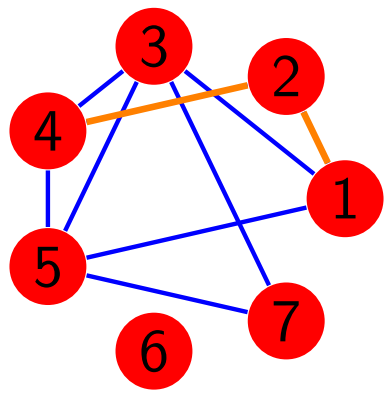

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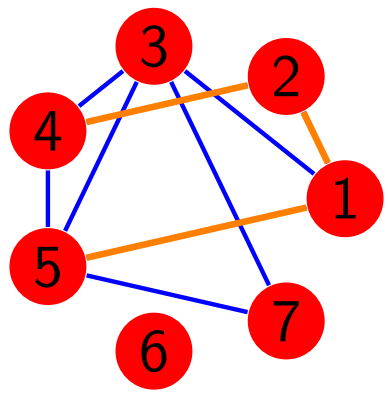

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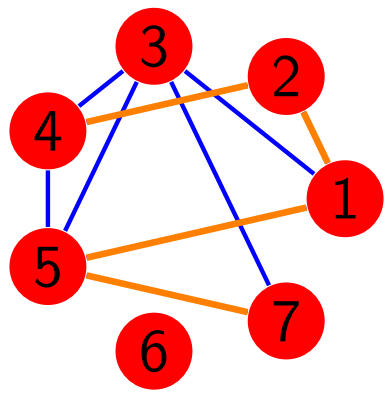

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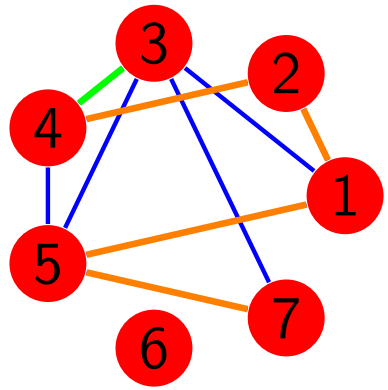

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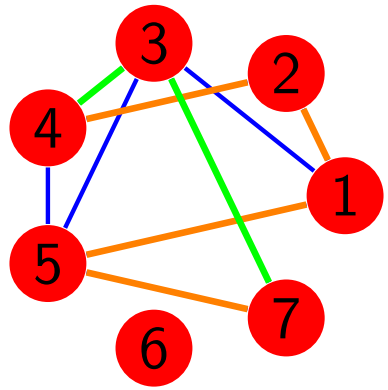

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Application 2: the network of human mobility

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People move too!

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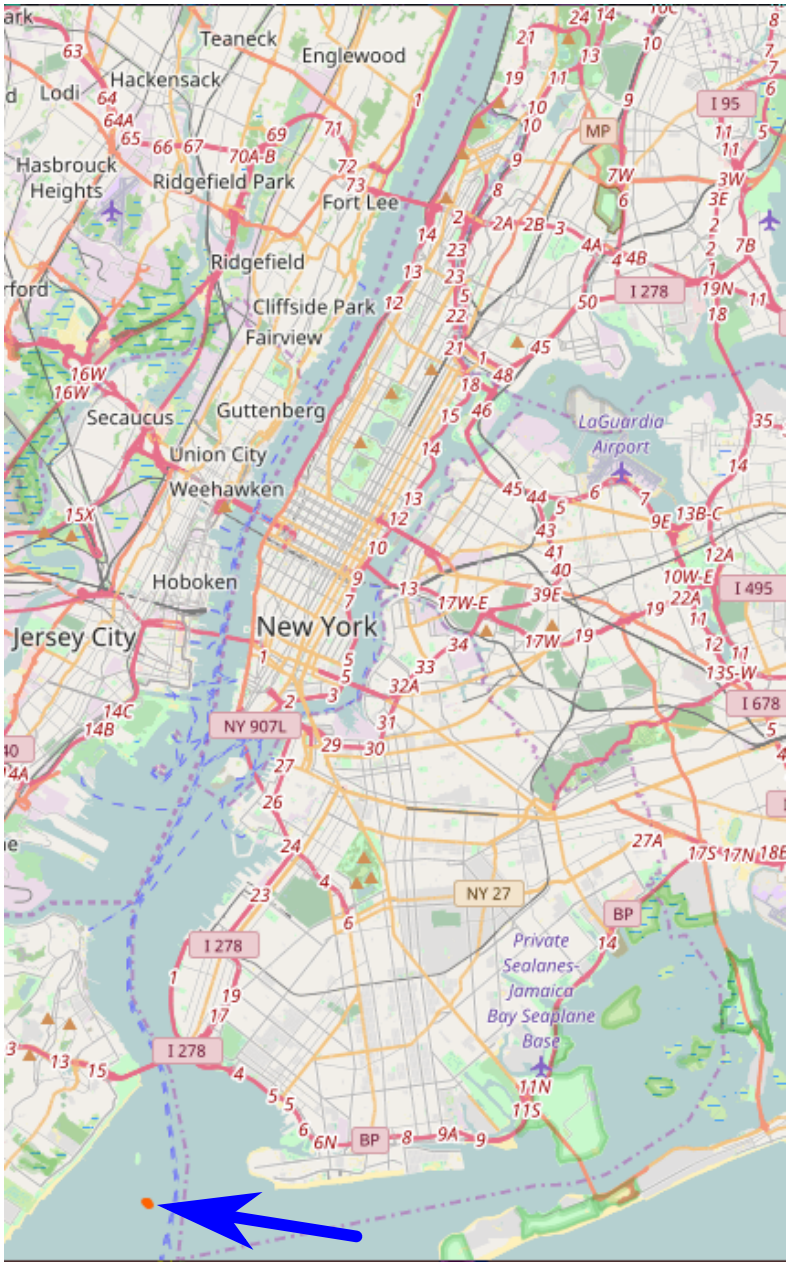
People move too!

Problem: spreading of epidemics

The “old school” approach to epidemics



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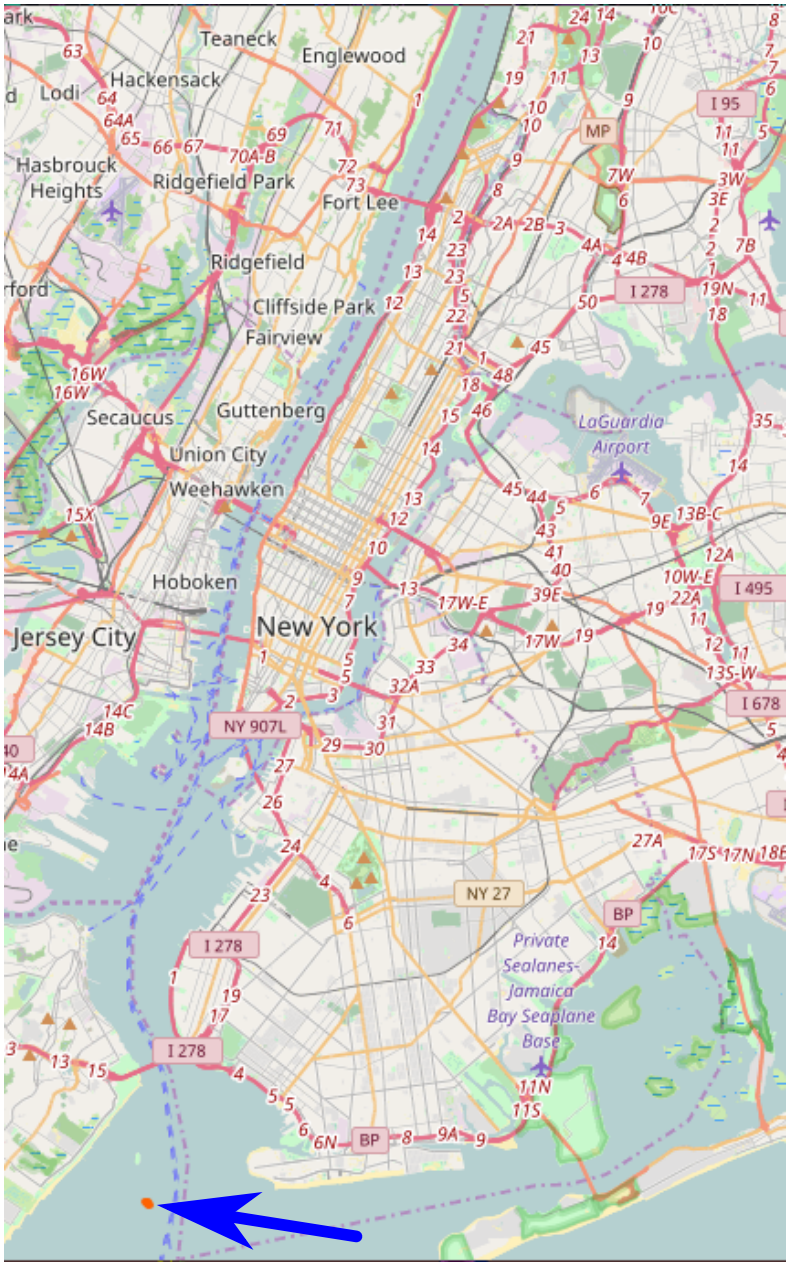

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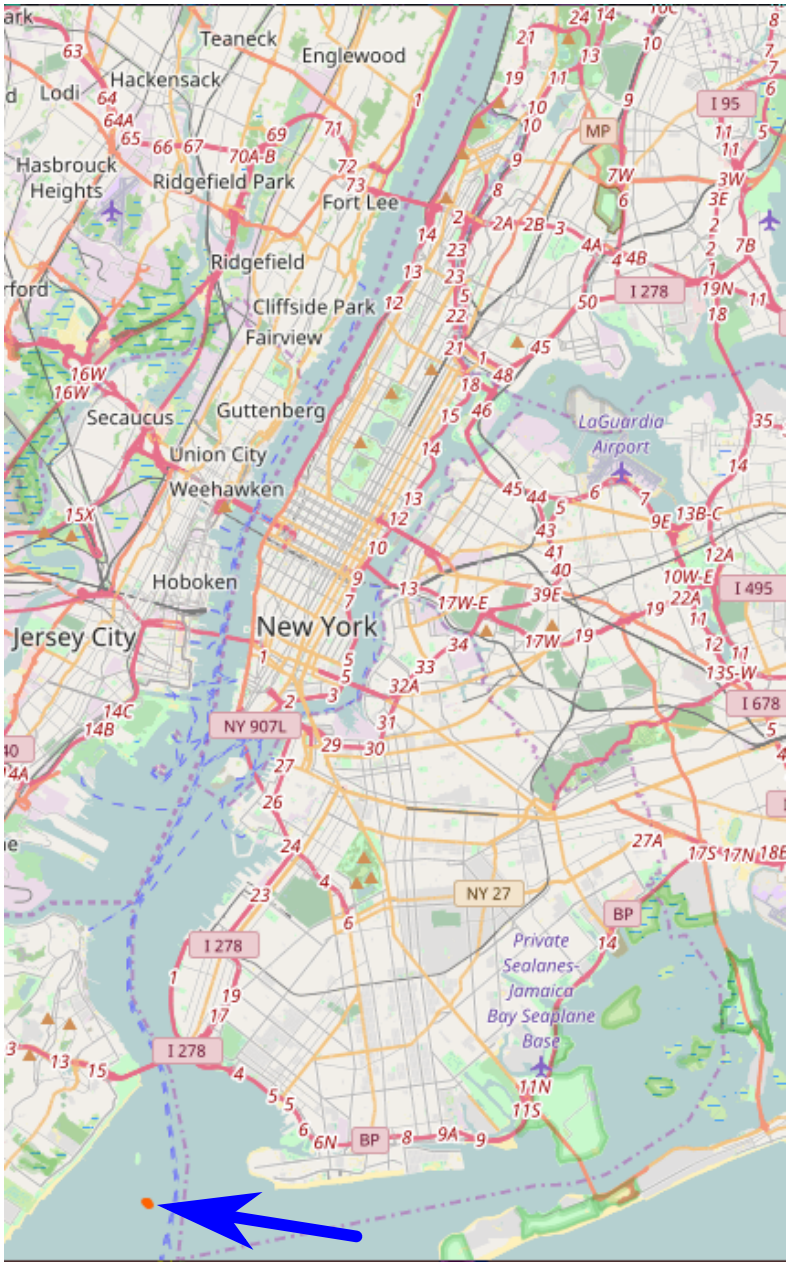

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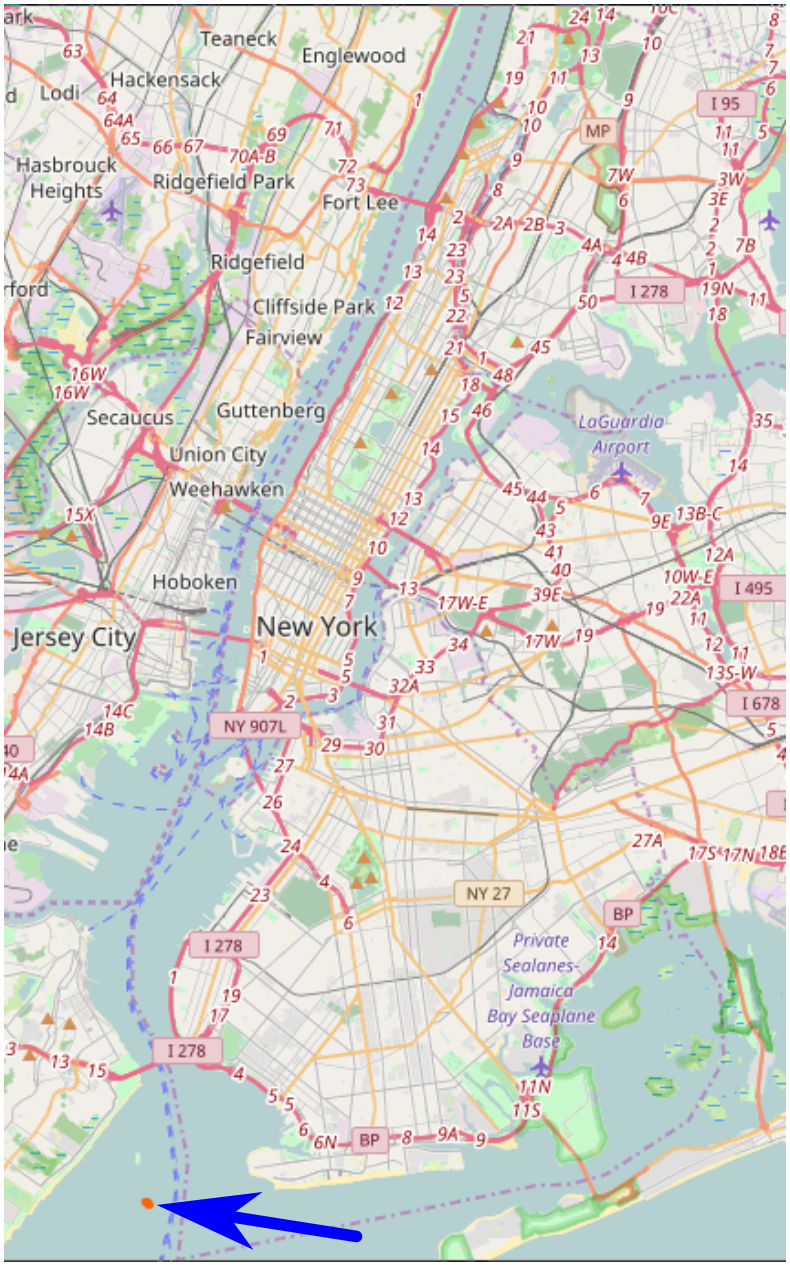

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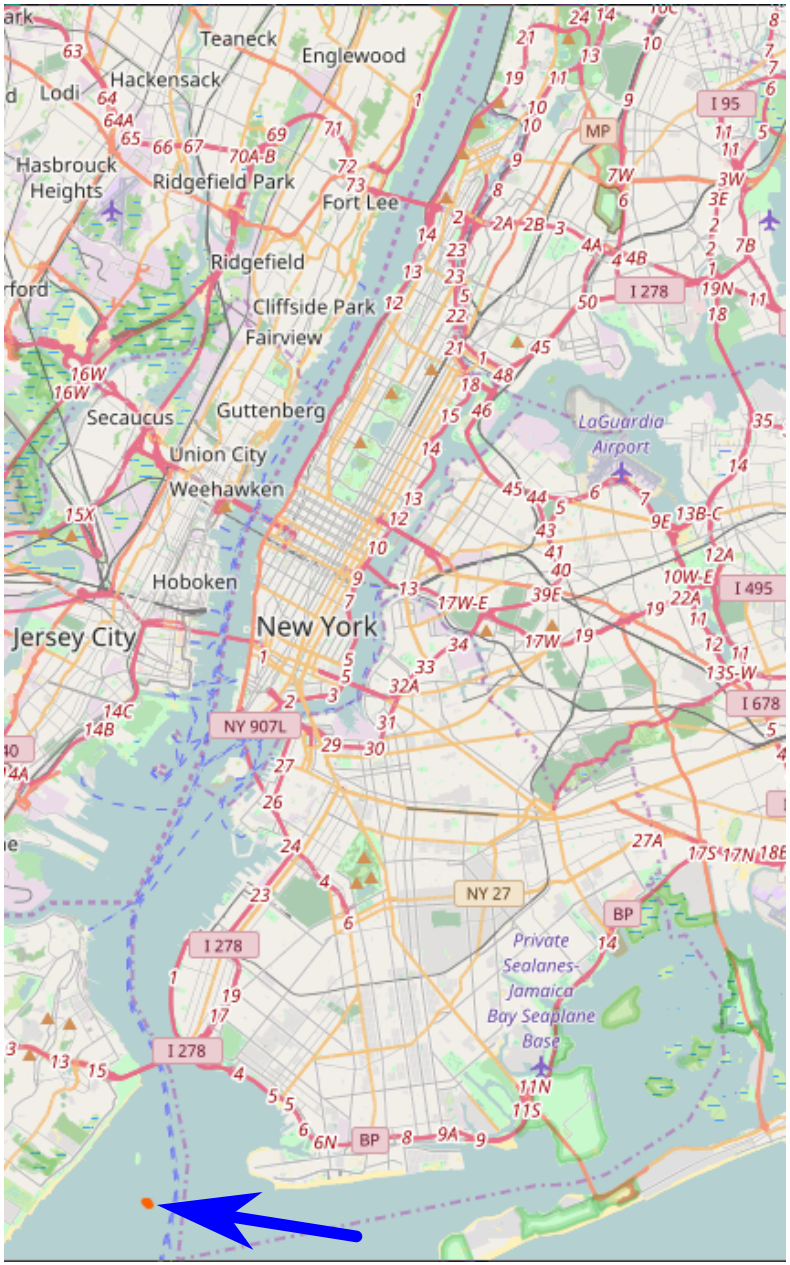

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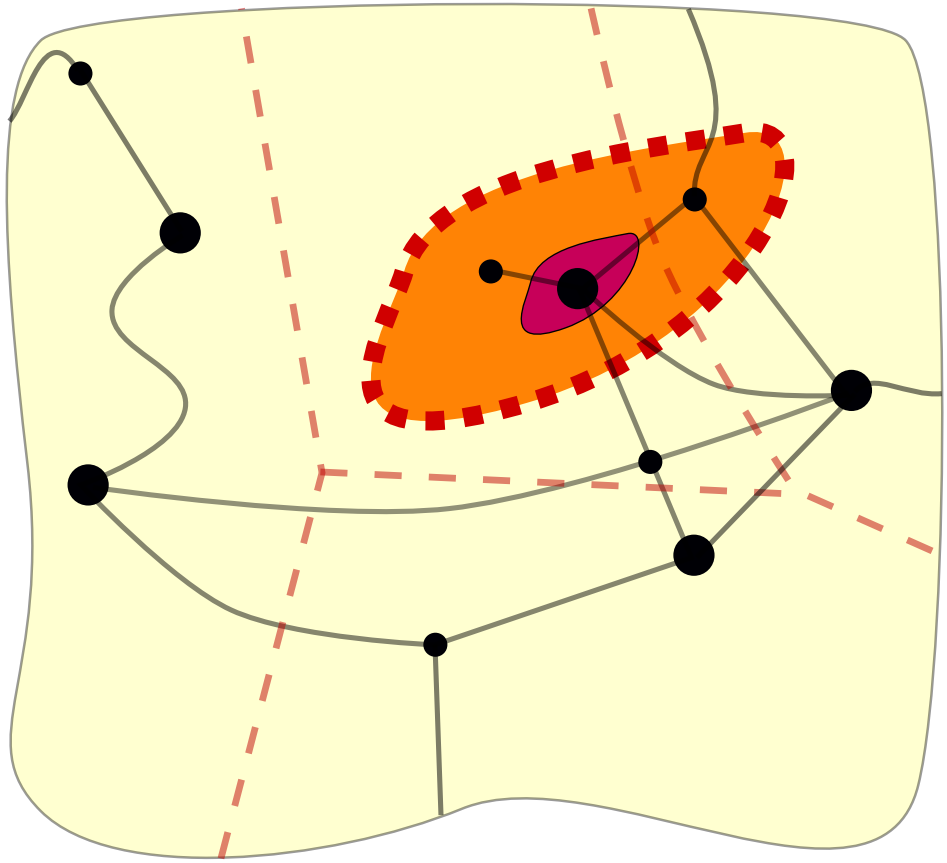
- passengers are isolated on the artificial Swinburne Island for several months: (only) 11 of them die
- *the journey from Naples to New York took around a week*, so the outburst was identified

The "old school" approach to epidemics

In general: geographically identify, and delimit, the outburst.



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Easier and quicker detection. . . but also much faster mobility with air traffic.

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We can answer questions such as:

- "How much/how quickly do we expect it to spread?"
- "Where is monitoring most important?"

Main concepts, II: *degree*

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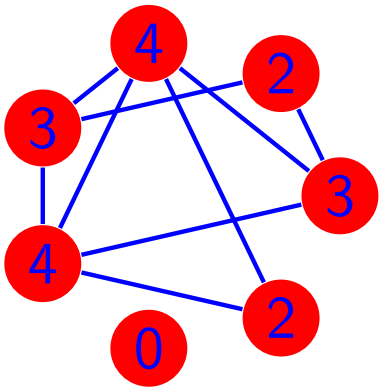
The *importance* of a node can be roughly estimated by looking at the number of edges touching it: the *degree*.



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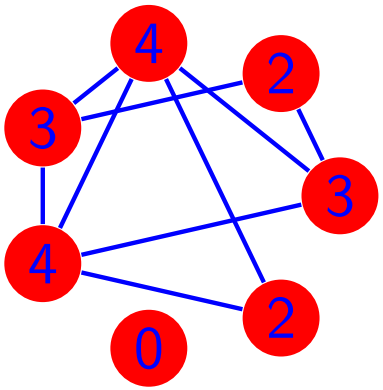
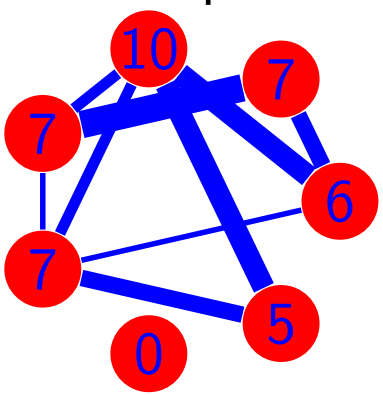
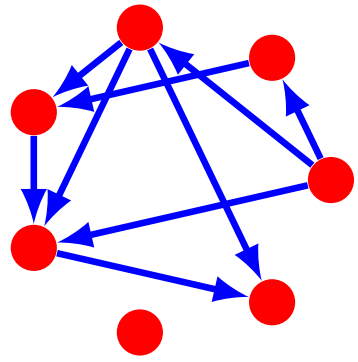


When talking about *weighted* nodes we want something (slightly!) more sophisticated: the *weighted degree*.



. . . but what is the *degree* in the network of Twitter accounts?



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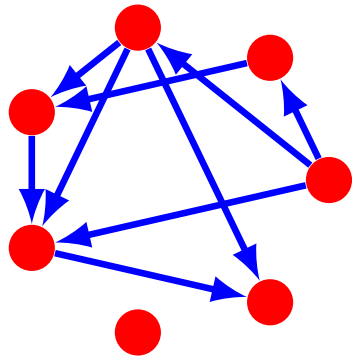

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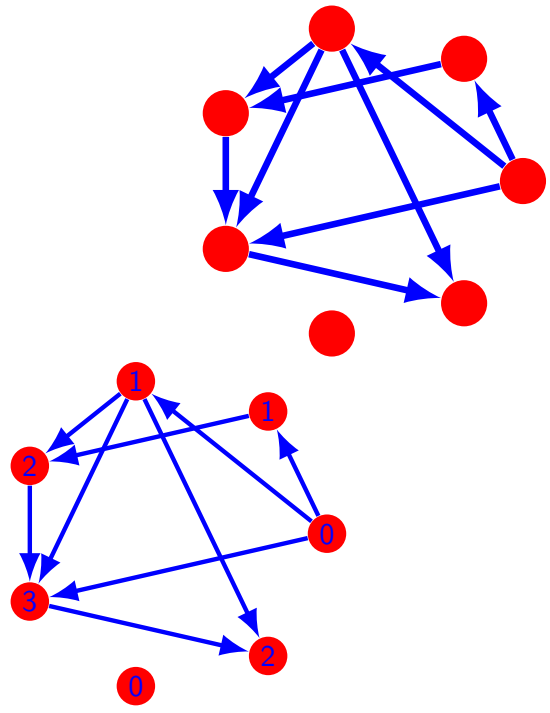

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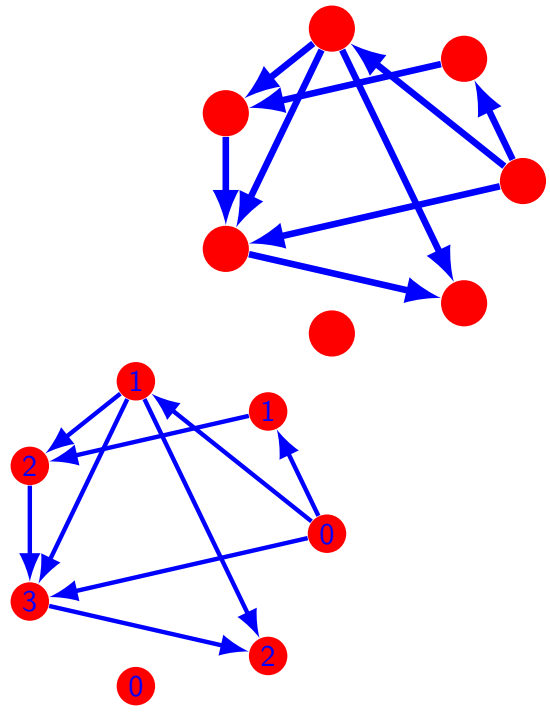

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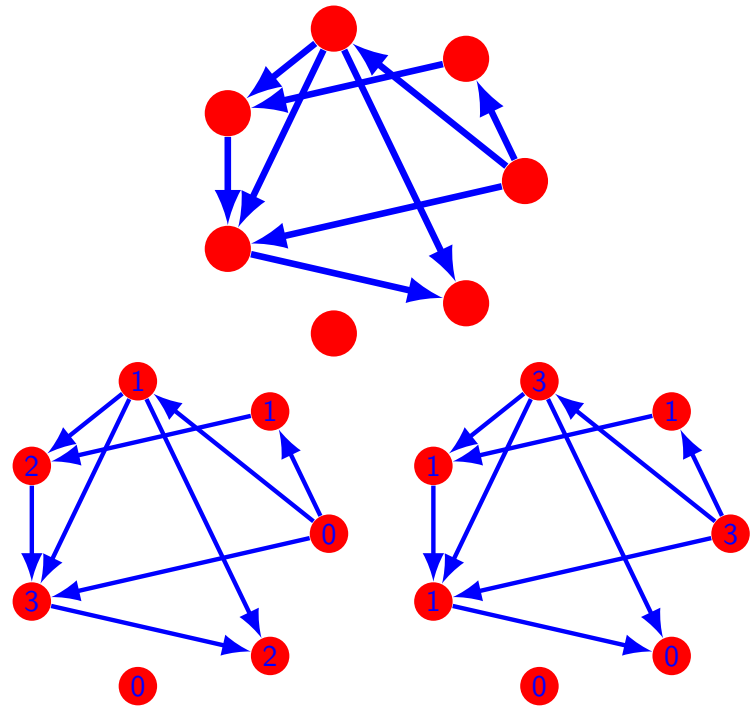

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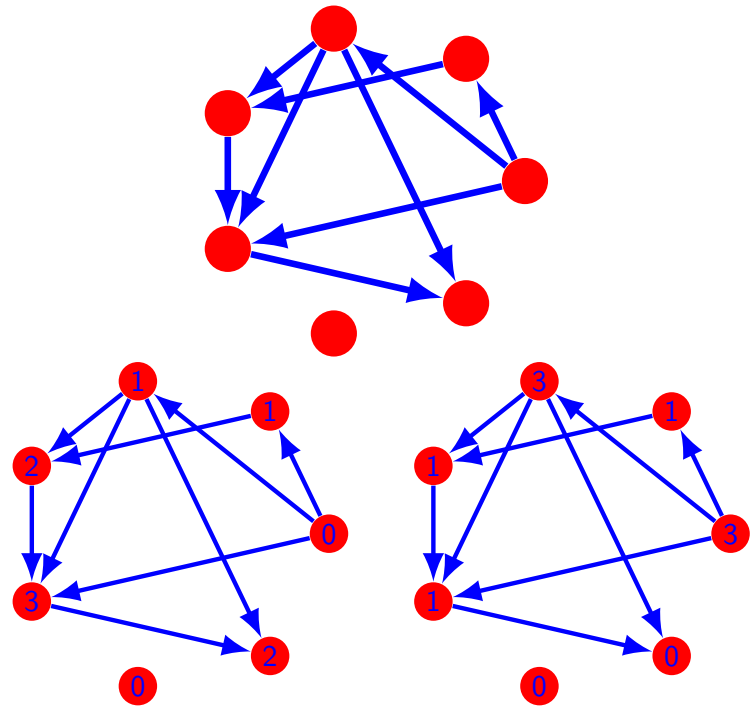

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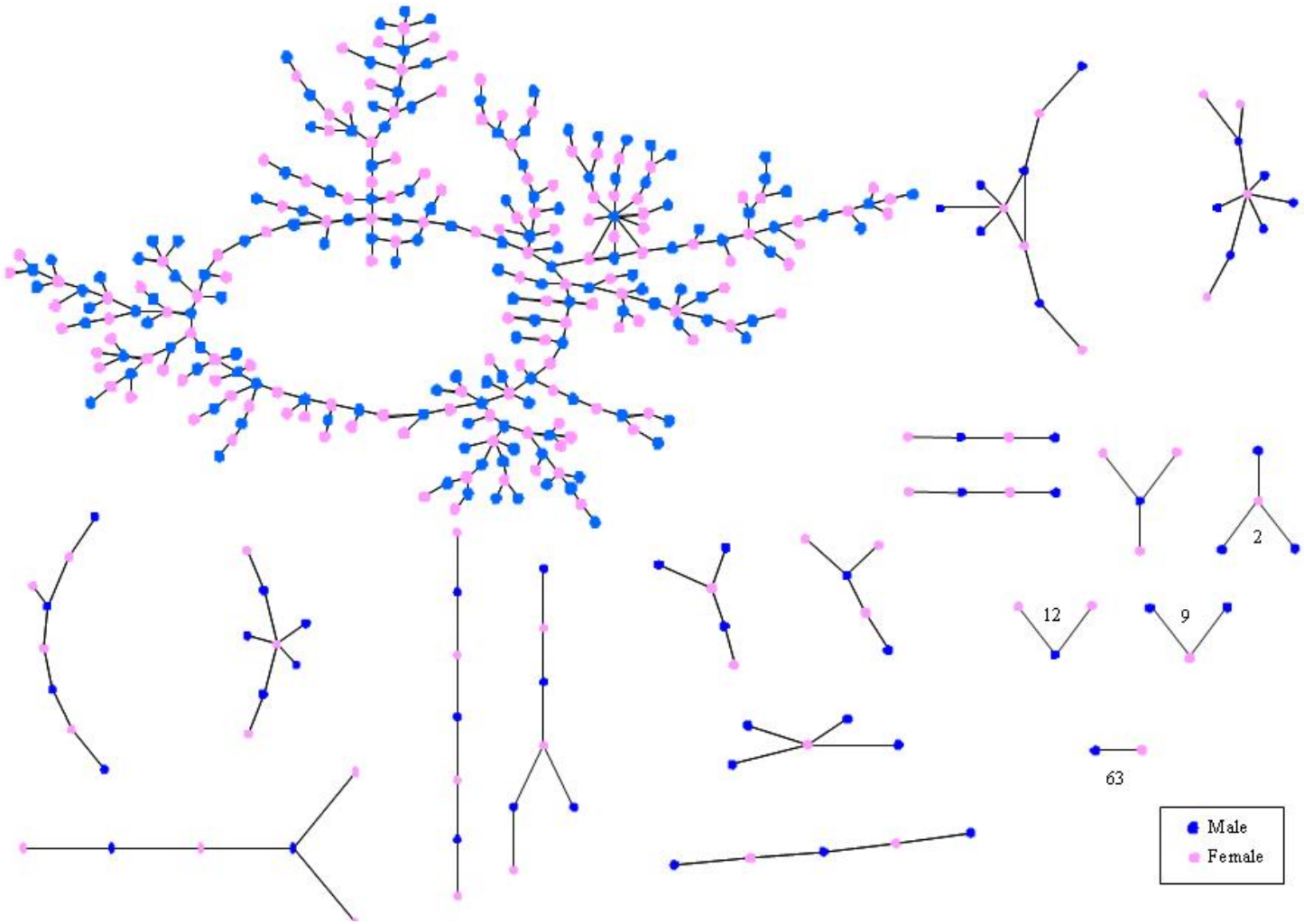

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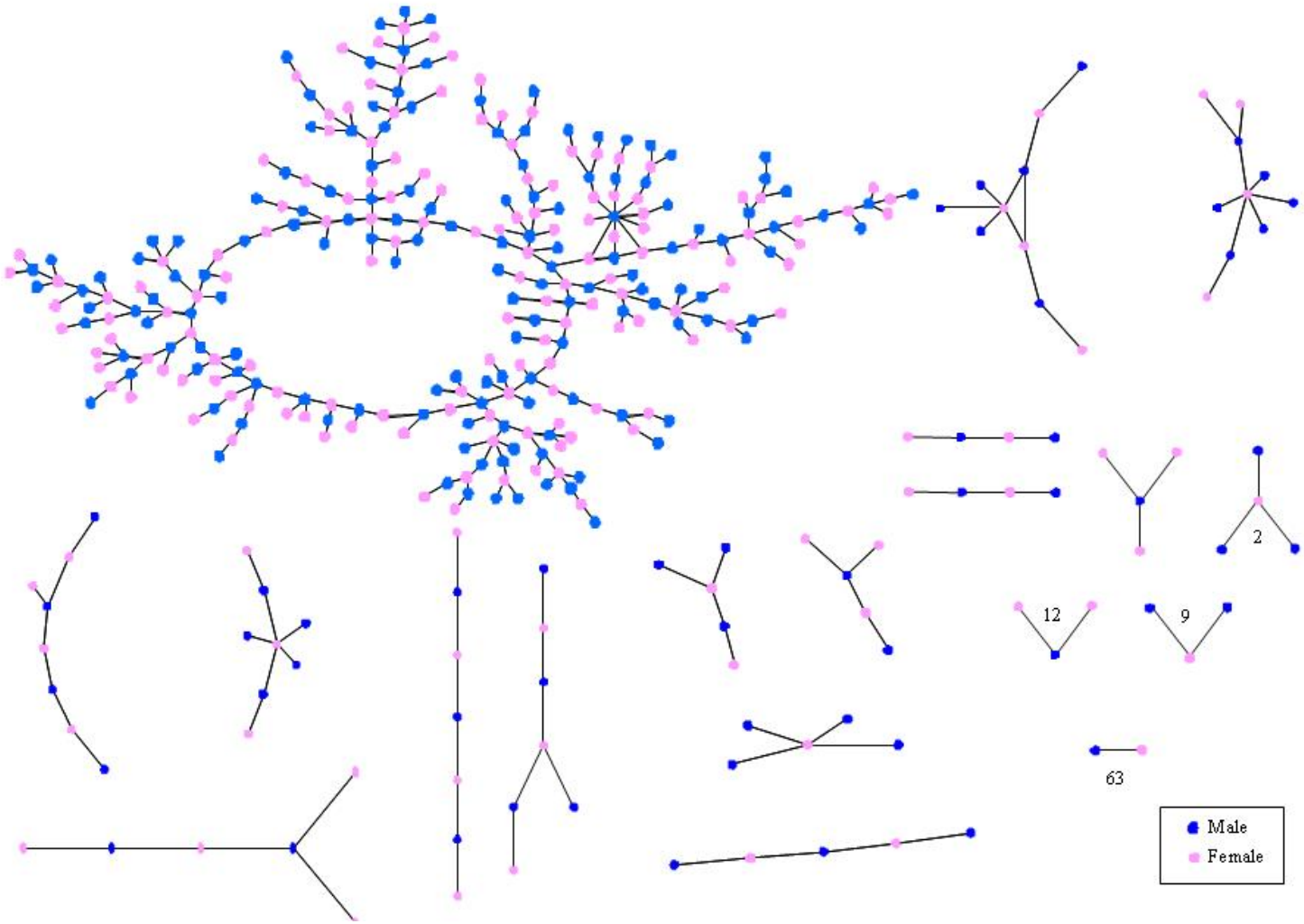

Degree may not really matter that much. . .

Main concepts, III: *centrality*

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Centrality of a node

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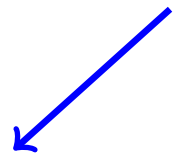

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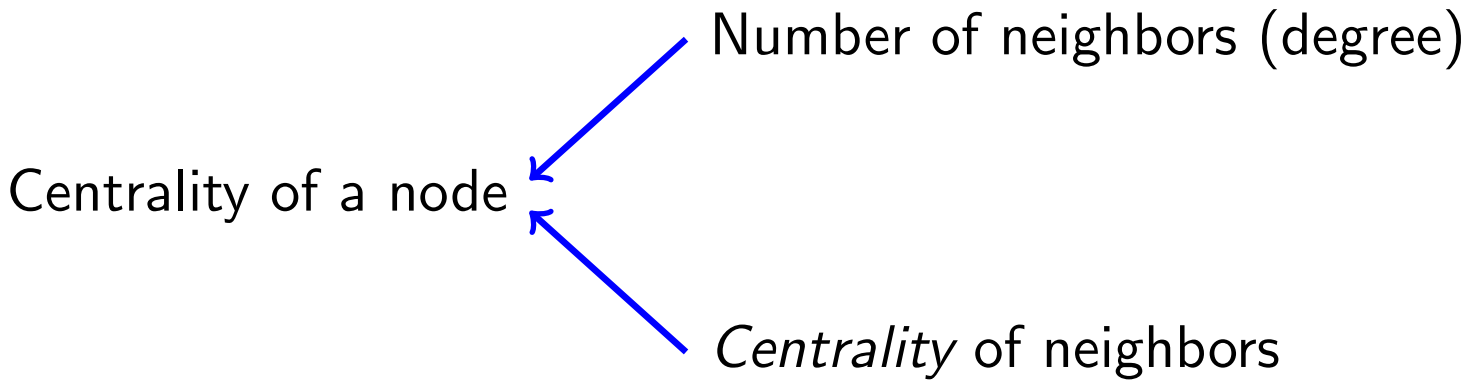

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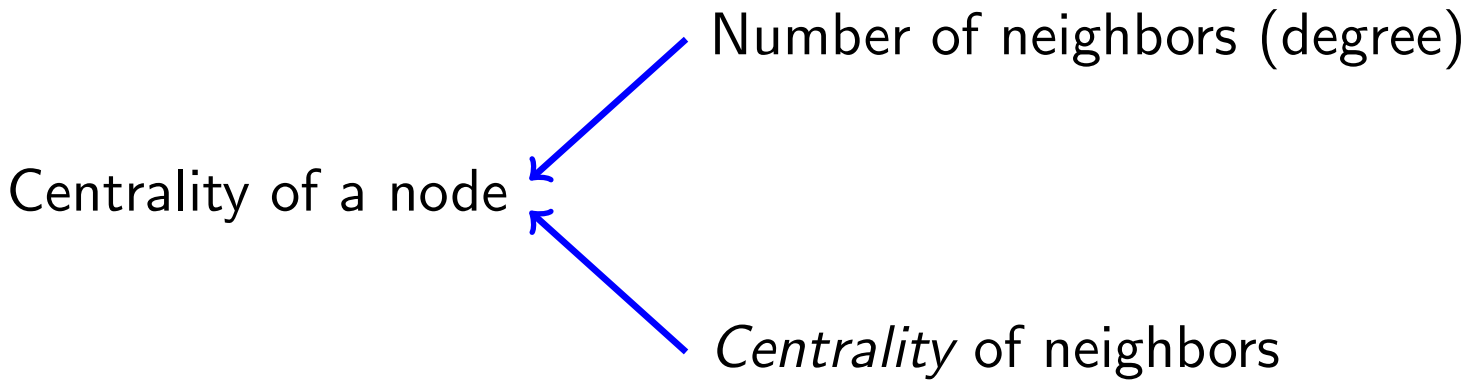

The intuition is simple

. . . the details can be tricky (many slightly different formulations)

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. . . with the *PageRank* algorithm.

How the PageRank works

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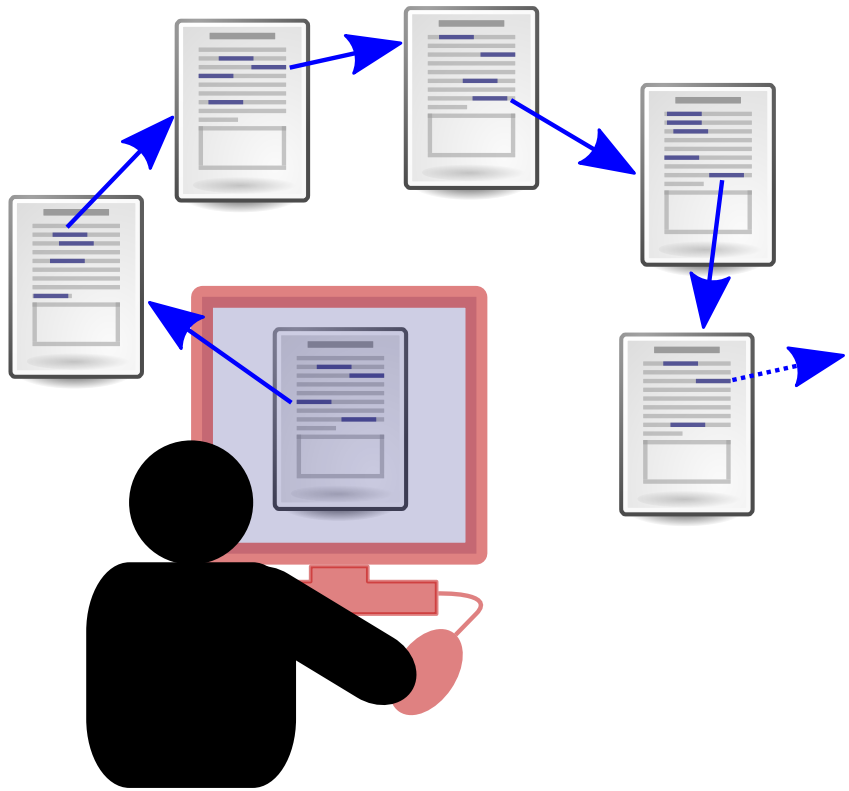

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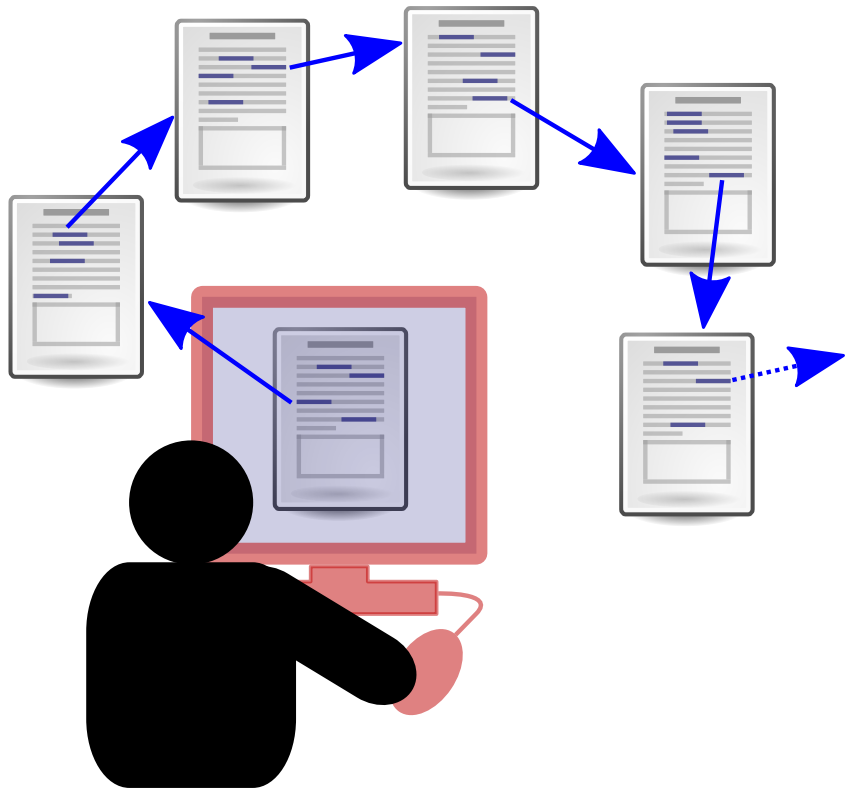

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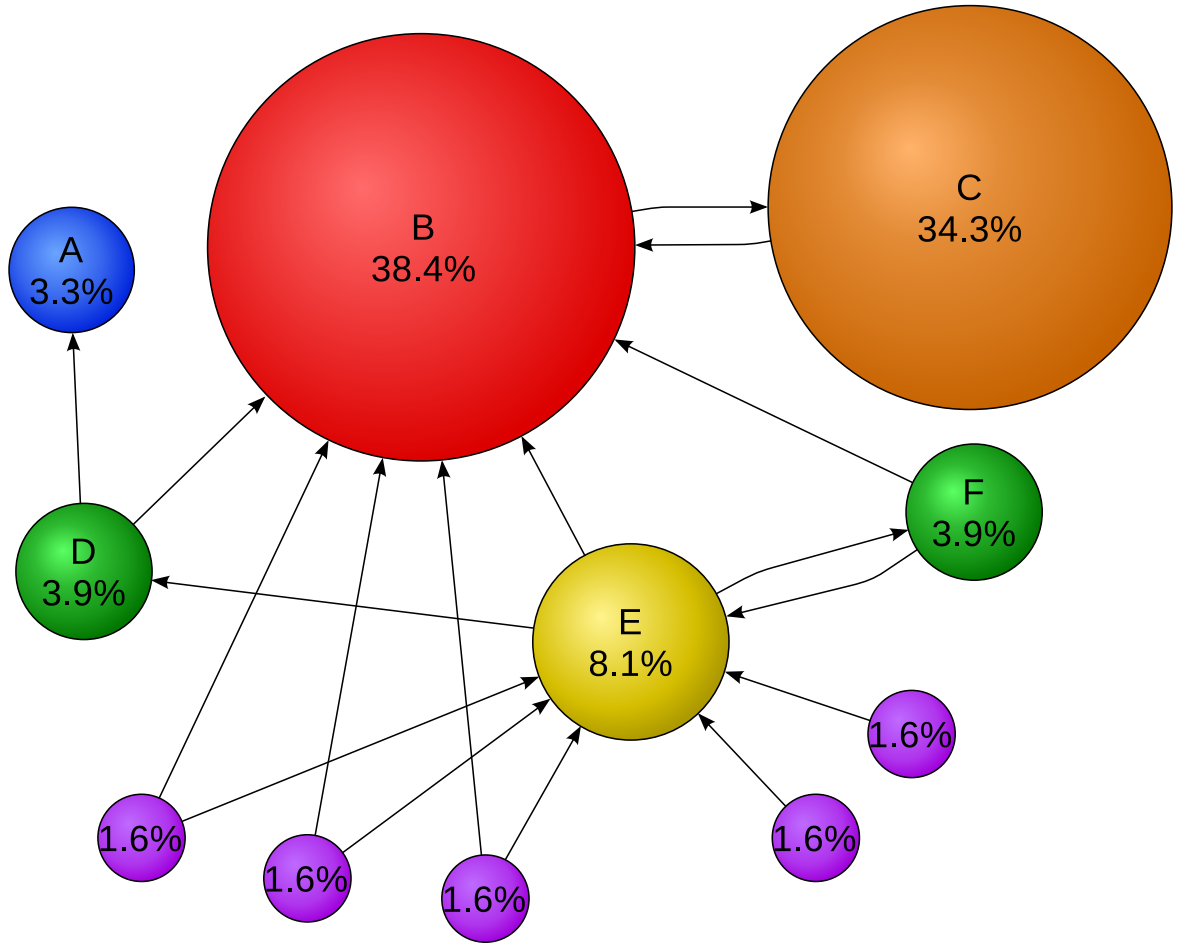
. . . which is the same as looking at the *centrality* of a page in the network of links!



Application 4: financial networks

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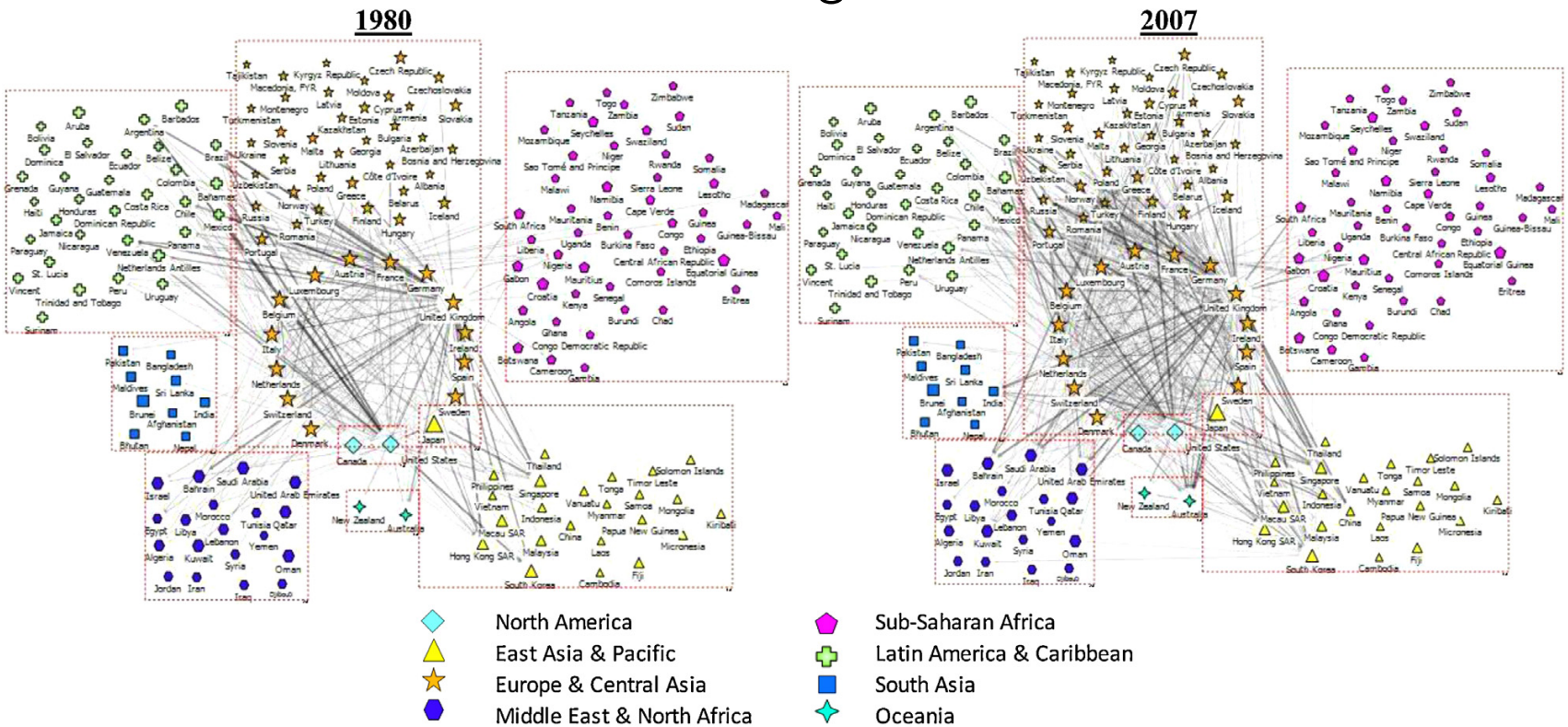
Global banking network:



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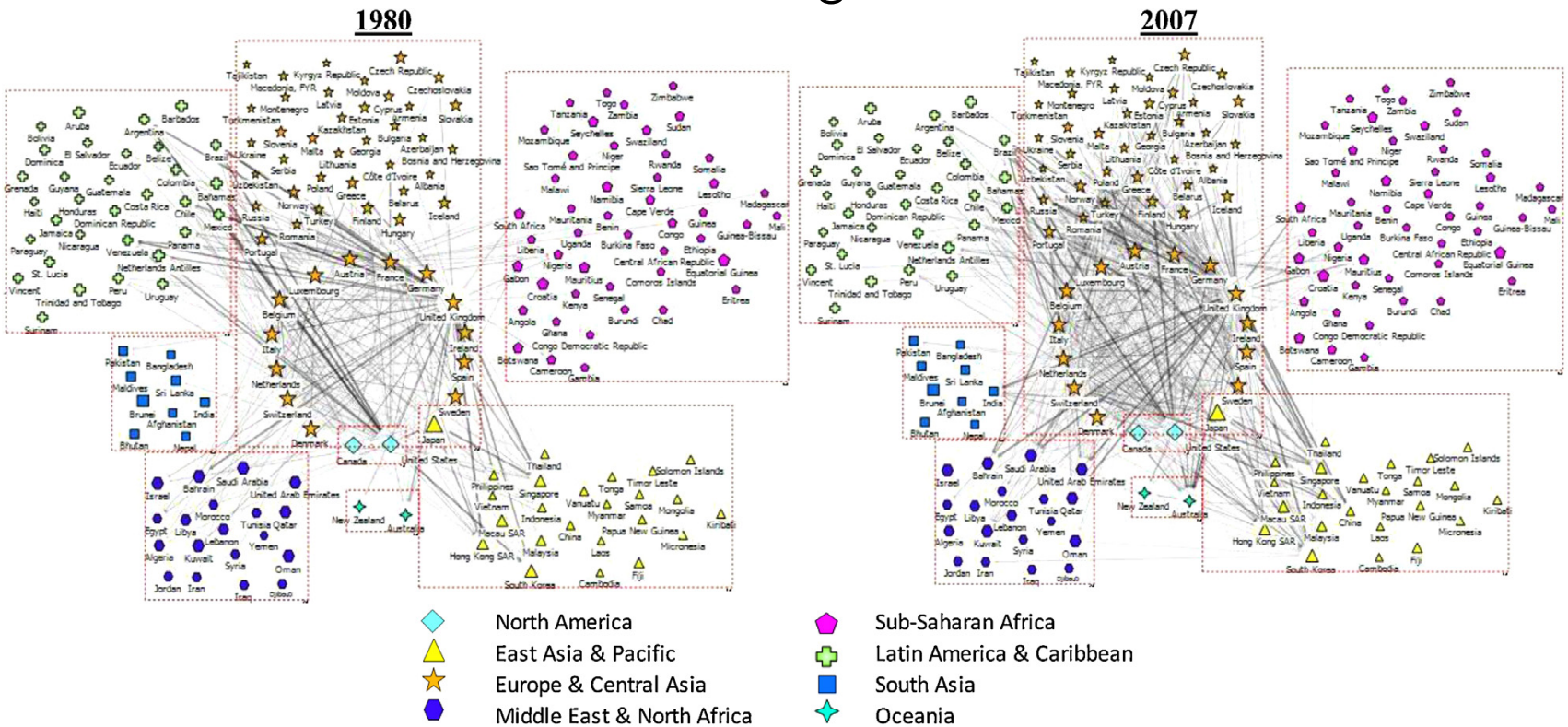

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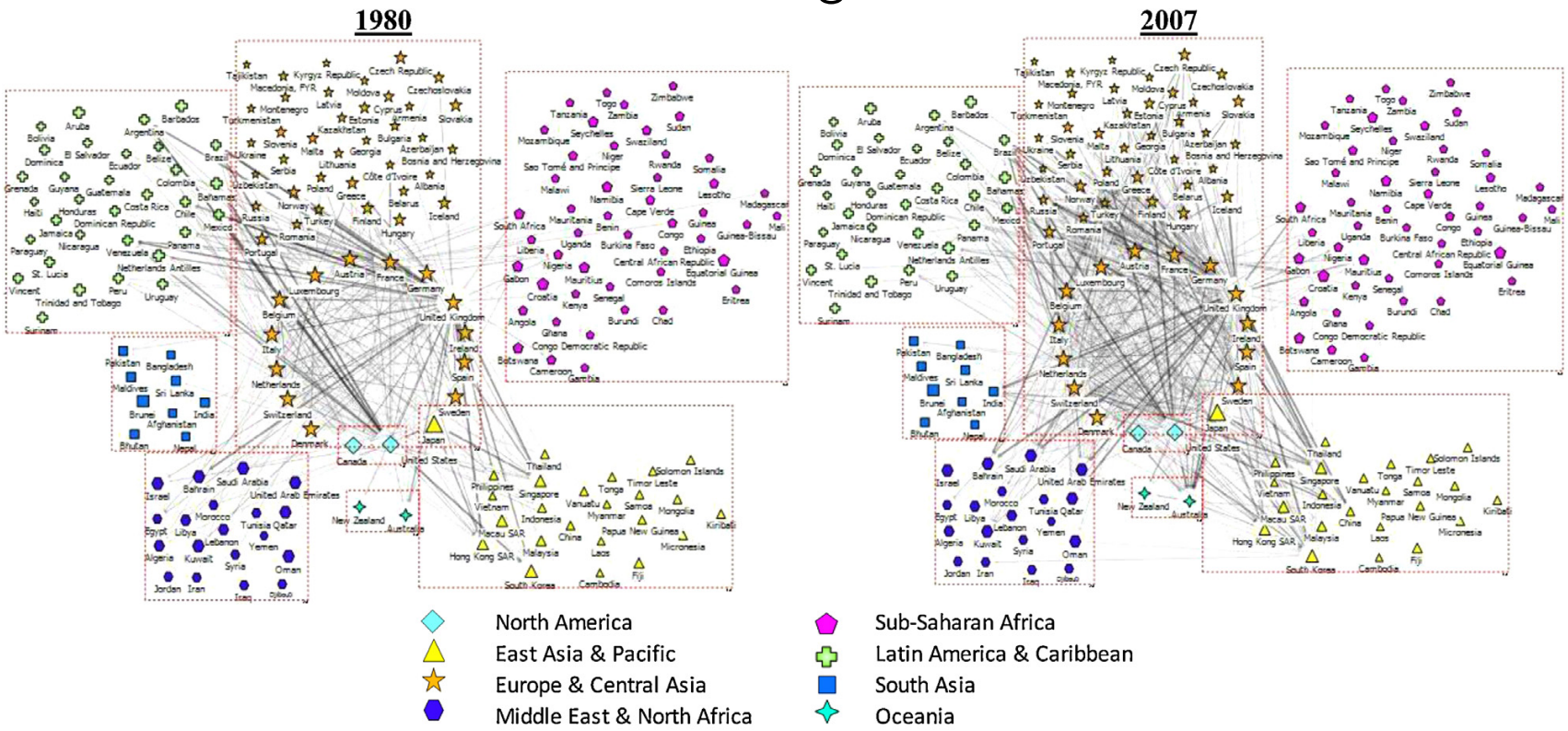

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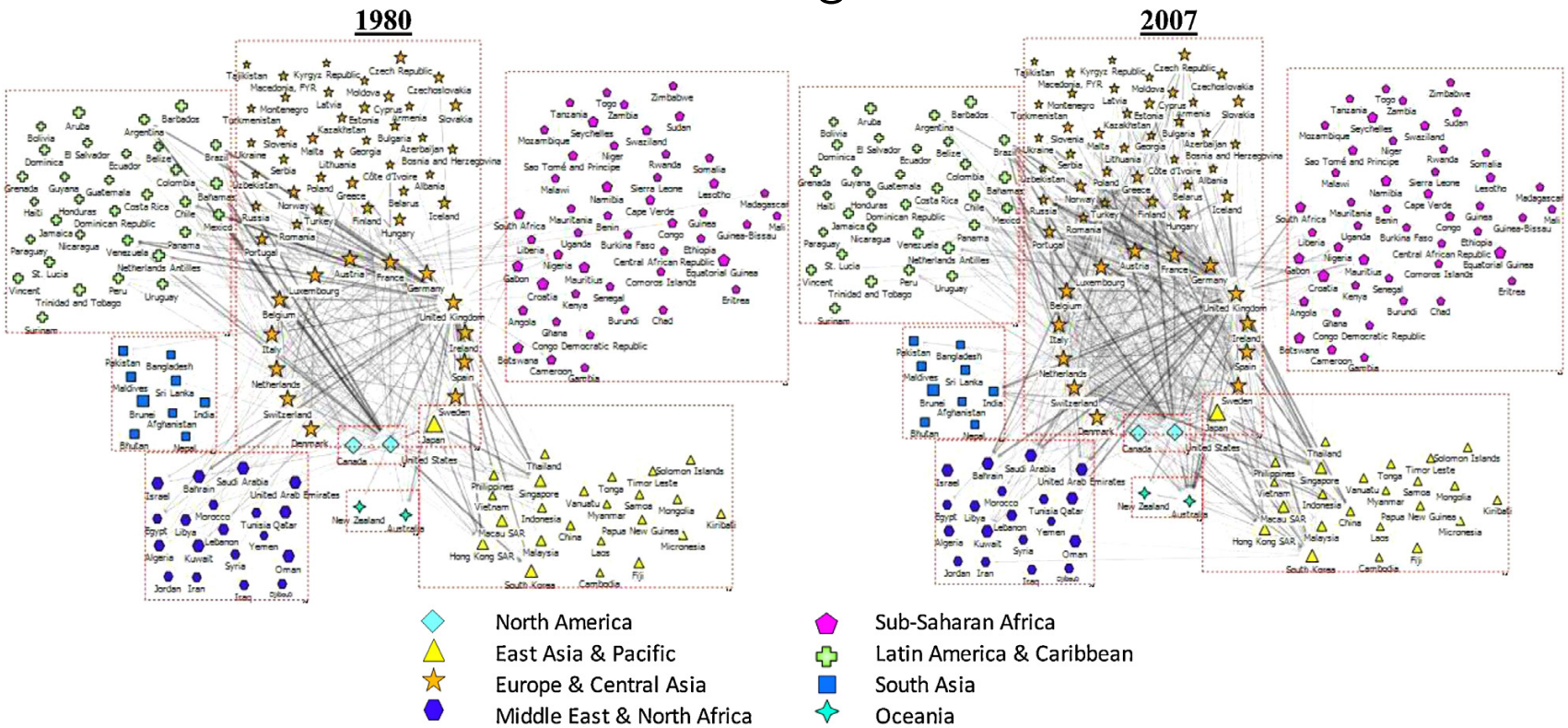

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Opportunity for growth. . . but also for *contagion* of financial losses, or even just risks.

The diffusion of a financial crisis

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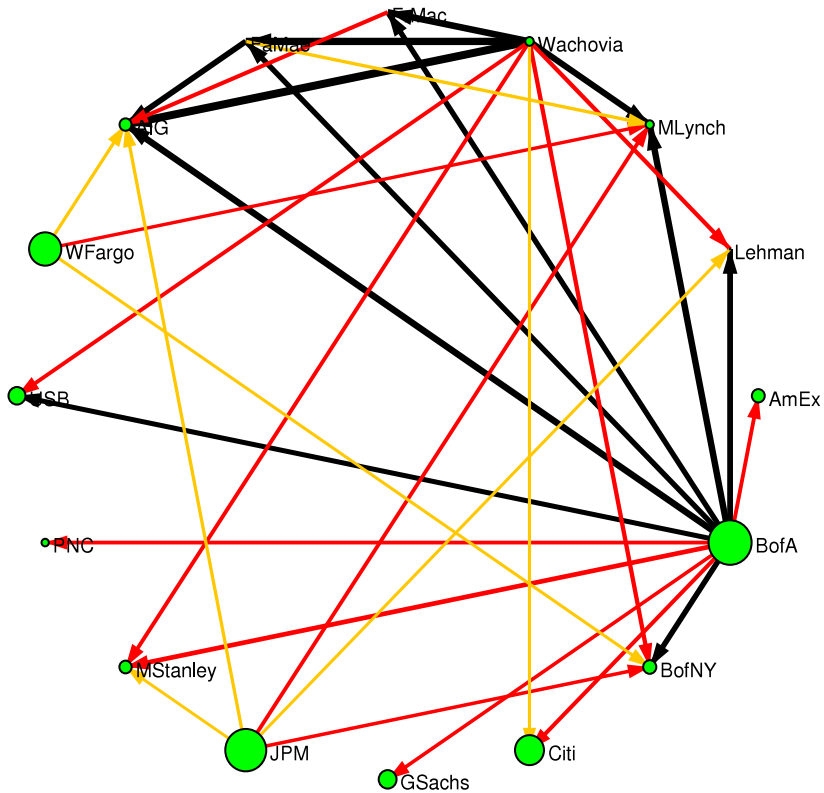

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(And indeed, they are now routinely examined by simulating *contagion* of financial losses over the network of banking relationships)

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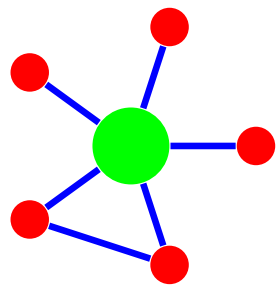
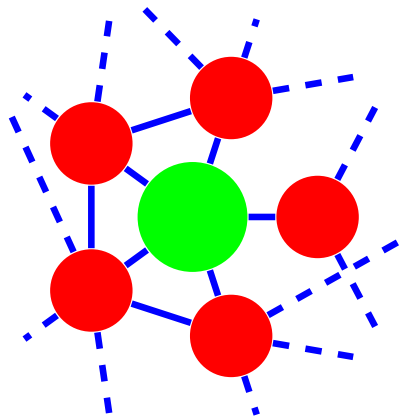
You might prefer  to 

Application 5: social marketing

If I want to put some ad/product on Facebook, who should I aim at?

Maybe *central profiles* in the network? It depends.

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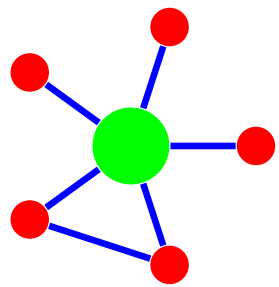
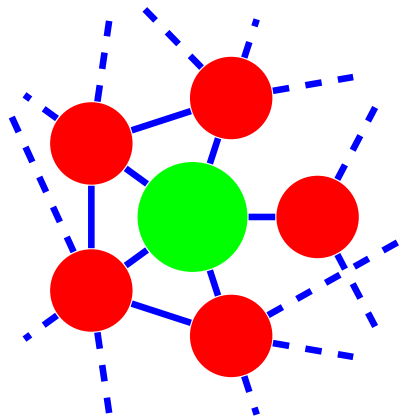
You might prefer  to 

Information is *more precious* when it is *scarcer*

Main concepts, VI: *clustering* and *small worlds*

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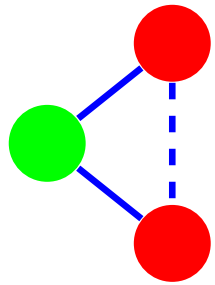

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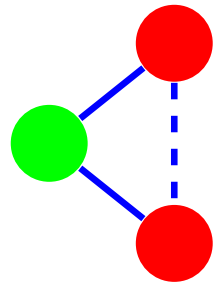

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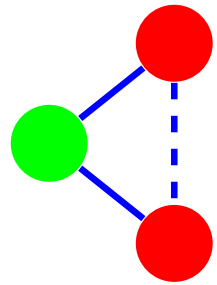

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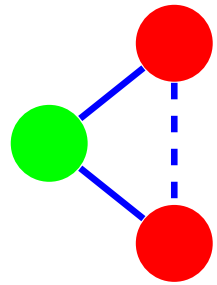

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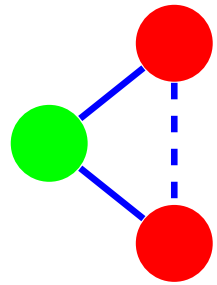

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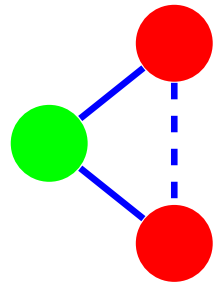

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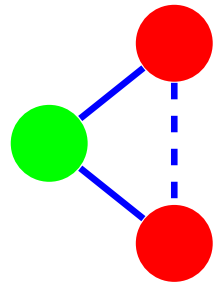

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Mainly because. . . of most central nodes.

Another (global) small world: the Erdős number

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(My Erdős number is 6: Paul Erdős - László Lovász - Herbert E Scarf - Kenneth J Arrow - Kaushik Basu - Luca Stanca - Pietro Battiston)

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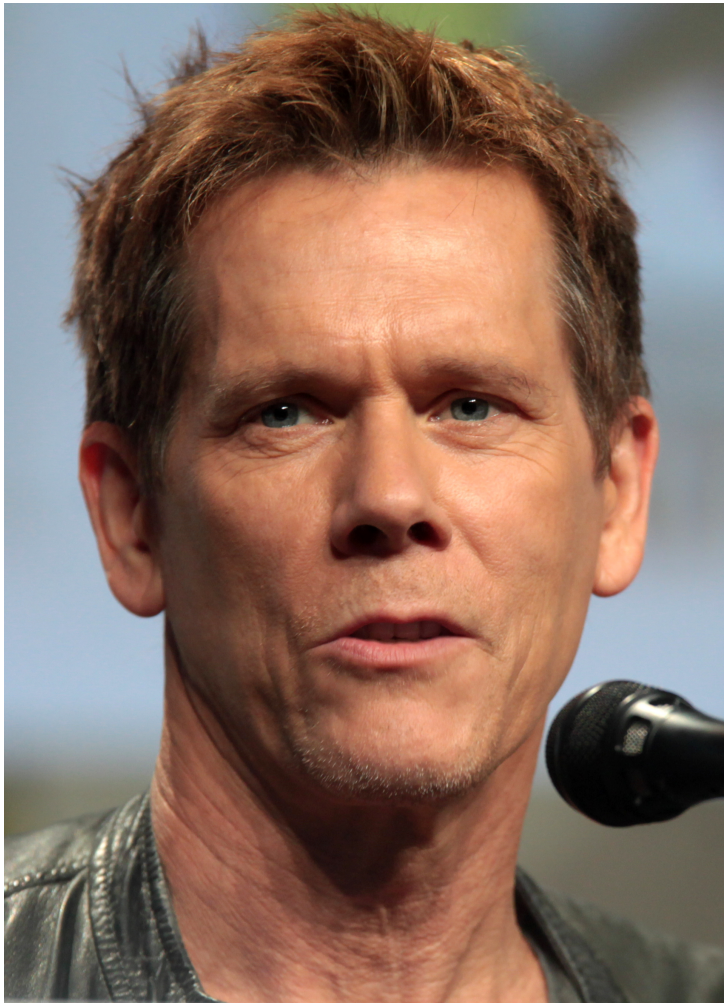

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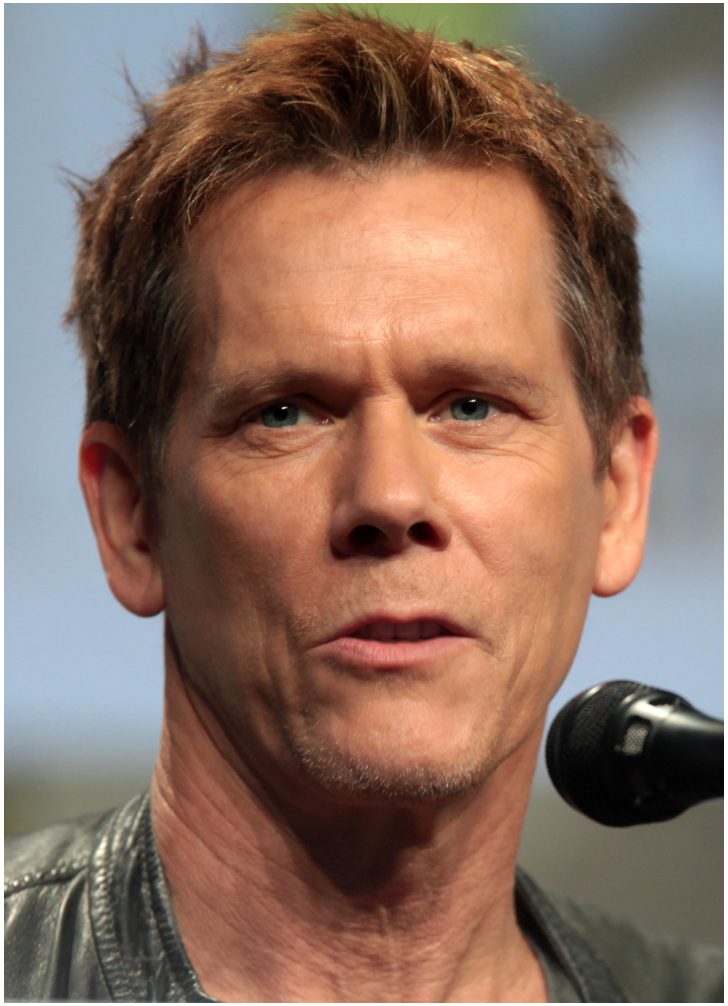

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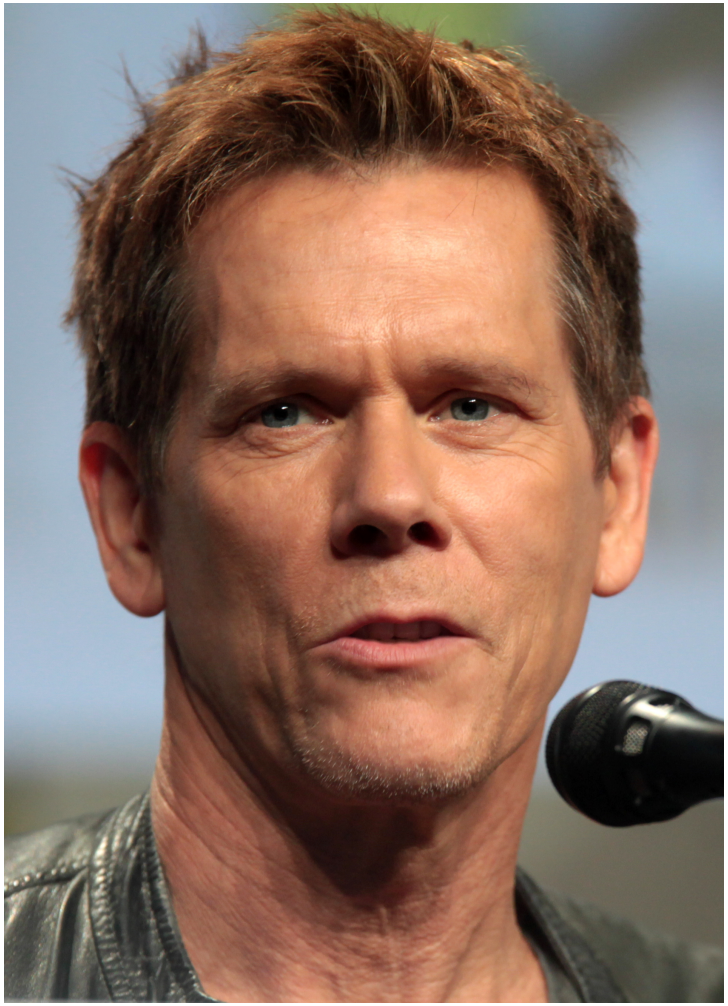

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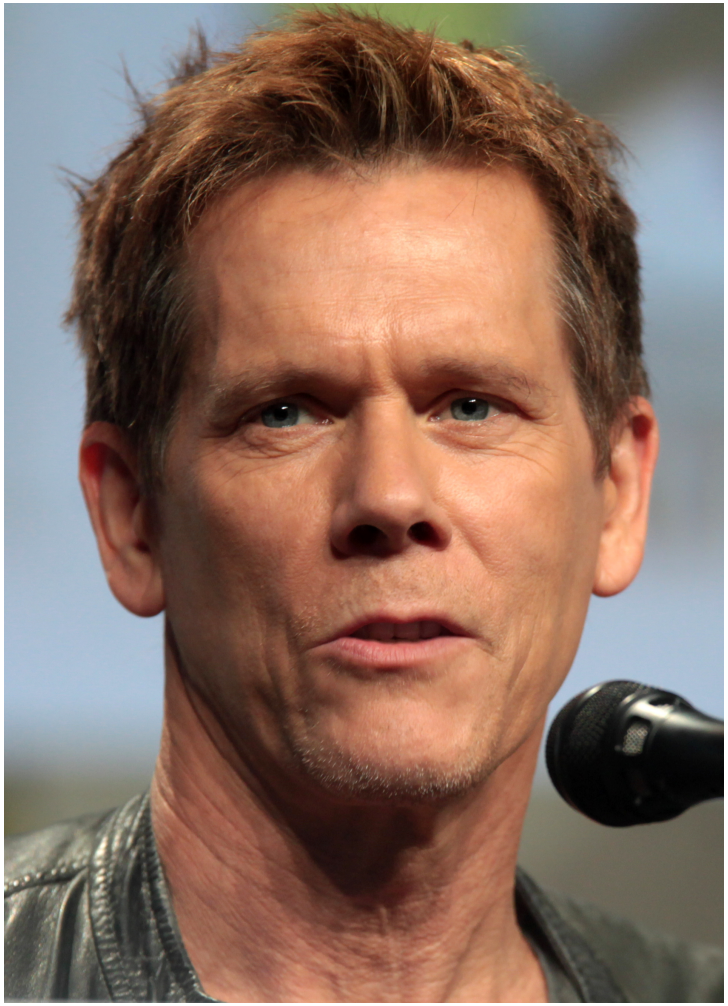

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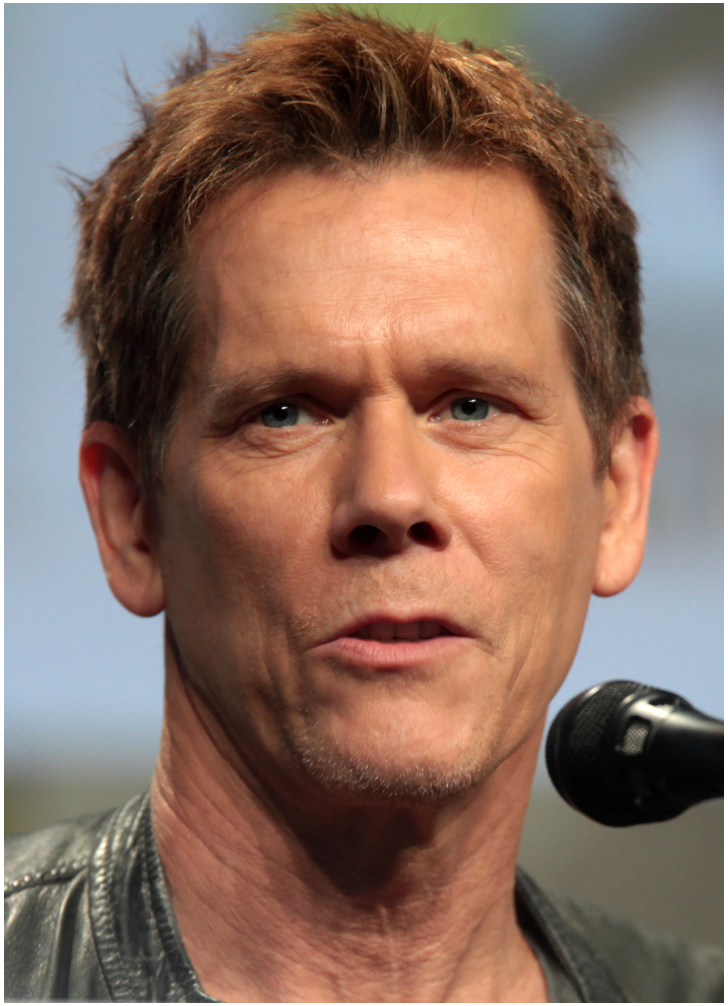

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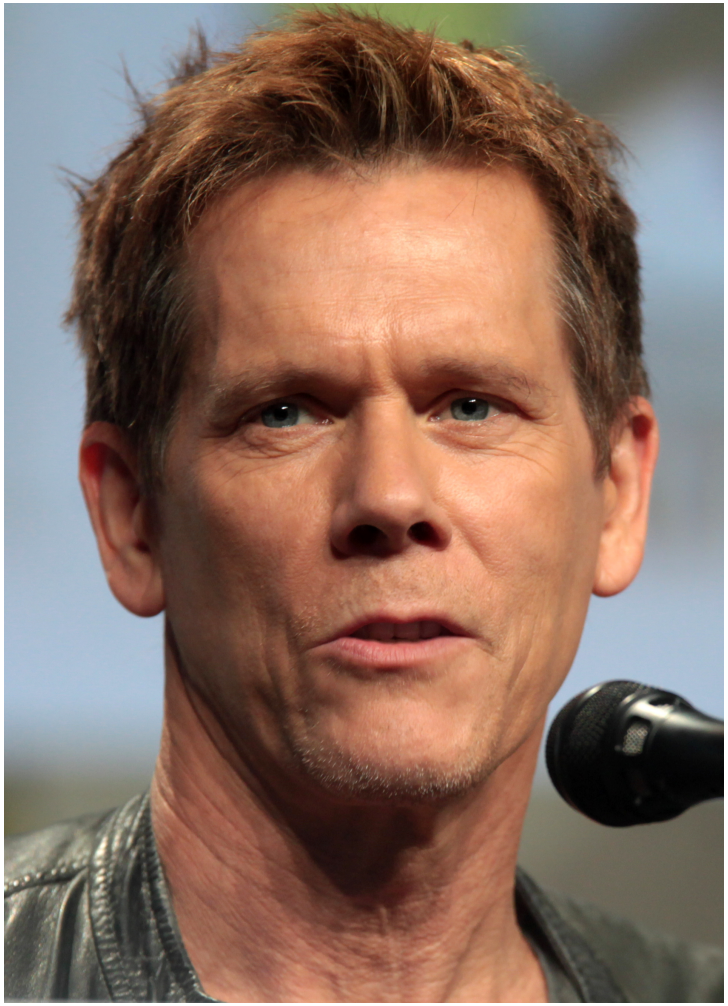

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Again: small world (usually below 6 for actors who *can* be linked to Bacon)

. . . and we can elaborate. . .

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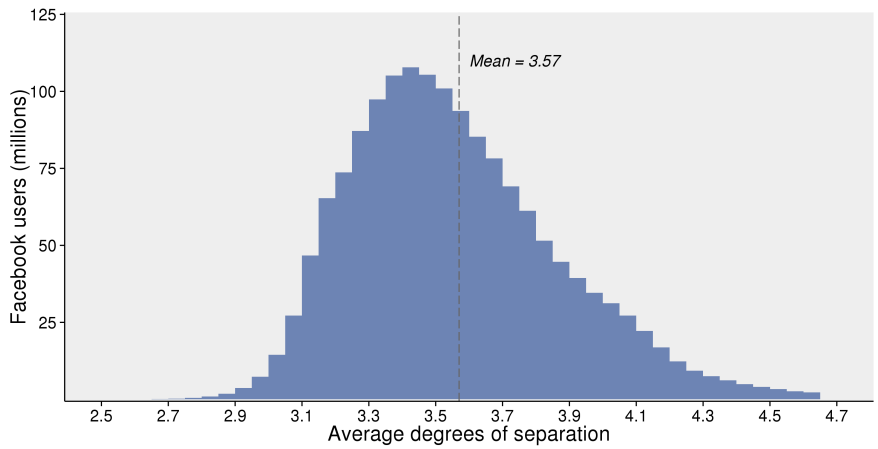
> *"The majority of the people on Facebook have averages between 2.9 and 4.2 degrees of separation."*



That's (only part of) it

Was it a long journey?

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Well, in the end it is just a matter of nodes and edges.

Image sources I

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