

Biological Networks

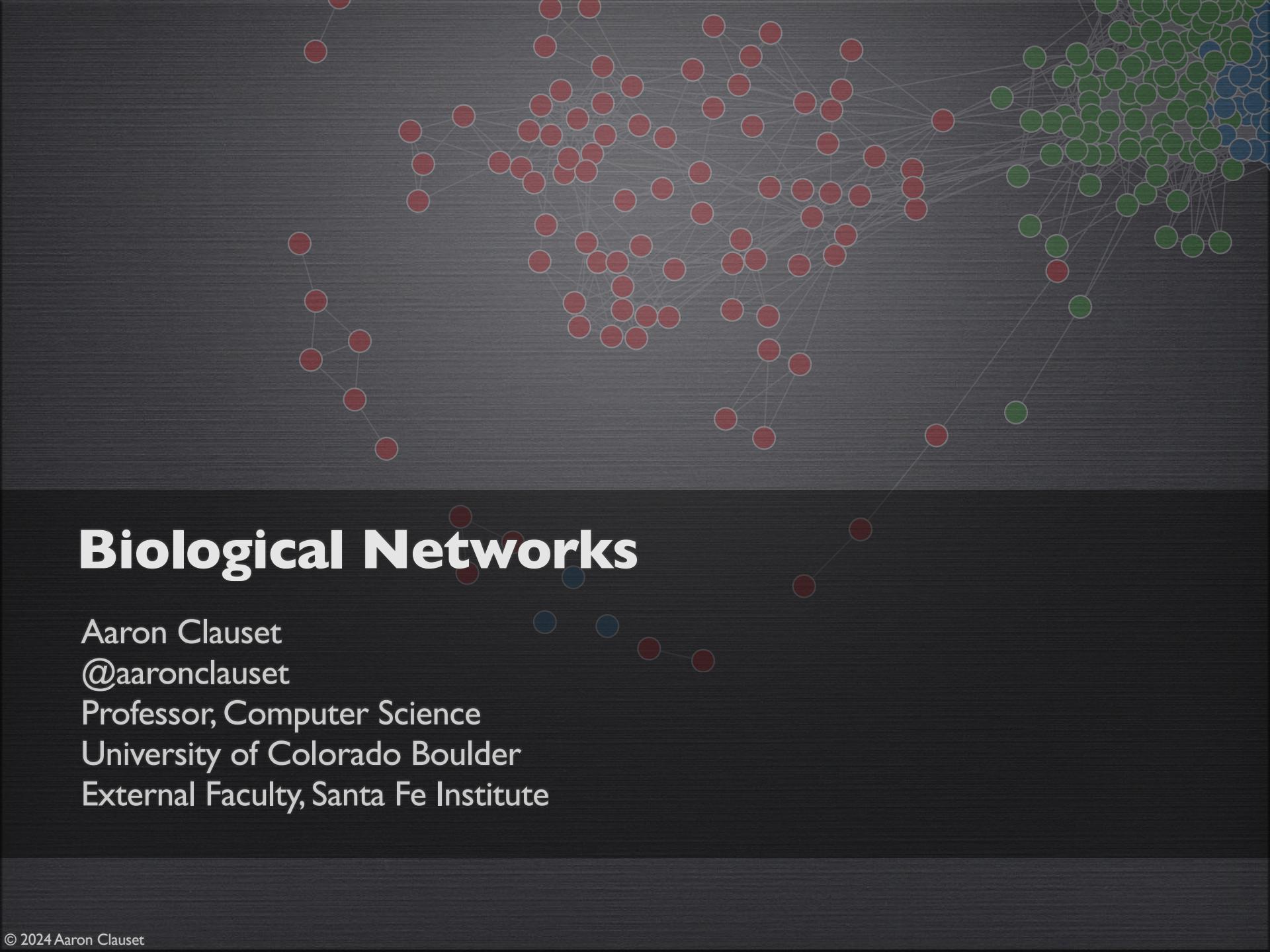
Aaron Clauset

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Professor, Computer Science

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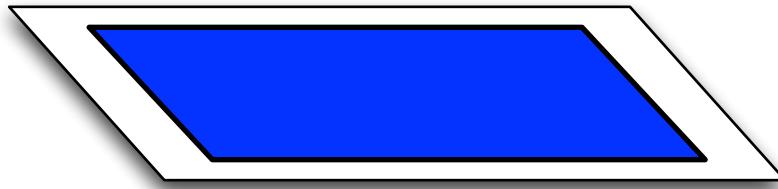
External Faculty, Santa Fe Institute



What are networks?

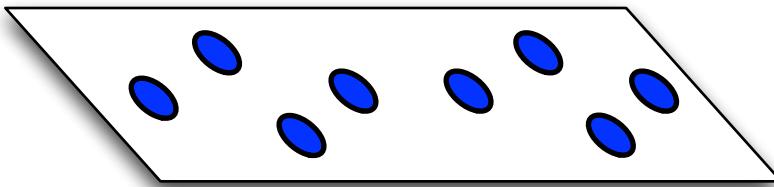
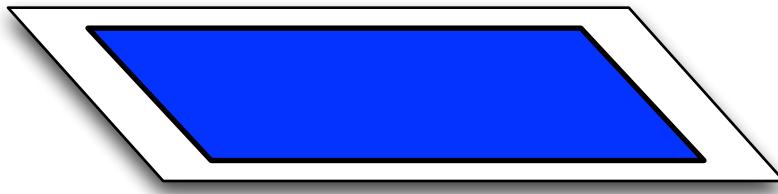
What are networks?

system or population



What are networks?

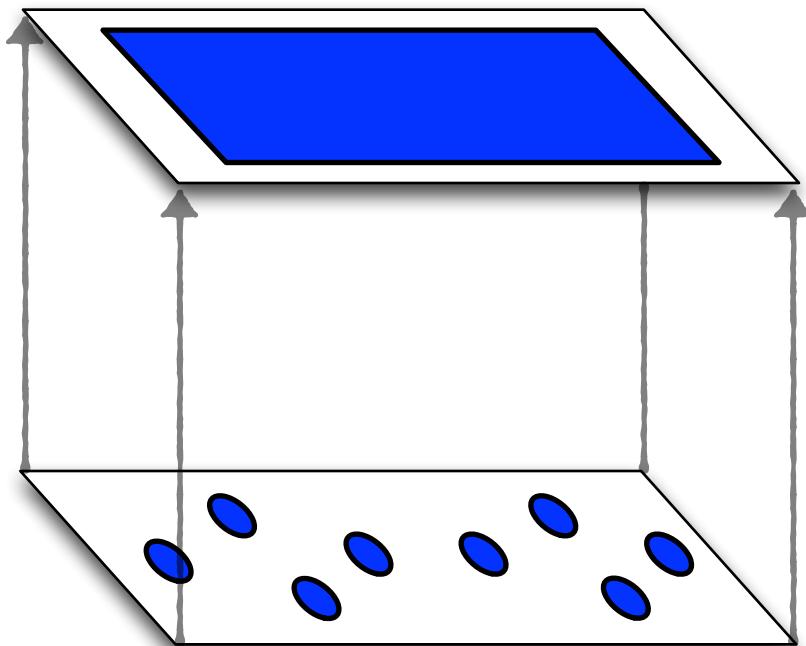
system or population



individuals or parts

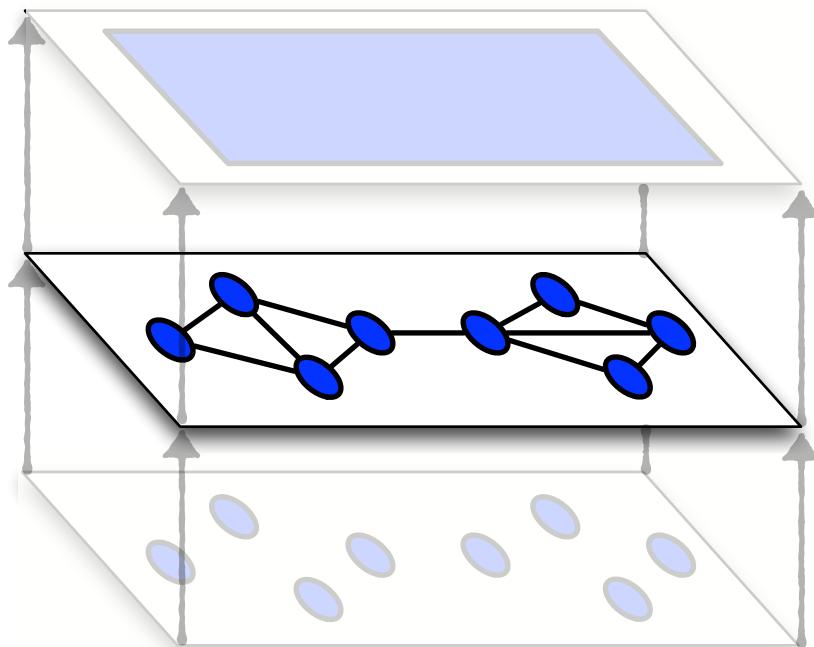
What are networks?

macro phenomena



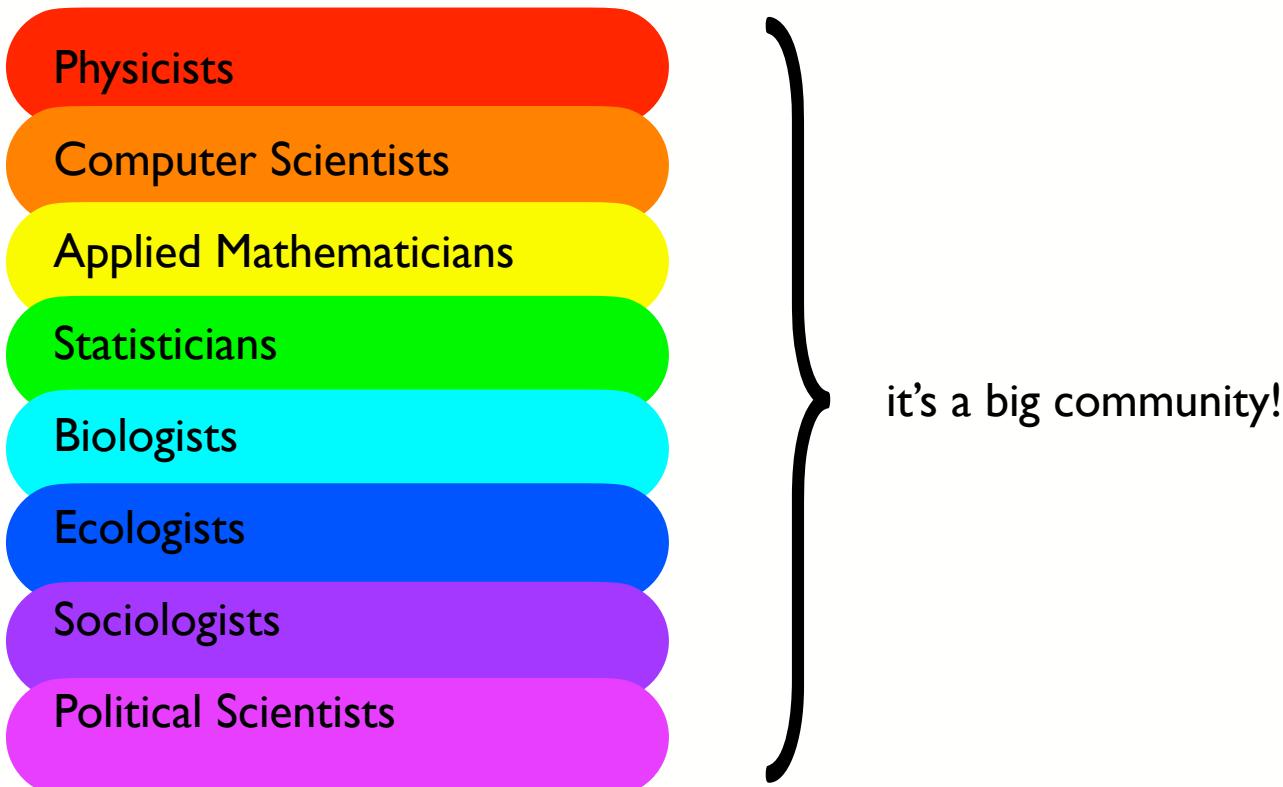
micro behavior

What are networks?



- an approach
- a representation of complexity
- connect "micro" to "macro"
- interactions within a system

Who studies networks?



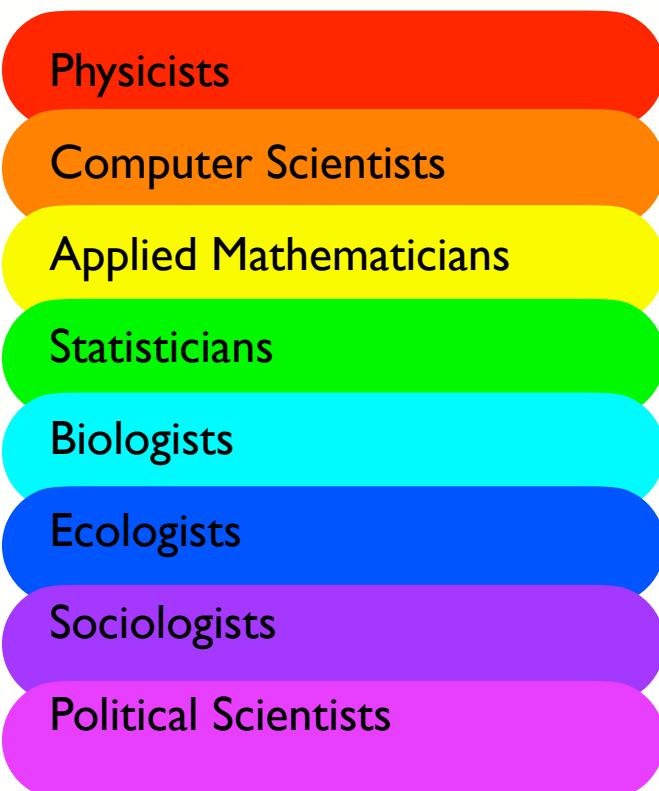
Who studies networks?



it's a big community!

- different traditions
- different tools
- different questions

Who studies networks?

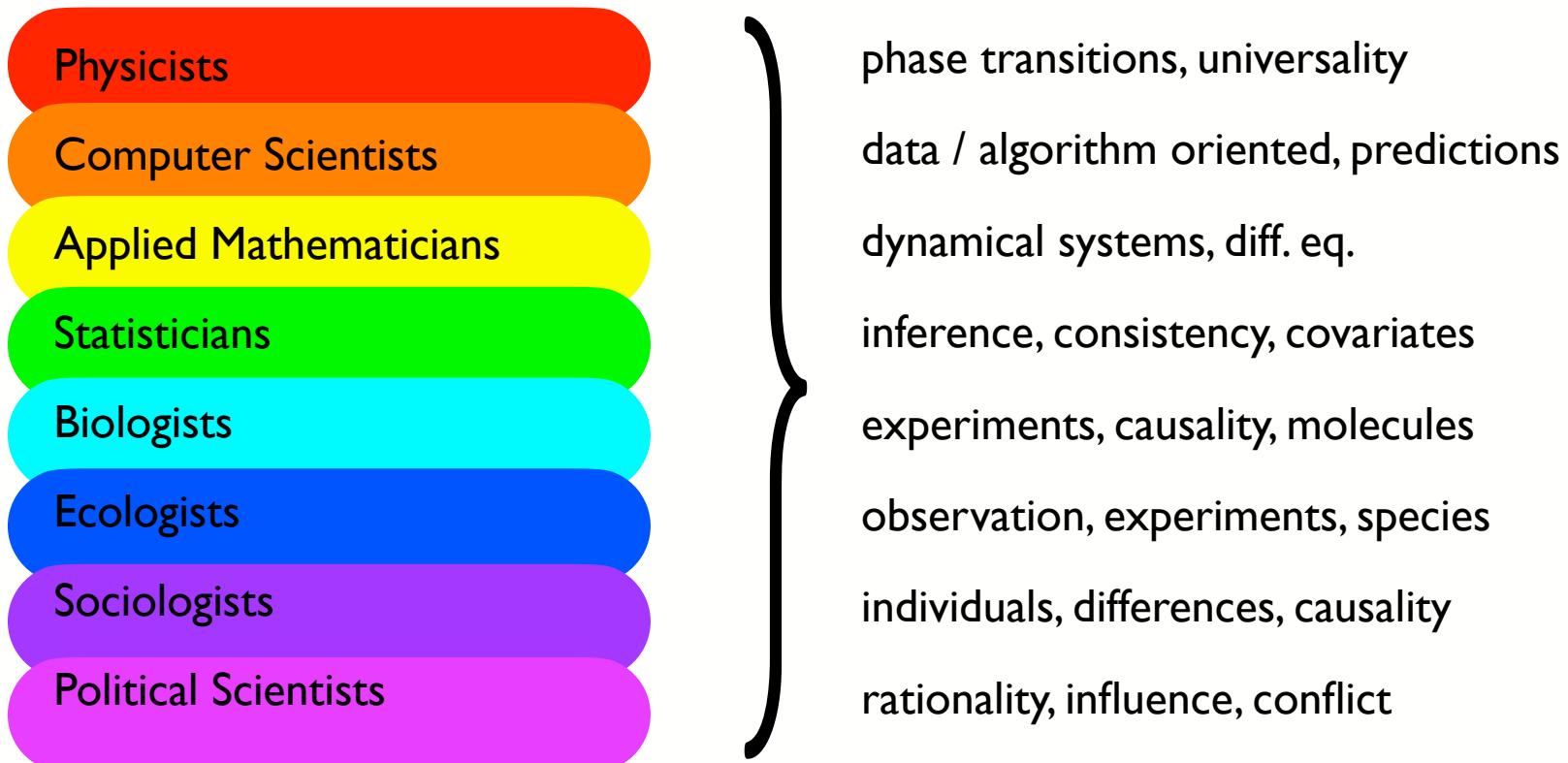


it's a big community!

- different traditions
- different tools
- different questions

increasingly, not ONE community, but
MANY, only loosely interacting
communities

Who studies networks?

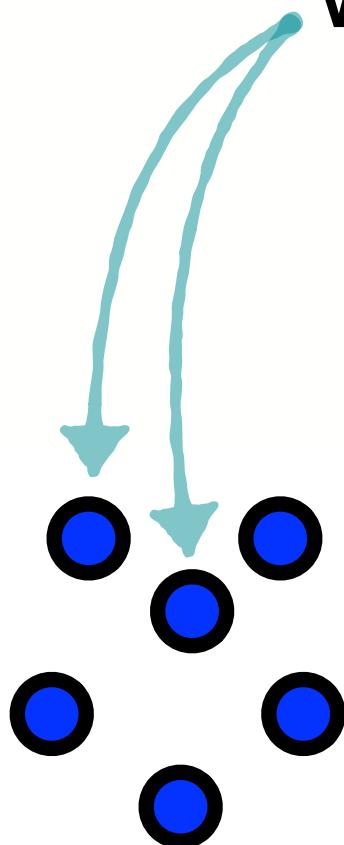


Two fundamental questions for using networks

Two fundamental questions for using networks

what is a vertex?

V distinct objects (vertices / nodes / actors)



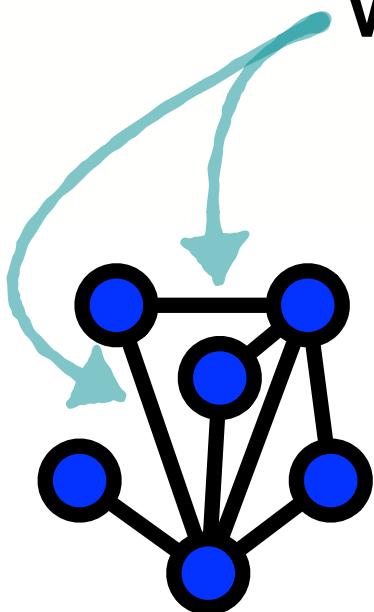
Two fundamental questions for using networks

what is a vertex?

V distinct objects (vertices / nodes / actors)

when are two vertices connected?

$E \subseteq V \times V$ pairwise relations (edges / links / ties)



Major types of networks

social

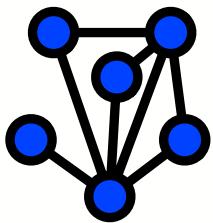
biological

information

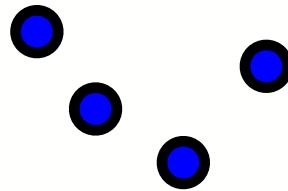
economic

transportation

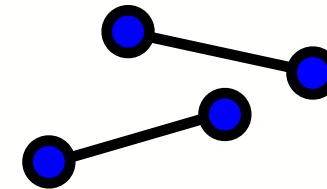
technological



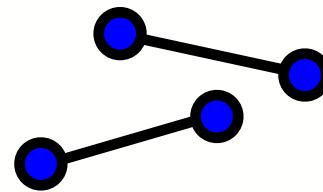
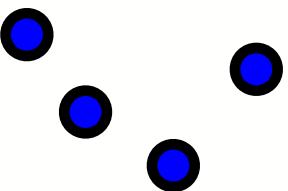
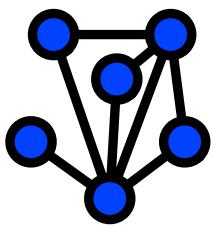
network



vertex



edge



network

Internet(1)

Internet(2)

vertex

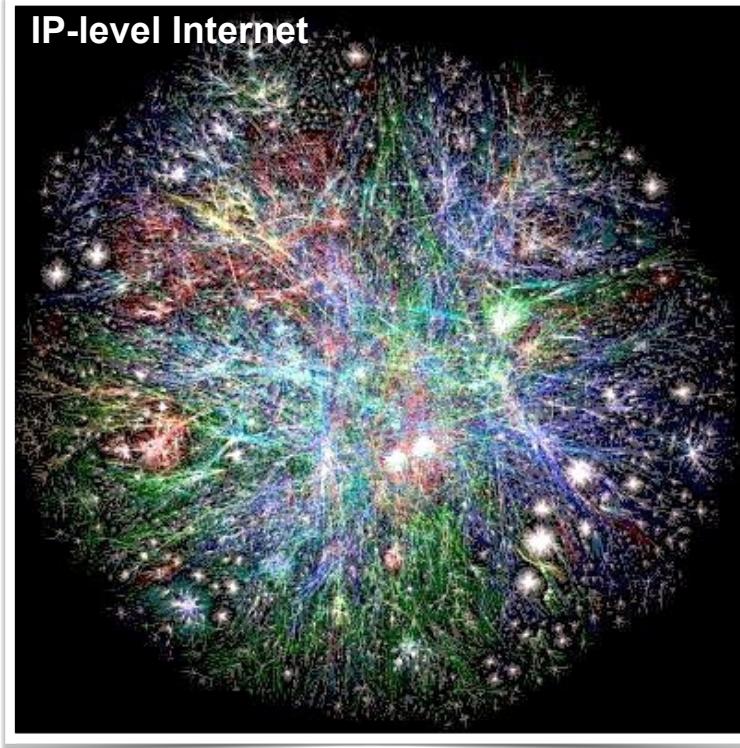
computer

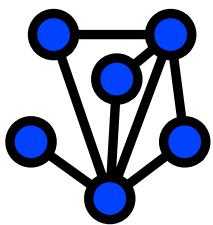
autonomous system (ISP)

edge

IP network adjacency

BGP connection





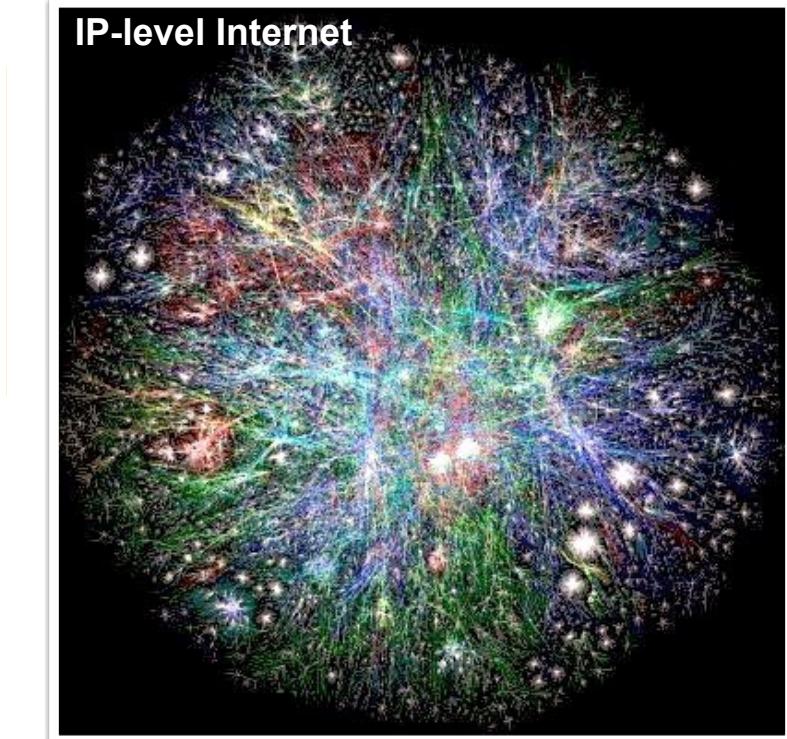
network

Internet(1)

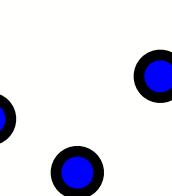
Internet(2)

	vertex	edge
Internet(1)	computer	IP network adjacency
Internet(2)	autonomous system (ISP)	BGP connection

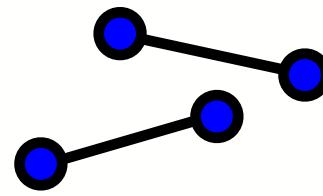
technological



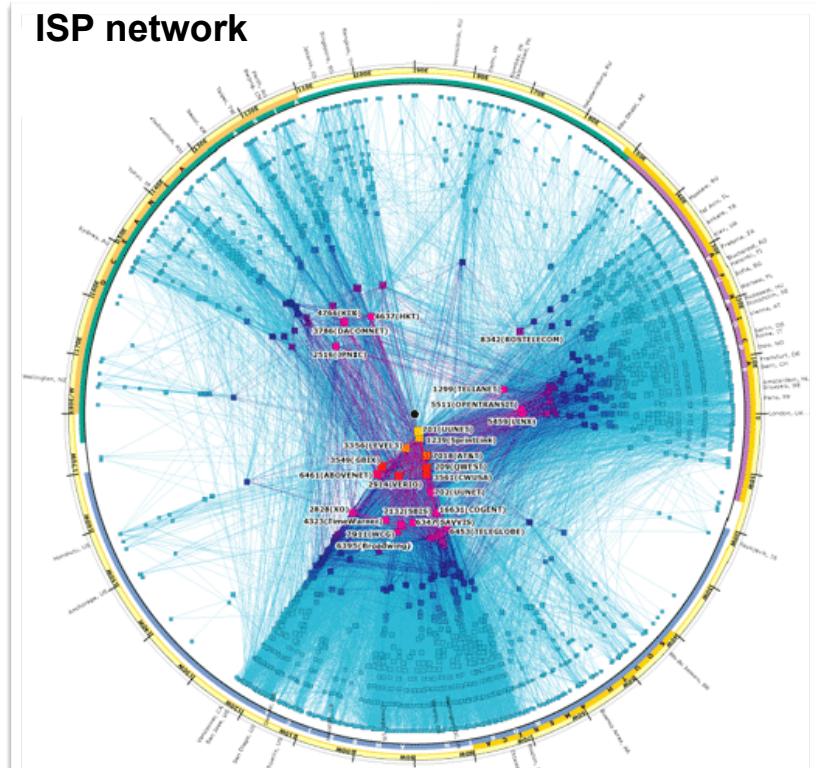
vertex

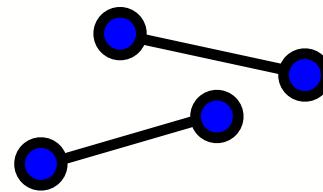
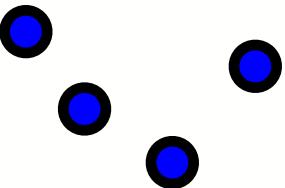
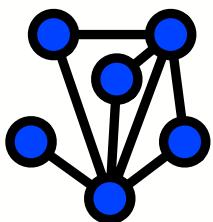


edge



ISP network





information
technological

network

Internet(1)

Internet(2)

software

World Wide Web

documents

vertex

computer

autonomous system (ISP)

function

web page

article, patent, or legal case

edge

IP network adjacency

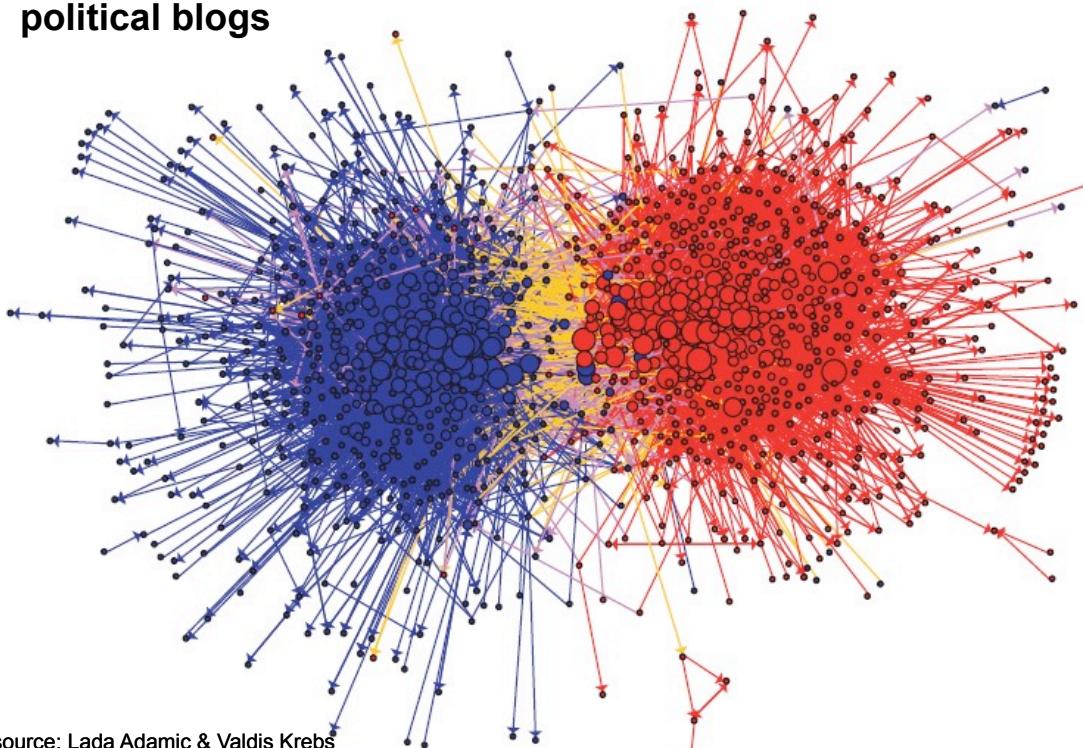
BGP connection

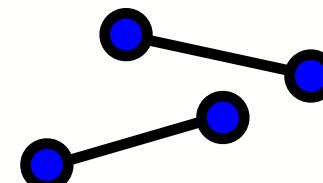
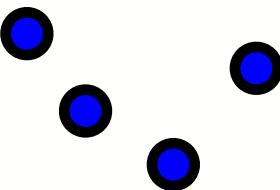
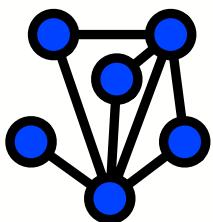
function call

hyperlink

citation

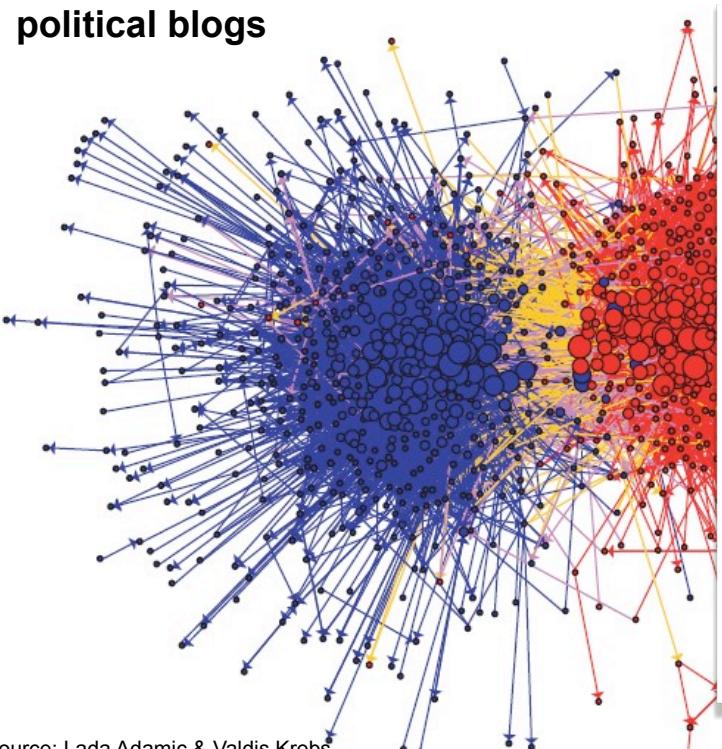
political blogs



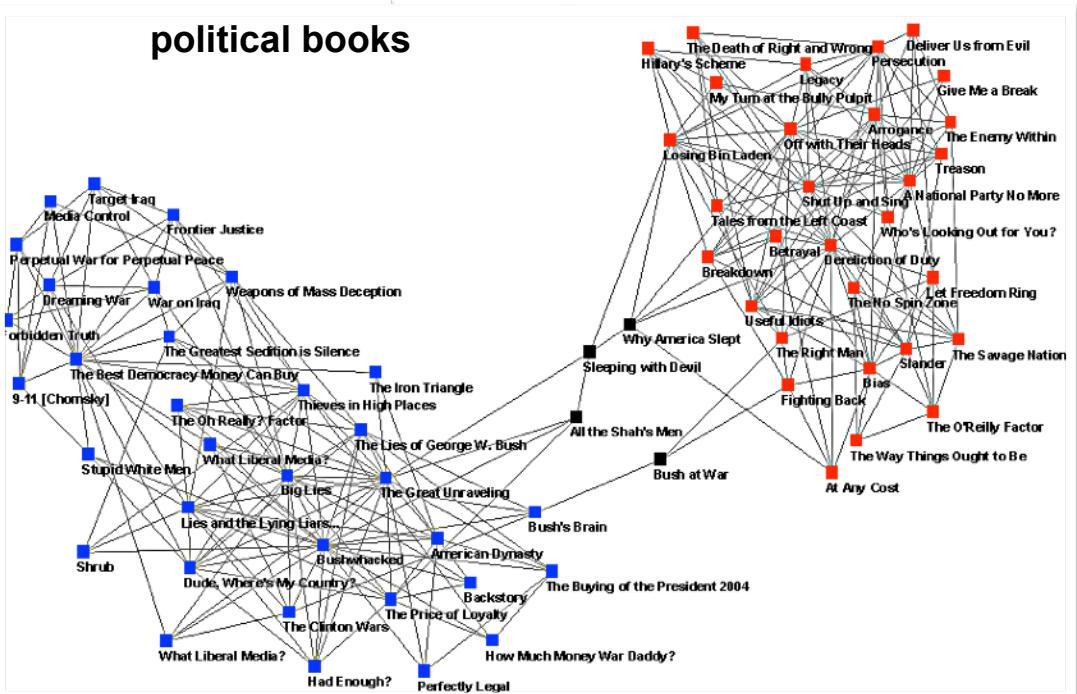


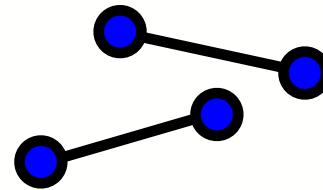
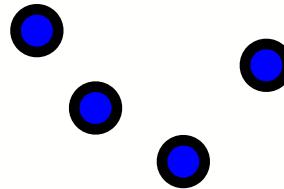
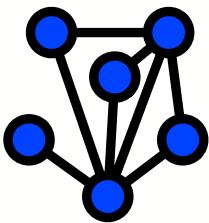
network	vertex	edge
Internet(1)	computer	IP network adjacency
Internet(2)	autonomous system (ISP)	BGP connection
software	function	function call
World Wide Web	web page	hyperlink
documents	article, patent, or legal case	citation

political blogs



political books





technological

network

Internet(1)

Internet(2)

software

World Wide Web

documents

power grid transmission

rail system

road network(1)

road network(2)

airport network

vertex

computer

autonomous system (ISP)

function

web page

article, patent, or legal case

generating or relay station

rail station

intersection

named road

airport

edge

IP network adjacency

BGP connection

function call

hyperlink

citation

transmission line

railroad tracks

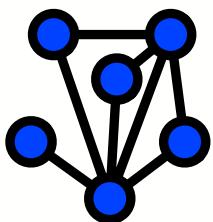
pavement

intersection

non-stop flight

information

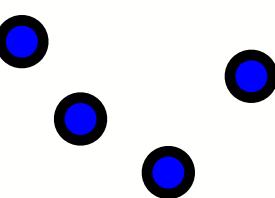
transportation



network

road network(1)

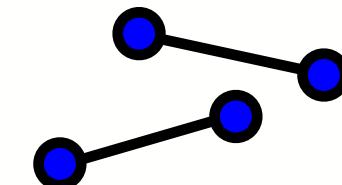
road network(2)



vertex

intersection

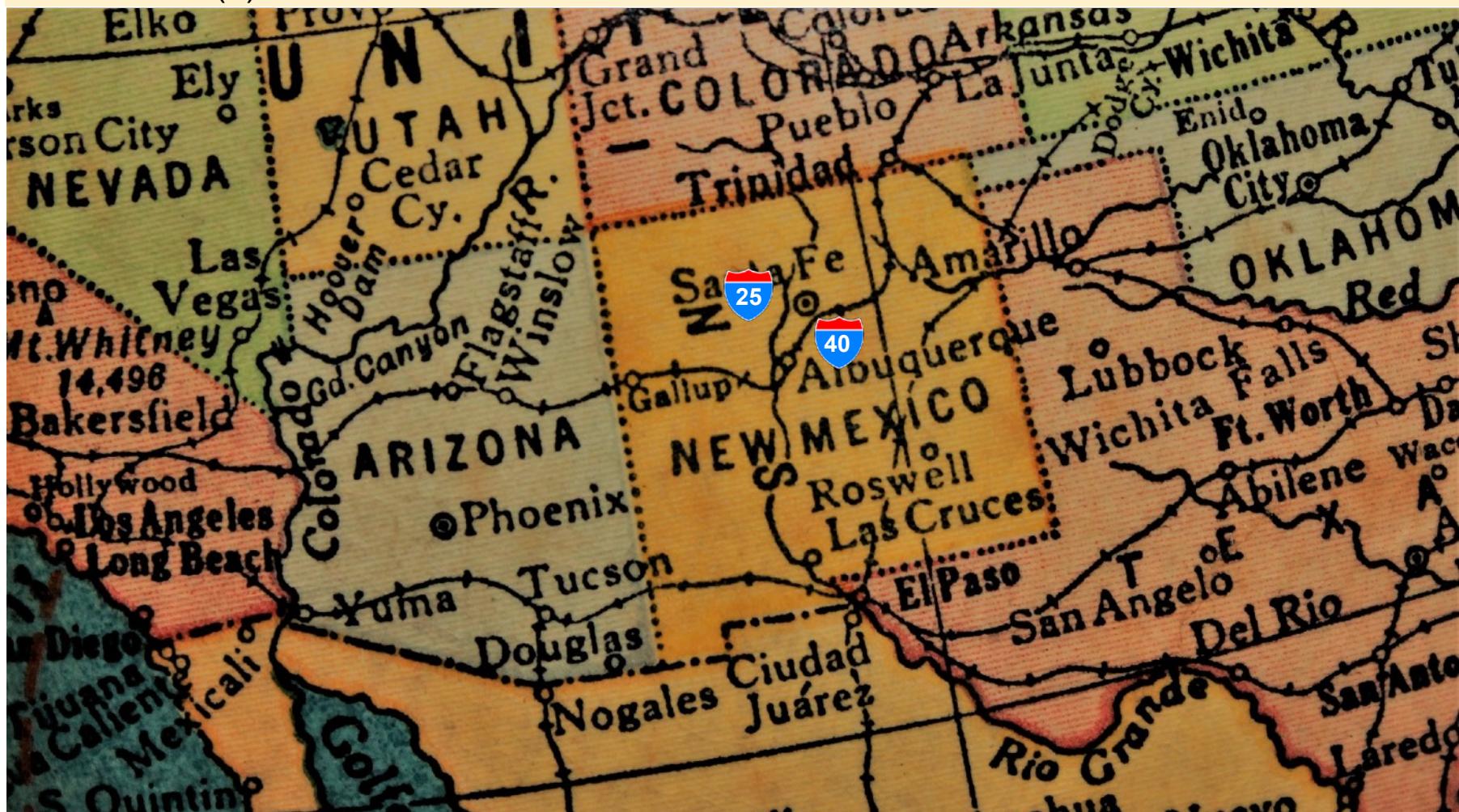
named road

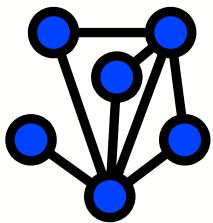


edge

pavement

intersection

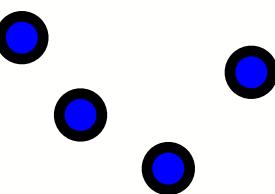




network

road network(1)

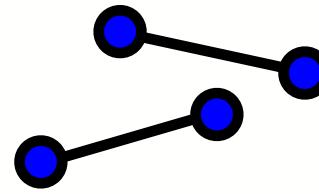
road network(2)



vertex

intersection

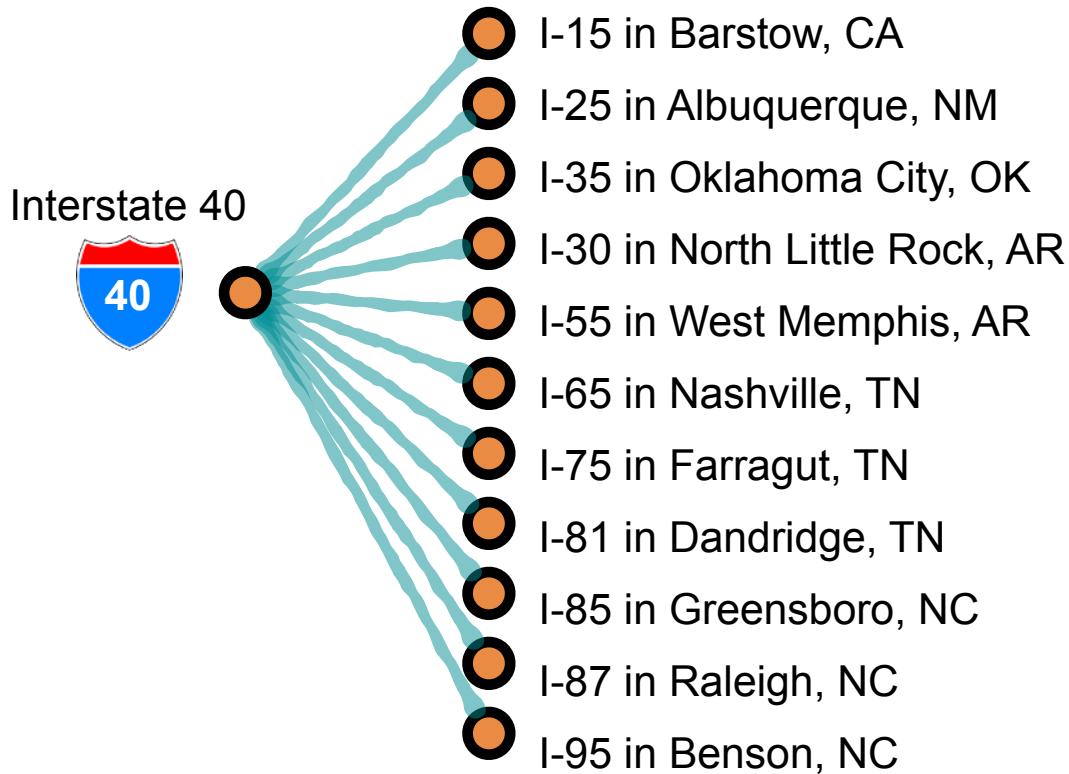
named road

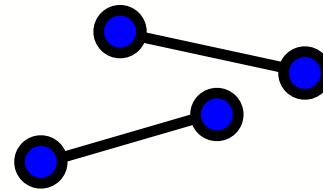
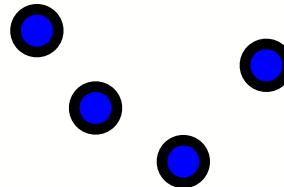
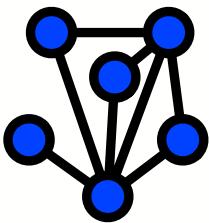


edge

pavement

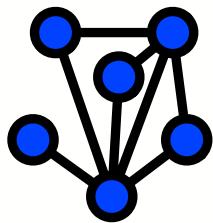
intersection





technological
information
transportation
social

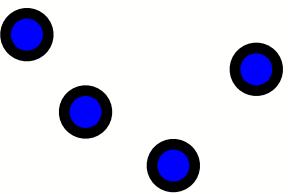
network	vertex	edge
Internet(1)	computer	IP network adjacency
Internet(2)	autonomous system (ISP)	BGP connection
software	function	function call
World Wide Web	web page	hyperlink
documents	article, patent, or legal case	citation
power grid transmission	generating or relay station	transmission line
rail system	rail station	railroad tracks
road network(1)	intersection	pavement
road network(2)	named road	intersection
airport network	airport	non-stop flight
friendship network	person	friendship
sexual network	person	intercourse



network

friendship network

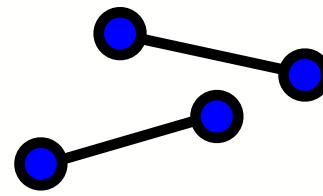
sexual network



vertex

person

person

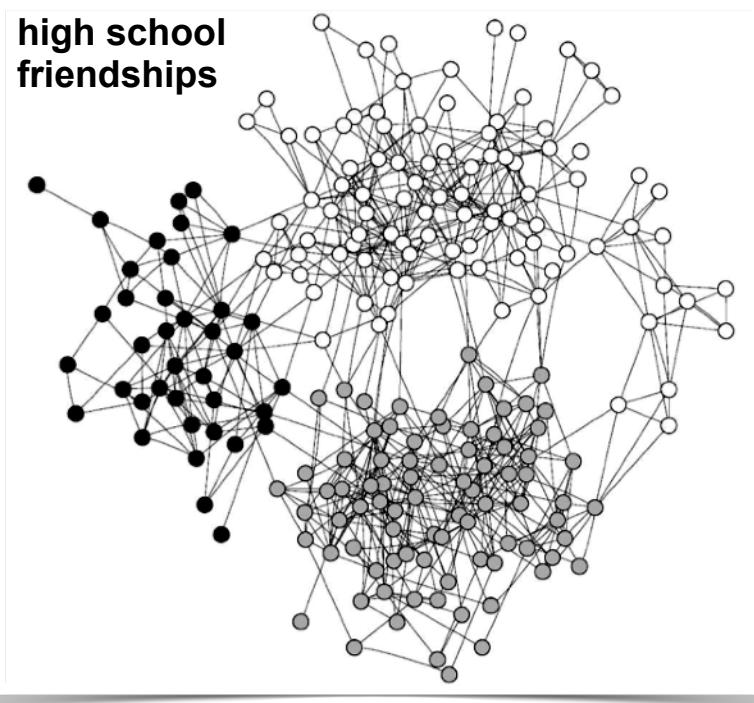


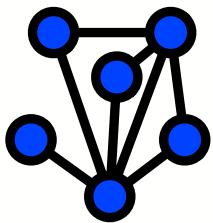
edge

friendship

intercourse

**high school
friendships**

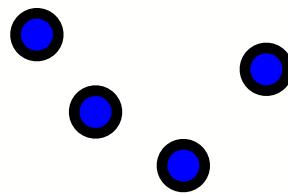




network

friendship network

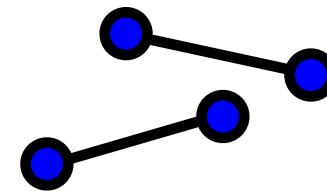
sexual network



vertex

person

person

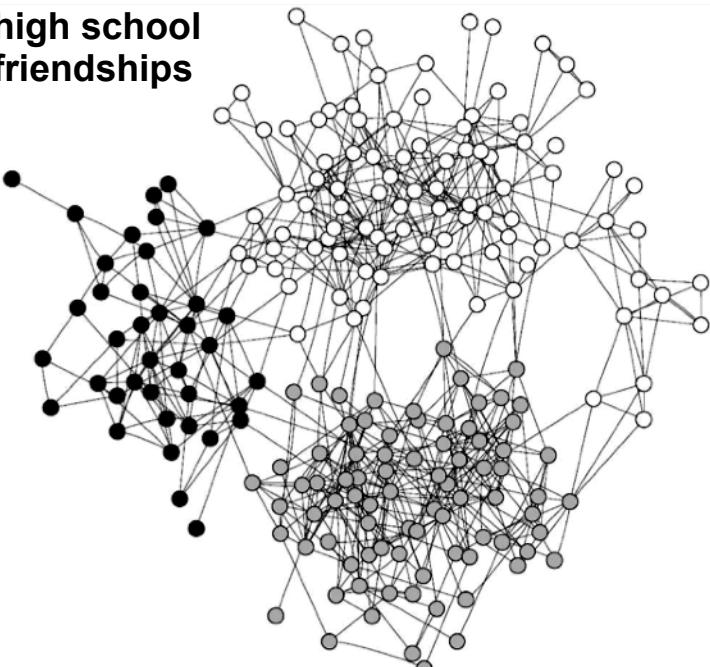


edge

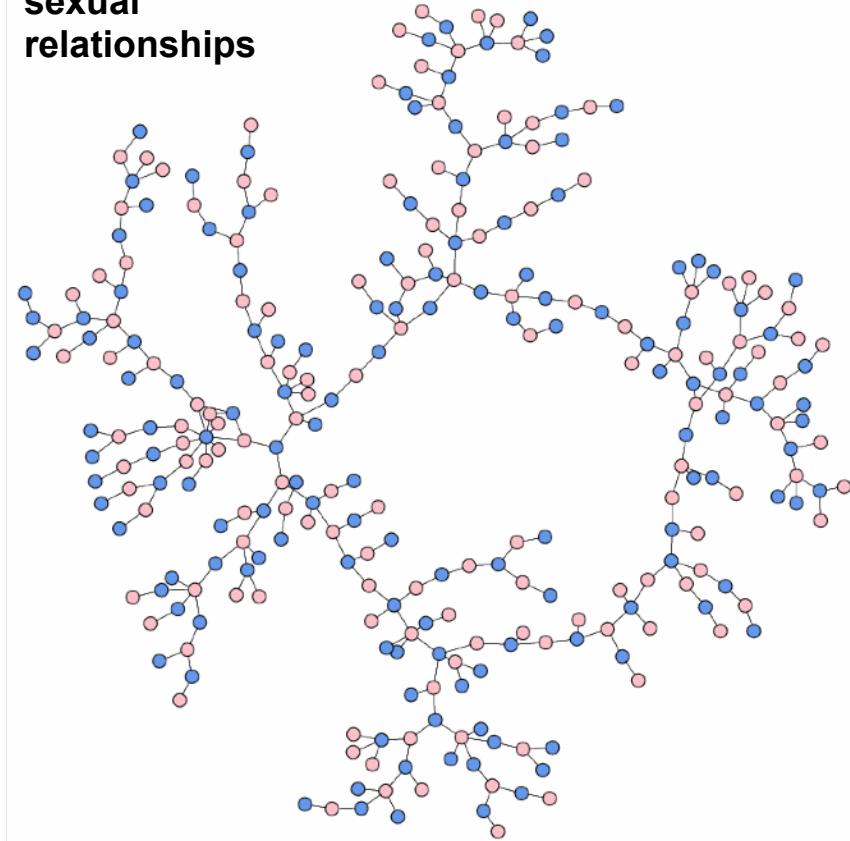
friendship

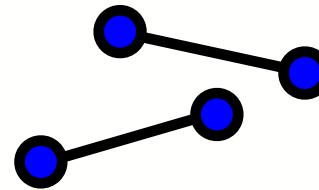
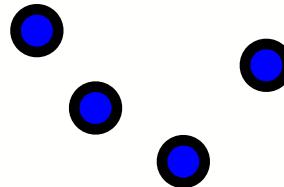
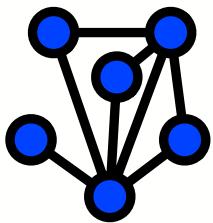
intercourse

**high school
friendships**

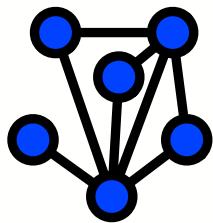


**sexual
relationships**



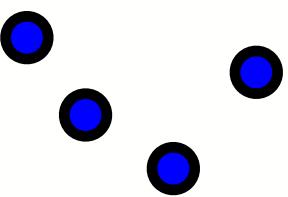


	network	vertex	edge
technological	Internet(1)	computer	IP network adjacency
	Internet(2)	autonomous system (ISP)	BGP connection
information	software	function	function call
	World Wide Web	web page	hyperlink
transportation	documents	article, patent, or legal case	citation
	power grid transmission	generating or relay station	transmission line
road network(1)	rail system	rail station	railroad tracks
	road network(2)	intersection	pavement
social	road network(3)	named road	intersection
	airport network	airport	non-stop flight
biological	friendship network	person	friendship
	sexual network	person	intercourse
metabolic network	metabolite	metabolic reaction	
	protein-interaction network	protein	binding
gene regulatory network	genes, mRNA, protein, complexes	regulatory effect	
	connectome	neuron	synapse
food web	species	predation or resource transfer	



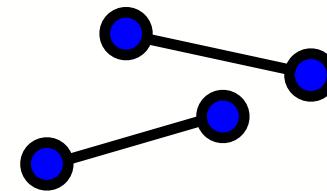
network

metabolic network



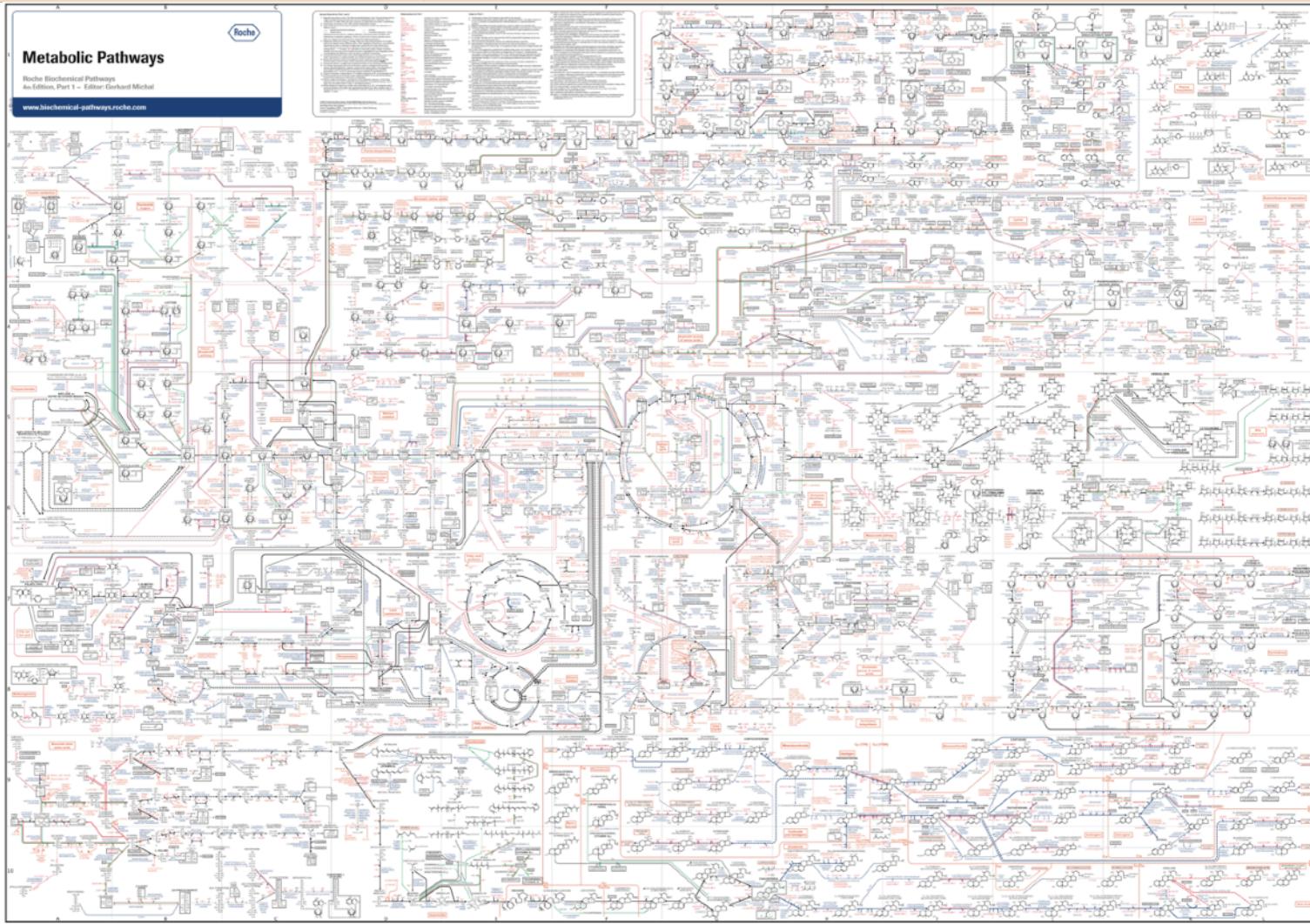
vertex

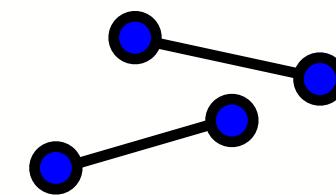
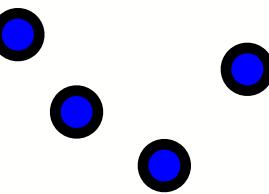
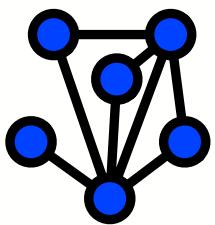
metabolite



edge

metabolic reaction





network

metabolic network

vertex

metabolite

protein interaction network

proteins

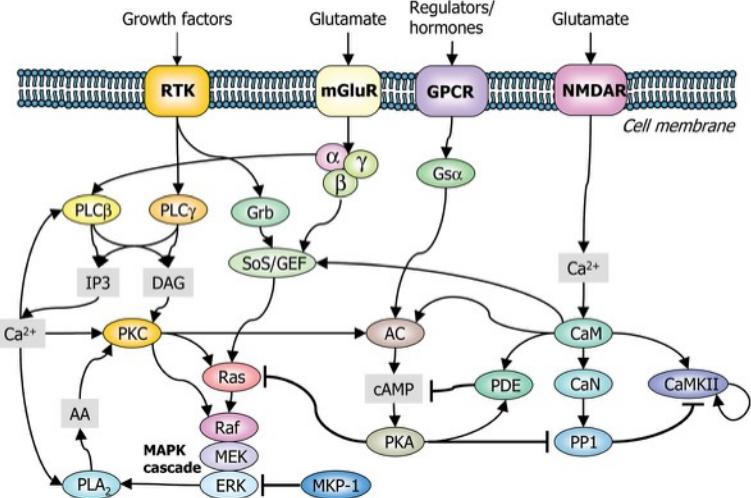
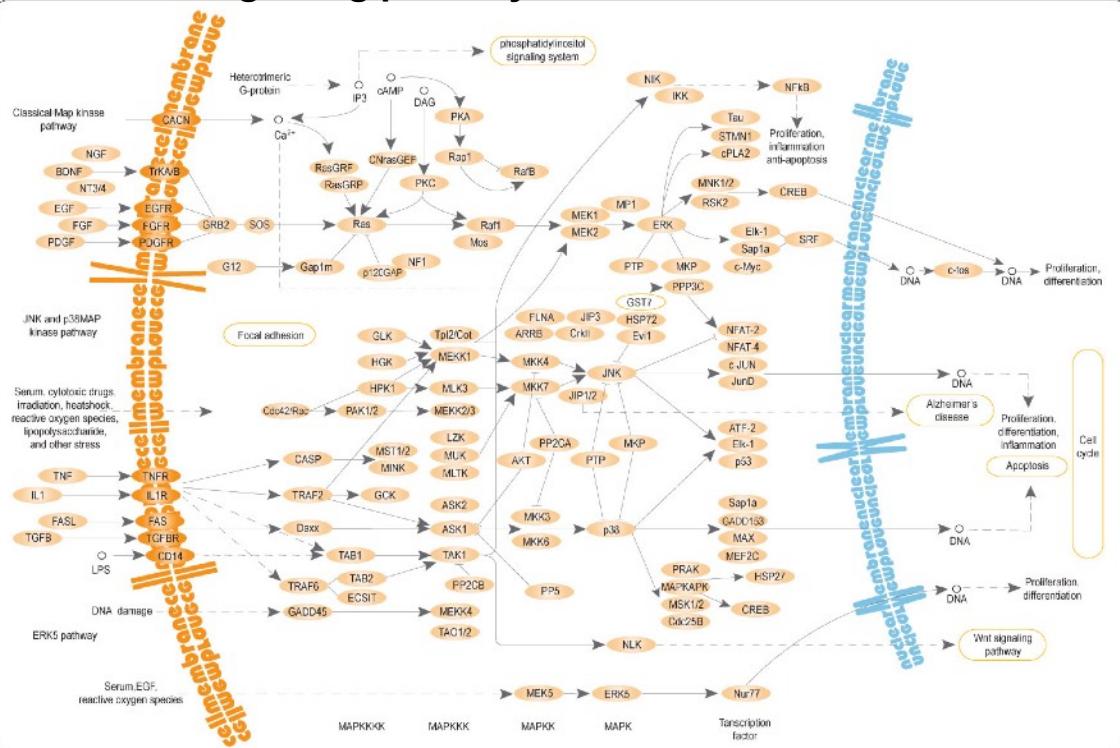
edge

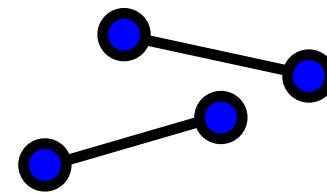
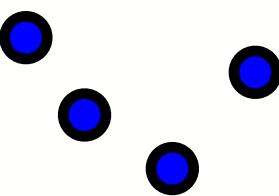
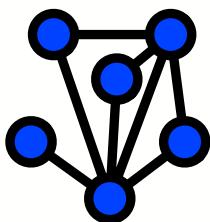
metabolic reaction

binding (activation, inhibition)

Signaling network (neurons)

MAPK/ERK signaling pathways





network

vertex

edge

metabolic network

metabolite

metabolic reaction

protein interaction network

proteins

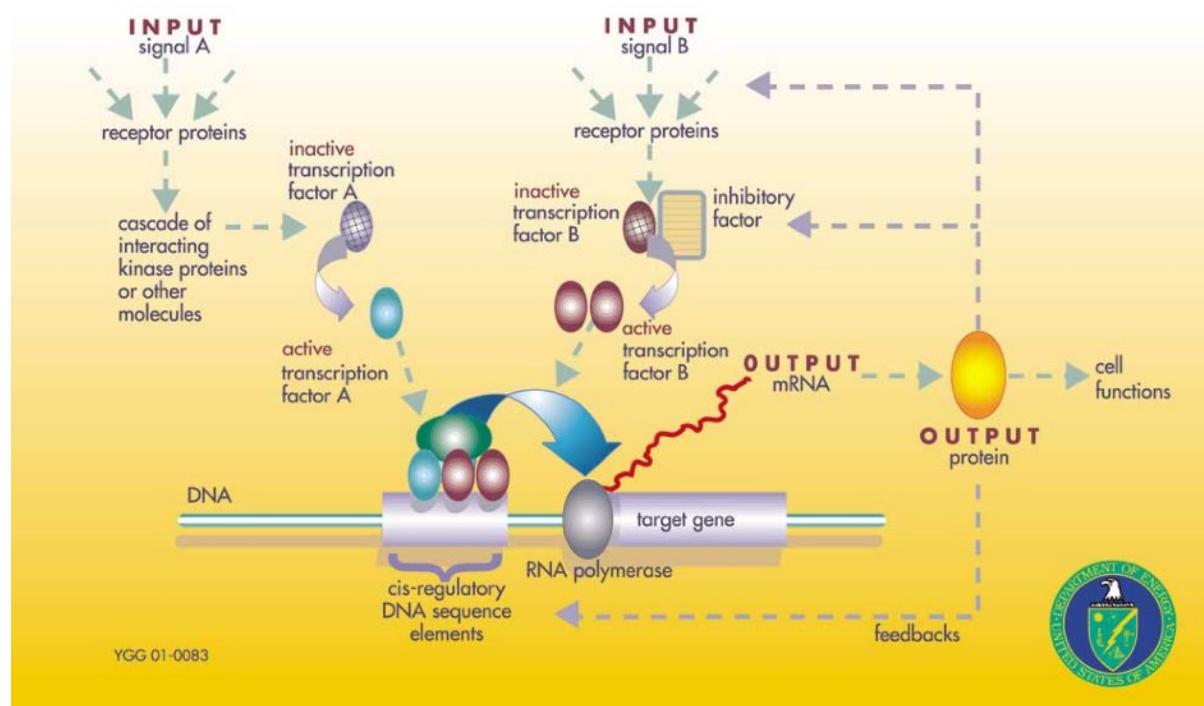
binding (activation, inhibition)

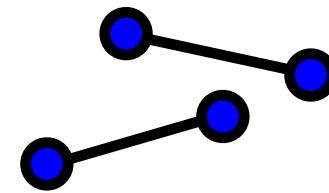
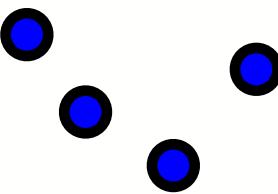
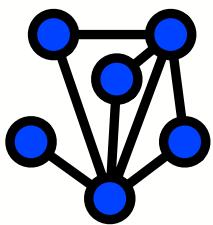
gene regulation

genes, mRNA, protein, complexes

regulatory effect

generic gene regulation





network

metabolic network

protein interaction network

gene regulation

connectome

vertex

metabolite

proteins

genes, transcription factors

neurons

edge

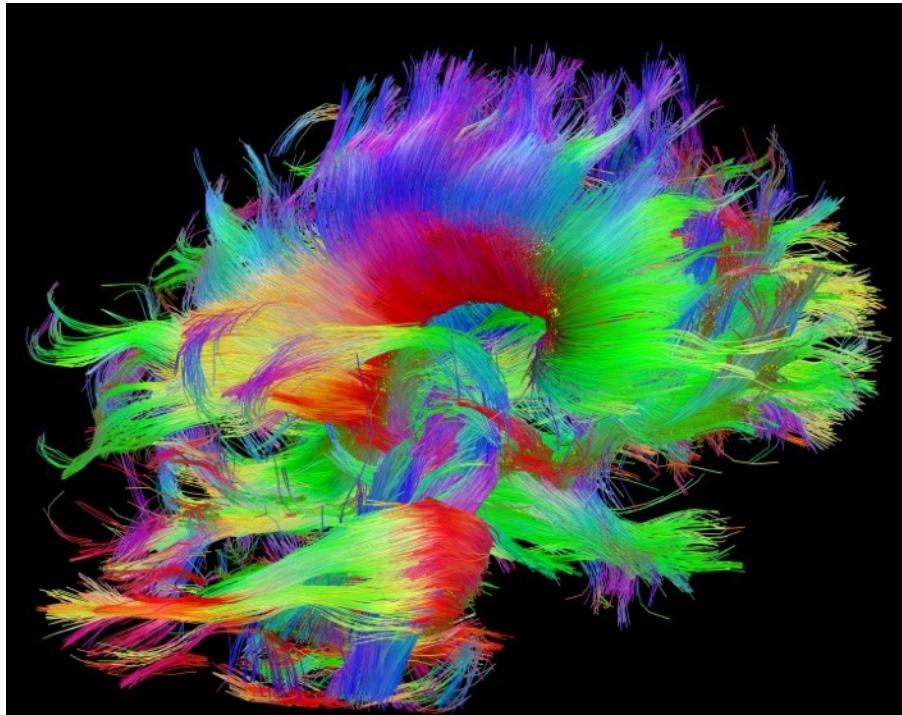
metabolic reaction

binding (activation, inhibition)

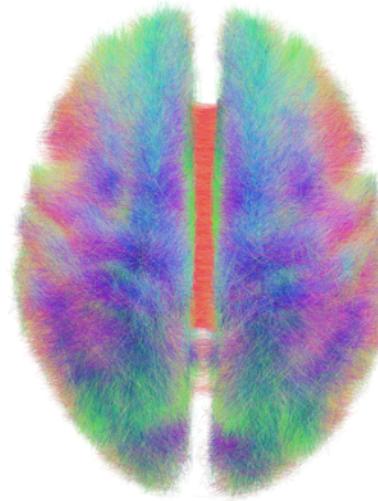
regulatory effect

synapse

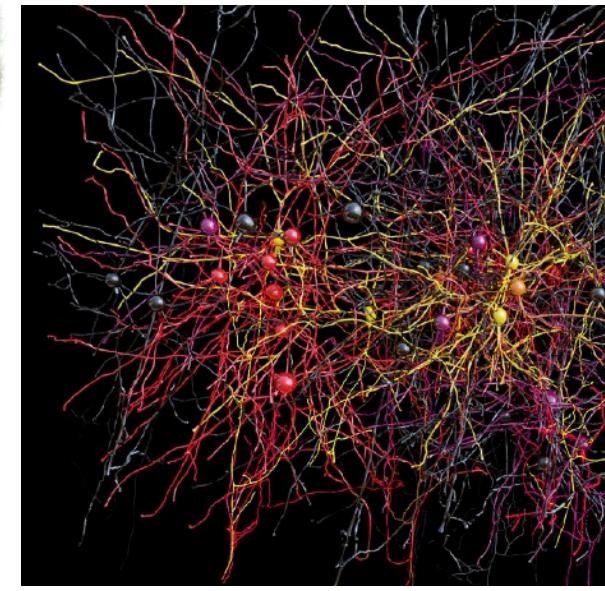
white matter fiber architecture

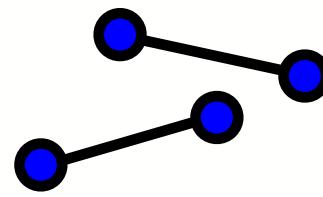
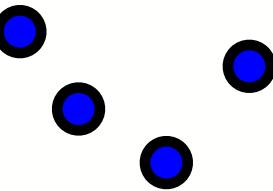
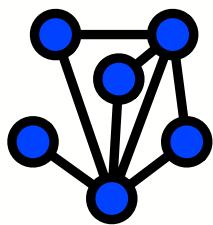


white matter fibers



cortical neurons





network

vertex

edge

metabolic network

metabolite

metabolic reaction

protein interaction network

proteins

binding (activation, inhibition)

gene regulation

genes, transcription factors

regulatory effect

connectome

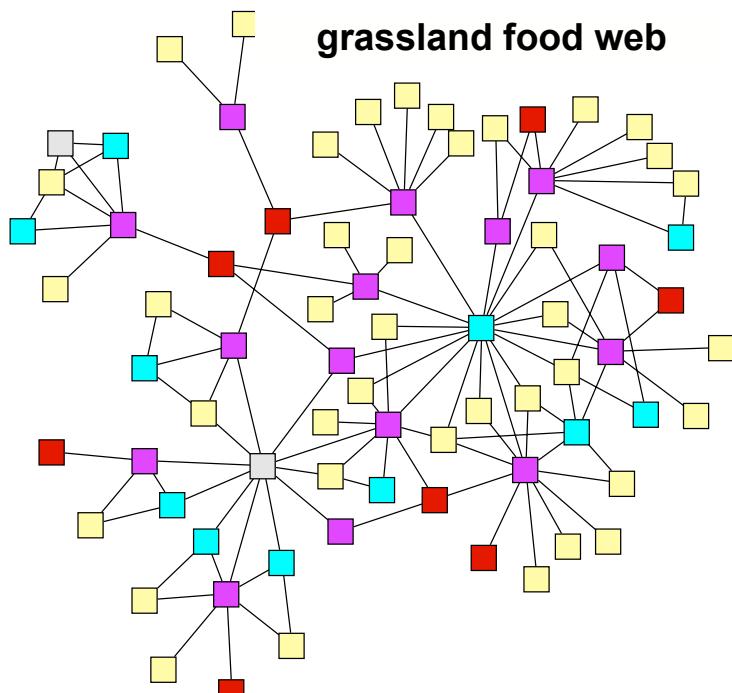
neurons

synapse

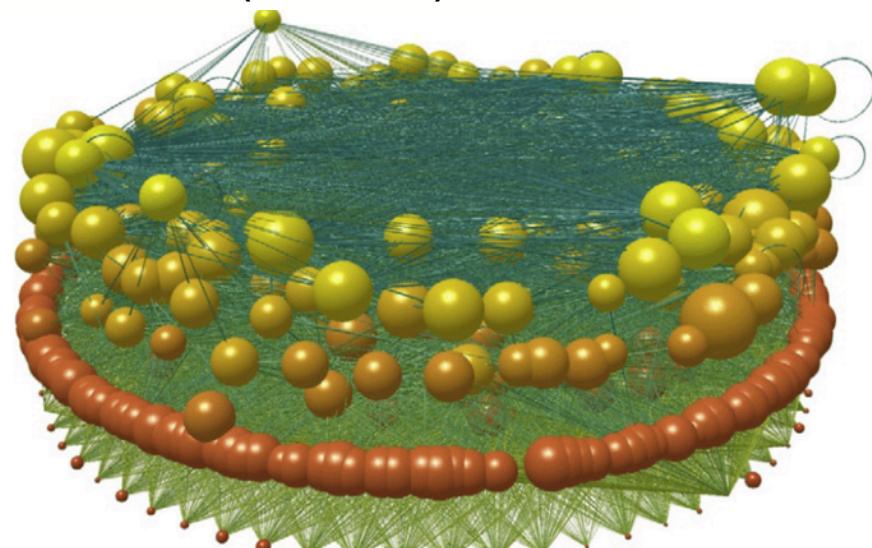
food web

species

predation or resource transfer



Weddell sea (Antarctica) food web



Six general areas

1. **fundamentals**: basic concepts and terminology
2. **exploratory analysis**: count & compare all the things — *describe* structural patterns in network data
3. **explanatory analysis**: convert network structure into node-level features, and do traditional correlational *explanatory modeling* (regression) of node attributes and local structural patterns
4. **random graph models**: use random graphs as *null models* to detect "non-random" patterns, to distinguish structural signals from structural noise
5. **processes & simulations**: explore structural or dynamical consequences of *network mechanisms* as variables interacting across edges
6. **predictive models**: predict missing or future data (node attributes or edges), using observed network data