Cx-Nets

Statistical physics of complex networks

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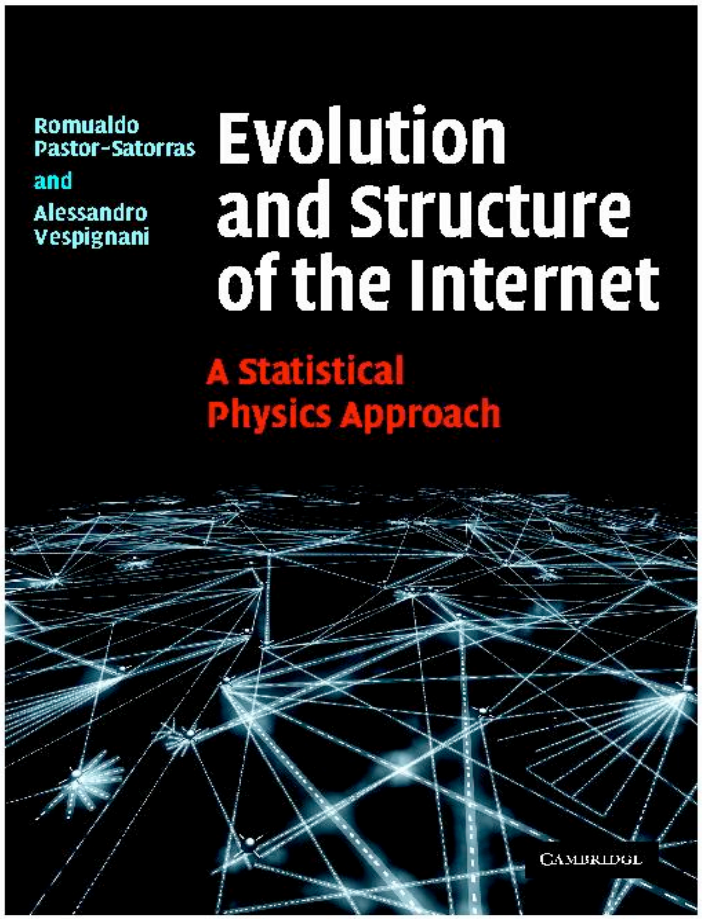
References: reviews

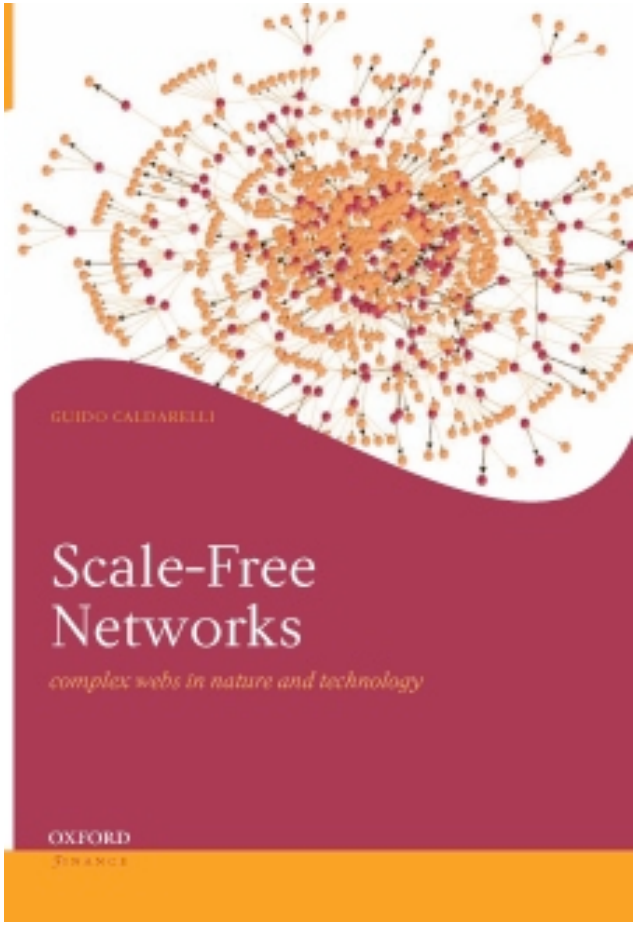
• **Statistical mechanics of complex networks**
Reka Albert, Albert-Laszlo Barabasi
Reviews of Modern Physics 74, 47 (2002)
cond-mat/0106096

• **The structure and function of complex networks**
M. E. J. Newman, SIAM Review 45, 167-256 (2003)
cond-mat/0303516

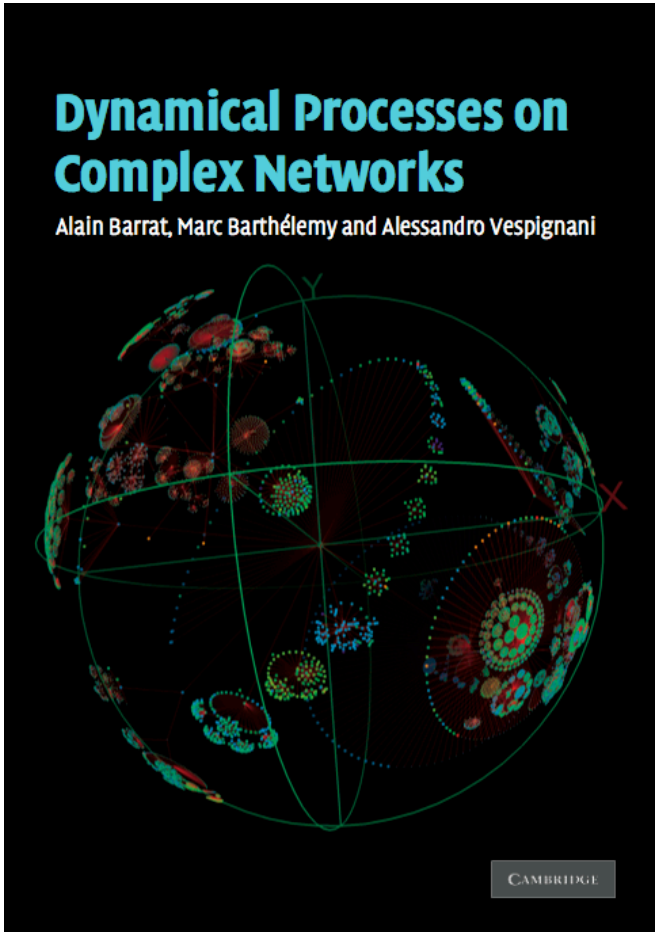
• **Evolution of networks**
S.N. Dorogovtsev, J.F.F. Mendes, Adv. Phys. 51, 1079 (2002)
cond-mat/0106144

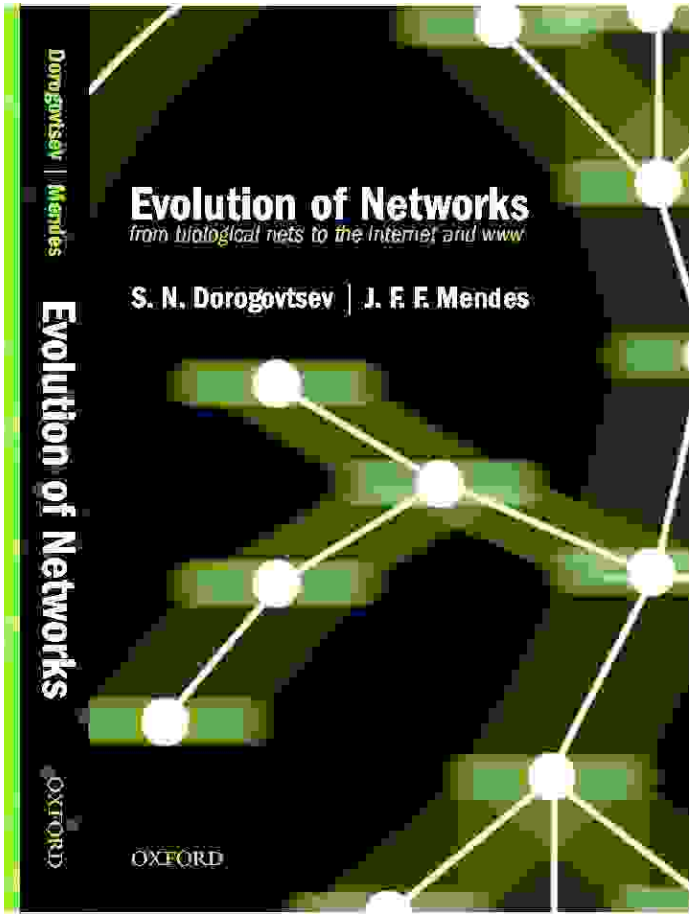
References: books





References: books



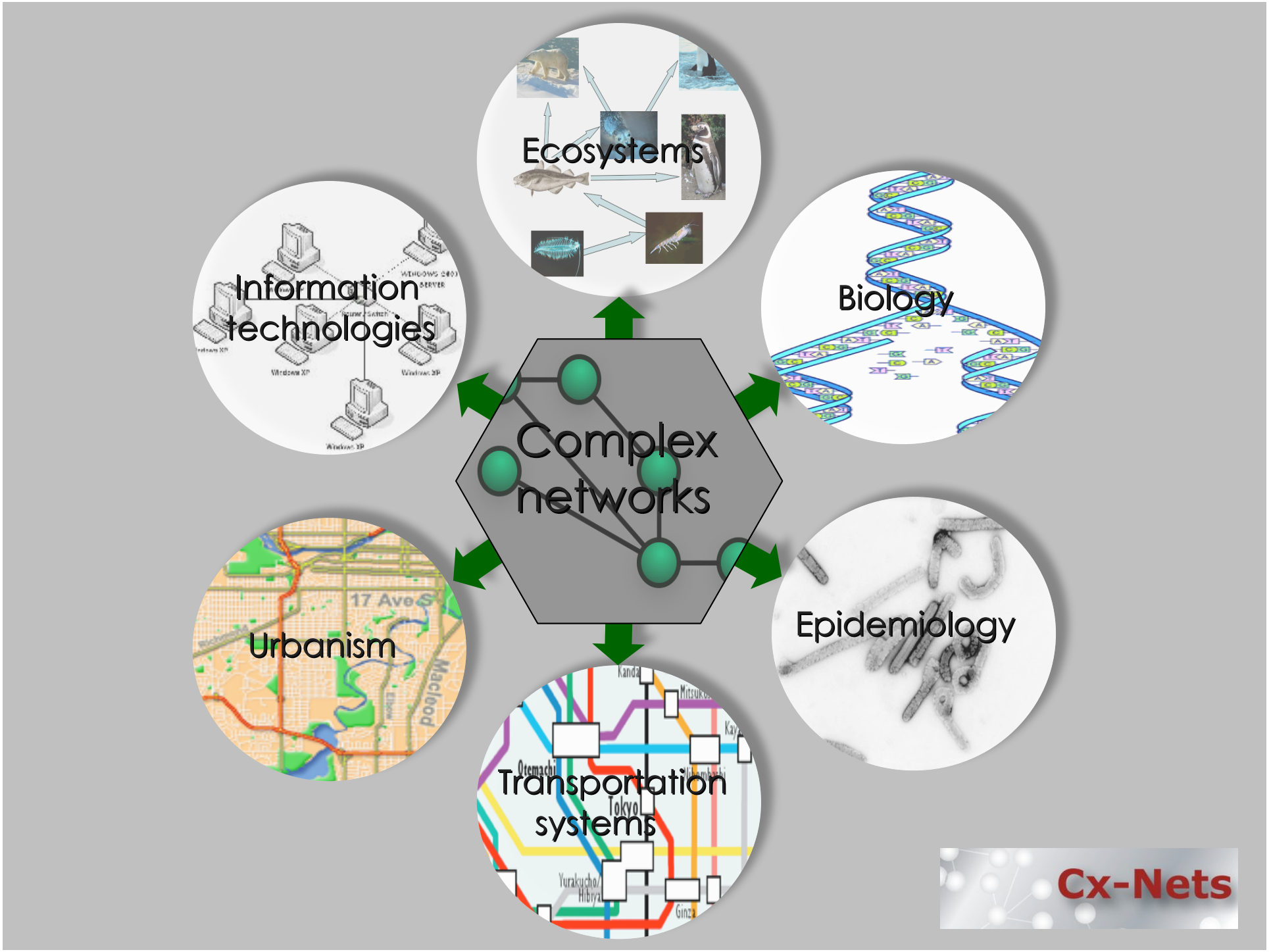


Outline

- I. Introduction: Complex networks
  - 1. Complex systems and networks
  - 2. Graph theory and characterization of large networks: tools
  - 3. Characterization of large networks: results
  - 4. Models
- II. Dynamical processes
  - 1. Resilience and vulnerability
  - 2. Epidemiology
- III. Advanced topics
  - 1. Global disease spread
  - 2. Community detection
  - 3. Evolution and formation of the urban street network in cities

Complex Systems

- No commonly accepted definition
- Properties
  - Large number of (possibly non-identical) interacting constituents
  - Emergent behavior
  - Adapt and evolve (resilient to failure)-different from complicated!
- Network structure (nodes+links)
  - Present everywhere-data recently available

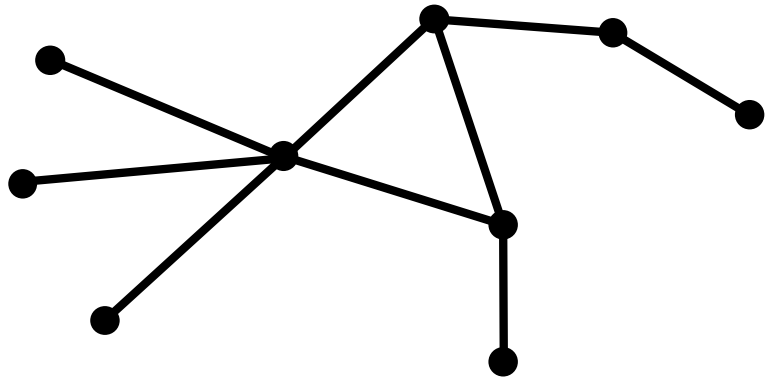

Ecosystems
Information technologies
Biology
Complex networks
Urbanism
Epidemiology
Transportation systems
Cx-Nets

Complex Systems - Methodology

- Theoretical & Empirical analysis
  - Data-driven research
  - Characterization and modeling
  - Dynamical processes (eg. Epidemics)
- Interdisciplinarity
  - Collaboration with scientists from other fields
  - Confront with the communities

What is a network ?

Network=set of nodes joined by links



Individuals
Computers
Web pages
Airports
Molecules
....

- very abstract representation

- very general

- convenient to describe many different systems

Networks and Physics

Most networks of interest are:

- Complex
- Very large

Statistical tools needed !

‘Statistical mechanics’ of large networks

Ubiquity of networks

	Nodes	Links
Social networks	Individuals	Social relations
IT: Internet WWW	Routers/AS Webpages	Cables Hyperlinks
Biology: PIN Ecosystems	Proteins Species	Hyperlinks Trophic relation
Infrastructures	Hubs	Airlines, roads, …

Example: social networks

Many social networks are the support of some dynamical processes

- (Epidemics)
- Rumor propagation
- Opinion/consensus formation
- Cooperative phenomena
- …

Scientific collaboration network

Nodes: scientists

Links: co-authored papers

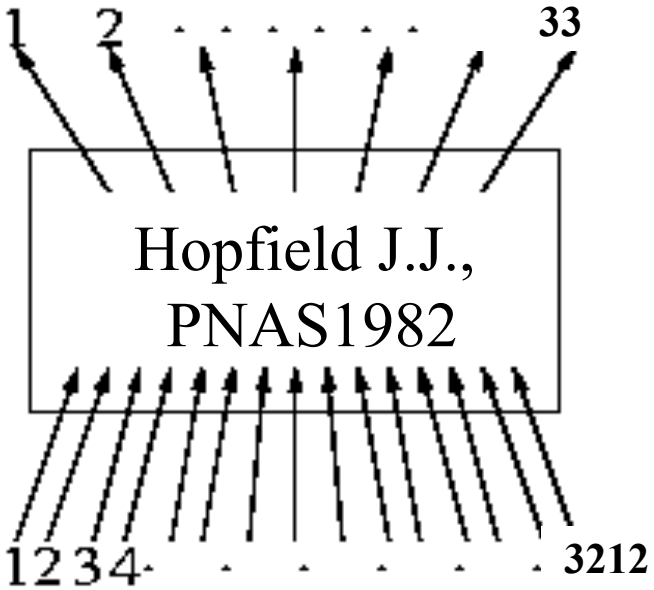
Weights: depending on

- number of co-authored papers
- number of authors of each paper
- number of citations…

Citation network

Nodes: papers

Links: citations



Science citation index
S. Redner

Actor's network

Nodes: actors
Links: cast jointly

John Carradine

Distance ?

The Sentinel (1977)

The story of Mankind (1957)

Ava Gardner

Groucho Marx

distance(Ava, Groucho)=2

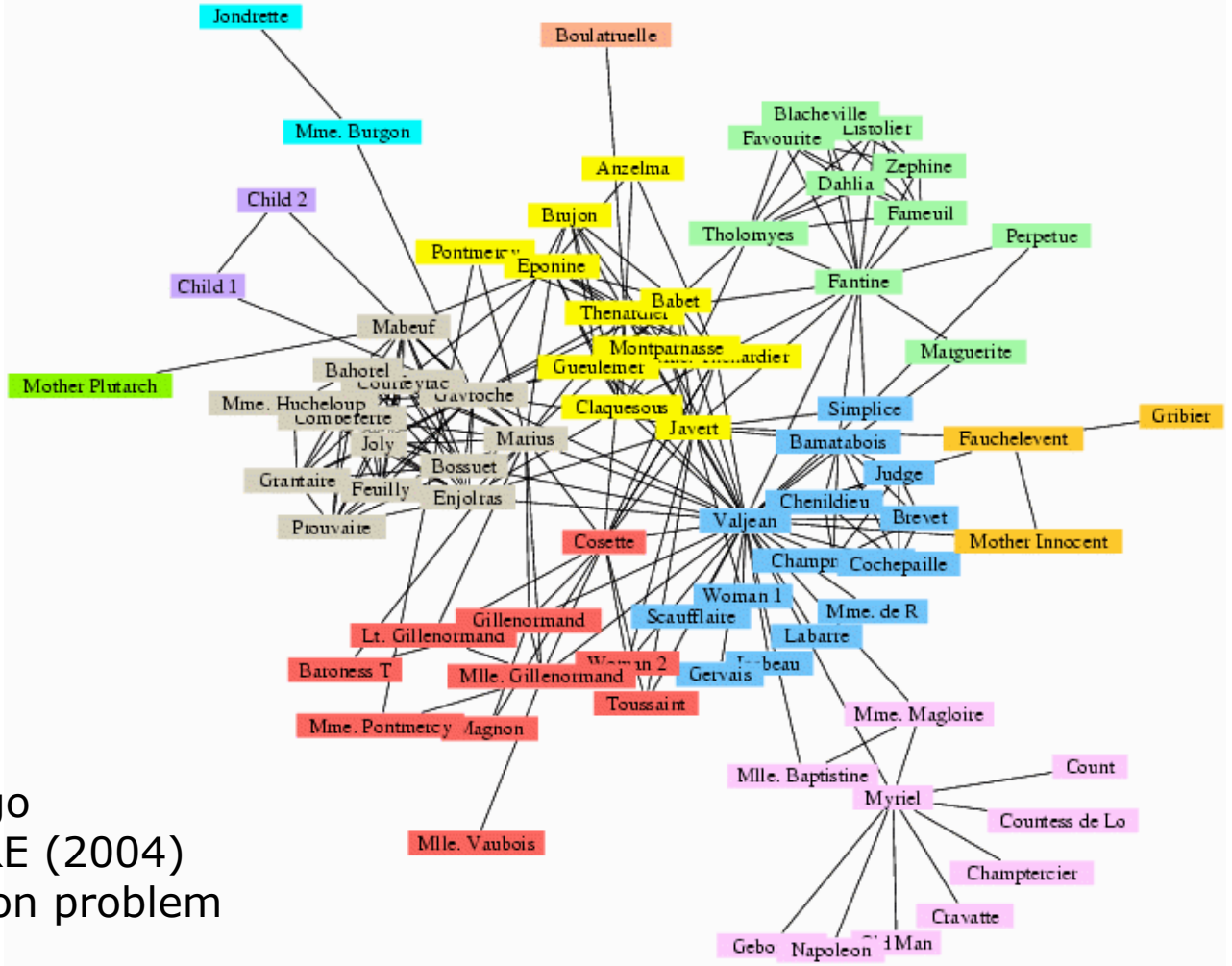
N = 212,250 actors
⟨k⟩ = 28.78

http://www.cs.virginia.edu/oracle/star_links.html

Character network

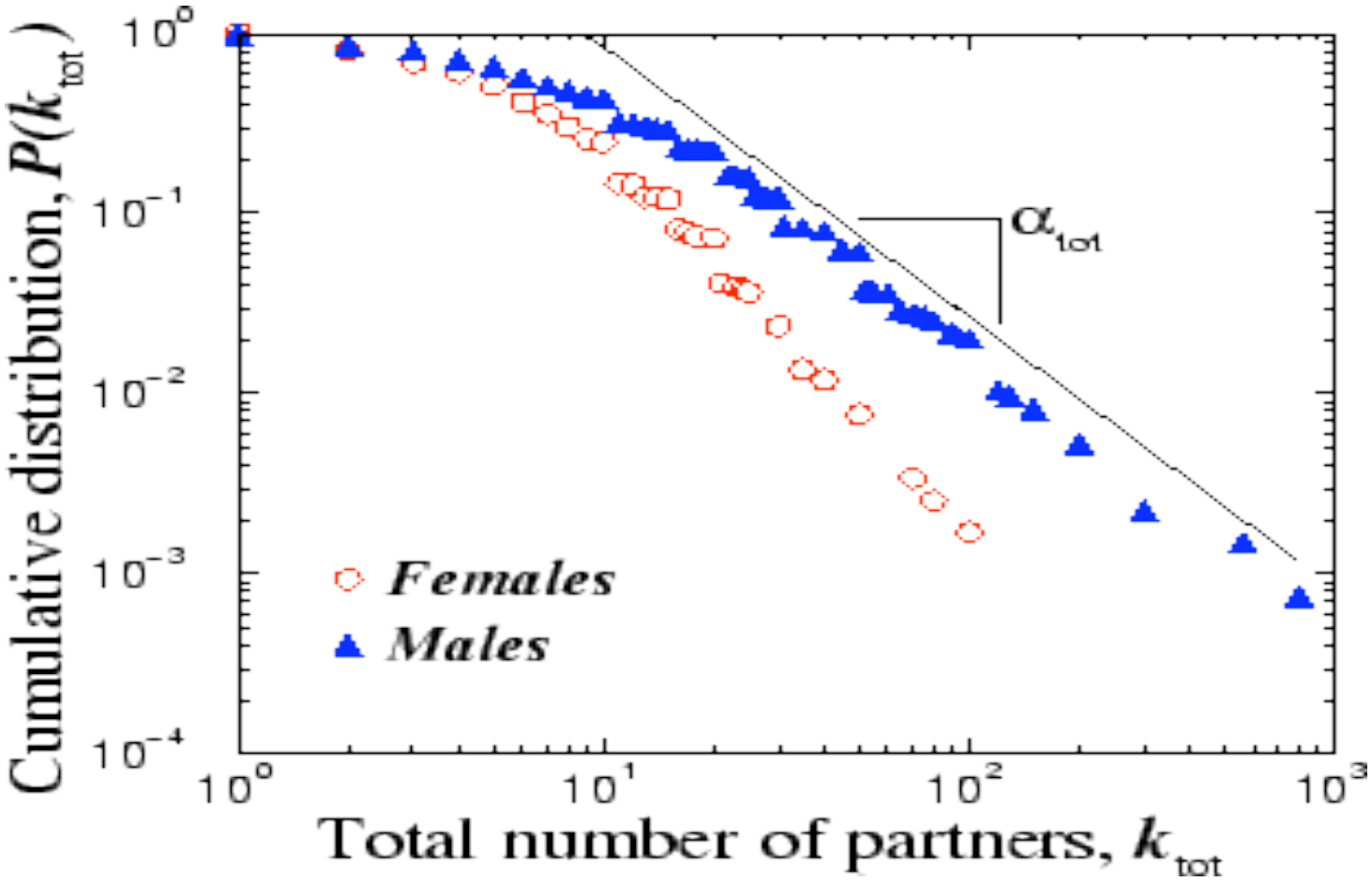
Nodes: characters

Links: co-appearance in a scene



Les Miserables-V. Hugo
Newman & Girvan, PRE (2004)
-> Community detection problem

The web of Human sexual contacts



Liljeros et al., Nature (2001)

Information technology

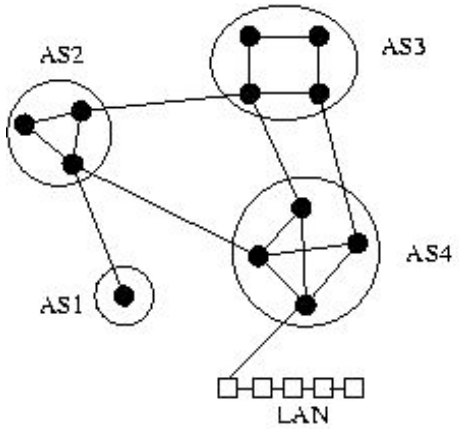
Importance of Internet and the web

- Congestion
- Virus propagation
- Cooperative/social phenomena (online communities, etc.)
- …

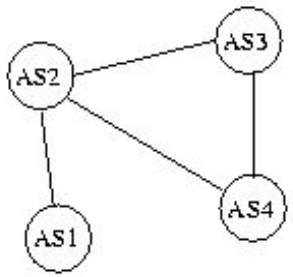
Internet

- Nodes=routers
- Links= physical connections

different granularities



Router Level



Autonomous System level

Internet mapping

- continuously evolving and growing
- intrinsic heterogeneity
- self-organizing

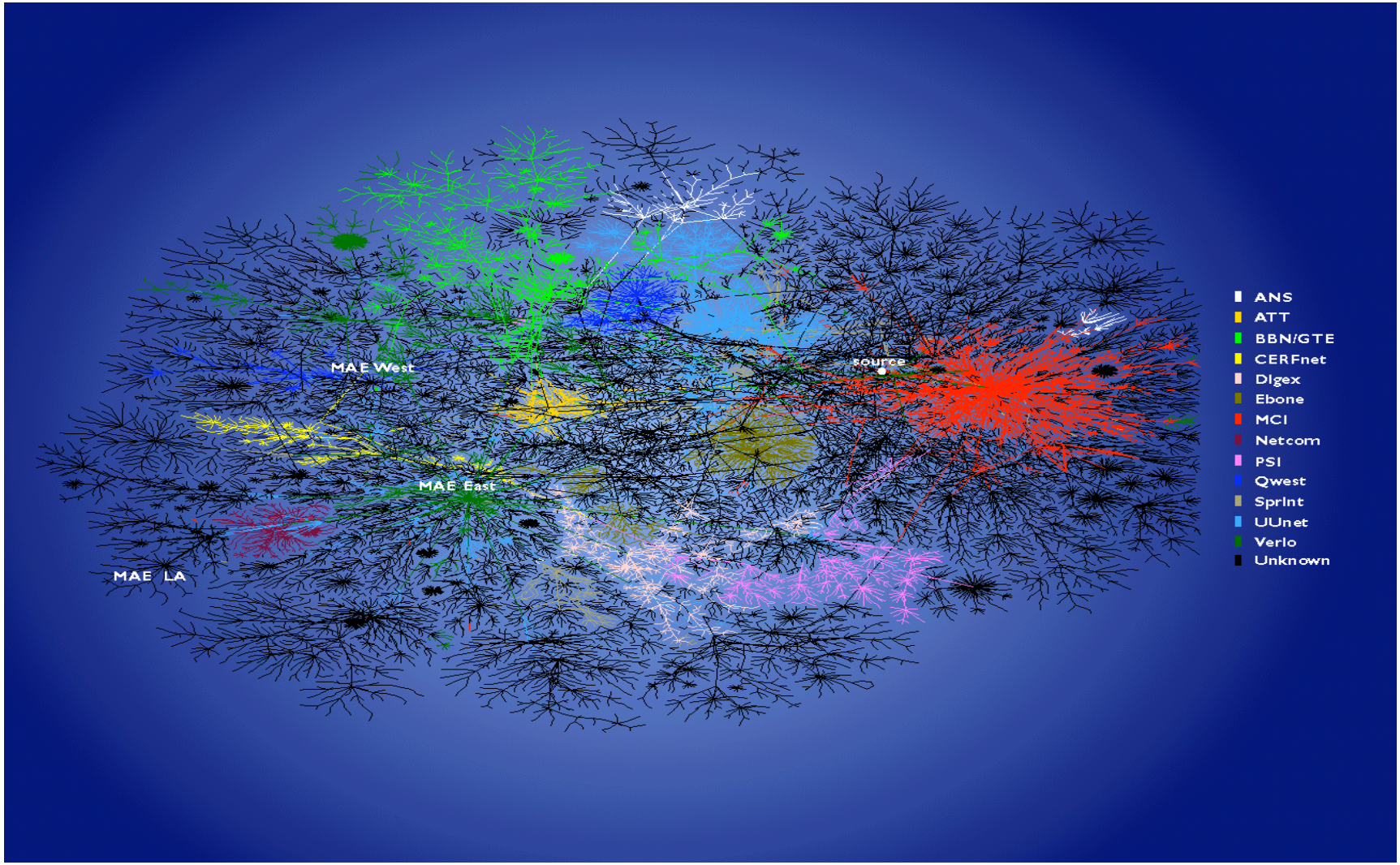
Largely unknown topology/properties

Many mapping projects (topology and performance):
CAIDA, NLANR, RIPE, …

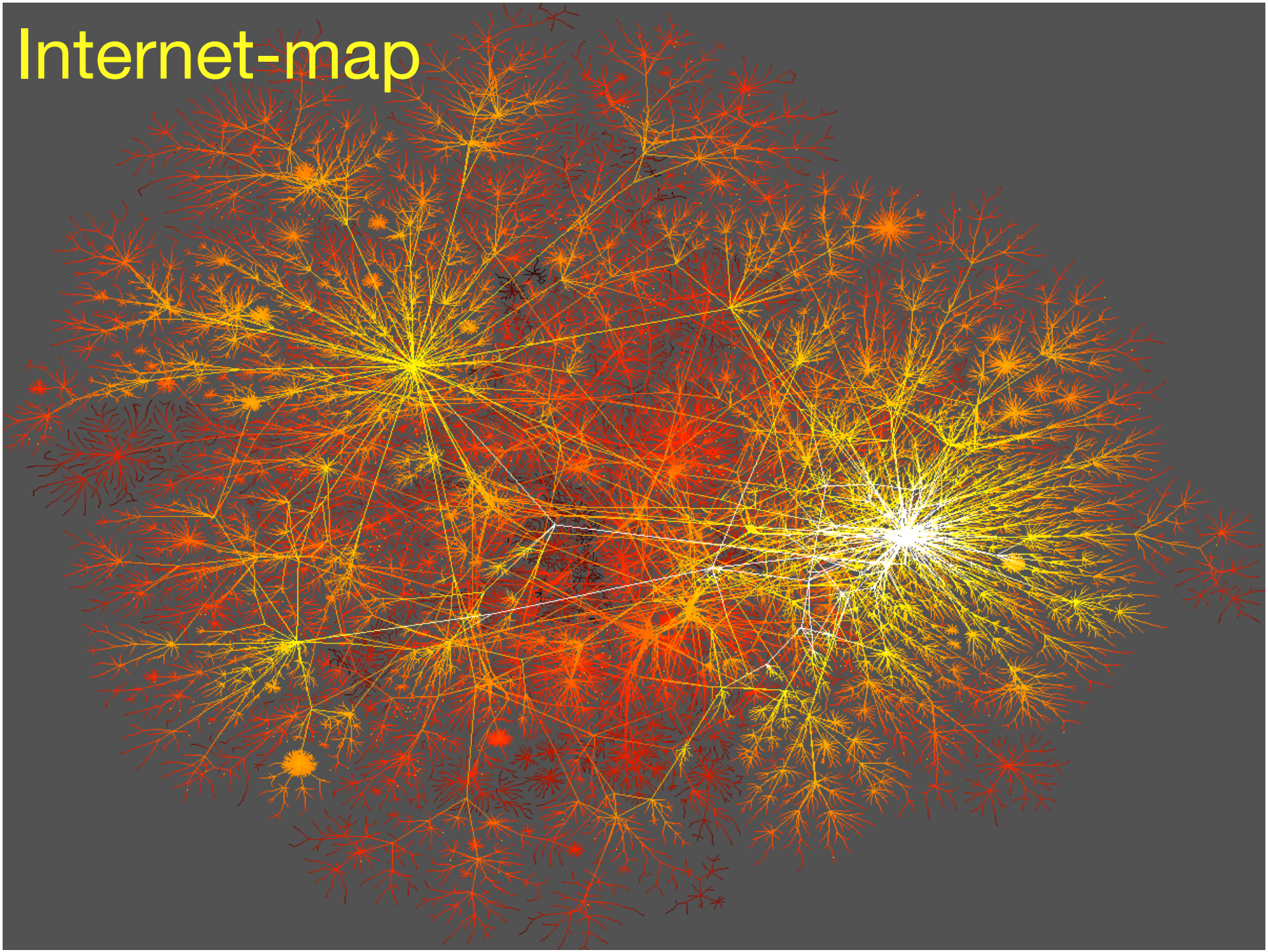
Internet backbone

Nodes: Computers, routers
Links: physical lines

Large-scale visualization



Internet-map

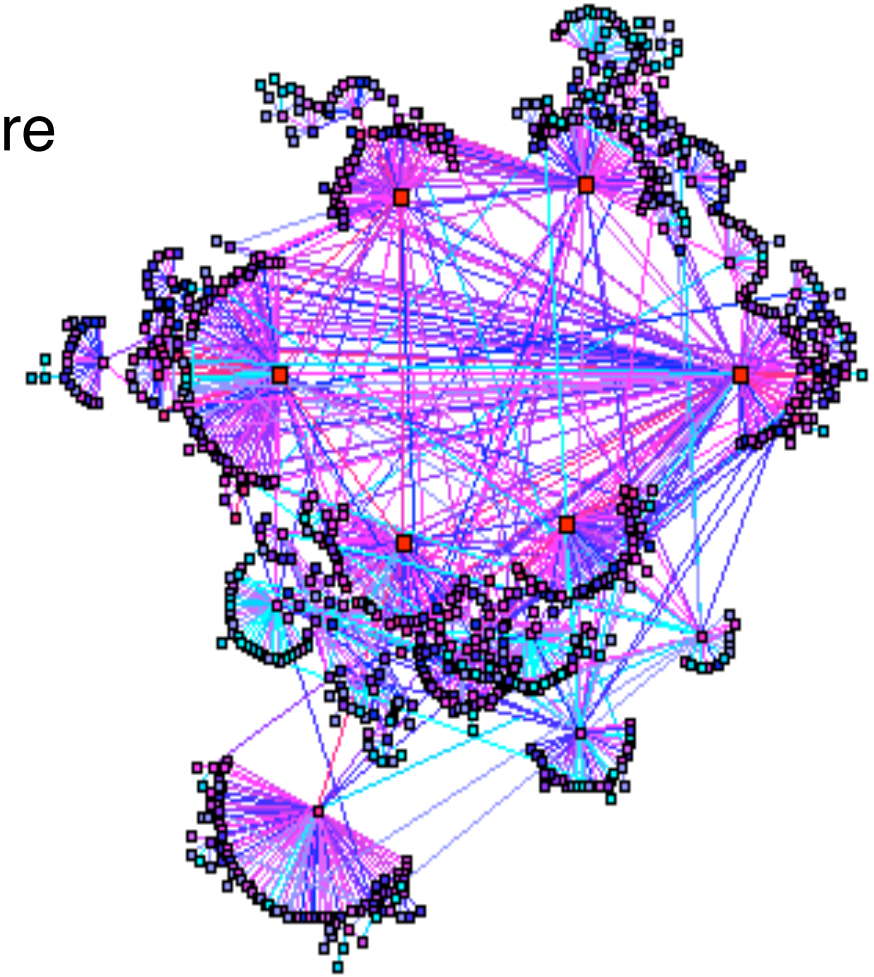


World Wide Web

Nodes: WWW documents
Links: URL links

Virtual network to find and share informations

Over 1 billion documents



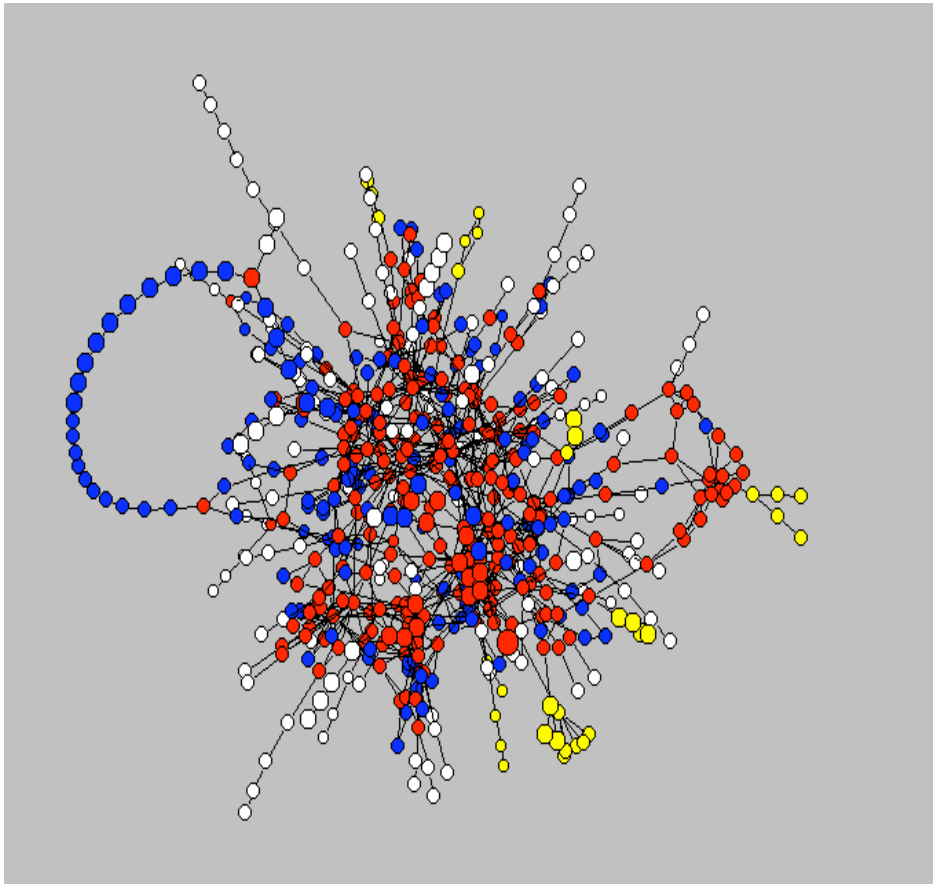
ROBOT: collects all URL's found in a document and follows them recursively

Networks in biology

- Cellular level: Extracting useful information from the huge amount of available data (genome, etc)
- Species level: Stability of ecosystems, biodiversity

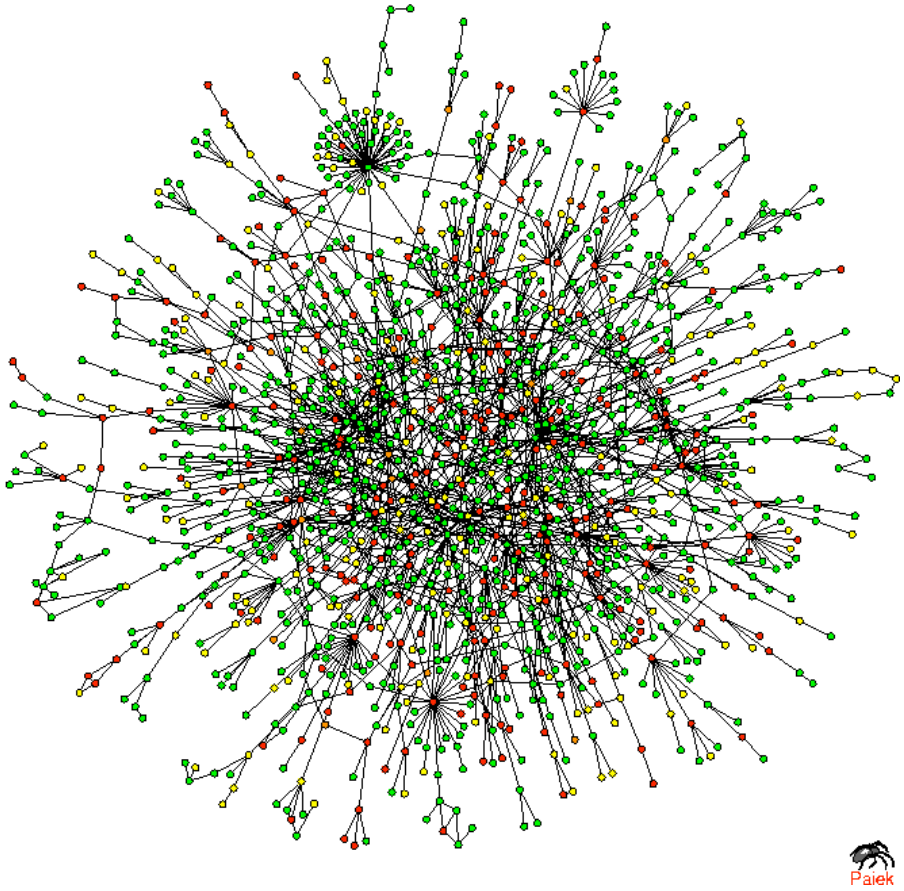
Metabolic Network

Nodes: metabolites
Links:chemical reactions



Protein Interactions

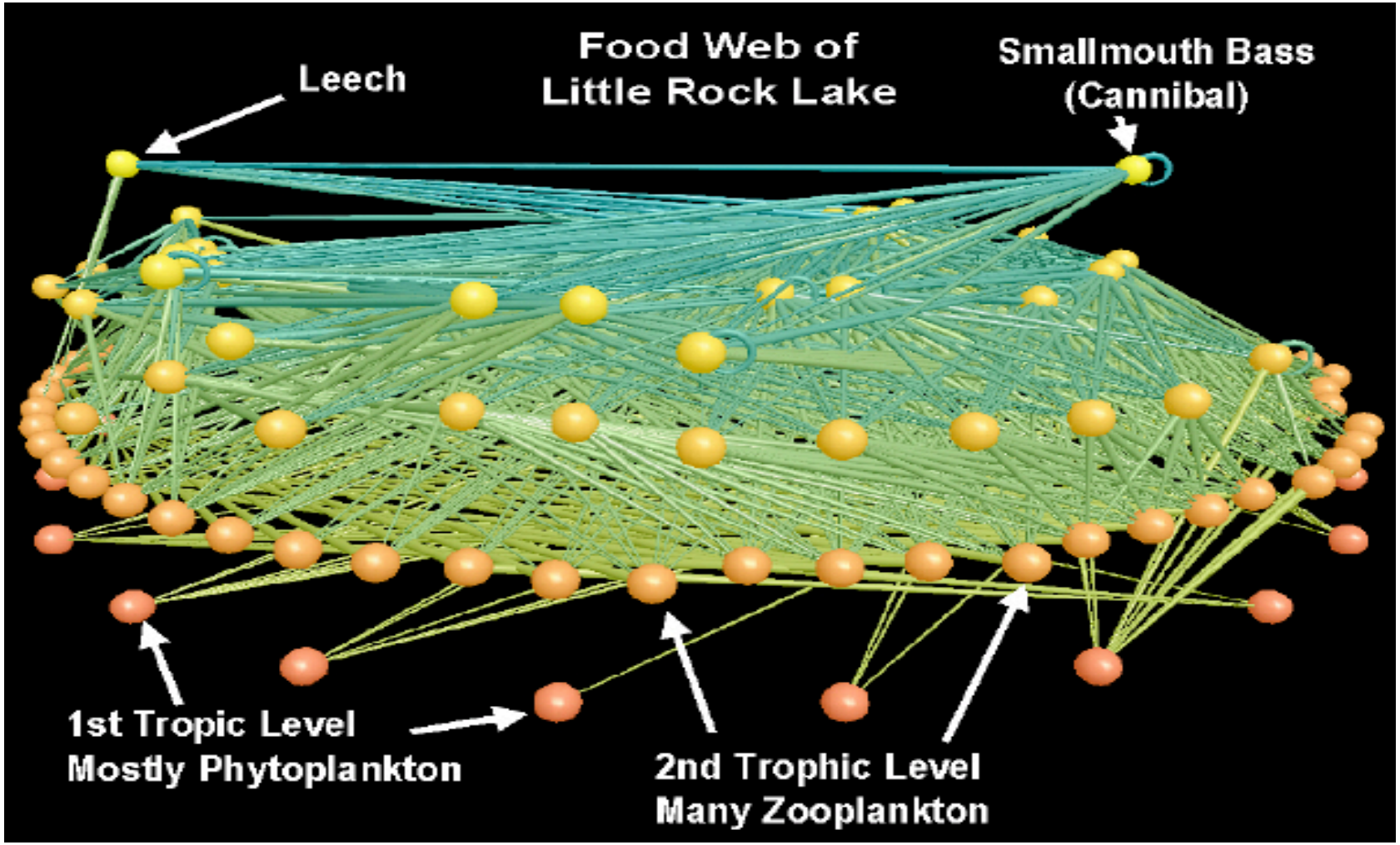
Nodes: proteins
Links: interactions



Food webs

Nodes: species

Links: feeds on



N. Martinez

Transportation networks

Transporting energy, goods or individuals

- formation and evolution

- congestion, optimization

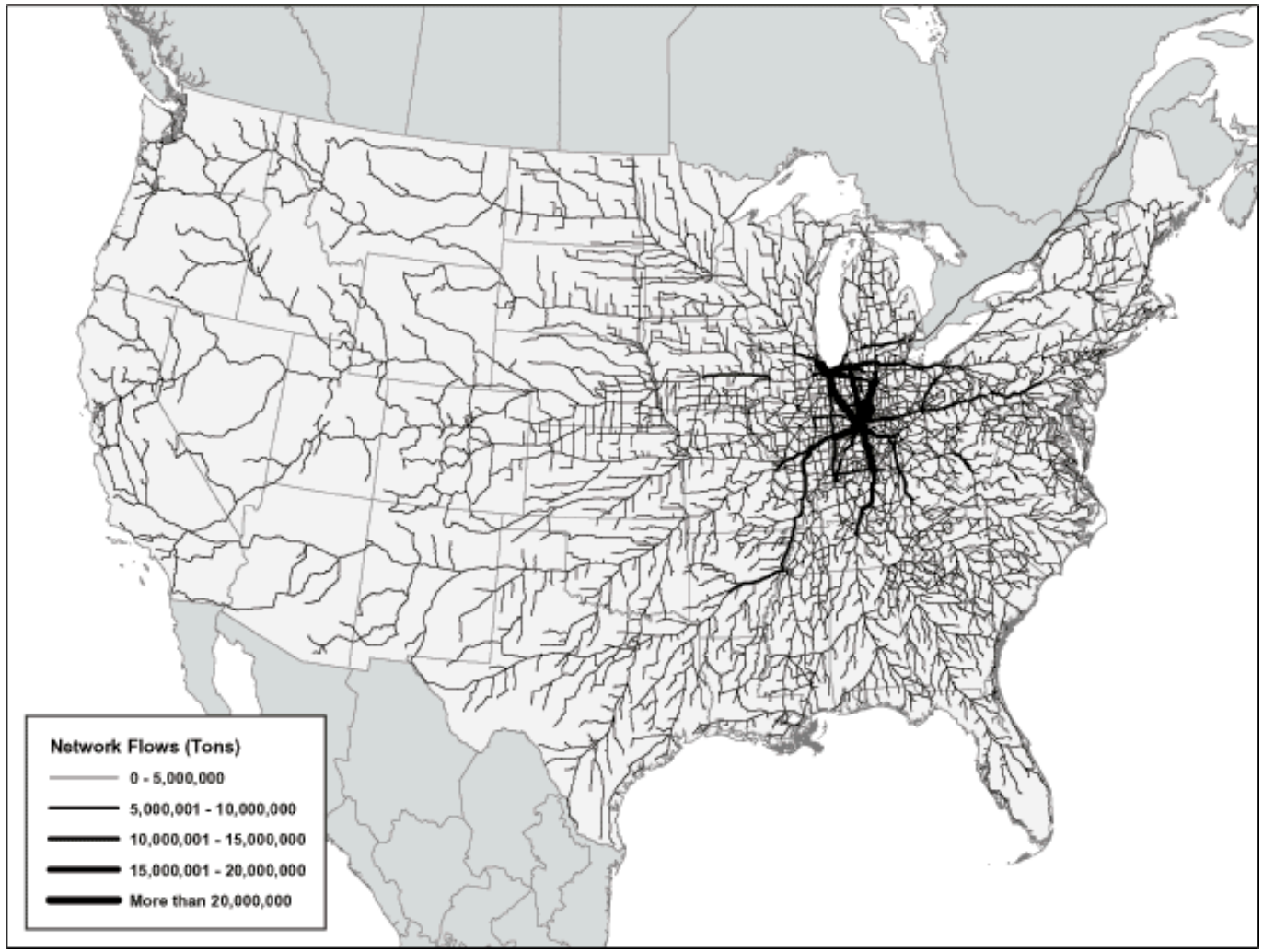
- disease spread

Transporting water

Nodes: intersections, auxins sources
Links: veins

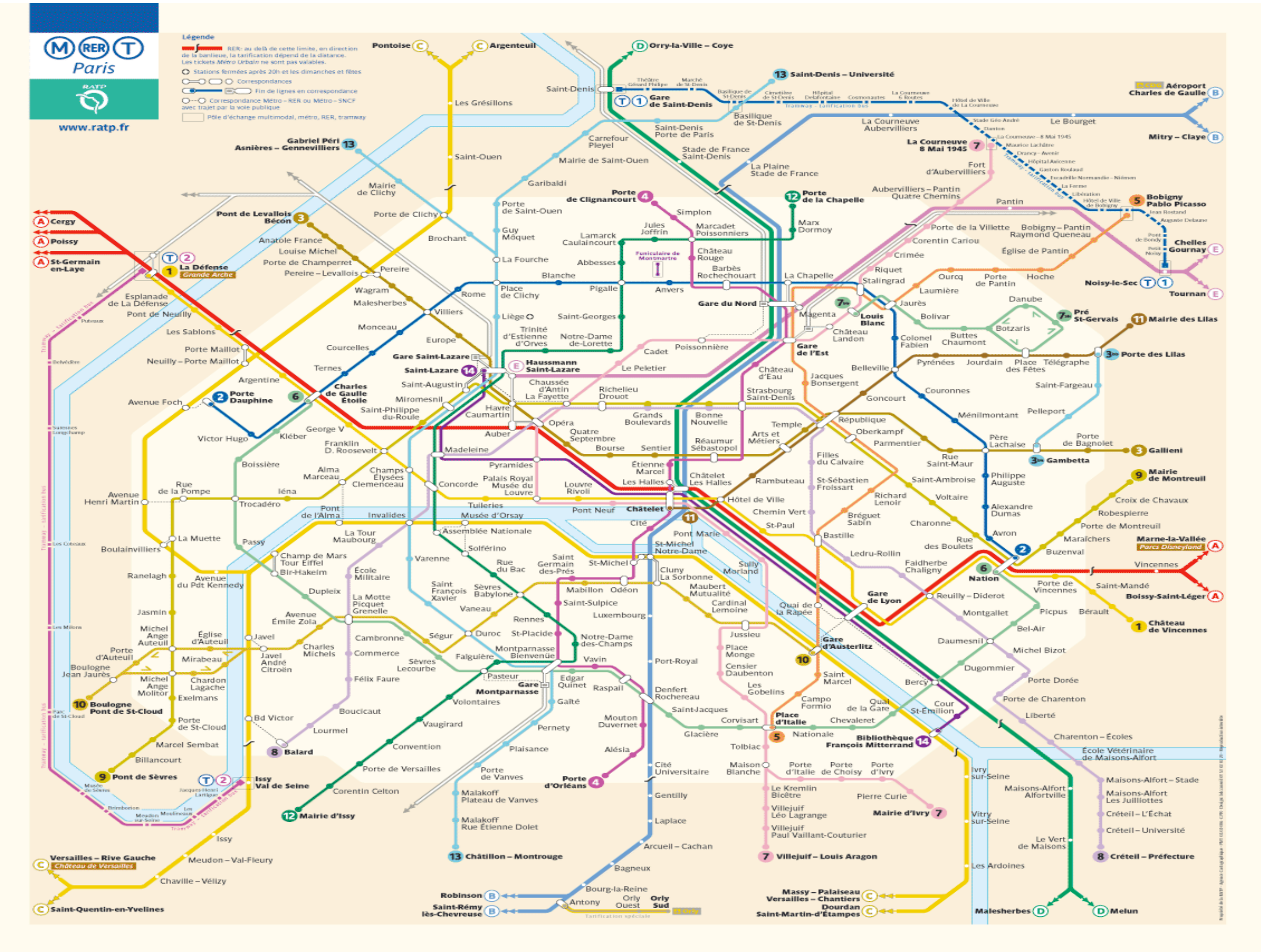
Example of a planar network

Transporting goods



State of Indiana (Bureau of Transportation statistics)

Transportation networks: intra city

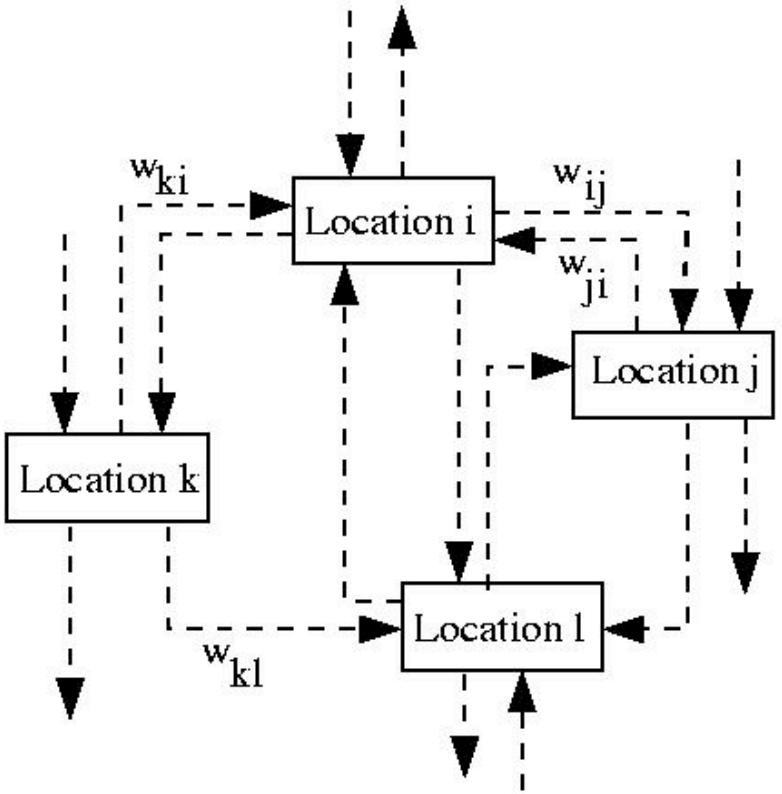


Transportation networks: intra city

TRANSIMS project

Nodes: locations (homes, shops, offices, …)

Links: flow of individuals



Person ID	Location ID	Location type	Arrival time	Departure time
116	4356	Home	00:00	07:00
116	98135	Work	08:00	11:00
116	71457	Work	11:20	13:00
116	98135	Work	13:20	17:00
116	4356	Home	18:00	19:15
116	21343	Social	19:30	21:00
116	4356	Home	21:00	07:00
324	12679	Home	00:00	07:00
324	431	School	08:00	14:00
324	12679	Home	14:30	19:00
⋮	⋮	⋮	⋮	⋮

Chowell et al Phys. Rev. E (2003)

Nature (2004)

Transportation networks: inter city

Nodes: cities

Links: commuters flow

Inter-cities movements

- Sardinian network:

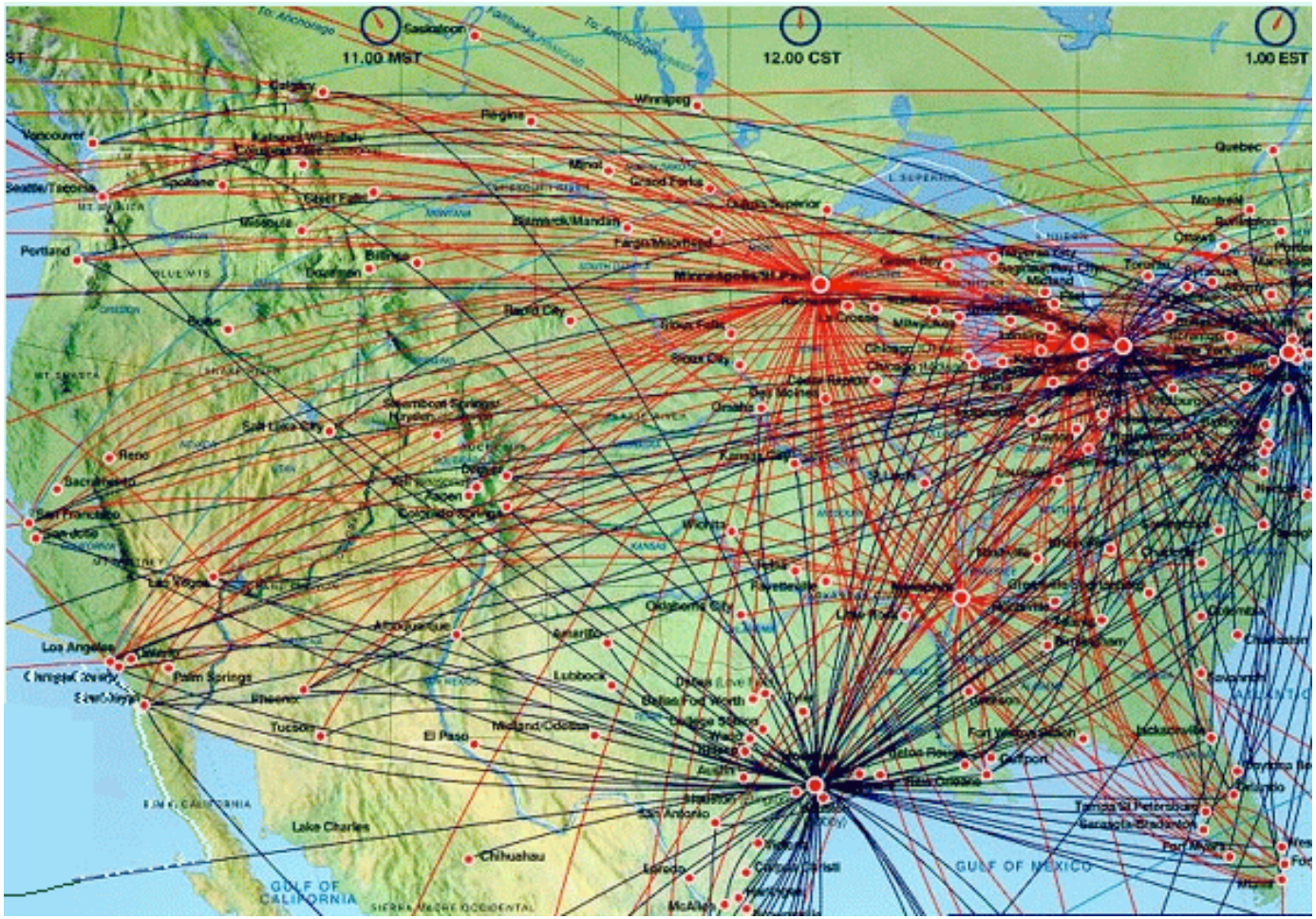
  -Nodes: 375 Cities

  - Link $w_{ji}=w_{ij}$:
  # of individuals going from i to j (daily and by any means)

DE MONTIS & AL, ENV. PLAN. 2007

Transportation networks: global scale

Nodes: airports
Links: direct flight



Studies on complex networks

- 1. Empirical studies

  Typology- find the general features

- 2. Modeling

  Basic mechanisms/reproducing stylized facts

- 3. Dynamical processes

  Impact of the topology on the properties of dynamical processes: epidemic spread, robustness, …

Empirical studies: Unprecedented amount of data…..

- Transportation infrastructures (eg. BTS)
- Census data (socio-economical data)
- Social networks (eg. online communities)

Empirical studies: sampling issues

- Social networks: various samplings/networks
- Transportation network: reliable data
- Biological networks: incomplete samplings
- Internet: various (incomplete) mapping processes
- WWW: regular crawls
- …

possibility of introducing biases in the measured network characteristics

Networks characteristics

Networks: of very different origins

Do they have anything in common?
Possibility to find common properties?

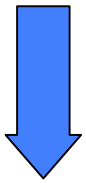
- The abstract character of the graph representation and graph theory allow to give some answers…
- Important ingredients for the modeling

Modeling complex networks

Microscopical processes

- many interacting elements
- dynamical evolution
- self-organisation

Statistical physics



Properties at the macroscopic level

Non-trivial structure
Emergent properties, cooperative phenomena

Model validation

Modeling other attributes: clustering, assortativity, spatial effects…

Comparison with large scale datasets