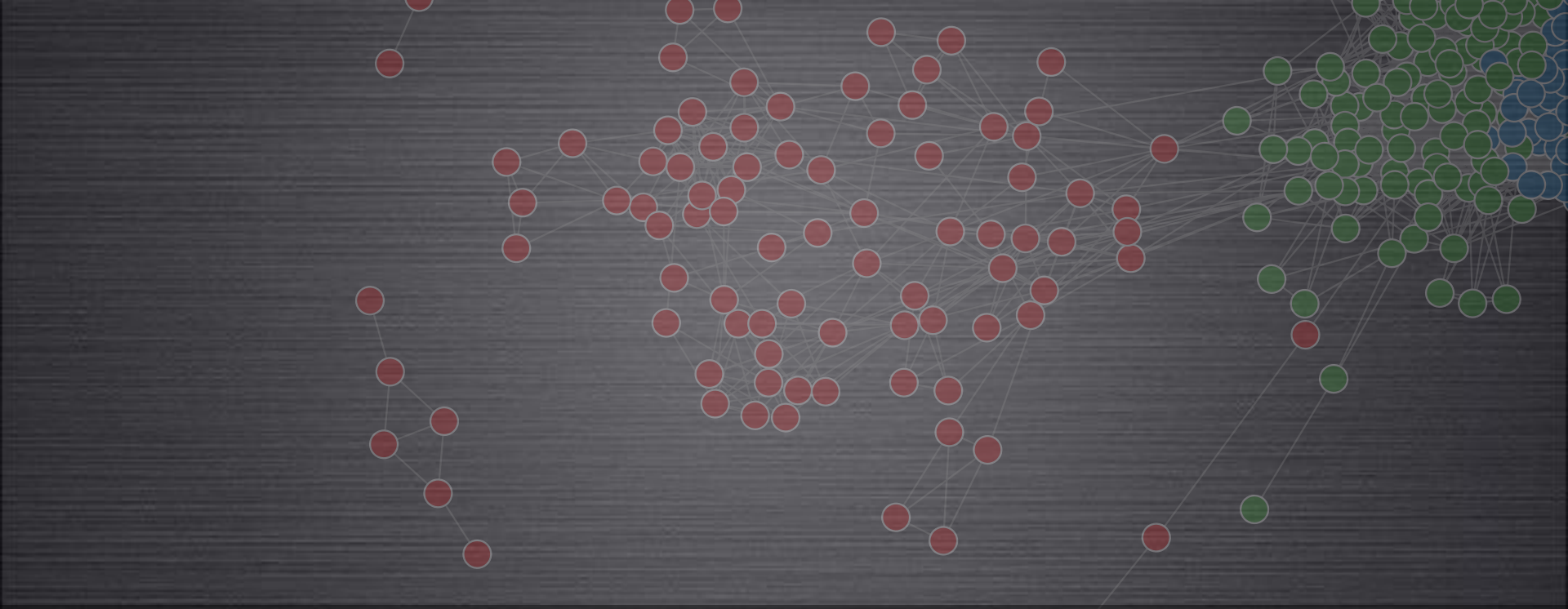


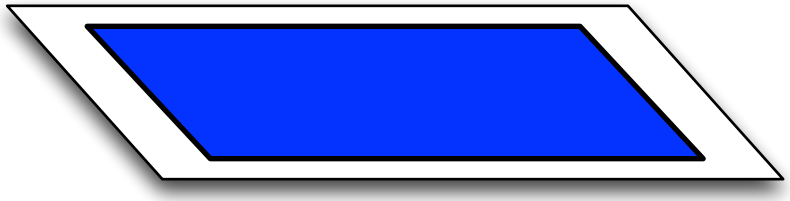
Biological Networks

Aaron Clauset
@aaronclauset
Professor, Computer Science
University of Colorado Boulder
External Faculty, Santa Fe Institute

What are networks?

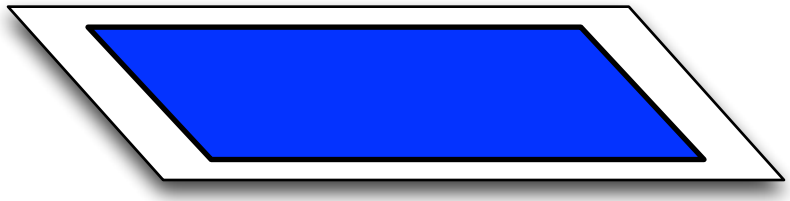
What are networks?

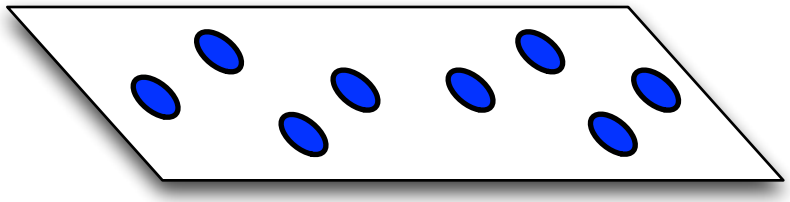
system or population



What are networks?

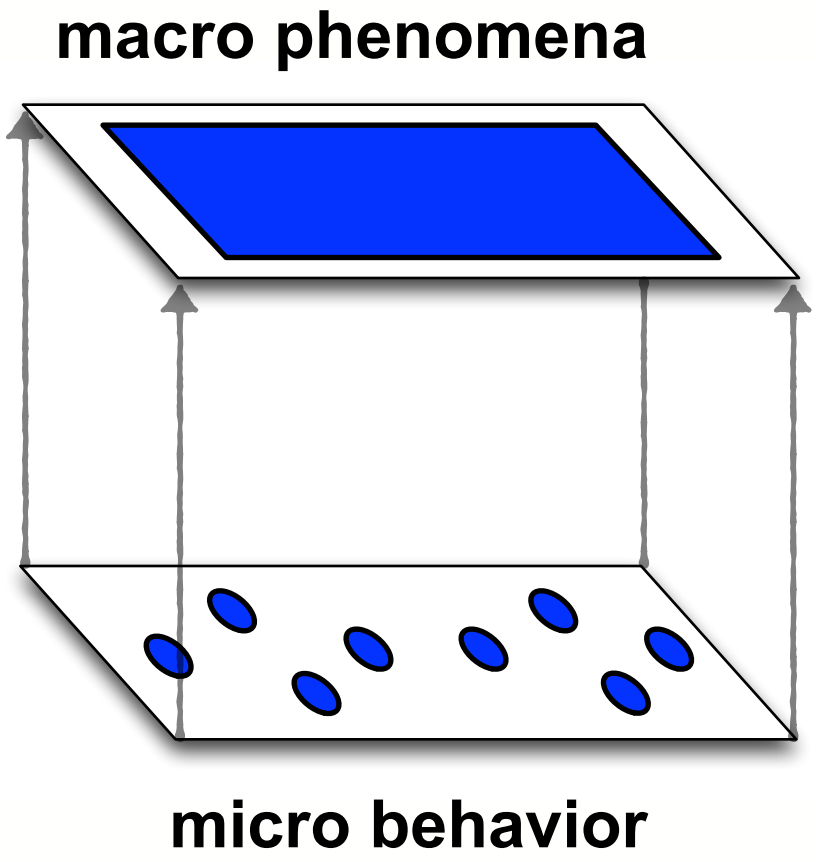
system or population



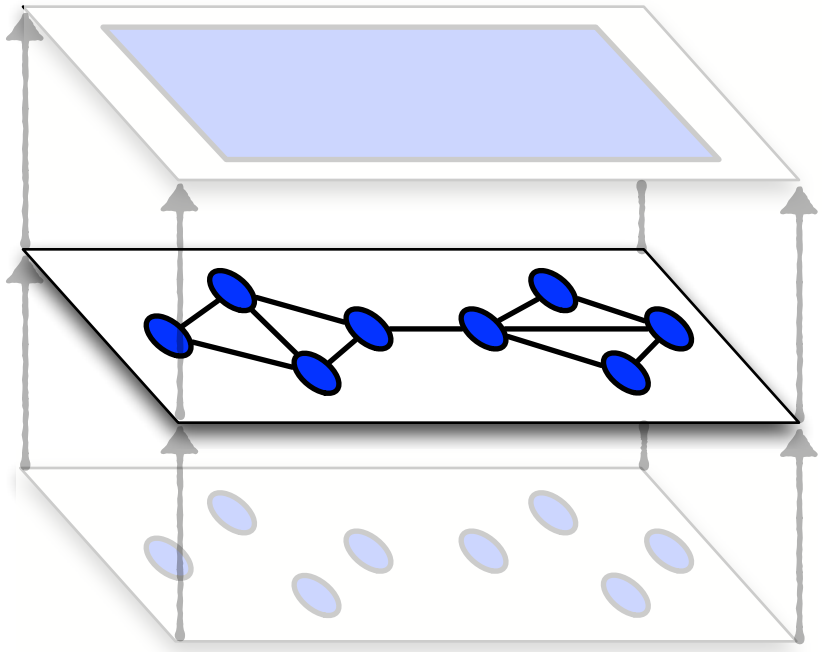


individuals or parts

What are networks?

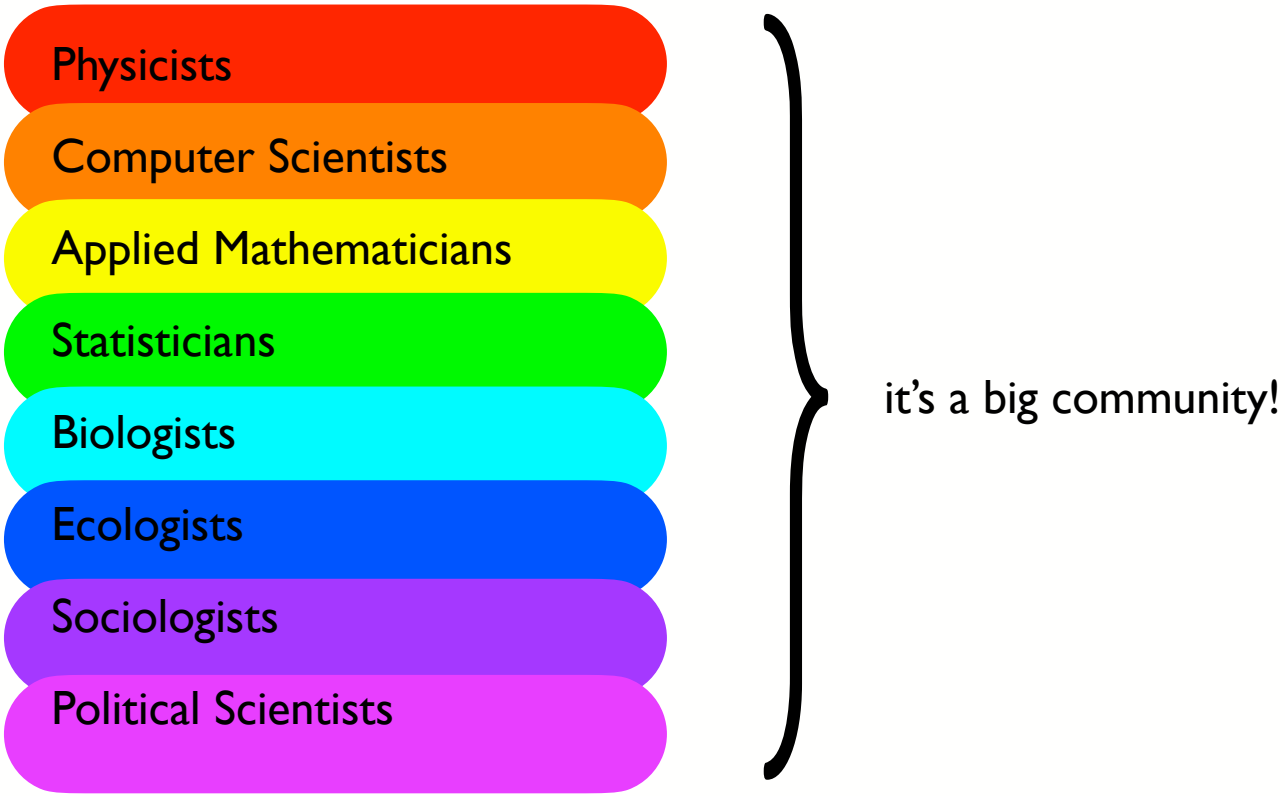


What are networks?

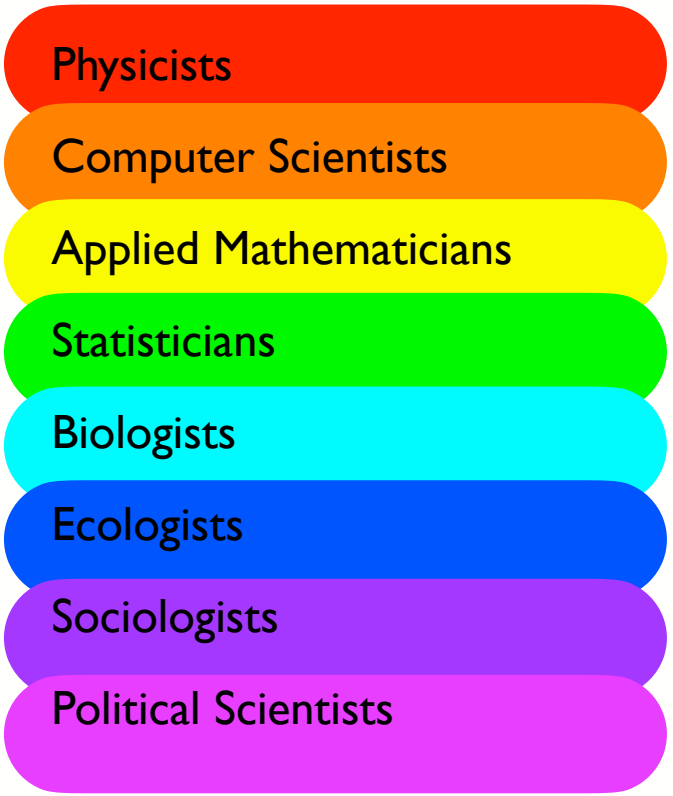


- an approach
- a representation of complexity
- connect "micro" to "macro"
- interactions within a system

Who studies networks?



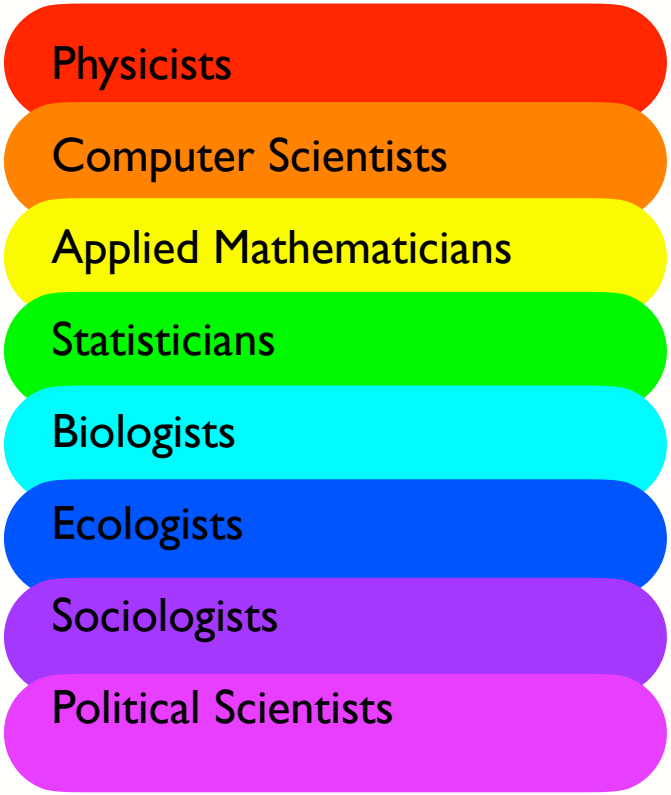
Who studies networks?



it's a big community!

- different traditions
- different tools
- different questions

Who studies networks?

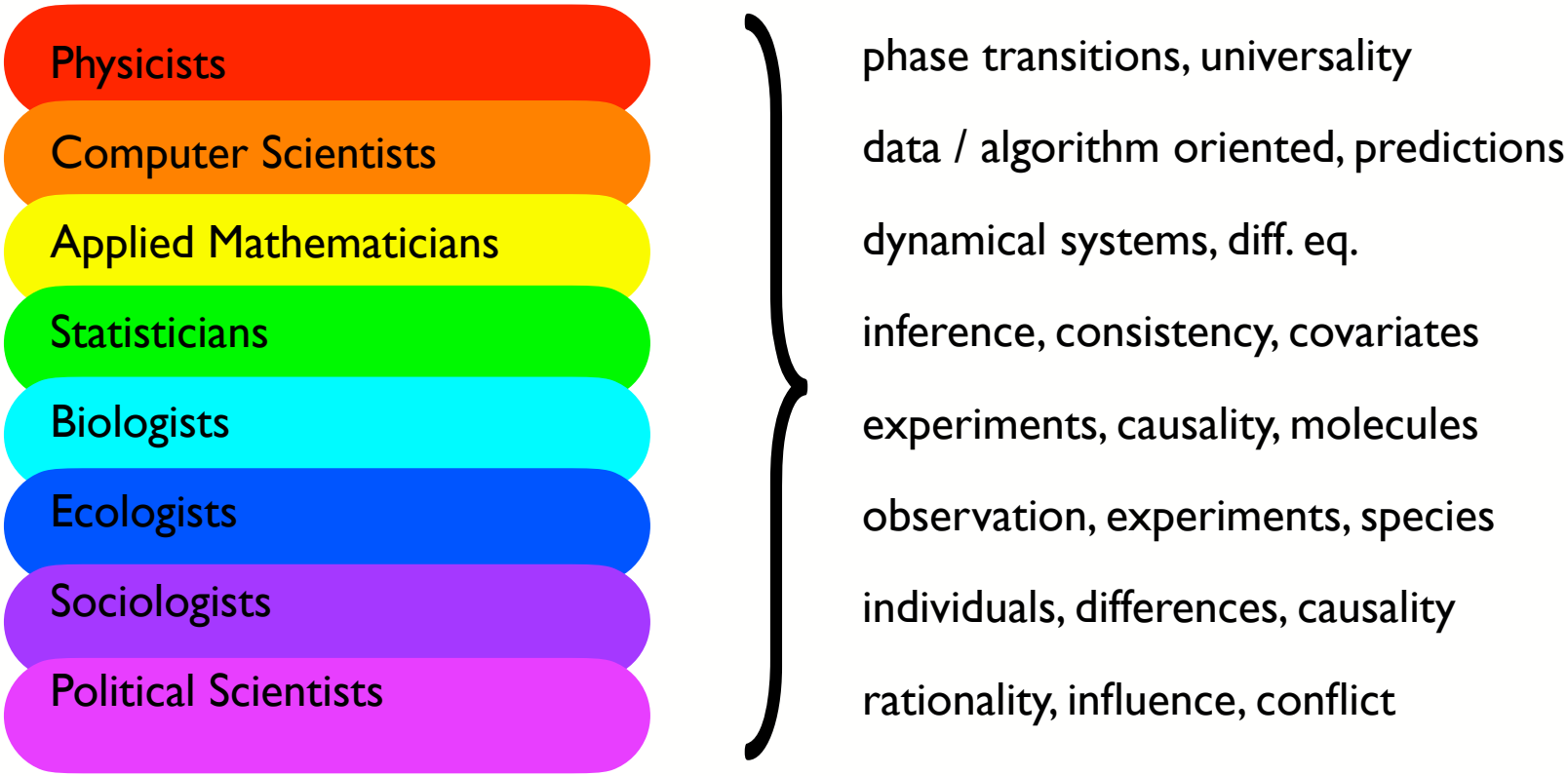


it's a big community!

- different traditions
- different tools
- different questions

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

Who studies networks?

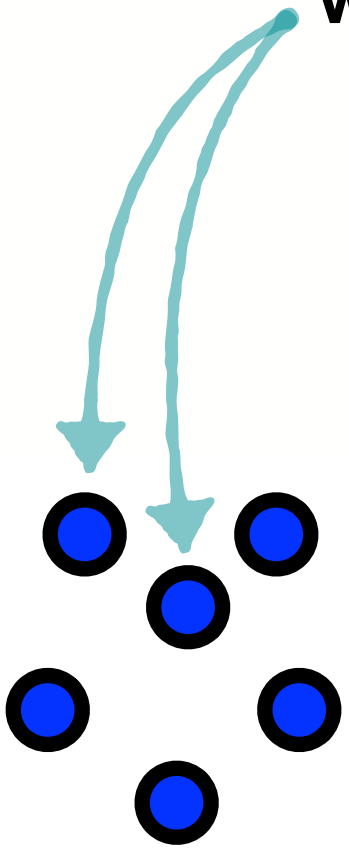


Two fundamental questions for using networks

Two fundamental questions for using networks

what is a vertex?

V distinct objects (vertices / nodes / actors)



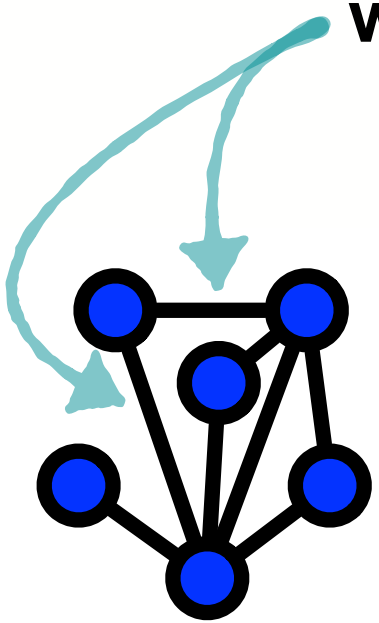
Two fundamental questions for using networks

what is a vertex?

V distinct objects (vertices / nodes / actors)

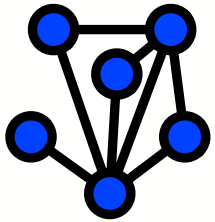
when are two vertices connected?

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

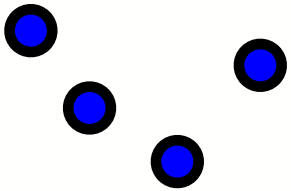


Major types of networks

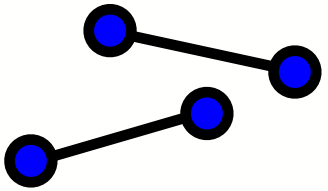
- social
- biological
- information
- economic
- transportation
- technological



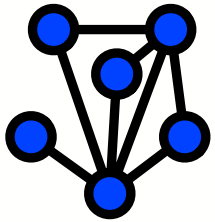
network

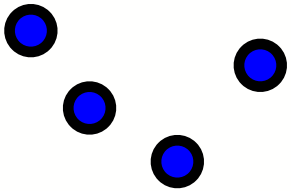


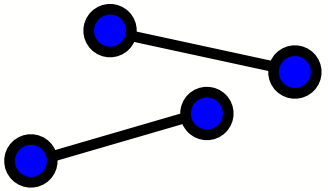
vertex



edge







technological

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

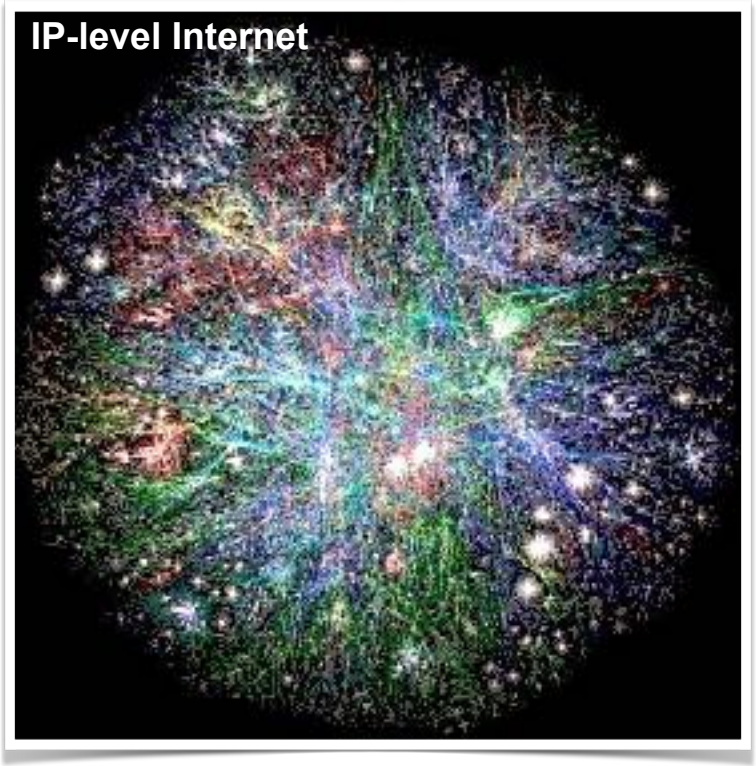
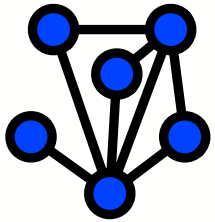
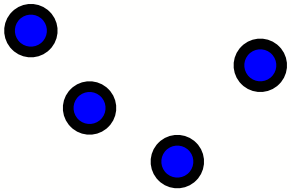
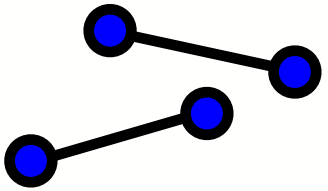


image source: CAIDA/UCSD

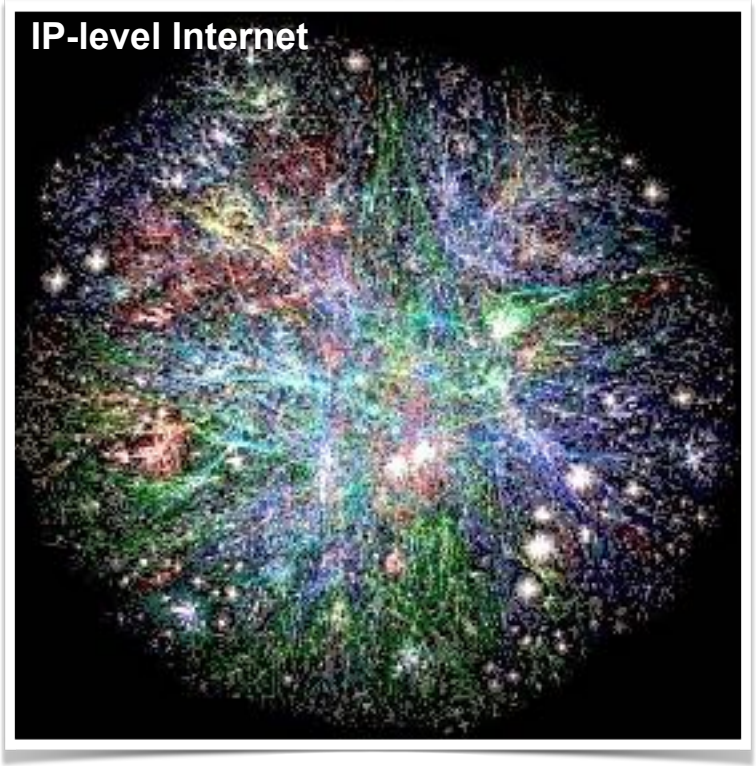






technological

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



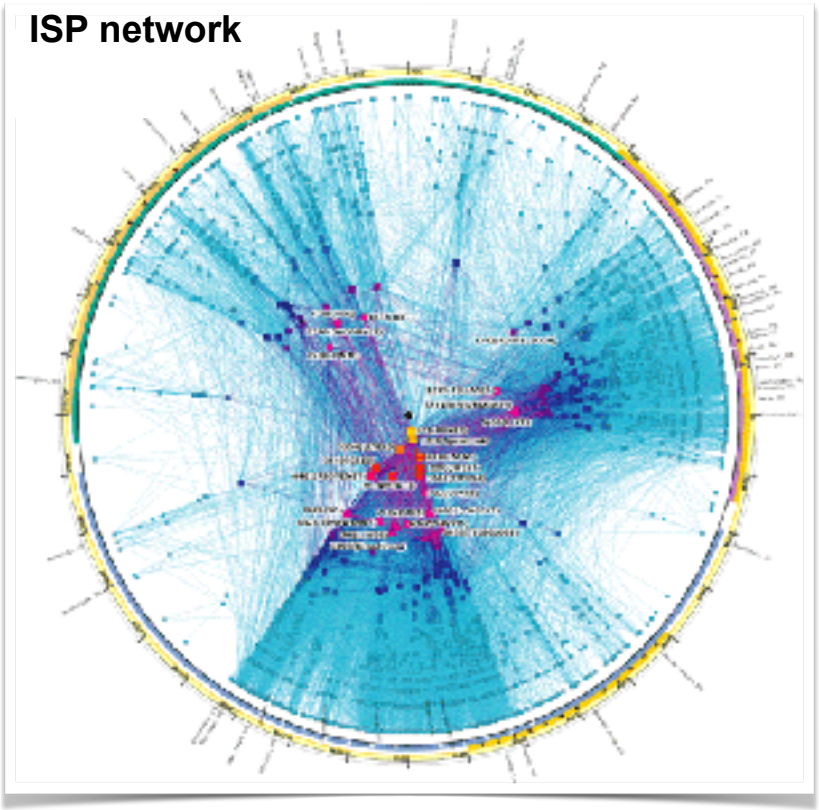
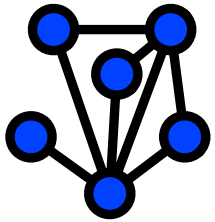
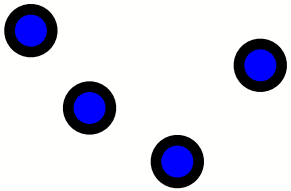
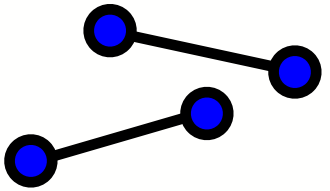


image source: CAIDA/UCSD







	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
	documents	article, patent, or legal case	citation

political blogs

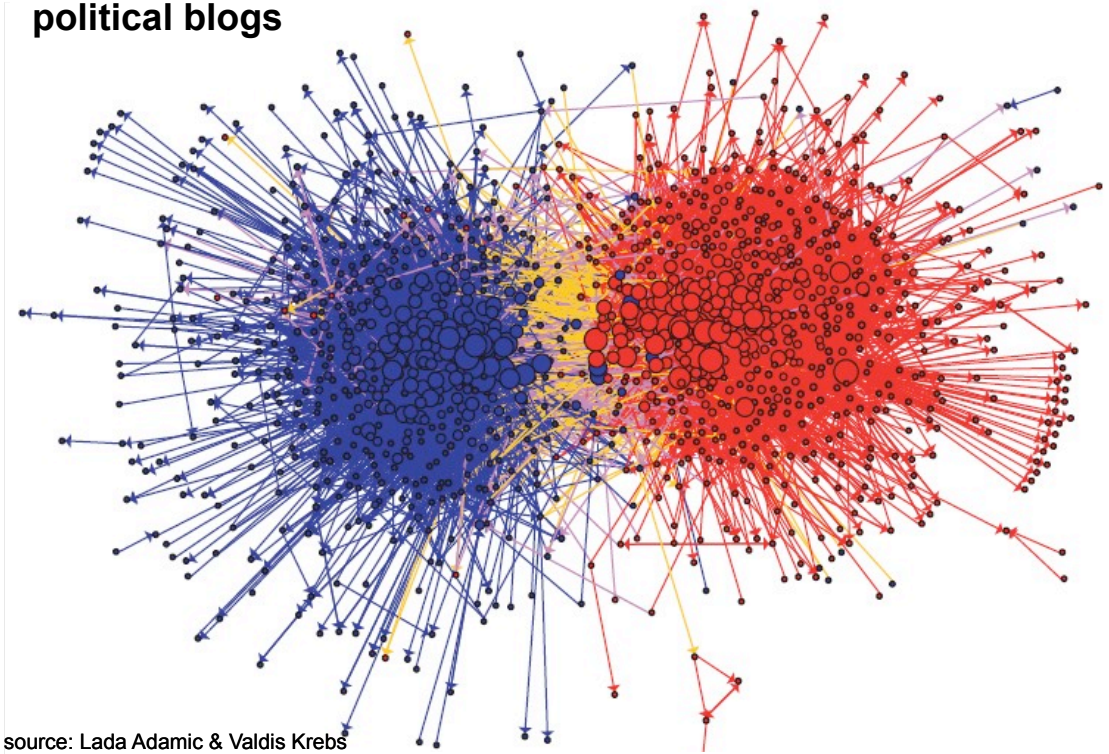
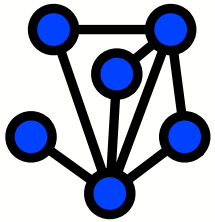
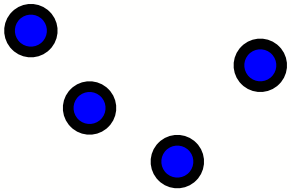
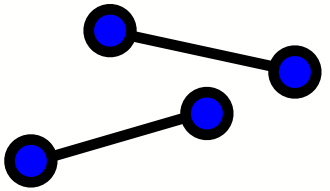


image source: Lada Adamic & Valdis Krebs

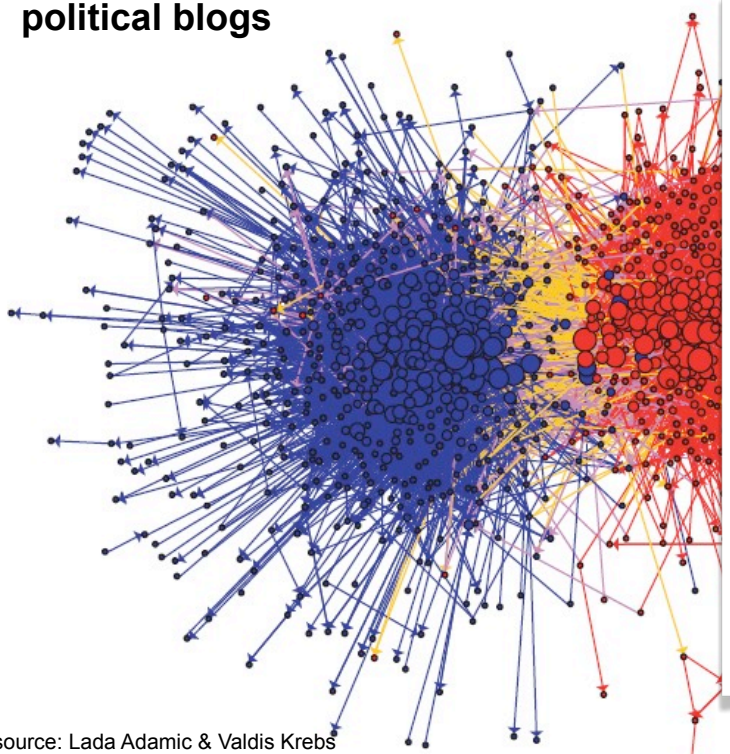






	network	vertex	edge
technological	Internet(1)	computer	IP network adjacency
technological	Internet(2)	autonomous system (ISP)	BGP connection
information	software	function	function call
information	World Wide Web	web page	hyperlink
information	documents	article, patent, or legal case	citation

political blogs



political books

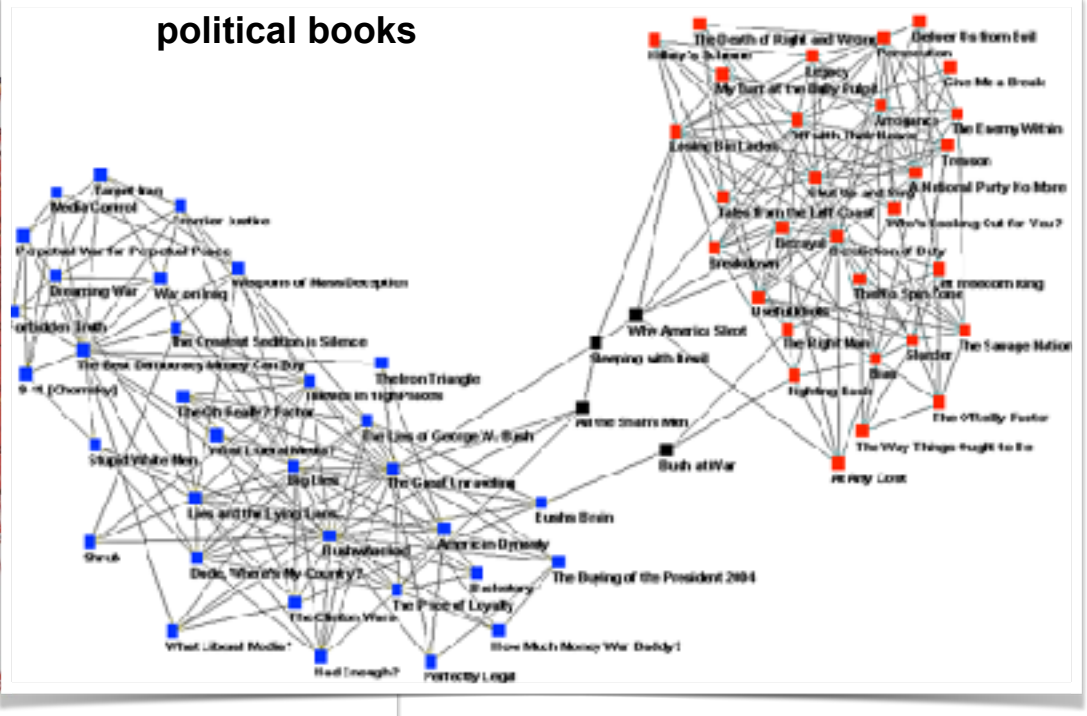
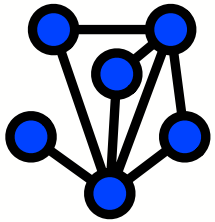
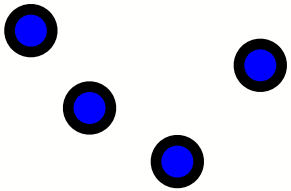
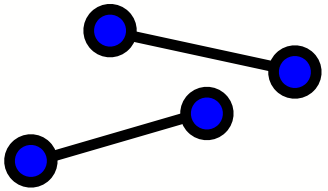


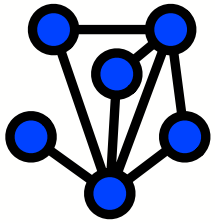
image source: Lada Adamic & Valdis Krebs

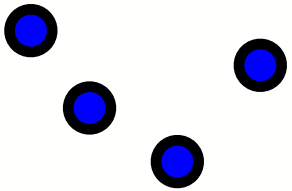


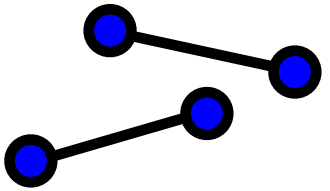




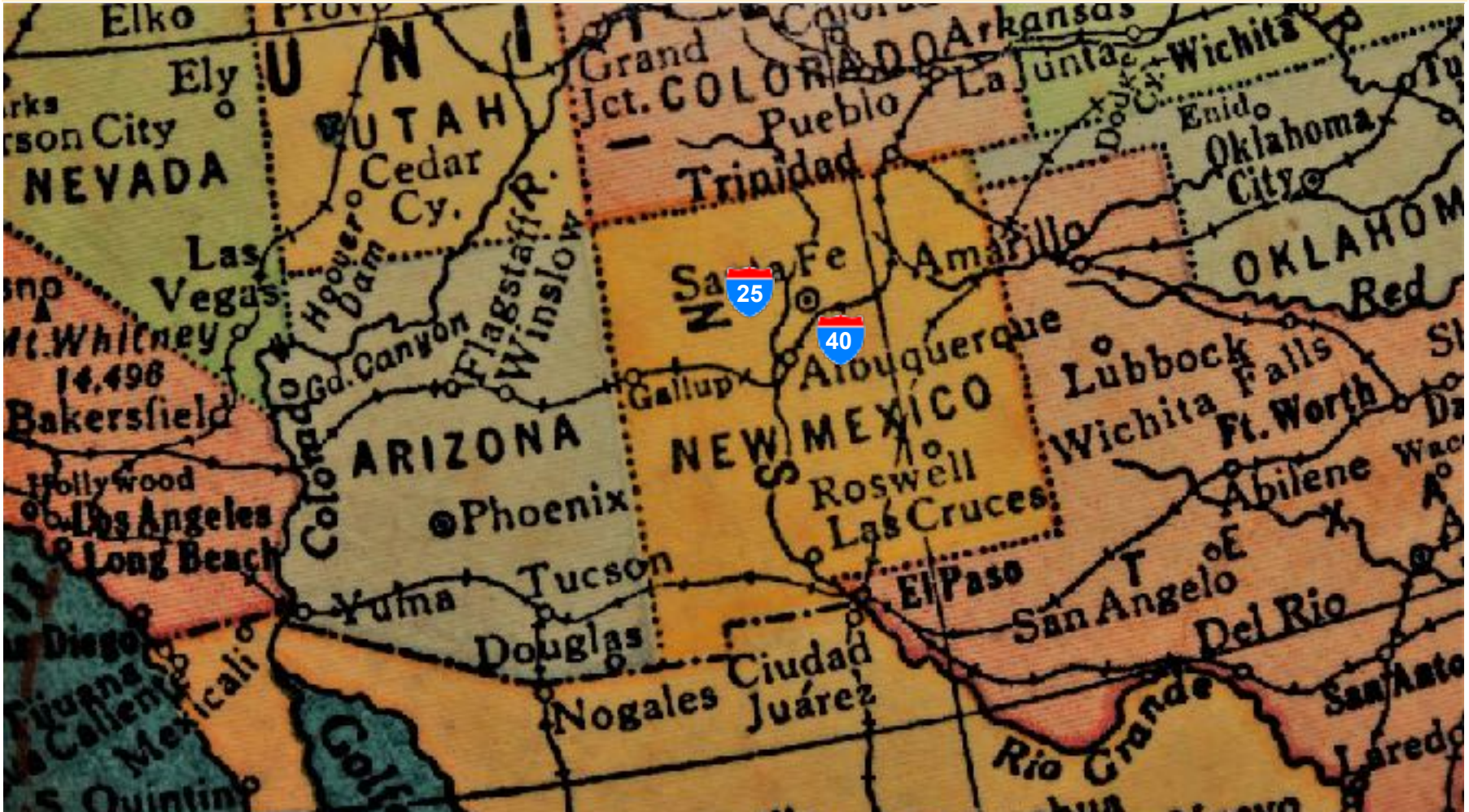
	network	vertex	edge
technological	Internet(1)	computer	IP network adjacency
	Internet(2)	autonomous system (ISP)	BGP connection
information	software	function	function call
	World Wide Web	web page	hyperlink
	documents	article, patent, or legal case	citation
transportation	power grid transmission	generating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

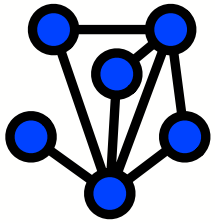


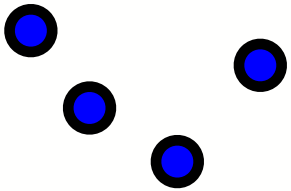


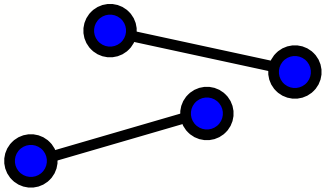


network	vertex	edge
road network(1)	intersection	pavement
road network(2)	named road	intersection

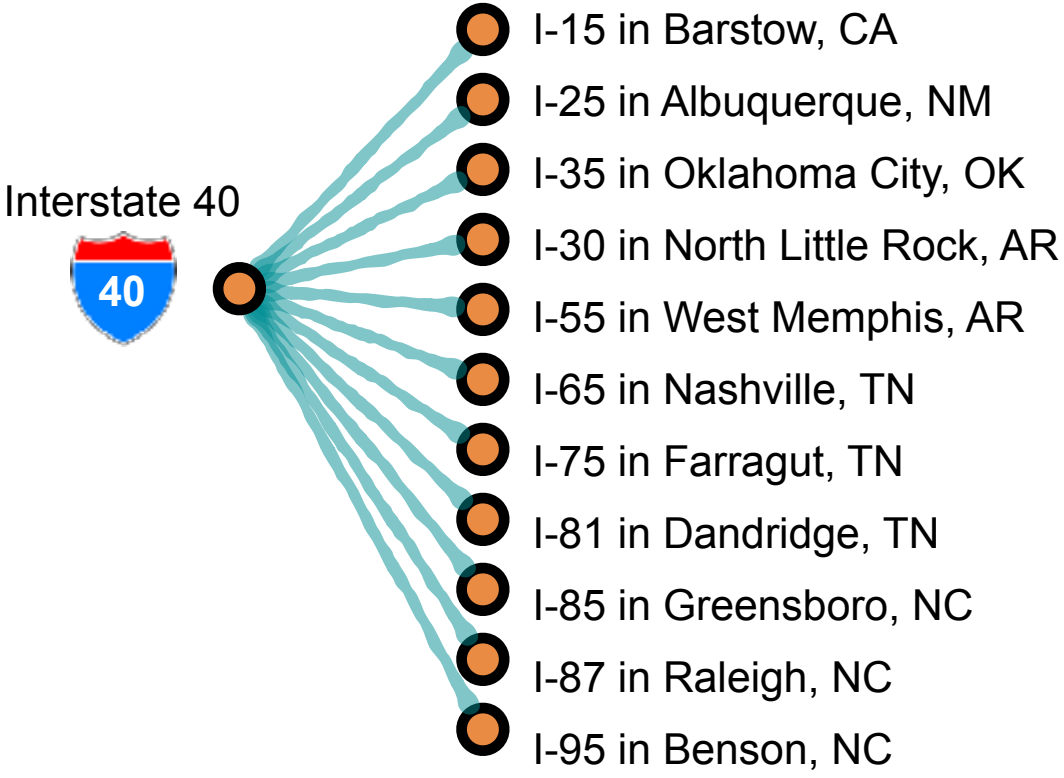


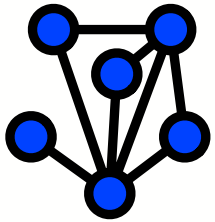


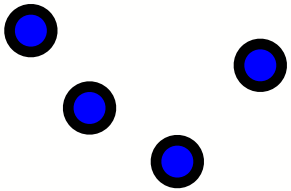


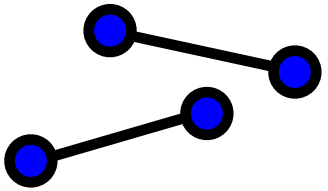


network	vertex	edge
road network(1)	intersection	pavement
road network(2)	named road	intersection

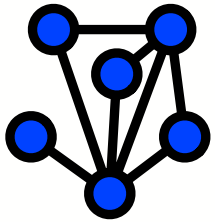


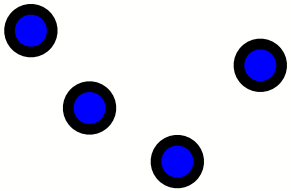


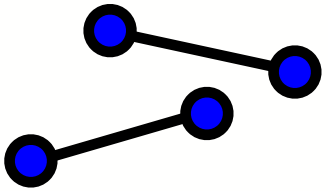




	network	vertex	edge
technological	Internet(1)	computer	IP network adjacency
	Internet(2)	autonomous system (ISP)	BGP connection
information	software	function	function call
	World Wide Web	web page	hyperlink
	documents	article, patent, or legal case	citation
transportation	power grid transmission	generating 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
social	friendship network	person	friendship
	sexual network	person	intercourse







network	vertex	edge
friendship network	person	friendship
sexual network	person	intercourse

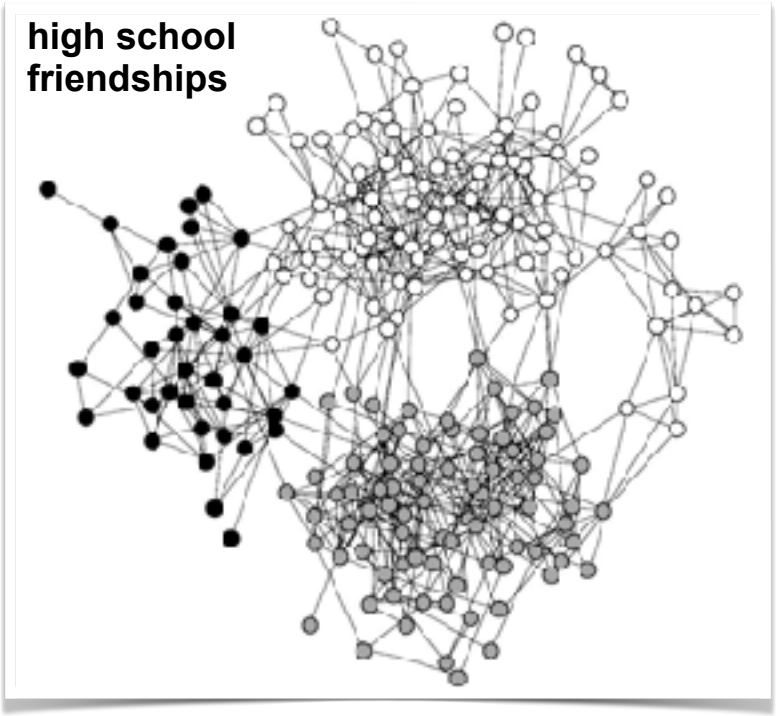
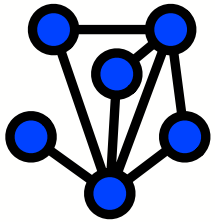
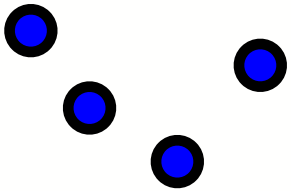
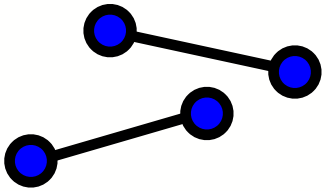


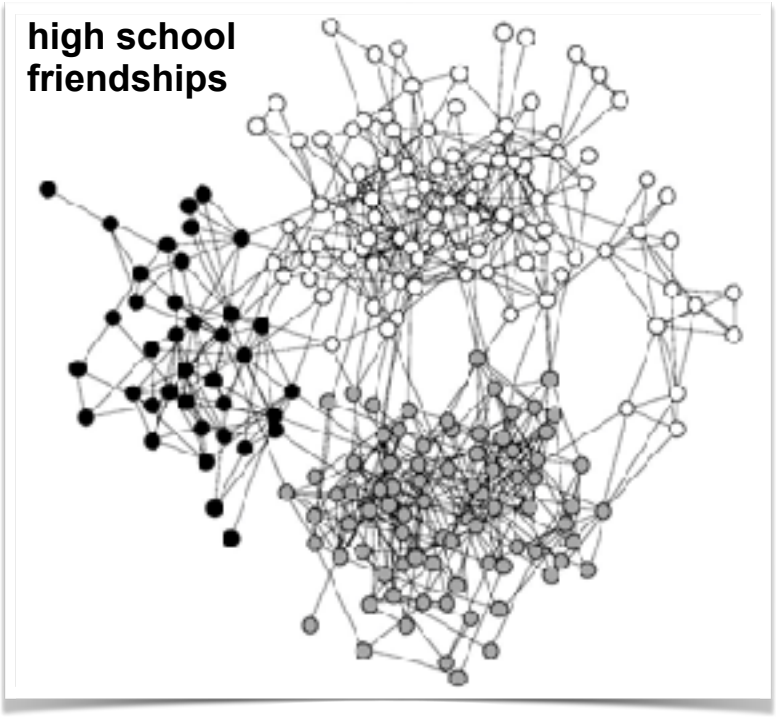
image source: Jim Moody & Mark Newman







network	vertex	edge
friendship network	person	friendship
sexual network	person	intercourse



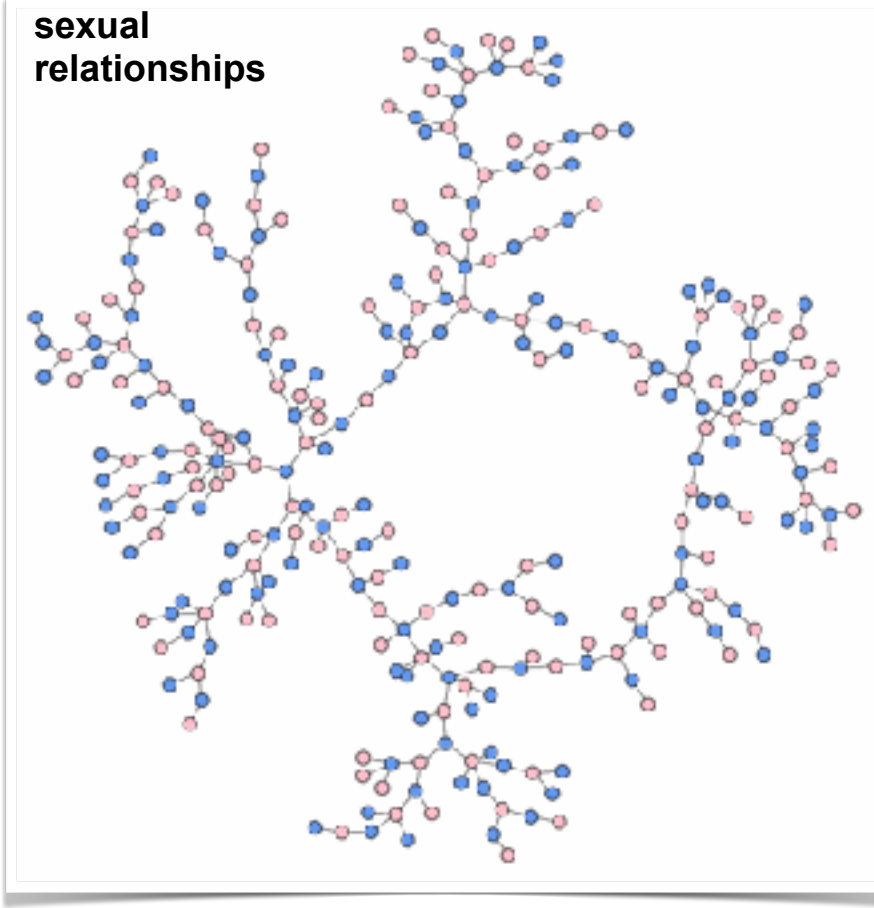
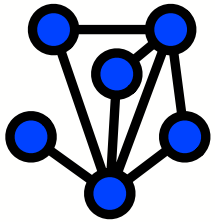
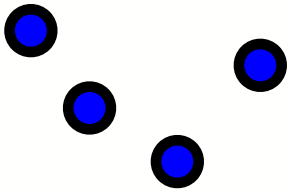
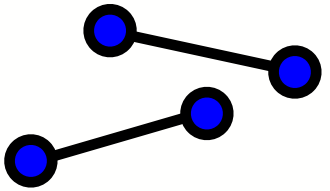
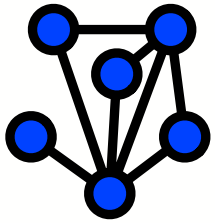
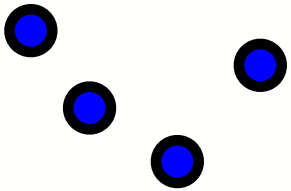


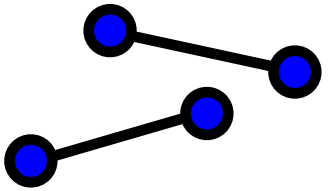
image source: Jim Moody & Mark Newman

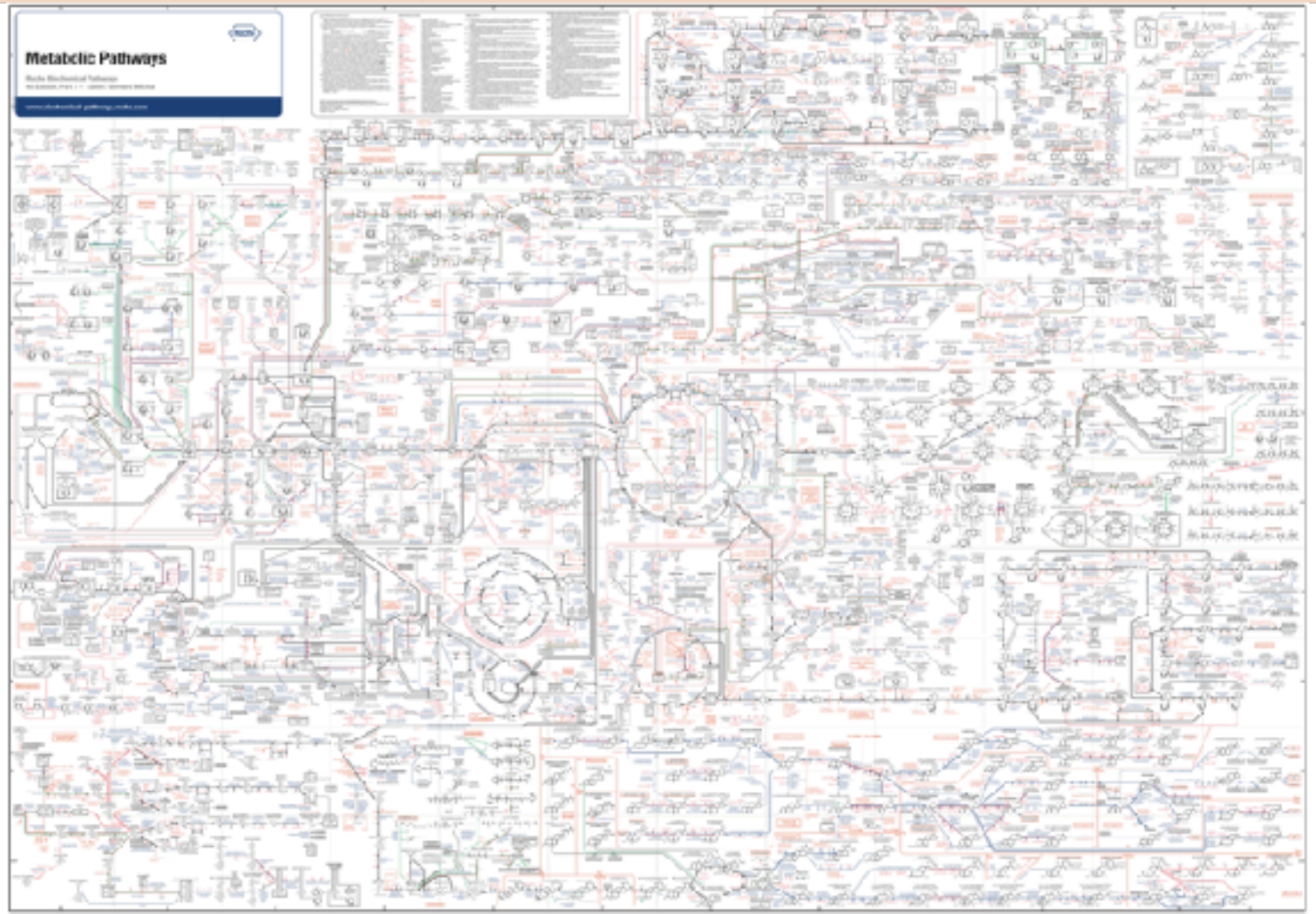
	network	vertex	edge
technological	Internet(1)	computer	IP network adjacency
	Internet(2)	autonomous system (ISP)	BGP connection
information	software	function	function call
	World Wide Web	web page	hyperlink
	documents	article, patent, or legal case	citation
transportation	power grid transmission	generating 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
social	friendship network	person	friendship
	sexual network	person	intercourse
biological	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

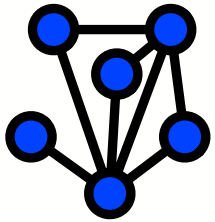


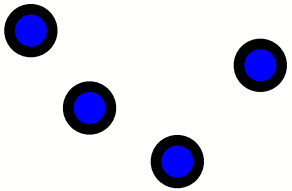


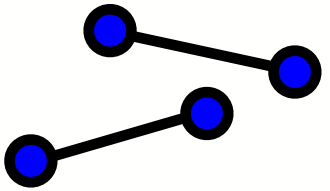


network	vertex	edge
metabolic network	metabolite	metabolic reaction





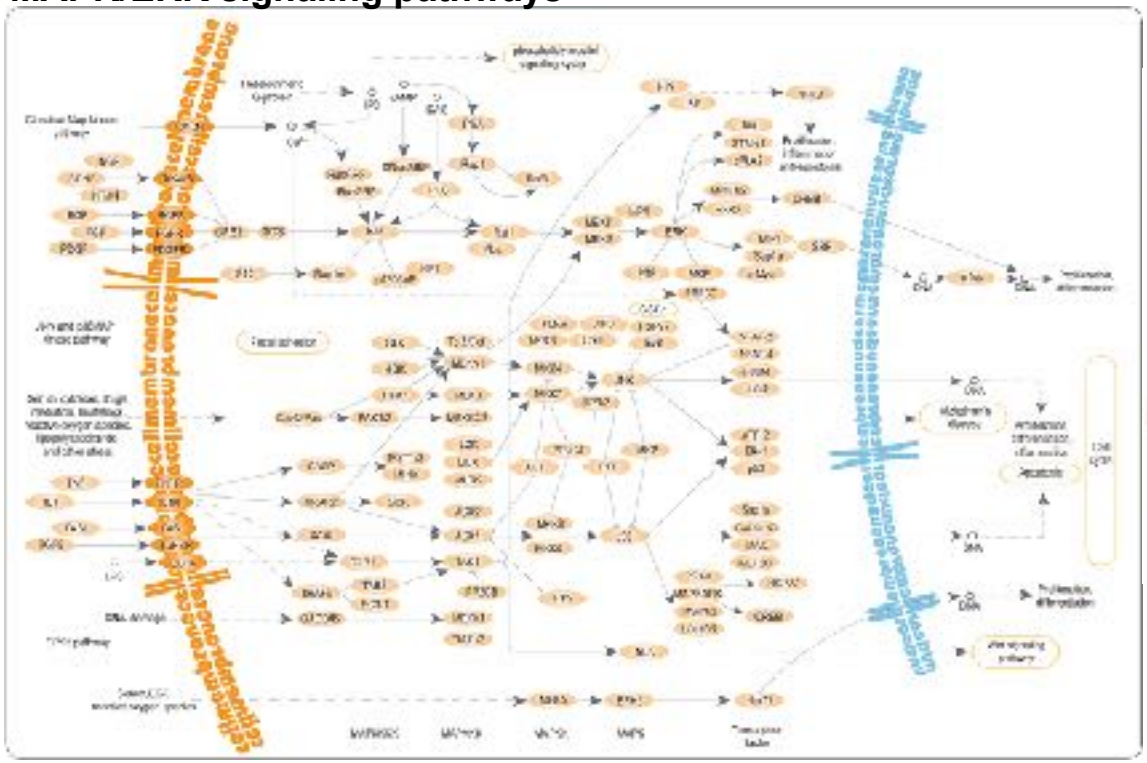




network	vertex	edge
metabolic network	metabolite	metabolic reaction
protein interaction network	proteins	binding (activation, inhibition)

Signaling network (neurons)

MAPK/ERK signaling pathways



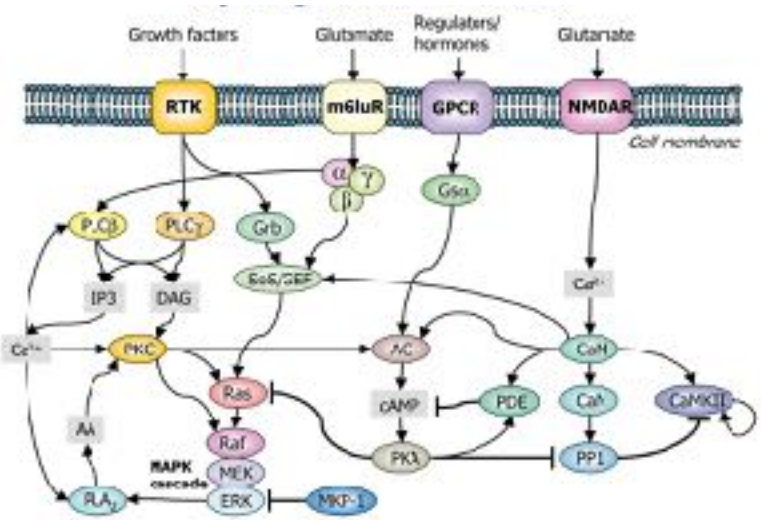
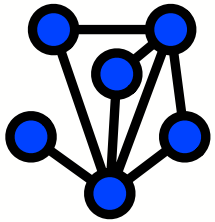
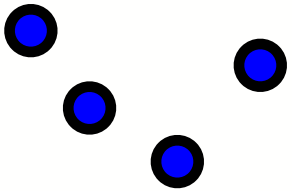
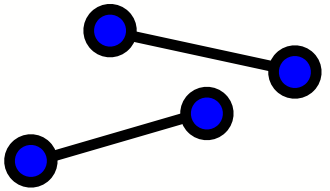


image source: wikimedia & Klipp and Liebermeister (2006)







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

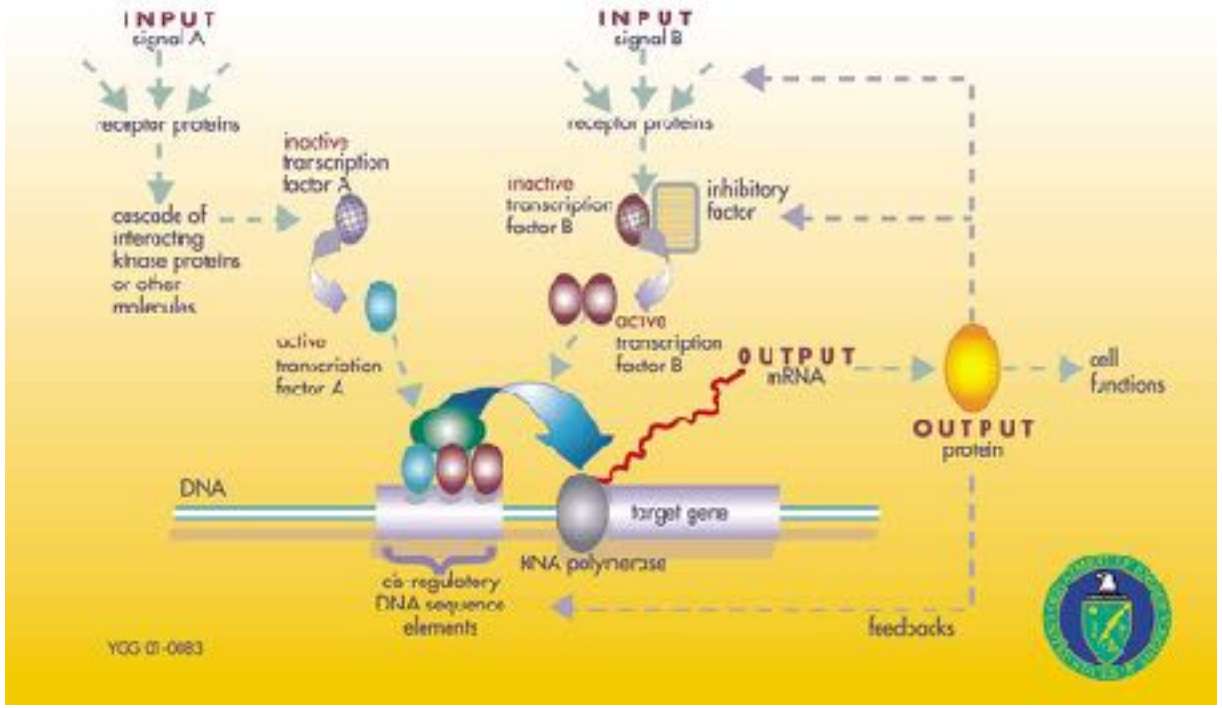
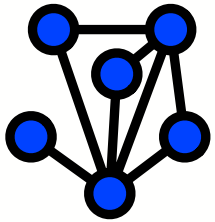
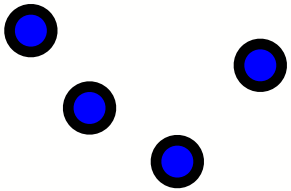
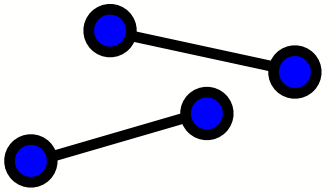


image source: US Dept. of Energy

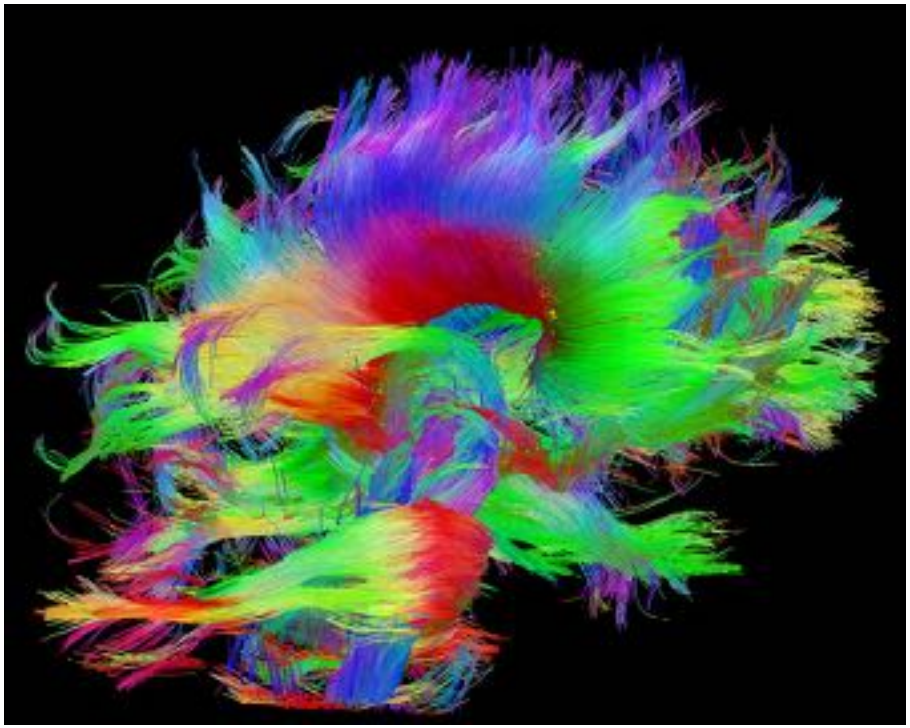




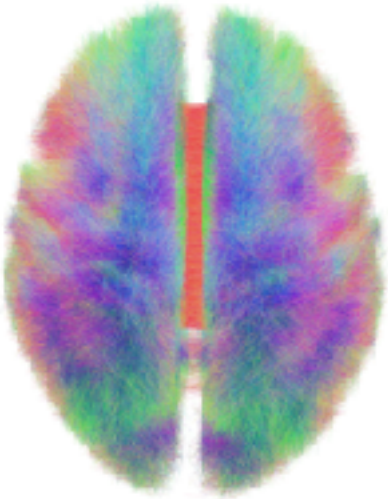


network	vertex	edge
metabolic network	metabolite	metabolic reaction
protein interaction network	proteins	binding (activation, inhibition)
gene regulation	genes, transcription factors	regulatory effect
connectome	neurons	synapse

white matter fiber architecture



white matter fibers



cortical neurons

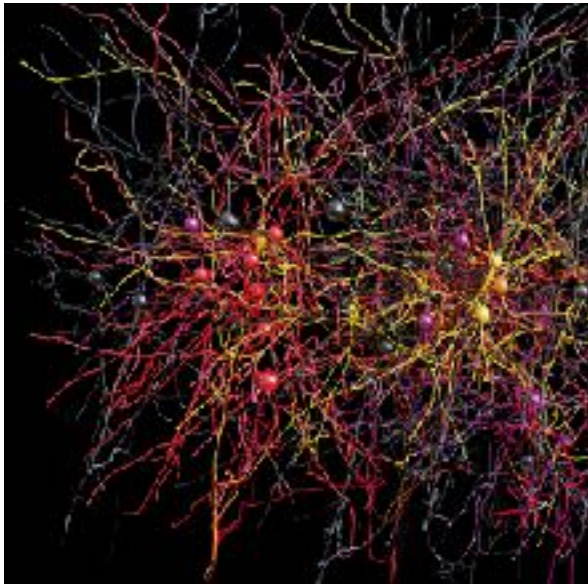
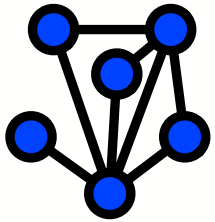
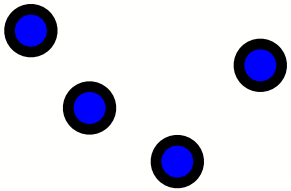
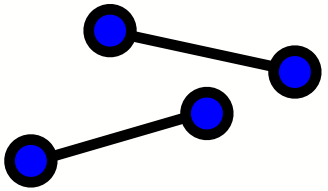


image source: Allen Institute

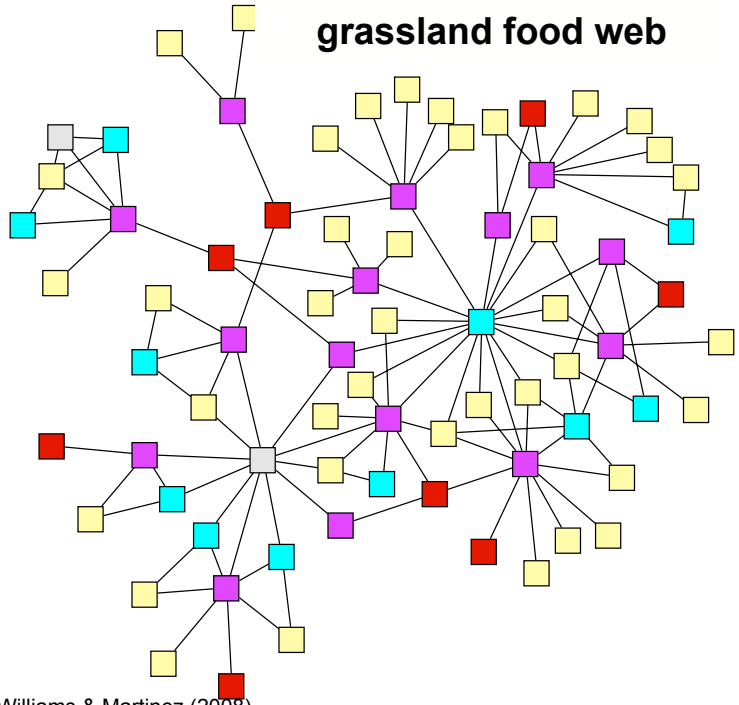






network	vertex	edge
metabolic network	metabolite	metabolic reaction
protein interaction network	proteins	binding (activation, inhibition)
gene regulation	genes, transcription factors	regulatory effect
connectome	neurons	synapse
food web	species	predation or resource transfer

grassland food web



Weddell sea (Antarctica) food web

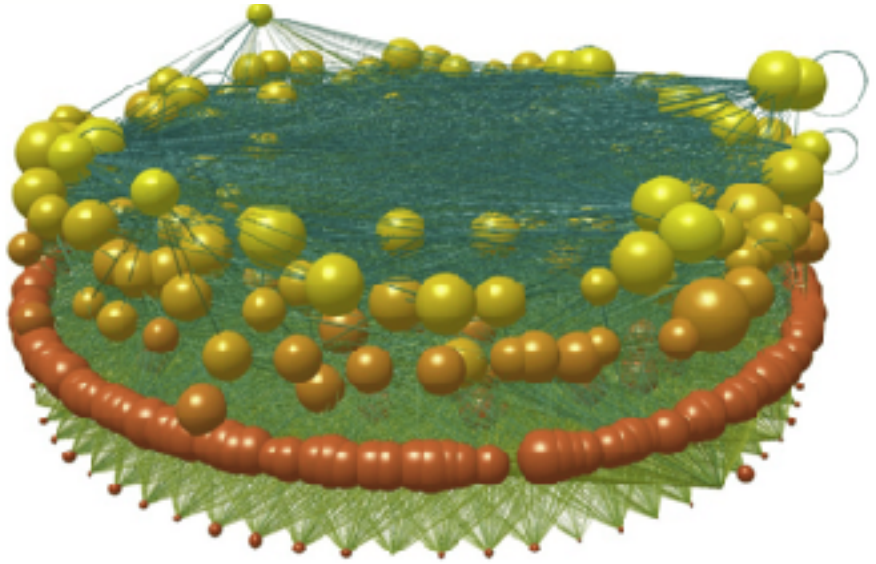


image source: Williams & Martinez (2008)

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