Survey of Knowledge Representations for Rules and Ontologies

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Concept of KR

- KR = Knowledge Representation
- A KR S is defined as a triple (LA, LC, |=), where:
  - LA is a formal language for specifying sets of assertion statements
  - LC is a formal language for specifying sets of conclusion statements
    - LC is not necessarily even a subset of LA. E.g., in declarative logic programs (LP). In first-order logic (FOL), LC is the same as LA.
  - |= is the <u>entailment</u> relation.
    - A |= C means C is sanctioned as a conclusion from the set of assertions A.
    - Conc(A,S) stands for the set of conclusions that are entailed by A in KR S. We assume here that Conc is a function.
    - Typically, e.g., in FOL and LP, entailment is defined formally in terms of <u>models</u>, i.e., truth assignments that satisfy the premises and meet other criteria.

Background: Example KR's

1. Relational databases: relational algebra, cf. SQL
   - A sub-kind of declarative Logic Programs (function-free Horn)
2. Mathematical classical logic: first-order logic (FOL), higher-order logic. *Most people learn it in school.*
   - E.g., used in program verification, and planning.
3. Rules in various flavors
   - Central abstraction: declarative Logic Programs (LP)
     - *Most people do NOT learn LP in school*
   - Key extension: Rulelog
4. Many others:
   - Bayesian probabilistic networks, Probabilistic LP, Markov Logic Networks, fuzzy logic; inductive, possibilistic, …
   - Modal logics, description logics, temporal logics, …
   - Answer Set Programs (another extension of LP)

What are "Ontology" and "Rule", in general

- Ontology is a purpose/subset of knowledge: definitional in flavor
  - A key aspect is: terminology
  - *Ex.: Lions are a subcategory within felines*
  - *Ex.: Every health care visit has a required copayment amount*
- Rule is an if-then logical implication. A fact is a special case of a rule.
  - *Ex.: During the mitosis phase of an animal's cell cycle, all DNA is replicated*
  - *Ex.: AAA members get a weekend discount of 20% on suites, at hotel chain X*
- Almost any kind of rules – or other logical – knowledge can be viewed as consisting of definitions … and thus "ontological" in a sense
  - Necessary and sufficient conditions for when a concept/relation/expression is true/false. E.g., cf. "concept learning" in empirical induction.
- "Rules" and "ontologies" are overlapping, not disjoint! (in general)
- Some KR's are aimed at particular kinds of ontological knowledge
  - E.g., Description Logic
  - As shorthand, knowledge specified in such a KR is called an "ontology"
    - Yet much of this knowledge may be facts rather than definitions.
    - (This can lead to confusion.)

Some Common Kinds of Ontological Knowledge

- Two common kinds of ontological knowledge are:
  - <u>Formalized vocabulary</u>
  - <u>Schemas</u>, e.g., of databases or object-oriented information models
  - These two kinds overlap, in general

- One basic sub-kind of formalized vocabulary is:
  - A list of categories ("classes"): each a predicate of arity 1
  - A subclassof hierarchy among such classes
  - A list of properties (sometimes called "attributes"): each a predicate of arity 2
  - Restrictions on the domain and range of each property
  - (Anti-) reflexivity, symmetry, and/or transitivity of various properties
  - (Non-) disjointness or equivalence of various pairs of classes or properties

- Description Logic: aimed at ontological knowledge
  - The KR basis for OWL and RDF-Schema (which is simpler than OWL)
  - Good for representing: many kinds of formalized vocabularies or schemas; some kinds of categorization/classification and configuration tasks
  - Severely limited in important ways

Need for Other Kinds of Ontologies *besides OWL*

- Forms of ontologies practically/commercially important in the world today*:
  - SQL DB schemas
  - "Conceptual models" in UML and E-R (Entity-Relationship)
  - OO inheritance hierarchies, procedural interfaces, datatype declarations
  - XML Schema
  - OWL is still emerging, wrt deployed usage – dwarfed by all the above
  - RIF – early emerging
  - LP/FOL/BRMS predicate/function signatures
  - Built-ins (e.g., SWRL/RuleML)
  - Equations and conversion-mapping functions
- Overall relationship of OWL to the others is as yet largely unclear
  - There are efforts on some aspects, incl. ODM (bridge to UML).
  - Bright spot is OWL-RL relationship to RIF: formulated as a set of RIF-BLD axioms.
- OWL cannot represent the nonmonotonic aspects of OO inheritance
- OWL does not yet represent, except quite awkwardly:
  - n-ary relations
  - ordering (sequencing) aspects of XML Schema

- (*NB: Omitted here are statistically flavored ontologies that result from inductive learning and/or natural language analysis.)

Declarative Logic Programs (LP) is the Core KR today

- **LP is the core KR of structured knowledge management today**
  - **Databases**
    - Relational, semi-structured, RDF, XML, object-oriented
    - SQL, SPARQL, XQuery
    - Each fact, query, and view is essentially a rule
  - **Business Rules – the commercially dominant kinds** (see next slide)
  - **Semantic Rules**
    - RuleML standards design, incl. SWRL. The main basis for RIF.
    - W3C Rule Interchange Format (RIF): -BLD, -Core. E.g., Jena tool.
  - **Extension: Rulelog.** E.g., Coherent's tool.
  - **Semantic Ontologies**
    - W3C RDF(S)
    - W3C OWL-RL (= the Rules subset). E.g., Oracle's tool for OWL.
  - **Overall: LP is "the 99%", classical logic is "the 1%"**

- **Relational DB's were the first successful semantic technology**
  - LP is the KR/logic that was invented to formalize them
- **The Semantic Web today is mainly based on LP KR** … and thus essentially equivalent to semantic rules
  - **You might not have realized that!**

Commercially Dominant Legacy Kinds of Business Rules

- E.g., in OO applications, workflows

- Production rules (OPS5 heritage): e.g.,
  - IBM ILOG, Fair Isaac, Drools, Oracle, Jess: rule-based Java/C++ objects.
- Event-Condition-Action (ECA) rules (loose family), cf.:
  - business process automation / workflow tools.
  - active databases; publish-subscribe.
- Prolog. *"logic programs": as a full programming language*
  - *"Logic programming" is different from "declarative logic programs"*

- LP is the core KR for production rules, ECA rules, and Prolog
  - … insofar as they are semantic (i.e., "declarative")
  - But they are each only partially semantic

KR View of Semantic Web related standards

Hazy wrt Standardization: more Framework, incl. about:
– Uncertainty (probabilistic, fuzzy); Provenance (proof, trust)

Logical Framework standards/designs: RIF-FLD, RuleML

LP (Logic Programs) family

- **Umbrella standards/designs**
  - RIF-Rulelog
  - RuleML-LP
- **Database Query Standards***
  - SQL
  - SPARQL
  - XQuery
- **Business Rules Families***
  - Production
    - RIF-PRD
  - ECA (Event-Condition-Action)
  - Prolog

Classical Logic

- **Umbrella standards/designs:**
  - CL (ISO Common Logic)
  - RuleML-FOL
- **Semantic/Web Standards (other)**
  - RDF
  - RDFS (Schema)
  - OWL RL (Rule Profile)
  - RIF-BLD (Basic Logic Dialect)
    - (and SWRL)
  - OWL DL (Description Logic)
  - OWL Full
  - SBVR (OMG Semantic Business Vocabulary and Rules)

*Via KR mapping to LP, maybe with restrictions

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LP

- **Horn**
- **Rest**

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*Via KR mapping to LP (sound, nearly complete)

Classical Logic – Family of KR's

- Fully general case: Higher-order logic (HOL) – used foundationally in mathematics
  - A predicate or function itself is a ***term*** (e.g., a variable, or even a complex term)
  - Its generality makes it very difficult to automate fully
  - As usual:
    - An atom is a predicate applied to an argument tuple of terms
    - A term is a constant, a (logical) variable, or a complex term
    - A complex term is a (logical) function applied to an argument tuple of terms
    - Formulas are formed from atoms by applying:
      - Quantifiers: $\forall$, $\exists$
      - Connectives: $\neg$, $\wedge$, $\vee$, $\Leftarrow$, $\Rightarrow$, $\Leftrightarrow$

- First-order logic (FOL) – used in computer science much more than is HOL
  - Restriction: each predicate or (logical) function must be a ***constant***
  - Much more amenable to automation than higher-order
  - Used in program verification, planning/scheduling constraint satisfaction

- Description Logic (DL) – used for ontologies in OWL. Actually, a sub-family.
  - Restricts patterns of variable appearances in certain ways
  - First-order. No functions.

Declarative ***Logic Programs (LP) – Family of KR's***

- Normal LP
  - Rule syntax: $H \leftarrow B_1 \wedge \ \ldots \wedge B_k \wedge \text{naf } B_{k+1} \wedge \ldots \wedge \text{naf } B_m$. $(m \geq 0)$
    - H and Bi's are atoms.
    - $\leftarrow$ is a kind of implication that lacks contraposition.
      Its lhs and rhs are called the rule's "head" and "body", respectively.
    - naf ("negation-as-failure") is a kind of negation that is logically non-monotonic. Intuitively, naf Bi means "not believe Bi".
  - Semantics (well-founded) is defined constructively via an iterated fixed point.
    - It has 3 truth values: *true*; *false* in the naf sense; and an intermediate "*undefined*", which can represent paradoxicality.

- Rulelog: extends normal LP. Adds several expressive features:
  - Meta knowledge – several aspects
    - Hilog (see next slide). Reification: formula can be treated as a term.
    - Defeasibility: rules can have exceptions, behaving non-monotonically
    - Rule id's: enables meta-statements about assertions, incl. for provenance
    - Restraint: bounded rationality, using the "undefined" truth value
  - Omniformity: classical-looking formulas can appear in head and body
  - *See Ontolog Forum 2013-06-20 session presentation for details.*

Important Restrictions ***(NB: can be combined)***

- ***Each of the restrictions below applies not only to Classical Logic but also to Logic Programs, Rulelog, and many other KR's***

- Hilog – important extension of first-order
  - Syntax is higher-order (a bit restricted)
  - Semantics reduces to first-order, however (via transformation)
  - Used in Common Logic (ISO), and thus
  - Used in Rulelog (draft RuleML/W3C standard)

- First-order
  - Each predicate or (logical) function is a *constant*

- Horn: every formula is a clause in which at most 1 literal is positive
  - Used in databases (SQL, SPARQL, XQuery), RIF-BLD, RDF(S)
  - Point of departure for normal LP and OWL-RL

- Function-free: no functions
  - Used in databases (SQL, SPARQL, Xquery), RIF-Core, OWL, RDF(S)

- Propositional: arity is zero. This is a further restriction of function-free.
  - Used in constraint satisfaction

Summary of Computational Complexity of KR's

- *For task of inferencing, i.e., answering a given query.*
  - *Tractable = time is polynomial in n, worst-case; n = |assertions|*
  - *Also: m = # of atoms ($m \leq n$). v = max # of distinct variables per rule.*

- FOL propositional: co-NP-complete, i.e., "exponential"
  - Blowup due to "reasoning-by-cases" with disjunctions
- FOL: undecidable
  - Blowup due to recursion thru functions

- Horn LP propositional: O(n), i.e., linear
- Normal LP propositional: $O(n \cdot m)$, i.e., quadratic
- Normal LP function-free: polynomial, if v is a constant (as is typical in practice)
- Horn or Normal LP: undecidable
  - Blowup due to recursion thru functions

- Rulelog: polynomial, if one employs the restraint feature (as is typical in practice)
  - With functions – and other features (hilog, defeasibility, etc.) that extend LP
  - Leverage "undefined" truth value to represent "not bothering"

Relationships/Bridges Between Classical and LP Families of KR

- Fundamental Theorem connects Horn LP to Horn FOL
  - Horn LP entails the same set of ground atoms as Horn FOL
    - (when $\leftarrow$ is replaced by $\Leftarrow$)
  - Horn LP is sound but incomplete wrt Horn FOL, which has additional non-ground-atom conclusions, notably: non-unit derived clauses; tautologies
- OWL-RL practical reasoning is thus essentially LP. Ditto RDF(S).

- Generalization: Rulelog is sound but incomplete wrt hilog FOL
  - (Certain restrictions apply)
  - Rulelog lacks "reasoning-by-cases"
    - Essentially it has the power of the unit resolution proof strategy
  - Rulelog reasoning in presence of conflict is usefully selective unlike hilog FOL
    - Rulelog has the defeasibility feature, i.e., handles conflict … while retaining a consistent set of conclusions
    - By contrast, classical logic is perfectly brittle: any conflict results in all sentences being concluded (i.e., garbage)

KR View of Semantic Web related standards

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For More Info

See the ff. longer AAAI-13 Rules tutorial, available at http://coherentknowledge.com/publications :

Benjamin Grosof, Michael Kifer, and Mike Dean.
Semantic Web Rules: Fundamentals, Applications, and Standards (abstract). Conference Tutorial (Slides for 4-hour tutorial),
27th AAAI Conference on Artificial Intelligence (AAAI-13),
Bellevue, Washington, July 15, 2013.

This is the latest iteration of a tutorial that since 2004 has been presented at numerous scientific conferences on web, semantic web, and AI.

A book is in early stages of preparation based on this tutorial.

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Thank You

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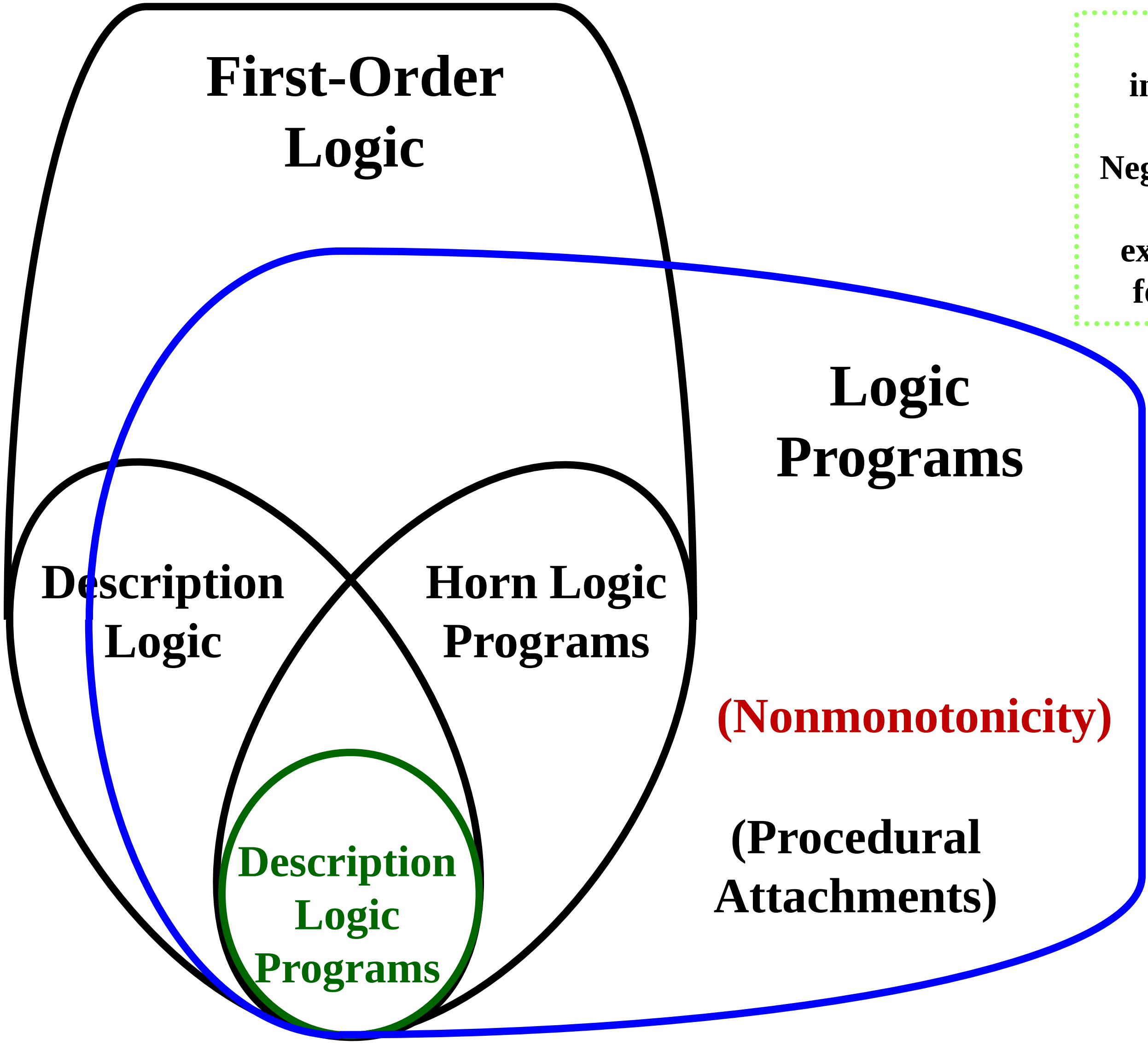
OPTIONALS FOLLOW

Venn Diagram: Expressive Overlaps among KRs

NB: Nonmon LP, including Courteous, relies on Default Negation as fundamental underlying KR expressive mechanism for nonmonotonicity



The "Spirit" of LP

The following summarizes the "spirit" of how LP differs from FOL:

- "Avoid Disjunction"
  - Avoid disjunctions of positive literals as expressions
    - In premises, intermediate conclusions, final conclusions
    - (conclude (A or B)) only if ((conclude A) or (conclude B))
  - Permitting such disjunctions creates exponential blowup
    - In propositional FOL: 3-SAT is NP-hard
    - In the leading proposed approaches that expressively add disjunction to LP with negation, e.g., propositional Answer Set Programs
  - No "reasoning by cases", therefore
- "Stay Grounded"
  - Avoid (irreducibly) non-ground conclusions

LP, unlike FOL, is straightforwardly extensible, therefore, to:

- Nonmonotonicity – defaults, incl. NAF
- Procedural attachments, esp. external actions

Examples – slide TODO ideally

- Higher-Order not First-Order
- First-Order Non-Horn
- Horn First-Order

- For now, see the AAAI-13 rules tutorial