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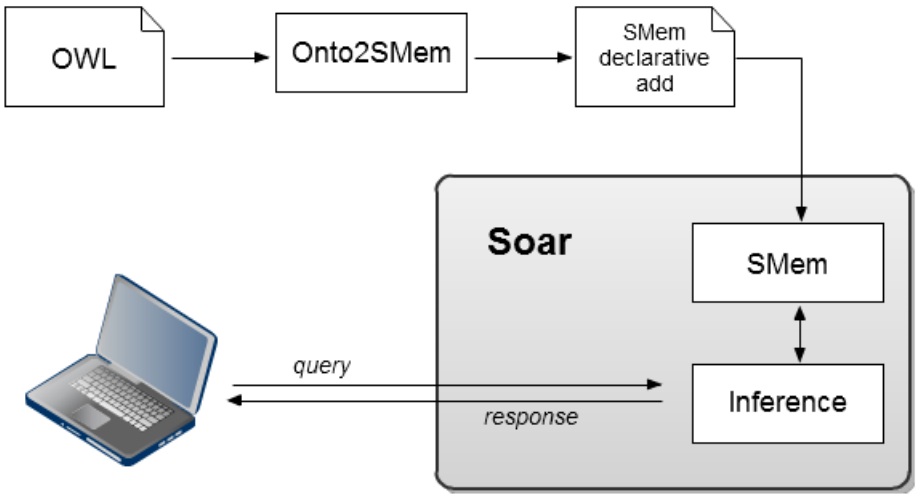
May 2010

Representing Ontologies and Reasoning with SMem

Introduction

- Tool (*Onto2SMem*) to generate declarative knowledge base in SMem from ontology
- Sound (if incomplete) inference
  - Proof of concept
  - Baseline implementation



SMem

- Semantic memory (SMem)
  - Store facts about world (declarative)
    - Graph: nodes, augmentations
  - Retrieval and storage
    - Cue- or non-cue –based retrievals
    - Efficient retrievals with activation bias
  - Memory or file (SQLite)

Ontology

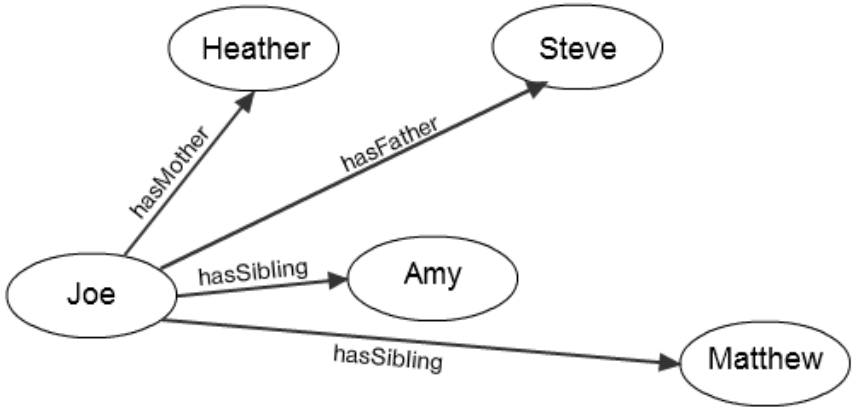
- Formal representation of domain
  - Classes and instances
    - E.g., Steve is an instance of Person
    - Classes have attributes (e.g., name, SSN), restrictions (e.g., Father must have at least one child)
  - Relationships expressed as properties
    - E.g., `isFatherOf(Person,Person)`
    - `isFatherOf(Steve,Matthew)`, so both Steve and Matthew are instances of Person

OWL

- Web Ontology Language
  - Based on descriptive logics
  - Two versions with multiple sublanguages with associated use cases and computational profiles
  - Represented in multiple formats, including XML/RDF
- http://www.w3.org/TR/owl-features/

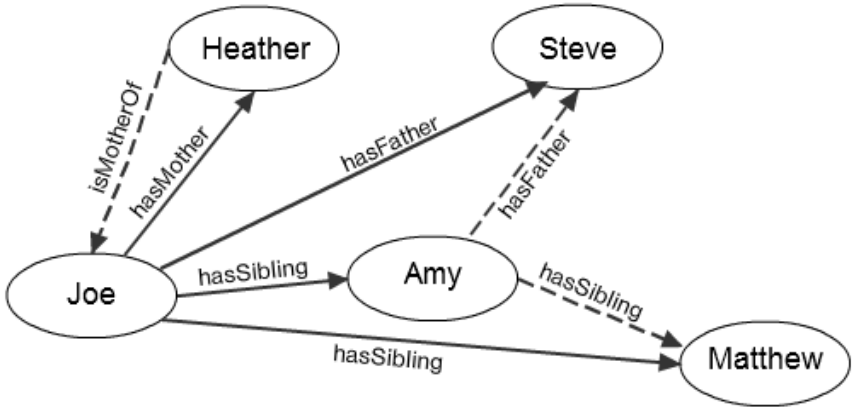
Ontology example

- Simple family example
- Must define
  - Relationships
    - `hasSibling(Person, Person)`
  - instances
    - Joe, Amy
  - instance relationships
    - `hasSibling(Joe,Amy)`



OWL: more than a graph

- Direct assertions easy to query
  - `hasMother(Joe, Heather)`
- Some relationships require inference
  - `isMotherOf(Heather, Joe)`
  - `hasSibling(Amy, Matthew)`
  - `hasFather(Amy,Steve)`



Notes about OWL

- OWL uses *open-world assumption*
  - With OWL, if not verifiably true or false, uncertain
    - Verifiably true if directly asserted or implied
    - Verifiably false if property restrictions imply
- OWL does not use the *unique name assumption*
  - OWL does not assume two names mean two distinct entities
  - Inferred or directly asserted (`sameAs` or `differentFrom`)

OWL features

- OWL 1 and OWL 2 have properties, property chains, property restrictions, quantifiers
  - OWL 1 guide: http://www.w3.org/TR/owl-features/
  - OWL 2 guide: http://www.w3.org/TR/2009/REC-owl2-primer-20091027/
- For our example, interested in:
  - Inverse properties
  - Symmetric properties
  - Transitive properties
  - Property chains
  - These must be preserved when representing ontology in SMem

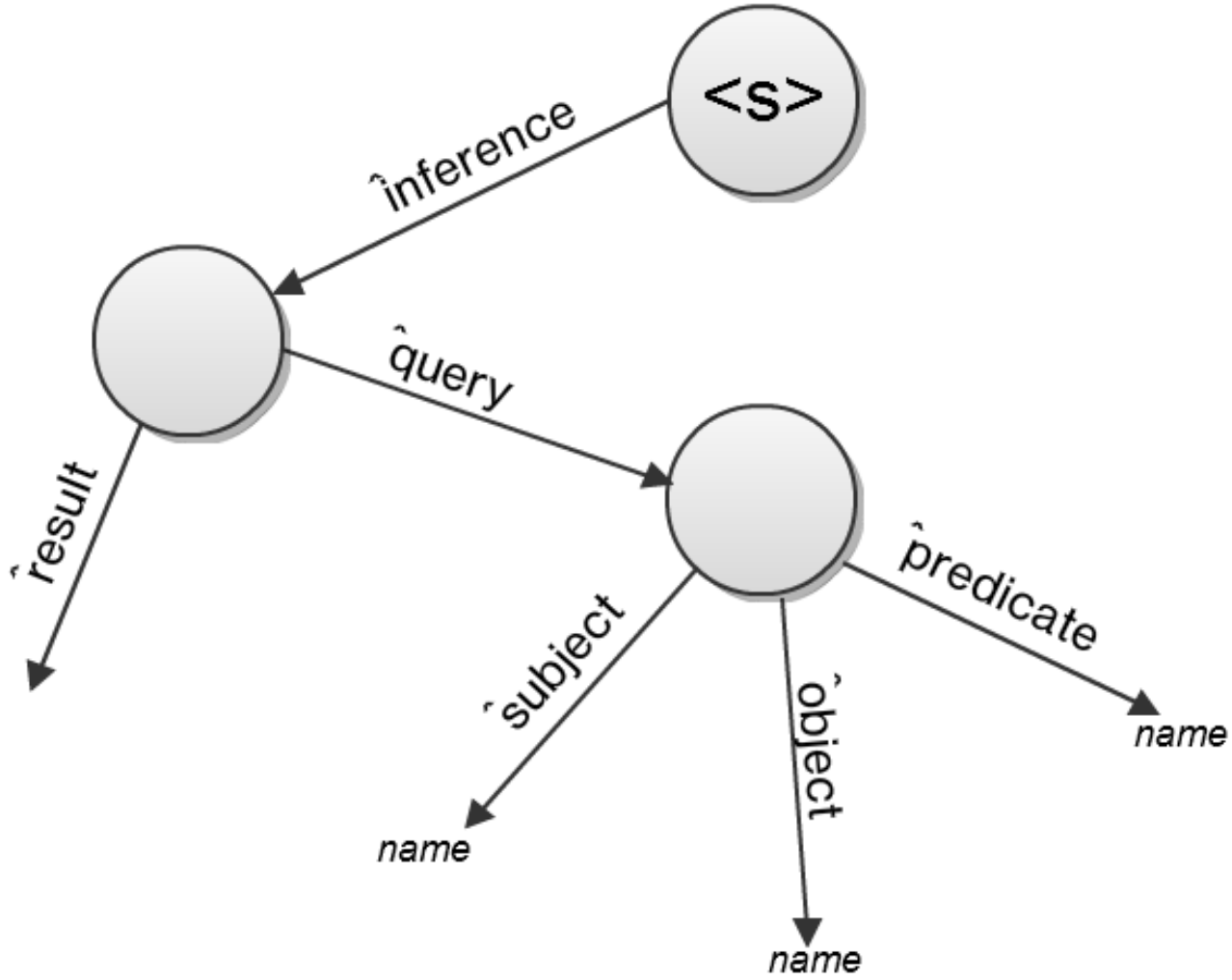
Onto2SMem

- Java utility using Jena framework API
  - Input: OWL file
  - Output: SMem declarative add commands
  - Allows use of existing ontologies in SMem
  - Preserves properties and arbitrary graph structure
  - Adds supporting collections useful for inference
- Onto2SMem
  - http://bryanesmith.com/soar/inference/
- Jena
  - http://jena.sourceforge.net/

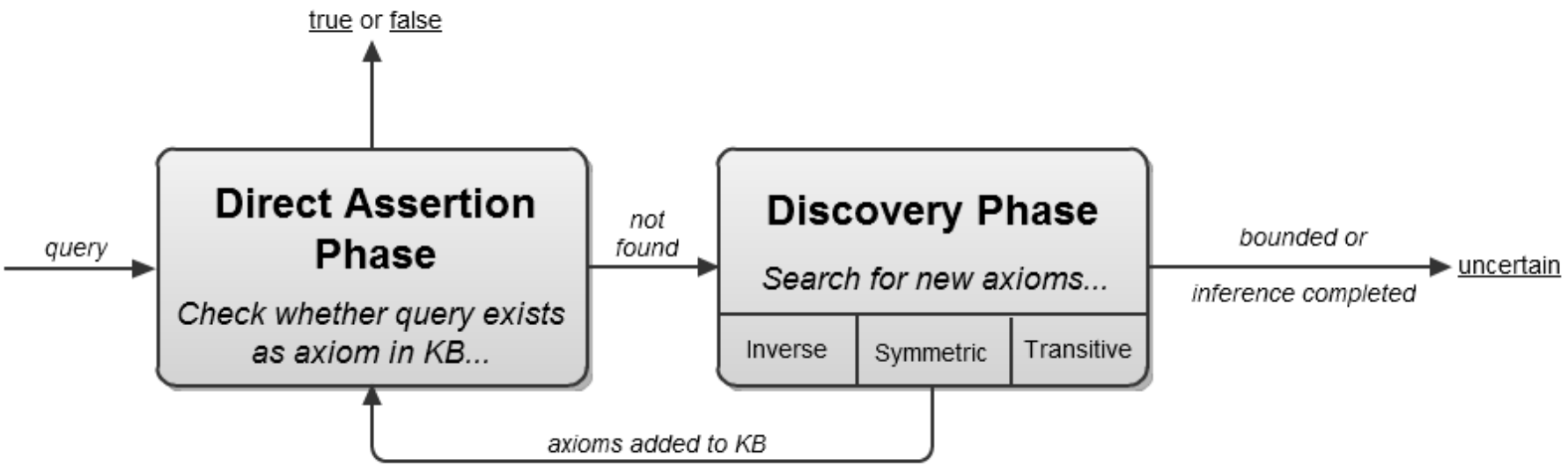
Inference with SMem

- Requirement: sound if incomplete
- Domain independent
  - Works with KB generated by Onto2SMem
- Implemented in Soar agent space
- Useful subset of OWL features
  - Inverse properties
  - Symmetric properties
  - Transitive properties
  - Property chains (not implemented)

Inference with SMem: interface



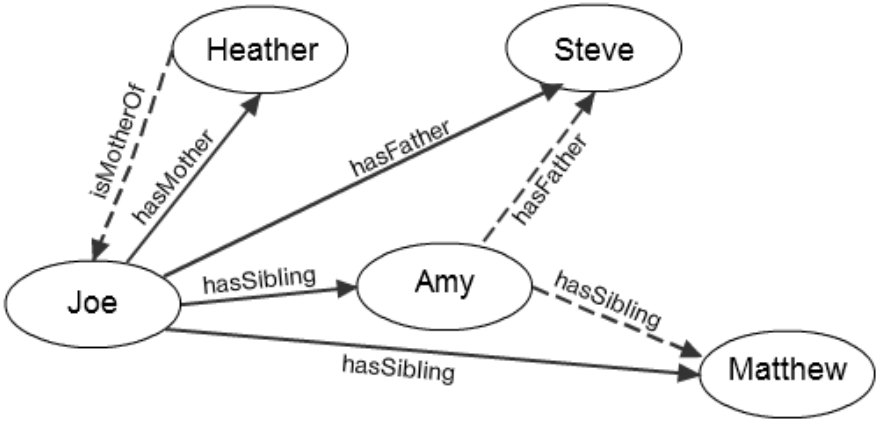
Inference with SMem: how it works



- Forward chaining
  - Iterative discovery of new axioms
- Unbounded
  - Bounded searches could be implemented

Initial demo: family relationships

- Using simple family ontology, inference tool finds missing relationships
- Subsequent runs using tool take require fewer decisions
  - First run: 497 decisions/10 true queries
  - Second run: 345 decisions/10 true queries
  - Replacing two true queries with uncertain resulted in approximately 4K decisions



Ontology: http://www.bryanesmith.com/ontologies/family-example.owl

Inference hypothesis

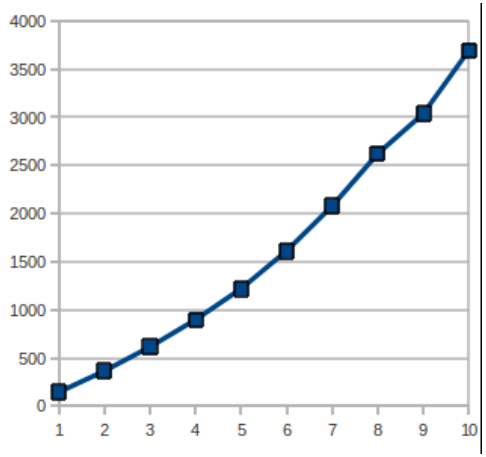
- Expecting polynomial or hyper-polynomial decision growth for inference as number of axioms increases
  - Due to transitive property check, which is $O(n^2)$
  - Might be ontology-dependent

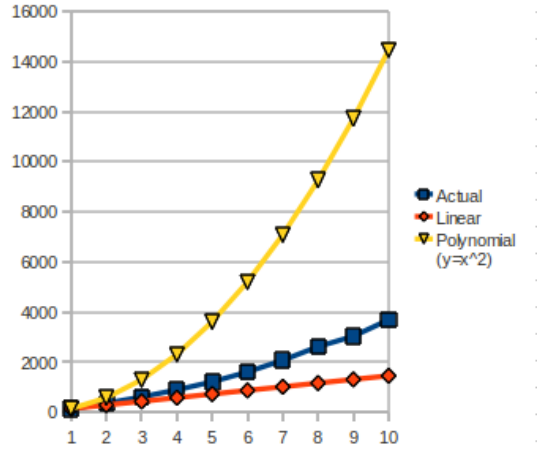
Preliminary testing

- What are the number of decisions required for agent to fulfill tasks?
  - Using 100 queries what is the impact of changing the number of families?
- Run agent twice
  - First run: inference + direct assertions
  - Second run: just direct assertions
    - Has "compiled" KB from first run
    - Steps(Inference) = Steps(Run #1) – Steps(Run #2)

Inference and growth

- Number of steps spent for inference appears polynomial with relation to elements in KB
  - Decisions per family in KB





Data are averages of 10 runs with 100 queries per condition.

Decision growth per variable

Growth	Search	Inference
Increase query count	n	-
Increase element count in KB	1	n^2

Thoughts

- (At least) polynomial decision growth for inference, but more testing needed
  - Verify trend with more data
  - Determine whether growth trend is ontology-specific

Recommendations for inference

1. Instead of single general-purpose inference engine, use cases with restrictions to guide implementations
   - Consider OWL sublanguages
   - Carefully crafted ontologies with certain DL properties can be much more efficient
     - Require knowledge of DL and efficient inference implementation
2. Introduce bounded searches
   - Optional parameter to limit total inference cycles
   - Default to unbounded search

Improving inference performance

1. During exploratory phase, terminate early if find result for query
   - Laziest approach most efficient
2. Use reinforcement learning for task ordering in exploratory phase
   - Reward based on number of new axioms found
   - Works with KBs with certain trends in the types of relationships
     - Assuming order impacts total number of inference cycles require

Improving inference performance

3. Perform inference offline and use compiled KB with agent
   - SMem can store KB to disk
   - Still requires some estimation to determine whether feasible

Conclusions

- Can represent ontologies in Soar using the SMem module
  - Preserve the semantics
  - Perform inference
- General-purpose inference is expensive
  - Use cases and restrictions to guide inference module development
  - Bounded searches and forward chaining provide value if agent can defer when uncertain

Nuggets versus coal

NUGGETS

- Preliminary feasibility demonstrated
- Domain and task independent
  - Reusable
- Sound
- Efficient queries after inference complete

COAL

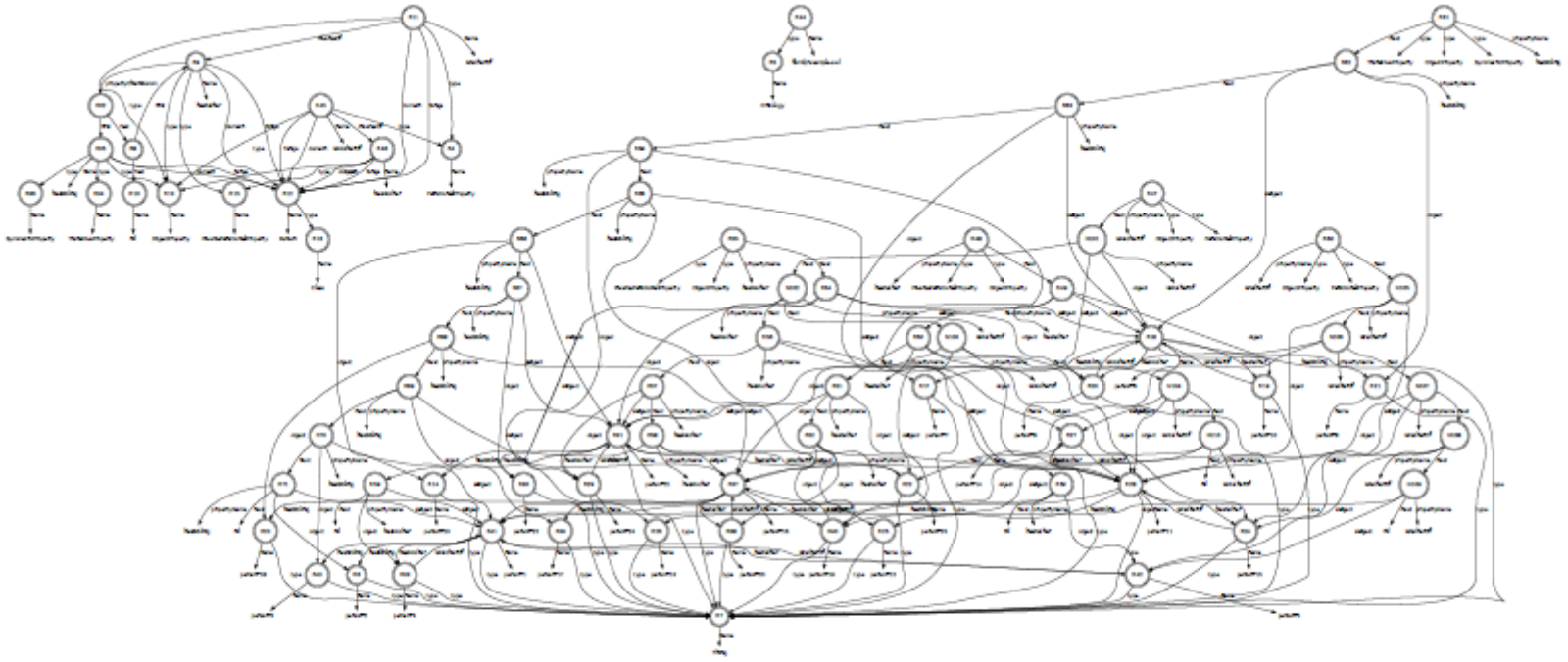
- Incomplete (subset of features)
- Unbounded with polynomial (or worse) growth for inference tasks
- Preliminary testing with few data points
  - Much more testing needed

ObjectIntersectionOf ObjectUnionOf ObjectComplementOf ObjectOneOf
ObjectAllValuesFrom ObjectSomeValuesFrom ObjectHasValue ObjectHasSelf
ObjectExactCardinality ObjectExactCardinality ObjectMaxCardinality
ObjectMaxCardinality ObjectMinCardinality ObjectMinCardinality
DataAllValuesFrom DataSomeValuesFrom DataHasValue DataExactCardinality
DataExactCardinality DataMaxCardinality DataMaxCardinality
DataMinCardinality DataMinCardinality DataAllValuesFrom
DataSomeValuesFrom ObjectInverseOf DataComplementOf
DataIntersectionOf DataUnionOf DataOneOf DatatypeRestriction SubClassOf
EquivalentClasses DisjointClasses DisjointClasses DisjointUnionOf
ObjectPropertyChain SubObjectPropertyOf ObjectPropertyDomain
ObjectPropertyRange EquivalentObjectProperties EquivalentObjectProperties
DisjointObjectProperties **InverseObjectProperties** FunctionalObjectProperty
InverseFunctionalObjectProperty ReflexiveObjectProperty
IrreflexiveObjectProperty **SymmetricObjectProperty**
AsymmetricObjectProperty **TransitiveObjectProperty** SubDataPropertyOf
DataPropertyDomain DataPropertyRange EquivalentDataProperties
DisjointDataProperties DisjointDataProperties FunctionalDataProperty
SameIndividual DifferentIndividuals DifferentIndividuals ClassAssertion
ObjectPropertyAssertion DataPropertyAssertion
NegativeObjectPropertyAssertion NegativeDataPropertyAssertion

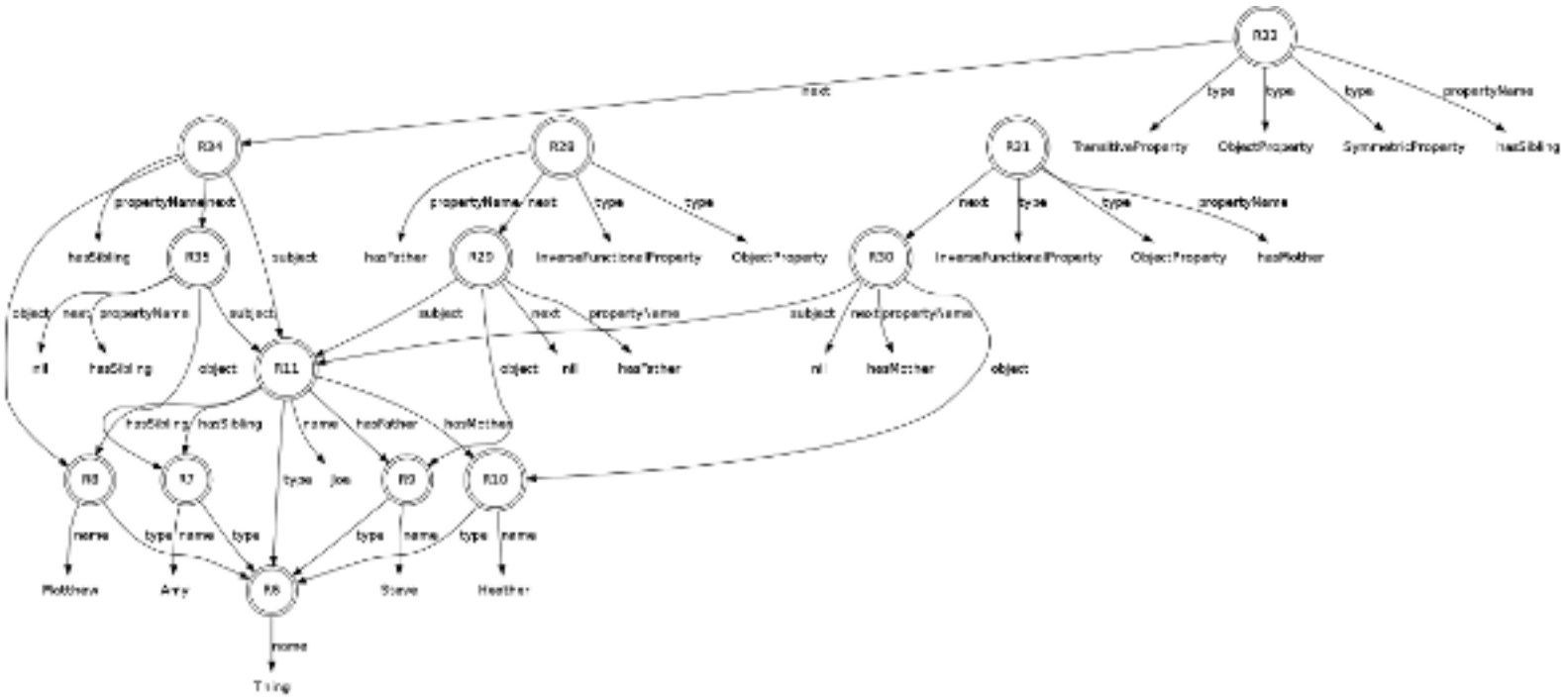
Questions?

- Onto2SMem, sample ontology, Soar agent with inference, these slides, and other tools:
  - http://bryanesmith.com/soar/inference/
- Jena (OWL Java API)
  - http://jena.sourceforge.net/
- Protégé (ontology editor)
  - http://protege.stanford.edu/

Thanks!

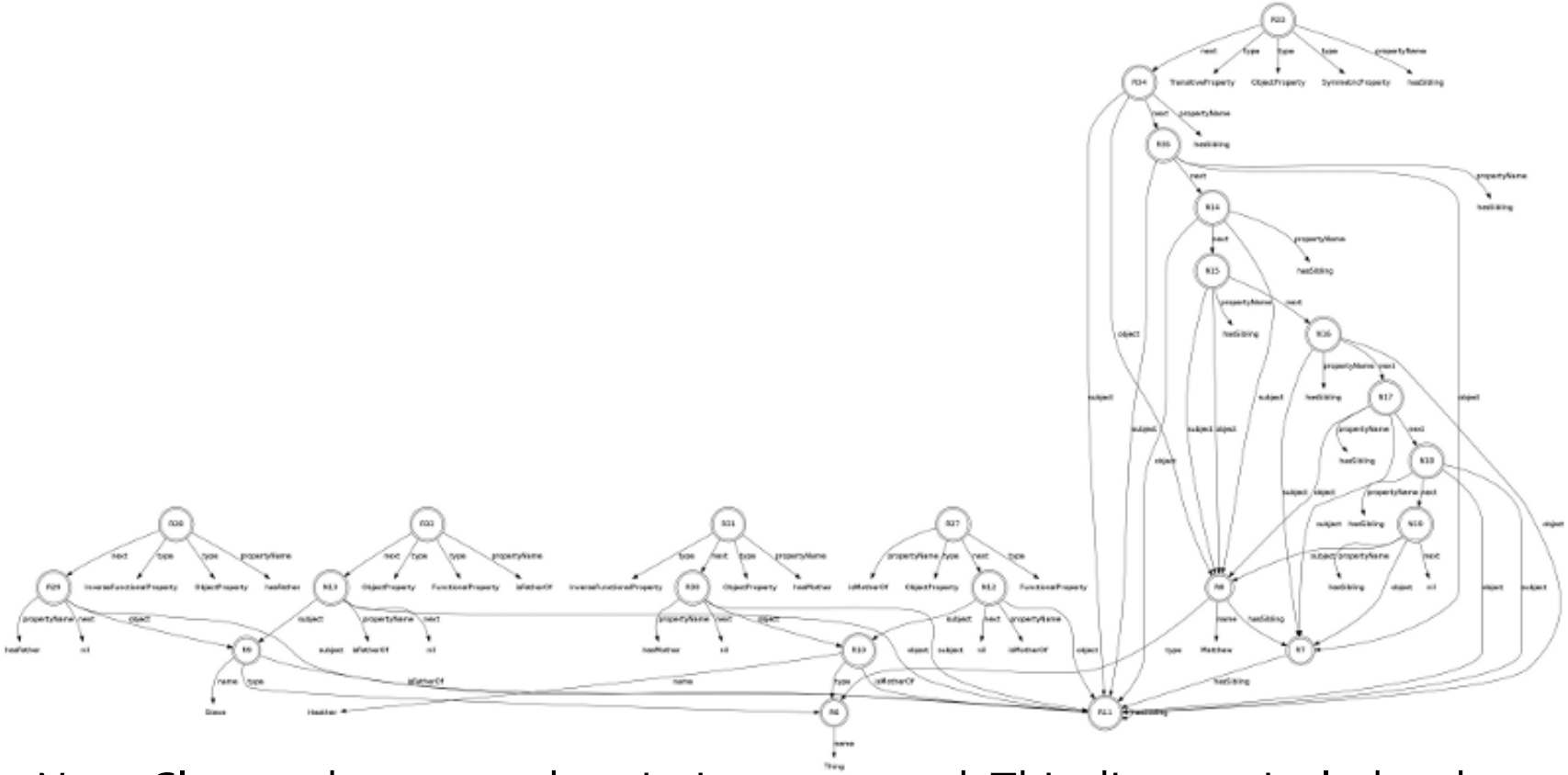


Appendix: Sample family KB before inference



Note: Class and property descriptions removed. This diagram includes the instances and supporting data structures used for inference.

Appendix:
Sample family KB after inference



Note: Class and property descriptions removed. This diagram includes the instances and supporting data structures used for inference.

Appendix: Inference with inverse properties

- Properties can be defined as inverse
  - `isMotherOf(A,B)` and `hasMother(B,A)`
  - `isFatherOf(A,B)` and `hasFather(B,A)`
- Functional relationships (e.g., `isFatherOf`) and inverse functional relations (e.g., `hasFather`) useful restrictions
  - Entity matching

Appendix:
OWL and inverse properties

```
<owl:ObjectProperty
   rdf:about="#isMotherOf"> <rdf:type
   rdf:resource="&owl;FunctionalProperty"/>
   <rdfs:range rdf:resource="#Person"/>
   <rdfs:domain rdf:resource="#Person"/>
   <owl:inverseOf rdf:resource="#hasMother"/>
</owl:ObjectProperty>
```

Appendix: Inference with symmetric property

- Property is symmetric if property(A,B) → property(B,A)
  - `hasSibling(Joe,Amy)` → `hasSibling(Amy,Joe)`

Appendix: OWL and symmetric property

```
<owl:ObjectProperty rdf:about="#hasSibling">
   <rdf:type
   rdf:resource="&owl;SymmetricProperty"/>
   <rdf:type
   rdf:resource="&owl;TransitiveProperty"/>
   <rdfs:domain rdf:resource="#Person"/>
   <rdfs:range rdf:resource="#Person"/>
</owl:ObjectProperty>
```

Appendix: Inference with transitive property

- Property is transitive if property(A,B), property(B,C) → property(A,C)
  - `hasSibling(Joe,Amy), hasSibling(Amy,Matthew) → hasSibling(Joe,Matthew)`

Appendix: OWL and transitive property

```
<owl:ObjectProperty rdf:about="#hasSibling">
   <rdf:type
   rdf:resource="&owl;SymmetricProperty"/>
   <rdf:type
   rdf:resource="&owl;TransitiveProperty"/>
   <rdfs:domain rdf:resource="#Person"/>
   <rdfs:range rdf:resource="#Person"/>
</owl:ObjectProperty>
```

Appendix: Inference with property chain

- $property_1(e_1, e_2)$, $property_2(e_2,e_3),\ldots,property_M(e_{N-1}, e_N) \rightarrow property(e_1,e_N)$
  - `hasFather(a,b), hasSister(b,c) → hasAunt(a,c)`
  - `hasSibling(a,b), hasFather(b,c) → hasFather(a,c)`

Appendix: OWL and property chain

```
<owl:ObjectProperty rdf:about="#hasFather">
    <rdf:type
    rdf:resource="&owl;InverseFunctionalProperty"/>
    <rdfs:domain rdf:resource="#Person"/>
    <rdfs:range rdf:resource="#Person"/>
    <owl:propertyChainAxiom
    rdf:parseType="Collection">
        <rdf:Description rdf:about="#hasSibling"/>
        <rdf:Description rdf:about="#hasFather"/>
    </owl:propertyChainAxiom>
</owl:ObjectProperty>
```

Appendix: Difference between OWL 1 and 2

- OWL 2 added:
  - Property chains
  - Asymmetric, reflexive, and disjoint properties
  - Qualified cardinality
  - etc.
- More information: http://www.w3.org/TR/2009/WD-owl2-overview-20090327/#New_Features

Appendix: OWL 1 sublanguages

- OWL Full
  - Unrestricted
  - Not decidable
- OWL DL
  - Disjointness between classes and instances
  - Axioms complete, form "tree-like structure"
  - Others
- OWL Lite
  - Forbidden constructs (e.g., oneOf, unionOf, disjointWith, etc)
  - Basically support "subclasses and property restrictions"
- More information: http://www.w3.org/TR/owl-ref/#Sublanguage-def

Appendix: OWL 2 sublanguages (profiles)

- OWL 2 EL
  - Useful for large number of classes and properties
  - Existential quantification
- OWL 2 QL
  - Designed for conjunctive queries with instances
    - LOGSPACE
  - Highly restricted
- OWL 2 RL
  - Restrictions that permit polynomial-time growth with rule-based reasoners (if-then)
- More information: http://www.w3.org/TR/owl2-profiles/

Appendix: Inference profile

- Loading state (25)
- Direct assertion (9)
- Adding axiom (23)
  - Plus reload state (23+25=48)
- Inverse properties (14+8*n*)
  - *n* = number of inverse properties
- Transitive properties (4 + *n*[8(*n*-*m*) + 14*m*])
  - *n* =number of axioms involving transitive properties
  - *m* = number of axiom pairs with transitive alignment
- Symmetric (2+8*n*)
  - *n* = number of symmetric properties