# Motivation – Data Structures

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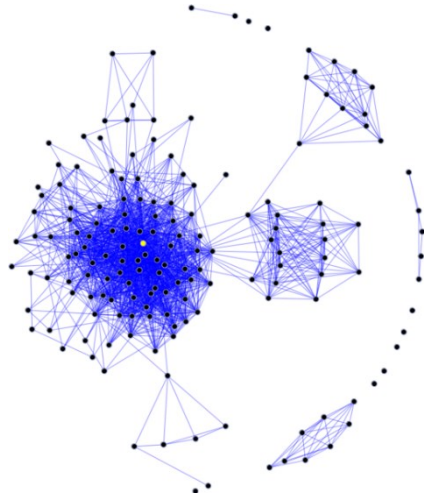
# Disciplines

- **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

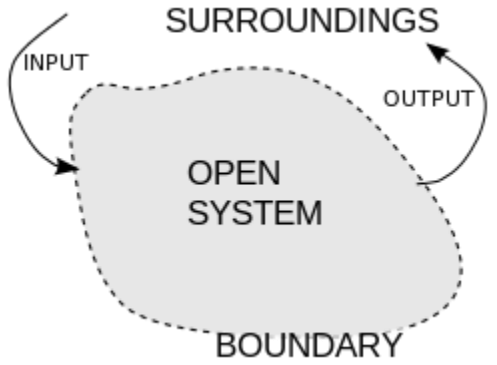
# Disciplines

- **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:** investigate social structures with networks and graph theory
- **Biology:** studies life and living organisms, physical structures of chemical, molecular interactions



# Systems

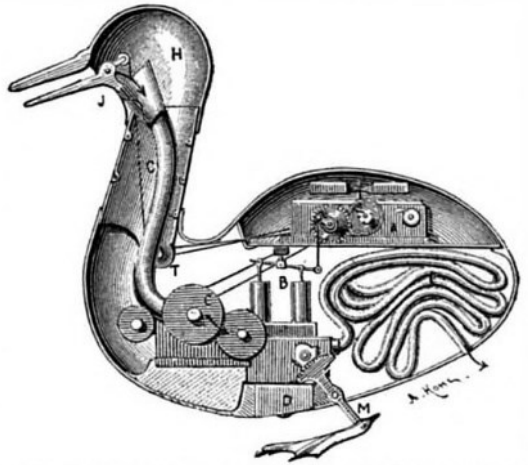
- An interdisciplinary domain
- Composed of many components (or entities) interacting with each other.
  - power grid, transportation or communication systems,
  - social and economic organizations (like cities),
  - organisms, a living cell, the human brain, and
  - an ecosystem, climate, entire universe.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




https://en.wikipedia.org/wiki/Complex_system

# Systems and Reductionism

- Reductionism is old domain since 16th 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

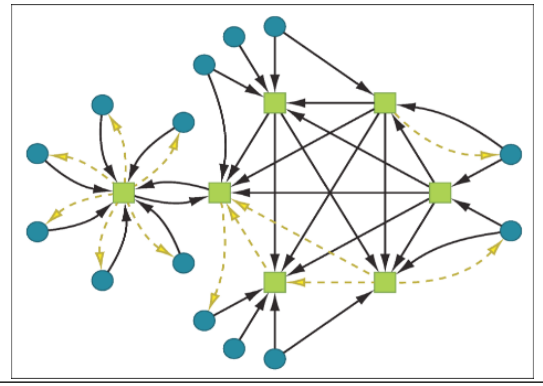



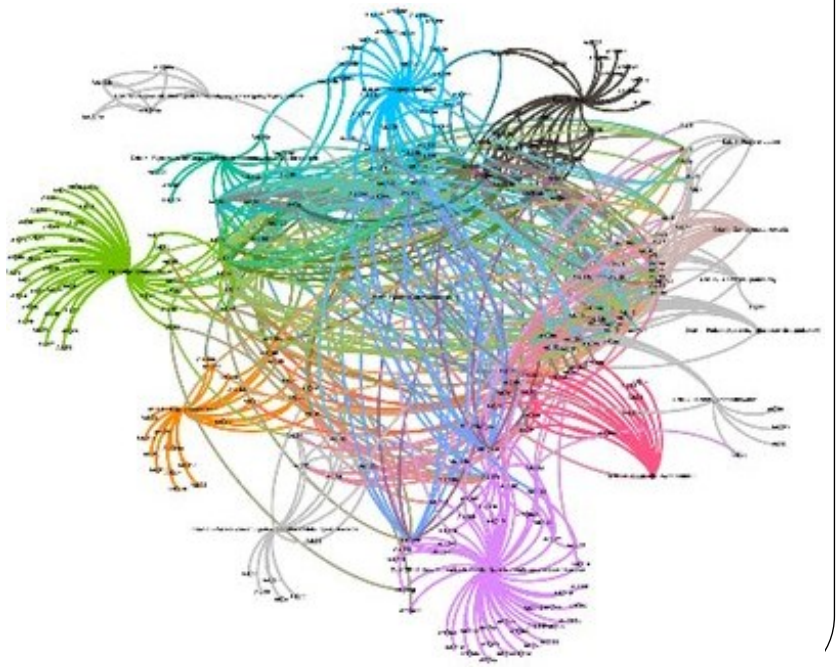
# System properties

- **Nonlinearity:** a set of simultaneous equations with the variables of a polynomial degree higher than one
- **Emergence:** entities have properties emerging only when the 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

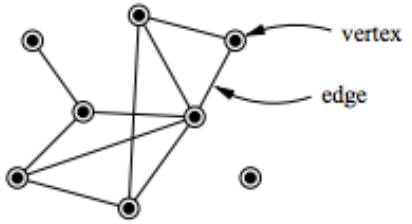
# System representation with Graph Theory

- 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

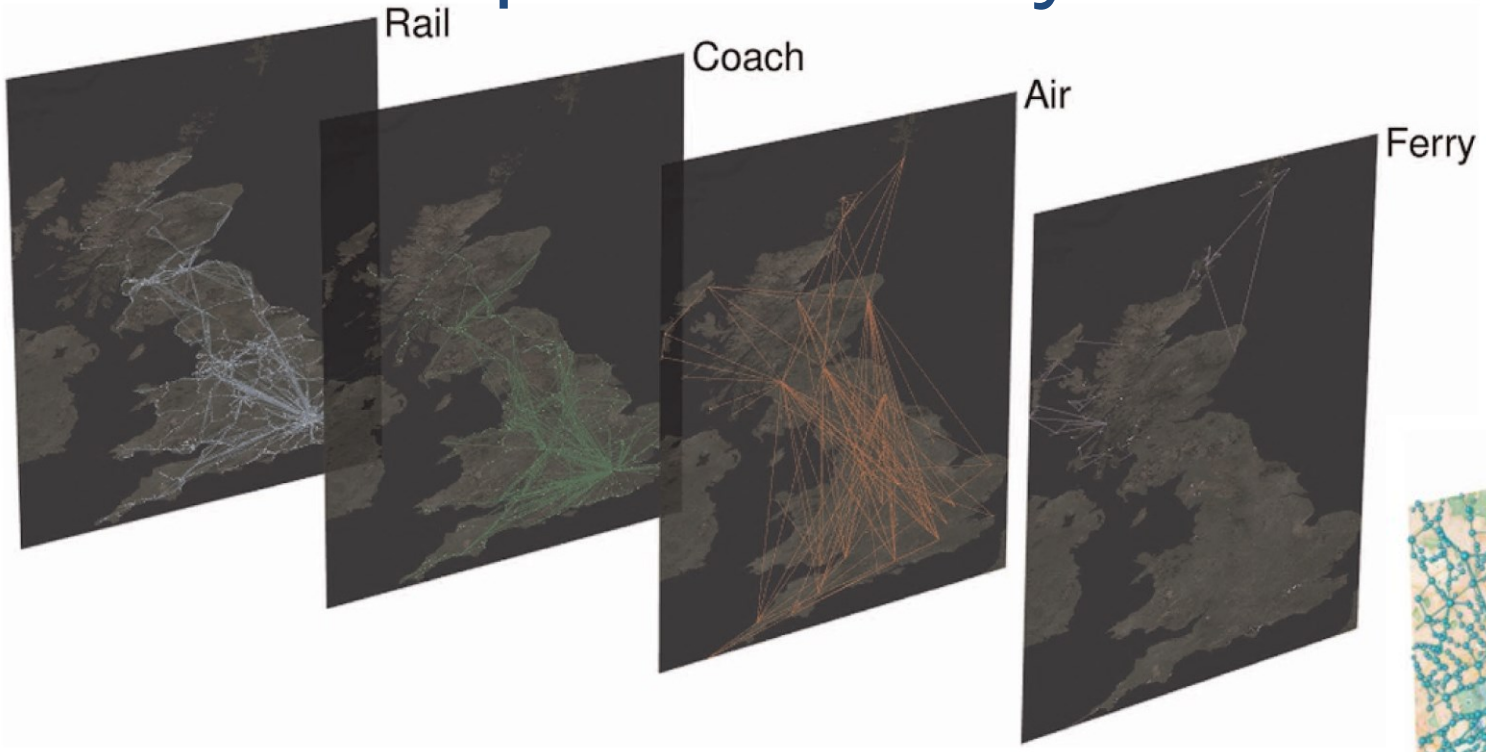



- Study of mathematical structures used to model relationship between discrete elements of a set
- Vertices (or nodes) are connected by edges (or links)
- Undirected graphs, where edges link two vertices symmetrically
- Directed graphs, where edges link two vertices asymmetrically
- Graph is an ordered 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

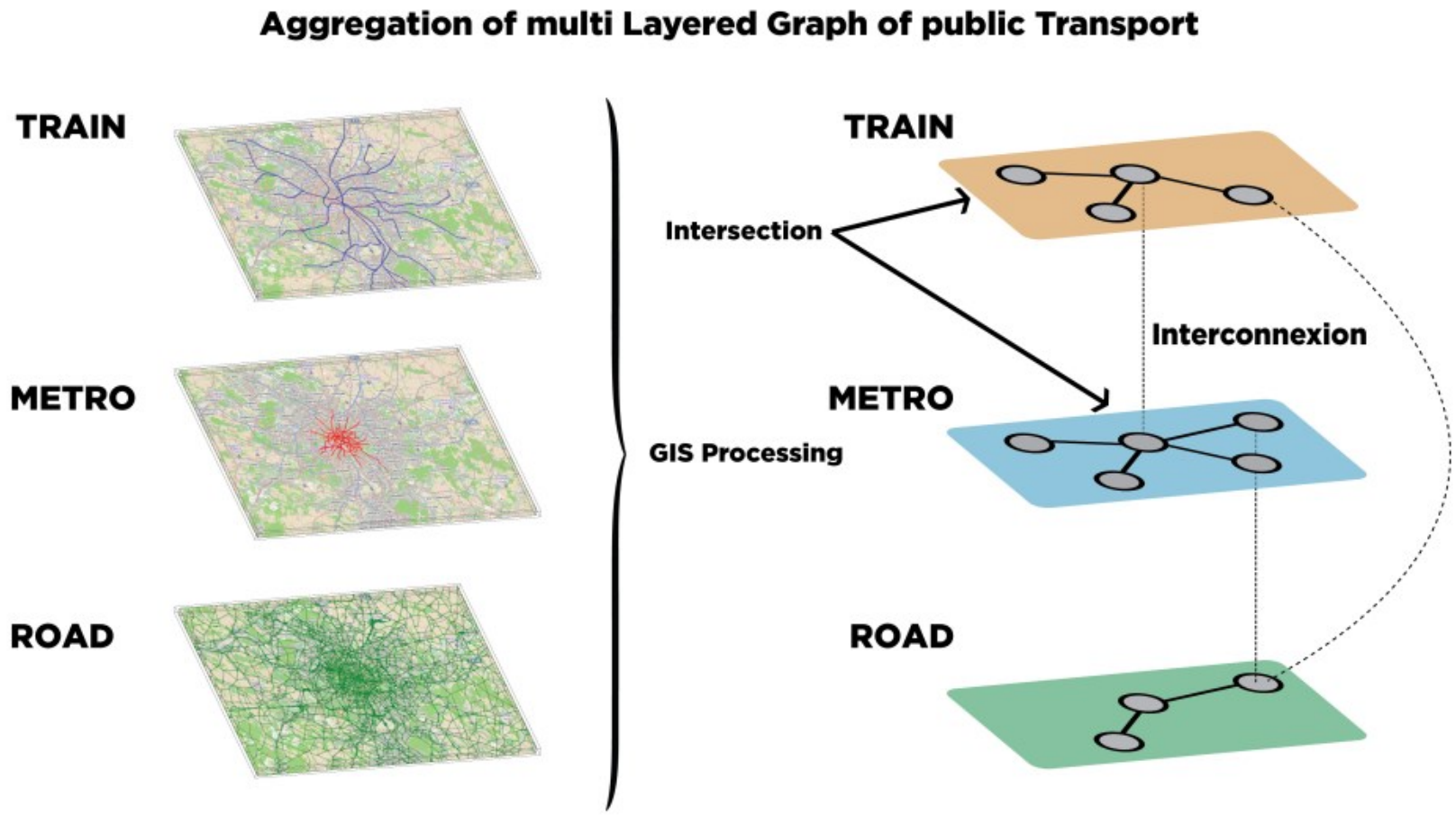
# Transport multi-layer network





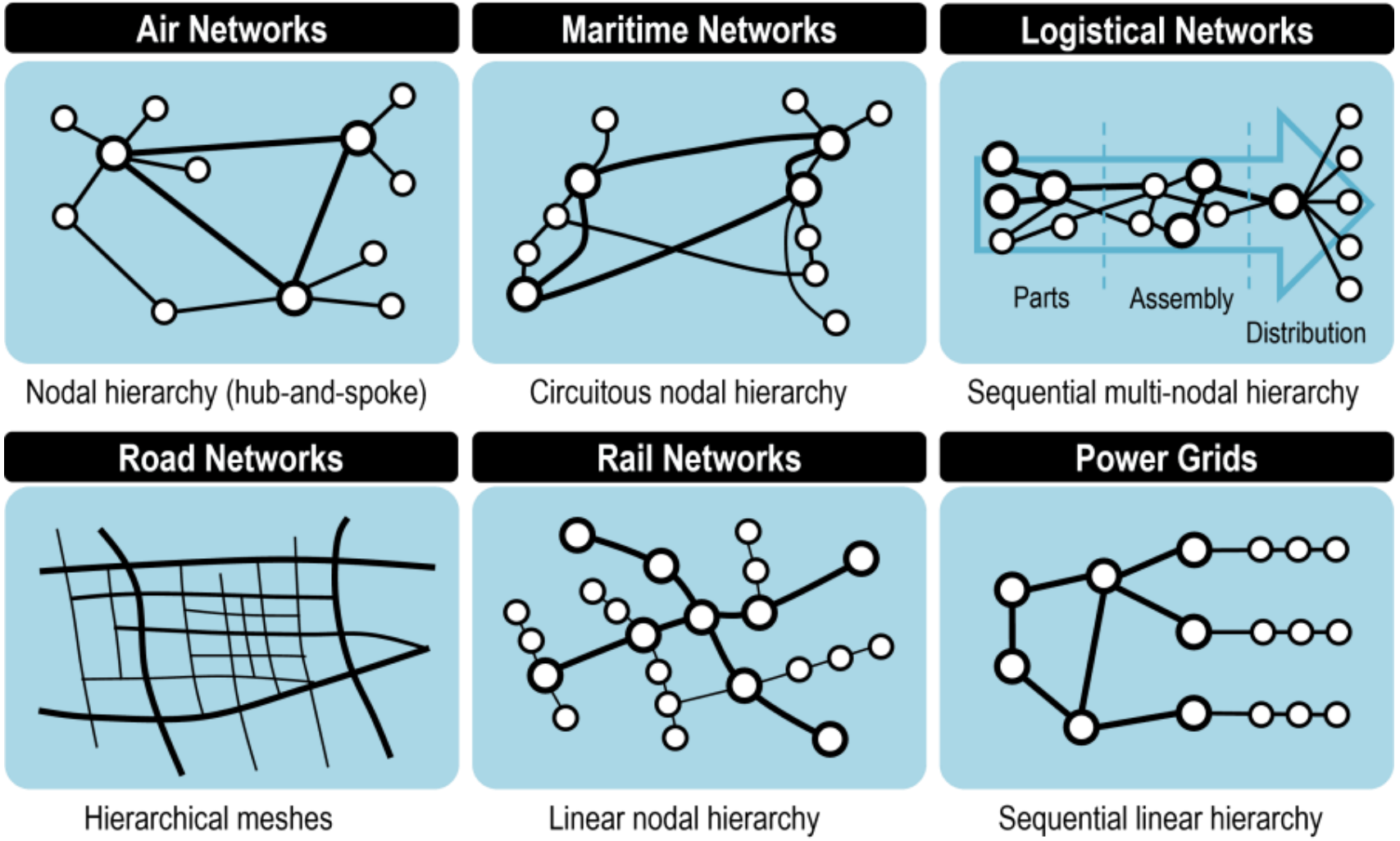
Gallotti, Riccardo, and Marc Barthelemy. "The multilayer temporal network of public transport in Great Britain." Scientific data 2.1 (2015): 1-8.

# Transport multi-layer network




Asgari, Fereshteh, et al. "CT-Mapper: Mapping sparse multimodal cellular trajectories using a multilayer transportation network." Computer Communications 95 (2016): 69-81.

# Types of Transportation Networks



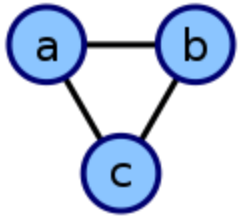

https://transportgeography.org/contents/chapter9/transportation-and-disasters/transportation-networks-vulnerabilities/

# System Representation

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

# System Representation

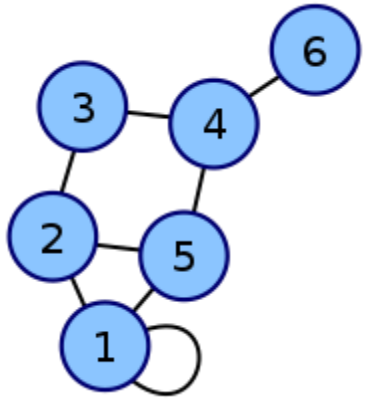
- Adjacency list is a collection of unordered lists used to represent a finite graph.
- List contains the set of neighbors of a vertex in the graph.
- Undirected graphs:
  - data structure two different linked list nodes for each edge




| Adjacency list representation | |
|---|---|
| a | b |
| a | c |
| b | a |
| b | c |
| c | a |
| c | b |

# System 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.

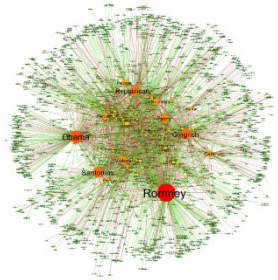



$$\begin{pmatrix} 2 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

# System Representation

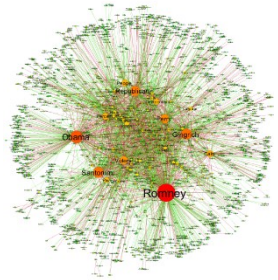
- Multilayer Network representation:
- Systems can be described by representing many interacting entities in
  - a Single network or
  - Multilayer networks
- Examples social networks, neural networks
- Co-occurring network structure made by links, activity as the nodes (e.g. community structure between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

# 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

# System Network analysis

- 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.

https://en.wikipedia.org/wiki/Complex_network

# System 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

# System 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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Bangla
Ευχαριστώ
Greek
Thank You
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