Ontologies for the Intelligence Community (OIC) 2009 Tutorial:

Information Semantics 101:

Semantics, Semantic Models, Ontologies, Knowledge Representation, and the Semantic Web

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Overview

- This course introduces Information Semantics, i.e., Semantics, Semantic Models, Ontologies, Knowledge Representation, and the Semantic Web
- Presents the technologies, tools, methods of ontologies
- Describes the Semantic Web and emerging standards

Brief Definitions (which we'll revisit):

- **Information Semantics: Providing semantic representation for our systems, our data, our documents, our agents**
- **Semantics: Meaning and the study of meaning**
- **Semantic Models: The *Ontology Spectrum:* Taxonomy, Thesaurus, Conceptual Model, Logical Theory, the range of models in increasing order of semantic expressiveness**
- **Ontology: An ontology defines the terms used to describe and represent an area of knowledge (subject matter)**
- **Knowledge Representation: A sub-discipline of AI addressing how to represent human knowledge (conceptions of the world) and what to represent, so that the knowledge is usable by machines**
- **Semantic Web: "*The Semantic Web is an extension of the current web in which information is given well-defined meaning, better enabling computers and people to work in cooperation*."**

- T. Berners-Lee, J. Hendler, and O. Lassila. 2001. The Semantic Web. In *The Scientific American,* May, 2001.

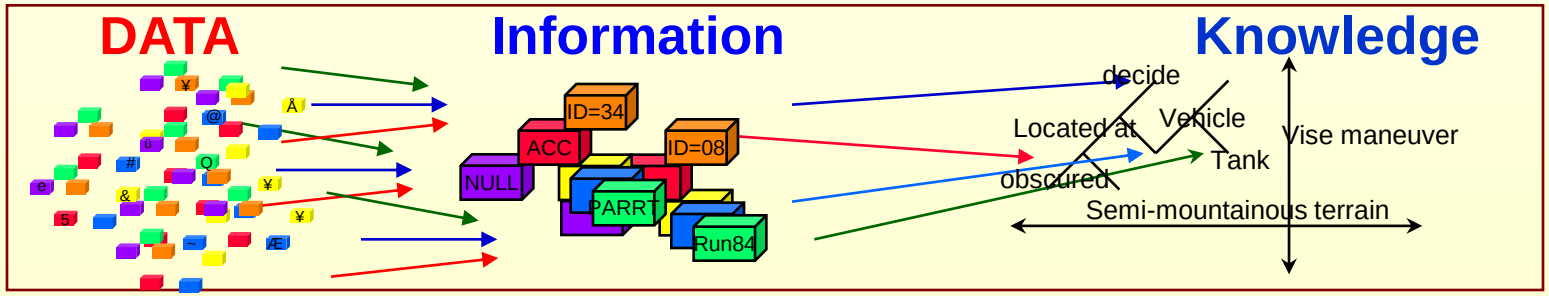
Schedule

- Morning
  - 9:00-10:20: Part 1: Syntax, Semantics, Ontology Spectrum, Taxonomies
  - 10:20-10:40: Break
  - 10:40-12:00: Part 2: Thesauri, Conceptual Models, Logical Theories (Strong Ontologies)
  - 12:00-1:20: Lunch
- Afternoon
  - 1:20-2:40: Part 3: Knowledge Representation, Logic, Ontological Engineering
  - 2:40-3:00 Break
  - 3:00-4:20: Part 4: The Semantic Web

Agenda, Part 1:
Semantics, Semantic Models, and Ontologies

The Problem

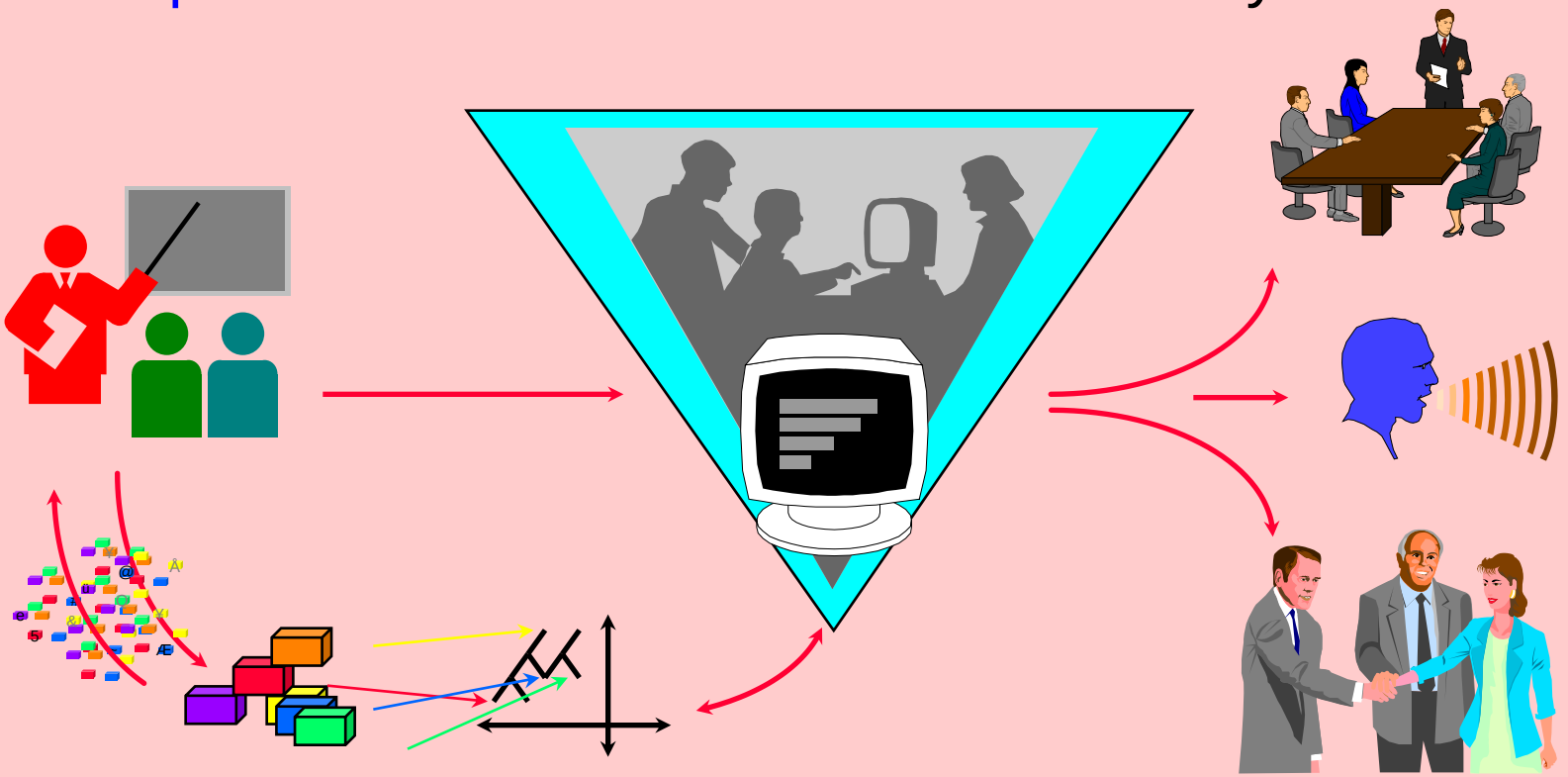
- With the increasing complexity of our systems and our IT needs, we need to go to human level interaction
- We need to maximize the amount of Semantics we can utilize
- From data and information level, we need to go to human *semantic* level interaction



- And represented semantics means multiply represented semantics, requiring *semantic integration*

The Solution

- We need to offload the very real, heavy cognitive interpretation burden from humans to our systems



- We need to represent human semantics using machine-interpretable ontologies

Advancing Along the Interpretation Continuum

Richer Metadata: RDF/S

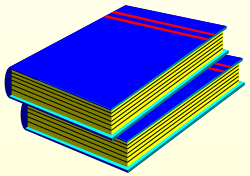
Simple Metadata: XML

Very Rich Metadata: DAML+OIL

Human interpreted ***Computer interpreted***

Interpretation Continuum

DATA
- **Relatively unstructured**
- **Random**

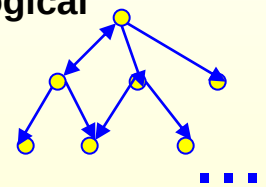


- **Info retrieval**
- **Web search**

- **Text summarization**
- **Content extraction**
- **Topic maps**

- **Reasoning services**
- **Ontology Induction**

KNOWLEDGE
- **Very structured**
- **Logical**



Display raw documents; All interpretation done by humans

Find and correlate patterns in raw docs; display matches only

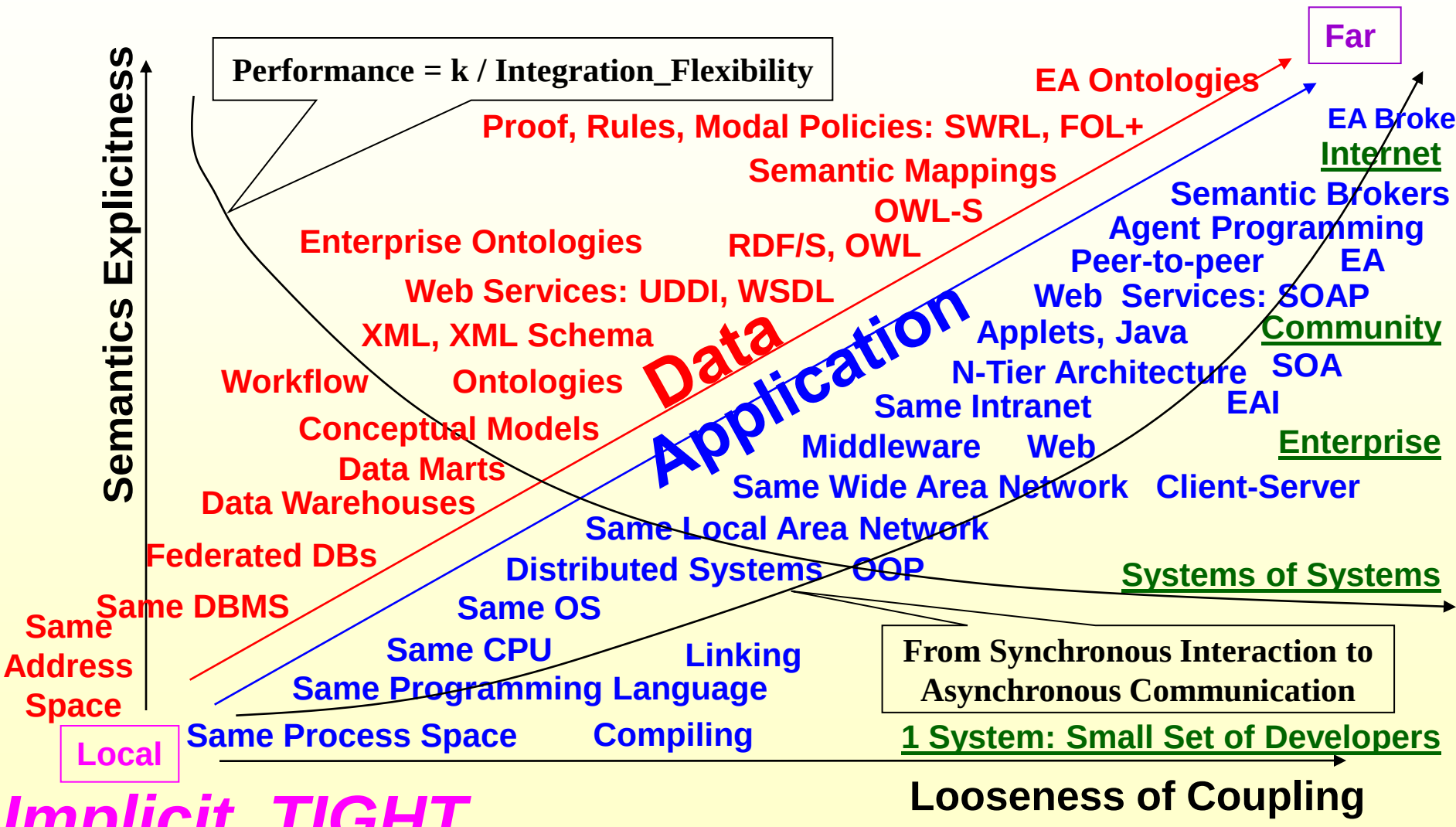
Store and connect patterns via conceptual model (i.e,. an ontology); link to docs to aid retrieval

Automatically acquire concepts; evolve ontologies into domain theories; link to institution repositories (e.g., MII)

Automatically span domain theories and institution repositories; inter-operate with fully interpreting computer

Moving to the right depends on increasing automated semantic interpretation

Motivation: Tightness of Coupling & Semantic Explicitness



Information Semantics

- Provide semantic representation (meaning) for our systems, our data, our documents, our agents
- Focus on machines more closely interacting at human conceptual level
- Spans Ontologies, Knowledge Representation, Semantic Web, Semantics in NLP, Knowledge Management
- Linking notion is Ontologies (rich formal models)
- Content is King or should be!
  - And the better the content…

It All Depends on What 'is' is

- Semantics is meaning
- "Oh, it's just semantics": Wrong!
  - Implies that it's quibbling about meaning, i.e., meaningless meaning, mincing words, not substantive or contentful distinctions
- "Real" semantics is about meaning
  - What meaning do we assign our squiggles on the page, pixels on the screen, ink on a map, sounds in a track, bits on a disk, flickering shades of dark & light on a film, squinting of an eye, a shrug?
  - What is the meaning of: '45-XG-92+@55' ?
  - Is it the same or similar to 'abk3#40'?
  - What is the meaning of 'the man hit the ball'? 'Green ideas sleep furiously'? 'Hit man the the ball'? 'Joe is a abk3#40'?
  - It's the meaning of systems, data, document, agents, humans

Semantics

- Semantics is meaning
  - Literal & figurative
  - Both context independent & context dependent
  - Meaning & use (intent of the meaning)
  - Natural language, programming & formal languages
  - Informal & formal
  - Express the meaning in a loose/strict, natural language definition or description
    - Semantics (Merriam-Webster, http://www.m-w.com/cgi-bin/dictionary)

      1 : the study of meaning: a : the historical and psychological study and the classification of changes in the signification of words or forms viewed as factors in linguistic development b (1) : semiotic (2) : a branch of semiotics dealing with the relations between signs and what they refer to and including theories of denotation, extension, naming, and truth.
  - Express the meaning in a logical, mathematically rigorous manner
    - All students who took the test passed.

      $\forall x$: (student(x) $\wedge$ took_test(x) $\rightarrow$ passed_test(x))
- Syntax vs. Semantics: based on Language

Syntax

- A Language has a Syntax (set of symbols, & formation rules) & a Semantics (what the symbols, well-formed formulas mean)
- A formal language can be identified by its set of well-formed formulas; a natural language by its set of sentences (infinite)
- Syntax is form & structure
  - Symbols
  - Tokens/Types
    - Restricted words of a programming language
      - Do, While, Until, If, Then, Else, Declare
    - User defined constants & variables
      - A = 7 + 3; Y = A + 1; While Count < 5 Do
  - Order: how do words combine
    - To form a program?
    - To form a sentence?
    - Rules for combining
- Applies to Natural Languages, Programming Languages, Formal Languages, including Logics, Knowledge Representation/Ontology Languages!

Syntax: Propositional Logic

- PL is a Language having a Syntax & a Semantics
  - A set of symbols:
    - Logical Constants: True, False (or T, F)
    - Logical Variables (or propositional symbols): p, q, r, …
    - Logical Operators (or connectives): $\neg$, $\vee$, $\wedge$, $\rightarrow$, $\leftrightarrow$, (,)
  - Formulas (Well-formed Formulas or WFFs) of PL (we will call these ***propositions***)
    - Any propositional symbol is a WFF of PL
    - If α and β are WFFs, then so are $(\alpha \vee \beta)$, $(\alpha \wedge \beta)$, $(\alpha \rightarrow \beta)$, $(\alpha \leftrightarrow \beta)$, and $(\neg\alpha)$ [and note that we will dispense with parentheses where we can]
    - Nothing else is a WFF.
  - So the following are WFFs: p, $\neg$p, p $\vee$ q, p $\wedge$ q, (p $\wedge$ q) $\rightarrow$ r
  - Propositions are things that are true or false

Propositions in English:

If John is a management employee, then John manages an organization.

John is a management employee.

John manages an organization (MP)

Propositions in PL:

p $\rightarrow$ q

p

---

q (MP: Modus Ponens)

Still Need Semantics!

Predicate Logic: Add Predicates, Individuals, Quantifiers

Propositions & Predicates in English:

If John is a management employee, then John manages an organization.

John is a management employee.

John manages an organization (MP)

Propositions & Predicates in First Order Predicate Logic:

$p(x) \rightarrow q(x)$

$p(john)$

$q(john)$ **(MP: Modus Ponens)**

Propositions & Predicates in English:

Everyone who is a management employee manages some organization.

Or:

For everyone who is a management employee, there is some organization that that person manages.

John is a management employee.

There is some organization that John manages.

Propositions & Predicates in First Order Predicate Logic:

$\forall x.\ [p(x) \rightarrow \exists y.\ [q(y) \wedge r(x,y)]]$

"For all x, if x is a p, then there is some y such that y is a q, and x is in the r relation to y"

$p(john)$

$\exists y.\ [q(y) \wedge r(john,y)]]$

(MP: Modus Ponens)

Still Need Semantics!

Semantics: Interpretation

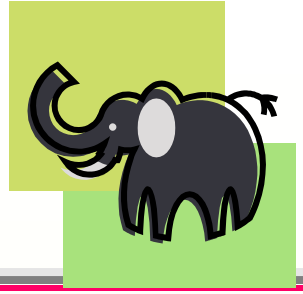
- Interpretation:
  - An *interpretation* of a formal language is an assignment of meanings to its symbols and/or formulas [Hunter, 1973, p.6-7]
  - "An interpretation of PL is an assignment to each propositional symbol (logical variable) of one or other (but not both) of the truth values truth and falsity" [Hunter, 1973, p. 57-58, over next few slides]
- Truth tables: $\neg p \vee (q \wedge r) \equiv (p \rightarrow q) \wedge (p \rightarrow r)$

p	q	r	$\neg p$	$(q \wedge r)$	$\neg p \vee (q \wedge r)$	$(p \rightarrow q)$	$(p \rightarrow r)$	$(p \rightarrow q) \wedge (p \rightarrow r)$
T	T	T	F	T	T	T	T	T
T	T	F	F	F	F	T	F	F
T	F	T	F	F	F	F	T	F
T	F	F	F	F	F	F	F	F
F	T	T	T	T	T	T	T	T
F	T	F	T	F	T	T	T	T
F	F	T	T	F	T	T	T	T
F	F	F	T	F	T	T	T	T

Proof Theory (Syntax) vs. Model Theory (Semantics)

- **Proof Theory**: deductive apparatus of a language
  - ***Axioms***: declaring by fiat certain formulas of L
  - ***Rules of Inference***: determines which relations between formulas of L are relations of *immediate consequence* of L
    - i.e., from $\alpha \Rightarrow \beta$ in one step
    - More generally, ***syntactic consequence*** is: iff there is a derivation in PL of the set of formulas β from the set of formulas α, written α **|-** β
  - Apply rules to Axioms to derive Theorems
  - ***Theorem***: a formula of a formal language that satisfies purely syntactic requirements and has no meaning
- Formal Model: a model of a formula of L is an interpretation of L for which the formula comes out true (a proposition)
- **Model Theory**: the theory of interpretations of languages
  - ***Logical Validity:*** **'|=** α**'** means that α is a logically valid formula of PL iff α is true for every interpretation of PL
  - ***Semantic consequence****: '*α **|=** β**'** means β is a semantic consequence of α iff there is no interpretation of PL for which α is true and β is false

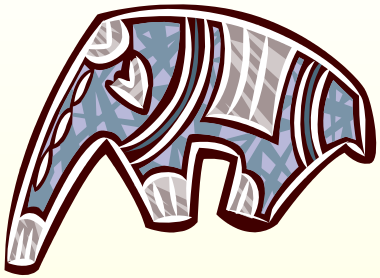
Ontology Elephants



There is no single real elephant

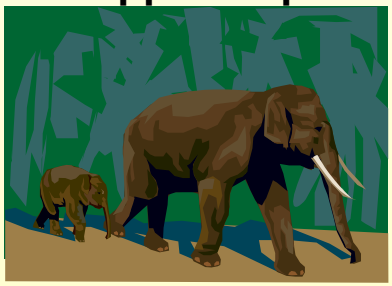
There must be a purpose for an elephant: use cases?

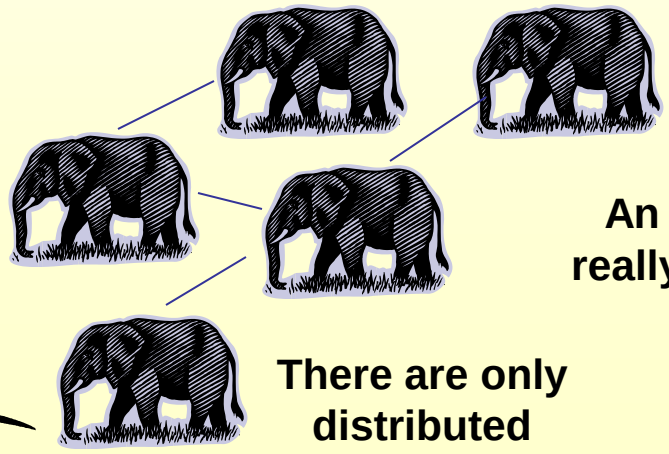
An elephant is abstract



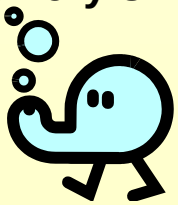
An elephant is very abstract

There must be an upper elephant



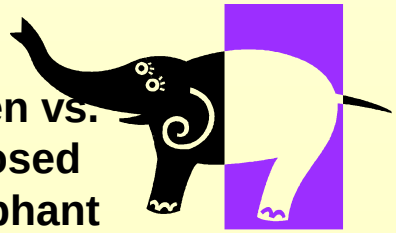


An elephant is really very simple



An elephant is the result of consensus

Open vs. Closed Elephant



There are only distributed elephants & their mappings

Some Issues

- We are like the blind men & the elephant: describing the ontology elephant from our own perspectives, which is of course what we most know about

- Multiple communities converging on semantics, with their own perspectives, concepts: see Ontology Spectrum
  - Logicians, formal ontologists, formal semanticists, some computer scientists
  - Librarian, information scientists
  - Object-oriented, development, programmers & software engineers
  - Classical AI knowledge representation folks
  - Database theorists & practitioners
  - Web community
  - Service Oriented Architecture (SOAs), Web services, enterprise architecture folks
  - Business & government analysts

- Problems:
  - Key distinctions are glossed over: term vs. concept, label vs. model, machine vs. human interpretablity, syntax vs. semantics-pragmatics (sense, reference, discourse, speech acts)

Ontology & Ontologies 1

- An ontology defines the terms used to describe and represent an area of knowledge (subject matter)
  - An ontology also is the model (set of concepts) for the meaning of those terms
  - An ontology thus defines the vocabulary and the meaning of that vocabulary
- Ontologies are used by people, databases, and applications that need to share domain information
  - Domain: a specific subject area or area of knowledge, like medicine, tool manufacturing, real estate, automobile repair, financial management, etc.
- Ontologies include computer-usable definitions of basic concepts in the domain and the relationships among them
  - They encode domain knowledge (modular)
  - Knowledge that spans domains (composable)
  - Make knowledge available (reusable)

Ontology & Ontologies 2

- The term ***ontology*** has been used to describe models with different degrees of structure (Ontology Spectrum)
  - **Less structure:** Taxonomies (Semio/Convera taxonomies, Yahoo hierarchy, biological taxonomy, UNSPSC), Database Schemas (many) and metadata schemes (ICML, ebXML, WSDL)
  - **More Structure:** Thesauri (WordNet, CALL, DTIC), Conceptual Models (OO models, UML)
  - **Most Structure:** Logical Theories (Ontolingua, TOVE, CYC, Semantic Web)
- Ontologies are usually expressed in a logic-based language
  - Enabling detailed, sound, meaningful distinctions to be made among the classes, properties, & relations
  - More expressive meaning but maintain “computability”
- Using ontologies, tomorrow's applications can be "intelligent”
  - Work at the human conceptual level
- Ontologies are usually developed using special tools that can model rich semantics

Big O: Ontology, Little o: ontology

- **Philosophy:** "a particular system of categories accounting for a certain vision of the world" or domain of discourse, a conceptualization (Big O)
- **Computer Science:** "an engineering product consisting of a specific vocabulary used to describe a part of reality, plus a set of explicit assumptions regarding the intended meaning of the vocabulary words", "a specification of a conceptualization" (Little o)
- **Ontology Engineering:** towards a formal, logical theory, usually 'concepts' (i.e., the entities, usually classes hierarchically structured in a special subsumption relation), 'relations', 'properties', 'values', 'constraints', 'rules', 'instances', so:
- **Ontology (in our usage):**

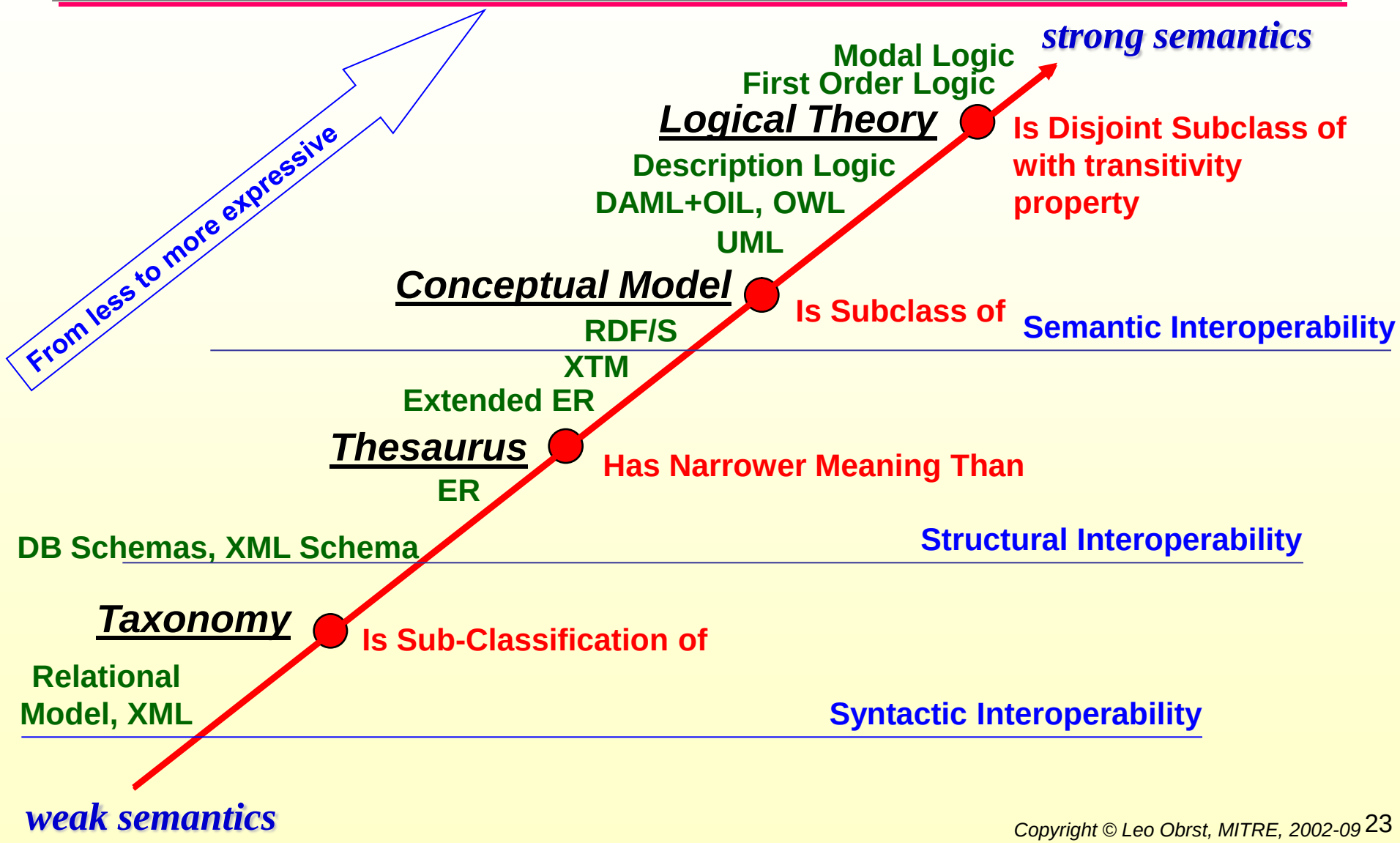
1) **A logical theory**
2) **About the world or some portion of the world**
3) **Represented in a form semantically interpretable by computer**
4) **Thus enabling automated reasoning comparable to a human's**

* The first two definitions are derived from Guarino, 98; Guarino & Giaretta, 95; Gruber, 93, 94

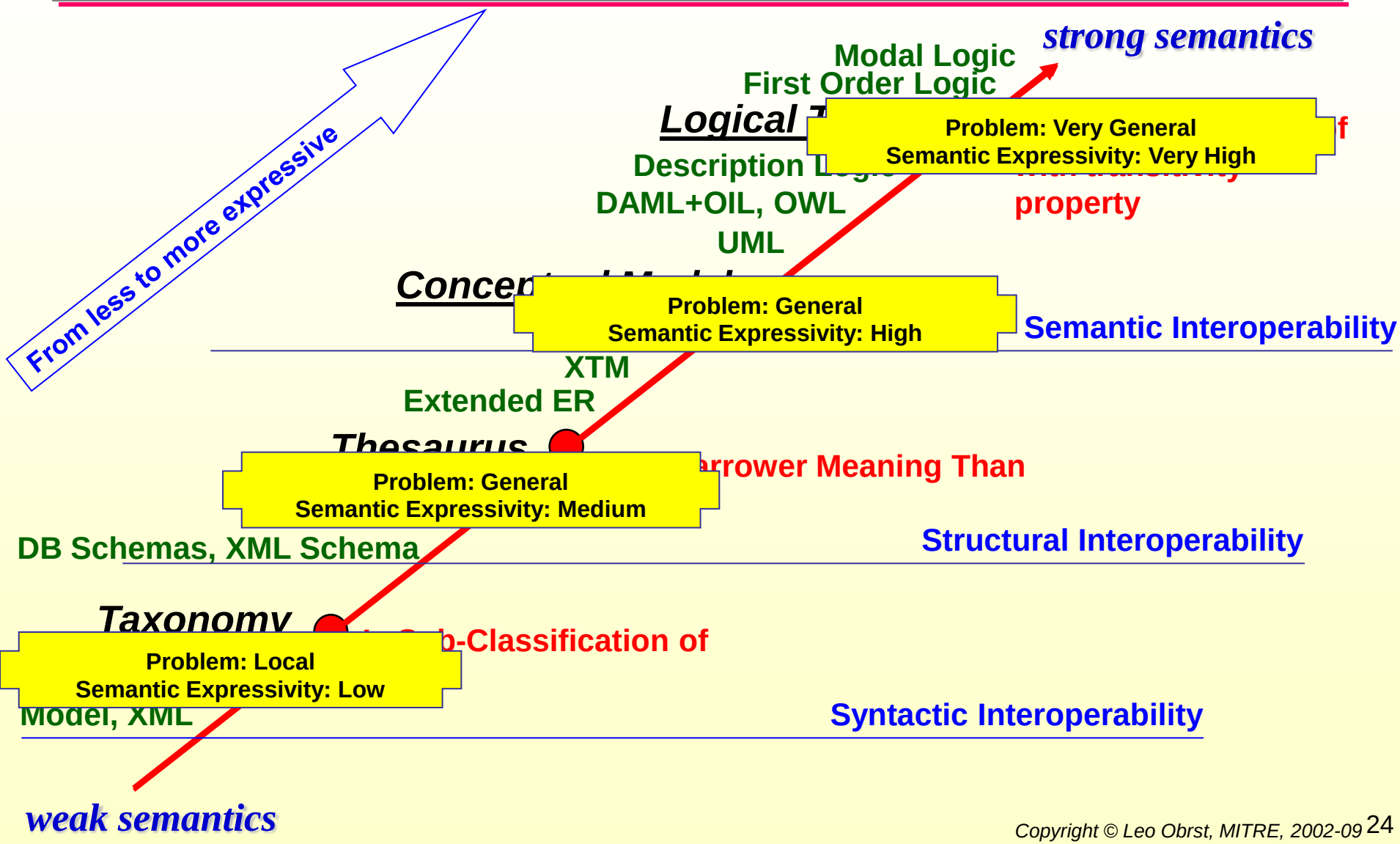
Ontology thus includes:

- **Objects (things) in the many domains of interest**
- **The relationships between those things**
- **The properties (and property values) of those things**
- **The functions and processes involving those things**
- **Constraints on and rules about those things**

Ontology Spectrum: Range of Models

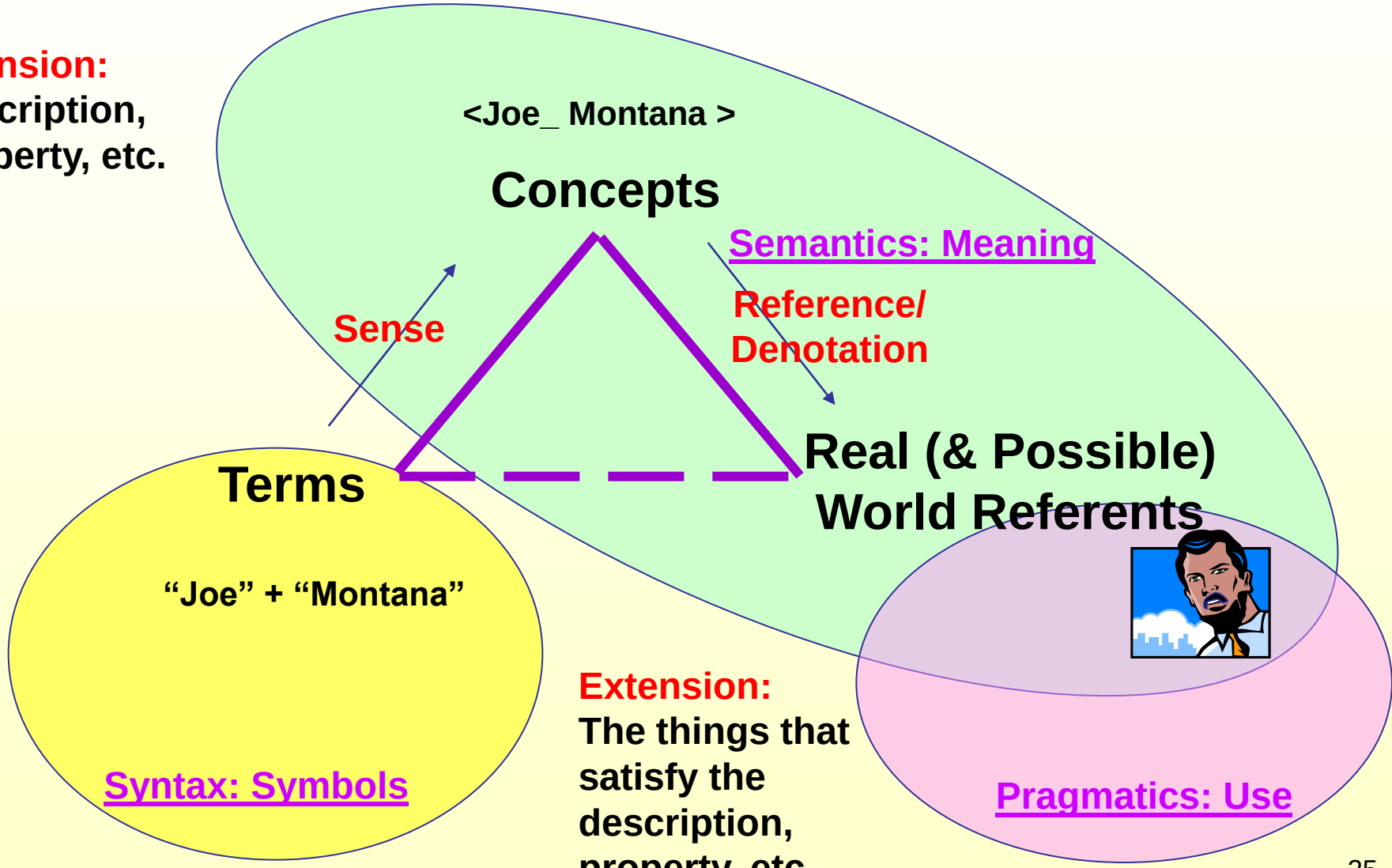


Ontology Spectrum: Generality & Expressiveness



Triangle of Signification

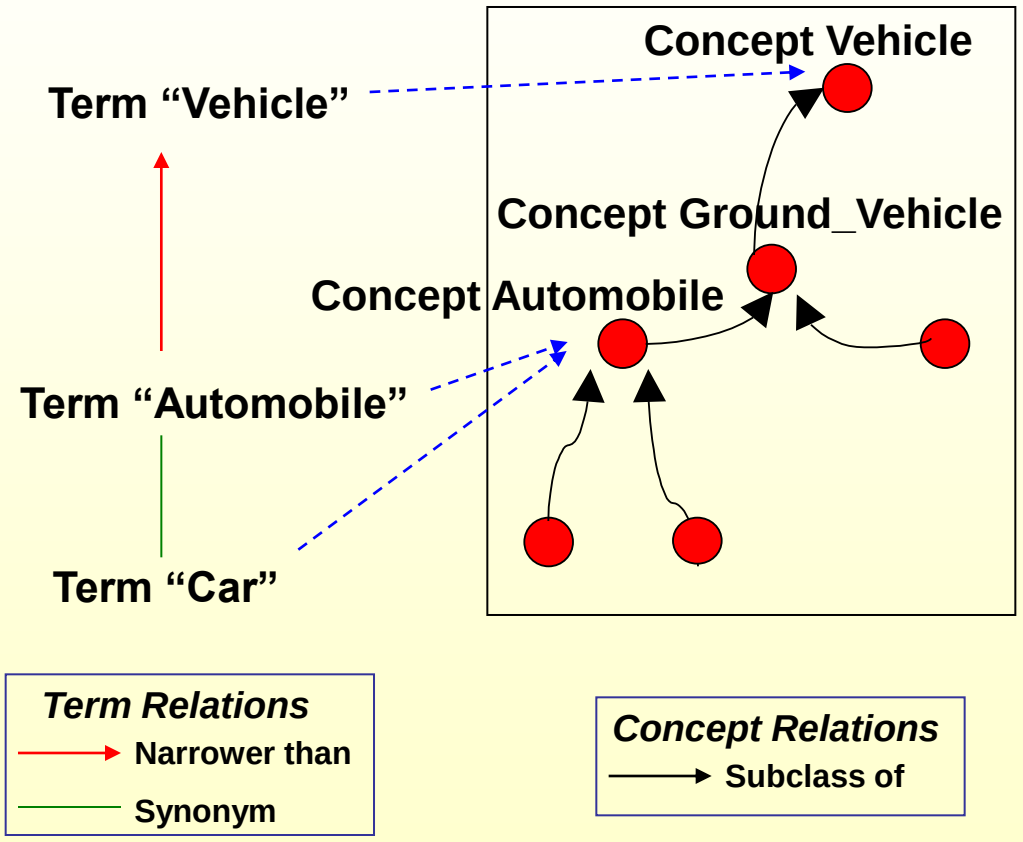
Intension:
Description, Property, etc.



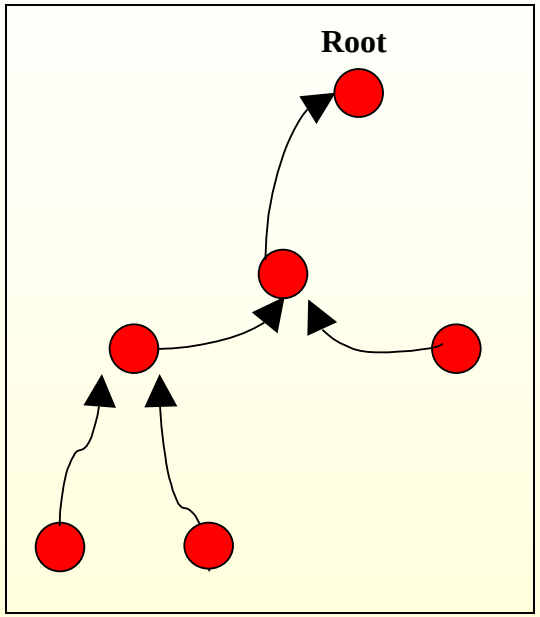
Extension:
The things that satisfy the description, property, etc.

Term vs. Concept

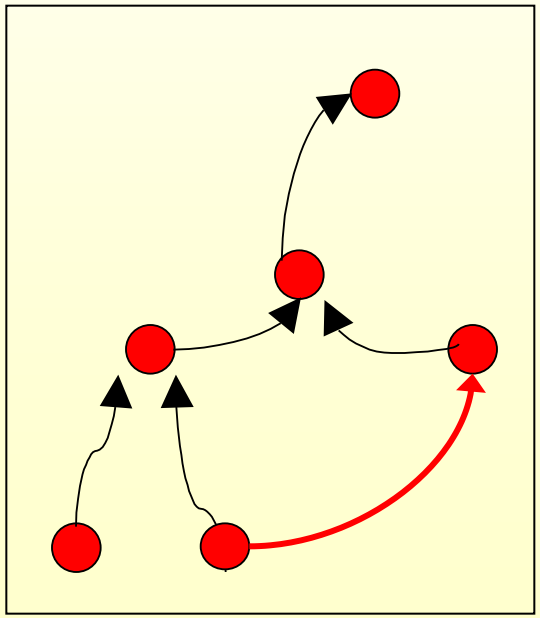
- **Term (terminology):**
  - Natural language words or phrases that act as indices to the underlying meaning, i.e., the concept (or composition of concepts)
  - The syntax (e.g., string) that stands in for or is used to indicate the semantics (meaning)
- **Concept:**
  - A unit of semantics (meaning), the node (entity) or link (relation) in the mental or knowledge representation model



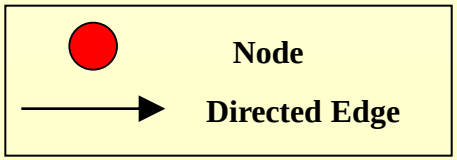
Tree vs. Graph

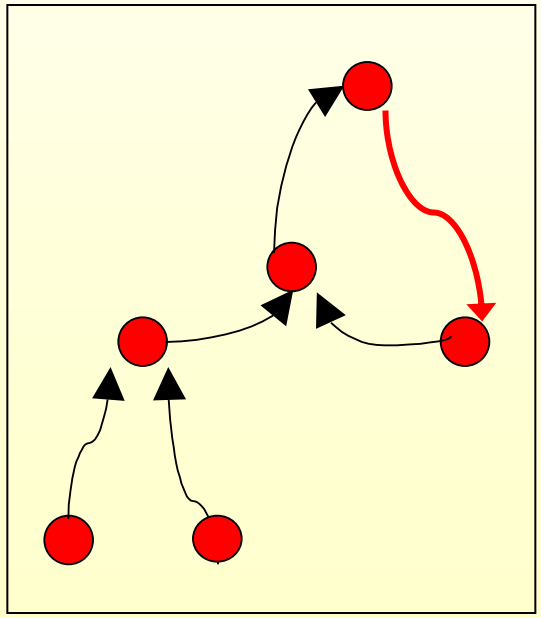


Tree



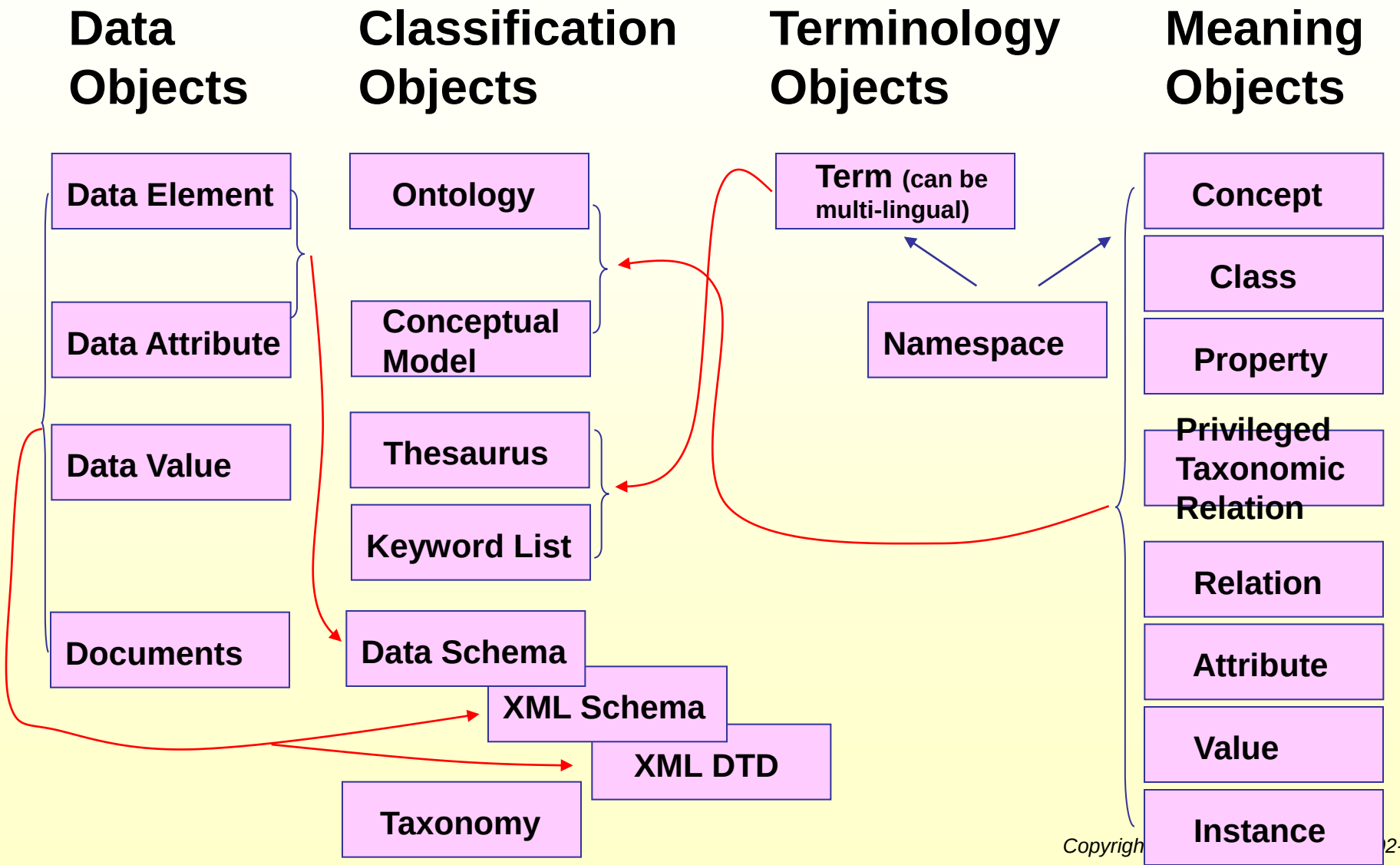
Directed Acyclic Graph



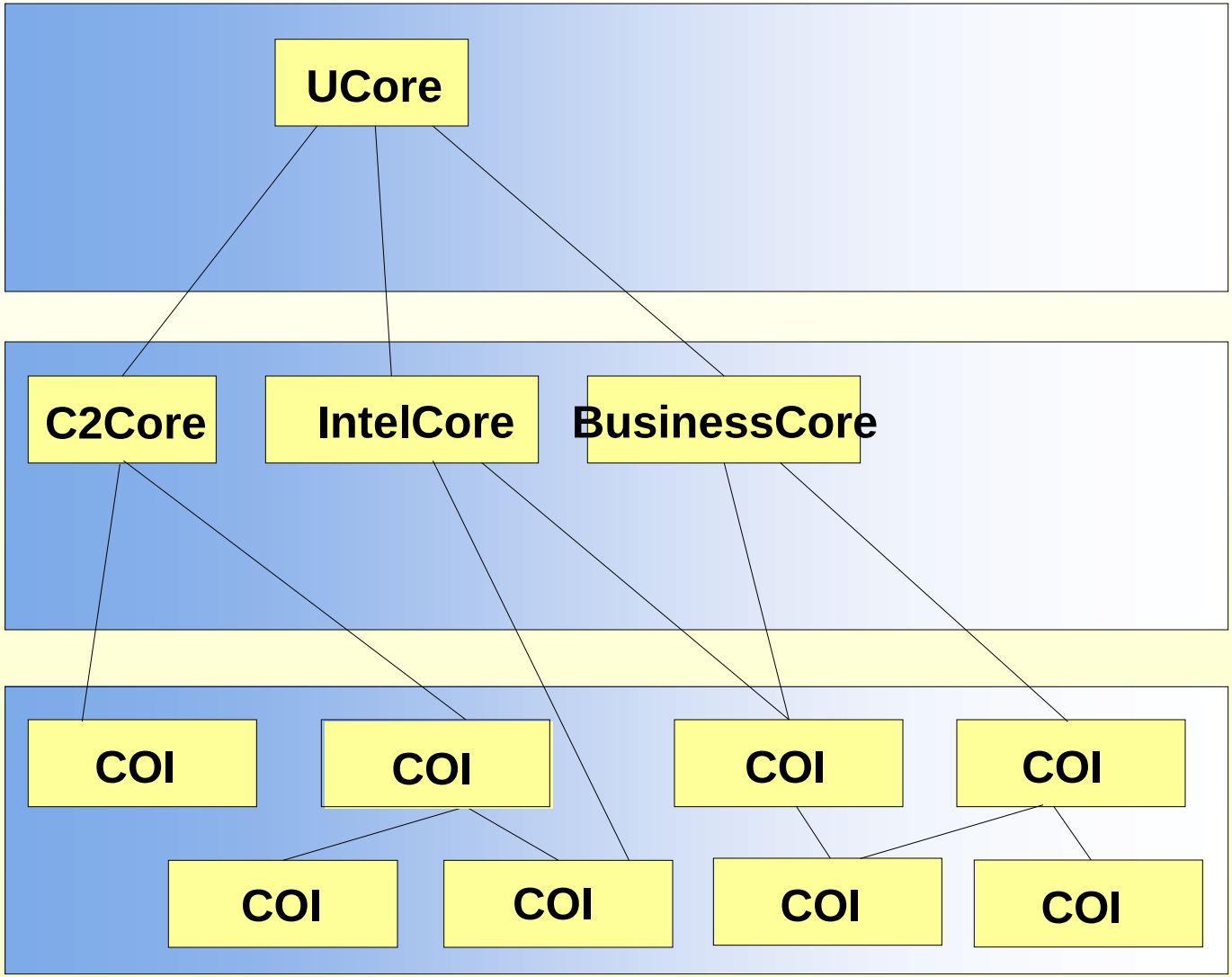


Directed Cyclic Graph

Example: Metadata Registry/Repository – Contains Objects + Classification



Universal Core (UCore), Common Cores, Community of Interest (COI) Vocabularies



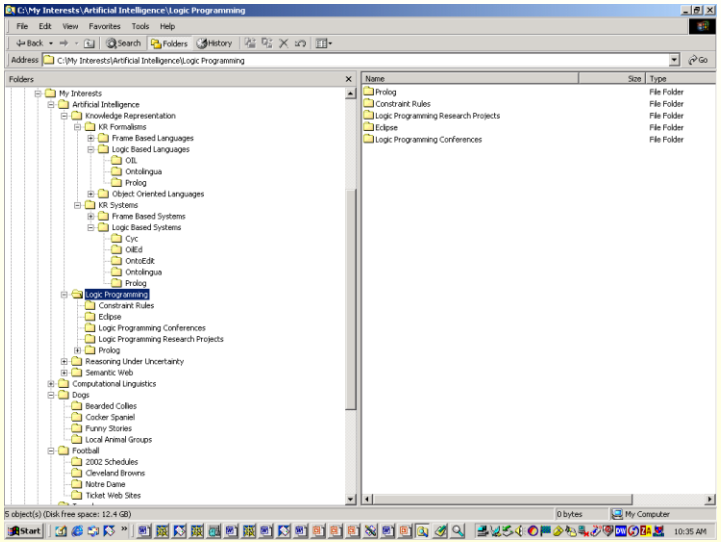
Taxonomy: Definition

- Taxonomy:
  - A way of classifying or categorizing a set of things, i.e., a classification in the form of a hierarchy (tree)
- IT Taxonomy:
  - The classification of information entities in the form of a hierarchy (tree), according to the presumed relationships of the real world entities which they represent
- Therefore: A taxonomy is a semantic (term or concept) hierarchy in which information entities are related by either:
  - The ***subclassification of*** relation (weak taxonomies) or
  - The ***subclass of*** relation (strong taxonomies) for concepts or the **narrower than** relation (thesauri) for terms
  - **Only the subclass/narrower than relation is a subsumption (generalization/specialization) relation**
  - **Subsumption (generalization/specialization) relation:** the mathematical subset relation
  - Mathematically, strong taxonomies, thesauri, conceptual models, and logical theories are minimally Partially Ordered Sets (posets), i.e., they are ordered by the subset relation
    - They may be mathematically something stronger (conceptual models and logical theories)

Taxonomies: Weak

Example: Your Folder/Directory Structure

- No consistent semantics for parent-child relationship: arbitrary ***Subclassification Relation***
- NOT a *generalization / specialization* taxonomy

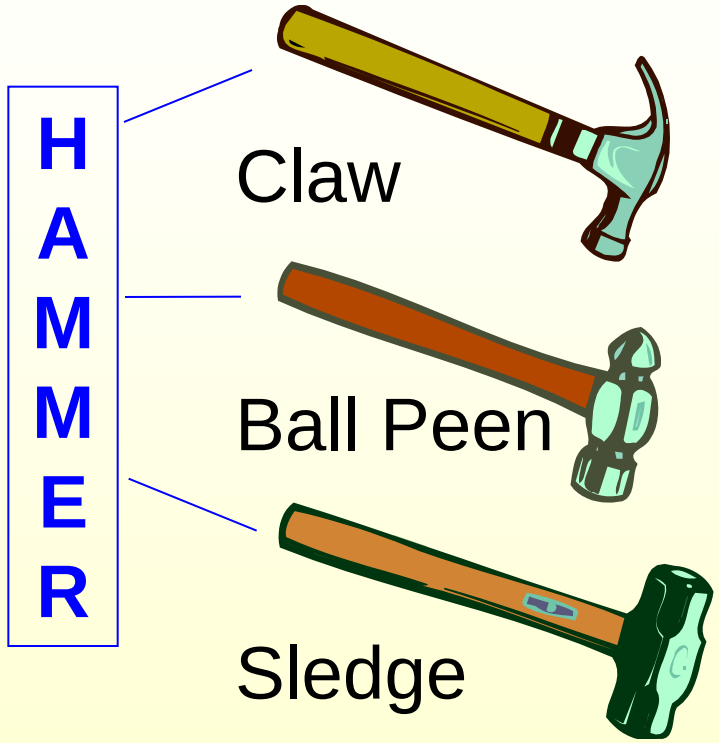


Example: UNSPSC

Segment	Family	Class	Commodity	Title
10	00	00	00	Live Plant and Animal Material and Accessories and Supplies
10	10	00	00	Live animals
10	10	15	00	Livestock
10	10	15	01	Cats
10	10	15	02	Dogs

Taxonomies: Strong

- Consistent semantics for parent-child relationship: ***Narrower than (terms) or Subclass (concepts) Relation***
- *A generalization/specialization* taxonomy
- **For concepts:** Each information entity is distinguished by a property of the entity that makes it unique as a subclass of its parent entity (a synonym for property is attribute or quality)
- **For terms:** each child term **implicitly** refers to a concept which is the subset of the concept referred to by its parent term

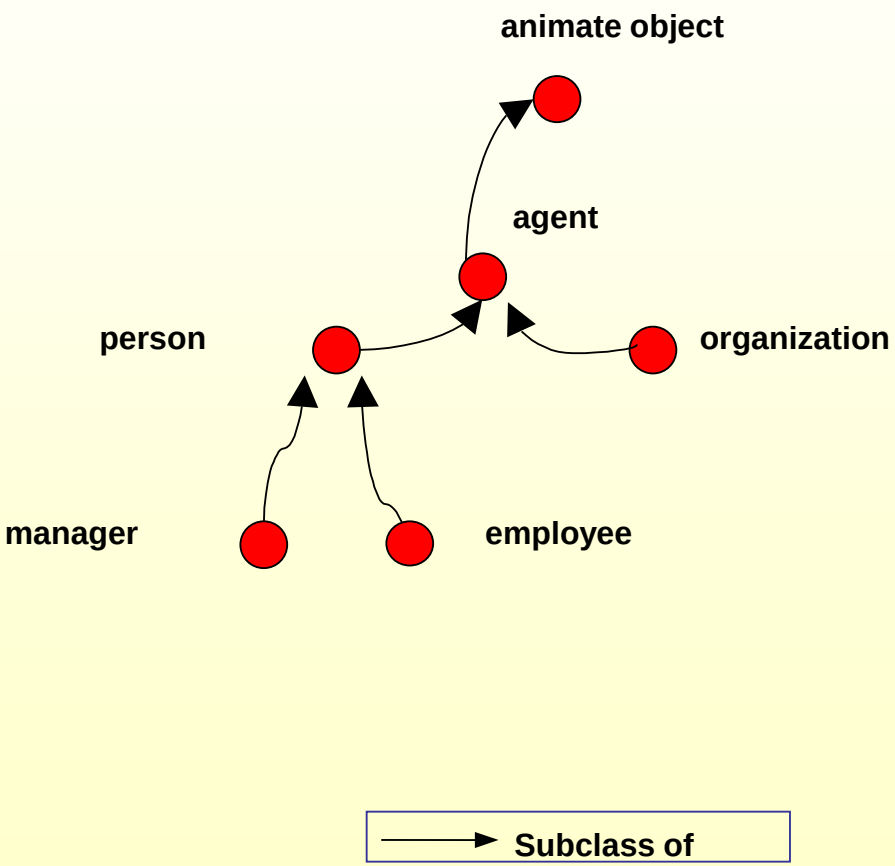


- **What are the *distinguishing properties* between these three hammers?**
  - **Form (physical property)**
  - **Function (functional property)**
- **"Purpose proposes property" (form follows function) – for human artifacts, at least**

Two Examples of Strong Taxonomies

Many representations of trees

Simple HR Taxonomy



Linnaeus Biological Taxonomy

Kingdom: Animalia

Phylum: Chordata

Subphylum: Vertebrata

Class: Mammalia

Subclass: Theria

Infraclass: Eutheria

Order: Primates

Suborder: Anthropoidea

Superfamily: Hominoidea

Family: Hominidae

Genus: Homo

Species: sapiens

Class: Diapsida (Reptiles, Dinosaurs, Birds)

Another, mostly strong Taxonomy: Dewey Decimal System

Code	Description	Code	Description
500	Natural sciences & mathematics	550	Earth sciences
501	Philosophy & theory	551	Geology, hydrology, meteorology
502	Miscellany	552	Petrology
503	Dictionaries & encyclopedias	553	Economic geology
504	Not assigned or no longer used	554	Earth sciences of Europe
505	Serial publications	555	Earth sciences of Asia
506	Organizations & management	556	Earth sciences of Africa
507	Education, research, related topics	557	Earth sciences of North America
508	Natural history	558	Earth sciences of South America
509	Historical, areas, persons treatment	559	Earth sciences of other areas
510	Mathematics	560	Paleontology Paleozoology
511	General principles	561	Paleobotany
512	Algebra & number theory	562	Fossil invertebrates
513	Arithmetic	563	Fossil primitive phyla
514	Topology	564	Fossil Mollusca & Molluscoidea
515	Analysis	565	Other fossil invertebrates
516	Geometry	566	Fossil Vertebrata (Fossil Craniata)
517	Not assigned or no longer used	567	Fossil cold-blooded vertebrates
518	Not assigned or no longer used	568	Fossil Aves (Fossil birds)
519	Probabilities & applied mathematics	569	Fossil Mammalia
520	Astronomy & allied sciences	570	Life sciences
521	Celestial mechanics	571	Not assigned or no longer used
522	Techniques, equipment, materials	572	Human races
523	Specific celestial bodies &	573	Physical anthropology
525	Earth (Astronomical geography)	575	Evolution & genetics
526	Mathematical geography	576	Microbiology
527	Celestial navigation	577	General nature of life
528	Ephemerides	578	Microscopy in biology
529	Chronology	579	Collection and preservation
530	Physics	580	Botanical sciences
531	Classical mechanics Solid mechanics	581	Botany
532	Fluid mechanics Liquid mechanics	582	Spermatophyta (Seed-bearing plants)
533	Gas mechanics	583	Dicotyledones
534	Sound & related vibrations	584	Monocotyledones
535	Light & paraphotic phenomena	585	Gymnospermae (Pinophyta)
536	Heat	586	Cryptogamia (Seedless plants)
537	Electricity & electronics	587	Pteridophyta (Vascular cryptograms)
538	Magnetism	588	Bryophyta
539	Modern physics	589	Thallobionta & Prokaryotae
540	Chemistry & allied sciences	590	Zoological sciences
541	Physical & theoretical chemistry	591	Zoology
542	Techniques, equipment, materials	592	Invertebrates
543	Analytical chemistry	593	Protozoa, Echinodermata, related phyla
544	Qualitative analysis	594	Mollusca & Molluscoidea
545	Quantitative analysis	595	Other invertebres

When is a Taxonomy enough?

- Weak taxonomy:
  - When you want ***semantically arbitrary parent-child term or concept relations***, when the ***subclassification relation*** is enough
  - I.e., sometimes you just want users to navigate down a hierarchy for your specific purposes, e.g, a quasi-menu system where you want them to see locally (low in the taxonomy) what you had already displayed high in the taxonomy
  - Application-oriented taxonomies are like this
  - Then, in general, you are using weak ***term*** relations because the nodes are not really meant to be **concepts,** but only words or phrases that will be significant to the user or you as a classification devise
- Strong taxonomy:
  - When you really want to use the semantically consistent **narrower-than** (terms) or **subclass** (concepts) **relation** (a true subsumption or subset relation)
  - When you want to partition your general conceptual space
  - When you want individual conceptual buckets
  - **Note: the subclass relation only applies to concepts; it is not equivalent (but is similar) to the narrower-than relation that applies to terms in thesauri**
- **You need more than a taxonomy if you need to either:**
  - **Using narrower than relation: Define term synonyms and cross-references to other associated terms, or**
  - **Using subclass relation: Define properties, attributes and values, relations, constraints, rules, on concepts**

Take Break!

Part 2: Thesauri, Conceptual Models, & Logical Theories (Strong Ontologies)

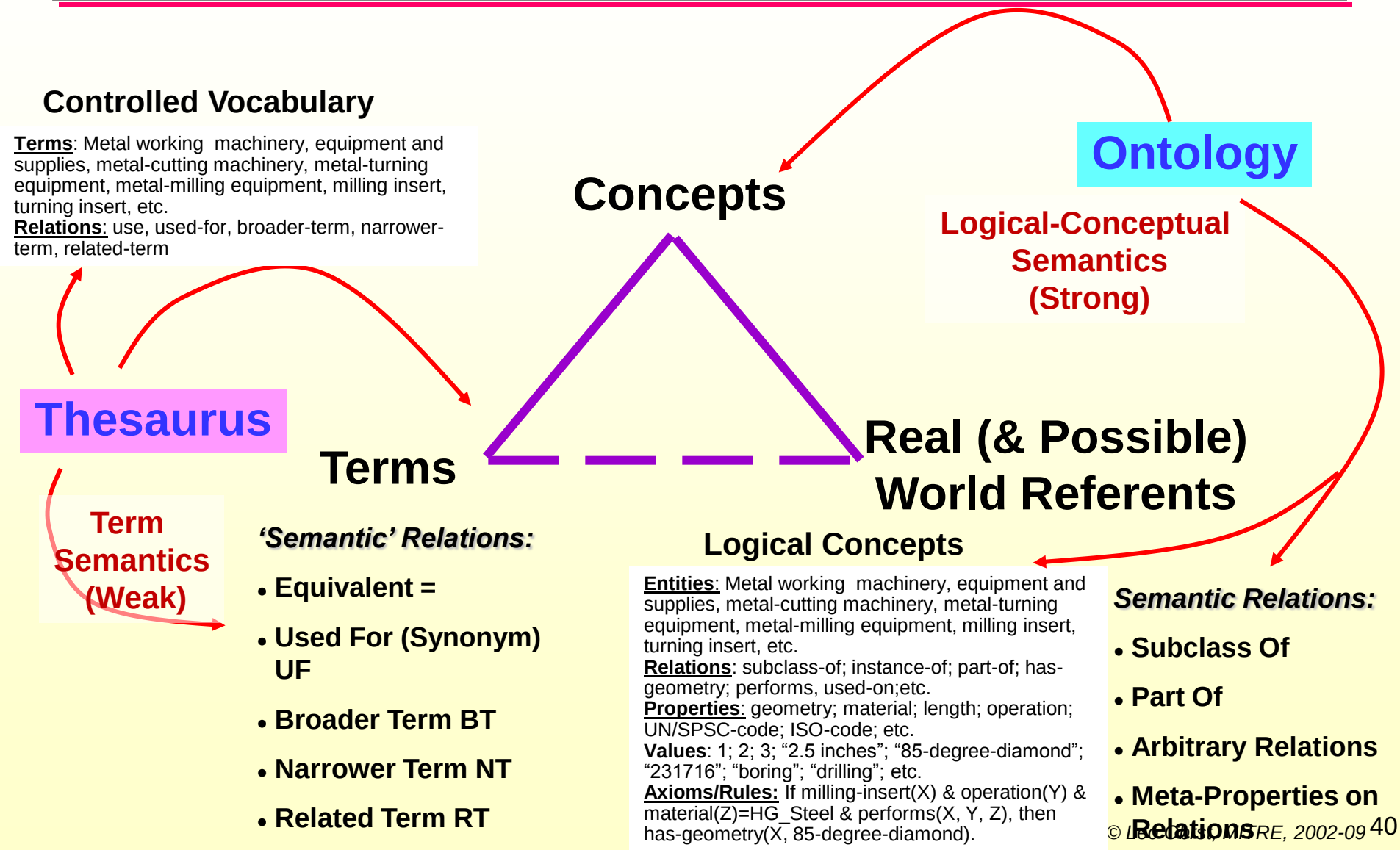
Thesaurus: Definition

- From ANSI INISO 239.19-1993, (Revision of 239.194980):
  - A **thesaurus is a controlled vocabulary** arranged in a known order and structured so that equivalence, homographic, hierarchical, and associative relationships among terms are displayed clearly and identified by standardized relationship indicators
  - The **primary purposes of a thesaurus** are to facilitate retrieval of documents and to achieve consistency in the indexing of written or otherwise recorded documents and other items
- Four Term Semantic Relationships:
  - **Equivalence:** synonymous terms
  - **Homographic:** terms spelled the same
  - **Hierarchical:** a term which is broader or narrower than another term
  - **Associative:** related term
- A consistent semantics for the hierarchical parent-child relationship: broader than, narrower than
- This hierarchical ordering is a *Subsumption (i.e., generalization/specialization)* relation
- Can view just the *narrower-than* subsumption hierarchy as a **term taxonomy**
- Unlike Strong subclass-based Taxonomy, Conceptual Model, & Logical Theory: the relation is between Terms, NOT Concepts

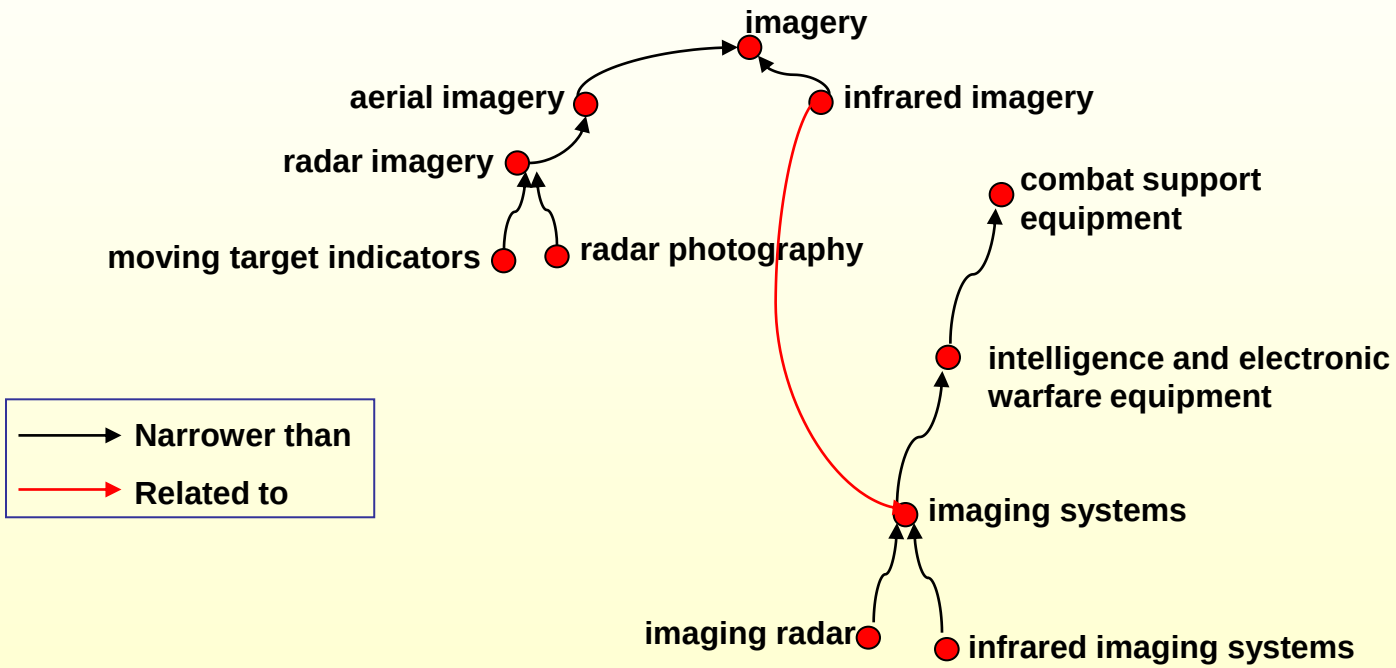
Thesaural Term Relationships

Semantic Relation	*Definition*	*Example*
Synonym **Similar to** **Equivalent** **Used For**	A term X has nearly the same meaning as a term Y.	"Car" is a synonym for "automobile".
Homonym **Spelled the Same** **Homographic**	A term X is spelled the same way as a term Y, which has a different meaning	The "bank" which is a financial institution is a homonym for the "bank" which is the side of a river or stream.
Broader Than **(Hierarchic: parent of)**	A term X is broader in meaning than a term Y.	"Vehicle" has a broader meaning than "automobile".
Narrower Than **(Hierarchic: child of)**	A term X is narrower in meaning than a term Y.	"Automobile" has a narrower meaning than "vehicle".
Associated **Associative** **Related**	A term X is associated with a term Y, i.e., there is some unspecified relationship between the two.	A "comb" is associated with a "barber".

Thesaurus vs. Ontology



Center For Army Lessons Learned (CALL) Thesaurus Example



When is a Thesaurus enough?

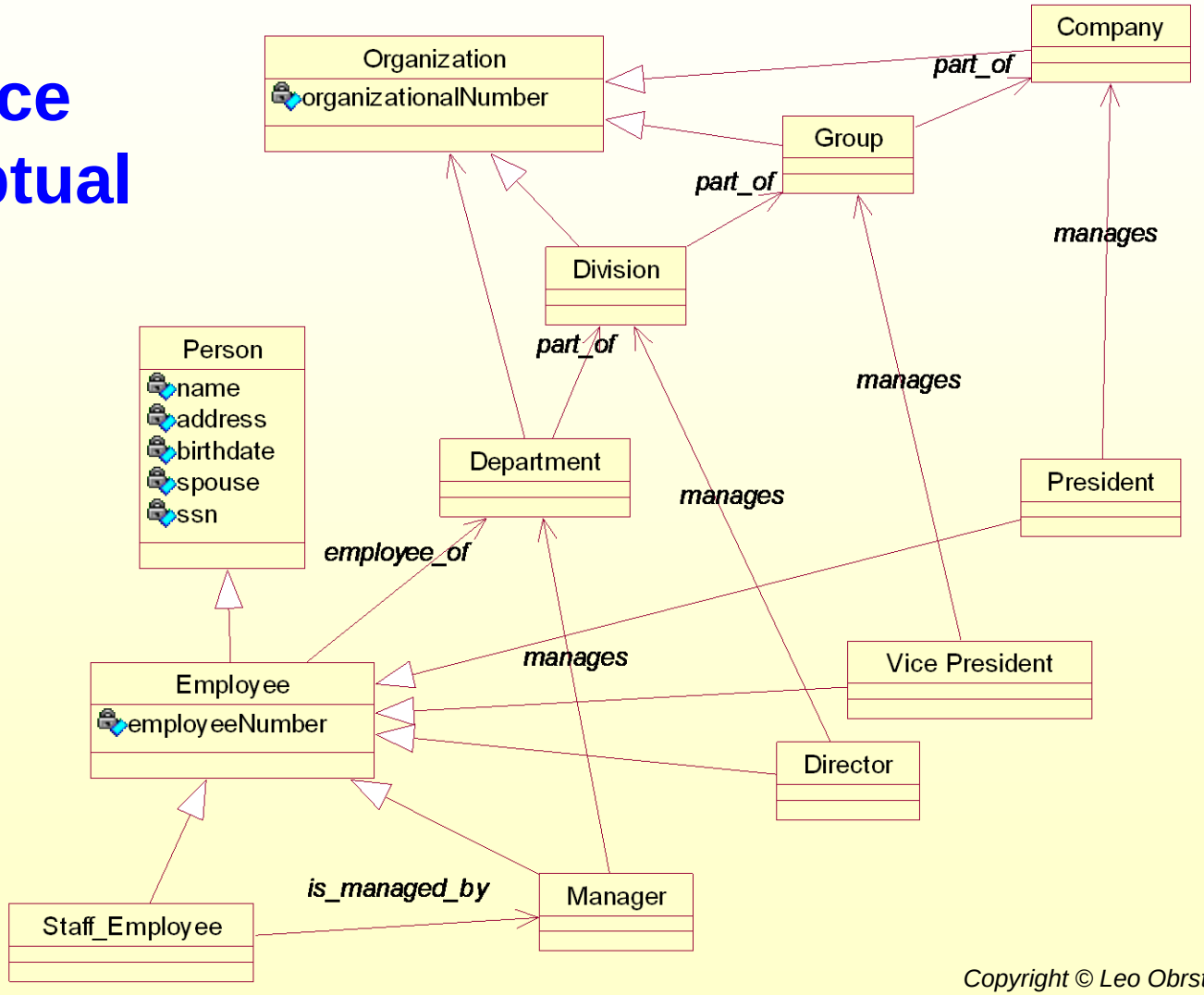
- When you don't need to define the concepts of your model, but only the terms that refer to those concepts, i.e., to at least partially index those concepts
- Ok, what does that mean?
- If you need an ordered list of terms and their synonyms and loose connections to other terms (cross-references)
- Examples:
  - If you need to use term buckets (sets or subsets) to use for term expansion in a keyword-based search engine
  - If you need a term classification index for a registry/repository, to guarantee uniqueness of terms and synonyms within a Community of Interest or namespace that might point to/index a concept node
- **You need more than a thesaurus** if you need to define properties, attributes and values, relations, constraints, rules, on concepts
  - You need either a **conceptual model** (weak ontology) or a **logical theory** (strong ontology)

Conceptual Models: Weak Ontologies

- Many conceptual domains cannot be expressed adequately with a taxonomy (nor with a thesaurus, which models term relationships, as opposed to concept relationships)
- Conceptual models seek to model a portion of a domain that a database must contain data for or a system (or, recently, enterprise) must perform work for, by providing users with the type of functionality they require in that domain
- UML is paradigmatic modeling language
- Drawbacks:
  - Models mostly used for documentation, required human semantic interpretation
  - Limited machine usability because cannot directly interpret semantically
  - Primary reason: there is no Logic that UML is based on
- **You need more than a Conceptual Model** if you need machine-interpretability (more than machine-processing)
  - You need a logical theory (high-end ontology)

Conceptual Model: UML Example

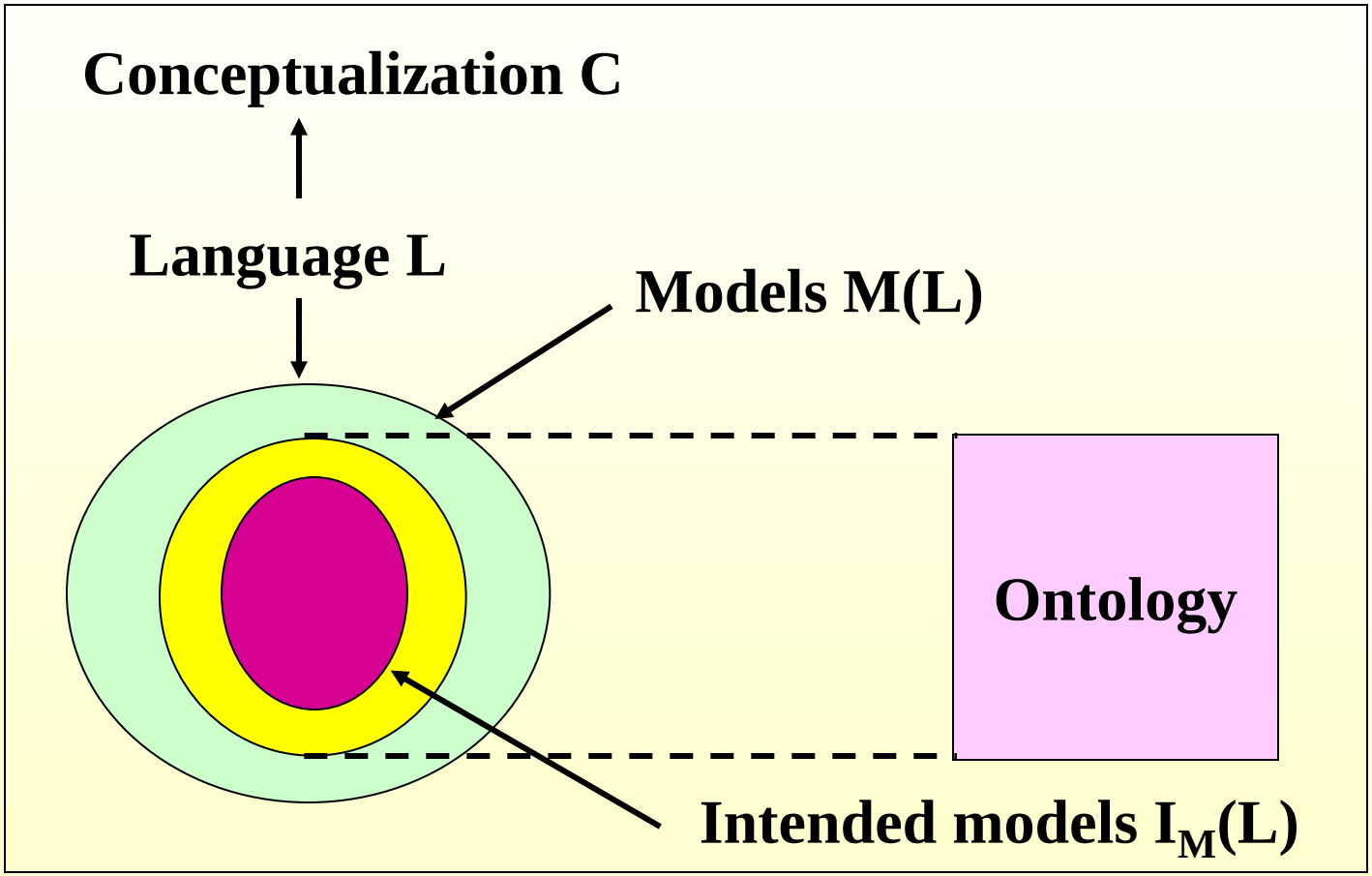
Human Resource Conceptual Model



Logical Theories: Strong Ontologies

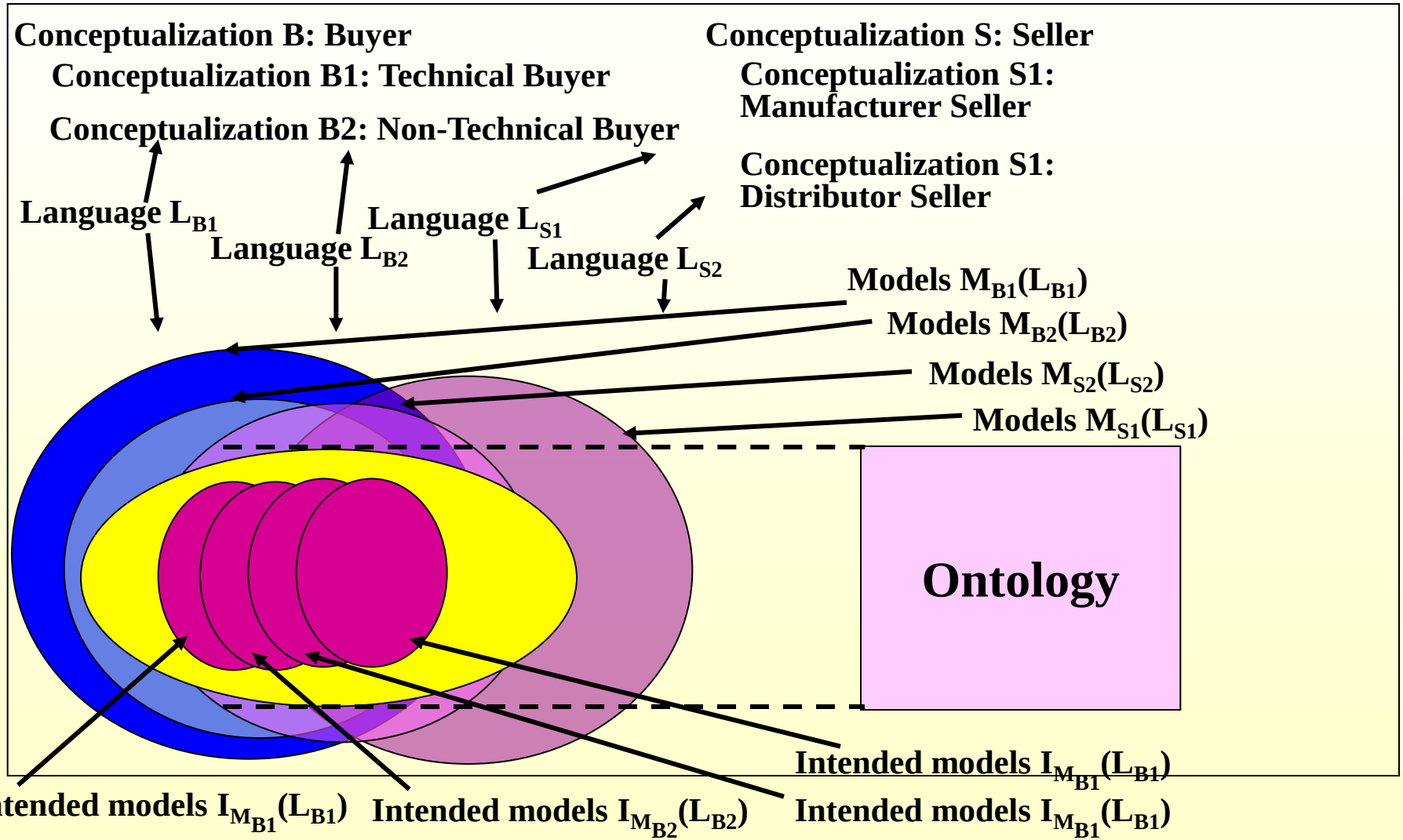
- Can be either Frame-based or Axiomatic
  - Frame-based: node-and-link structured in languages which hide the logical expressions, entity-centric, like object-oriented modeling, centering on the entity class, its attributes, properties, relations/associations, and constraints/rules
  - Axiomatic: axiom/rule-structured in languages which expose the logical expressions, non-entity-centric, so axioms that refer to entities (classes, instances, their attributes, properties, relations, constraint/rules) can be distributed

Logical Theories: More Formally

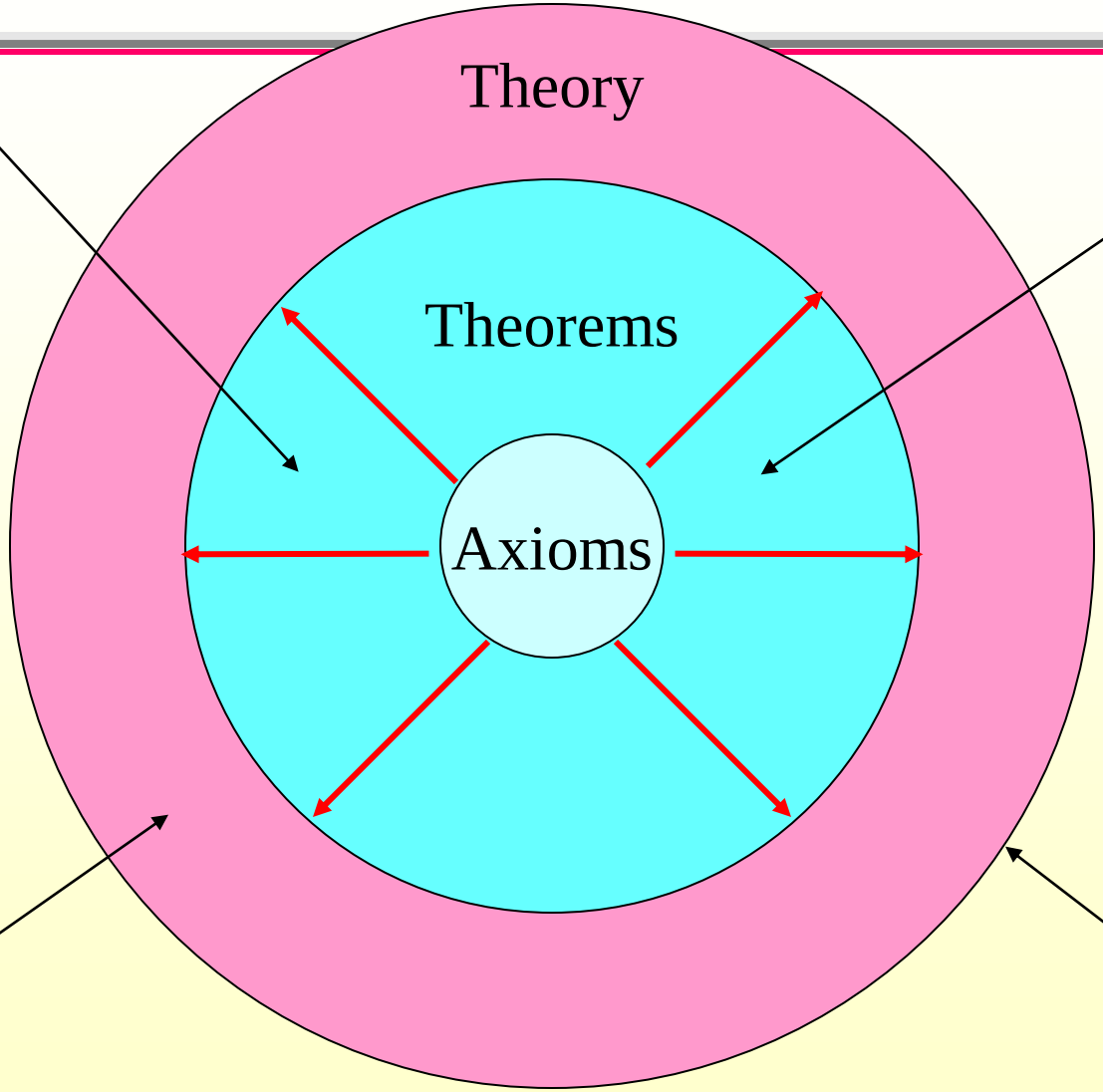


* N. Guarino. 1998. Formal ontology in information systems, pp. 3-15. In Formal Ontology in Information Systems, N. Guarino, ed., Amsterdam: IOS Press. Proceedings of the First International Conference (FOIS'98), June 6-8, Trent, Italy, p. 7

A More Complex Picture (from E-Commerce)



Axioms, Inference Rules, Theorems, Theory



(1) Theorems are licensed by a valid proof using ***inference rules*** such as Modus Ponens

(2) Theorems proven to be true can be added back in, to be acted on subsequently like axioms by inference rules

(3) Possible other theorems (as yet unproven)

(4) Ever expanding theory

Axioms

Class(Thing)

Class(Person)

Class(Parent)

Class(Child)

If SubClass(X, Y) then X is a subset of Y. This also means that if A is a member of Class(X), then A is a member of Class(Y)

SubClass(Person, Thing)

SubClass(Parent, Person)

SubClass(Child, Person)

ParentOf(Parent, Child)

NameOf(Person, String)

AgeOf(Person, Integer)

If X is a member of Class (Parent) and Y is a member of Class(Child), then $\neg$ (X =Y)

Inference Rules

And-introduction: given P, Q, it is valid to infer P $\wedge$ Q.

Or-introduction: given P, it is valid to infer P $\vee$ Q.

And-elimination: given P $\wedge$ Q, it is valid to infer P.

Excluded middle: P $\vee$ $\neg$P (i.e., either something is true or its negation is true)

Modus Ponens: given P $\rightarrow$ Q, P, it is valid to infer Q

Theorems

If P $\wedge$ Q are true, then so is P $\vee$ Q.

If X is a member of Class(Parent), then X is a member of Class(Person).

If X is a member of Class(Child), then X is a member of Class(Person).

If X is a member of Class(Child), then NameOf(X, Y) and Y is a String.

If Person(JohnSmith), then $\neg$ ParentOf(JohnSmith, JohnSmith).

Ontology Representation Levels

Level	Example Constructs
Knowledge Representation (KR) Language (Ontology Language) Level: Meta Level to the Ontology Concept Level	Class, Relation, Instance, Function, Attribute, Property, Constraint, Axiom, Rule
Ontology Concept (OC) Level: Object Level to the KR Language Level, Meta Level to the Instance Level	Person, Location, Event, Parent, Hammer, River, FinancialTransaction, BuyingAHouse, Automobile, TravelPlanning, etc.
Ontology Instance (OI) Level: Object Level to the Ontology Concept Level	Harry X. Landsford III, Ralph Waldo Emerson, Person560234, PurchaseOrderTransactionEvent6117090, 1995-96 V-6 Ford Taurus 244/4.0 Aerostar Automatic with Block Casting # 95TM-AB and Head Casting 95TM

Meta-Level to Object-Level

Meta-Level to Object-Level

Language

Ontology (General)

Knowledge Base (Particular)

Ontology Example from Electronic Commerce: the general domain of machine tooling & manufacturing; note that these are expressed in English, but usually would be in expressed in a logic-based language	
Concept	**Example**
Classes (general things)	Metal working machinery, equipment and supplies, metal-cutting machinery, metal-turning equipment, metal-milling equipment, milling insert, turning insert, etc.
Instances (particular things)	An instance of metal-cutting machinery is the "OKK KCV 600 15L Vertical Spindle Direction, 1530x640x640mm 60.24"x25.20"x25.20 X-Y-Z Travels Coordinates, 30 Magazine Capacity, 50 Spindle Taper, 20kg 44 lbs Max Tool Weight, 1500 kg 3307 lbs Max Loadable Weight on Table, 27,600 lbs Machine Weight, CNC Vertical Machining Center"
Relations: subclass-of, (kind_of), instance-of, part-of, has-geometry, performs, used-on, etc.	A kind of metal working machinery is metal cutting machinery, A kind of metal cutting machinery is milling insert.
Properties	Geometry, material, length, operation, ISO-code, etc.
Values:	1; 2; 3; "2.5", inches"; "85-degree-diamond"; "231716"; "boring"; "drilling"; etc.
Rules (constraints, axioms)	If milling-insert(X) & operation(Y) & material(Z)=HG_Steel & performs(X, Y, Z), then has-geometry(X, 85-degree-diamond). [Meaning: if you need to do milling on High Grade Steel, then you need to use a milling insert (blade) which has a 85-degree diamond shape.]

Example: Inference and Proof

Proof Using Inference Rule of Modus Ponens

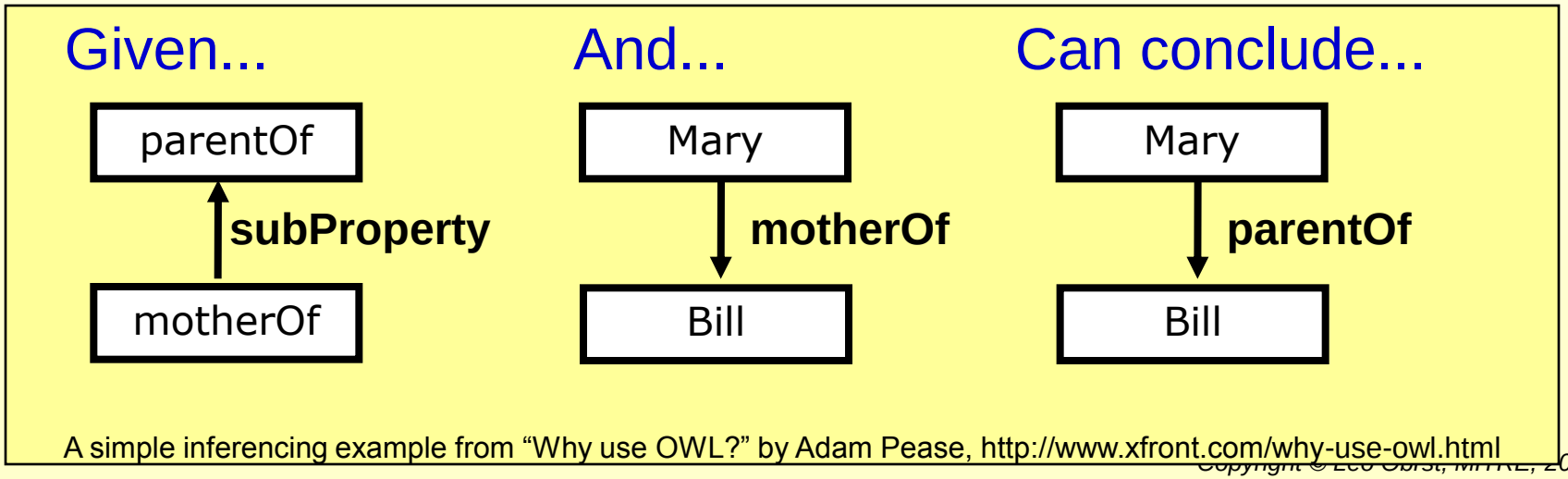
Given: **If motherOf is a subProperty of parentOf, and Mary is the mother of Bill, then Mary is the parentOf Bill**

motherOf is a subProperty of parentOf

Mary is the motherOf Bill

Infer: **Mary is the parentOf Bill**

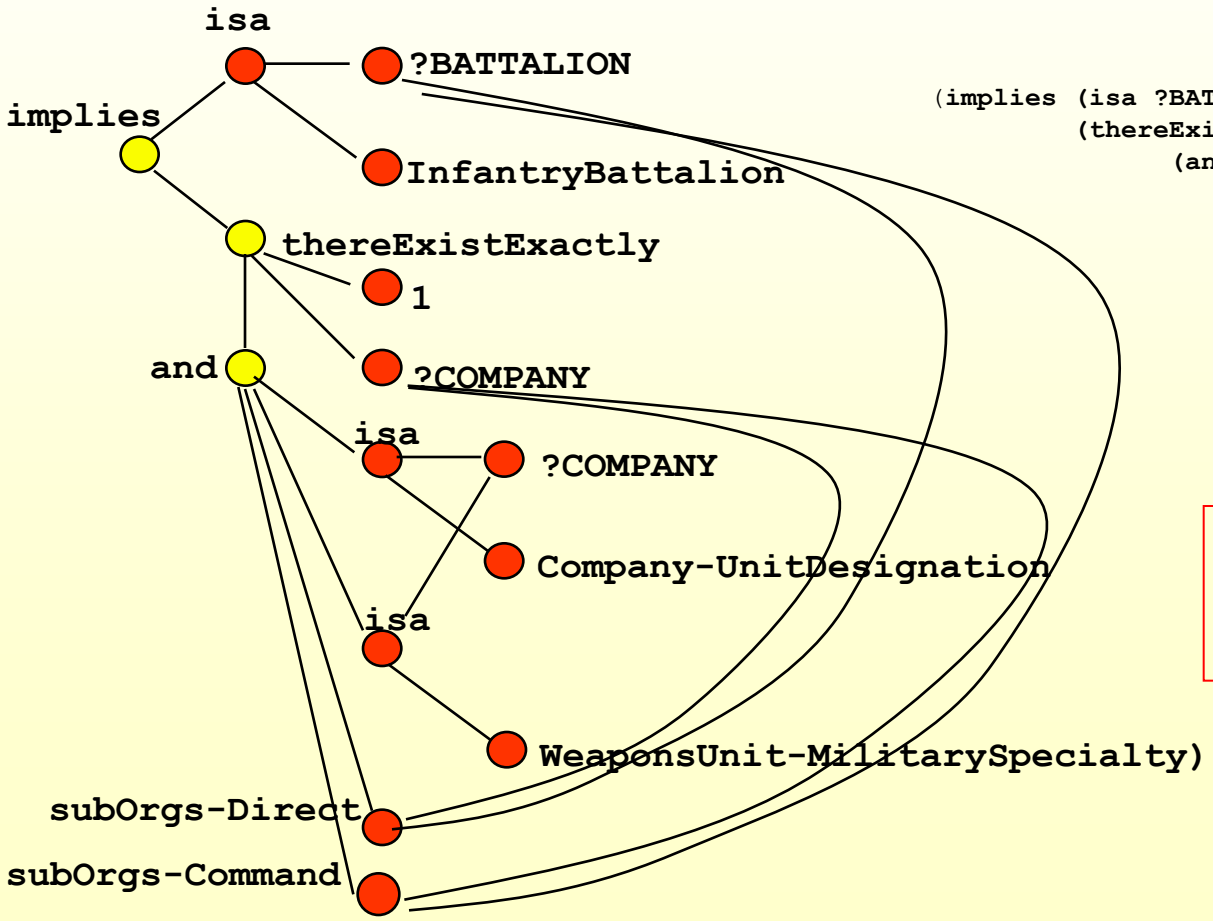
Deduction A method of reasoning by which one infers a conclusion from a set of sentences by employing the axioms and rules of inference for a given logical system.



A simple inferencing example from "Why use OWL?" by Adam Pease, http://www.xfront.com/why-use-owl.html

Ontology/KR
Expressible as Language and Graph

- **In ontology and knowledge bases, nodes are predicate, rule, variable, constant symbols, hence graph-based indexing, viewing**
- **Links are connections between these symbols: Semantic Net!**

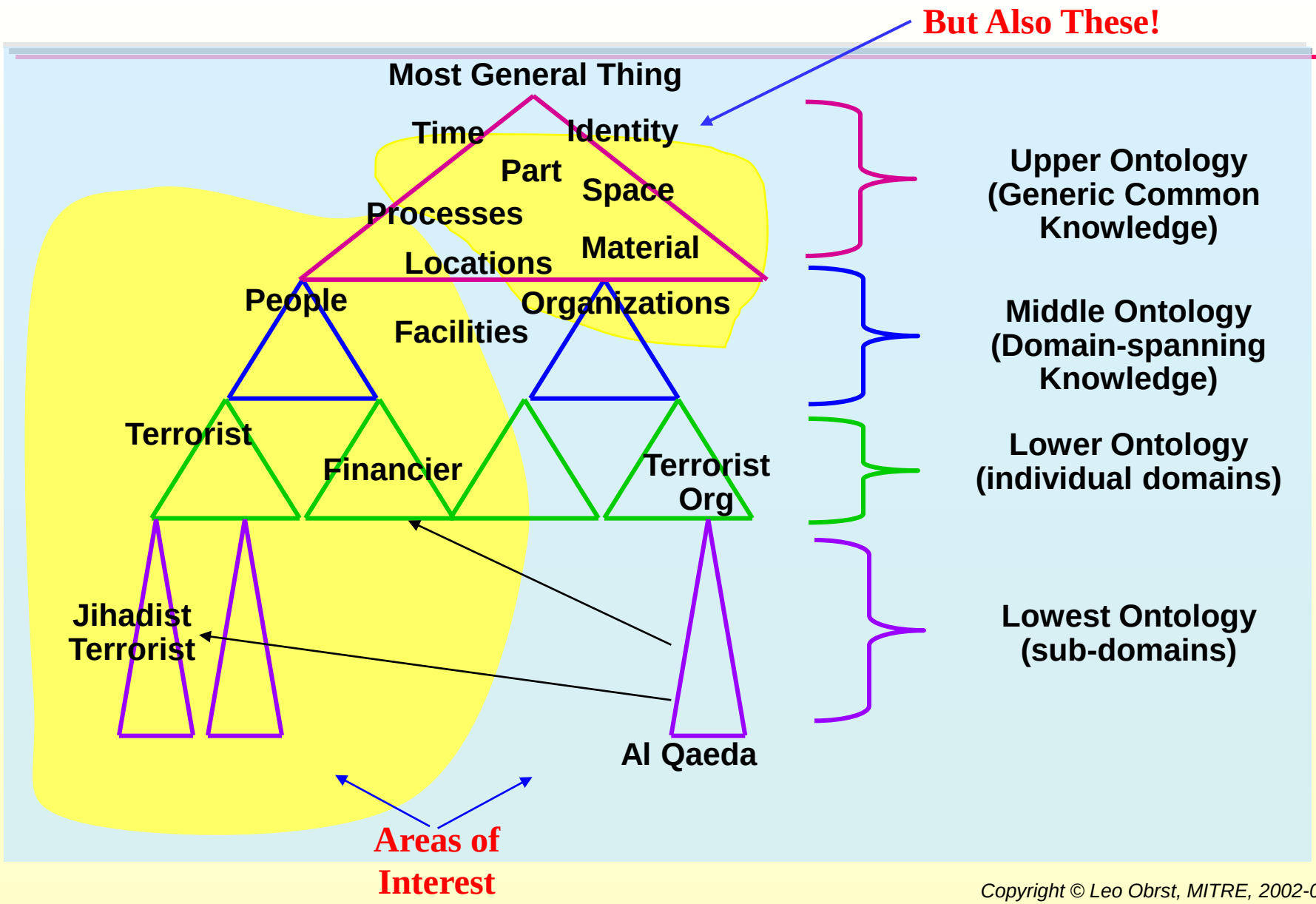



```
(implies (isa ?BATTALION InfantryBattalion)
         (thereExistExactly 1 ?COMPANY
               (and (isa ?COMPANY Company-UnitDesignation)
                    (isa ?COMPANY
                         WeaponsUnit-MilitarySpecialty)
                  (subOrgs-Direct ?BATTALION ?COMPANY)
                  (subOrgs-Command ?BATTALION ?COMPANY))))
```

CYC MELD Expression Example

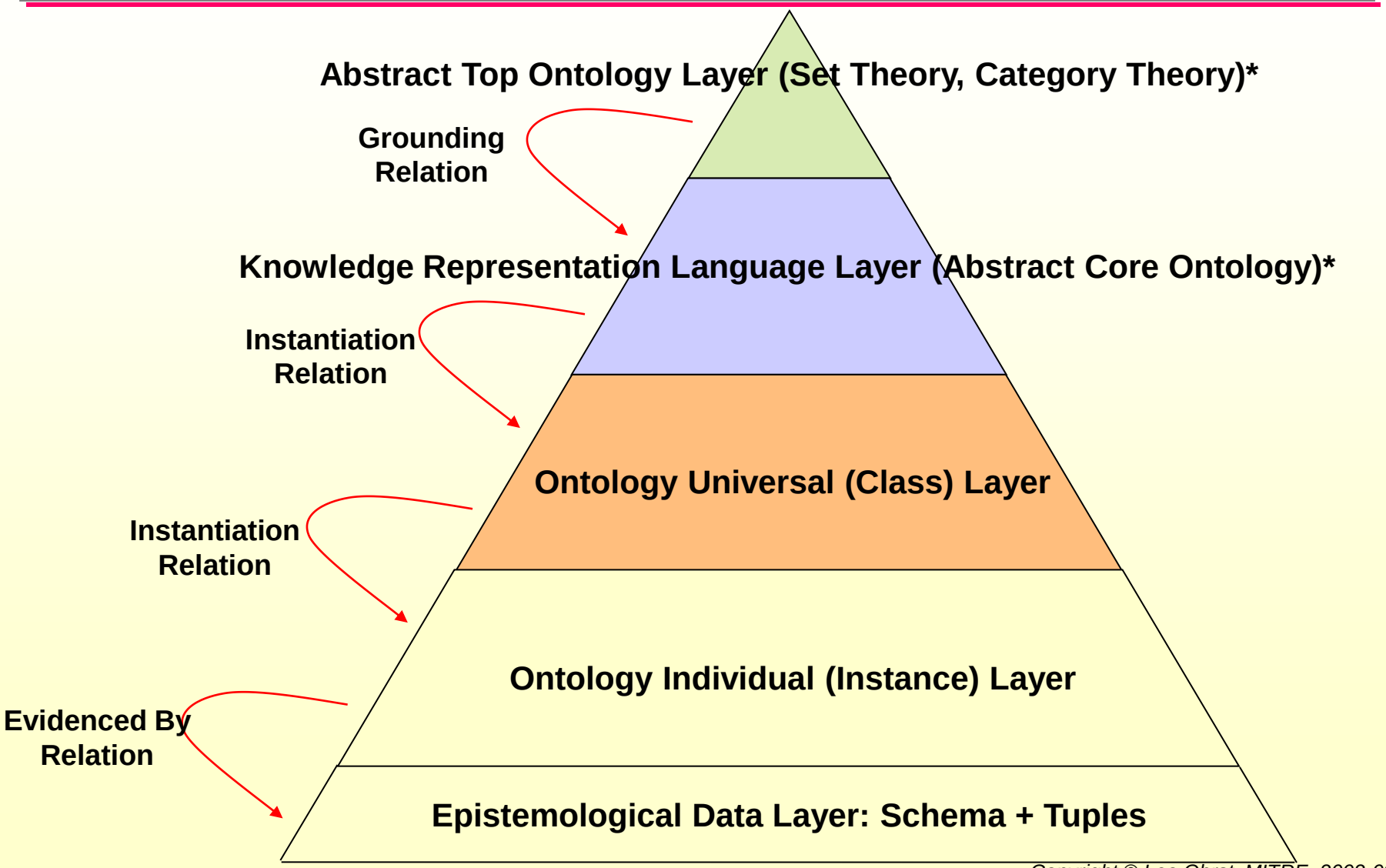
What's important is the logic!

Upper, Middle, Domain Ontologies



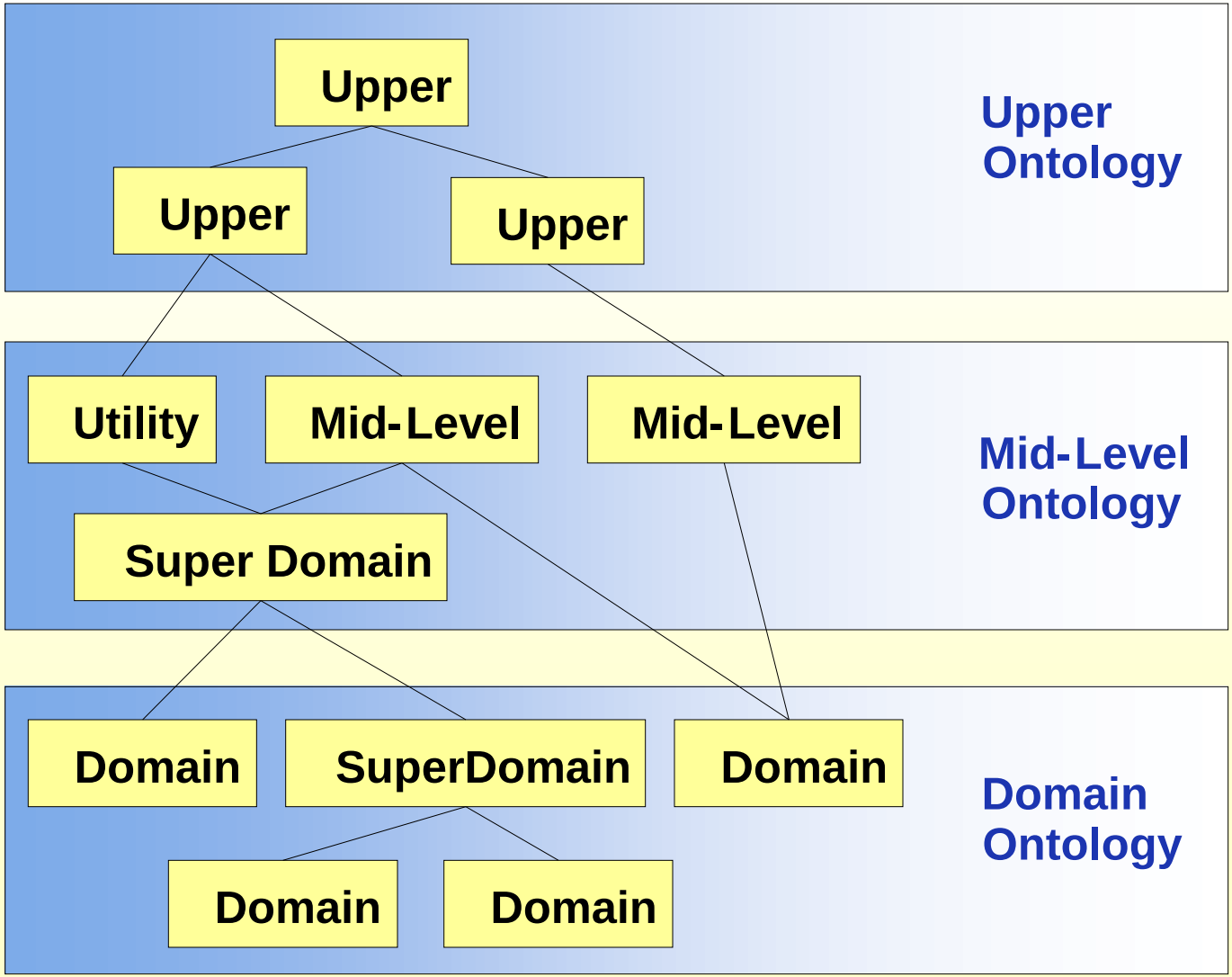
Ontology Content Architecture: More Complex View

* Adapted from: Herre, Heinrich, and Frank Loebe. 2005. A Meta-ontological Architecture for Foundational Ontologies. In: R. Meersman and Z. Tari (Eds.): CoopIS/DOA/ODBASE 2005, LNCS 3761, pp. 1398–1415, 2005. Springer-Verlag Berlin Heidelberg.



Ontology Universals & Individuals Layer: Upper, Mid-Level, Domain Ontologies

Adapted from: Pulvermacher, M.; S. Semy; L. Obrst. 2005. Toward the Use of an Upper Ontology for U.S. Government and U.S. Military Domains: An Evaluation. MITRE Technical Report, MTR 04B0000063, November, 2005.



Ontology Lifecycle

4) Analysis 3
- What are the resources available to harvest: vocabularies, schemas, taxonomies, conceptual models, ontologies?
- Are there domain standards, upper/middle ontologies to embed what we create within?

3) Analysis 2
- What are the referents, concepts: entities, relations, properties, rules?
- What are the terms that index the referents: terminology?

Requirements

2) Analysis 1 (Competency Questions)
- *Bottom-Up*: What are semantics of current data sources?
- *Top-Down:* What would you like to ask?

1) Rationale: **Why do you need**

8) Analysis 4
- Refine with domain experts, end users

9) Design 3
- Refine conceptualization

10) Implement 2
- Refine ontology

11) Deploy 1
- Provide ontology application services

12) Deploy 2
- Correct problems

13) Analysis 5
- Interrogate users
- Refine reqs
- More resources?

14) Design 4
- How can changes needed be made?
- Refine reqs

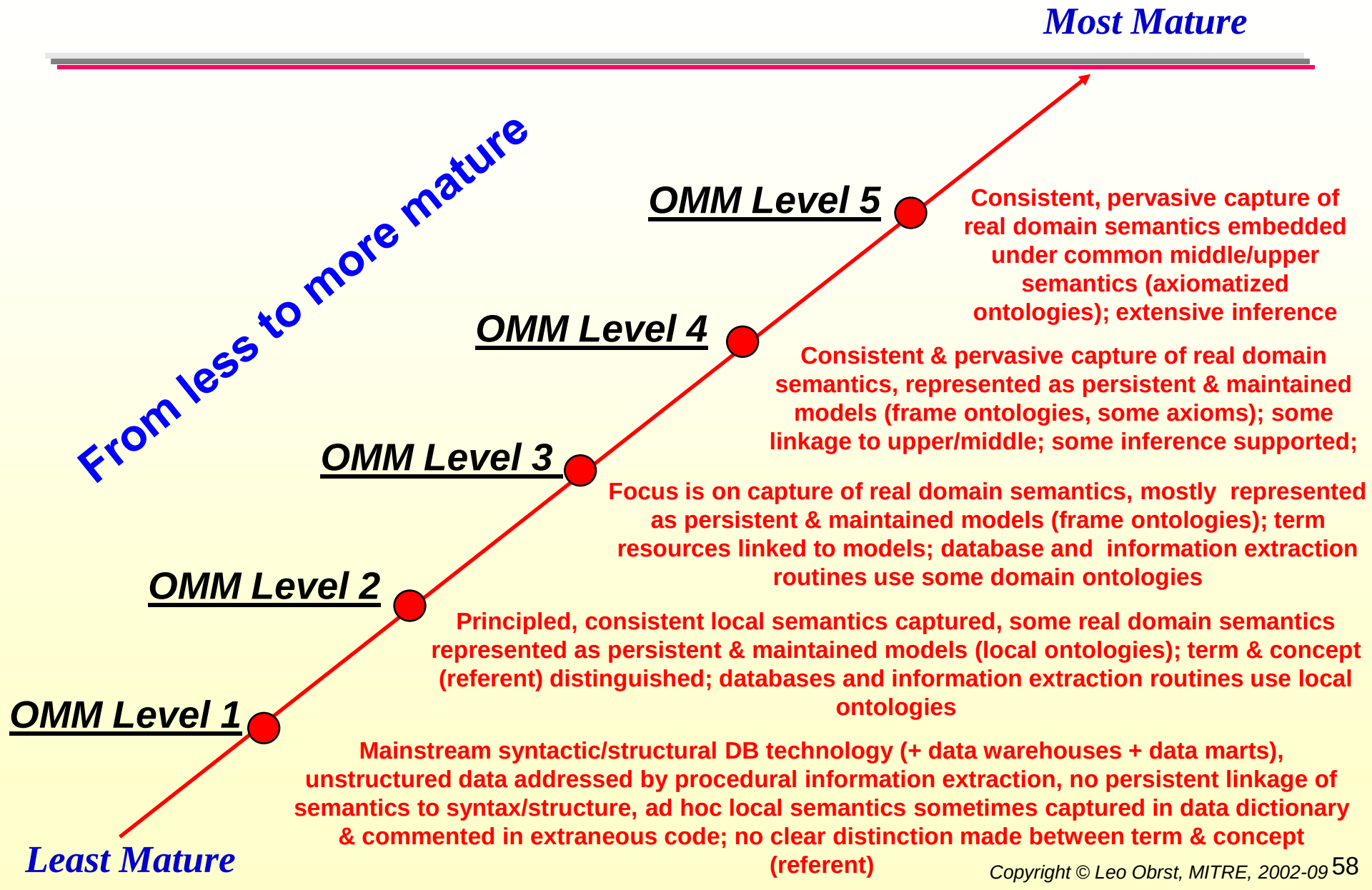
5) Design 1
- What ontology architecture do we choose?
- How expressive is the ontology language we need?
- What conceptualization?
- How do we model these entities, relations, properties, rules?
- What are the instances of these?
- What data sources mappings can link to these? How?
- What kinds of ontology tools do we need?

6) Implement 1
- Implement the ontology server we will need: periodicity, granularity, configuration management
- Implement the infrastructure, services of our architecture: enhance the server with

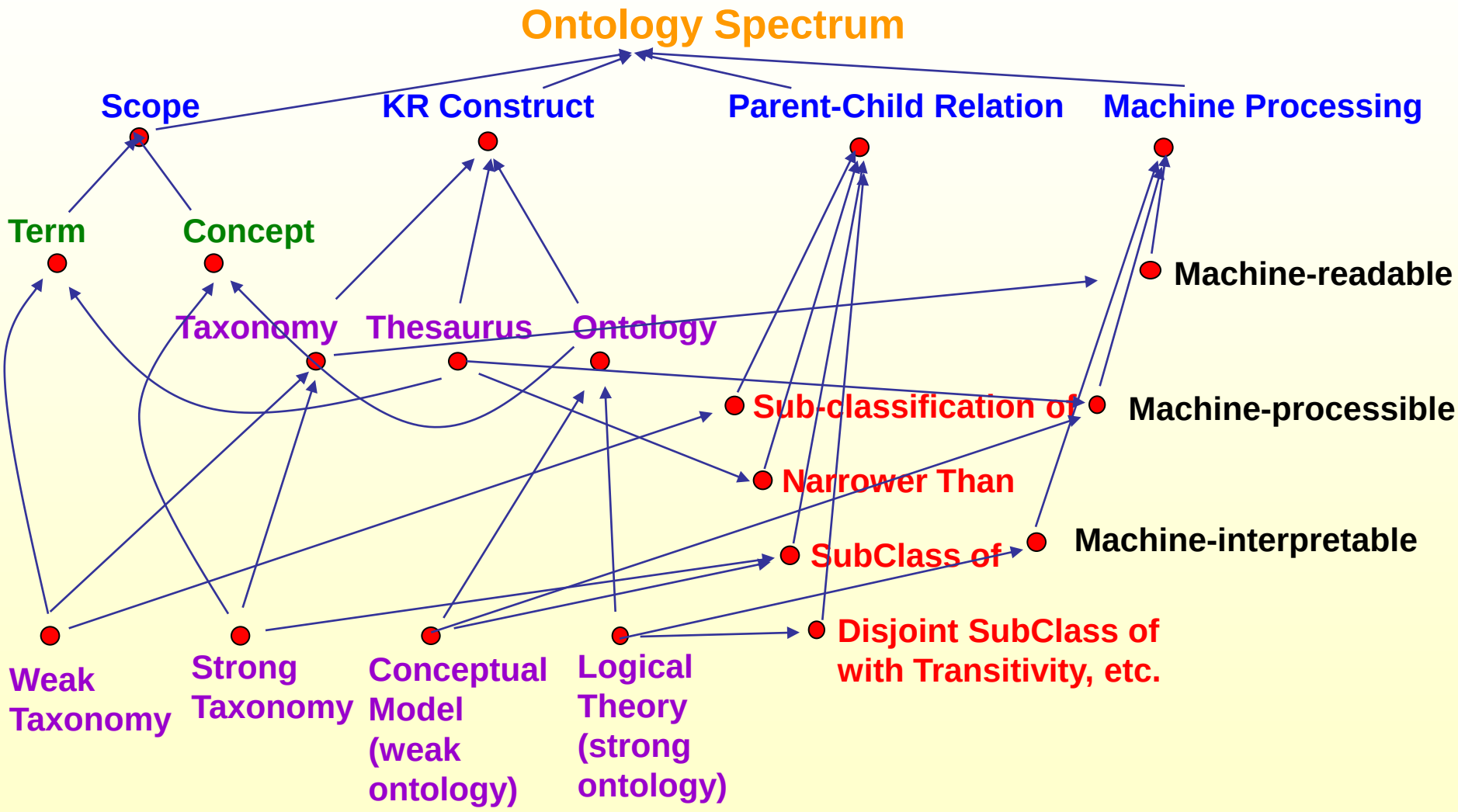
7) Design 2
- Are we done with ontology development?

ns as queries against
nswers returned quickly
ts/end users?

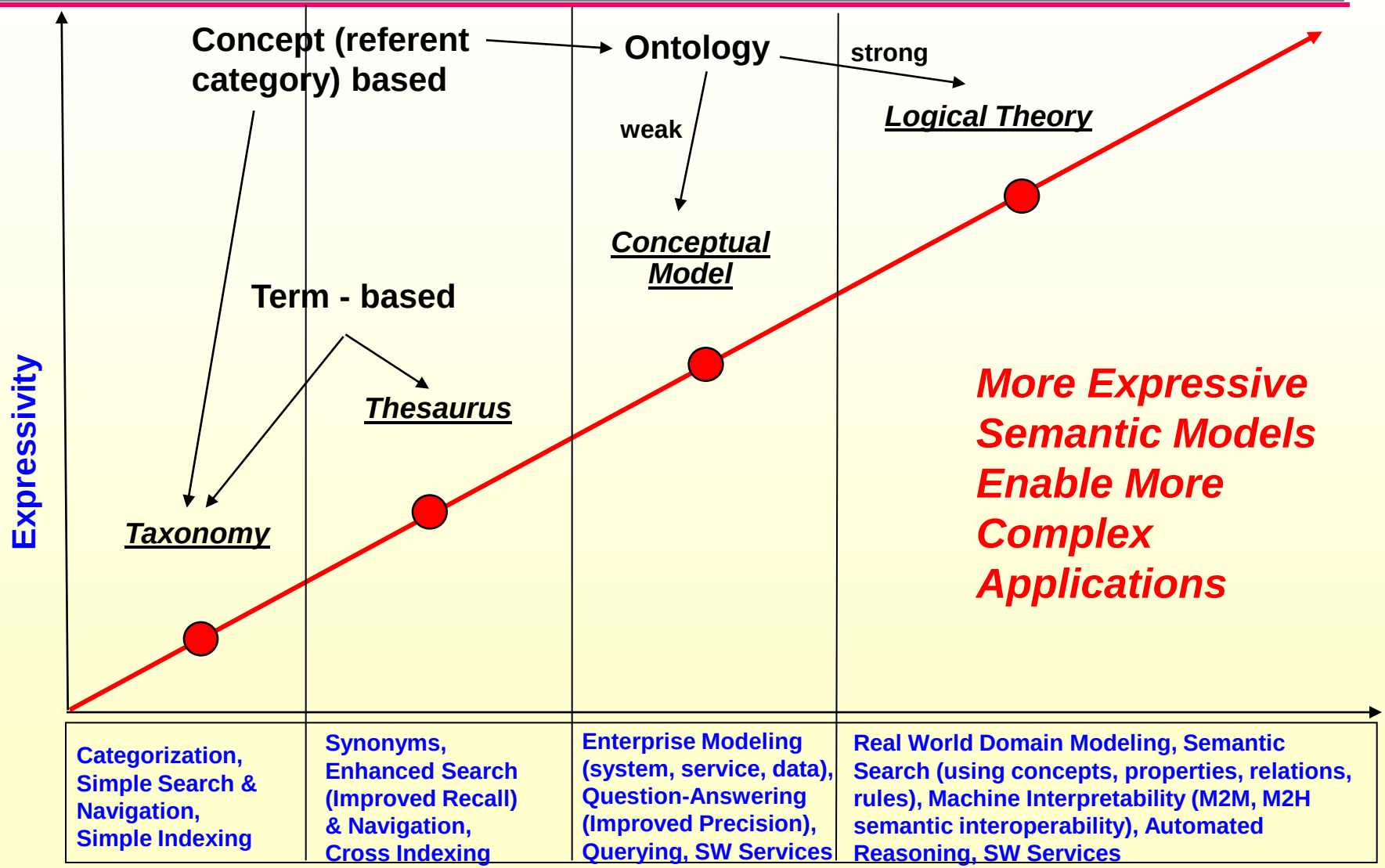
Ontology Maturity Model



Summary of Ontology Spectrum: Scope, KR Construct, Parent-Child Relation, Processing Capability

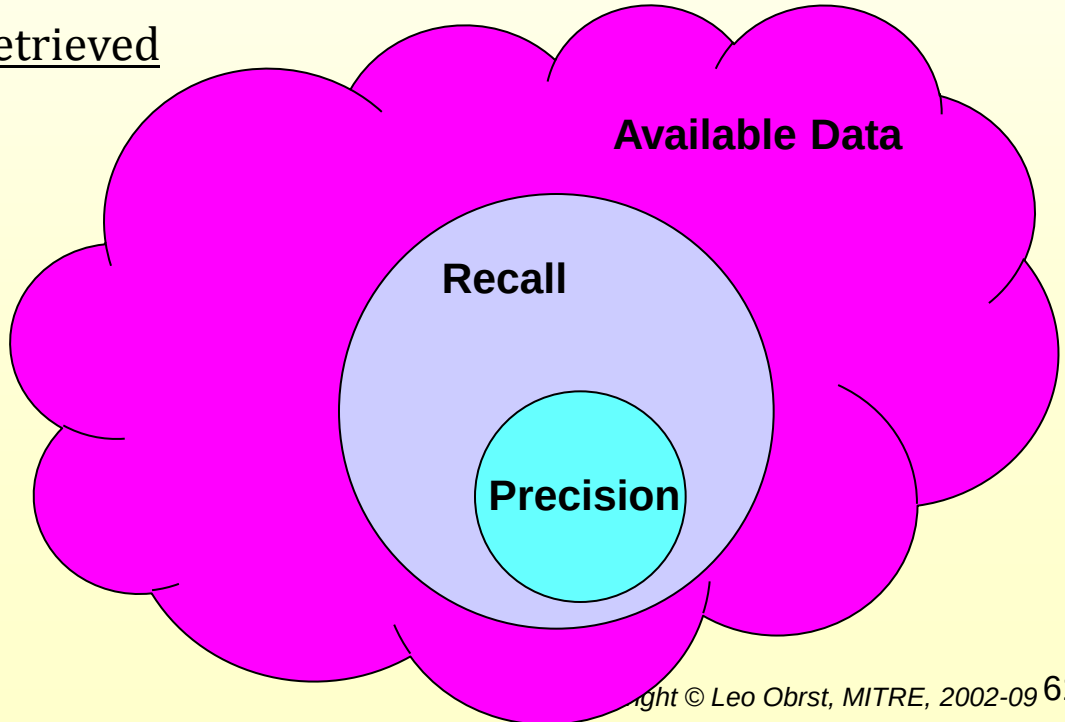


Ontology Spectrum: Complexity of Applications



Recall and Precision

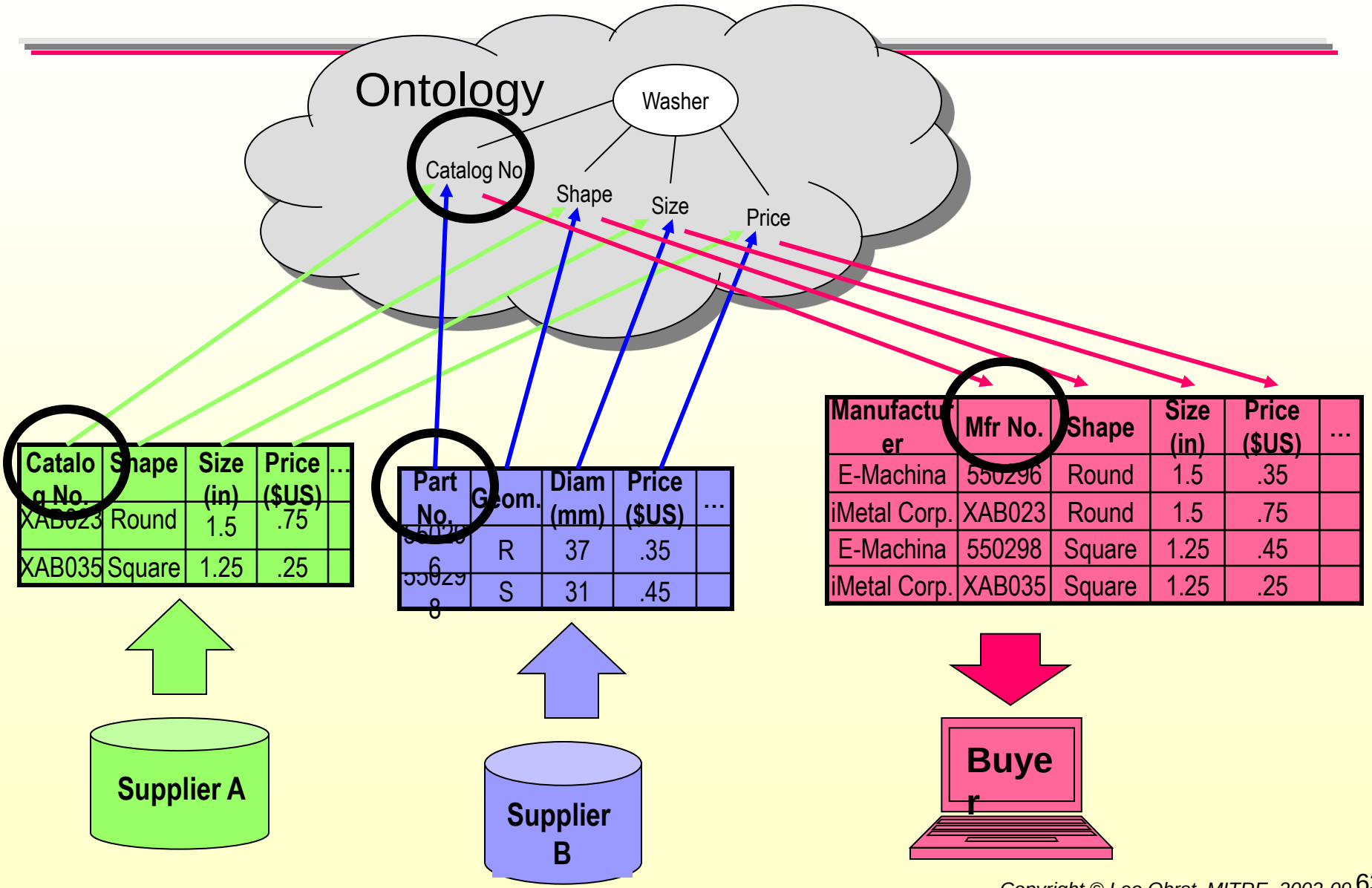
Recall	The percentage of relevant documents retrieved **Calculation:** Number of relevant docs retrieved Number of relevant docs
Precision	The percentage of retrieved documents judged relevant **Calculation:** Number of relevant docs retrieved Number of docs retrieved



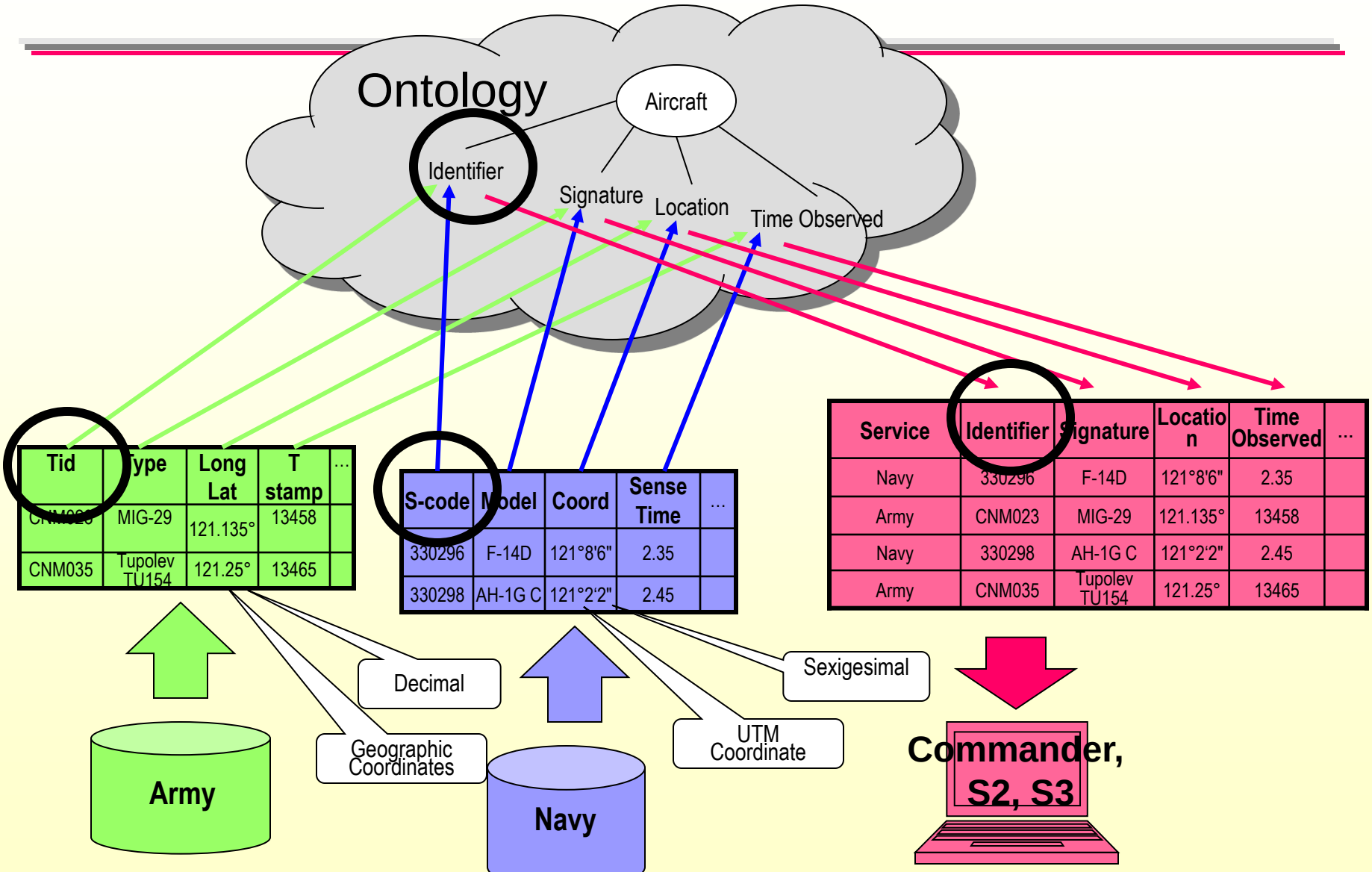
What Problems Do Ontologies Help Solve?

- Heterogeneous database problem
  - Different organizational units, Service Needers/Providers have radically different databases
  - Different **syntactically:** what's the format?
  - Different **structurally:** how are they structured?
  - Different **semantically:** what do they mean?
  - They all speak different languages
- Enterprise-wide system interoperability problem
  - Currently: system-of-systems, vertical stovepipes
  - Ontologies act as conceptual model representing enterprise consensus semantics
  - Well-defined, sound, consistent, extensible, reusable, modular models
- Relevant document retrieval/question-answering problem
  - What is the meaning of your query?
  - What is the meaning of documents that would satisfy your query?
  - Can you obtain only meaningful, relevant documents?

A Business Example of Ontology

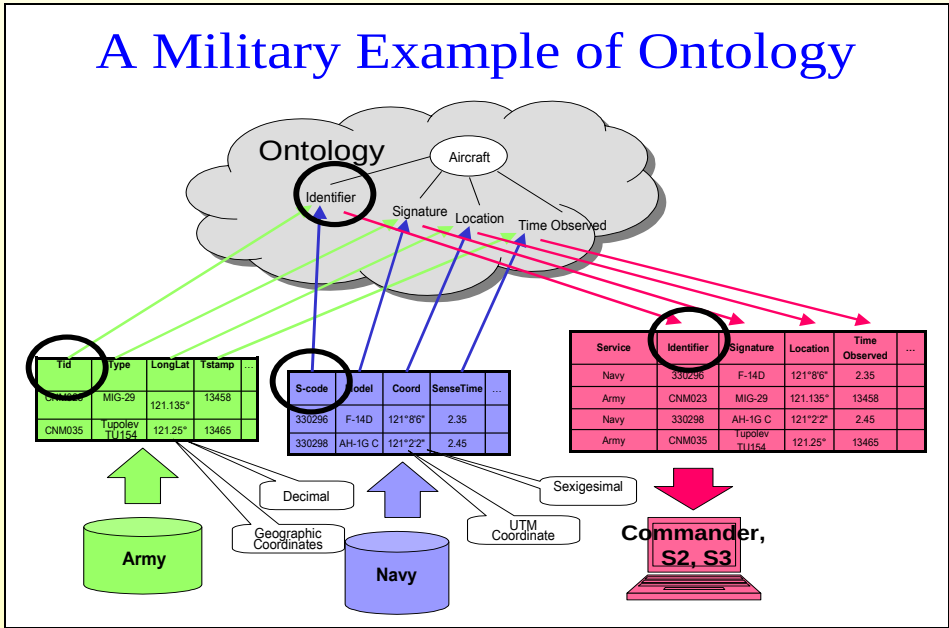


A Military Example of Ontology



Ontologies & the Data Integration Problem

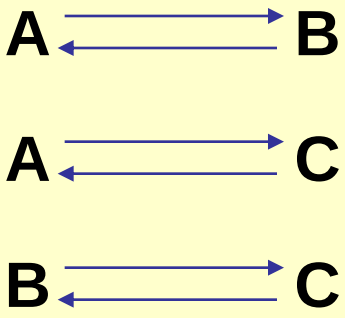
- DBs provide generality of storage and efficient access
- Formal data model of databases insufficiently semantically expressive
- The process of developing a database discards meaning
  - Conceptual model → Logical Model → Physical Model
  - Keys signify some relation, but no solid semantics
  - DB Semantics = Schema + Business Rules + Application Code
- Ontologies can represent the rich common semantics that spans DBs
  - Link the different structures
  - Establish semantic properties of data
  - Provide mappings across data based on meaning
  - Also capture the rest of the meaning of data:
    - Enterprise rules
    - Application code (the inextricable semantics)



Complexity of Semantic Integration with/without Ontologies

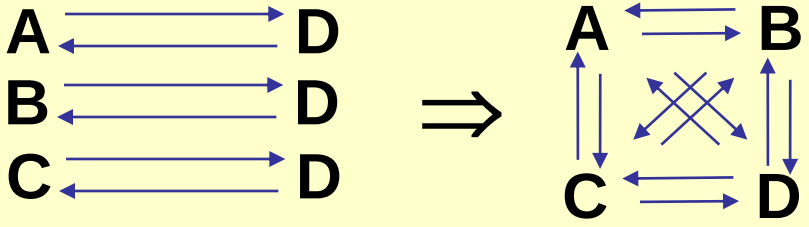
- An ontology allows for near linear semantic integration (actually 2n-1) rather than near n^2 (actually n^2 - n) integration
  - Each application/database maps to the "lingua franca" of the ontology, rather than to each other

Ordinary Integration: N^2



2 Nodes	2 Edges
3 Nodes	6 Edges
4 Nodes	12 Edges
5 Nodes	20 Edges

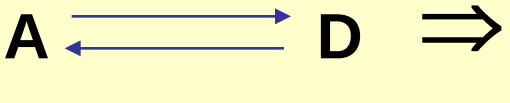
Add D:

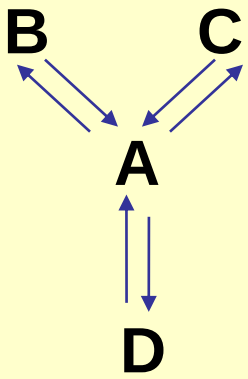


Ontology Integration: N

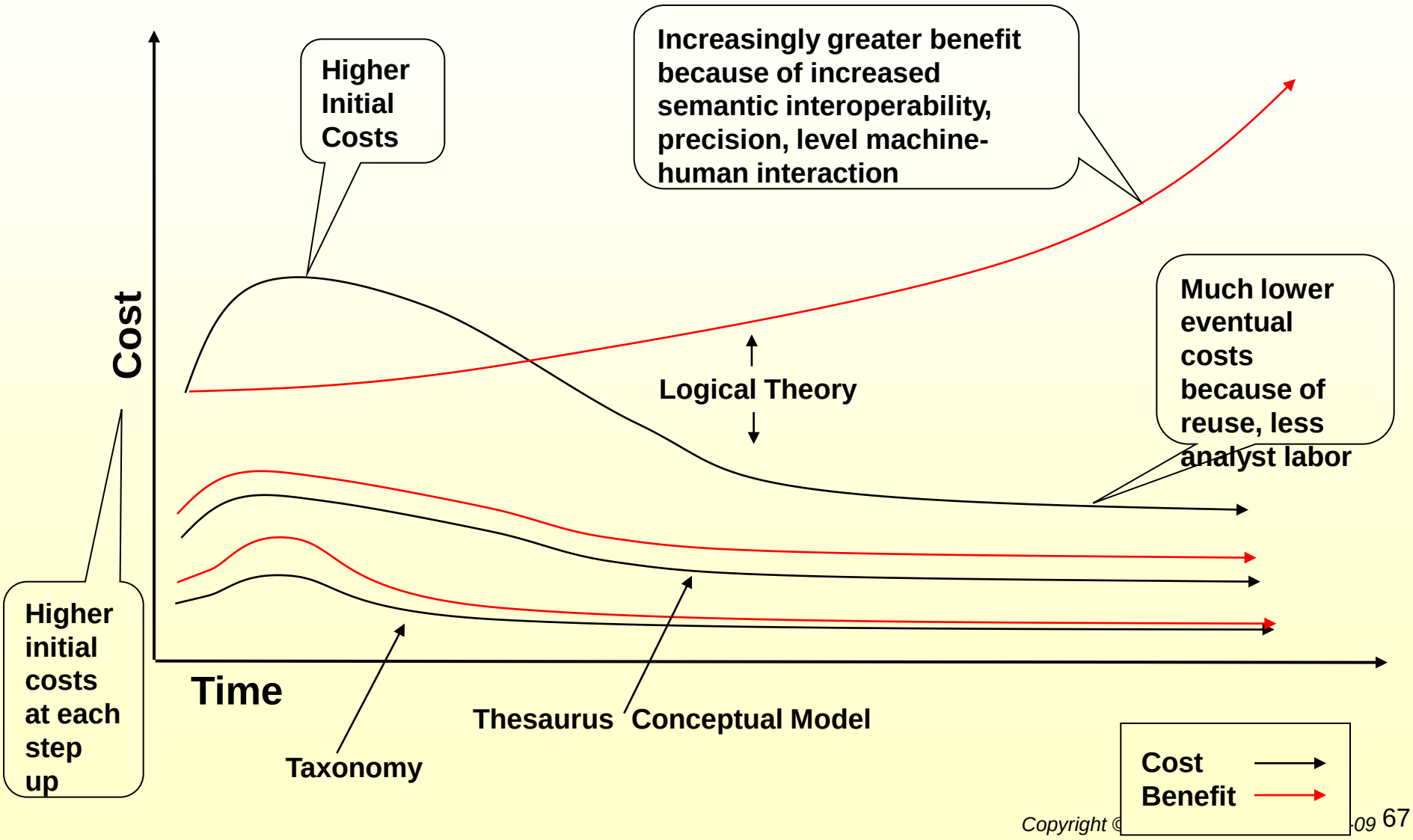
2 Nodes	2 Edges
3 Nodes	4 Edges
4 Nodes	6 Edges
5 Nodes	8 Edges

Add D:





Approximate Cost/Benefit of Moving up the Ontology Spectrum



Parts 1 & 2 Conclusions

- Ontology: a specification of a conceptualization, vocabulary + model, theory
- Informally, ontology and model are taken to be synonymous, i.e, a description of the structure and meaning of a domain, a conceptual model
- Bottom Line: *an Ontology* models *Concepts, i.e.,* the entities (usually structured in a class hierarchy with *multiple inheritance*), relations, properties (attributes), values, instances, constraints, and rules used to model one or more domains
  1) **A logical theory**
  2) **About the world or some portion of the world**
  3) **Represented in a form semantically interpretable by computer**
  4) **Thus enabling automated reasoning comparable to a human's**
- Logically, you can view an ontology as a set of *Axioms* (statements and constraints/rules) about some domain
- Using the axioms and some defined *Inference Rules* (example: Modus Ponens), you can derive (prove true) *Theorems* about that domain, and thus derive knew knowledge

Lunch!

Agenda, Part 3a: Knowledge Representation

26 Years: Knowledge Representation & Engineering Research Threads Converging*

Don't Use This Slide!

Category Theory
Domain Theory
Denotational Semantics
Truth Maintenance Systems
Category Theory: Theoretical CS apps - Denotational Semantics, Type Theory
Category Theory: Software Spec.
KIDS
SPECware
EMYCIN
MYCIN
Expert Systems
Dempster-Shafer Evidence Theory
Probabilistic Inference
Bayesian Networks
Hybrid KR
Distributed Reasoning
Semantic Networks
Frame Problem
Assumption -based Systems
Decision Theory
Game Theory
Graph Partitioning
Knowledge Partitioning
GPS
CG
Default Logic
Abduction
Circumscription
Microtheories
Logic KBs
BDI Agents
NetL
SOAR
Non-monotonic Logic
Frame-based KR
Reactive Agents
IATlite
SWRL
RIF
Spreading Activation
Distributed AI
KQML
RDF/S
DAML
OWL
Now!
Actors
Classic
Formalization of Context
PowerLOOM
NSF KDI
OWL-S
Blackboard Architectures
CYC
KL-ONE
LOOM
Formal Ontology
TOVE
DARPA HPKB
DARPA RKF
Planning
WAM
Description Logics
KADS
ARPA KSI
1983
1990
2002
Constraint Logic
PARKA
Ontological Engineering
DLP
Answer Set
IKL
KIF
GFP
Ontolingua
CL
PARLOG
Prolog III
Prolog II
Linear Logic
BinProlog
OKBC
Prolog
Constraint Satisfaction
LIFE
Finite Domain Constraint Solvers
PARKA-DB
OZ
Theorem Proving
Feature Logics
ECLiPSe
CHIP

Knowledge R&D
Logic/Constraints
Agents
Recent DARPA

*And 20 yrs more before this!

What is Knowledge Representation?

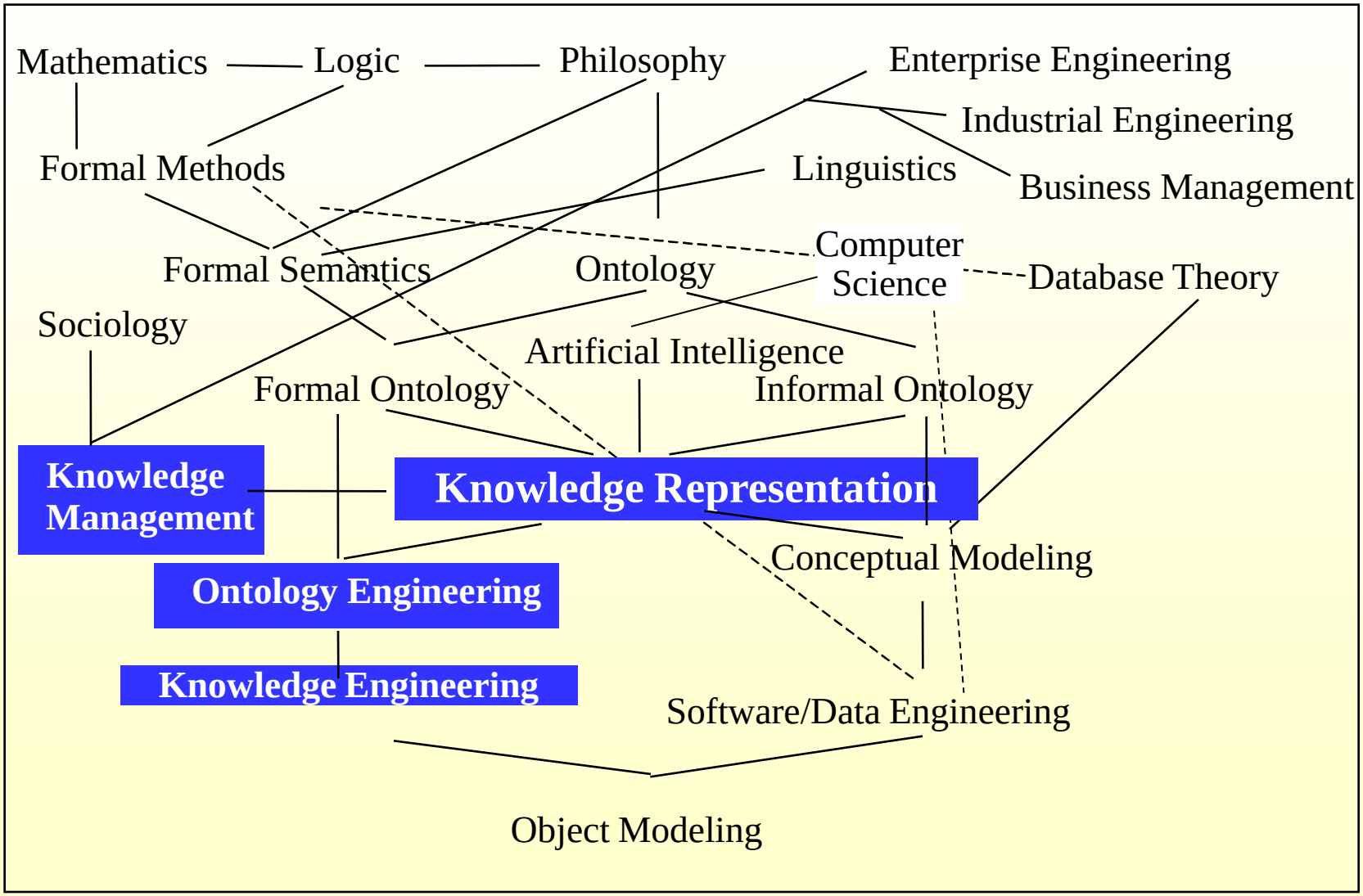
- Principles of KR: Davis, Shrobe, Szolovits (1993)*:
  - A KR is a surrogate for real things, events, relationships
  - A KR is a set of ontological commitments, a model for a particular conception of the world
  - A KR is a partial theory of intelligent reasoning
  - A KR is a medium for efficient computation
  - A KR is a medium of human expression
- Principled, Declarative, Modular, Reusable: Represent Once!
- Other issues:
  - Design & development vs. runtime implementation/use
  - Knowledge partioning and compilation
  - Representation tightly coupled with Reasoning Methods: the Language determines the Reasoning

*Adapted from John Sowa. 2001. Knowledge Representation: Logical, Philosophical, and Computational Foundations, Pacific Grove, CA: BROOKS/COLE, p. 135.

Evolution of KR

- KR derived from semantic networks of 60s-70s, Quillian, 1968; Minsky, 1975; Brachman, 1978
- Brachman & Levesque, 1985: survey of newer semantic nets, frame-based languages: KL-ONE (Brachman & Schmolze, 1985)
- First Principles of KR Conference, Toronto, 1989
- Increasing formalization, logicization: SIGART bulletin 2:3, 1991: seminal encapsulation of state of the art
- Principles of KR: David, Shrobe, Szolovits (1993)
- Development of a sound theoretical basis for the syntax, semantics, and inference methods employed: DLs
- DARPA Knowledge Sharing Initiative (KSI , early 90s): Knowledge Interchange Format (KIF), Ontolingua, Generic Frame Protocol (GFK), rise of Ontological Engineering
- DARPA High Performance Knowledge Bases (HPKB), Rapid Knowledge Formation (RKF) (late 90s): Open Knowledge Base Connectivity (OKBC) language
- DARPA Agent Markup Language (DAML) (early 2000s): DAML+ OIL, OWL

Knowledge Representation and Related Disciplines



Semantic Networks

- "A semantic network is a graph structure in which nodes (or vertices) represent concepts, while the arcs between these nodes represent relations among concepts."
  - based on Quillian, 1968: http://www.compapp.dcu.ie/~tonyv/encyc/semantic.html
- Semantic Networks were not formally defined
- Reasoning methods were based on implementation strategies, not on formal language
- First formalization based on logic: the "frame" language KL-ONE

Expert Systems & Their Problems

- Based on "production rules" using the Rete Algorithm:
  - **Condition-Action** (antecedent/consequent) Rules: If Conditions α hold, then execute Actions β,
  - where α are predicates true of the state of the environment at time of rule-firing (e.g, "AND <temperature >= 212 degrees>, <oil_flowing = true>)
  - and β are actions such as "push rule 14 onto Agenda", or set "AlertMonitor = true", etc., which thereby changes the state of the environment, allowing other rules to prospectively fire (if their conditions are met)s
  - **Forward Chaining**: go from state of the world and see which conditions of which rules match that state, firing off rules that apply
  - **Backward Chaining**: start at a rule's goal (the theorem to be proved true), assume it to be true, then its antecedent conditions would generate new goals, with the new goals matching the consequents of other rules
- All knowledge is represented at same level: non-modular, non-reusable, unmaintainable
- Undebuggable when complex, non-deterministic rule-firings
- Experts don't necessarily have insight into "how" they know things
- Everyone speaks a natural language, but few can describe the properties of a natural language (coherently, consistently)

Frame Languages

- **Frame-based systems are KR systems that use frames**
- **Introduced by Marvin Minsky (1975) to represent domain knowledge**
  - **Represent a stereotypical situation**
  - **Way of structuring knowledge**
  - **A network of nodes and relations**
  - **Generic (nonterminal) knowledge bottoming out in instances (terminals)**
- **The notion of a frame corresponds to early LISP programming language terminology: slot & filler, record-based, defstruct-like**
- **Frames represent Concepts, have additional information attached to them: definitional, how to use, etc**
- **In frame terminology, a concept is a Class, and a relation is a Slot**
- **Attributes (sometimes called properties) are just slots defined on a domain (a specific class subtree) or one of its subdomains (a subclass of a domain class).**
- **Frames are close to the OO Paradigm: i.e., they are *object-centered* (entity or class-centered)**
- **First formalized frame KR language: KL-One**
- **Bottom Line: Frames are equivalent to a Logical Representation**

Frame Languages: Example

- **(defineClass StationWagon**
  (superclass Automobile)
  (doors 5)
  (model *noDefault*)
  (manufacturer Manufacturer))

- **(defineInstance inst-345678**
  (class StationWagon)
  (doors 3)
  (model Taurus)
  (manufacturer Ford)
  (weight WeightMeasure))

- Can have multiple parents
- Inheritance of slots (relations, attributes):
  - SubClass (isa) relation
  - InstanceOf relation
- Defaults & Overrides
- Define new slots
- Can view a Frame as a Type

Axiom-based (Axiomatic) KR 1

- These are based on a formalized logic
- Typically First Order Logic (Predicate Calculus), or a subset of FOL
  - Could be based on weaker Propositional Logic, which only represents *propositions*, i.e., expressions that are true or false
  - Examples: “It’s cold outside”, “John is sick”, “The current President of the United States is George W. Bush”
  - All of these are either true or false, or possibly unknown: “Unicorns are nice”
  - But each of these is an X which is either true or false
  - We would like to get more expressive, talk logically about individuals (instances) and predicates (relations, properties, attributes) inside the *proposition*
  - The FOL enables us to talk about instances: “Some people don’t like peaches”, i.e., *There are some X who are people and those X don’t like peaches.*
- Contain axioms, which are logical expressions asserted to be true, all the time, given what we know about the world: *All humans are mortal*

Axiom-based (Axiomatic) KR 2

- Theorems are proven by using inference rules applied to axioms:
  - Prove: John is mortal
  - Proof: If all humans are mortal, and John is a human, then John is mortal
  - Theorems, once proven, **add *to the knowledge*** *that is in your ontology model:* ***they generate NEW knowledge***
- A number of threads:
  - Description Logics
  - But also Logic Programming as in Prolog
  - Cyc, KIF (Knowledge Interchange Format)
  - Theorem provers that use FOL or higher-order logic
  - RDF/S and OWL are axiom-based, though by design, they also contain *frame-based* representation. Why? To assist developers and users who know the *Object-Oriented paradigm* of entity (class) centered or focused modeling
- Bottom-line: an axiom-based ontology system is not object-centered like an OO modeling system, but instead has the modeling knowledge about any given object (e.g., entity or relation) *distributed* across the ontology

Issues: Expressivity

- What do you want to do with your KR language?
  - Build an ontology, build a knowledge base
  - Check consistency of your knowledge
  - Check completeness of your knowledge
  - I.e., Model checking, model finding
  - Automatically classify new concepts, assertions
  - Query the KB (search & navigation)
  - Perform other inference (sometimes called rule-based reasoning)
    - Deduction
    - Induction
    - Abduction
  - Add probabilistic reasoning
  - Reason over beliefs (Truth Maintenance Systems), i.e., evidential reasoning
  - Have built in modal operators: necessity/possibility, obligation/permission/prohibition, temporal, etc.

Propositional & Predicate Logic

- Propositional Logic
  - Limitation: cannot speak about individuals (instances)
  - Granularity not fine enough
  - Propositions: truth-functions

If Plato is human, then Plato is mortal	$p \rightarrow q$	
Plato is human	p	
_____		
Plato is mortal	q	Modus Ponens

- Predicate Logic
  - Finer distinctions: can talk about individuals (instances)

If Plato is human, then Plato is mortal	$\forall x: p(x) \rightarrow q(x)$	
Plato is human	$p(plato)$	
_____		
Plato is mortal	$q(plato)$	Modus Ponens

  - An instantiated predicate is a proposition, e.g., human(plato) = true

Modal Logic

- Modal Logic: want to express and reason about various other kinds of states of affairs, possibility vs. necessity, etc.
  - Introduce new sentential operators (focus only on propositional modal logic)

Logic	Symbols	Expressions Symbolized
Modal Logic	□	**It is necessary that ..**
	◇	**It is possible that ..**
Deontic Logic	**O**	**It is obligatory that ..**
	P	**It is permitted that ..**
	F	**It is forbidden that ..**
Temporal Logic	**G**	**It will always be the case that ..**
	F	**It will be the case that ..**
	H	**It has always been the case that ..**
	P	**It was the case that..**
Doxastic Logic	**Bx**	**x believes that ..**

- http://plato.stanford.edu/entries/logic-modal/

Modal Propositions & Predicates

Modal Propositions and Predicates in English	**Modal Propositions and Predicates in Logic**
1) Necessarily, if John is an unmarried man, John is a bachelor.	$\Box\Box(P \rightarrow Q)$
2) Possibly, if John likes sugar, he likes chocolate.	$\Diamond(P \rightarrow Q)$
3) Necessarily, an unmarried man is a bachelor.	$\Box(\forall x.\ unmarriedMan(x) \rightarrow bachelor(x))$
4) Necessarily, every human has parents.	$\Box(\forall x.\ human(x) \rightarrow hasParents(x))$
5) If a person works at a company, it's possible that he is not an employee. (he could be a contractor, for example)	$\exists x.\ person(x) \wedge company(y) \wedge worksAt(x, y) \rightarrow \Diamond\neg employeeOf(x, y)$

Description Logic: Definitions

- What is a Description Logic? Terminological Logic, Concept Logic, based on: Concept Language, Term Subsumption Language
  - A declarative formalism for the representation and expression of knowledge and sound, tractable reasoning methods founded on a firm theoretical (logical) basis
    - **DL frame-based semantic network + logic (compositional syntax and model-theoretic semantics)**
    - **usual logical formulation of a concept would be as a single-variable predicate, i.e., in lambda calculus, as (MacGregor, 1991):**
    - **adult males: $\lambda x.$ Male(x) $\cup$ Adult(x)**
  - **Expressive, sound & complete, decidable, classical semantics, tractable reasoning**
  - Function-free FOL using at most 3 variables (basic)
- A *description*: an expression in a formal language that defines a set of instances or tuples
- DL: a syntax for constructing descriptions and a semantics that defines the meaning of each description

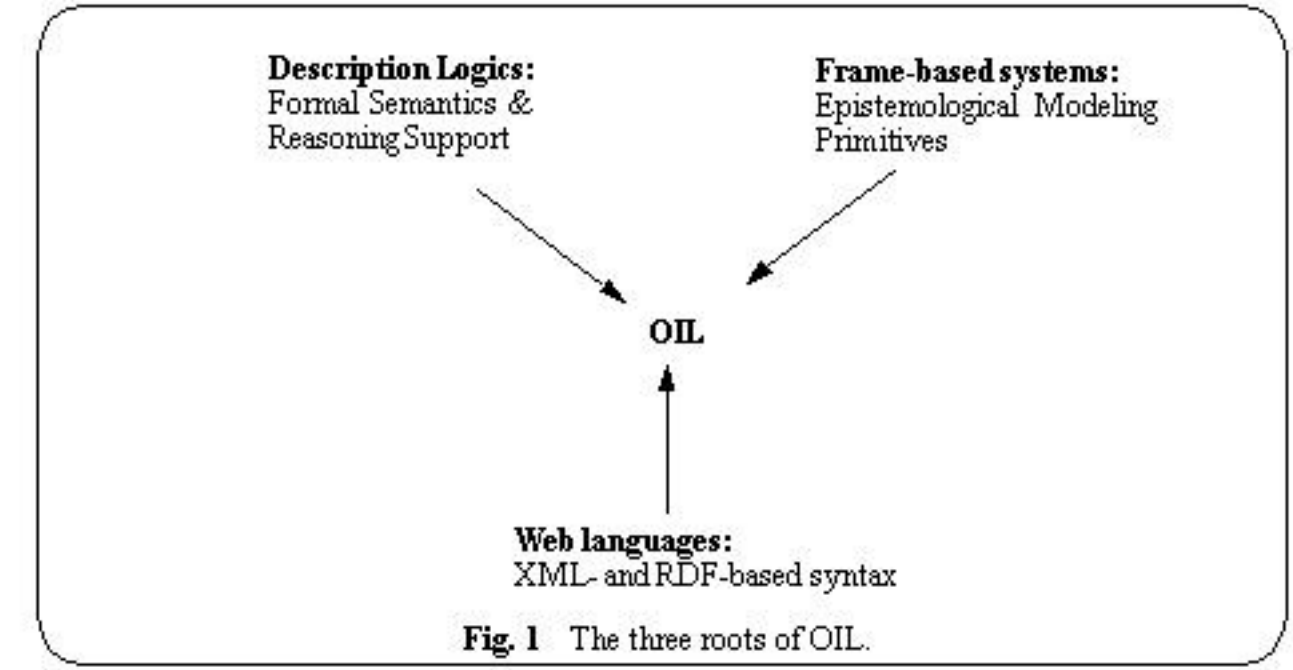
Description Logic: Components

- *T-box: Terminological box – concepts, classes, predicates*
  - One or more subsumption hierarchies/taxonomies of descriptions
  - Terminological axioms: introduce names of concepts, roles
  - Concepts: denote entities
  - Roles: denote properties (binary predicates, relations)
  - OO? No, but related. Why: no generally agreed upon formal basis to OO, though attempts (emerging UML)
    - **Isa generalization/specialization, Top/ Bottom**
    - **Part-of: mereology, mereotopology (parts+connections)**
    - **Other relations: aggregation, etc.**
  - Subsumption: comparable to matching or unification in other systems
- *A-box: Assertional box – individuals, constants*
  - Instances in the OO world, tuples in the DB world

Description Logic: Inference Methods & Properties

- Inference Methods (all based on subsumption)
  - **classification: where do descriptions belong in hierarchies (subsumers, subsumees)**
  - **detecting contradiction: are descriptions coherent/satisfiable and is the KB consistent/satisfiable**
  - **completion inference: what are the logical consequences of axioms, inheritance**
- Inference algorithms properties:
  - **soundness: any expression that can be derived from the KB is logically implied by that KB**
  - **completeness: any expression that is logically implied by the KB can be derived**
  - **decidability: can a sound and complete algorithm be constructed?**
  - **complexity: is it tractable (worst-case polynomial time) or intractable?**
  - **expressivity: [for formal definition of expressivity of T-Box (Baader, 1990); A-Box (Speel, 1996a, p. 69)]**
    - **roughly: expressivity and tractability are inversely proportional**
    - **some expressive formalisms may be intractable or even undecidable**

Example: OIL, which became DAML+OIL, which became OWL



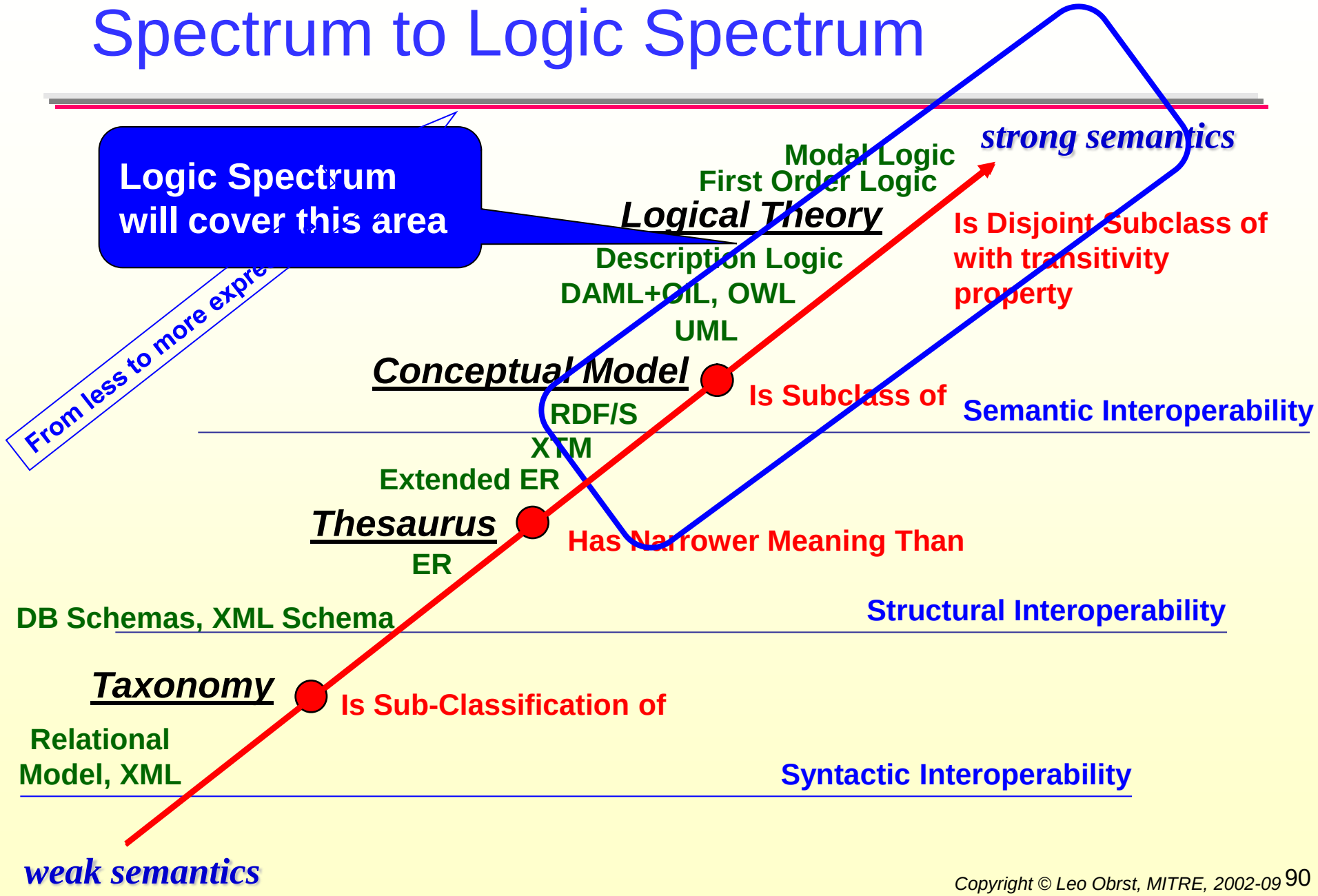
Ontology Inference Layer/Language
(OIL, now merged as DAML+OIL)

Horrocks I. , D. Fensel, J. Broekstra, S. Decker, M. Erdmann, C. Goble, F. van Harmelen, M. Klein, S. Staab, R. Studer, and E. Motta. 2000. The Ontology Inference Layer OIL. http://www.ontoknowledge.org/oil/TR/oil.long.html

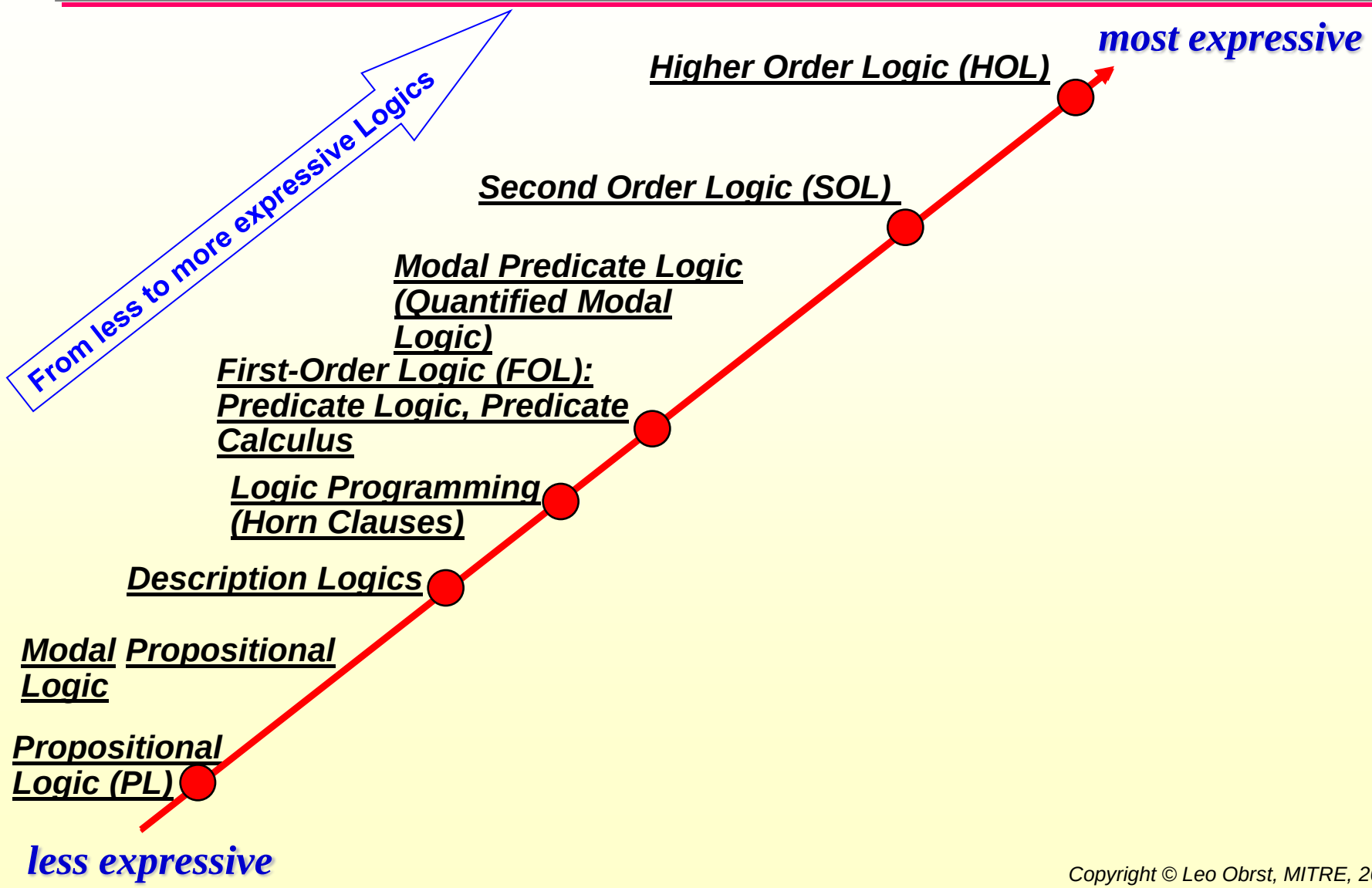
First Order & Higher Order Logics: the basis of other Ontology Languages

- **FOL semi-decidable**
  - **Decidable: there is an effective method for telling whether or not each formula of a system is a theorem of that system or not**
  - **Semi-decidable: If a formula really is a theorem of a system, eventually will be able to prove it is, but not if it is not: may never terminate**
- **Second Order: sometimes used in linguistics**
  - **"Tall", "Most", etc.**
  - **Quantification over Individual & Predicate variables**
  - **$\exists\phi$ (ϕ (a) $\wedge$ F(ϕ)): "John has an unusual property"**
- **CYC: MELD, CYCL, has some constrained 2nd order reasoning**
- **Theorem-provers**
  - **HOL, Otter, etc.**
- **Prolog & Cousins**
  - **Restricted FOL: Horn Clauses (only 1 un-negated term in a formula, resolution method proves the contradiction of the negation of a term)**
  - **Non-standard negation: negation by finite failure**
  - **Closed World Assumption**
  - **Declarative + Operational Semantics: use of Cut**
- **Other: Conceptual Graphs, UML, Expert System Shells, Modal Logics**

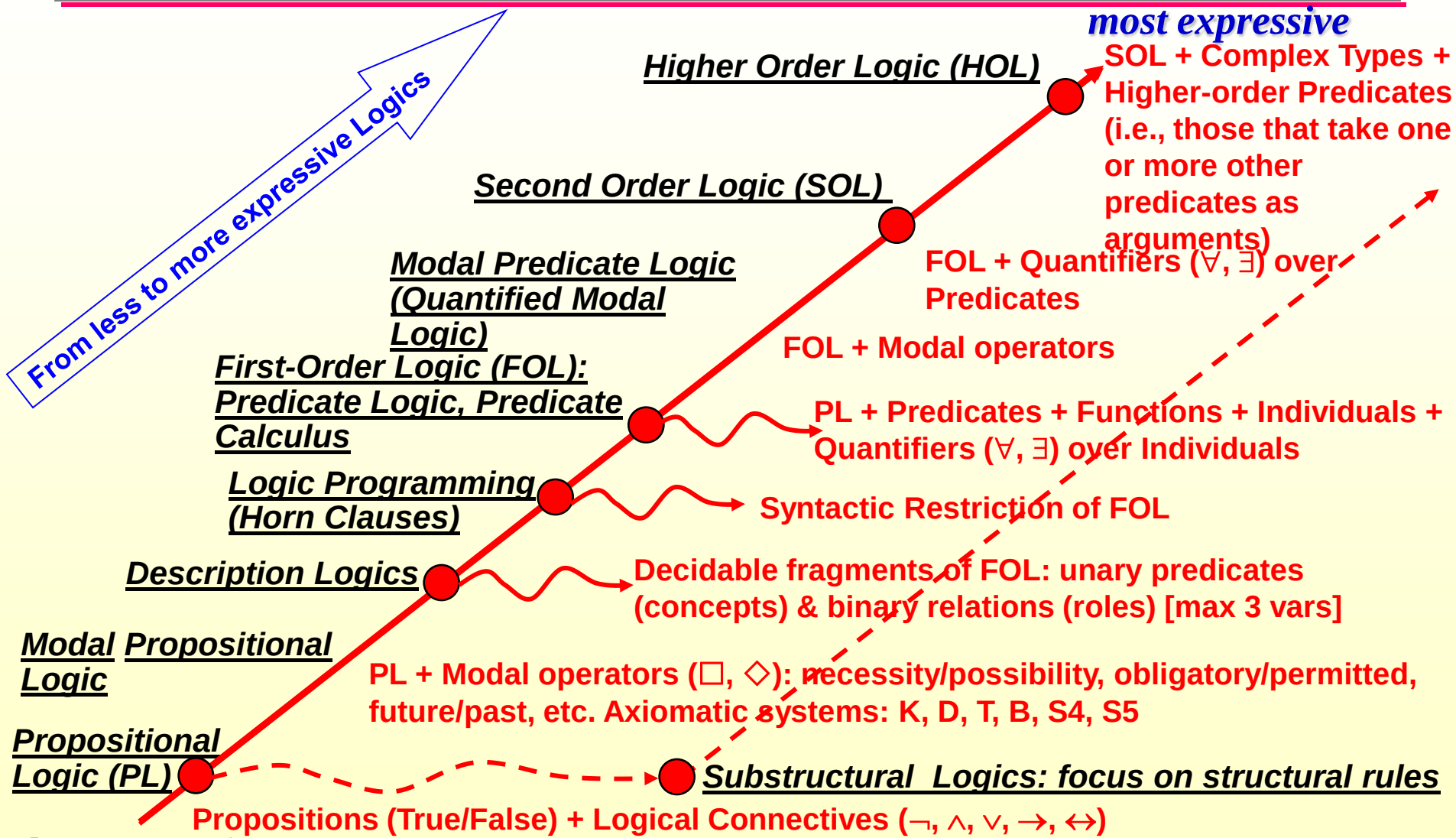
Looking Ahead: From Ontology Spectrum to Logic Spectrum



Logic Spectrum



Logic Spectrum: Classical Logics: PL to HOL



Agenda, Part 3b: Ontological Engineering

Ontology Modeling Issues

- What do you model in? **KR Language**
  - OO Frame vs. DL or FOL Axiom?
- What do you model? **Concepts**
- Concepts:
  - Concepts "stand in for" objects in the real world (possible world)
  - Entities & relations
  - Universals & Particulars
  - Classes & Instances/Individuals
- How are Concepts modeled?

How are Concepts Modeled?

- Meta-class, Class, Instance
  - If have a meta-class Class, then all Classes are instances of that
  - Remember the 3 Representation Levels: Meta, Object, Instance
  - An Instance is a specific thing, a member of a Class, which is a general thing: John X. Smith is an Instance of the Class Person
- Distinguished relations: subclass/isa, instance_of, part_of (part-whole), composition_of, etc.
  - The semantics of these are defined in the meta-level or the upper ontology
- Class as unary relation: Person(X)
- Attribute as relation, reification of relations (as first class citizens, etc.)
- Domain & range of relation
  - works_at(Person, Org) Domain: Person Range: Org
- Slots & roles: relations "attached" to an instance
  - Slots: in frame systems
  - Roles: in description logics
- Others: times, events, processes, purposes, contexts, agents, functions

How To Create a Better Taxonomic Backbone to an Ontology*

- Formal Ontological Analysis: consider "meta" properties such as identity, rigidity, unity (whole)
- **Identity:** how does an entity change but keep its identity?
  - What are its essential properties?
  - If you change its parts, does it keep its identity?
  - Different properties/same parts, different parts/same properties
  - Persistence over time
- **Rigidity:** if having a certain property is essential for all instances
  - Having a brain is essential for a person
  - Having an arm is not essential for a person
  - Necessary and sufficient properties
  - Only rigid properties can provide identity
- **Unity:** parts, whole, connectedness of parts, boundaries of the whole
  - Mereotopology: Parts + Connectedness
  - Collections: the sum is not a whole (five cups of coffee)
  - Plural Wholes: the sum is also a whole (ballplayers vs. team)
  - Statue of Venus vs. the clay that constitutes the statue
    - Venus de Milo: the missing arms were part of the statue of Venus
    - The missing clay was part of the glob of clay that had been formed into the arms

*Based on OntoClean methoddology. Cf. Guarino, Nicola, and Christopher Welty. 2001. Conceptual Modeling and Ontological Analysis. http://reliant.teknowledge.com/IJCAI01/Guarino.ppt.

Ontology Modeling Issues: Ontological Levels*, Multiple Dimensions

- Physical
  - Atomic *(a minimal grain of matter)*
  - Static *(a configuration, a situation)*
  - Mereological *(an amount of matter, a collection)*
  - Topological *(a piece of matter)*
  - Morphological *(a cubic block, a constellation)*
- Functional *(an artifact, a biological organ)*
- Biological *(a human body)*
- Intentional *(a person, a robot)*
- Social *(a company)*

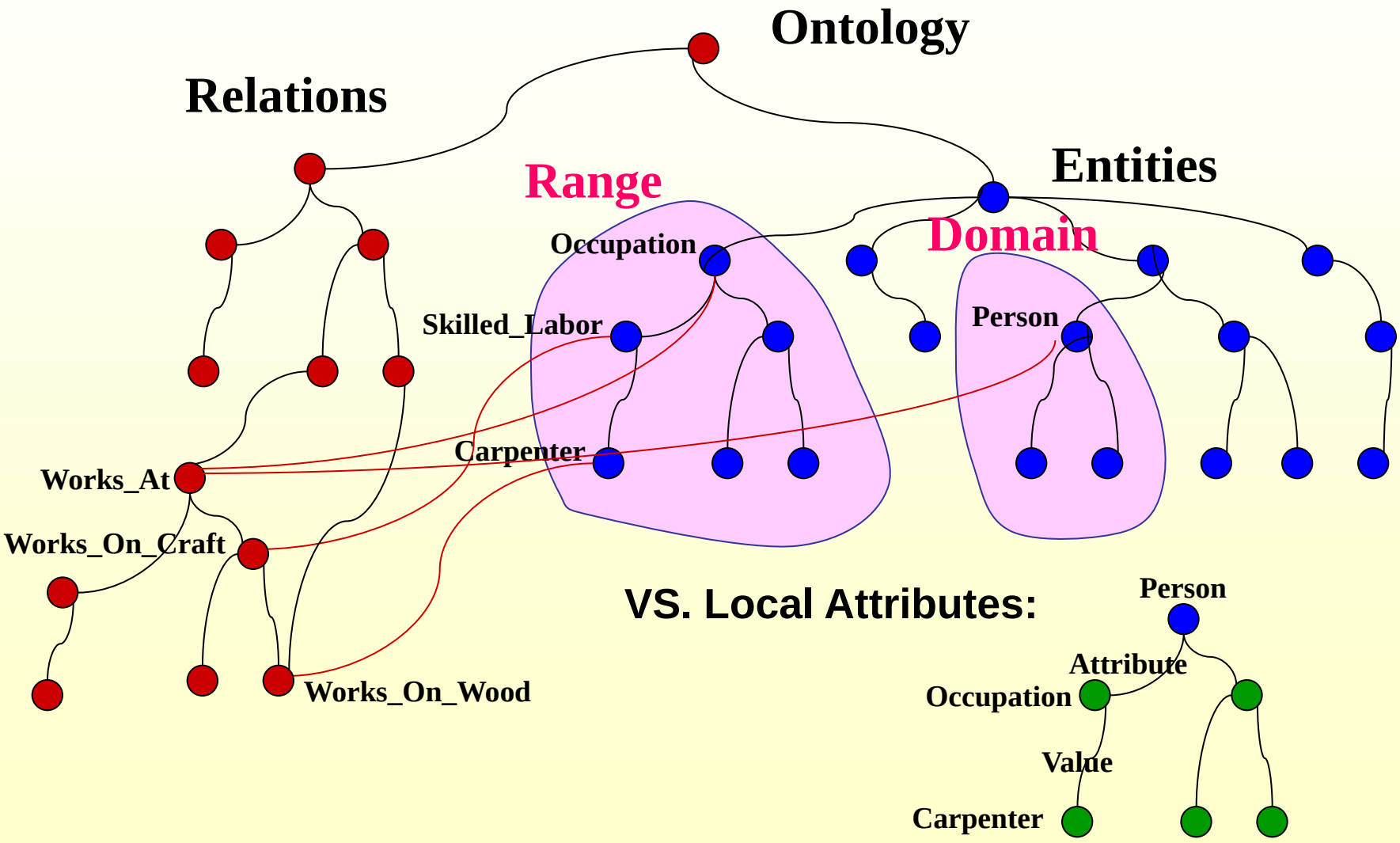
*Guarino, Nicola, and Christopher Welty. 2001. Conceptual Modeling and Ontological Analysis. http://reliant.teknowledge.com/IJCAI01/Guarino.ppt

Ontology Modeling Issues: Well-Founded Ontologies - Some Basic Design Principles*

- ***Be clear about the domain***
  - particulars (individuals)
  - universals (classes and relations)
  - linguistic entities (nouns, verbs, adjectives...)
- ***Take identity seriously***
  - Different identity criteria imply ***disjoint classes***
- ***Isolate a basic taxonomic structure***
  - Every entity must instantiate a rigid property with identity
  - Physical objects can change parts and remain the same, but amounts of matter cannot
  - Only *sortals* like “person” (as opposite to “red”) are good candidates for being *taxons* (classes in subclass relation)
  - *Sortals:* objects which carry *identity*
  - *Categories:* objects which generalize *sortals*
- ***Make an explicit distinction between types and roles (and other property kinds)***

*Guarino, Nicola, and Christopher Welty. 2001. Conceptual Modeling and Ontological Analysis. http://reliant.teknowledge.com/IJCAI01/Guarino.ppt.

Ontology Modeling Issues: Reifying Relations?



Ontology Modeling Issues: Guidelines for Building Ontologies*

- How and when to create classes in an ontology that will be useful for reasoning:
  - Every slot (property, relation) on a class must apply to all instances of all subclasses
  - Classes should not be defined solely to allow inheritance of some common attribute by a small number of subclasses
  - Man-made artifacts will be defined primarily by their function and only secondarily by physical attributes

***From a document prepared by Pat Cassidy & other of my ontologist ex-employees, and me, 2000.**

Ontology Modeling Issues: Guidelines for Building Ontologies*

Subclass relation

- A subclass must inherit all slots (properties, relations) from its parent and remoter ancestor classes
- Everything that is true of the instances of a parent class must also be true of instances of the descendent classes (children, etc.)
- Specifically, all slot values and value types of a parent must be true of the slot values and types of the subclasses
  - e.g. if the class "knife" is a subclass of "CuttingDevice", and a cutting device is defined as a device designed for cutting, then all the members of the subclasses of knife must also be designed for cutting. A steak knife, a bread knife, and a pocket knife are all designed for cutting, and the classes "steak_knife", "bread_knife" and "pocket_knife" are therefore legitimate subclasses of "knife". A class "knife_box" would *not* be a subclass of knife, nor would "knife_handle". There may be doubtful cases, e.g. a butter knife which has a dull blade, but even this is intended for *cutting butter* (a dictionary definition is: “a small knife with a dull blade, for cutting, serving, or spreading butter.”). A butter knife would thus also qualify as a *spreading instrument*.

Ontology Modeling Issues: Guidelines for Building Ontologies*

Subclass relation

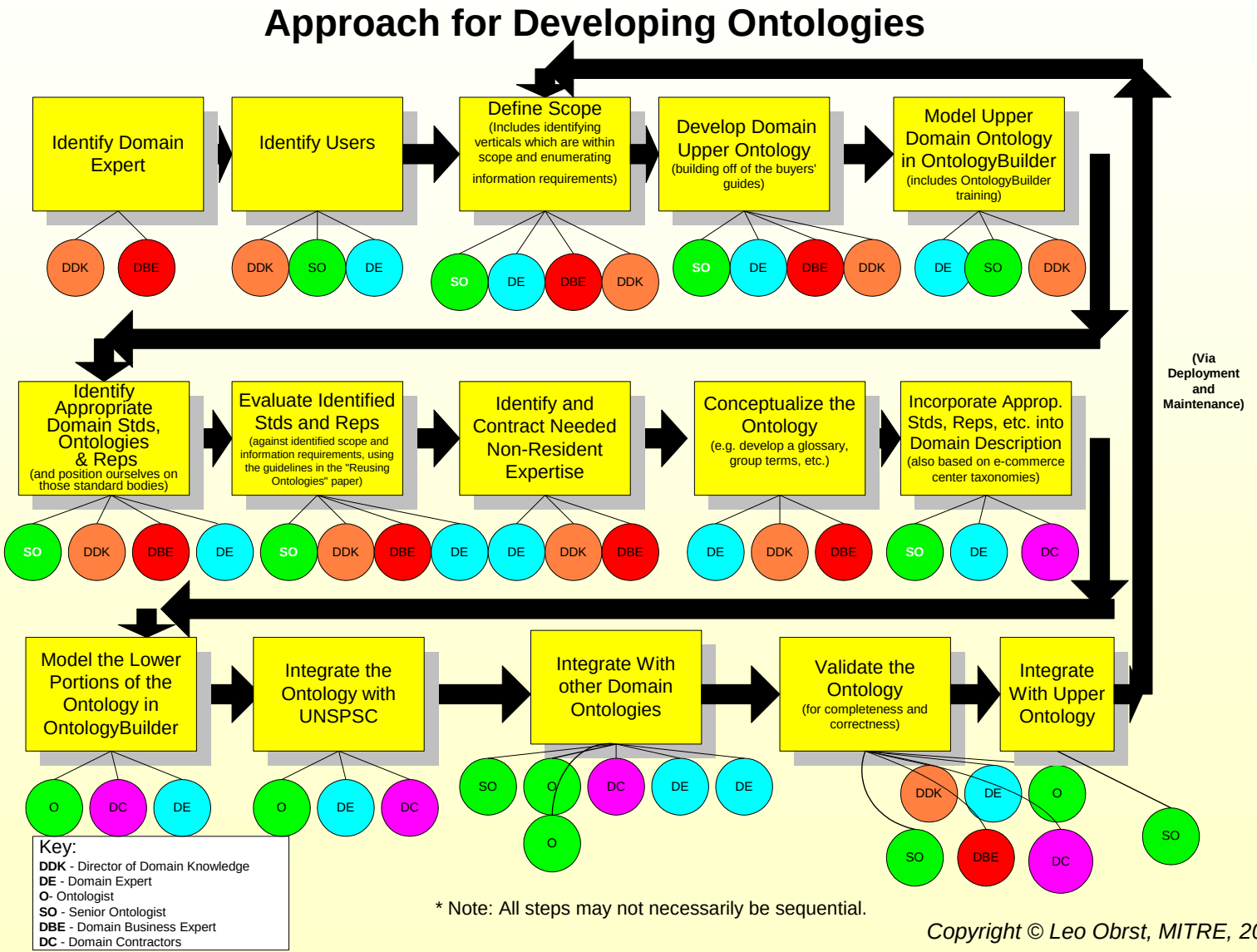
- There can be a use for a mechanism that will allow "cancellation" of inheritance of a slot/property/relation (i.e., to contradict some assertion that is made about all of the instances of a class)
- Convenient to allow some mechanism to recognize abnormalities about specific instances of things
- For base ontology, don’t need these

Ontology Modeling Issues: Guidelines for Building Ontologies*

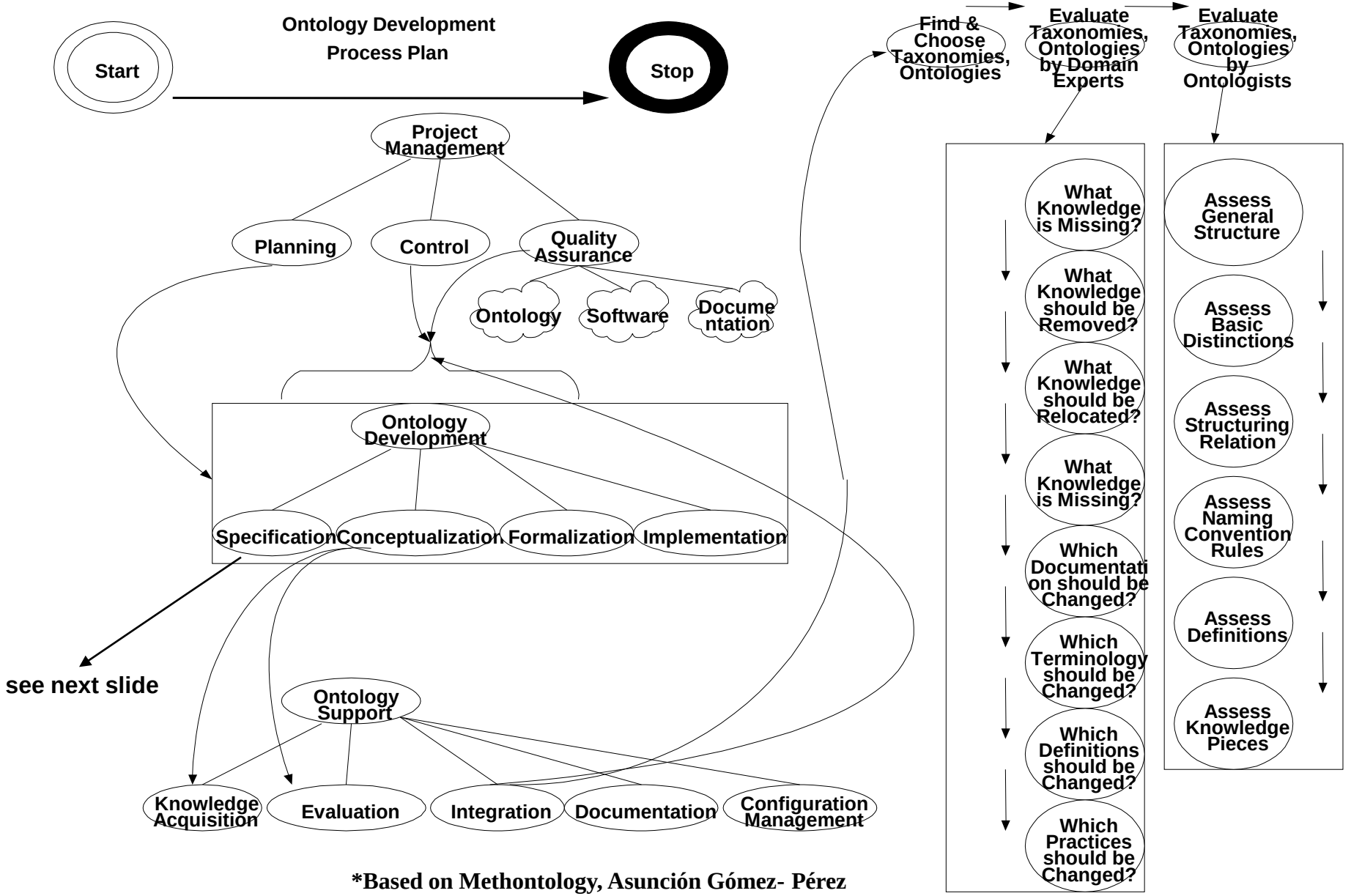
When to define classes in order to inherit slots (properties, relations):

- Each slot that we attach to a class asserts something about the object that are members of that class
- The more we can say about members of a class, the more detailed and accurate our reasoning can be
- There are two ways of associating slots (attributes) to a class
  - by making it a subclass of another class
  - by directly attaching slots to the class
  - (Sometimes it is not obvious which way is best)

Ontology Development Methodology: An Example

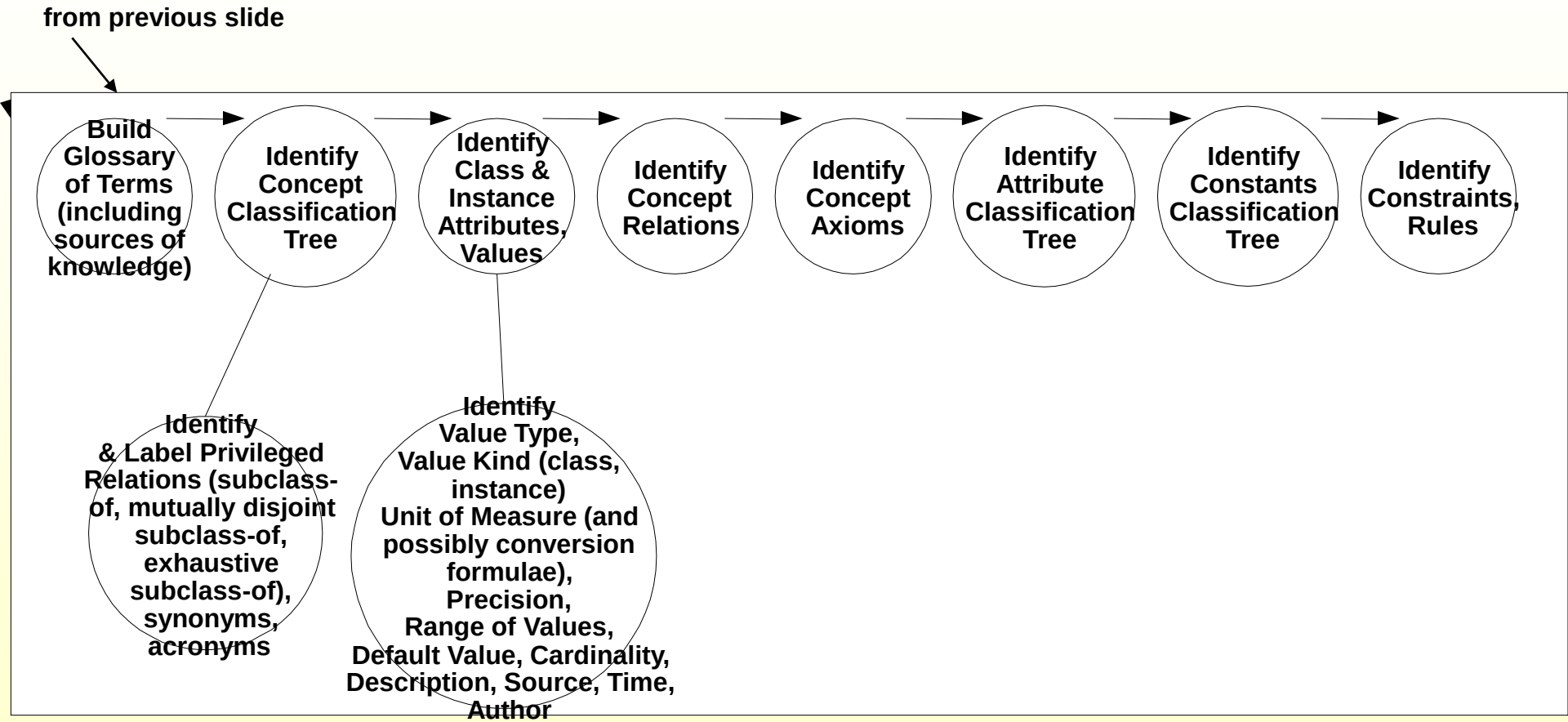


Ontology Development Process Plan: Based on Methontology



*Based on Methontology, Asunción Gómez- Pérez

Ontology Development Process Plan



Agenda, Part 4: Semantic Web

The Semantic Web

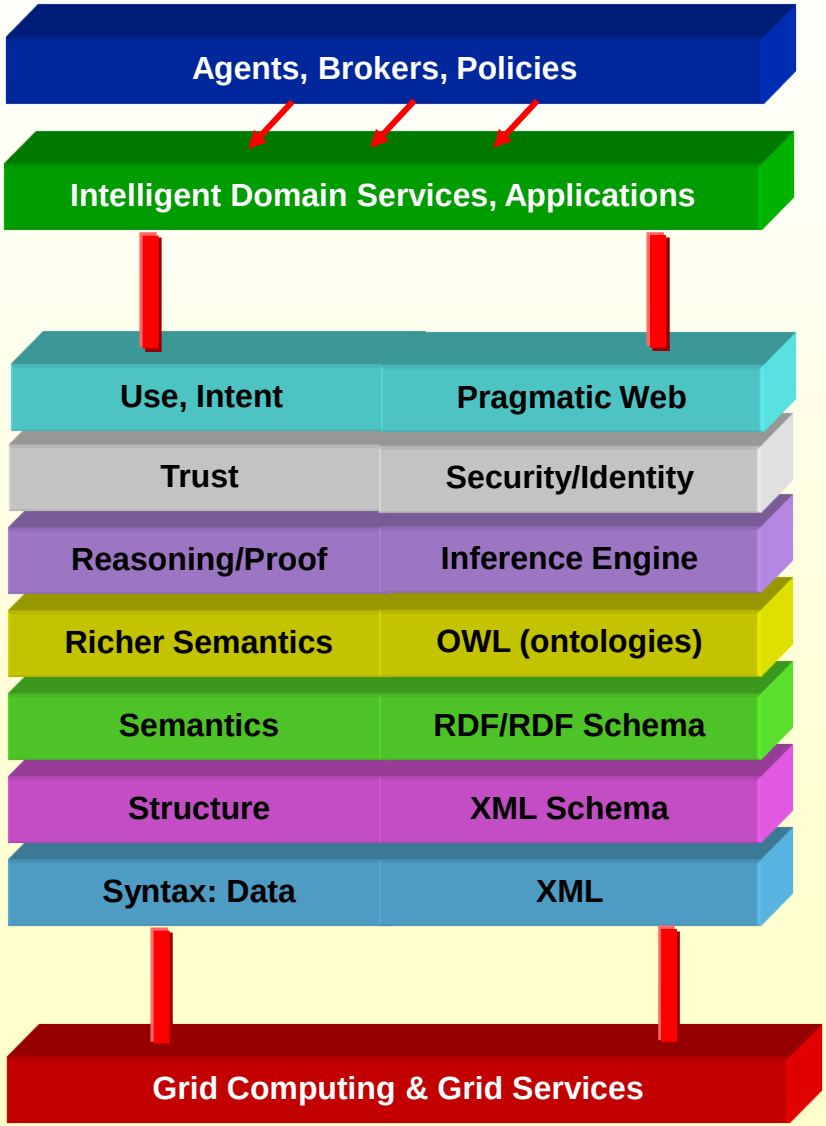
- Current Web is a collection of links and resources: machine-readable, not machine-understandable, semantically-interpretable

- T*he Semantic Web is an extension of the current web in which information is given well-defined meaning, better enabling computers and people to work in cooperation*.
  - T. Berners-Lee, J. Hendler, and O. Lassila. 2001. The Semantic Web. In *The Scientific American,* May, 2001, http://www.scientificamerican.com/2001/0501issue/0501berners-lee.html

- Languages to support machine-interpretable semantics of Web data, artifacts
  - T. Berners-Lee: The Semantic Web & Challenges. http://www.w3.org/2003/Talks/01-sweb-tbl/slide3-0.html..

- Machines will be able to consume machine-readable information, better enabling computers and people to work, learn and exchange knowledge more effectively
  - Eric Miller, The Semantic Web from the W3C Perspective. http://www.ercim.org/EU-NSF/semweb/slides/miller-w3/slide4-0.html

Semantic Web Stack



- **Semantic Brokers**
- **Intelligent Agents**
- **Advanced Applications**

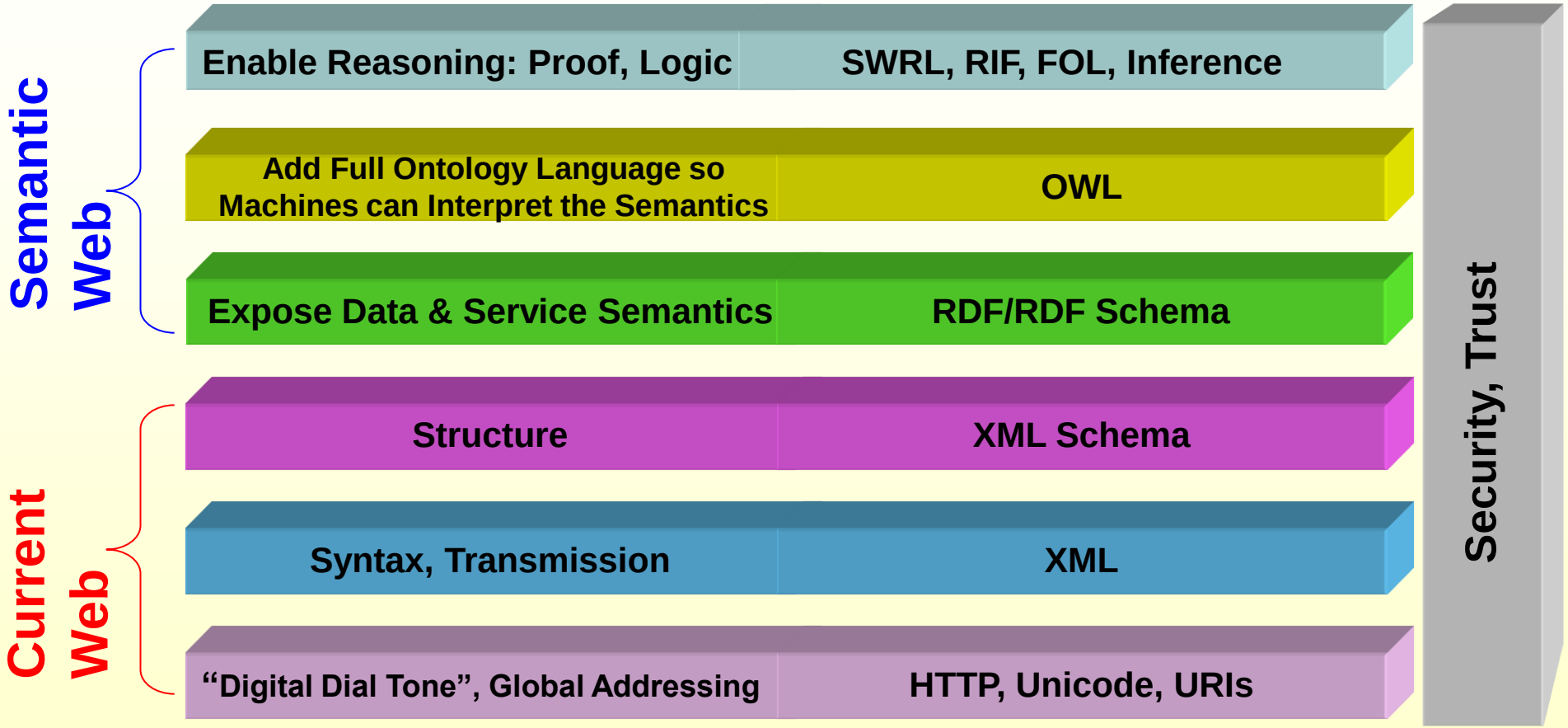
Semantic Web Technologies

Mature Web Technologies

- **Grid & Semantic Grid**

RULES

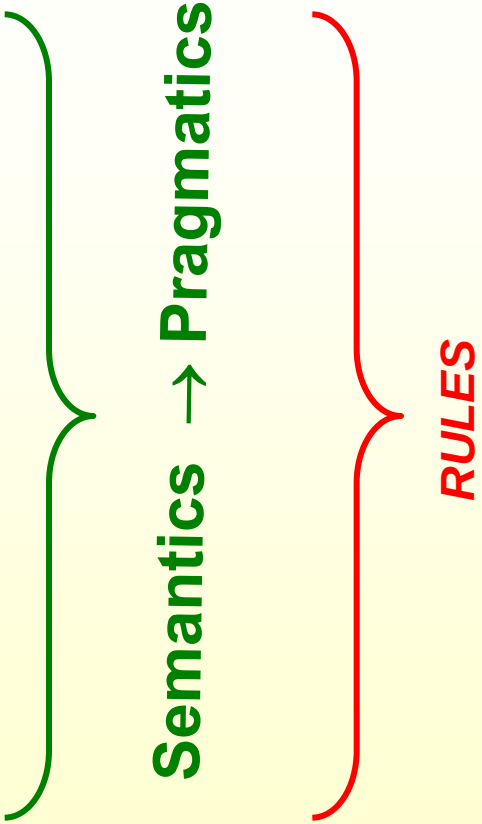
Semantic Web: Another View



- Anyone, anywhere can add to an evolving, decentralized "global database"
- Explicit semantics enable looser coupling, flexible composition of services and data

Semantic Web Services Stack

OWL, OWL-S, SAWSDL, SWRL, RIF	Service Entities, Relations, Rules
RDF/S	Service Instances
BPEL4WS (Business Process Execution Language for Web Services)	Service Flow & Composition
Trading Partner Agreement	Service Agreement
UDDI/WS Inspection	Service Discovery (focused & unfocused)
UDDI	Service Publication
WSDL	Service Description
WS Security	Secure Messaging
SOAP, REST, etc.	XML Messaging
HTTP, FTP, SMTP, MQ, RMI over IIOP	Transport



Adapted from: Bussler, Christoph; Dieter Fensel; Alexander Maedche. 2003. A Conceptual Architecture for Semantic Web Enabled Web Services. SIGMOD Record, Dec 2002. http://www.acm.org/sigmod/record/issues/0212/SPECIAL/4.Bussler.pdf.

Semantic Web Languages

- Numerous efforts have led to recent convergence on W3C recommendations
- 10 Feb ’04 W3C released recommendations on
  - Resource Description Framework (RDF)
    - Used to represent information and to exchange knowledge in the Web
  - OWL Web Ontology Language (OWL) as W3C
    - Used to publish and share sets of terms called ontologies, supporting advanced Web search, software agents and knowledge management
  - See http://www.w3.org/ for more information
- RDF and OWL are now international standards
- Both RDF and OWL observe the *Open World Assumption*: new knowledge can always be added to what already exists

What the Languages Provide: RDF/S

- RDFS enables you to make simple, generic statements about your Web object classes, properties
- RDF enables you to make specific statements about your Web object instances (of those classes, properties)
- RDF/S enables you also to make statements about statements (reification), but tells you nothing about those embedded statements
- A set of RDF statements can be viewed in 3 ways:
  - **A set of triples: consider them as rows/tuples in a database**
  - **A directed graph: consider them as a complex, navigatable data structure**
  - **An inference closure over the relations of the graph: consider them as as a machine-interpretable representation of knowledge from which an inference engine can infer new knowledge not expressly encoded**

RDF/S, a spectrum of views: *database row, graph structured object, inference closure*

Resource Description Framework/Schema (RDF/S)

- There is one Language, two levels: RDF is the Language
  - **RDFS** expresses **Class** level relations describing acceptable instance level relations
  - **RDF** expresses **Instance** level semantic relations phrased in terms of a triple:
  - **Statement: <resource, property, value>, <subject, verb, object>, <object1, relation1, object2>**
- *Resources*
  - All things being described by RDF expressions are called resources
    - **An entire Web page such as the HTML document**
    - **Part of a Web page**
    - **A collection of pages**
    - **An object that is not directly accessible via the Web**
  - Always named by URIs plus optional anchor ids
- *Properties*
  - A specific aspect, characteristic, attribute, or relation used to describe a resource
  - Specific meaning
  - Permitted values
  - Relationship with other properties
- *Statements*
  - A specific resource together with a named property plus the value of that property for that resource is an RDF statement

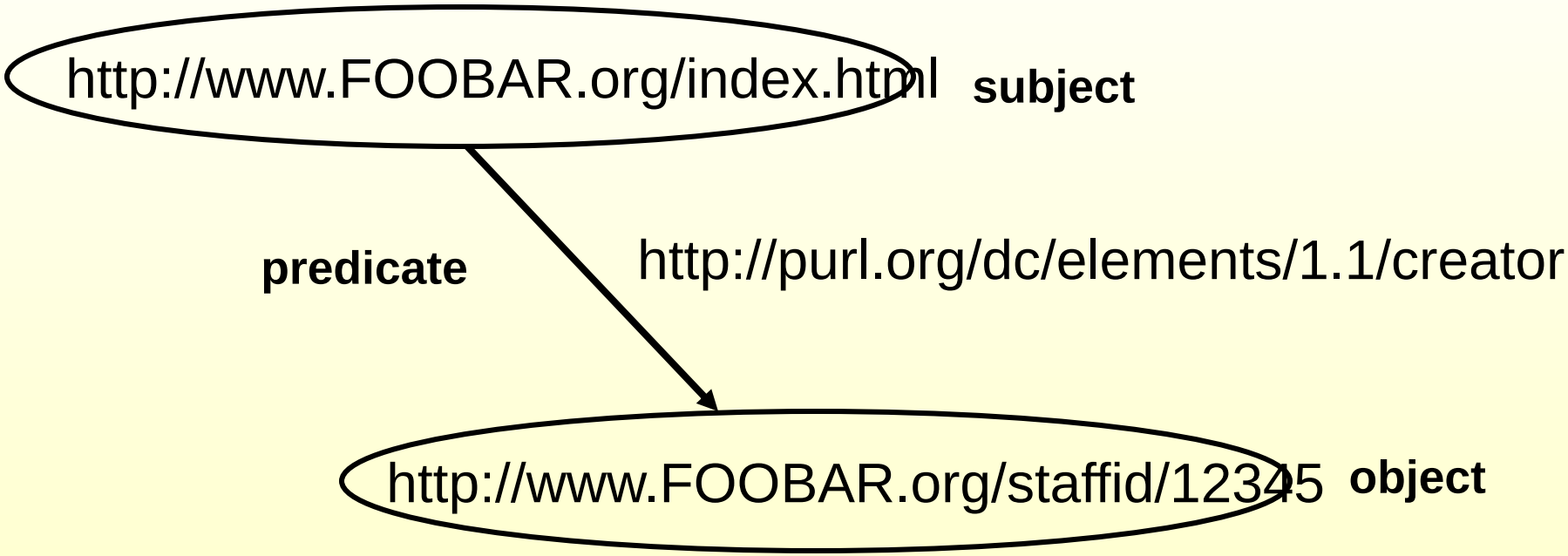
Positive, Existential subset of First Order Logic: no NOT, no ALL: Can't represent "John is NOT a terrorist", "All IBMers are overpaid"

RDF/S Model: Statements

- *Statements*
  - A specific resource together with a named property plus the value of that property for that resource is an RDF statement
  - I.e., Triples:
    - <Subject Predicate Object>
    - <Resource Property PropertyValue>
    - <Leo,hasColleague,Barry>
  - PropertyValue can be:
    - another resource (referenced via URI)
    - A literal (primitive datatype defined by XML), i.e., a resource (specified by a URI) or a simple string or other primitive datatype defined by XML

RDF/S Model: A Directed Graph

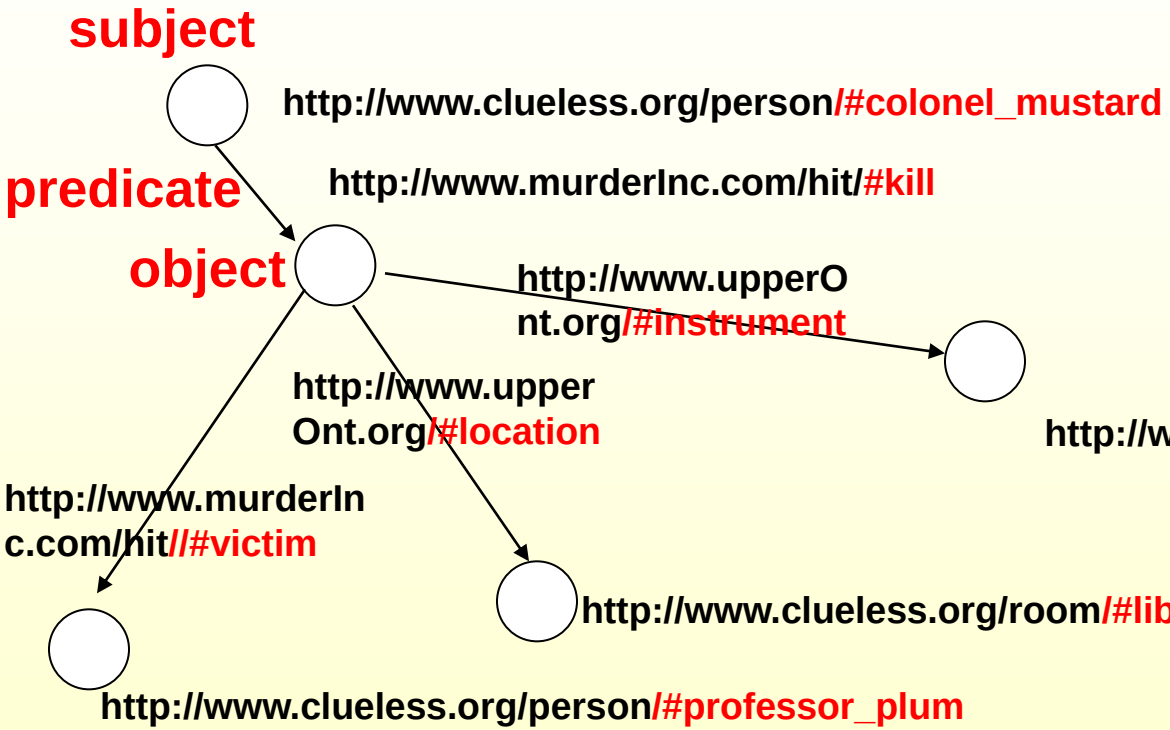
*"The creator of page http://www.FOOBAR.org/index.html is http://www.FOOBAR.org/staffid/12345"



This is also a conceptual graph (with URIs as names)

RDF/S Model: A Directed Graph

Colonel Mustard killed Professor Plum in the Library with the Lead Pipe



- Predicate: relation or attribute
- If the predicate is a relation, then the Object is another "object"
- If the predicate is an attribute, then the Object is a "value"

NOTE: This is also a conceptual graph (with URIs as "names")

Reification: **A statement about a statement (but uninterpreted, no truth asserted):**
John thinks X, where X = "Colonel Mustard killed Professor Plum in the Library with the Lead Pipe"; don't know what X 'means'

What the Languages Provide: OWL

- OWL enables you to make complex, generic statements about your Web object classes, properties
- OWL's instances are expressed as RDF statements
- OWL has 3 dialects/layers, increasingly more complex: **OWL-Lite, OWL-DL, OWL-Full**
- OWL is only an ONTOLOGY language (like RDFS) & a Description Logic (classification via subsumption)
- OWL uses everything below it in the Semantic Web stack:
  - **Has a presentation/exchange XML syntax, XML datatypes**
  - **RDF instances**
  - **RDFS generic (ontology) statements: how depends on the OWL dialect**
  - **OWL is expressed in an XML exchange and presentation syntax**
- OWL enables you to map among ontologies:
  - **Import one ontology into another: all things that are true in the imported ontology will thereby be true in the importing ontology**
  - **Assert that a class, property, or instance in one ontology/knowledge base is equivalent to one in another ontology**

OWL Language Levels*

Language Level	Description
OWL Full	The complete OWL. For example, a class can be considered both as a collection of instances (individuals) and an instance (individual) itself.
OWL DL (description logic)	Slightly constrained OWL. Properties cannot be individuals, for example. More expressive cardinality constraints.
OWL Lite	A simpler language but one that is more expressive than RDF/S. Simple cardinality constraints only (0 or 1).

*Daconta, Obrst, Smith, 2003; cf. also OWL docs at http://www.w3.org/2001/sw/WebOnt/

OWL LITE

- OWL Lite enables you to define an ontology of classes and properties and the instances (individuals) of those classes and properties

- This and all OWL levels use the *rdfs:subClassOf* relation to defined classes that are subclasses of other classes and which thus inherit those parent classes properties, forming a subsumption hierarchy, with multiple parents allowed for child classes

- Properties can be defined using the *owl:objectProperty* (for asserting relations between elements of distinct classes) or *owl:datatypeProperty* (for asserting relations between class elements and XML datatypes), *owl:subproperty, owl:domain,* and *owl:range* constructs

*Daconta, Obrst, Smith, 2003; cf. also OWL docs at http://www.w3.org/2001/sw/WebOnt/

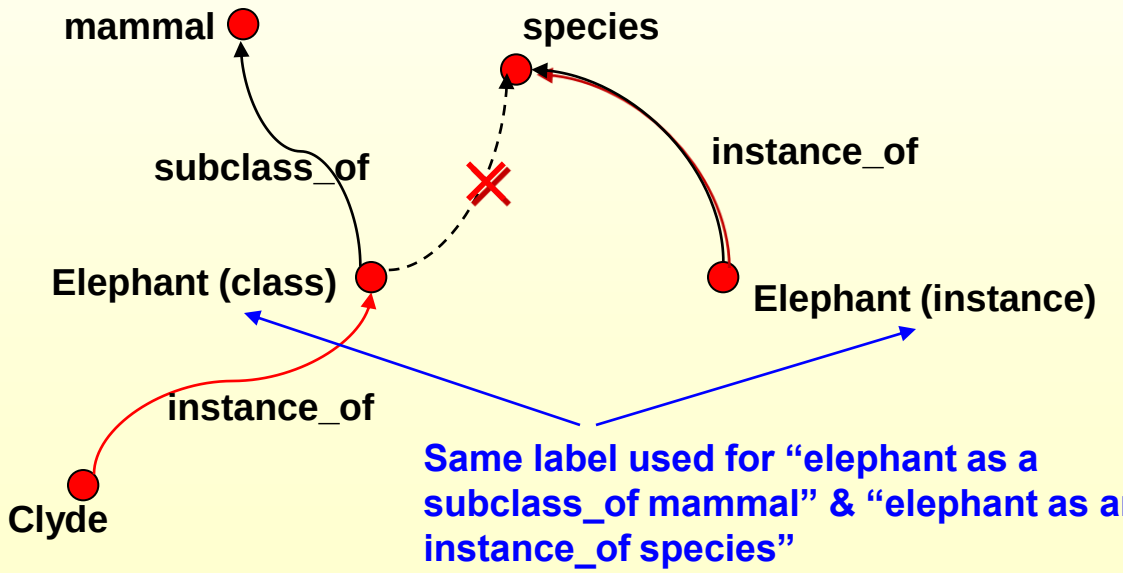
OWL DL

- OWL DL extends OWL Lite by permitting cardinality restrictions that are not limited to 0 or 1
- Also, you can define classes based on specific property values using the *hasValue* construct
- At the OWL DL level, you can create *class expressions* using Boolean combinators (set operators) such as *unionOf, intersectionOf,* and *complementOf*
- Furthermore, classes can be enumerated (listed) using the *oneOf* construct or specified to be disjoint using *disjointWith* construct

*Daconta, Obrst, Smith, 2003; cf. also OWL docs at http://www.w3.org/2001/sw/WebOnt/

OWL FULL

- OWL Full extends OWL DL by permitting classes to be treated simultaneously as both collections and individuals (instances)
- Also, a given *datatypeProperty* can be specified as being *inverseFunctional*, thus enabling, for example, the specification of a string as a unique key



****Clyde is an elephant.**

Elephant is a species.

Therefore, Clyde is a species.

WRONG!

Clyde is an elephant.

Elephant is a mammal.

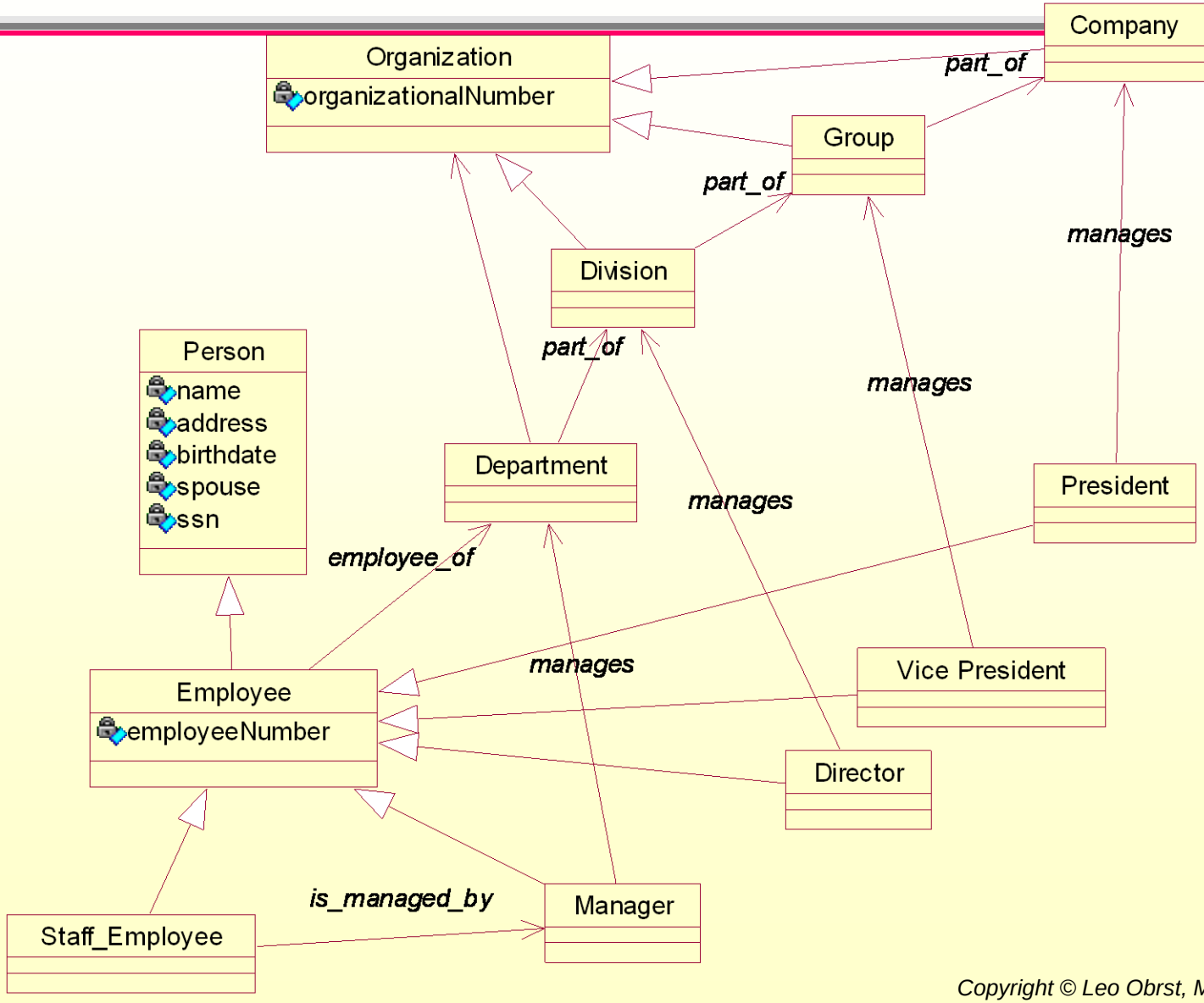
Therefore, Clyde is a mammal.

RIGHT!

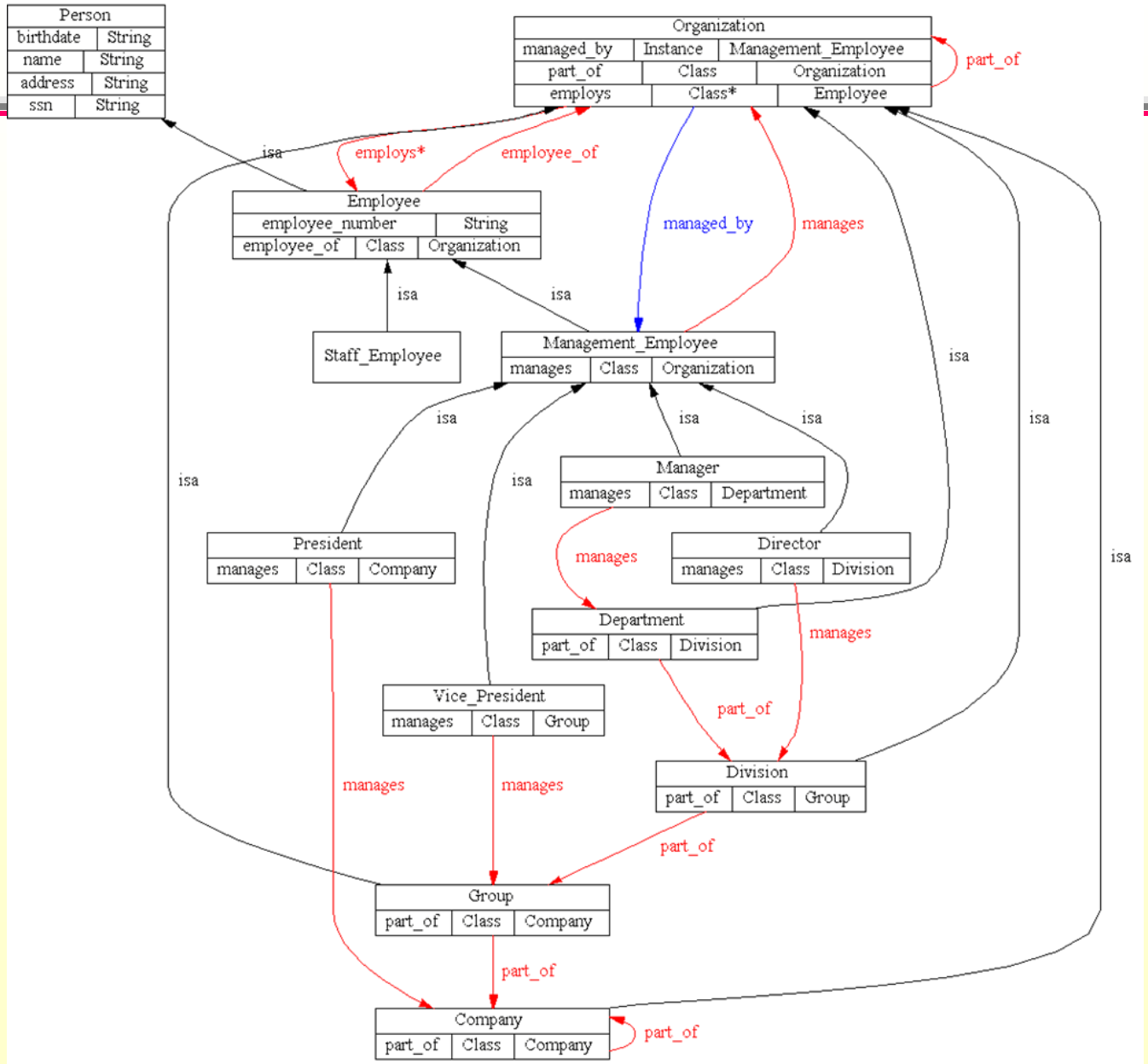
*Daconta, Obrst, Smith, 2003; cf. also OWL docs at http://www.w3.org/2001/sw/WebOnt/

**Sowa, John. 2000. Knowledge Representation: Logical, Philosophical, and Computational Foundations. Pacific Grove, CA: Brooks/Cole Thomson Learning.

Human Resource Model in UML



Human Resource Ontology in Protégé



OWL Human Resource Ontology Fragment

- Define a class called *Management_Employee* (1), then a subclass of that class, called *Manager* (2), and finally, an instance of the Manager class – *JohnSmith* (3)
  - The *subclass* relation is *transitive,* meaning that *inheritance* of properties from the parent to the child (subclass of parent) is enabled
  - So a *Manager* inherits all the properties defined for its superclass *Management_Employee*

```
1. <owl:Class rdf:ID="Management_Employee">
2. <owl:Class rdf:ID="Manager">
        <rdfs:subClassOf
  rdf:resource="#Management_Employee"/>
   </owl:Class>
3. <Manager rdf:ID="JohnSmith" />
```

- Define the property *employs* with domain *Organization* and range, *Employee*

```
<owl:ObjectProperty rdf:ID="employs">
   <rdfs:domain rdf:resource="#Organization"/>
   <rdfs:range rdf:resource="#Employee"/>
 </owl:ObjectProperty>
```

OWL Human Resource Ontology Fragment

- Define property *employee_of* with domain *Employee*, range *Organization*

```
<owl:ObjectProperty rdf:ID="employee_of">
   <rdfs:domain rdf:resource="#Employee"/>
   <rdfs:range rdf:resource="#Organization"/>
 </owl:ObjectProperty>
```

- *employee* and *employee-_of* are inverses of each other
- In OWL, this inverse relation can be stated in a different way, with the same semantics

```
<owl:ObjectProperty rdf:ID="employee_of">
   <owl:inverseOf rdf:resource="#employs" />
 </owl:ObjectProperty>
```

OWL Wine Ontology: Snippets*

- **Header, Namespace information**

```
<owl:Ontology rdf:about=""> <rdfs:comment>An example OWL
  ontology</rdfs:comment> <owl:priorVersion
  rdf:resource="http://www.w3.org/TR/2003/PR-owl-guide-20031215/wine"/>
  <owl:imports rdf:resource="http://www.w3.org/TR/2004/REC-owl-guide-
  20040210/food"/> <rdfs:label>Wine Ontology</rdfs:label>  …
```

- **Three Root Classes**

```
<owl:Class rdf:ID="Winery"/>
<owl:Class rdf:ID="Region"/>
<owl:Class rdf:ID="ConsumableThing"/>
```

- **Define a Subclass**

```
<owl:Class rdf:ID="PotableLiquid"> <rdfs:subClassOf
  rdf:resource="#ConsumableThing" /> ... </owl:Class>
```

- **Define an Individual (Instance)**

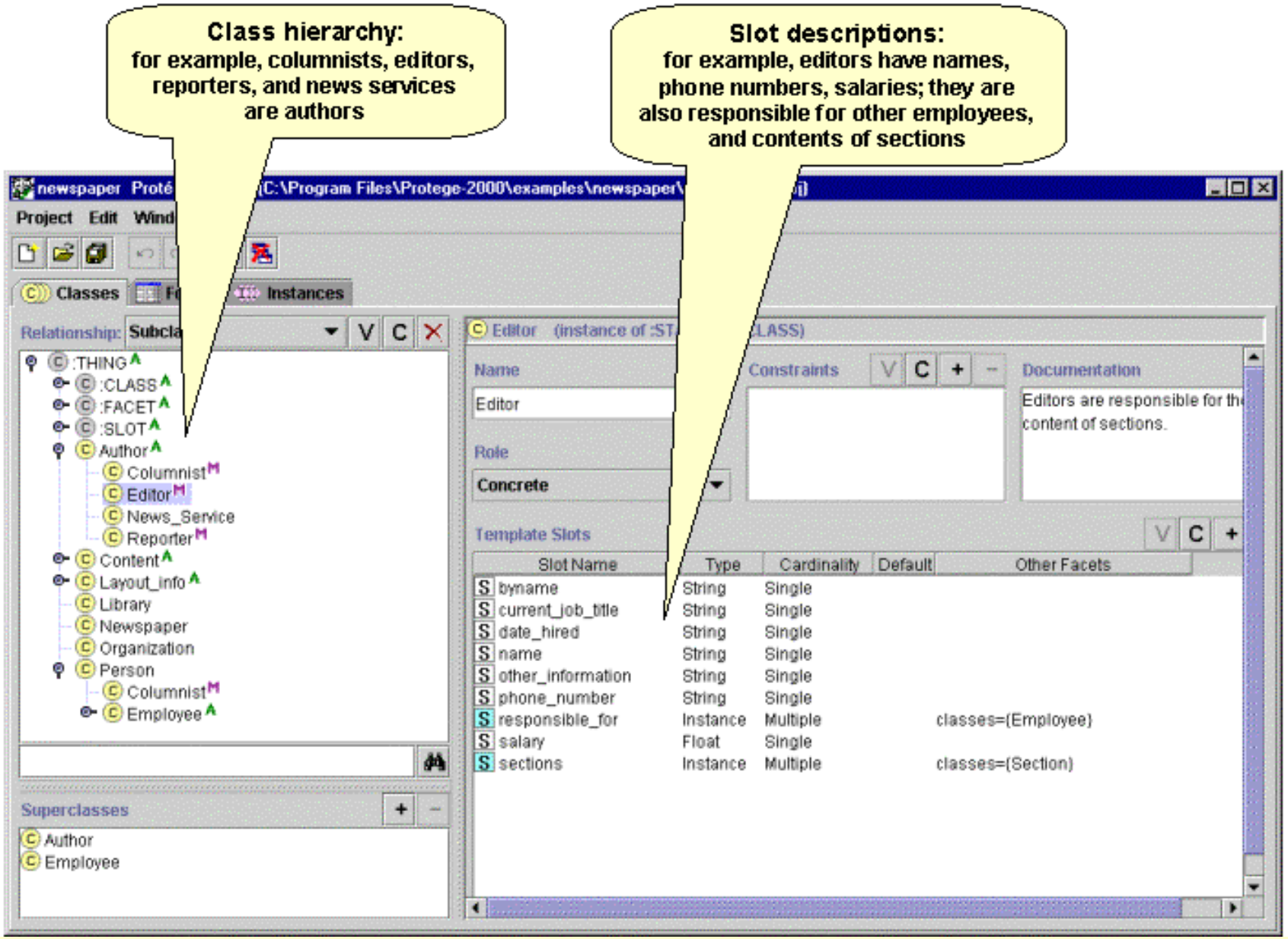
```
<owl:Thing rdf:ID="CentralCoastRegion" /> <owl:Thing
  rdf:about="#CentralCoastRegion"> <rdf:type rdf:resource="#Region"/>
  </owl:Thing>
```

- **Define a property**

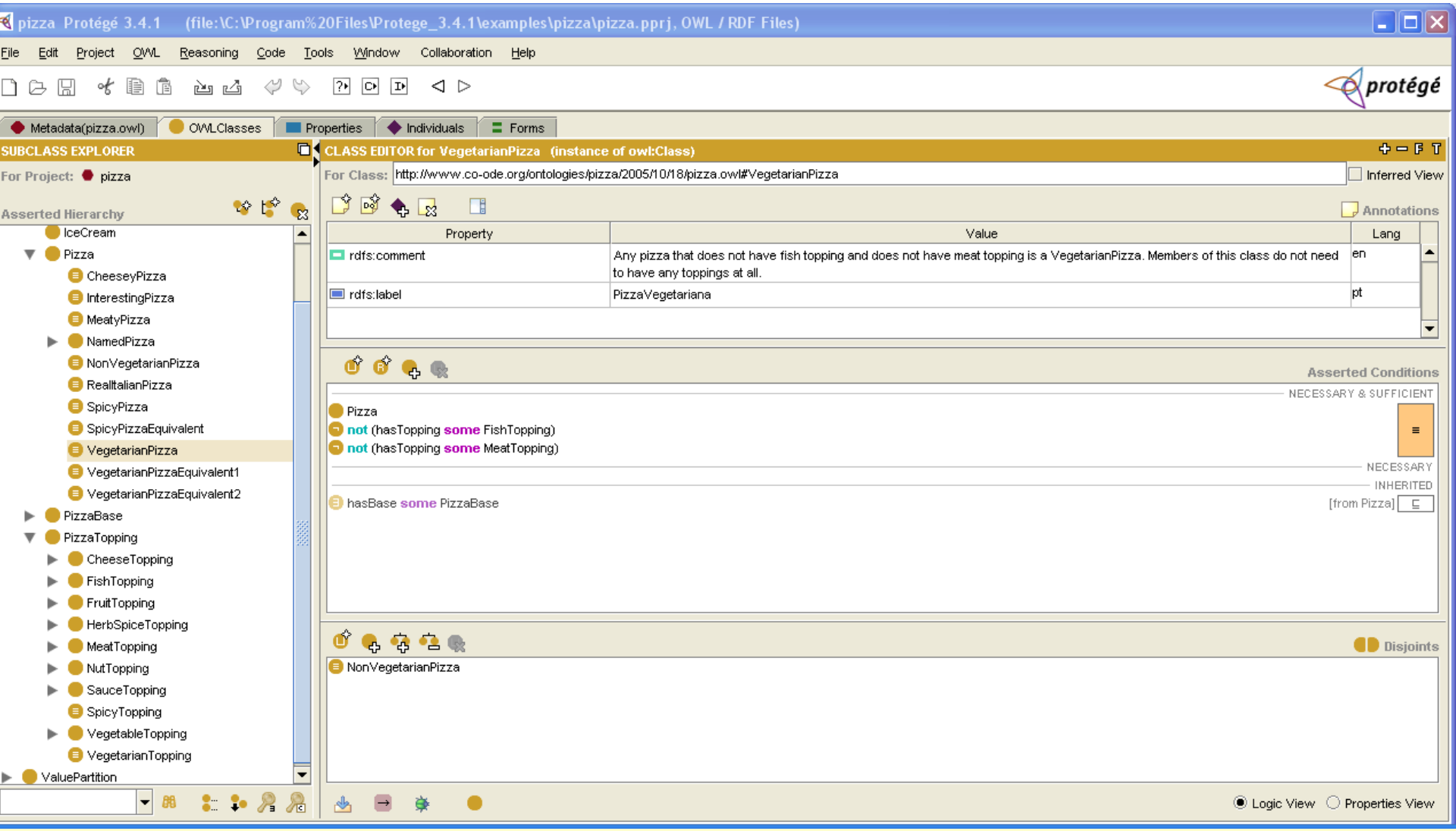
```
<owl:ObjectProperty rdf:ID="madeFromGrape"> <rdfs:domain
  rdf:resource="#Wine"/> <rdfs:range rdf:resource="#WineGrape"/>
  </owl:ObjectProperty>
```

*** From the OWL Guide, http://www.w3.org/TR/2004/REC-owl-guide-20040210/**

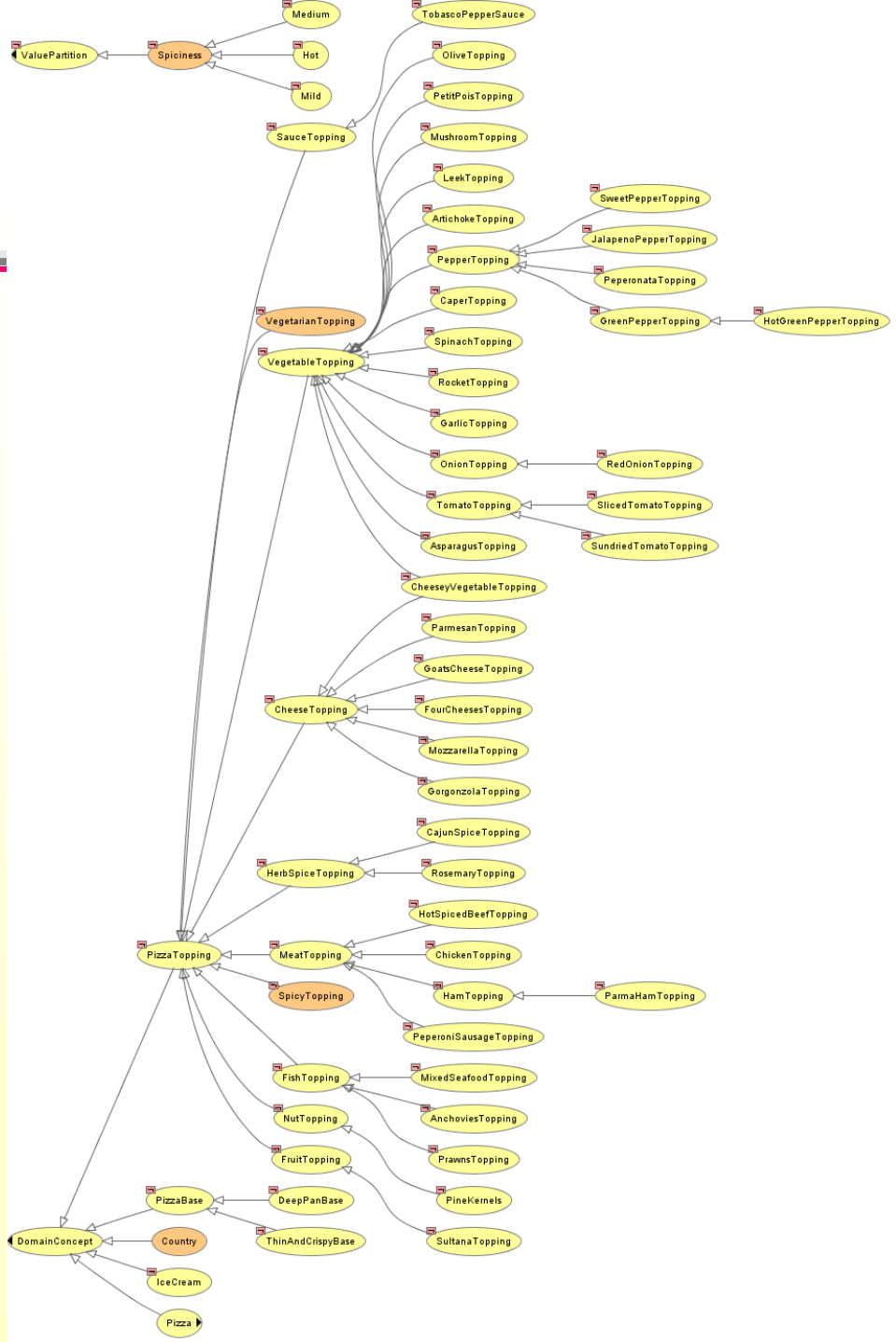
Protégé Example: http://protege.stanford.edu/



Protégé: OWL Pizza Ontology



Protégé: OWLViz partial view of Pizza



OWL 2 (1)

- OWL 2 is a Proposed W3C Recommendation (22 Sept 2009)*
- Compatible with OWL 1 (04 Feb 2004)
- New features
  - Increased datatype coverage: Designed to take advantage of the new datatypes and clearer explanations available in XSD 1.1 (not yet a recommendation)
  - Syntactic Sugar for more easily saying things in OWL:
  - New constructs that increase expressivity
  - Simple meta-modeling capabilities
  - Extended annotation capabilities
  - Profiles

*** http://www.w3.org/TR/2009/PR-owl2-new-features-20090922/**

OWL 2 (2)

- Syntactic Sugar for more easily saying things in OWL:
  - DisjointUnion:
    - DisjointUnion(:CarDoor :FrontDoor :RearDoor :TrunkDoor) : A :CarDoor is exclusively either a :FrontDoor, a :RearDoor or a:TrunkDoor and not more than one of them.
  - DisjointClasses
    - DisjointClasses(:LeftLung :RightLung) : Nothing can be both a :LeftLung and a :RightLung.
  - NegativeObject(Data)PropertyAssertion
    - NegativeObjectPropertyAssertion(:livesIn :ThisPatient :IleDeFrance) :ThisPatient does not live in the :IleDeFrance region.
  - Self-restriction on Properties: “local reflexivity”
    - SubClassOf(:AutoRegulatingProcess ObjectHasSelf(:regulate)): Auto-regulating processes regulate themselves.
  - Property Qualified Cardinality Restrictions: counted cardinality restrictions (Min, Max, Exact)
    - ObjectMaxCardinality(3 :boundTo :Hydrogen): Class of objects bound to at most three different :Hydrogen
  - Many others

OWL 2 (3)

- Simple meta-modeling capabilities:
  - Punning: allows different uses of the same term and an individual
  - OWL 2 DL still imposes certain restrictions: it requires that a name cannot be used for both a class and a datatype and that a name can only be used for one kind of property; semantically names are distinct for reasoners
- Annotations:
  - AnnotationAssertion: for annotation of ontology entities
  - Annotation: for annotations of axioms and ontologies
  - Etc.
- New constructs that increase expressivity
  - Declarations: a declaration signals that an entity is part of the vocabulary of an ontology. A declaration also associates an entity category (class, datatype, object property, data property, annotation property, or individual) with the declared entity
  - Declaration(NamedIndividual(*:Peter*)): *Peter* is declared to be an individual

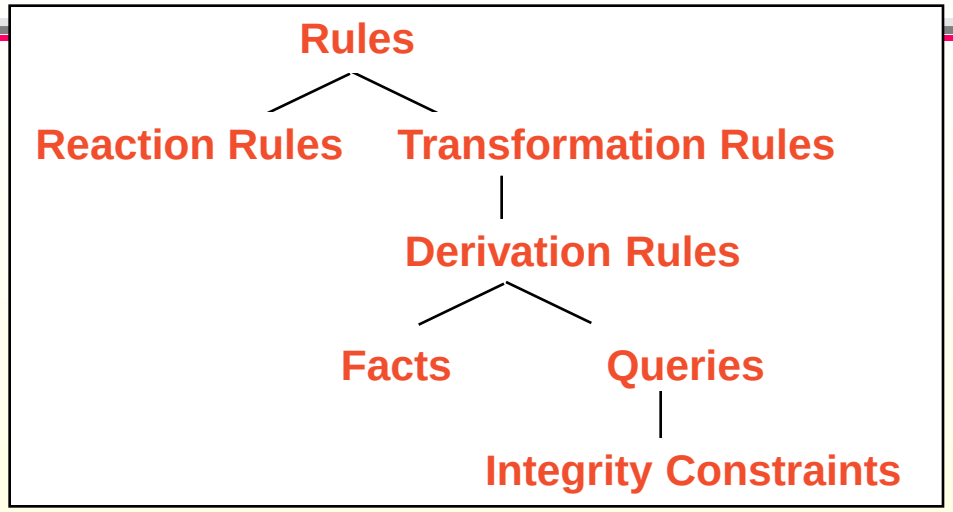
OWL 2 (4)

- Profiles:
  - OWL 1 defined two major dialects, OWL DL and OWL Full, and one syntactic subset (OWL Lite)
  - Needs:
    - Some large-scale applications (e.g., in the life sciences) are mainly concerned with language scalability and reasoning performance problems and are willing to trade off some expressiveness in return for computational guarantees, particularly w.r.t. classification
    - Other applications involve databases and so need to access such data directly via relational queries (e.g., SQL)
    - Other applications are concerned with interoperability of the ontology language with rules and existing rule engines
  - Therefore, 3 profiles (sublanguages, i.e., syntactic subsets of OWL 2) are defined: OWL 2 EL, OWL 2 QL, and OWL 2 RL*
- And more!

*** http://www.w3.org/TR/2009/PR-owl2-profiles-20090922/**

Semantic Web Rules: RuleML, SWRL (RuleML + OWL), RIF

RuleML Rule Taxonomy*



*Adapted from Harold Boley, Benjamin Grosof, Michael Sintek, Said Tabet, Gerd Wagner. 2003. RuleML Design, 2002-09-03: Version 0.8. http://www.ruleml.org/indesign.html

- ***Reaction rules*** can be reduced to general rules that return no value. Sometimes these are called "condition-action" rules. Production rules in expert systems are of this type
- ***Transformation rules*** can be reduced to general rules whose 'event' trigger is always activated. A Web example of transformation rules are the rules expressed in XSLT to convert one XML representation to another. "Term rewrite rules" are transformation rules, as are ontology-to-ontology mapping rules
- ***Derivation rules*** can be reduced to transformation rules that like characteristic functions on success just return true. Syntactic $A \vdash_P B$ and Semantic Consequence $A \models_P B$ are derivation rules
- ***Facts*** can be reduced to Facts can be reduced to derivation rules that have an empty (hence, 'true') conjunction of premises. In logic programming, for example, facts are the ground or instantiated relations between "object instances"
- ***Queries*** can be reduced to derivation rules that have – similar to refutation proofs – an empty (hence, 'false') disjunction of conclusions or – as in 'answer extraction' – a conclusion that captures the derived variable bindings
- ***Integrity constraints*** can be reduced to queries that are 'closed' (i.e., produce no variable bindings)

So Which Rules Are Useful, Good, Bad, Ugly?

☺ Good

- Logical rules are declarative, confirmable by human beings, machine semantically-interpretable, non-side-effecting
- Logical rules can express everything that production (expert system) rules, procedural rules can
- Logical rules can express business, policy rules, static/dynamic rules

☠ Bad

- Rules expressed in procedural code if-then-else case statements are non-declarative, inspectable by human beings, confirmable with documentation and observance of conformance to documentation, side-effecting (ultimate side-effect: negating a value and returning true for that value)

☹ Ugly

- Expert systems rules "simulate" inference, are pre-logical, have side-effects, tend toward non-determinism, force all knowledge levels to the same level (this is why ontologies and ontological engineering came about), are horrible to debug

Example: Inference and Proof

Proof Using Inference Rule of Modus Ponens

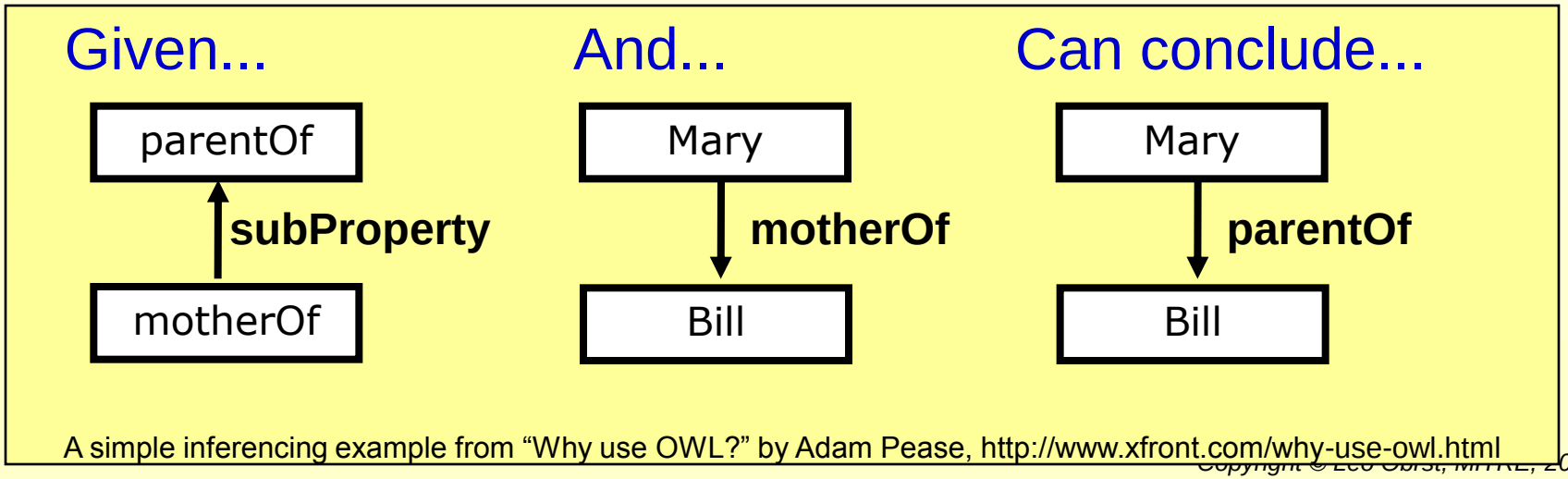
Given: **If motherOf is a subProperty of parentOf, and Mary is the mother of Bill, then Mary is the parentOf Bill**

motherOf is a subProperty of parentOf

Mary is the motherOf Bill

Infer: **Mary is the parentOf Bill**

Deduction A method of reasoning by which one infers a conclusion from a set of sentences by employing the axioms and rules of inference for a given logical system.



A simple inferencing example from "Why use OWL?" by Adam Pease, http://www.xfront.com/why-use-owl.html

Rule Interchange Format (RIF)*

- RIF is a rule language based on XML syntax
- RIF provides multiple versions, called *dialects:*
  - **Core:** the fundamental RIF language, and a common subset of most rule engines (It provides "safe" positive datalog with builtins)
  - **BLD (Basic Logic Dialect**): adds to Core: logic functions, equality in the *then*-part, and named arguments (This is positive Horn logic, with equality and builtins)
  - **PRD (Production Rules Dialect):** adds a notion of forward-chaining rules, where a rule *fires* and then performs some action, such as adding more information to the store or *retracting* some information (This is comparable to production rules in expert systems, sometimes called condition-action, event-condition-action, or reaction rules)

•**http://www.w3.org/2005/rules/wiki/RIF_Working_Group**
•**http://www.w3.org/2005/rules/wiki/RIF_FAQ**

Trust

- Trust requires
  - ***Identity:*** knowing that the person, agent, organization, software application, or Semantic Web ontology is who they say they are; digital signatures, PKI, etc., help establish this
  - ***Credibility, Trustworthiness:*** knowing that the Semantic Web artifact was created by a reputable agent, organization, i.e., one that has a reputation for quality, truth, response to customers, commitment to error correction, and adherence to self-advertised use and intent policies
  - ***Proof:*** being able to prove that the response you, your agent, or your inference engine is given to a query, function call, or service request on the Semantic Web is indeed true, and correctly follows; an explanation or trace that ensures this
  - ***Security and Privacy:*** being able to ensure that access to your property and to the rights you grant are strictly enforced at the sufficient granularity of detail you or your policy requires

Use / Intent

- Semantic Web artifacts define their meaning using ontologies, fact/knowledge bases, and Semantic Web services
- Those semantic models and services are intended to
  - Represent what you mean
  - Be used by others in the way you meant them to be used
- The *Pragmatic Web* concerns the correct interpretation of semantic models and services in context
  - i.e., according to the use and intent they were created for, perhaps in a specific process/workflow model
  - By a human, an agent, or another Semantic Web service
- Policy: in many cases, you will declare a Semantic Web policy about how your Semantic Web models and services need to be interpreted and used
  - Like business rules and pragmas in computer programming
  - Coercions will be needed, but violations should be flagged – as violating the use and intent of your semantics
  - Policy helps stabilize the Semantic Web
  - Policy helps maintain your and your site's credibility
  - Policy helps agents and services interpret how they should interpret your models and services

Where is the Technology Going?

- "The Semantic Web is very exciting, and now just starting off in the same grassroots mode as the Web did 10 years ago ... In 10 years it will in turn have revolutionized the way we do business, collaborate and learn."
  - Tim Berners-Lee, CNET.com interview, 2001-12-12
- We can look forward to:
  - Semantic Integration/Interoperability, not just data interoperability
  - Applications and services with trans-community semantics
  - Device interoperability in the ubiquitous computing future: achieved through semantics & contextual awareness
  - True realization of intelligent agent interoperability
  - Intelligent semantic information retrieval & search engines
  - Next generation semantic electronic commerce/business & web services
  - Semantics beginning to be used once again in NLP

🔑 ***Key to all of this is effective & efficient use of explicitly represented semantics (ontologies)***

The Point (s)

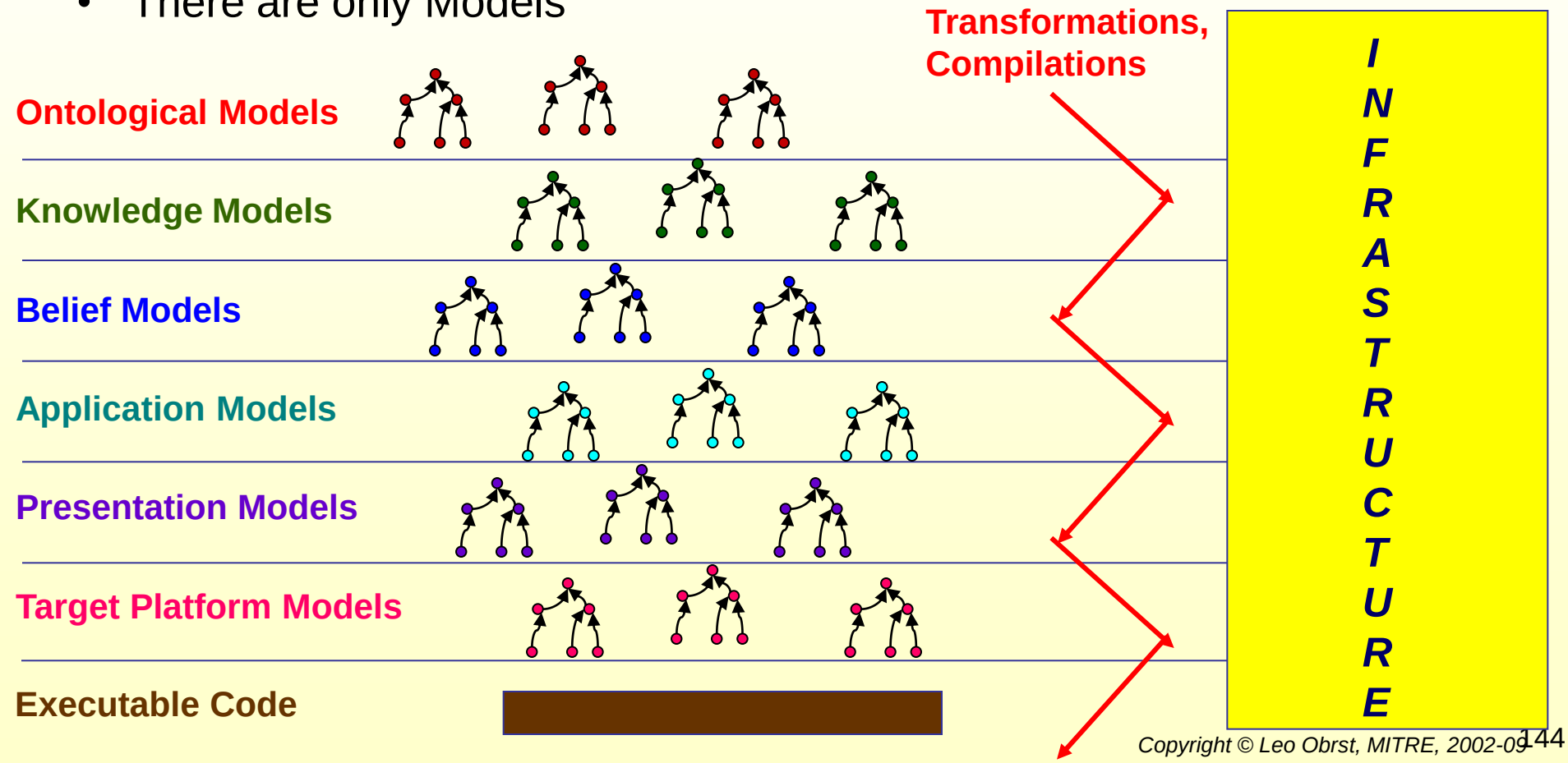
- The point is that we need to model our best human theories (naïve or scientific, depending on our system needs)
- In a declarative fashion (so that humans can easily verify them)
- And get our machines to work off them, as **models** of what humans do and **mean**
- We need to build our systems, our databases, our intelligent agents, and our documents on these **models of human meaning**
- These models must:
  - Represent once (if possible)
  - Be semantically reasonable (sound)
  - Be modular (theories or micro-theories or micro-micro-theories)
  - Be reused. Be composable. Be plug-and-playable
  - Be easily created and refined. Adaptable to new requirements, dynamically modifiable
  - Be consistent or boundably consistent so that our machines can reason and give use conclusions that are sound, trustable or provable, and secure
- We need to enable machines to come up to our human conceptual level (rather than forcing humans to go down to the machine level)

Conclusion

- We have discussed Syntax and Semantics, and what the distinctions are
- Ontology Spectrum and the Range of Semantic Models: from Taxonomy (both Weak and Strong) to Thesaurus to Conceptual Model (Weak Ontology) to Logical Theory (Strong Ontology)
- Knowledge Representation: Semantic Networks to Frame-based KR to Description Logics to Full Logic (Propositional and FOL), including Logic Programming
- Ontology Engineering: How to Model, i.e., Concepts and Relationships, Principles
- Semantic Web: RDF/S, OWL, SWRL, RIF, more: trust

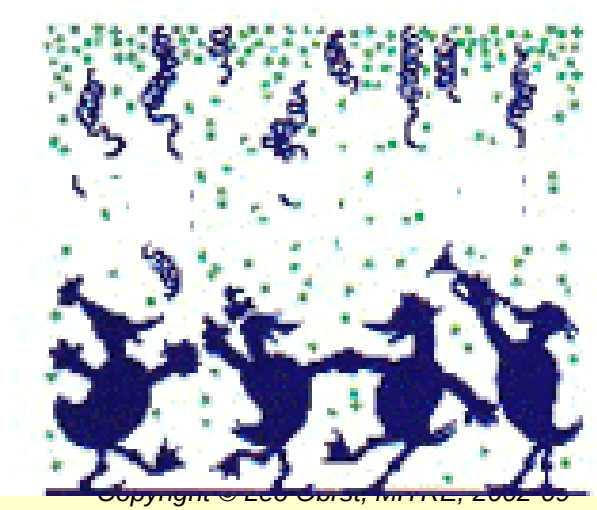
What do we want the future to be?

- 2100 A.D: models, models, models
- There are no human-programmed programming languages
- There are only Models



Conclusions: Some Philosophers and Ontology

- Aristotle: “To be is to be”
- Nietzsche: “To do is to be”
- Sartre: “To be is to do”
- Husserl: “To do should be to be”
- Sinatra: “Shoo be do be do”
  - My way or the highway?



Thank You!

Questions? lobrst@mitre.org