

# Complex systems and Complex Networks

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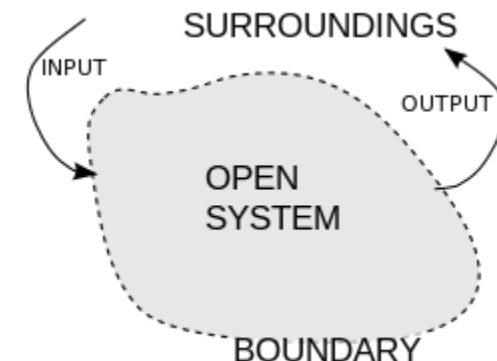
PDPM

Indian Institute of Information Technology,  
Design and Manufacturing, Jabalpur

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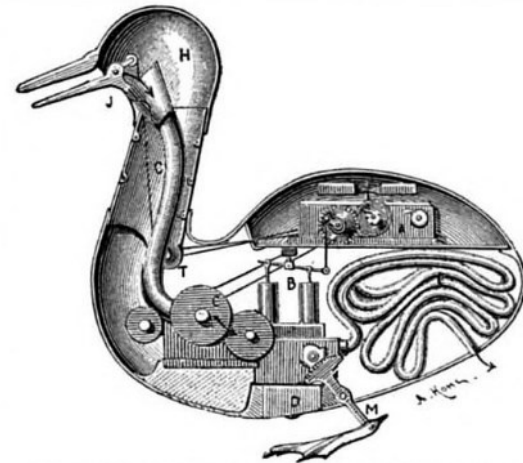
# Complex system

- An interdisciplinary domain
- Composed of many components (or entities) interacting with each other.
  - power grid, transportation or communication systems,
  - social and economic organizations (like cities),
  - organisms, a living cell, the human brain, and
  - an ecosystem, climate, entire universe.
- Behavior is hard to model with dependencies, relationships,
  - interactions between their components or
  - interactions between system and its environment



# Complex system and Reductionism

- Reductionism is old domain since 16<sup>th</sup> century
- explains system in terms of parts and their interactions
  - Define a domain of possible parts
  - Generate inputs over the interaction between parts
  - Perform a deterministic computation on the input data
  - Aggregate the results
- interprets a complex system as the sum of its parts



# Complex system properties

- **Nonlinearity:** a set of simultaneous equations with the variables of a polynomial degree higher than one
- **Emergence:** entities have properties emerging only when they interact together
- **Spontaneous order** arises from interactions between component of disordered system
- **Adaptation:** behavior of mutation and self-organization for the changes
- **Feedback loops:** outputs are routed back as inputs as part of a chain of cause-and-effect that forms a circuit or loop

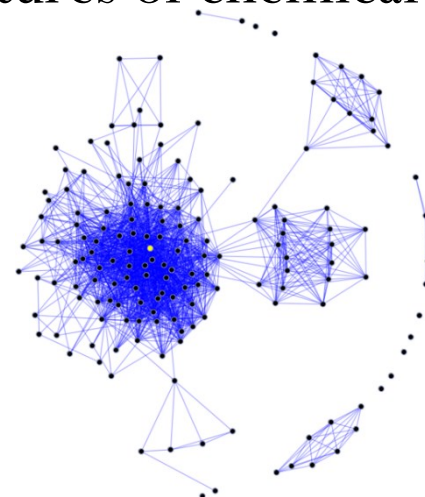


# Complex system and Disciplines

- **Statistical physics:** methods of probability theory and statistics, and mathematical tools
  - deals with large populations and approximations,
- **Information theory:** quantification, storage, and communication of information (e.g. signals)
  - Subfield of Communication, Electronics, and Computer Science
- **Nonlinear dynamics:** the change of the output is not proportional to the change of the input.
  - Changes in variables over time, or, space etc.
  - Measures chaotic, unpredictable, or counterintuitive

# Complex system and Disciplines

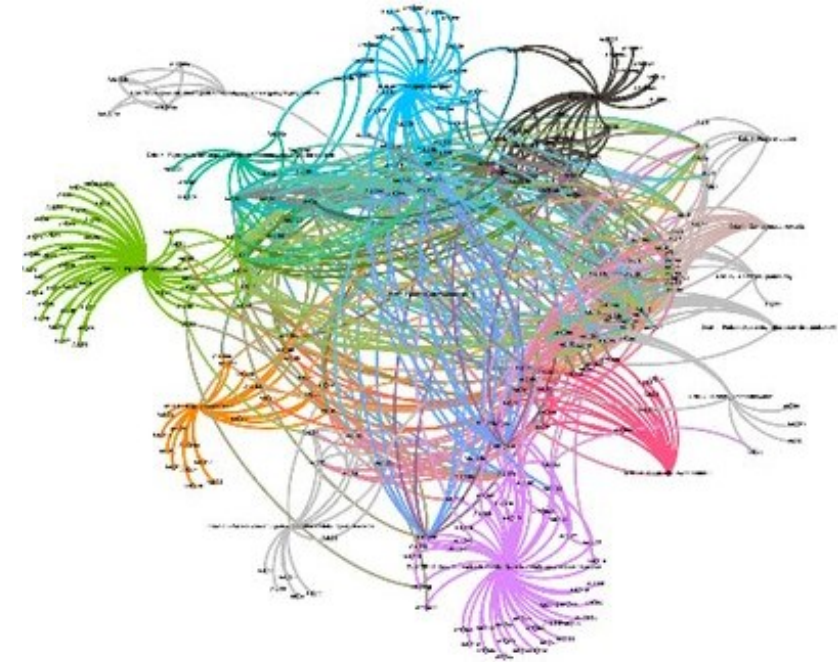
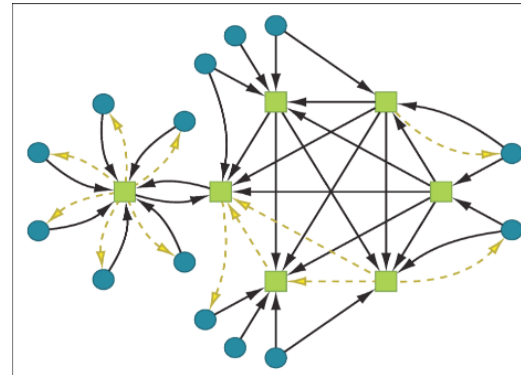
- **Computer science:** programming creates complex systems, and application involving complex real-world data,
- **Sociology:** studies human behaviour, social behavior, society, patterns of social relationships, social interaction, and culture
- **Social network analysis:** investigate social structures with networks and graph theory
- **Biology:** studies life and living organisms, physical structures of chemical, molecular interactions





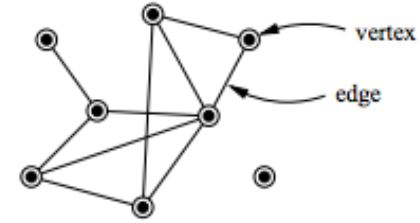
# Complex system and Graph Theory

- Represented with a network (graph)
  - nodes represent the components (or entities) and
  - edges (or links) represents entities' interactions.
- Depicts collection of discrete objects and relationships between them
  - persons within an organization,
  - logic gates in a circuit,
  - genes in gene regulatory networks, or
  - between any other set of related entities





# Graph Theory



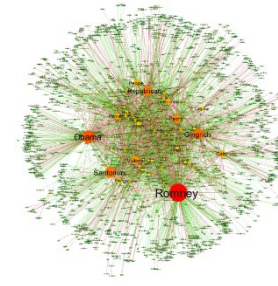
- Study of mathematical structures used to model relationship between discrete elements of a set
- Vertices (or nodes) are connected by edges (or links)
- Undirected graphs, where edges link two vertices symmetrically
- Directed graphs, where edges link two vertices asymmetrically
- Graph is an ordered triple  $G = (V, E, \emptyset)$ 
  - $V$  is a set of vertices (or nodes)
  - $E$  is a set of edges (or links)
  - $\emptyset: E \rightarrow \{\{x, y\} \mid x, y \in V \text{ and } x \neq y\}$  an incidence function mapping every edge to an unordered pair of vertices

# Network Theory



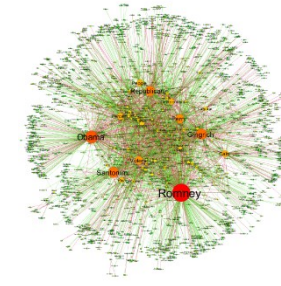
- Graph representing symmetric or asymmetric relations between discrete objects
- Graph with nodes and/or edges have attributes (e.g. names)
- Network theory is a subdomain of Graph theory
- Network theory is applied graph theory

# Graph or Network Theories



- **Graph colouring:** e.g. coloring a graph so that
  - no two adjacent vertices have the same color, or
  - no two coincident edges are the same color
- **Matching** is a set of edges without common vertices
- **Route problems:** e.g. shortest path problem
  - minimum spanning tree (MST): a subset of the connected edges that connects all the vertices together, without any cycles, and with minimum possible total edge weight.
  - traveling salesman problem (TSP): “Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?”

# Graph or Network Theories



- **Network flow:** “Directed graph where each edge has a capacity and each edge receives a flow, where the amount of flow on an edge cannot exceed the capacity of the edge”
- **Transport problem:** study of optimal transportation and allocation of resources.
- **Trans-shipment problem:** a subgroup of transportation problems, where, transportation may or must go through intermediate nodes, possibly changing modes of transport
- **Critical path analysis:** identifying the longest dependent activities and measuring the time required to complete a project
- **PERT** to analyze and represent the tasks involved in completing a given project

# Complex Networks

- Non-trivial topological features in networks representing real systems
- e.g. theories: Network motifs are small subgraphs that are over-represented in the network
- Examples of Complex networks are
  - computer networks,
  - biological networks,
  - technological networks,
  - brain networks,
  - climate networks and
  - social networks.

# Complex Network analysis

- **Electric power systems analysis:**
  - a graph consists from representing electric power aspects (e.g., transmission line impedances)
- **Biological network analysis:**
  - analysis of molecular networks
  - visualize the nature and strength of interactions between species
  - Gene Regulatory Networks (GRN), Metabolic networks, Protein-Protein Interaction, molecular interactions
- **Operations research:** logistical networks, social networks, epistemological networks

# Complex Network analysis

- **Computer science:** graphs are used to represent networks of communication, data organization, computational devices, the flow of computation, etc.
  - **Link analysis:** the link structure of a World Wide Web, Internet, Computer Network
  - website can be represented by a directed graph,
  - the vertices represent web pages and directed edges represent links from one page to another
- **Social network analysis:**
  - graph with the structure of relationships between social entities.
  - entities are persons, groups, organizations, nation states, web sites, or scholarly publications

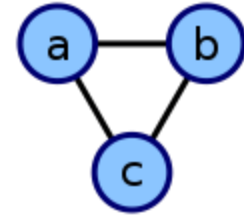


# Complex systems Representation

- Complex systems can be represented by Complex networks
- Complex networks can represent connections between component (or entities)
- Complex network can be represented as a graph with
  - vertices (or nodes) representing entities and
  - edges (or links, or connections) representing the relationship between components.

# Complex systems Representation

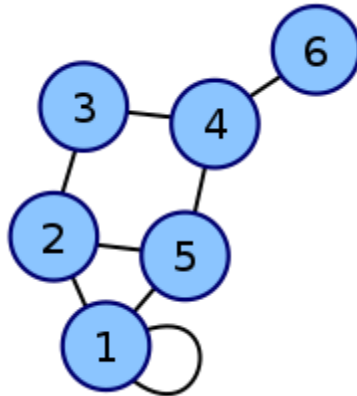
- Adjacency list is a collection of unordered lists used to represent a finite graph.
- List contains the set of neighbors of a vertex in the graph.
- Undirected graphs:
  - data structure two different linked list nodes for each edge



Adjacency list representation	
a	b
a	c
b	a
b	c
c	a
c	b

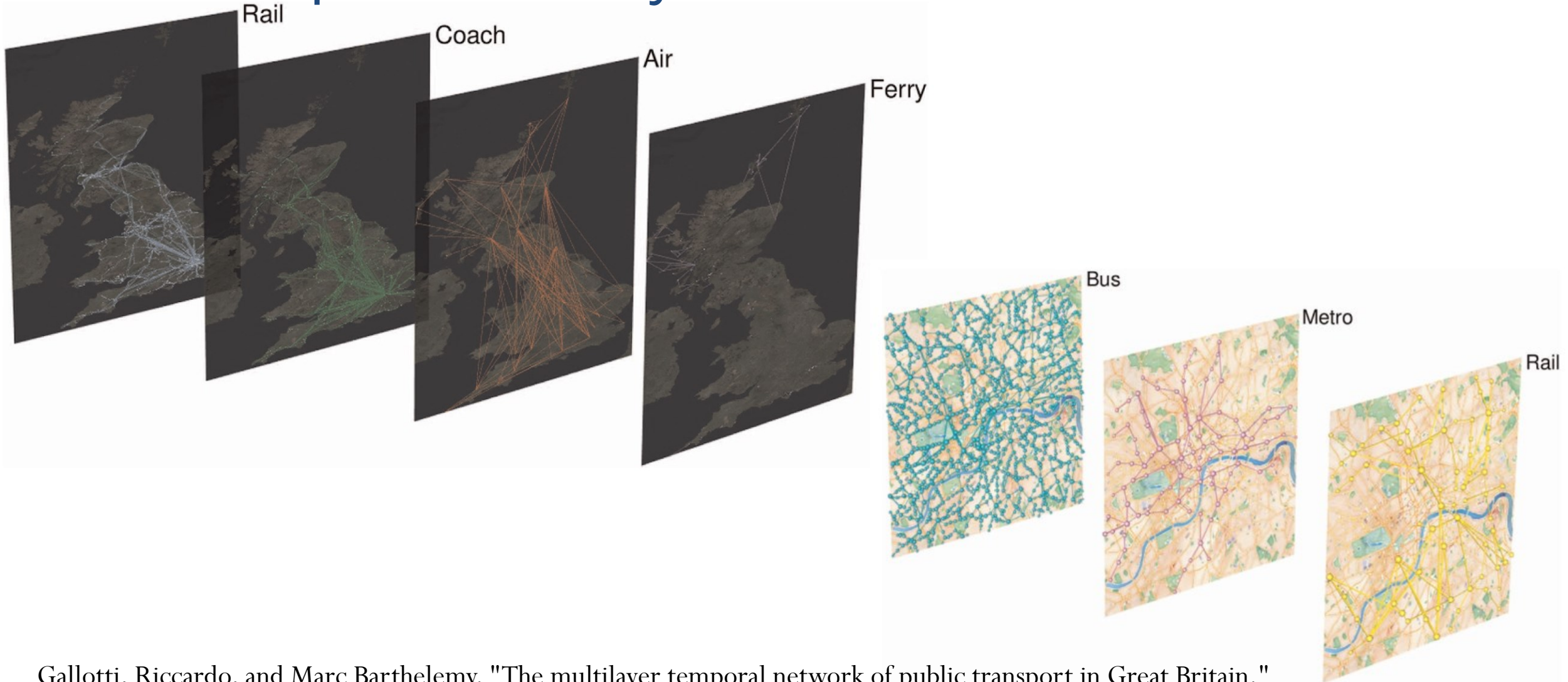
# Complex systems Representation

- Adjacency matrix is a square matrix used to represent a finite graph.
- Matrix with rows and columns are indexed by vertices
- an adjacency list is more space-efficient than an adjacency matrix (stored as a two-dimensional array)
- adjacency list is as simple
- Matrix are 2-Dimensional representation.



$$\begin{pmatrix} 2 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

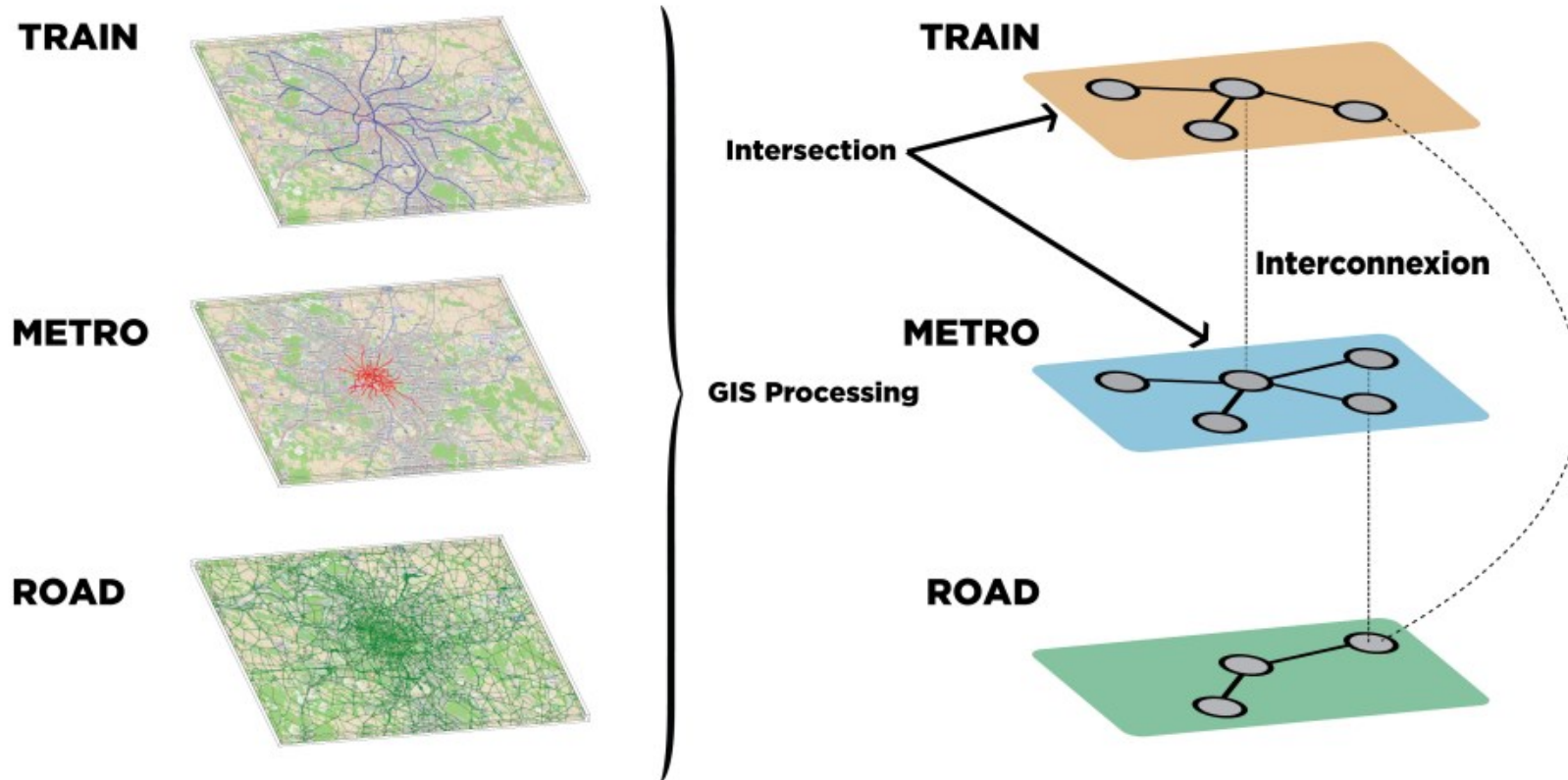
# Transport multi-layer network



Gallotti, Riccardo, and Marc Barthelemy. "The multilayer temporal network of public transport in Great Britain." Scientific data 2.1 (2015): 1-8.

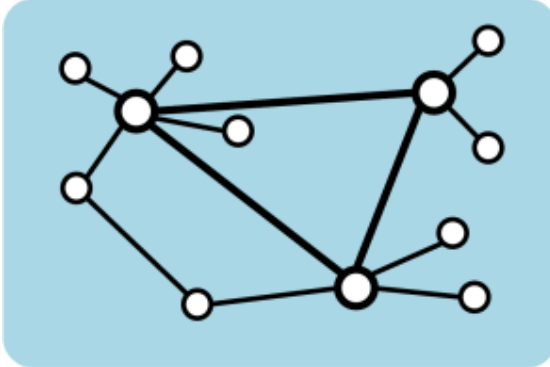
# Transport multi-layer network

## Aggregation of multi Layered Graph of public Transport



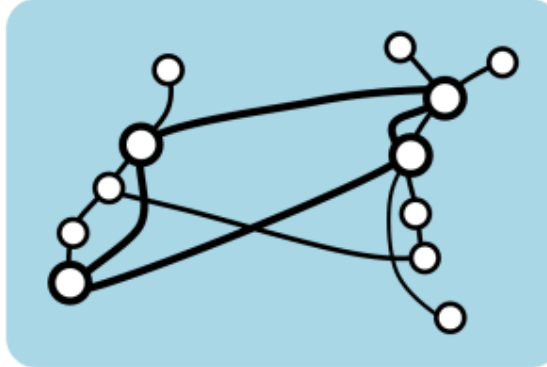
# Types of Transportation Networks

**Air Networks**



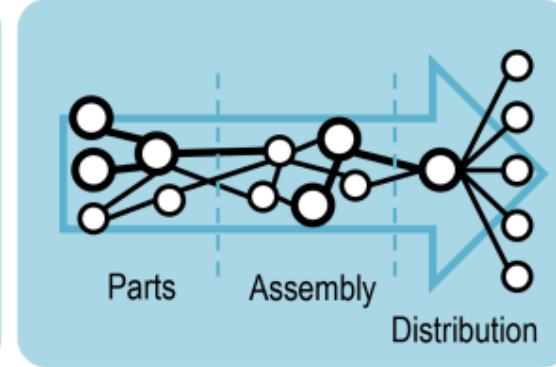
Nodal hierarchy (hub-and-spoke)

**Maritime Networks**



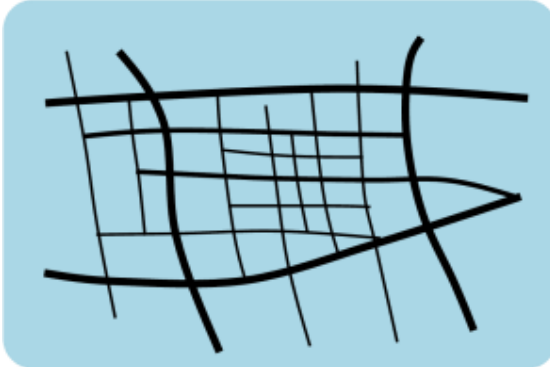
Circuitous nodal hierarchy

**Logistical Networks**



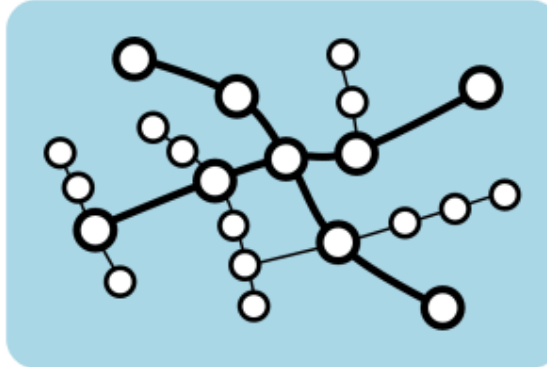
Sequential multi-nodal hierarchy

**Road Networks**



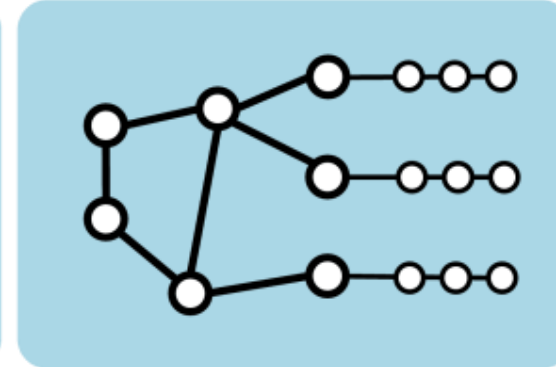
Hierarchical meshes

**Rail Networks**



Linear nodal hierarchy

**Power Grids**



Sequential linear hierarchy

# Complex systems Representation

- Multilayer Network representation:
- Complex systems can be described by representing many interacting entities in
  - a Single network or
  - Multilayer networks
- Examples social networks, neural networks
- Co-occurring network structure made by links, activity as the nodes (e.g. community structure between multi-links).
- Dynamic entity relationships can be represented with multilayer networks, multiplex networks, and network of networks.



ขอบคุณ

Thai

Grazie  
Italian

תודה רבה  
Hebrew

धन्यवादः  
Sanskrit

ধন্যবাদ  
Bangla

Ευχαριστώ  
Greek

Thank You  
English

ಧನ್ಯವಾದಗಳು  
Kannada

Спасибо  
Russian

Gracias  
Spanish

شكراً  
Arabic

<https://sites.google.com/site/animeshchaturvedi07>

Obrigado  
Portuguese

多謝  
Traditional  
Chinese

Merci  
French

धन्यवाद  
Hindi

Danke  
German

多谢  
Simplified  
Chinese

நன்றி  
Tamil

ありがとうございました  
Japanese

감사합니다  
Korean