Knowledge-Based Systems (KBS)

Machine Learning and Knowledge Engineering

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2 – KBS – Knowledge Engineering and Representation Formalisms

1. Overview: Inference and Knowledge
2. Fundamentals of Knowledge Engineering
3. Knowledge Representation – Basic Principles
4. Basic Techniques of Knowledge Representation
5. Knowledge Representation By (Three) Example(s)

Before we start: About Inference

- Given a knowledge base, how can we infer new knowledge?
- Can we generate/learn a knowledge base from observations?
- What about explanations? Can this somehow be integrated?

Coming back to making conclusions from existing knowledge.

- How do humans do this?
- And how can we model it in a KBS?

KBS – About Inference

- Inference relation: R
- Knowledge: K
- New (inferred) knowledge: O
- With: $(K, O) \in R$

Examples:

- Given some knowledge (formalized in a knowledge base), we can then infer new knowledge
- Given some observations, we can hypothesize some "more general" knowledge
- Given some observations, we can generate explanations (potentially also utilizing some formalized knowledge)

Inference: Basic Computational Modeling

Core element of a KBS: Knowledge base

- Inference: Relation between formalized (given) knowledge, and new (inferred) knowledge – respectively, their knowledge representations
- Syntax of KR language: How to build sentences in the language
- Semantics: "Meaning", i. e., which concepts of the world to represent do the sentences relate to
- Example: $x \leq y$

Modeling:

- With K, O given by syntactic elements, then R is a binary relation on the syntactic level
- $(K, O) \in R$ iff. a human infers *semantics(O)* given *semantics(K)*

Perspectives on R

- *Deduction*: Given K we can infer O given R
- *Abduction*: Given O provide an explanation (K) for O
- *Test*: Check if O logically follows from K
- *Induction*: Learn from a set of observations O some new K, i. e., in a (rule-based) representation

- Original proposal of specific inference types according to [Peirce 1931]: Deduction, Abduction, Induction
- However, many more possible, e. g., relating to inference from uncertain knowledge, etc.

Knowledge Engineering

What is Knowledge Engineering?

- "Knowledge engineering (KE) refers to all technical, scientific and social aspects involved in building, maintaining and using knowledge-based systems." (Wikipedia)
- "Knowledge engineering is a field within artificial intelligence that develops knowledge-based systems. Such systems are computer programs that contain large amounts of knowledge, rules and reasoning mechanisms to provide solutions to real-world problems. [...]" (https://www.igi-global.com/dictionary/)

From Data to Information and Knowledge

So, what about knowledge?
Our working definition of knowledge:

- organized/structured information, with a
- declarative representation

Some questions to start with:

- What is data?
- What is then information?
- What, ultimately is knowledge?
- Is there a relationship between those?
- If so, how can we characterize this relationship?

Data, Information and Knowledge

From [Davenport & Prusak, 1998]:

- "*Data* is a set of discrete, objective facts about events. [....] Data by itself has little relevance or purpose."
- "*Information* is a message, usually in the form of a document or an audible or visible communication. Information is meant to change the way the receiver perceives something, to have an impact on his judgment and behavior. It must inform; it is data that makes a difference."

Knowledge

From [Davenport & Prusak, 1998]:

- "*Knowledge* is a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. In organizations, it often becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms."
- So, according to [Devlin 1999]:
  - Data = symbol + syntax
  - Information = data + meaning
  - Knowledge = internalized information + ability to use it.

KR Principles

Five Principles of Knowledge Representation Formalisms

- "A knowledge representation is
  - a surrogate,
  - a medium of human expression,
  - a set of ontological commitments,
  - a fragmentary theory of intelligent reasoning,
  - and a medium for pragmatically efficient computation."

  [Davis, Shrobe, Szolovits, 1993]
- They way, in which each type of knowledge representation addresses these principles, characterizes their "spirit". Each knowledge representation somehow addresses these (partially contradicting positions) in a specific way.

KR as a Surrogate

- “Knowledge representation is most fundamentally a surrogate, a substitute for the thing itself, used to enable an entity to determine consequences by thinking rather than acting. [...]
- Reasoning is a process that goes on internally [of a person or program], while most things it wishes to reason about exist only externally.”
  [Davis, Shrobe, Szolovits, 1993]

KR as a Medium of Human Expression

- "Knowledge representations are [...] the medium of expression and communication in which we tell the machine (and perhaps one another) about the world. [...] Knowledge representation is thus a medium of expression and communication for the use by us. [...] A representation is the language in which we communicate, hence we must be able to speak it without heroic effort." [Davis, Shrobe, Szolovits, 1993]
- [Davis, Shrobe, Szolovits, 1993] ask: "What things are easily said in the language and what kind of things are so difficult as to be pragmatically impossible?"

KR as Ontological Commitment

- A knowledge representation
  - "is a set of ontological commitments, i.e., an answer to the following question: ‚In what terms should we think about the world? [...]
  - In selecting any representation, we are [...] making a set of decisions about how and what to see in the world. [...]
  - We (and our reasoning machines) need guidance in deciding what in the world to attend to, and what to ignore."

  [Davis, Shrobe, Szolovits, 1993]

KR as Fragmentary Theory of Intelligent Reasoning

- "The initial conception of a knowledge representation is typically motivated by some insight indicating how people reason intelligently, or by some belief about what it means to reason intelligently at all."
  [Davis, Shrobe, Szolovits, 1993]
- The authors mention five areas/perspectives, which discuss intelligent problem solving:
  - Mathematical Logics
  - Psychology
  - Biology
  - Statistics
  - Economics

Models of Knowledge

These different perspectives on knowledge representation lead to different models of knowledge:

- Biology: Networks – Neural Networks
- Mathematical Logics: Deduction – Logical Calculus, Prolog
- Statistics – Uncertainty: Fuzzy-Logics, Bayesian Networks
- Philosophy/Psychology: Semantic Networks, Frames, Ontologies, Knowledge Graphs
- Economics: Goals – Case-Based Reasoning, Agents

Models of Knowledge

- Symbolic Representations
  - Symbolic representation are surrogats for things of the (external) world.
  - Manipulation via inference processes
  - Advantages:
    - Knowledge is captured via a formal representation
    - Representations are readable and meaningful
- Non-symbolic representations
  - Examples: Analog maps and diagrams, neural networks
  - Advantages:
    - Often fewer assumptions need to be made
    - Non-symbolic representations can often deal better with imprecise knowledge

KR as a Medium for Efficient Computation

Knowledge representation

- „is a medium for pragmatically efficient computation, i.e., the computational environment in which thinking is accomplished.
- One contribution to this pragmatic efficiency is supplied by the guidance a representation provides for organizing information so as to facilitate making the recommended inferences."

[Davis, Shrobe, Szolovits, 1993]

Expressiveness vs. Efficiency

Fundamental Trade-off: Expressiveness vs. Efficiency (!)

Desired Properties

- Expressive representation, complete inference procedures
- Efficient computation (tractability: polynomial complexity)

However: Both does not go together!

Example: PL1 is expressive, but does not provide efficient computation procedures. This trade-off exists for knowledge representation in general (Levesque & Brachman, 1985).

Expressiveness vs. Efficiency – Approaches

- Expressive/general representations using approximate inference methods
- Specialized representations (targeting a specific domain)
- Potentially: multiple representations targeting a domain (individual specializations)

- Examples:
  - Datalog (e. g., vs. Prolog)
  - Answer Set Programming
  - OWL – OWL Lite, OWL DL, OWL Full (OWL = Web Ontology Language)

KR Semantics

Semantics of Knowledge Representation Formalisms/Languages

- KR languages enable the formal modeling of knowledge
- Its *semantics*, i. e., the "meaning" of the individual language constructs, can be defined in different ways:
  - Operational semantics: The semantics are defined via algorithms, working on language constructs (early semantic networks/frames)
  - Semantic equivalence: Translation in KR formalisms with known semantics (e. g., Frames $\rightarrow$ PL1)

Declarative Semantics

- Syntactic KR structures are related to elements of abstract structures via an "interpretation" (function)
- Example: Set theoretic semantics for PL1
- Advantages:
  - Consistency of a knowledge base can be formally captured (and tested)
  - Subsumption relations can be computed (based on extensions: Extension of one concept is subset of extension of another concept)
  - Correctness and completeness of inference methods can be defined (e. g., for calculating subsumption relations)
- Disadvantage: Semantics is only defined extensionally, intensional aspects are not captured ("morning star", "evening star" and Venus have same meaning/semantics; also – "round rectangle" and "unicorn")

Knowledge Representation Basics

Basic techniques of knowledge representation

- Logic (First-Order/Predicate Logic, PL1)
- Rules
- Objects/Frames
- Constraints
- Probabilistic Reasoning

First-Order Logic

First-Order Logic (PL1) – also called *Predicate Logic*, *First-Order Predicate Calculus*

- Advantages for KR:
  - Well-known, formal notation
  - Domain can be described via axioms
  - Formal semantics!
  - Inference via deduction
- Disadvantages:
  - PL1 is not decidable (It is undecidable, whether a formula of PL1 is valid)
  - High complexity of inference processes
  - Not expressive enough for some applications

Brief Recap: First-Order/Predicate Logic (PL1)

- Example statements:

$$x > 2, \quad x = y + 7, \quad x + y = z$$

- Important: truth value – no meaning without values of x, y, z.
- But: We *can* make propositions given such statements.
- A *predicate* is a property that is affirmed or denied about a *subject* (also called: variable, argument) of a *statement*.
- Example:

$$\text{“}\underbrace{x}_{\text{subject}}\ \underbrace{\text{is greater than 3”}}_{\text{predicate}}$$

- Functional symbol for predicate (P); subject (x) as an argument (to the symbol): $P(x)$

Propositional Function (Predicate)

Definition 1

We call a statement of the form $P(x_1, x_2, \ldots, x_n)$ a *propositional function* P. Here, $(x_1, x_2, \ldots, x_n)$ is an n-tuple and P is a predicate.

A propositional function is a function that

- evaluates to true or false;
- takes one or more arguments;
- expresses a *predicate* involving the argument(s);
- becomes a proposition, whenever values are assigned to the arguments (also, cf. when those are "bound").

Universe of discourse: set of all things to express (about); i. e., set of all (valid) objects that can be assigned to a variable in a propositional function.

Also: *Function symbols* which are used to build more complex expressions – but are no *predicates* (!)

Quantifiers

- Predicate $\rightsquigarrow$ proposition: assign fixed values.
- Another way: *quantification*. Then, predicate true (or false) for
  - *all* possible values in the universe of discourse, or for
  - *some* value(s) in the universe of discourse.
- Respective *Quantification* – two *quantifiers*:
  - *Universal* quantifier ($\forall$), e. g.,

$$\forall x(Q(x) \rightarrow P(x))$$

  - *Existential* quantifier ($\exists$), e. g.,

$$\exists x \exists y P(x)$$

Universal Quantifier

Definition 2

We define the *universal quantification* of a predicate $P(x)$ as: "$P(x)$ is true for all values of x in the universe of discourse."

In notation:

$$\forall x P(x)$$

which can be read "for all x"

If the universe of discourse is finite, e. g., $\{n_1, n_2, \ldots, n_k\}$, then the universal quantifier is simply the conjunction of all of its elements:

$$\forall x P(x) \iff P(n_1) \land P(n_2) \land \cdots \land P(n_k)$$

Existential Quantifier

Definition 3

We define the *existential quantification* of a predicate $P(x)$ as: "There exists an x in the universe of discourse such that $P(x)$ is true."

In notation:

$$\exists x P(x)$$

which can be read "there exists an x"

If the universe of discourse is finite, e. g., $\{n_1, n_2, \ldots, n_k\}$, then the existential quantifier is simply the disjunction of all of its elements:

$$\exists x P(x) \iff P(n_1) \lor P(n_2) \lor \cdots \lor P(n_k)$$

Mixing/Reordering Quantifiers

- Existential and universal quantifiers can be used together, e. g.,

$$\forall x \exists y P(x, y)$$

- However: Read left to right (!)
- $\forall x \exists y P(x, y)$, for example, not equivalent to $\exists y \forall x P(x, y)$
- N.B.: Ordering is important:
  - $\forall x \exists y Loves(x, y)$: everybody loves somebody
  - $\exists y \forall x Loves(x, y)$: There is someone loved by everyone

Binding Variables

- When a quantifier is used on a variable x, x is called *bound*
- If no quantifier is used on a variable in a predicate statement, then x is called *free*
- Example:
  - $\exists x \forall y P(x, y)$: both x and y are bound
  - $\forall x P(x, y)$: x is bound, y is free
- In a *well-formed formula*, all variables are properly quantified
- We call the set of all variables bound by a common quantifier its *scope*

Negation

Negation can also be used with quantified expressions.

Lemma 4

Let $P(x)$ be a predicate. Then the following hold.

$$\neg\forall x P(x) \equiv \exists x \neg P(x)$$

$$\neg\exists x P(x) \equiv \forall x \neg P(x)$$

$\rightsquigarrow$ quantified version of De Morgan's Law

PL1 - Syntax Overview

Symbols:	• constants	A, B, C
	• variables	x, y, z
	• predicate symbols	p, q
	• function symbols	f, g
	• relation symbols	$\wedge, \vee, \neg, \rightarrow$
	• quantifiers	$\forall, \exists$
Terms:	• constants	A, B
	• variables	x, y
	• function symbols, applied to correct number of terms e.g., $(fx(fBB))$	
Formulas:	• predicate symbols, applied to correct number of terms (atomic formulas) e.g., $(pxy(fxB))$	
	• If r and s are formulas, then $(r \wedge s), (r \vee s), (\neg r)$ and $(r \rightarrow s)$ are formulas.	
	• If x is a variable and p a formula, then $(\exists xp)$ and $(\forall xp)$ are formulas.	
Axioms:	• proposition calculus axioms, specification axiom, "quantifier shift axiom"	
Rules of inference:	• modus ponens, generalization rule	

Summary: Axioms & Rules of Inference

- Axioms:
  - Transfer of axioms from propositional calculus
  - Specification axiom: $(\forall x P(x) \rightarrow P(\mathit{value}))$, with *value* being a definite value (i. e., a substitution of a variable via a value)
  - "Quantifier shift axiom": $(\forall x(A \rightarrow B)) \equiv (A \rightarrow \forall x B)$, where x may not appear relevantly in A (i. e., moving the quantifier in)
- Rules of inference
  - Modus ponens – example from propositional calculus: A and $A \rightarrow B$ together imply B.
  - Generalization rule: A implies $(\forall x A)$

Rules

As we already discussed – rules are a classic and widely used representation for expert systems.

Example:

```
IF (battery OK)
AND (Value FuelGauge > 0)
AND (PetrolFilter clean)
THEN (Problem = IgnitionSystem)
```

Rules – Overview

Rules ...

- model human problem solving
- provide a rather natural representation of expert knowledge
- capture experiences based on problems which have been previously solved by the expert
- are adaptable regarding their basic formalism, to also incorporate e. g., statements about uncertainties or expectations
- usually offer a domain-specific compromise between expressive power and efficiency

Basic Types of Rules

- A rule consists of a *precondition* (premise) and an *action* (conclusion)
- Two types of actions:
  - Implications (w.r.t. truth values) $\rightsquigarrow$ (1) in the example
  - Changing a state ("side-effect") $\rightsquigarrow$ (2) in the example

Example:

(1)	If	1.	stiff neck and
		2.	high temperature and
		3.	impairment of consciousness occur together,
	then		meningitis is suspected.
(2)	stack(box1, box2)		
	if	1.	clear(box1)
		2.	holding(box2)
	then	1.	on(box2, box1)
		2.	clear(box2)
		3.	holding()

Inference – Forward Chaining

Components of the rule interpreter: **1. data base**
2. rules

(1) DATA ← initial data base,
(2) *until* DATA satisfies termination condition *do*
(3) *begin*
(4) choose executable rule R whose precondition is satisfied by DATA,
(5) DATA ← result of applying action part of R to DATA,
(6) *end.*

Selection process (4) - two steps:

1. Pre-selection: Determine the set of all executable rules (*conflict set*), i. e., those which are currently applicable
2. Selection: Select a rule from the conflict set, using a conflict resolution strategy (trivial: select first rule; more advanced: apply most specific rule)

Frames / Semantic Networks

- Specifying properties of subjects
- Basically: *subject*, *predicate*, *object*, where *predicate* determines the type of the property, and *object* is the according property value.
- Alternatively: *individual*, *property*, *value*

As we have already seen:

- Logic (predicate):

$$prop(Individual, Property, Value)$$

- triple representation:

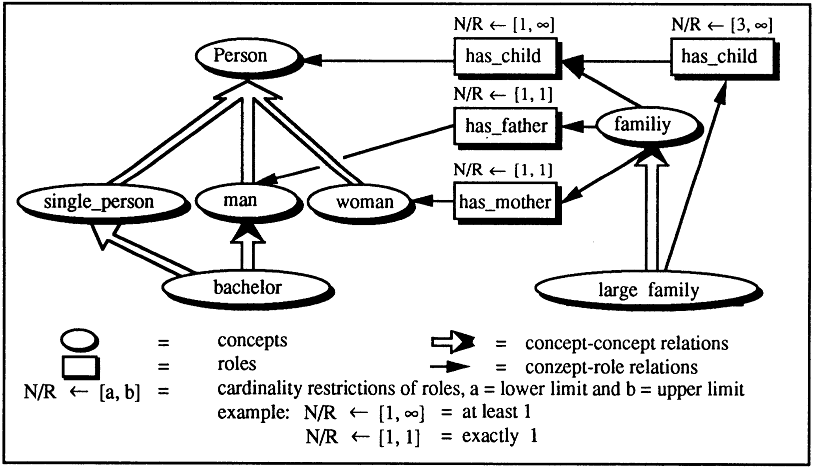
$$\langle individual, property, value \rangle$$

Frame Representations

- Basic idea: Set of facts can be better structured; properties of objects – providing stereotypes, with default values
- Similar to object-oriented formalisms (attributes, inheritance hierarchies, default procedures etc.)
- Inheritance: From general to more specific ($\rightsquigarrow$ reuse)
- Attached procedures – performed/monitor value changes

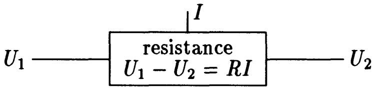
Object	Property	Values
elephant	is-a:	mammal
	color:	gray
	has:	trunk
	size:	large
	habitat:	ground

Example: Concepts *bachelor* & *large family* KL-ONE



Constraints

Example: Simulation of electrical circuits – Electrical Resistance



- Represent relationships between variables (undirected (!))
- In particular: Local boundary conditions, which need to be fulfilled for any possible solution
- Example – timetable/scheduling: One free day a week, for a particular person
- Solution space restricted by constraint
- Constraint system: Find solution, considering all restrictions
- Common forms: tables, functions, predicates, . . .

Probabilistic Reasoning

- Classical logic: Proposition either true or false
- Uncertainty: Proposition with a certain probability
- Basic of probabilistic reasoning:
  - Attach probabilities to propositions
  - This expresses uncertainty
- Statistically derived uncertainties: probabilities
- Estimated by humans (difficult to provide exact probabilities): Uncertain reasoning $\rightsquigarrow$ evidence, certainty factors

Probabilistic Reasoning – Techniques

- Bayes' Theorem
- Historic systems: INTERNIST, MYCIN, MED1
- Dempster-Shafter Theorem
- Probabilistic Networks/Markov Networks
- Bayesian Networks