Knowledge Representation and Reasoning

Chapter 12

Some material adopted from notes by
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Overview

- Approaches to knowledge representation
- Deductive/logical methods
  - Forward-chaining production rule systems
  - Semantic networks
  - Frame-based systems
  - Description logics
- Abductive/uncertain methods
  - What's abduction?
  - Why do we need uncertainty?
  - Bayesian reasoning
  - Other methods: Default reasoning, rule-based methods, Dempster-Shafer theory, fuzzy reasoning

Introduction

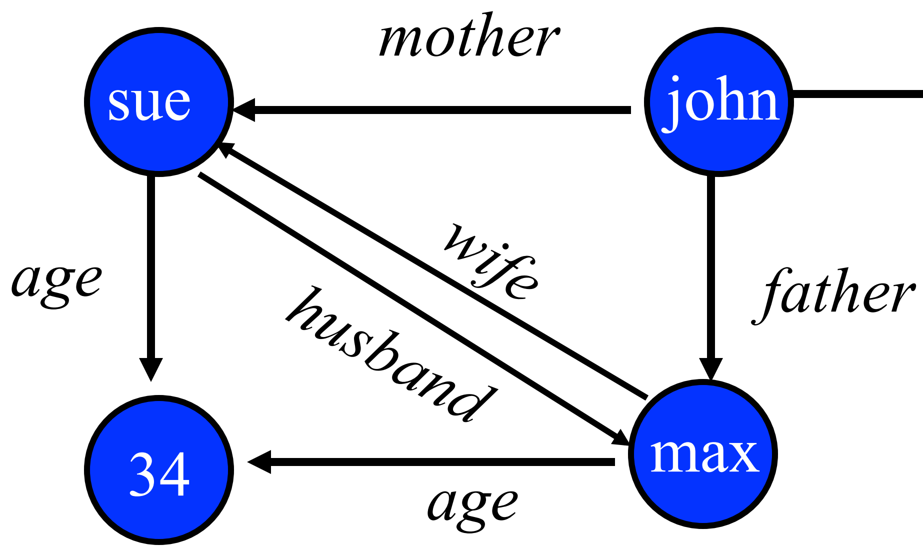
- Real knowledge representation and reasoning systems come in several major varieties
- These differ in their intended use, expressivity, features,…
- Some major families are
  - Logic programming languages
  - Theorem provers
  - Rule-based or production systems
  - Semantic networks
  - Frame-based representation languages
  - Databases (deductive, relational, object-oriented, etc.)
  - Constraint reasoning systems
  - Description logics
  - Bayesian networks
  - Evidential reasoning

Semantic Networks

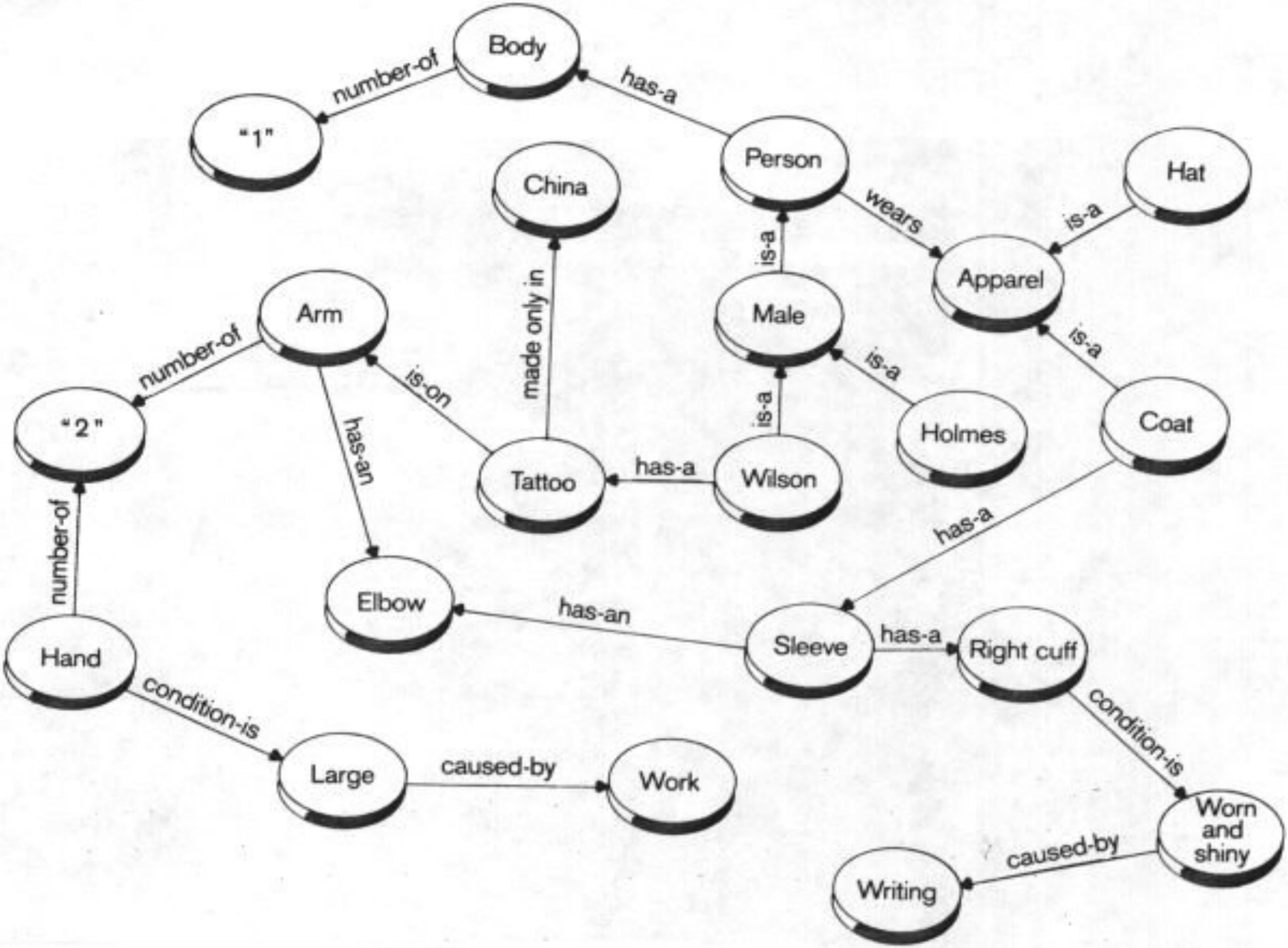
- Simple representation scheme: a graph of labeled nodes and labeled, directed arcs to encode knowledge
  - often used for static, taxonomic, concept dictionaries
- Typically used with a special set of accessing procedures that perform "reasoning"
  - e.g., inheritance of values and relationships
- Semantic networks popular in 60s & 70s, less used in '80s &'90s, back since '00s as RDF
  - less expressive than other formalisms: both a feature & bug!
- The **graphical depiction** associated with a semantic network is a significant reason for their popularity

Nodes and Arcs

Arcs define binary relationships that hold between objects denoted by the nodes

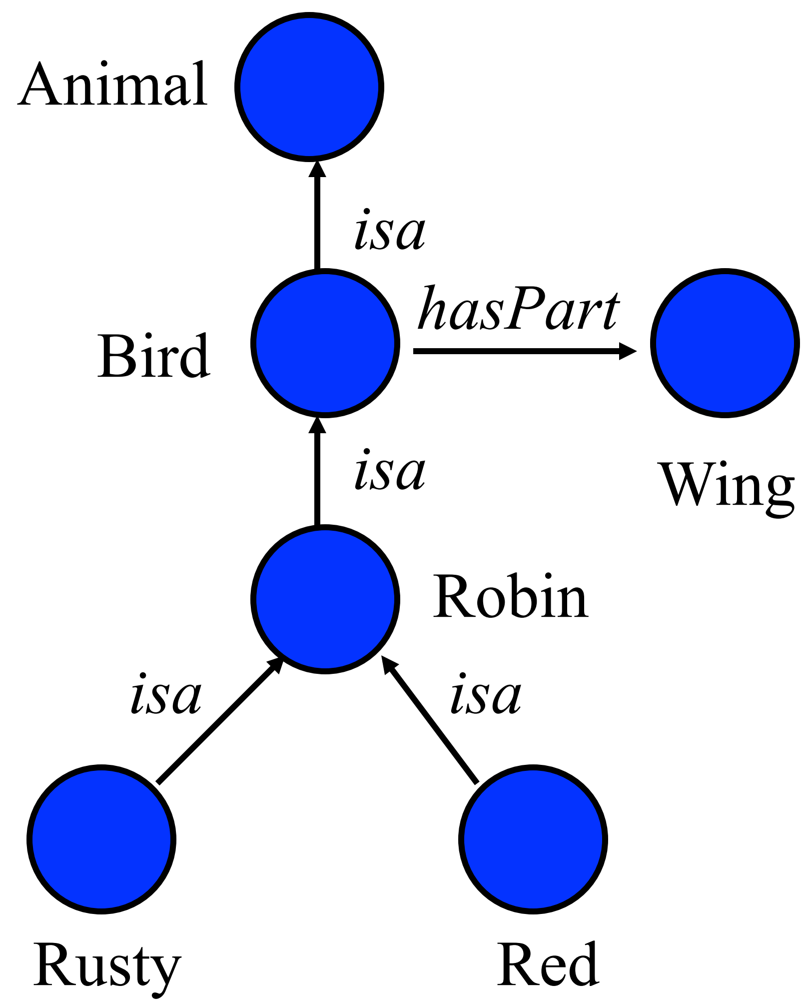


mother(john, sue)
age(john, 5)
wife(sue, max)
age(max, 34)
...


Body
number-of
"1"
has-a
Person
China
Hat
wears
is-a
is-a
made only in
Apparel
Male
Arm
number-of
is-a
is-on
is-a
"2"
has-an
is-a
Holmes
Coat
Tattoo
has-a
Wilson
number-of
has-a
Elbow
has-an
Hand
Sleeve
has-a
Right cuff
condition-is
condition-is
Large
caused-by
Work
Worn and shiny
caused-by
Writing

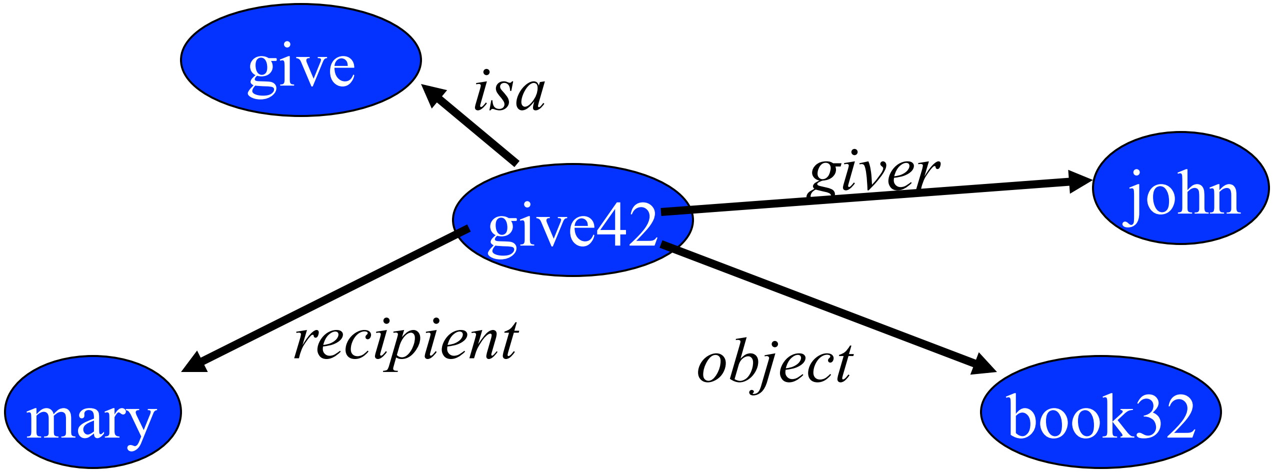
Semantic Networks

- The ISA (is-a) or AKO (a-kind-of) relation is often used to link instances to classes, classes to superclasses
- Some links (e.g. hasPart) are inherited along ISA paths.
- The *semantics* of a semantic net can be relatively informal or very formal
  - often defined at the implementation level



Reification

- Non-binary relationships can be represented by "turning the relationship into an object"
- Logicians and philosophers call this "reification"
  - reify v : consider an abstract concept to be real
- We might want to represent the generic give event as a relation involving three things: a giver, a recipient and an object, give(john,mary,book32)



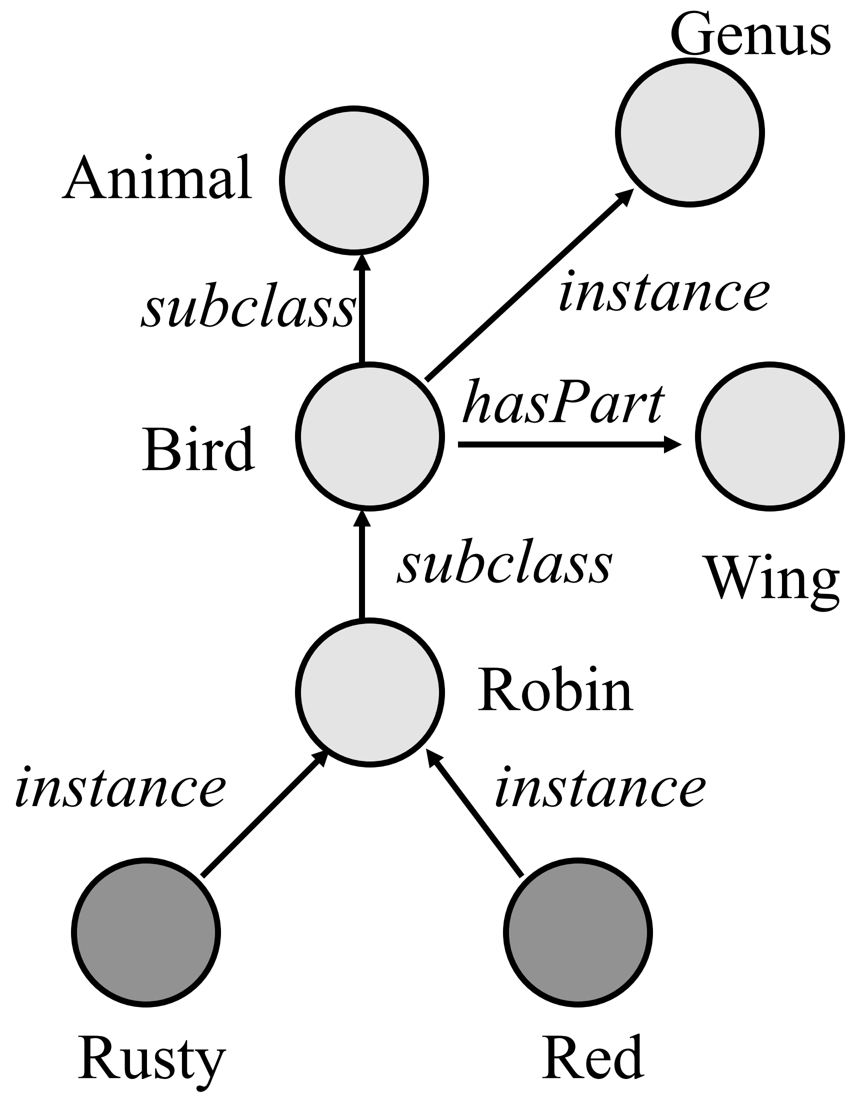
Individuals and Classes

Many semantic networks distinguish

- nodes representing individuals & those representing classes
- subclass from instance_of relation

Formalization must deal with nodes like *Bird*

- OWL uses punning



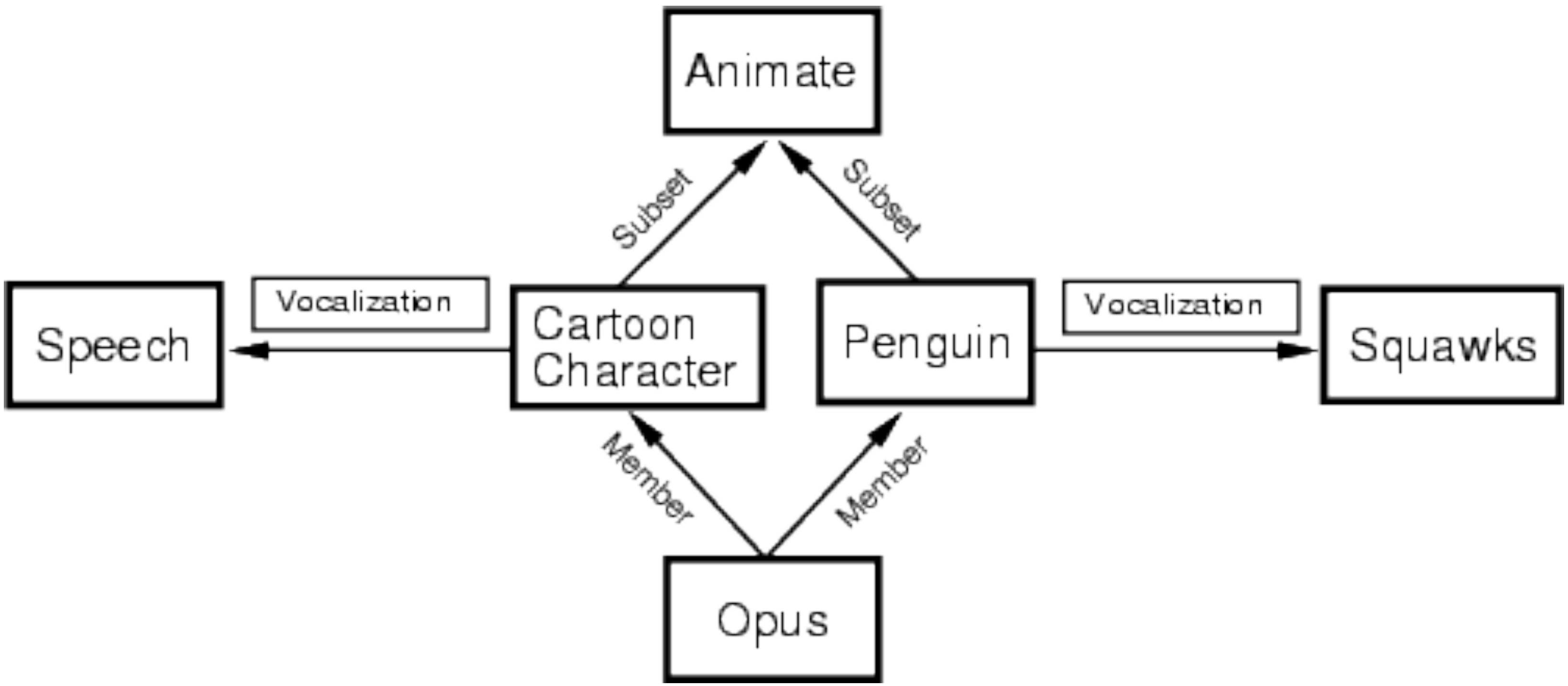
Link types

Link Type	Semantics	Example
$A \xrightarrow{Subset} B$	$A \subset B$	$Cats \subset Mammals$
$A \xrightarrow{Member} B$	$A \in B$	$Bill \in Cats$
$A \xrightarrow{R} B$	$R(A, B)$	$Bill \xrightarrow{Age} 12$
$A \xrightarrow{\boxed{R}} B$	$\forall x \; x \in A \Rightarrow R(x, B)$	$Birds \xrightarrow{\boxed{Legs}} 2$
$A \xrightarrow{\boxed{\boxed{R}}} B$	$\forall x \; \exists y \; x \in A \Rightarrow y \in B \land R(x, y)$	$Birds \xrightarrow{\boxed{\boxed{Parent}}} Birds$

Inference by Inheritance

- An important kind of reasoning done in semantic nets is inheritance along subclass and instance links
- Semantic networks differ in details of
  - Inheriting along subclass or instance links, e.g
    - Only inherit values on instance links
  - inheriting multiple different values, e.g.
    - All possible values are inherited, ***or***
    - Only the "closest" value or values are inherited

Conflicting inherited values

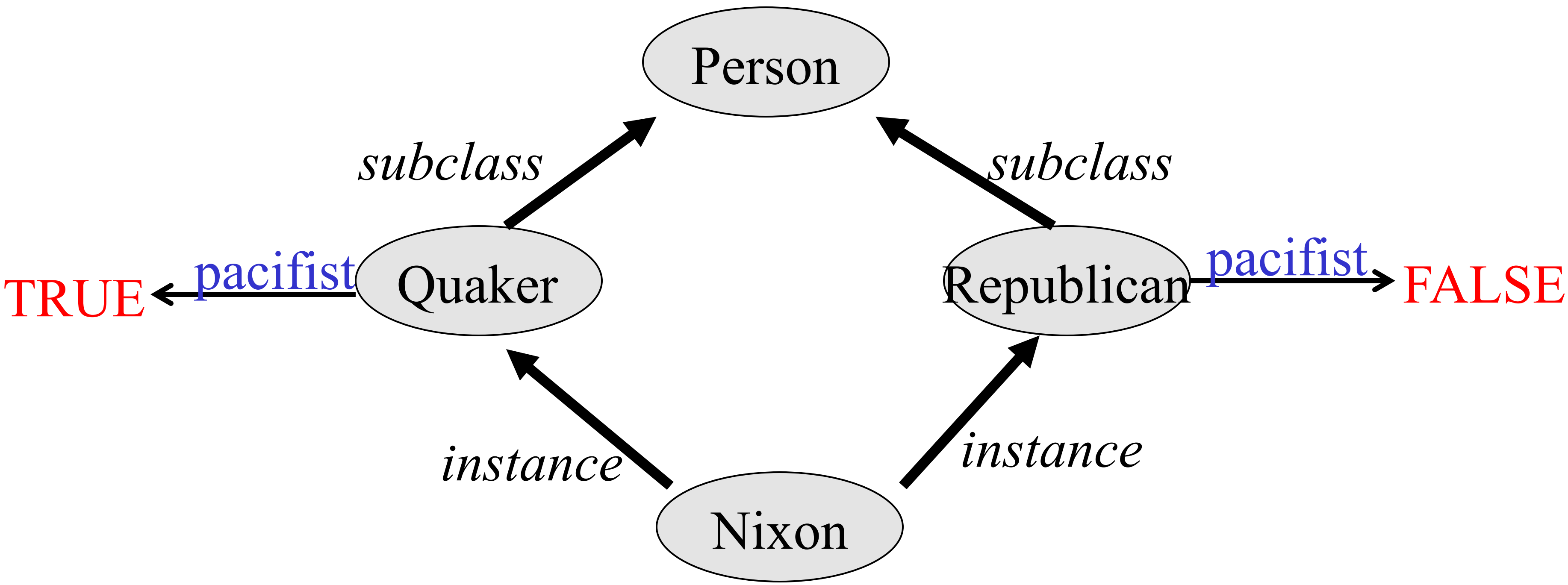


Multiple inheritance

- A node can have any number of super-classes that contain it, enabling a node to inherit properties from multiple parent nodes and their ancestors in the network
- These rules are often used to determine inheritance in such "tangled" networks where multiple inheritance is allowed:
  - If $X<A<B$ and both A and B have property P, then X inherits A's property.
  - If $X<A$ and $X<B$ but neither $A<B$ nor $B<A$, and A and B have property P with different and inconsistent values, then X does not inherit property P at all.

Nixon Diamond

- This was a classic example circa 1980

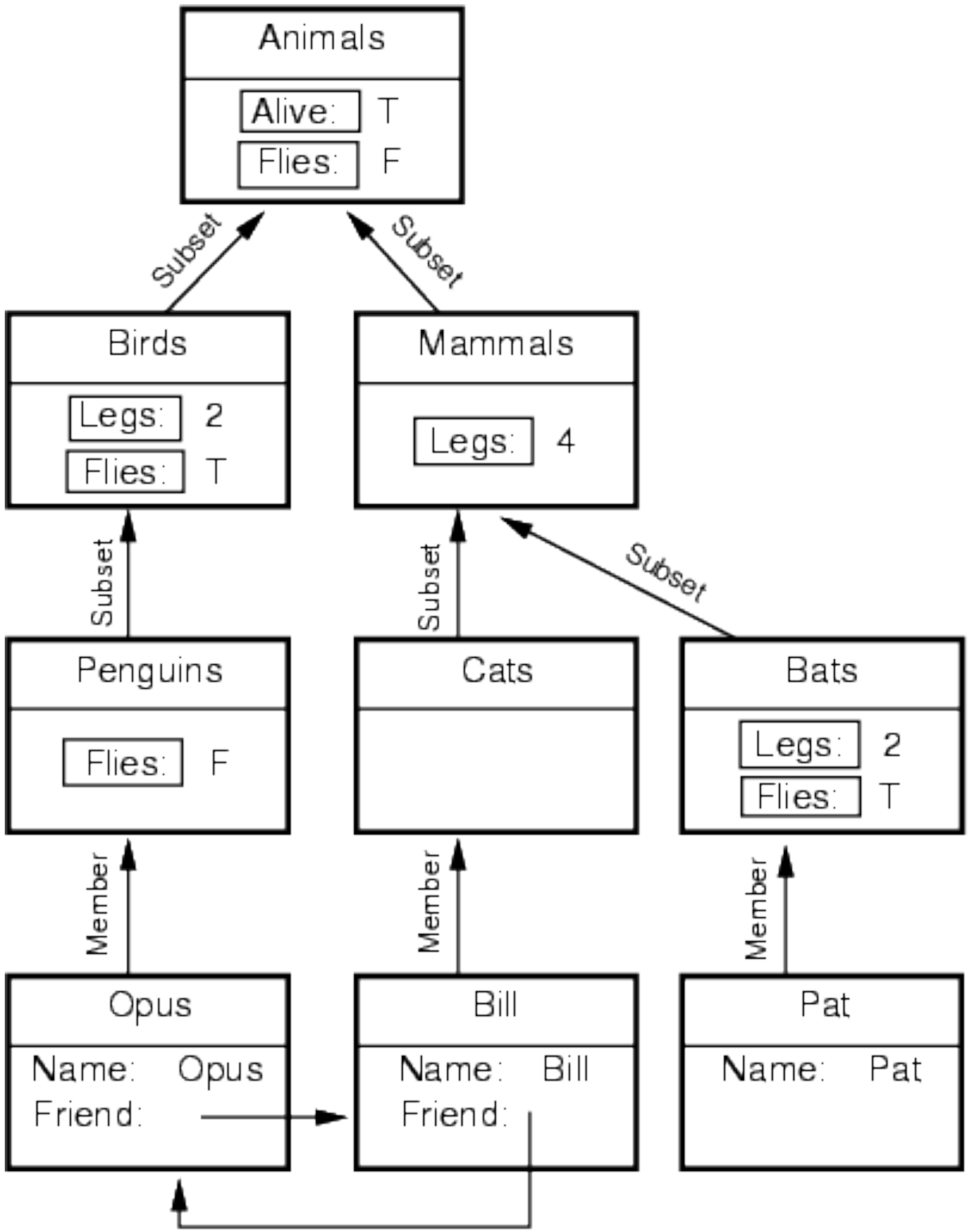


From Semantic Nets to Frames

- Semantic networks morphed into Frame Representation Languages in the 70s and 80s
- A frame is a lot like the notion of an object in OOP, but has more meta-data
- A **frame** has a set of **slots**
- **Slots** represents relations to other frame or literal values (e.g., number or string)
- A slot has one or more **facets**
- A **facet** represents some aspect of the relation

Facets

- A slot in a frame can hold more than a value
- Other facets might include:
  - **Value**: current fillers
  - **Default:** default fillers
  - **Cardinality:** minimum and maximum number of fillers
  - **Type:** type restriction on fillers, e.g another frame
  - **Procedures:** if-needed, if-added, if-removed
  - **Salience:** measure on the slot's importance
  - **Constraints:** attached constraints or axioms
- In some systems, the slots themselves are instances of frames.



(a) A frame-based knowledge base

Rel(Alive,Animals,T)
Rel(Flies,Animals,F)

Birds $\subset$ Animals
Mammals $\subset$ Animals

Rel(Flies,Birds,T)
Rel(Legs,Birds,2)
Rel(Legs,Mammals,4)

Penguins $\subset$ Birds
Cats $\subset$ Mammals
Bats $\subset$ Mammals
Rel(Flies,Penguins,F)
Rel(Legs,Bats,2)
Rel(Flies,Bats,T)

Opus $\in$ Penguins
Bill $\in$ Cats
Pat $\in$ Bats
Name(Opus,"Opus")
Name(Bill,"Bill")
Friend(Opus,Bill)
Friend(Bill,Opus)
Name(Pat,"Pat")

(b) Translation into first-order logic

Description Logics

- Description logics are a family of frame-like KR systems with a formal semantics.
  - E.g., KL-ONE, OWL
- An additional kind of inference done by these systems is automatic **classification**
  - finding the right place in a hierarchy of objects for a new description
- Current systems keep the languages simple, so that all inference can be done in polynomial time (in the number of objects), ensuring tractability of inference
- The Semantic Web language OWL is based on description logic

Abduction

- **Abduction** is a reasoning process that tries to form plausible explanations for observations
  - Distinctly different from deduction and induction
  - Inherently unsound and uncertain
- Uncertainty is an important issue in abductive reasoning
- Some major formalisms for representing and reasoning about uncertainty
  - Mycin's certainty factors (an early representative)
  - **Probability theory (esp. Bayesian belief networks)**
  - Dempster-Shafer theory
  - Fuzzy logic
  - Truth maintenance systems
  - Nonmonotonic reasoning

Abductive reasoning

- **Definition**: reasoning that derives an explanatory hypothesis from a given set of facts
  - The inference result is a **hypothesis** that, if true, could **explain** the occurrence of the given facts
- Example: Dendral, an expert system to construct 3D structure of chemical compounds
  - Fact: mass spectrometer data of the compound and its chemical formula
  - KB: chemistry, esp. strength of different types of bounds
  - Reasoning: form a hypothetical 3D structure that satisfies the chemical formula, and that would most likely produce the given mass spectrum

Abduction examples (cont.)

- Example: Medical diagnosis
  - Facts: symptoms, lab test results, and other observed findings (called manifestations)
  - KB: causal associations between diseases and manifestations
  - Reasoning: one or more diseases whose presence would causally explain the occurrence of the given manifestations
- Many other reasoning processes (e.g., word sense disambiguation in natural language process, image understanding, criminal investigation) can also been seen as abductive reasoning

abduction, deduction & induction

Deduction:	major premise:	All balls in the box are black	**A => B**
	minor premise:	These balls are from the box	**A**
			---------
	conclusion:	These balls are black	**B**
Abduction:	rule:	All balls in the box are black	**A => B**
	observation:	These balls are black	**B**
			-------------
	explanation:	These balls are from the box	**Possibly A**
Induction:	case:	These balls are from the box	**Whenever A then B**
	observation:	These balls are black	**-------------**
	hypothesized rule:	All ball in the box are black	**Possibly A => B**

Deduction: from causes to effects

Abduction: from effects to causes

Induction: from specific cases to general rules

Abductive reasoning characteristics

- *Conclusions* are **hypotheses**, not theorems (may be false *even if* rules and facts are true)
  - E.g., misdiagnosis in medicine
- There may be multiple plausible hypotheses
  - Given rules A => B and C => B, and fact B, both A and C are plausible hypotheses
  - Abduction is inherently uncertain
  - Hypotheses can be ranked by their plausibility (if it can be determined)

Reasoning as a hypothesize-and-test cycle

- **Hypothesize**: generate hypotheses, any of which would explain the given facts
- **Test**: plausibility of all or some of these hypotheses
- One way to test a hypothesis H is to ask whether something that is currently unknown–but can be predicted from H–is actually true
  - If we also know A => D and C => E, then ask if D and E are true
  - If D is true and E is false, then hypothesis A becomes more plausible (**support** for A is increased; **support** for C is decreased)

Non-monotonic reasoning

- Abduction is *non-monotonic* reasoning
- Monotonic: your knowledge can only increase
  - Propositions don’t change their truth value
  - You never unknow things
- In abduction: plausibility of hypotheses can increase/ decrease as new facts are collected
- In contrast, deductive inference is **monotonic:** it never change a sentences truth value, once known
- In abductive (and inductive) reasoning, some hypotheses may be discarded, and new ones formed, when new observations are made

Default logic

- Default logic is another kind of non-monotonic reasoning
- We know many facts which are mostly true, typically true, or true by default
  - E.g., birds can fly, dogs have four legs, etc.
- Sometimes these facts are wrong however
  - Ostriches are birds, but can not fly
  - A dead bird can not fly
  - Uruguay President José Mujica has a three-legged dog

Negation as Failure

- Prolog introduced the notion of *negation as failure,* which is widely used in logic programming languages and many KR systems
- Proving P in classical logic can have three outcomes: true, false, unknown
- Sometimes being unable to prove something can be used as evidence that it is not true
- This is typically the case in a database context
  - Is John registered for CMSC 671?
- If we don't find a record for John in the registrar's database, he is not registered

Default reasoning in Prolog

```
%% this is a simple example of default reasoning in Prolog
:- dynamic can_fly/1, neg/1, bird/1, penguin/1, eagle/1, dead/1, injured/1.

%% We'll use neg(P) to represent the logical negation of P.
%% The \+ operator in prolog can be read as 'unprovable'

% Assume birds can fly unless we know otherwise.
can_fly(X) :-  bird(X), \+ neg(can_fly(X))

bird(X) :- eagle(X).
bird(X) :- owl(X).
bird(X) :- penguin(X).

neg(can_fly(X)) :- penguin(X).
neg(can_fly(X)) :- dead(X).
neg(can_fly(X)) :- injured(X).

% here are some individuals
penguin(chilly).
penguin(tux).
eagle(sam).
owl(hedwig).
```

Circumscription

- Another useful concept is being able to declare a predicate as 'complete' or circumscribed
  - If a predicate is complete, then the KB has all instances of it
  - This can be explicit (i.e., materialized as facts) or implicit (provable via a query)
- If a predicate, say link(From,To) is circumscribed then not being able to prove that link(nyc,tampa) means that neg(link(nyc,tampa)) is true

Default Logic

- We have a standard model for first order logic
- There are several models for defualt reasoning
  - All have advantages and disadvantages, supporters and detractors
- None is completely accepted
- Default reasoning also shows up in object oriented systems
- And in epistemic reasoning (reasoning about what you know)
  - Does President Obama have a wooden leg?

Sources of Uncertainty

- Uncertain **inputs --** missing and/or 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 deductive, 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 action with the highest expected utility (principle of **Maximum Expected Utility**)

Bayesian reasoning

- We will look at using probability theory and Bayesian reasoning next time in some detail
- Bayesian inference
  - Use probability theory & information about independence
  - Reason diagnostically (evidence (effects) to conclusions (causes)) or causally (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

- Rule-based methods
  - Certainty factors (Mycin): propagate simple models of belief through causal or diagnostic rules
- Evidential reasoning
  - 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