INDIAN INSTITUTE OF INFORMATION TECHNOLOGY

Knowledge Representation and Reasoning

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Knowledge Representation (KR)

- Knowledge can be represented in an explicit declarative form, suitable for processing by dedicated symbolic reasoning engines.
- Exploitation of knowledge implicitly through semantically grounded inference mechanisms.
- Well-established and lively field of research within AI
- KR has contributed to the theory and practice of various areas in AI
  - agents, automated planning and natural language processing,
  - fields beyond AI: data management, semantic web, verification, software engineering, robotics, computational biology, and cyber security.
- Use of, or contributions to, the principles and practice of KR.
  - Field of applications, experiments, developments, and tests

https://kr.org

Knowledge Representation (KR)

KR and Reasoning deal with the following topics.

1. Topics in logical theory and the theory of computation, including
   a. Nonmonotonic logic
   b. Complexity theory
2. Studies in application areas, including
   a. Temporal reasoning
   b. Formalisms for reasoning about planning, action and change, and causality
   c. Meta reasoning
   d. Reasoning about context
   e. Reasoning about values and desires
   f. Reasoning about the mental states of other agents, and especially about knowledge and belief
   g. Spatial reasoning
   h. Reasoning about vagueness

Stanford Encyclopedia of Philosophy **Logic and Artificial Intelligence** https://plato.stanford.edu/entries/logic-ai/

Knowledge Representation (KR)

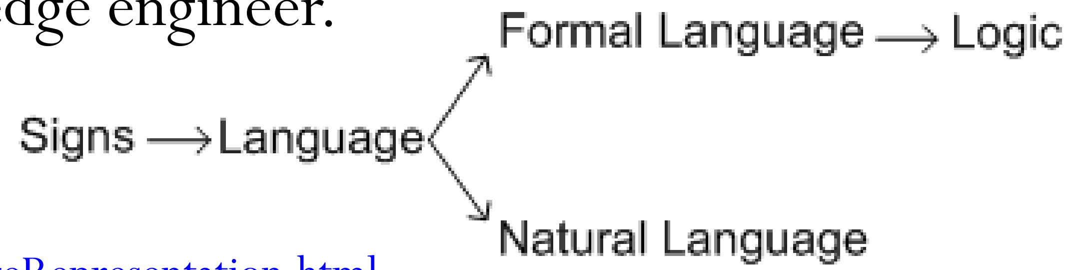
KR and Reasoning deal with the following topics.

3. Argumentation and argumentation theory
4. Aggregation problems of many kinds, such as the integration of conflicting knowledge sources
5. Studies in application techniques, including
   a. Logic programming
   b. Description logics
   c. Theorem proving
   d. Model construction
6. Studies of large-scale applications, including
   a. Cognitive robotics
   b. Merging, updating, and correcting knowledge bases

Stanford Encyclopedia of Philosophy **Logic and Artificial Intelligence** https://plato.stanford.edu/entries/logic-ai/

Knowledge Sharing

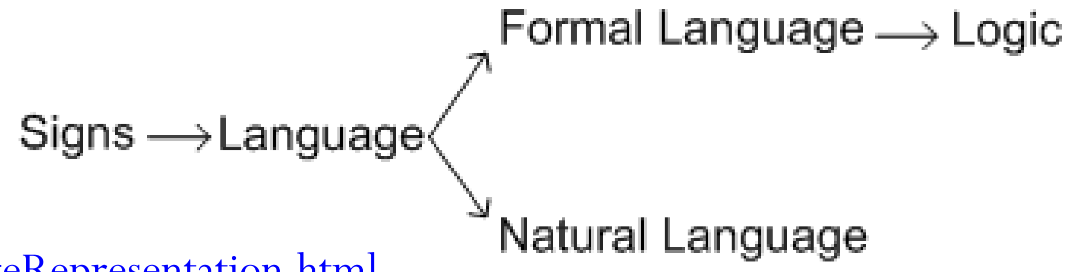
- **Social agents** gets access to more than the knowledge it has been able to build up
- Agents have access to more than individual experiences and even unprecedented situations can be resolved satisfactorily.
- Knowledge exchange mechanisms based on signs and thus studied by Semiotics.
- **Semiotics:** the study of signs and symbols and their use or interpretation.
- **Symbols** are **surrogates** (takes place of something else) for the external things.
- Symbols and links between them form a model of the external system that can be manipulated to simulate it or reason about it.
- Useful to Application designer or Knowledge engineer.



https://rhizomik.net/html/~roberto/thesis/html/KnowledgeRepresentation.html

Knowledge Sharing

- **Ambiguity** also allows exploration of new possibilities because knowledge is not confined in a restrictive immutable form.
- **Example: DNA** and **Metaphors** (used in place of another to suggest a likeness or analogy between them)
  - produces a new interpretation of a previous representation inside a particular context
- **Knowledge engineers** who manage knowledge tools.
- **Domain experts** who understand the application domain.
- Domain experts should be able to read and verify the domain definitions and rules written by knowledge engineers.



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Knowledge Representations

- The knowledge accumulations in the knowledge management systems can be
  - **Logic:** provides the formal structure and rules of inference.
  - **Ontology:** defines the kinds of things that exist in the application domain.
  - **Computation:** supports the applications that distinguish knowledge representation from pure philosophy.
- Application of Knowledge Representation techniques are enormous.
- Computers provides powerful processors of more or less rich information sources.
- Interpretation of the results is carried out by the agents (or human users).

https://rhizomik.net/html/~roberto/thesis/html/KnowledgeRepresentation.html

Knowledge Representations

- KR is used in Artificial Intelligence System
- Knowledge is more than the sum of its Knowledge Representation.
- **World Wide Web** is becoming the biggest accumulation of knowledge.
- Application of logic and ontology to the task of constructing computable models of some domain.
- **Logic** and **Ontology** provide the formalization mechanisms required to make expressive models.
- Computational resources provide great quantities of knowledge expressed that can be automated.

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Knowledge Representation Principles

- **Surrogate** (takes place of something else): symbols are used to represent external things that cannot be stored in a computer, i.e. physical objects, events, and relationships.
- **Set of ontological commitments:** Ontology determines the categories of things that exist or may exist in an application domain.
- **Fragmentary theory of intelligent reasoning:** To support reasoning about modelled things in a domain, behavior and interactions. Explicit axioms or compiled into computable programs.
- **Medium for efficient computation:** Encode knowledge in a form that can be processed efficiently by the available computing equipment (hardware and programming).
- **Medium for human expression:** KR language facilitate communication between the Knowledge engineer and the domain expert.

https://rhizomik.net/html/~roberto/thesis/html/KnowledgeRepresentation.html

R. Davis, H.S. & Szolovits, P.: "What is knowledge representation?". AI Magazine, Vol. 14, No. 1, pp. 17-33, 1993

Levels of representation

- KRs range from computer-oriented forms to conceptual ones nearer to those present in our real-world models.
- Five knowledge levels can be established using this criterion:

Computer Oriented

  - Implementational: computer level includes data structures such as atoms, pointers, lists and other programming notations.
  - Logical: symbolic logic like propositions, predicates, variables, quantifiers and Boolean operations are included.
  - Epistemological: defining concept types with subtypes, inheritance, and structuring relations.
  - Conceptual: semantic relations, linguistic roles, objects and actions.
  - Linguistic: computers distant level, it deals with arbitrary concepts, words and expressions of natural languages.

Real World

https://rhizomik.net/html/~roberto/thesis/html/KnowledgeRepresentation.html

Brachman, R.J.: "On the Epistemological Status of Semantic Networks". In Findlet, N.V. (ed.): "Associative Networks: Representation and Use of Knowledge by Computers". Academic Press, pp. 3-50, 1979

Logic (universal language & mathematical principles)

- **Vocabulary:** collection of symbols represented as chars, words, icons, or even sounds.
  - **Logical symbols:** they are domain-independent, e.g. quantifiers like "$\forall$" or connectives like "$\wedge$".
  - **Constants:** these are domain dependent and identify individuals, properties or relations in the application domain, or universe of discourse. E.g. "car number", "mobile number"
  - **Variables:** they are unbounded symbols whose range of application is governed by quantifiers.
  - **Punctuation:** utility symbols that separate or group other symbols, e.g. commas and parenthesis.
- **Syntax:** a logic grammar rules that determine how symbols combine to form well-formed sentences.
- **Semantics:** to make meaningful statements that determines how the constants and variables relate to things in the universe of discourse. to distinguish true statements from false.
- **Inference:** to get something more than a notation. Rules that determine how patterns are generated from others. Reasoning mechanisms automation to generate new knowledge from previous one.

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Model checking

- Given a **Knowledge Base (KB)**, does sentence S hold?
- Basically generate and test:
  - Generate all the possible models
  - Consider the models M in which KB is TRUE
  - If $\forall$M S, then S is **provably true**
  - If $\forall$M $\neg$S, then S is **provably false**
  - Otherwise ($\exists$M1 S $\wedge$ $\exists$M2 $\neg$S): S is **satisfiable** but neither provably true or provably false

Generalized Logic

- General case: **Given**
  - **atomic sentences** $P_1, P_2, \ldots, P_N$
  - **implication sentence** $(Q_1 \wedge Q_2 \wedge \ldots \wedge Q_N) \rightarrow R$
    - $Q_1, \ldots, Q_N$ and R are atomic sentences
  - **substitution** $subst(\theta, P_i) = subst(\theta, Q_i)$ for $i=1,\ldots,N$
  - **Derive new sentence: subst(θ, R)**
- Substitutions
  - subst(θ, α) denotes the result of applying a set of substitutions defined by θ to the sentence α
  - A substitution list $\theta = \{v_1/t_1, v_2/t_2, \ldots, v_n/t_n\}$ means to replace all occurrences of variable symbol v_i by term t_i
  - Substitutions are made in left-to-right order in the list
  - subst({x/IceCream, y/Ziggy}, eats(y,x)) = eats(Ziggy, IceCream)

Knowledge Base (KB) example

- KB:
  - allergies(X) $\rightarrow$ sneeze(X)
  - cat(Y) $\wedge$ allergic-to-cats(X) $\rightarrow$ allergies(X)
  - cat(Felix)
  - allergic-to-cats(Lise)
- Goal:
  - sneeze(Lise)

Knowledge base Agent

function KB-AGENT(*percept*) **returns** an *action*
  persistent: *KB*, a knowledge base
      t, a counter, initially 0, indicating time

  TELL(*KB*, MAKE-PERCEPT-SENTENCE(*percept*, *t*))
  action ← ASK(*KB*, MAKE-ACTION-QUERY(*t*))
  TELL(*KB*, MAKE-ACTION-SENTENCE(*action*, *t*))
  $t \leftarrow t + 1$
  return *action*

Figure 7.1 A generic knowledge-based agent. Given a percept, the agent adds the percept to its knowledge base, asks the knowledge base for the best action, and tells the knowledge base that it has in fact taken that action.

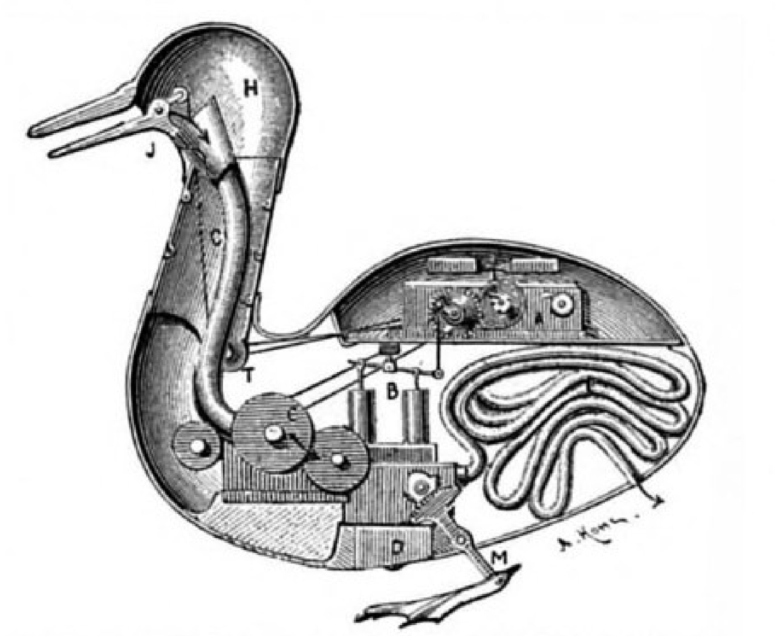
Knowledge engineering

- Modeling the “right” conditions and the “right” effects at the “right” level of abstraction is very difficult
- Knowledge engineering create and maintain knowledge bases for intelligent reasoning
  - **Logic** is a great knowledge representation language for many AI problems
  - **Propositional logic** is the simple foundation and fine for some AI problems
  - **First order logic** (FOL) is much more expressive as a KR language and more commonly used in AI
  - **Variations**: horn logic, higher order logic, three-valued logic, probabilistic logics, etc.
- Automated knowledge acquisition and machine learning tools can fill the gap.
- Intelligent systems should be able to **learn**
  - about the conditions and effects, just like we do!
  - when to pay attention to, or reason about, certain aspects of processes, depending on the context!

Knowledge Representation:
Complex Systems and Graphs (Networks)

Complex system 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

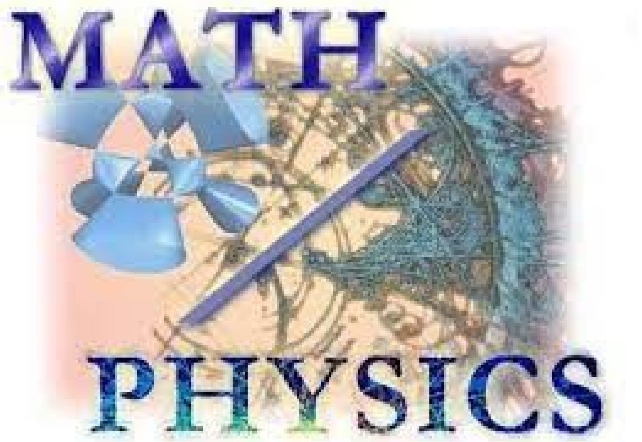


Complex system properties

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

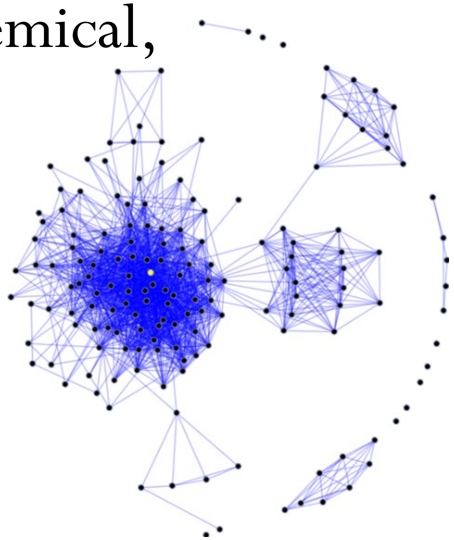
Complex system and Disciplines

- **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

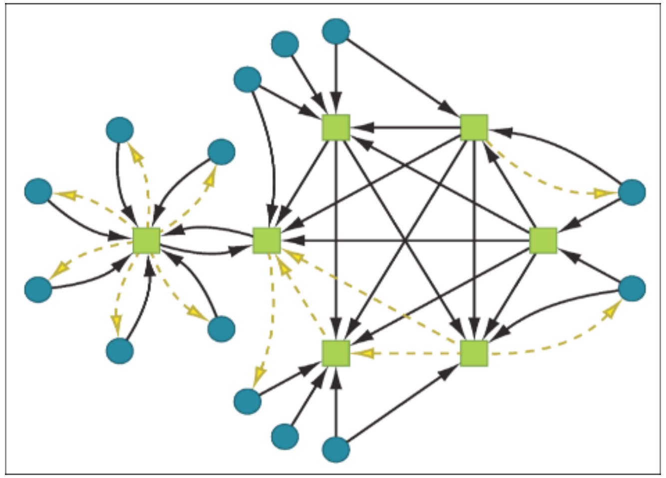


Complex system and Disciplines

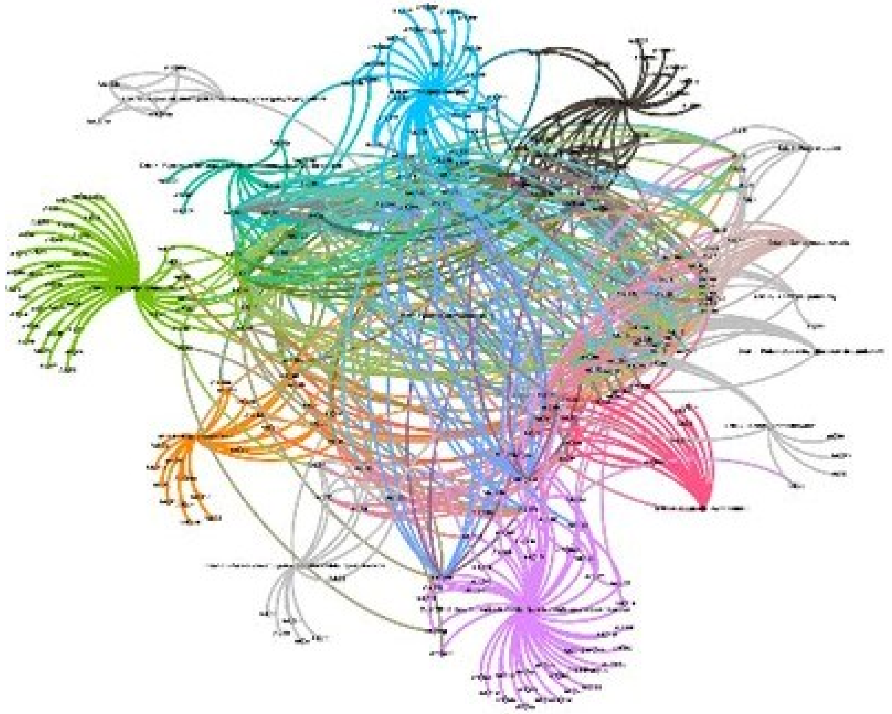
- **Computer science:** programming creates complex systems, and application involving complex real-world data,
- **Sociology:** studies human behaviour, social behavior, society, patterns of social relationships, social interaction, and culture
- **Social network analysis:** investigate social structures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



Complex system and Graph Theory

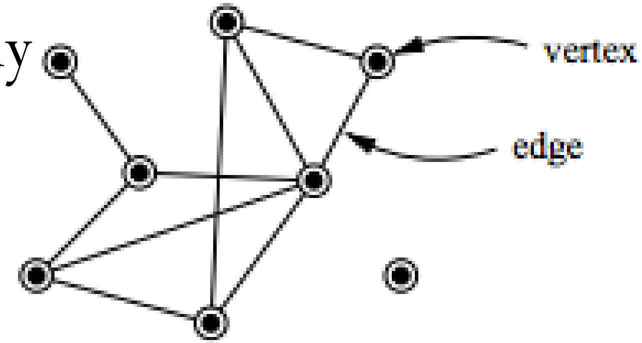


- Represented with a network (graph)
  - nodes represent the components (or entities) and
  - edges (or links) represents entities' interactions.
- Depicts collection of discrete objects and relationships between them
  - persons within an organization,
  - logic gates in a circuit,
  - genes in gene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



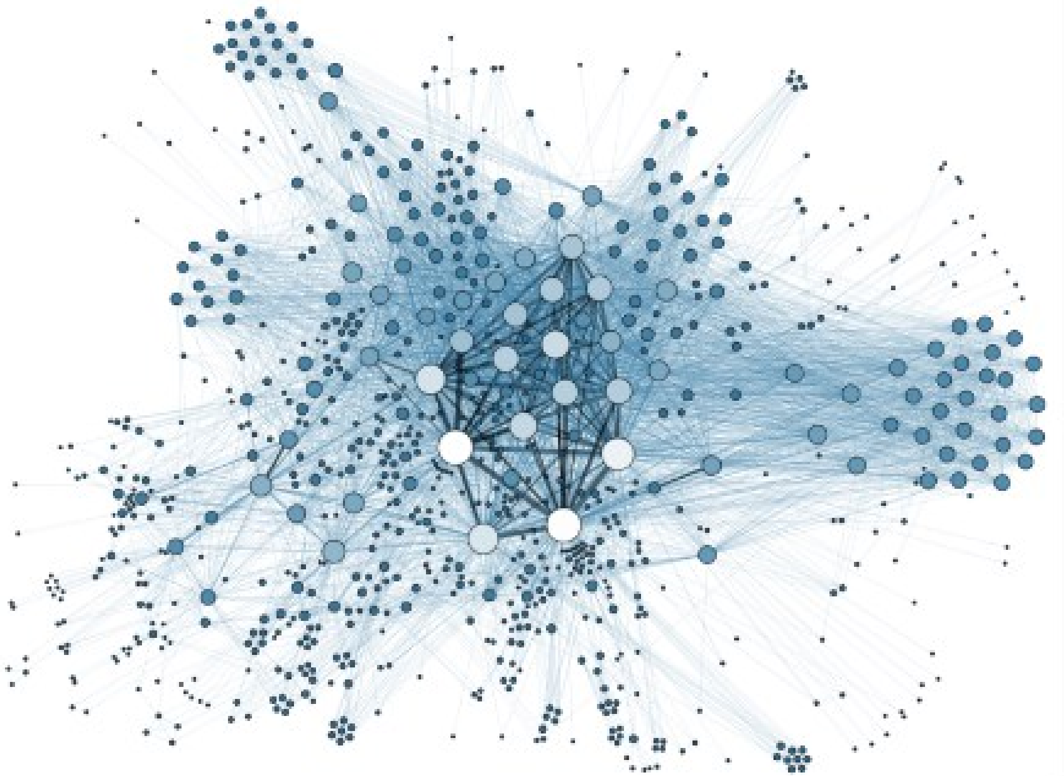
Graph Theory

- 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 $G = (V, E, \varnothing)$
  - V is a set of vertices (or nodes)
  - E is a set of edges (or links)
  - $\varnothing: E \rightarrow \{\{x, y\} \mid x, y \in V \text{ and } x \neq y\}$ an incidence function mapping every edge to an unordered pair of vertices

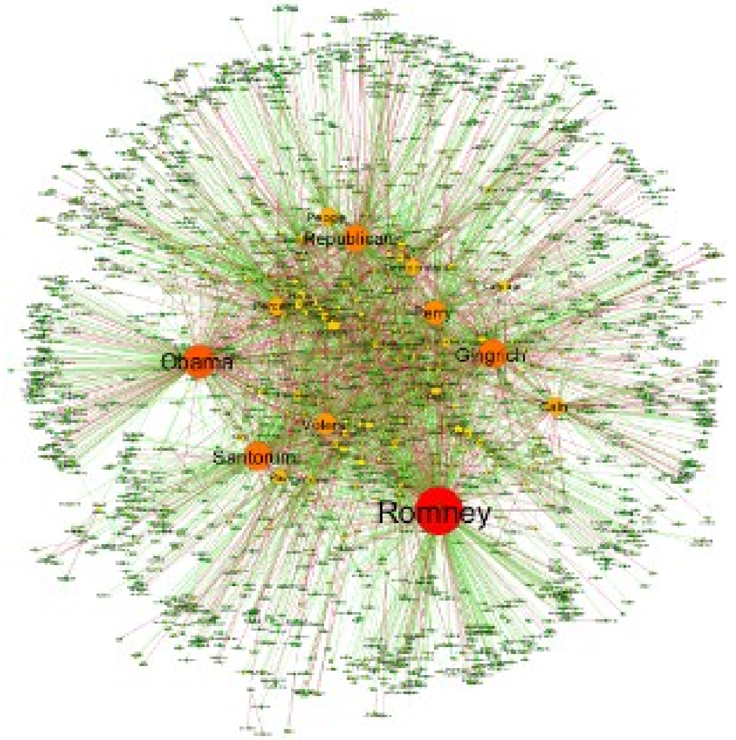


Network Theory

- 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

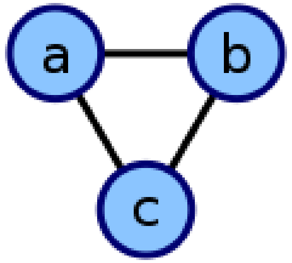
- **Network flow:** "Directed graph where each edge has a capacity and each edge receives a flow, where the amount of flow on an edge cannot exceed the capacity of the edge"
- **Transport problem:** study of optimal transportation and allocation of resources.
- **Trans-shipment problem:** a subgroup 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 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

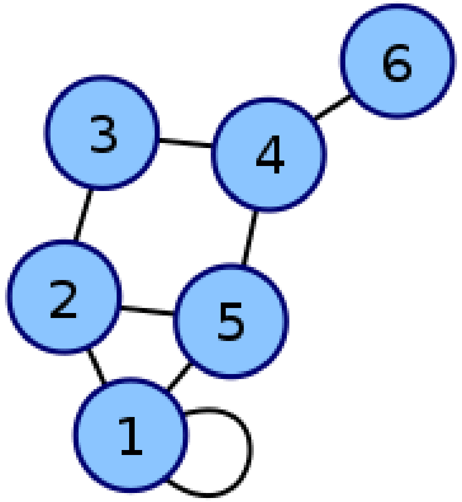
- Adjacency list is a collection of unordered lists used to represent a finite graph.
- List contains the set of neighbors of a vertex in the graph.
- Undirected graphs:
  - data structure two different linked list nodes for each edge



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.



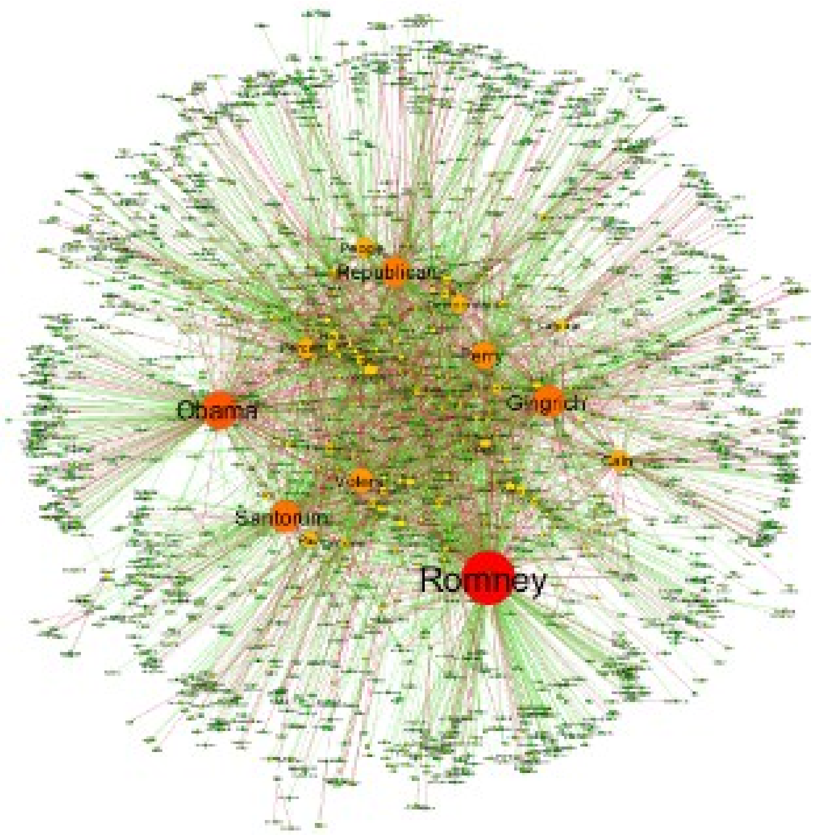
$$\begin{pmatrix} 2 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

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.

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.



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

Complex Network analysis

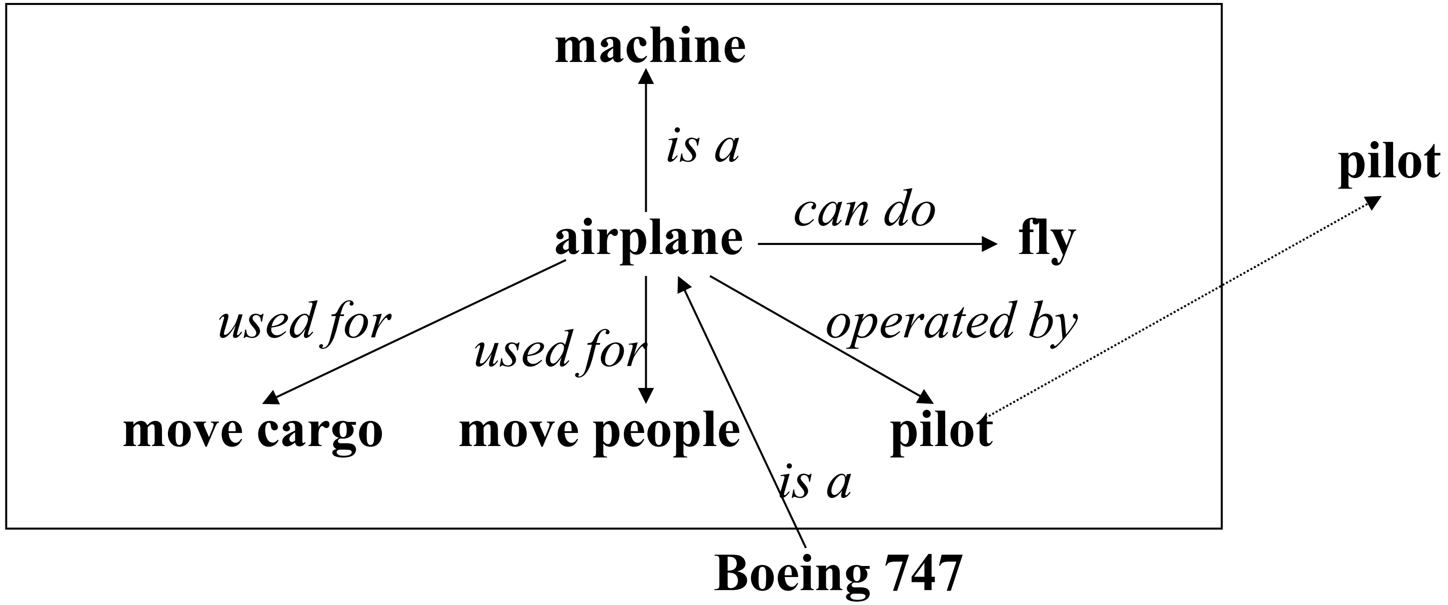
- **Electric power systems analysis:**
  - a graph consists from representing electric power aspects (e.g., transmission line impedances)
- **Biological network analysis:**
  - analysis of molecular networks
  - visualize the nature and strength of interactions between species
  - Gene Regulatory Networks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

Complex Network analysis

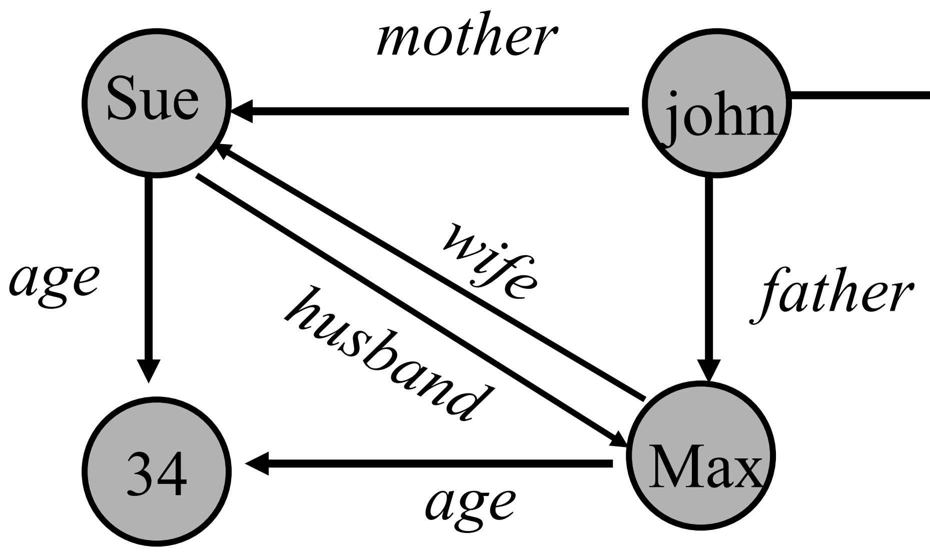
- **Computer science:** graphs are used to represent networks of communication, data organization, computational devices, the flow of computation, etc.
  - **Link analysis:** the link structure of a World Wide Web, Internet, Computer Network
  - website can be represented by a directed graph,
  - the 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

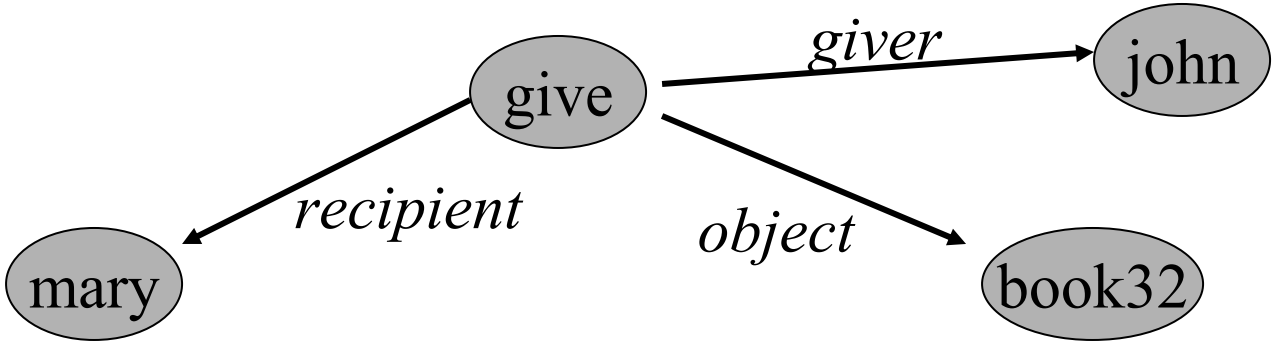
Nodes (Vertices) and Links (Arcs)

- **Nodes** for words /entities / objects / classes
- Directed **links** for relations/associations between words
  - Each link has its own meaning, define binary relationships between objects.
- All nodes define words and meaning (semantics) of the associated links
- Otherwise, follow the links to the definitions of related words



Semantic Graphs

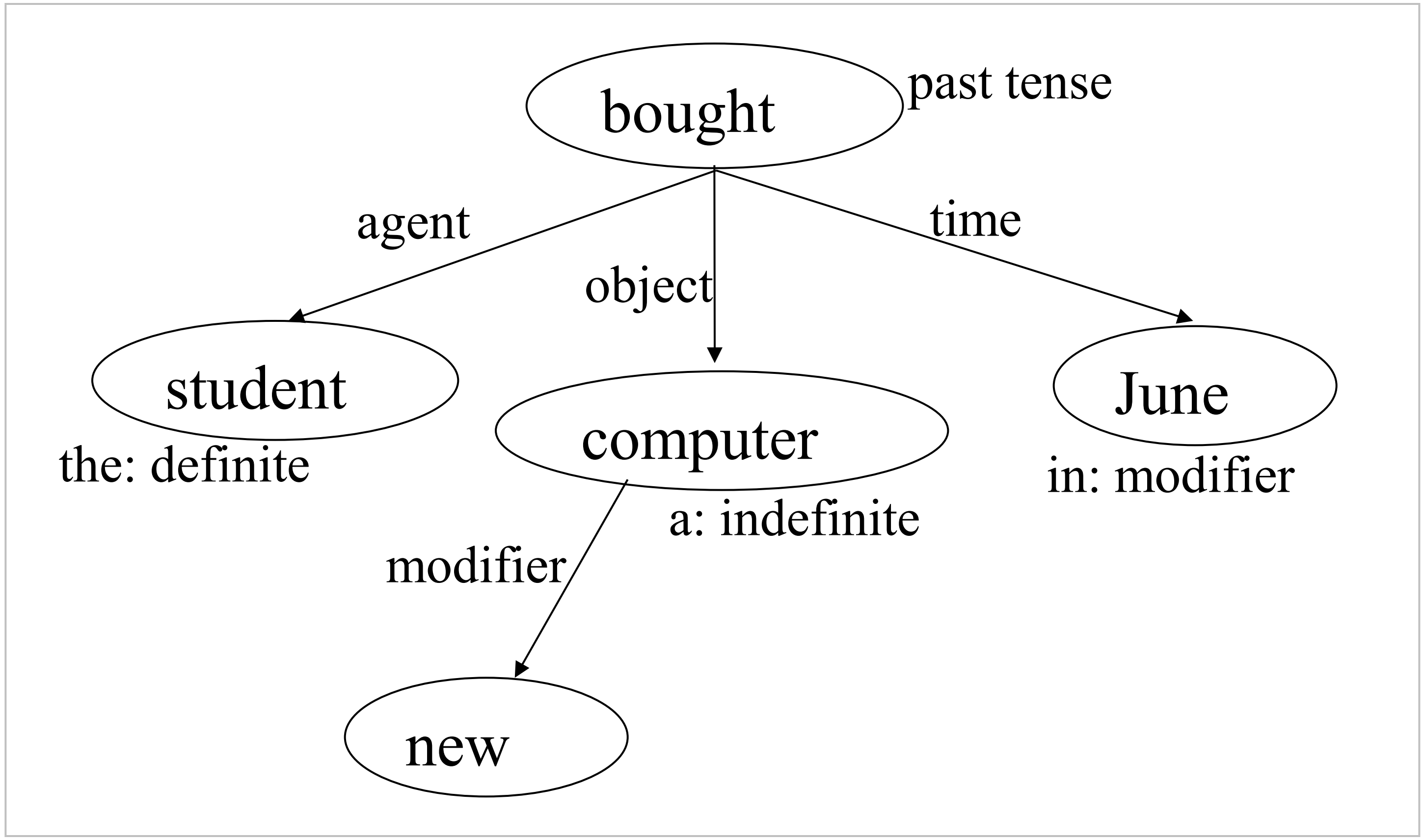




Subject-predicate-object triples:

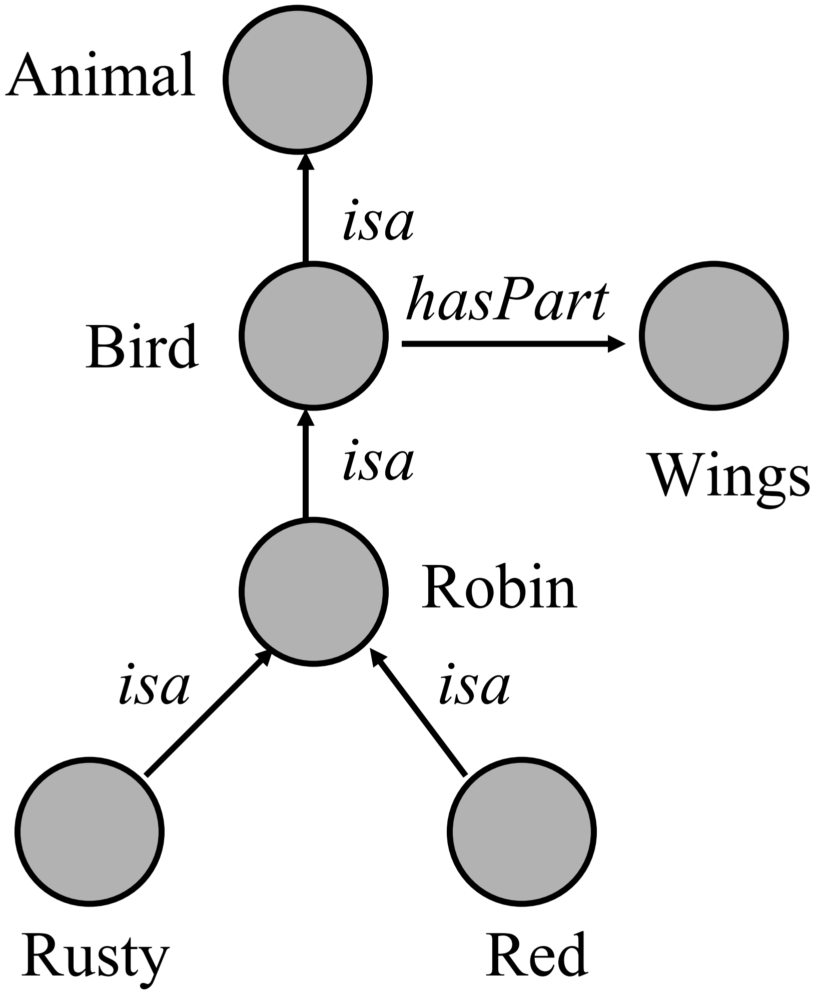
mother(john, sue)
age(john,5)
wife(sue, max)
age(sue, 34)
...

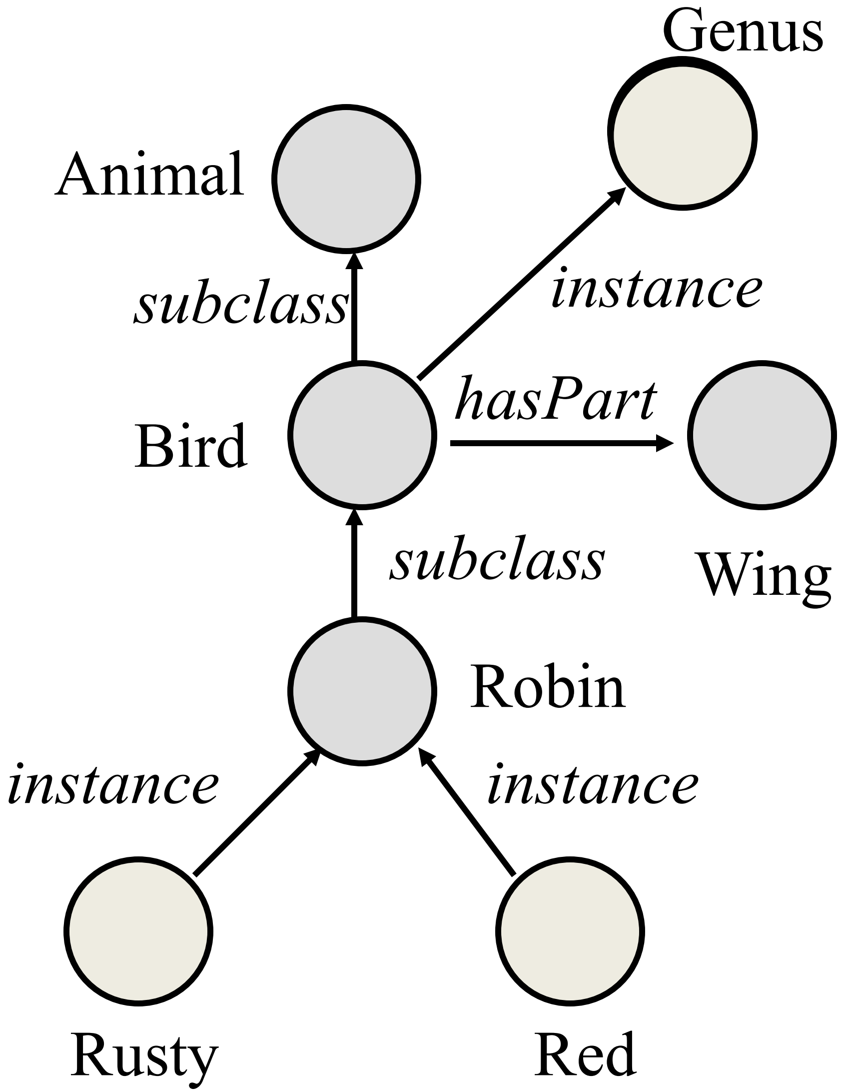
Semantic Graphs



The student bought a new computer in June.

Relation: is a, subclass, instance-of





Reasoning

Deduction, Abduction, and Induction

Deduction:	major premise:	All balls in the box are black
	minor premise:	These balls are from the box
	conclusion:	These balls are black

A => B
A

B

Abduction:	rule:	All balls in the box are black
	observation:	These balls are black
	explanation:	These balls are from the box

A => B
B

Possibly A

Induction:	case:	These balls are from the box
	observation:	These balls are black
	hypothesized rule:	All ball in the box are black

Whenever A then B

Possibly A => B

Deduction reasons from causes to effects

Abduction reasons from effects to causes

Induction reasons from specific cases to general rules

Sources of uncertainty

- Uncertain **inputs**
  - Missing data
  - Noisy data
- Uncertain **knowledge**
  - Multiple causes lead to multiple effects
  - Incomplete enumeration of conditions or effects
  - Incomplete knowledge of causality in the domain
  - Probabilistic/stochastic effects
- Uncertain **outputs**
  - Abduction and induction are inherently uncertain
  - Default reasoning, even in deductive fashion, is uncertain
  - Incomplete deductive inference may be uncertain
- Probabilistic reasoning only gives probabilistic results (summarizes uncertainty from various sources)

Decision making with uncertainty

- **Rational** behavior:
  - For each possible action, identify the possible outcomes
  - Compute the **probability** of each outcome
  - Compute the **utility** of each outcome
  - Compute the probability-weighted **(expected) utility** over possible outcomes for each action
  - Select the action with the highest expected utility (principle of **Maximum Expected Utility**)

Bayesian reasoning

- Probability theory
- Bayesian inference
  - Use probability theory and information about independence
  - Reason diagnostically (from evidence (effects) to conclusions (causes)) or causally (from causes to effects)
- Bayesian networks
  - Compact representation of probability distribution over a set of propositional random variables
  - Take advantage of independence relationships

Other uncertainty representations

- Default reasoning
  - Nonmonotonic logic: Allow the retraction of default beliefs if they prove to be false
- Rule-based reasoning
  - Certainty factors: Mycin is a historic expert system in artificial intelligence for medical diagnosis, propagate simple models of belief through causal or diagnostic rules.
- Evidential reasoning (Belief Theory or Evidence Theory or Dempster-Shafer theory)
  - Bel(P) is a measure of the evidence for P;
    Bel(¬P) is a measure of the evidence against P;
    together they define a belief interval (lower and upper bounds on confidence)
- Fuzzy reasoning
  - Fuzzy sets: How well does an object satisfy a vague property?
  - Fuzzy logic: "How true" is a logical statement?

Uncertainty tradeoffs

- **Bayesian networks:** Nice theoretical properties combined with efficient reasoning make BNs very popular; limited expressiveness, knowledge engineering challenges may limit uses
- **Nonmonotonic logic:** Represent commonsense reasoning, but can be computationally very expensive
- **Certainty factors:** Not semantically well founded
- **Dempster-Shafer theory:** Has nice formal properties, but can be computationally expensive, and intervals tend to grow towards [0,1] (not a very useful conclusion)
- **Fuzzy reasoning:** Semantics are unclear (fuzzy!), but has proved very useful for commercial applications

ขอบคุณ
Thai

Grazie
Italian

תודה רבה
Hebrew

धन्यवादः
Sanskrit

ಧನ್ಯವಾದಗಳು
Kannada

Ευχαριστώ
Greek

Thank You
English

Gracias
Spanish

Спасибо
Russian

Obrigado
Portuguese

شكراً
Arabic

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

Merci
French

多謝
Traditional Chinese

धन्यवाद
Hindi

Danke
German

多谢
Simplified Chinese

நன்றி
Tamil
Tamil

ありがとうございました
Japanese

감사합니다
Korean