

Announcement

- Homework 2
 - Due: Oct. 5, 11:59pm
- Programming Assignment 2
 - Due: Oct. 19, 11:59pm (three weeks)

Announcement

- Reminder
 - Homework 1 and Project 1a due 11:59pm today!
 - Project 1b due Oct. 5, 11:59pm

First-Order Logic

AIMA Chapter 8, 9

Pros of propositional logic

- ☺ Propositional logic allows partial/disjunctive/negated information
 - (unlike most data structures and databases)
- ☺ Propositional logic is **compositional**:
 - meaning of $B_{1,1} \wedge P_{1,2}$ is derived from meaning of $B_{1,1}$ and of $P_{1,2}$
- ☺ Meaning in propositional logic is **context-independent**
 - (unlike natural language, where meaning depends on context)

Cons of propositional logic

- ☹ Hard to identify “individuals” (e.g., Mary, 3)
- ☹ Can’t directly talk about properties of individuals or relations between individuals (e.g., “Bill is tall”)
- ☹ Generalizations, patterns, regularities can’t easily be represented (e.g., “all triangles have 3 sides”)

First-order logic

- Whereas propositional logic assumes the world contains **facts**...
- First-order logic (like natural language) assumes the world contains
 - **Objects**: people, houses, numbers, colors, baseball games, wars, ...
 - **Relations**: red, round, prime, bigger than, part of, comes between, ...
 - **Functions**: father of, best friend of, one more than, ...
- Also called first-order predicate logic

Syntax of FOL: Basic elements

- Logical symbols
 - Connectives $\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow$
 - Quantifiers \forall, \exists
 - Variables x, y, a, b, \dots
 - Equality $=$
- Non-logical symbols (ontology)
 - Constants KingArthur, 2, ShanghaiTech, ...
 - Predicates Brother, $>$, ...
 - Functions Sqrt, LeftLegOf, ...

Atomic sentences

Atomic sentence = *predicate* ($term_1, \dots, term_n$)
or $term_1 = term_2$

Term = *constant* or *variable*
or *function* ($term_1, \dots, term_n$)

Example:

Brother(KingJohn, RichardTheLionheart)

>(*Length*(*LeftLegOf*(Richard)), *Length*(*LeftLegOf*(KingJohn)))

Complex sentences

Complex sentences are made from atomic sentences using connectives

$$\neg S, S_1 \wedge S_2, S_1 \vee S_2, S_1 \Rightarrow S_2, S_1 \Leftrightarrow S_2,$$

Example:

$$\textit{Sibling}(\textit{KingJohn}, \textit{Richard}) \Rightarrow \textit{Sibling}(\textit{Richard}, \textit{KingJohn})$$

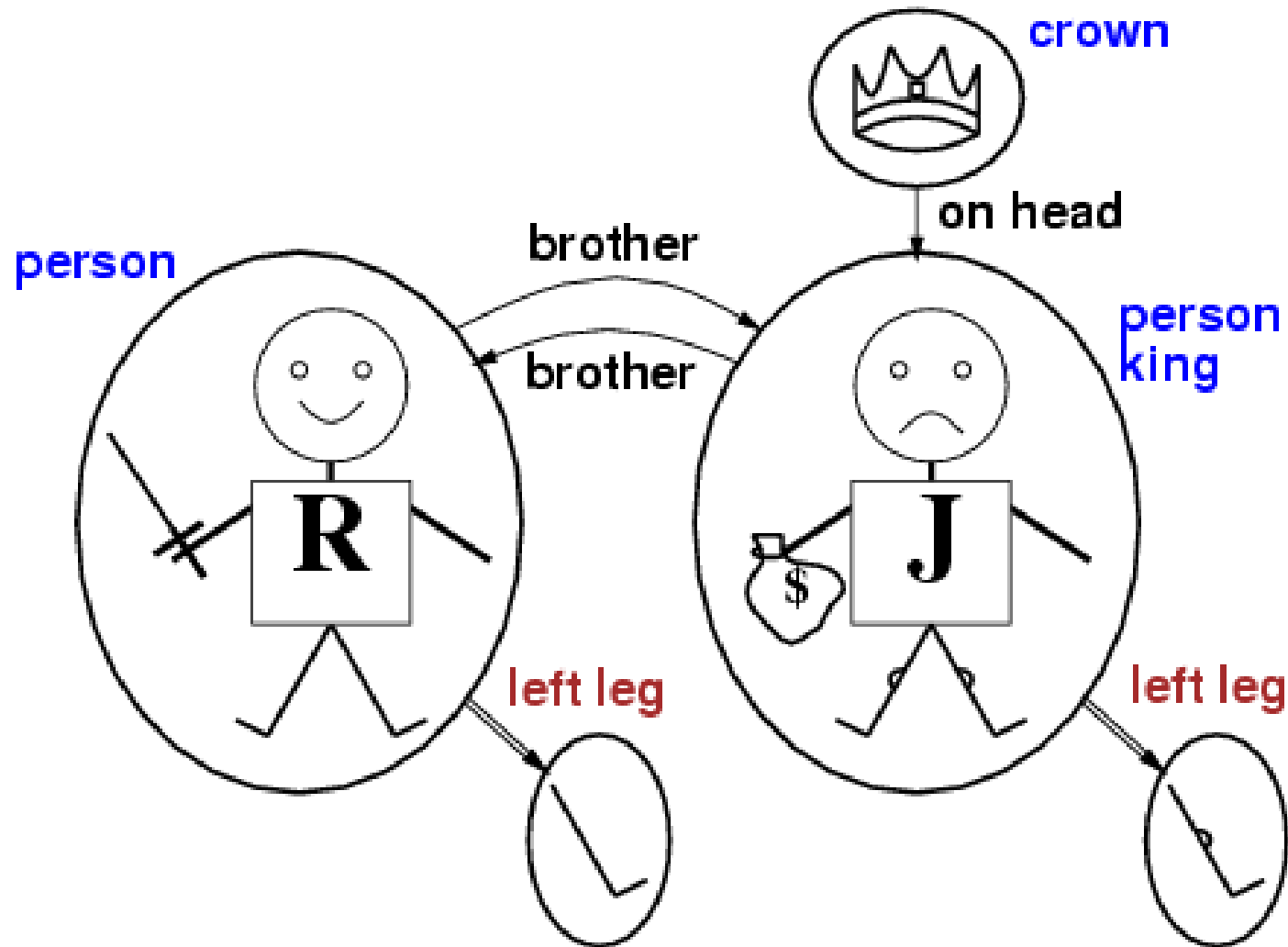
$$>(1,2) \vee \leq (1,2)$$

$$>(1,2) \wedge \neg >(1,2)$$

Semantics of FOL

- Sentences are true with respect to a **model**, which contains
 - **Objects** and **relations** among them
 - **Interpretation** specifying referents for
 - constant symbols** → **objects**
 - predicate symbols** → **relations**
 - function symbols** → **functional relations**
- An atomic sentence ***predicate(term₁, ..., term_n)*** is true iff the **objects** referred to by ***term₁, ..., term_n*** are in the **relation** referred to by ***predicate***

Models for FOL: Example



Models for FOL: Example

- Consider the interpretation:

Richard → Person R

John → Person J

Brother → the brotherhood relation

Under this interpretation, *Brother(Richard, John)* is true in the model.

Models for FOL

- How many models do we have? **Infinite!**

Models vary in:

- the number of objects (1 to ∞)
- the relations among the objects
- the mapping from constants to objects
- the mapping from predicates to relations
-

Quantifiers

- Allows us to express properties of collections of objects instead of enumerating objects by name
- Universal: “for all” \forall
- Existential: “there exists” \exists

Universal quantification

\forall <variables> <sentence>

Example: $\forall x \text{ } At(x, STU) \Rightarrow Smart(x)$

(Everyone at ShanghaiTech is smart)

$\forall x P$ is true in a model m iff P is true with x being each possible object in the model

- Roughly speaking, equivalent to the conjunction of instantiations of P

$At(John, STU) \Rightarrow Smart(John)$

$\wedge At(Richard, STU) \Rightarrow Smart(Richard)$

$\wedge At(STU, STU) \Rightarrow Smart(STU)$

$\wedge \dots$

A common mistake to avoid

- Typically, \Rightarrow is the main connective with \forall
- Common mistake: using \wedge as the main connective with \forall :

$$\forall x \text{ } At(x, STU) \wedge Smart(x)$$

means “Everyone is at STU and everyone is smart”

Existential quantification

\exists <variables> <sentence>

Example: $\exists x \text{ At}(x, \text{STU}) \wedge \text{Smart}(x)$

(Someone at ShanghaiTech is smart)

$\exists x P$ is true in a model m iff P is true with x being some possible object in the model

- Roughly speaking, equivalent to the disjunction of instantiations of P

$(\text{At}(\text{John}, \text{STU}) \wedge \text{Smart}(\text{John}))$

$\vee (\text{At}(\text{Richard}, \text{STU}) \wedge \text{Smart}(\text{Richard}))$

$\vee (\text{At}(\text{STU}, \text{STU}) \wedge \text{Smart}(\text{STU}))$

$\vee \dots$

Another common mistake to avoid

- Typically, \wedge is the main connective with \exists
- Common mistake: using \Rightarrow as the main connective with \exists :

$$\exists x \text{ } At(x, STU) \Rightarrow Smart(x)$$

is true if there is anyone who is not at STU!

Properties of quantifiers

- $\forall x \forall y$ is the same as $\forall y \forall x$
- $\exists x \exists y$ is the same as $\exists y \exists x$
- $\exists x \forall y$ is not the same as $\forall y \exists x$
 - $\exists x \forall y \text{ Loves}(x,y)$

“There is a person who loves everyone in the world”
 - $\forall y \exists x \text{ Loves}(x,y)$

“Everyone in the world is loved by at least one person”
- Quantifier duality: each can be expressed using the other
 - $\forall x \text{ Likes}(x, \text{IceCream}) \equiv \neg \exists x \neg \text{Likes}(x, \text{IceCream})$
 - $\exists x \text{ Likes}(x, \text{Broccoli}) \equiv \neg \forall x \neg \text{Likes}(x, \text{Broccoli})$

Sentences with variables

- A variable is free in a formula if it is not quantified
 - e.g., $\forall x P(x,y)$
- A variable is bound in a formula if it is quantified
 - e.g., $\forall x \exists y P(x,y)$
- In a FOL sentence, every variable must be bound.

FOL example: kinship

- Brothers are siblings

$$\forall x,y \text{ Brother}(x,y) \Rightarrow \text{Sibling}(x,y).$$

- "Sibling" is symmetric

$$\forall x,y \text{ Sibling}(x,y) \Leftrightarrow \text{Sibling}(y,x).$$

- One's mother is one's female parent

$$\forall x,y \text{ Mother}(x,y) \Leftrightarrow (\text{Female}(x) \wedge \text{Parent}(x,y)).$$

- A first cousin is a child of a parent's sibling

$$\forall x,y \text{ FirstCousin}(x,y) \Leftrightarrow \exists p,ps \text{ Parent}(p,x) \wedge \text{Sibling}(ps,p) \wedge \text{Parent}(ps,y)$$

FOL example: kinship

- Siblings are people with the same parents

$$\forall x,y \text{ Sibling}(x,y) \Leftrightarrow \exists m,f \text{ Parent}(m,x) \wedge \text{Parent}(f,x) \wedge \text{Parent}(m,y) \wedge \text{Parent}(f,y)$$

Is this correct?

Equality

$term_1 = term_2$ is true under a given interpretation if and only if $term_1$ and $term_2$ refer to the same object

Example: Siblings are people with the same parents:

$\forall x, y \text{ Sibling}(x, y) \Leftrightarrow [\neg(x = y) \wedge \exists m, f \neg(m = f) \wedge \text{Parent}(m, x) \wedge \text{Parent}(f, x) \wedge \text{Parent}(m, y) \wedge \text{Parent}(f, y)]$

FOL example

- True or false?

$\forall x \text{ CollegeStudent}(x) \Rightarrow \text{Student}(x)$

$\forall x \text{ Student}(x) \Rightarrow \text{CollegeStudent}(x)$

- Sentences are true/false **with respect to a model**

- No truth-value without a model!
- Symbols do not carry meanings by themselves

David Hilbert: “One must be able to say at all times
— instead of points, straight lines, and planes
— tables, chairs, and beer mugs.”



Inference in first-order logic

Universal instantiation (UI)

(Term without variables)

- For any sentence α , variable v and ground term g :

$$\frac{\forall v \alpha}{\text{Subst}(\{v/g\}, \alpha)} \longleftarrow \text{Substitute } v \text{ with } g \text{ in } \alpha$$

- Every instantiation of a universally quantified sentence is entailed by it
- UI can be applied multiple times to add new sentences
- E.g., $\forall x \text{ King}(x) \wedge \text{Greedy}(x) \Rightarrow \text{Evil}(x)$ yields:
 - $\text{King}(\text{John}) \wedge \text{Greedy}(\text{John}) \Rightarrow \text{Evil}(\text{John})$
 - $\text{King}(\text{Richard}) \wedge \text{Greedy}(\text{Richard}) \Rightarrow \text{Evil}(\text{Richard})$
 - $\text{King}(\text{Father}(\text{John})) \wedge \text{Greedy}(\text{Father}(\text{John})) \Rightarrow \text{Evil}(\text{Father}(\text{John}))$

Existential instantiation (EI)

- For any sentence α , variable v , and constant symbol k that **does not appear elsewhere in the knowledge base**:

$$\frac{\exists v \alpha}{\text{Subst}(\{v/k\}, \alpha)}$$

- EI can be applied once to replace an existential sentence
- E.g., $\exists x \text{Crown}(x) \wedge \text{OnHead}(x, \text{John})$ yields:

$$\text{Crown}(C_1) \wedge \text{OnHead}(C_1, \text{John})$$

provided C_1 is a new constant symbol, called a Skolem constant

Reduction to propositional inference

- Suppose the KB contains just the following:
 - $\forall x \text{ King}(x) \wedge \text{Greedy}(x) \Rightarrow \text{Evil}(x)$
 - $\text{King}(\text{John})$
 - $\text{Greedy}(\text{John})$
 - $\text{Brother}(\text{Richard}, \text{John})$

Reduction contd.

- Instantiating the universal sentence **in all possible ways**, we have:
 - $\text{King}(\text{John}) \wedge \text{Greedy}(\text{John}) \Rightarrow \text{Evil}(\text{John})$
 - $\text{King}(\text{Richard}) \wedge \text{Greedy}(\text{Richard}) \Rightarrow \text{Evil}(\text{Richard})$
 - $\text{King}(\text{John})$
 - $\text{Greedy}(\text{John})$
 - $\text{Brother}(\text{Richard}, \text{John})$
- The new KB is **propositionalized**: proposition symbols are
 - $\text{King}(\text{John})$, $\text{Greedy}(\text{John})$, $\text{Evil}(\text{John})$, $\text{King}(\text{Richard})$, etc.


Reduction contd.

- Every FOL KB can be propositionalized so as to preserve entailment
 - i.e., a ground sentence is entailed by new KB iff entailed by original KB
- A naïve idea for FOL inference:
 - propositionalize KB and query, apply resolution, return result
- Problem: with function symbols, there are infinitely many ground terms,
 - e.g., *Father(Father(Father(John)))*

Reduction contd.

- Theorem (Herbrand, 1930)
 - If a sentence α is entailed by an FOL KB, it is entailed by a **finite** subset of the propositionalized KB
- Idea:
 - For $n = 0$ to ∞ do
 1. create a propositional KB by instantiating with depth- n terms
 2. if α is entailed by this KB, return true

Function nesting levels



Does this work?

Reduction contd.

- Problem
 - works if α is entailed
 - infinite loops if α is not entailed
- Theorem (Turing, 1936; Church, 1936): entailment for FOL is **semi-decidable**
 - algorithms exist that say yes to every entailed sentence
 - but no algorithm exists that says no to every non-entailed sentence.

Problems with propositionalization

- Propositionalization generates many irrelevant sentences
- E.g., from:
 - $\forall x \text{ King}(x) \wedge \text{Greedy}(x) \Rightarrow \text{Evil}(x)$
 - $\text{King}(\text{John})$
 - $\forall y \text{ Greedy}(y)$

The query *Evil(John)* seems obviously true. But propositionalization produces lots of facts such as *Greedy(Richard)* that are irrelevant.

Unification

- Given:
 - $\forall x \text{ King}(x) \wedge \text{Greedy}(x) \Rightarrow \text{Evil}(x)$
 - $\text{King}(\text{John})$
 - $\forall y \text{ Greedy}(y)$
 - If we can find the substitution $\theta = \{x/\text{John}, y/\text{John}\}$, then we get
 - $\text{King}(\text{John}) \wedge \text{Greedy}(\text{John}) \Rightarrow \text{Evil}(\text{John})$
 - $\text{King}(\text{John})$
 - $\text{Greedy}(\text{John})$
- and we can answer the query *Evil(John)* immediately
- Unification finds substitutions that make different expressions identical
 - E.g., $\text{King}(x)$ vs. $\text{King}(\text{John})$; $\text{Greedy}(x)$ vs. $\text{Greedy}(y)$

Only variables can
be substituted



Unification

- $\text{Unify}(\alpha, \beta) = \theta$ if $\alpha\theta = \beta\theta$

p	q	θ
Knows(John,x)	Knows(John,Jane)	
Knows(John,x)	Knows(y,OJ)	
Knows(John,x)	Knows(y,Mother(y))	
Knows(John,x)	Knows(x,OJ)	

Unification

- $\text{Unify}(\alpha, \beta) = \theta$ if $\alpha\theta = \beta\theta$

p	q	θ
Knows(John,x)	Knows(John,Jane)	{x/Jane}
Knows(John,x)	Knows(y,OJ)	
Knows(John,x)	Knows(y,Mother(y))	
Knows(John,x)	Knows(x,OJ)	

Unification

- $\text{Unify}(\alpha, \beta) = \theta$ if $\alpha\theta = \beta\theta$

p	q	θ
Knows(John,x)	Knows(John,Jane)	{x/Jane}
Knows(John,x)	Knows(y,OJ)	{x/OJ,y/John}
Knows(John,x)	Knows(y,Mother(y))	
Knows(John,x)	Knows(x,OJ)	

Unification

- $\text{Unify}(\alpha, \beta) = \theta$ if $\alpha\theta = \beta\theta$

p	q	θ
Knows(John,x)	Knows(John,Jane)	{x/Jane}
Knows(John,x)	Knows(y,OJ)	{x/OJ,y/John}
Knows(John,x)	Knows(y,Mother(y))	{y/John,x/Mother(John)}
Knows(John,x)	Knows(x,OJ)	

Unification

- $\text{Unify}(\alpha, \beta) = \theta$ if $\alpha\theta = \beta\theta$

p	q	θ
Knows(John,x)	Knows(John,Jane)	{x/Jane}
Knows(John,x)	Knows(y,OJ)	{x/OJ,y/John}
Knows(John,x)	Knows(y,Mother(y))	{y/John,x/Mother(John)}
Knows(John,x)	Knows(x,OJ)	{fail}

Can be avoided by **standardizing apart**: eliminate overlap of variables, e.g., Knows(z,OJ)

Unification

- To unify $\text{Knows}(\text{John}, x)$ and $\text{Knows}(y, z)$,
 $\theta = \{y/\text{John}, x/z\}$ or $\theta = \{y/\text{John}, x/\text{John}, z/\text{John}\}$
 - The first unifier is more general than the second.
- There is a single **most general unifier** (MGU) that is unique up to renaming of variables.
 - $\text{MGU} = \{y/\text{John}, x/z\}$

FOL Inference

- Horn logic (the FOL case)
 - Forward chaining
 - Backward chaining
- General FOL
 - Resolution

Horn clauses in FOL

- $p_1 \wedge p_2 \wedge \dots \wedge p_n \Rightarrow q$
 - p_1, p_2, \dots, p_n, q are atomic sentences
 - All variables assumed to be universally quantified
- E.g., $human(x) \Rightarrow mortal(x)$

Generalized Modus Ponens (GMP)

$$\frac{p_1', p_2', \dots, p_n', (p_1 \wedge p_2 \wedge \dots \wedge p_n \Rightarrow q)}{q\theta} \quad \text{where } p_i'\theta = p_i \theta \text{ for all } i$$

Example: **King(John), Greedy(y), (King(x) \wedge Greedy(x) \Rightarrow Evil(x))**

p_1' is *King(John)* p_1 is *King(x)*

p_2' is *Greedy(y)* p_2 is *Greedy(x)*

Therefore, θ is $\{x/\text{John}, y/\text{John}\}$

q is *Evil(x)*, so $q\theta$ is ***Evil(John)***

Example knowledge base

- The US law says that it is a crime for an American to sell weapons to hostile nations. The country Nono, an enemy of America, has some missiles, and all of its missiles were sold to it by Colonel West, who is American.
- Prove that Col. West is a criminal

Example knowledge base contd.

... it is a crime for an American to sell weapons to hostile nations:

$American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$

Nono ... has some missiles, i.e., $\exists x Owns(Nono,x) \wedge Missile(x)$:

$Owns(Nono,M_1)$ and $Missile(M_1)$

... all of its missiles were sold to it by Colonel West

$Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$

Missiles are weapons:

$Missile(x) \Rightarrow Weapon(x)$

An enemy of America counts as "hostile":

$Enemy(x,America) \Rightarrow Hostile(x)$

West, who is American ...

$American(West)$

The country Nono, an enemy of America ...

$Enemy(Nono,America)$

Forward chaining proof

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$

American(West)

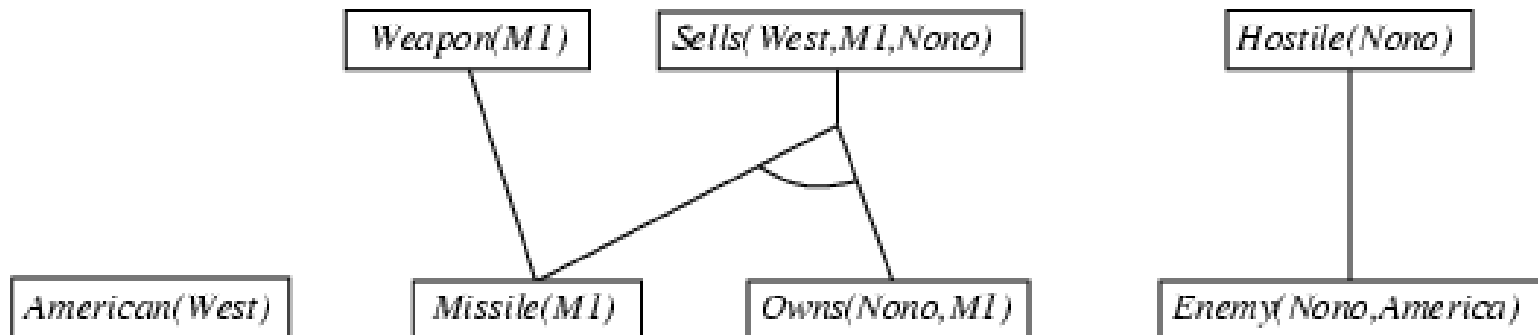
Missile(M1)

Owns(Nono,M1)

Enemy(Nono,America)

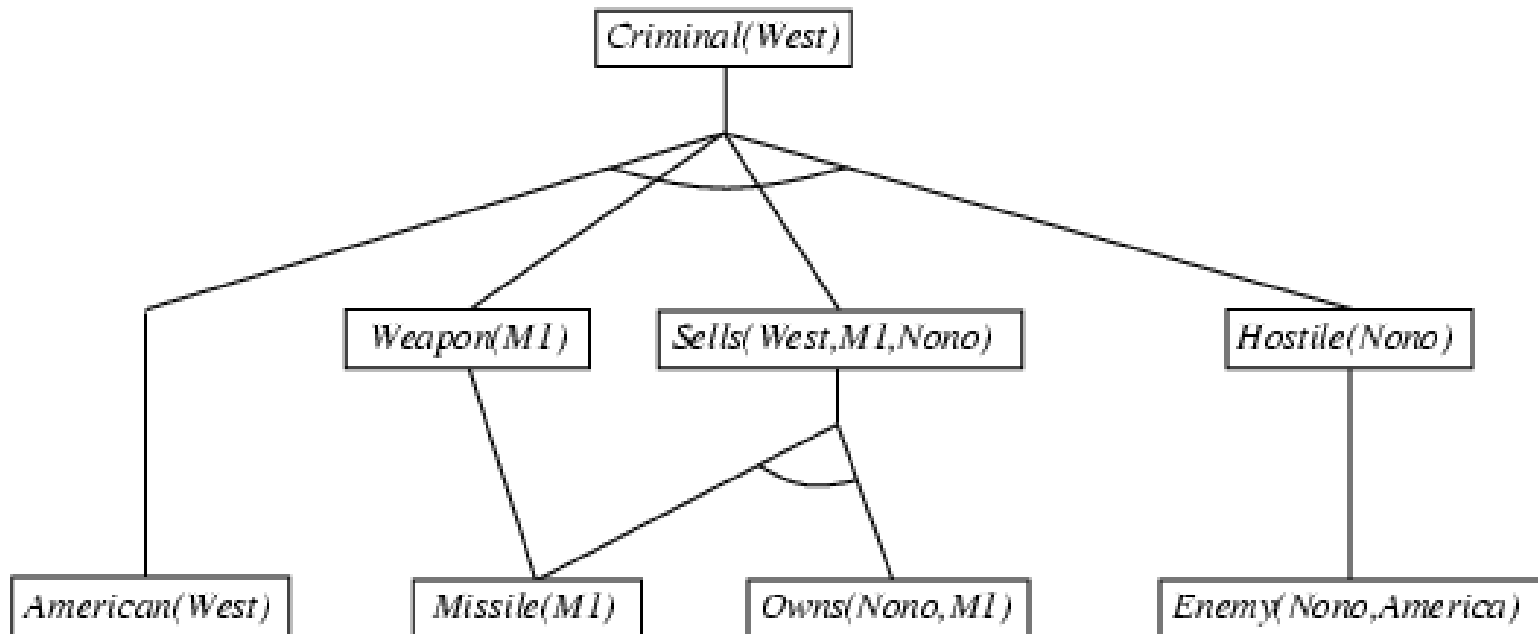
Forward chaining proof

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



Forward chaining proof

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



Properties of forward chaining

- Sound and complete for first-order Horn clauses
- FC terminates for first-order Horn clauses with **no functions** (Datalog) in finite number of iterations
- In general, FC may not terminate if α is not entailed
 - This is unavoidable: entailment with Horn clauses is also semi-decidable

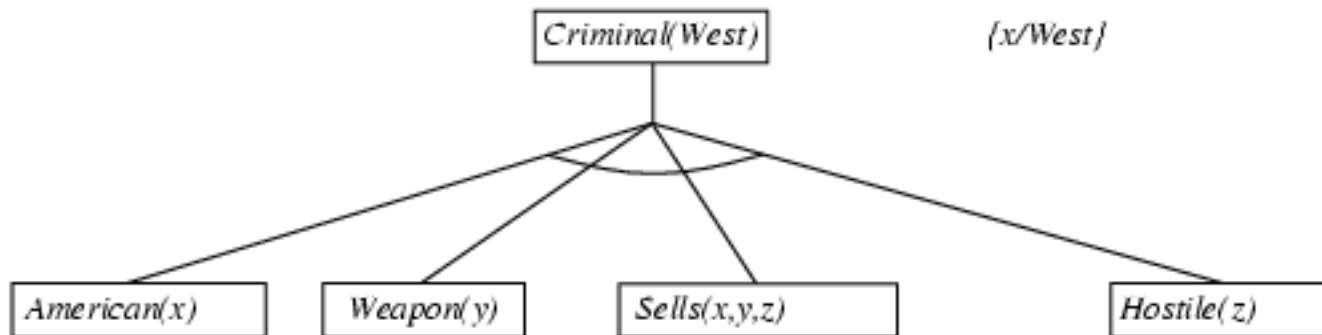
Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$

$Criminal(West)$

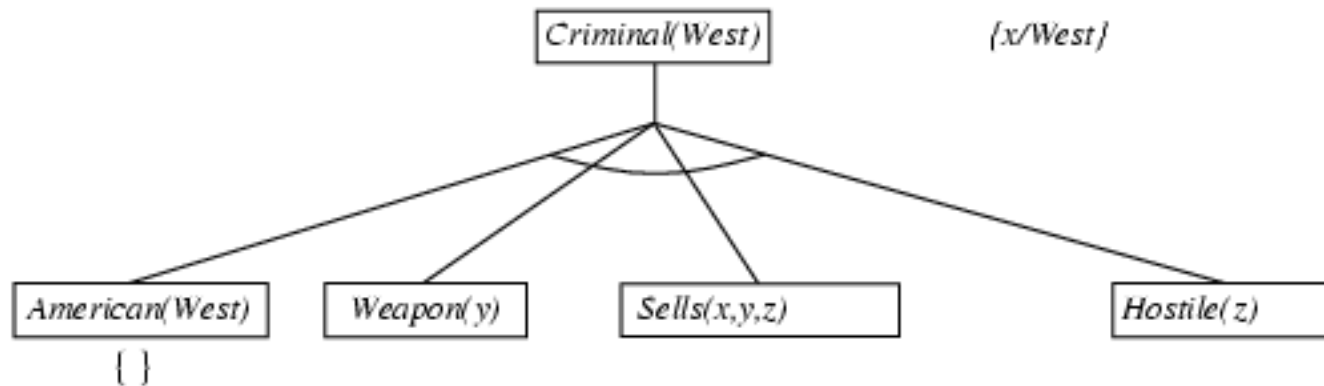
Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



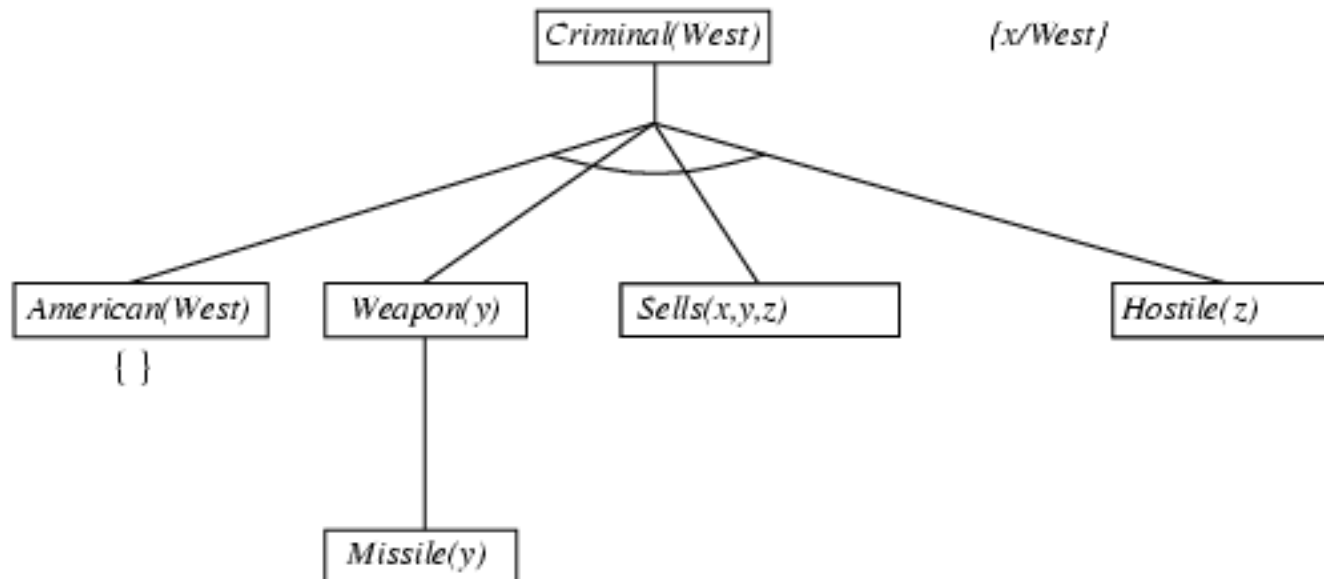
Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



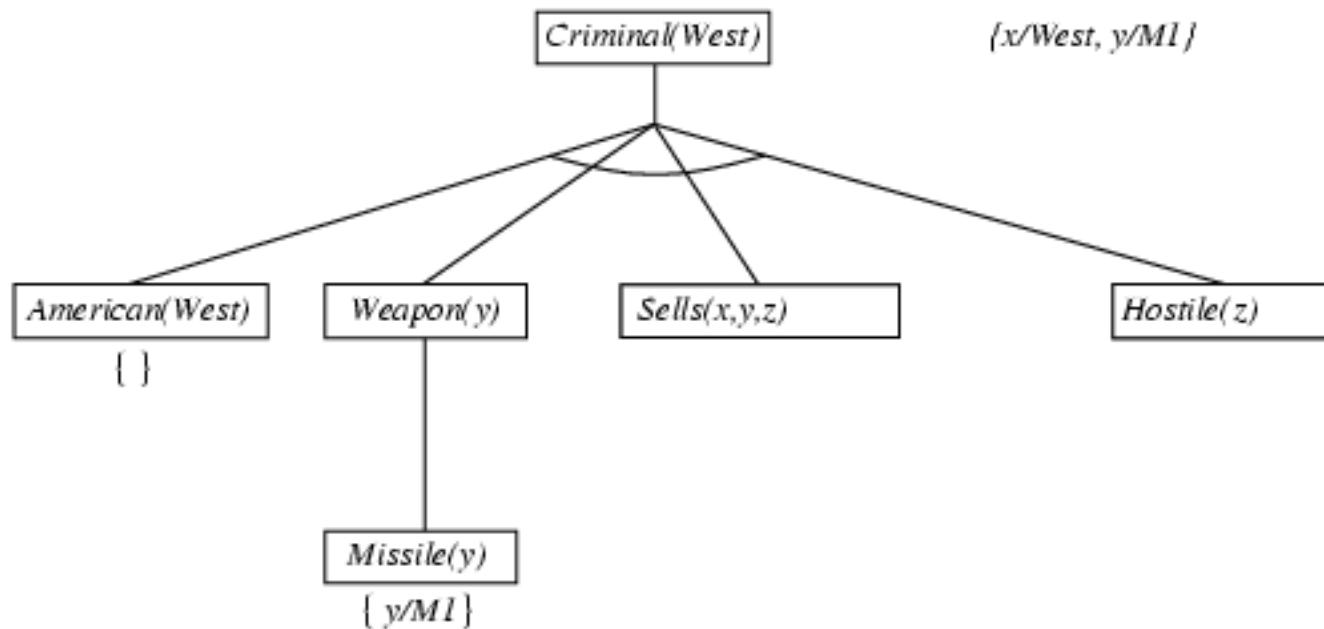
Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



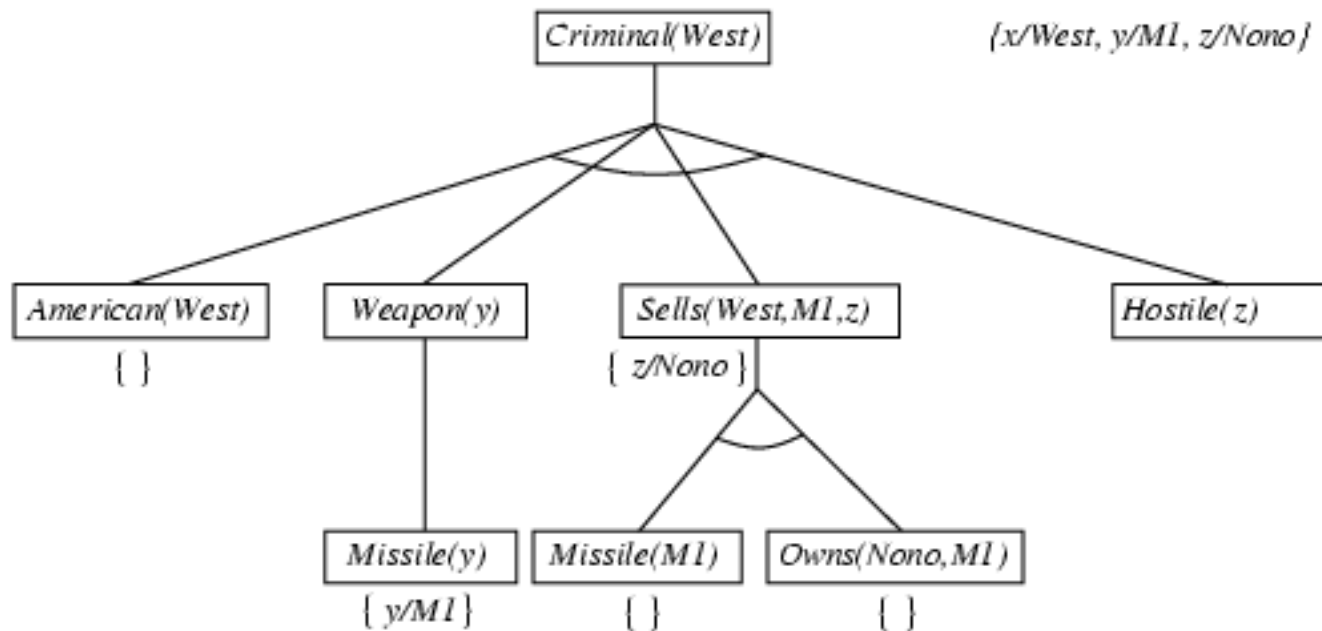
Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



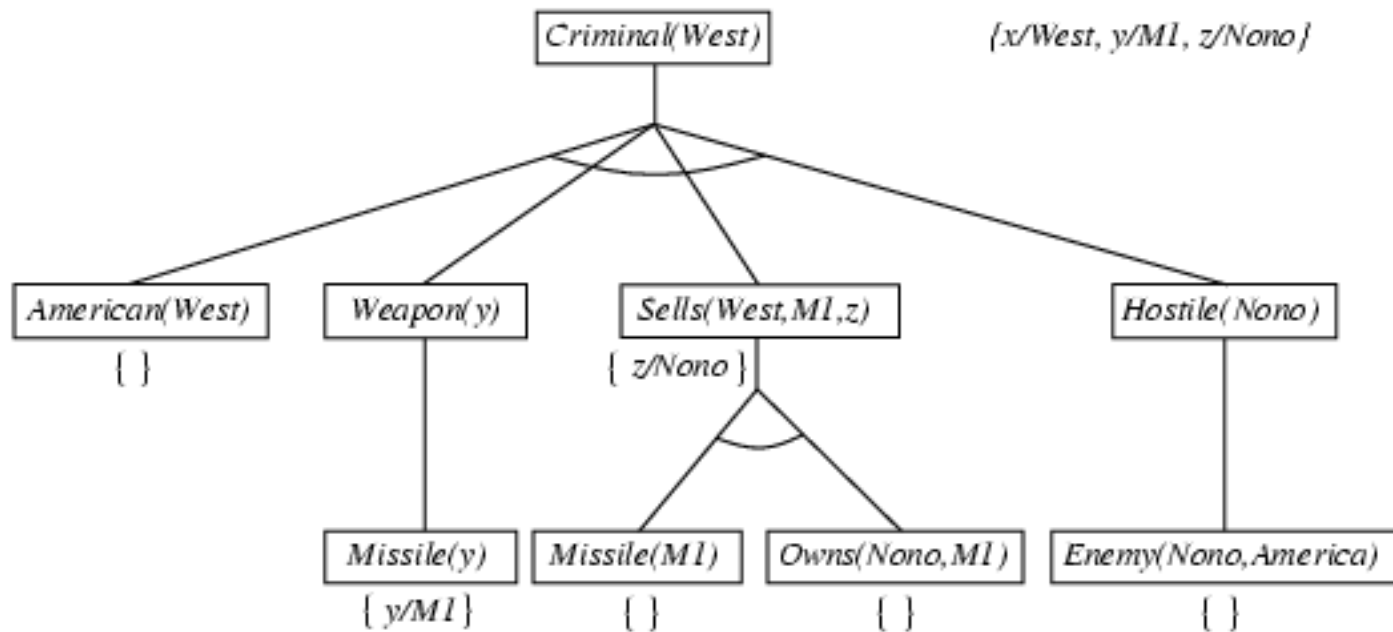
Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



Backward chaining example

- $American(x) \wedge Weapon(y) \wedge Sells(x,y,z) \wedge Hostile(z) \Rightarrow Criminal(x)$
- $Missile(x) \wedge Owns(Nono,x) \Rightarrow Sells(West,x,Nono)$
- $Missile(x) \Rightarrow Weapon(x)$
- $Enemy(x,America) \Rightarrow Hostile(x)$
- $Owns(Nono,M_1), Missile(M_1), American(West), Enemy(Nono,America)$



Backward chaining

- Depth-first recursive proof search: space is linear in size of proof
- Avoid infinite loops by checking current goal against every goal on stack
- Avoid repeated subgoals by caching previous results
- Widely used for [logic programming](#)

Logic programming

- Ordinary programming
 - Identify problem
 - Assemble information
 - Figure out solution
 - Encode solution
 - Encode problem instance as data
 - Apply program to data
- Logic programming
 - Identify problem
 - Assemble information
 - **<coffee break>** 😊
 - Encode info in KB
 - Encode problem instances as facts
 - Ask queries (run SAT solver)

Logic programming: Prolog

- Was widely used in Europe, Japan (basis of 5th Generation project)
- Basis: backward chaining with Horn clauses
 - Program = set of Horn clauses
 - Inference: depth-first, left-to-right backward chaining
- Additions:
 - Built-in predicates for arithmetic etc., e.g., $X \text{ is } Y * Z + 3$
 - Built-in predicates that have side effects (e.g., input and output predicates, assert/retract predicates)
- Closed-world assumption ("negation as failure")

Resolution

- Full first-order version:

$$\frac{\ell_1 \vee \dots \vee \ell_k, \quad m_1 \vee \dots \vee m_n}{(\ell_1 \vee \dots \vee \ell_{i-1} \vee \ell_{i+1} \vee \dots \vee \ell_k \vee m_1 \vee \dots \vee m_{j-1} \vee m_{j+1} \vee \dots \vee m_n)\theta}$$

where $\text{Unify}(\ell_i, \neg m_j) = \theta$.

- The two clauses are assumed to be standardized apart so that they share no variables.

- Example:

$$\frac{\neg \text{Rich}(x) \vee \text{Unhappy}(x) \quad \text{Rich}(\text{Ken})}{\text{Unhappy}(\text{Ken})}$$

with $\theta = \{x/\text{Ken}\}$

- Inference algorithm: applying resolution steps to $\text{CNF}(\text{KB} \wedge \neg \alpha)$
- Resolution is sound and complete for FOL

Conversion to CNF

$$\forall x [\forall y \text{ Animal}(y) \Rightarrow \text{Loves}(x,y)] \Rightarrow [\exists y \text{ Loves}(y,x)]$$

1. Eliminate biconditionals and implications

$$\forall x [\neg \forall y \neg \text{Animal}(y) \vee \text{Loves}(x,y)] \vee [\exists y \text{ Loves}(y,x)]$$

2. Move \neg inwards: $\neg \forall x p \equiv \exists x \neg p$, $\neg \exists x p \equiv \forall x \neg p$

$$\forall x [\exists y \neg(\neg \text{Animal}(y) \vee \text{Loves}(x,y))] \vee [\exists y \text{ Loves}(y,x)]$$

$$\forall x [\exists y \neg \neg \text{Animal}(y) \wedge \neg \text{Loves}(x,y)] \vee [\exists y \text{ Loves}(y,x)]$$

$$\forall x [\exists y \text{ Animal}(y) \wedge \neg \text{Loves}(x,y)] \vee [\exists y \text{ Loves}(y,x)]$$

3. Standardize variables: each quantifier should use a different variable

$$\forall x [\exists y \text{ Animal}(y) \wedge \neg \text{Loves}(x,y)] \vee [\exists z \text{ Loves}(z,x)]$$

Conversion to CNF contd.

$$\forall x [\exists y \text{ Animal}(y) \wedge \neg \text{Loves}(x,y)] \vee [\exists z \text{ Loves}(z,x)]$$

4. Skolemize: a more general form of existential instantiation. Each existential variable is replaced by a Skolem function of the enclosing universally quantified variables:

$$\forall x [\text{Animal}(F(x)) \wedge \neg \text{Loves}(x,F(x))] \vee \text{Loves}(G(x),x)$$

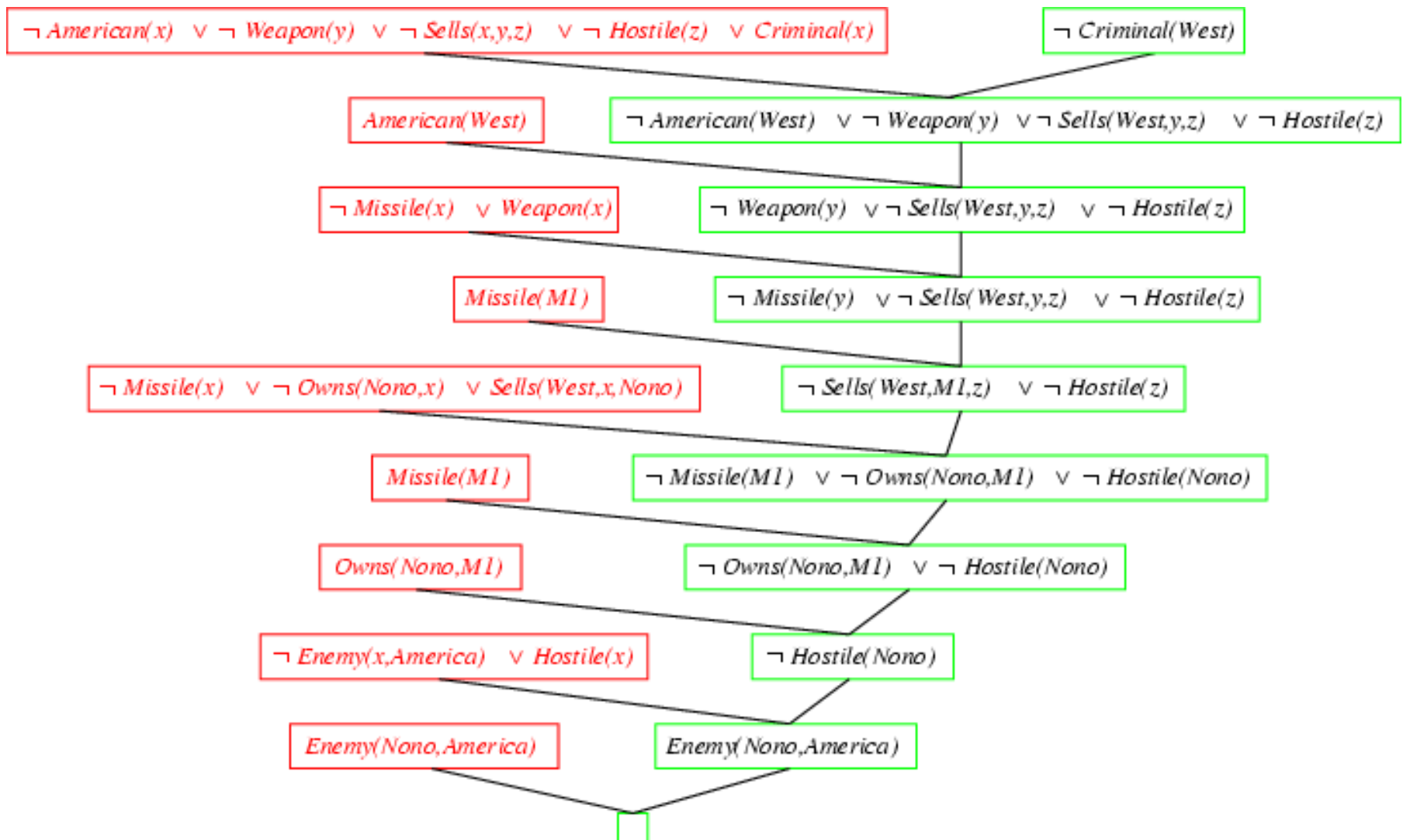
5. Drop universal quantifiers:

$$[\text{Animal}(F(x)) \wedge \neg \text{Loves}(x,F(x))] \vee \text{Loves}(G(x),x)$$

6. Distribute \vee over \wedge :

$$[\text{Animal}(F(x)) \vee \text{Loves}(G(x),x)] \wedge [\neg \text{Loves}(x,F(x)) \vee \text{Loves}(G(x),x)]$$

Resolution proof: Horn clauses



Semantic Web: Application of Logic to WWW



MORE ACM AWARDS



Search

TYPE HERE



A.M. TURING AWARD WINNERS BY...

ALPHABETICAL LISTING

YEAR OF THE AWARD

RESEARCH SUBJECT



Inventor of World Wide Web Receives ACM A.M. Turing Award

Sir Tim Berners-Lee Designed Integrated Architecture and Technologies that Underpin the Web

ACM named Sir Tim Berners-Lee, a Professor at Massachusetts Institute of Technology and the University of Oxford, the recipient of the 2016 ACM A.M. Turing Award. Berners-Lee was cited for

The Semantic Web

Since the late 1990s Berners-Lee's primary focus has been on trying to get Web publishers and technology companies to add a set of capabilities he called the "Semantic Web." Berners-Lee defined his idea as follows: "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."

commerce, and perform many other important activities.

The ACM Turing Award, often referred to as the "Nobel Prize of

FEATURED AWARD WINNER

Sir Tim Berners-Lee

For inventing the World Wide Web, the first web browser, and the fundamental protocols and algorithms allowing the Web to scale.

More on Sir Tim Berners-Lee and his work can be found [here](#).

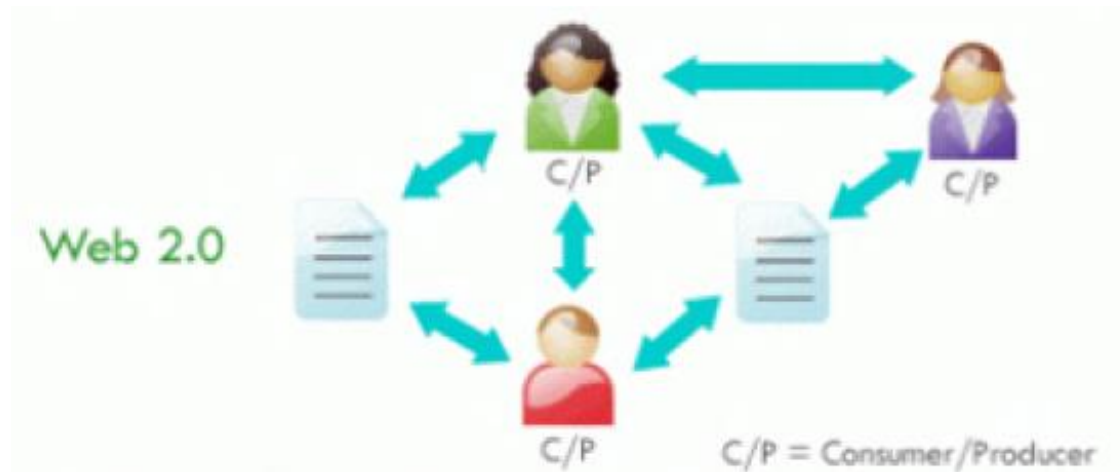
Web 1.0

- Information flows from providers to consumers
 - The majority of WWW users are consumers
 - Webpages are static and read-only



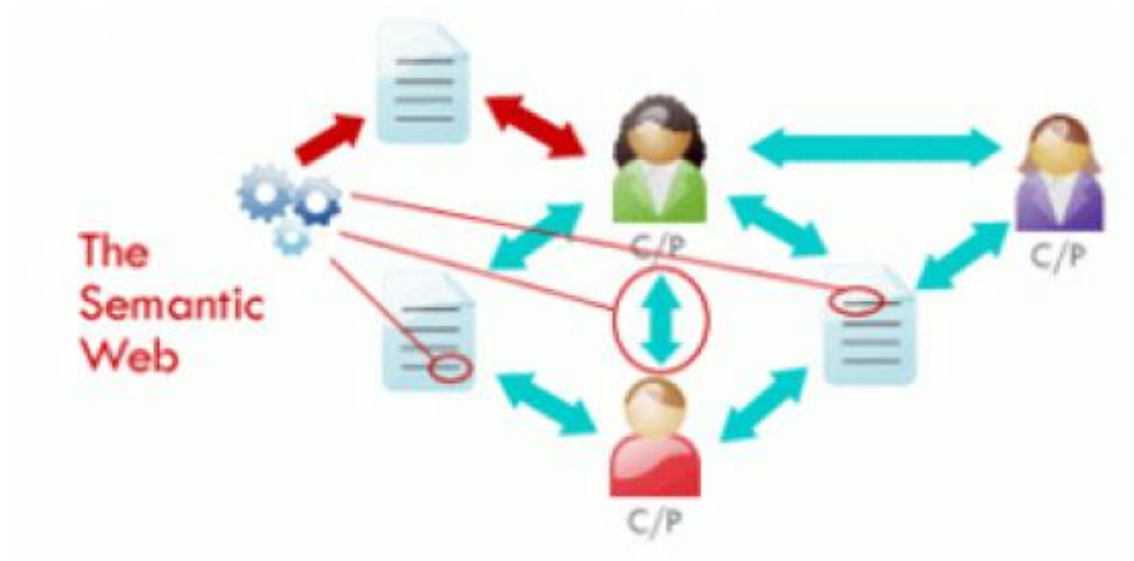
Web 2.0

- WWW users are both providers and consumers
 - Webpages are dynamic and interactive



Web 3.0 (Semantic Web)

- Computers mediate the information flow, helping users publish and acquire data
 - Semantic annotations (i.e., logic sentences) on data that can be understood and processed by computers
 - (Semantic Web is **Symbolic AI** applied to **WWW**)



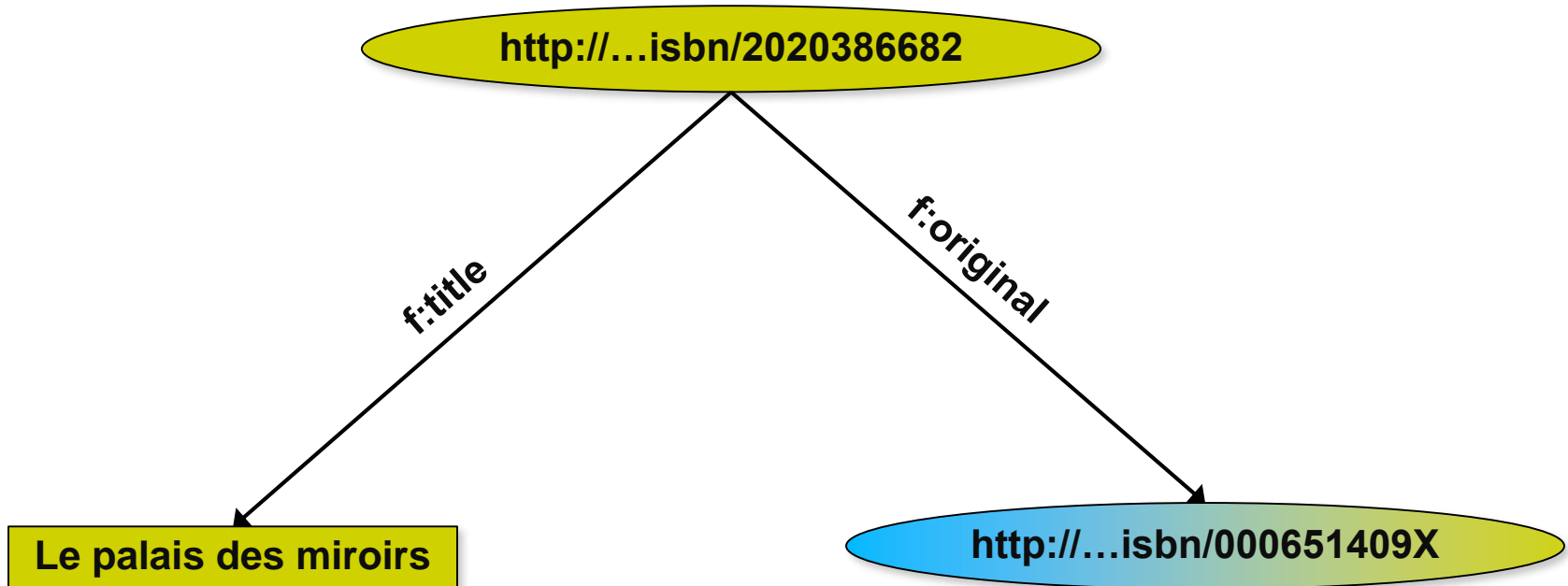
RDF

- RDF (Resource Description Framework)
 - The basic language of semantic web
 - RDF represents information with triples:
 - RDF Triple (s,p,o)
 - s/p/o: “subject”, “property”, and “object”
 - s and p are URIs
 - o is a URI or literal
 - URI (Uniform Resource Identifier): a unique string of characters used to identify a resource
- atomic sentence in FOL
- binary predicate in FOL
- constant in FOL

(`<http://...isbn...6682>`, `<http://.../title>`, `Le palais des miroirs`)

- RDF triples form a directed, labeled graph

Example

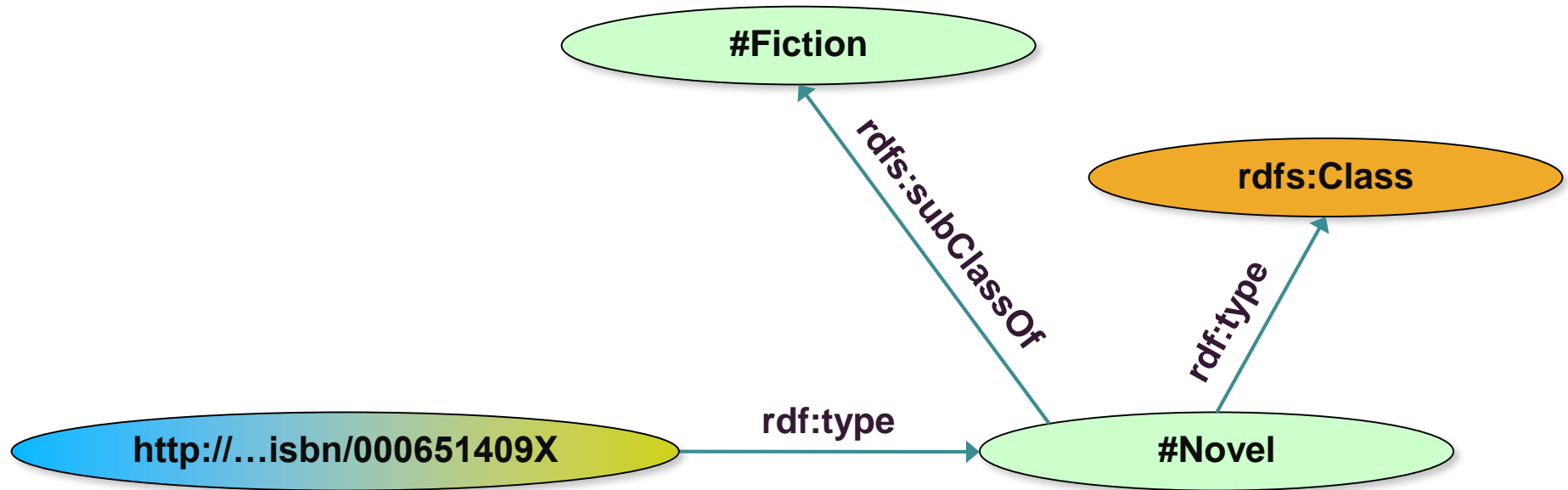


```
<rdf:Description rdf:about="http://.../isbn/2020386682">  
  <f:title xml:lang="fr">Le palais des miroirs</f:title>  
  <f:original rdf:resource="http://.../isbn/000651409X"/>  
</rdf:Description>
```

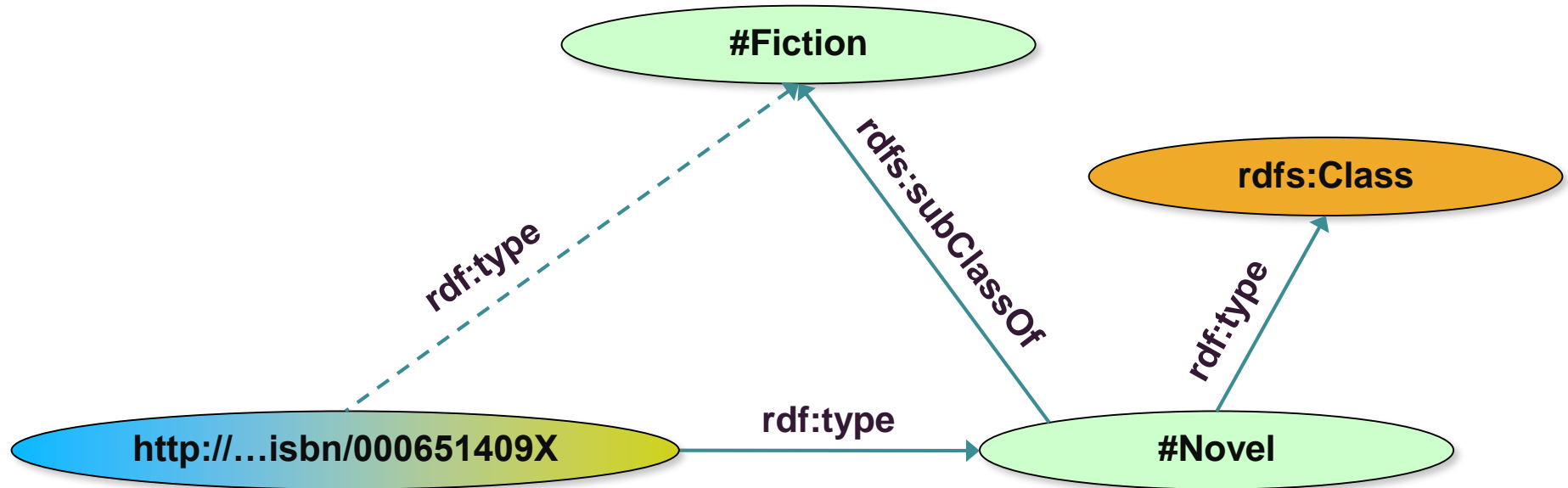
RDFS

- RDFS (RDF Schema) is used to specify the **ontology** (a set of constants and predicates)
 - “rdfs:Class”: a collection of resources
 - novel, fiction, ...
 - “rdf:type”: an individual belongs to a specific class
 - “«http://.../000651409X» is a novel”
 - “rdfs:subClassOf”: all instances of one are also the instances of the other
 - “every novel is a fiction”
 - rdfs:domain, rdfs:range, rdfs:subPropertyOf, etc.

Classes, Resources, ...



Inference



```
(<http://.../isbn/000651409X> rdf:type #Fiction)
```

New triples can be inferred from RDFS rules!

Inference

- The RDF Semantics document has a list of (33) inference rules:
 - “if such and such triples are in the graph, add this and this”

```
If:  
  uuu rdfs:subClassOf xxx .  
  vvv rdf:type uuu .  
Then add:  
  vvv rdf:type xxx .
```

- Can do that recursively until the graph does not change
 - *Forward chaining!*

OWL

- OWL (Web Ontology Language)
 - relies on RDF Schemas
 - a lot of extensions based on **description logic** (DL)
 - DL: more expressive than PL, less so than FOL
 - can be used to represent:
 - Term equivalences
 - Characterization of properties (e.g., symmetric, transitive)
 - Disjointness of classes
 - Construct classes by intersection, union, complement
 - Construct classes by restricting property values
 - etc.

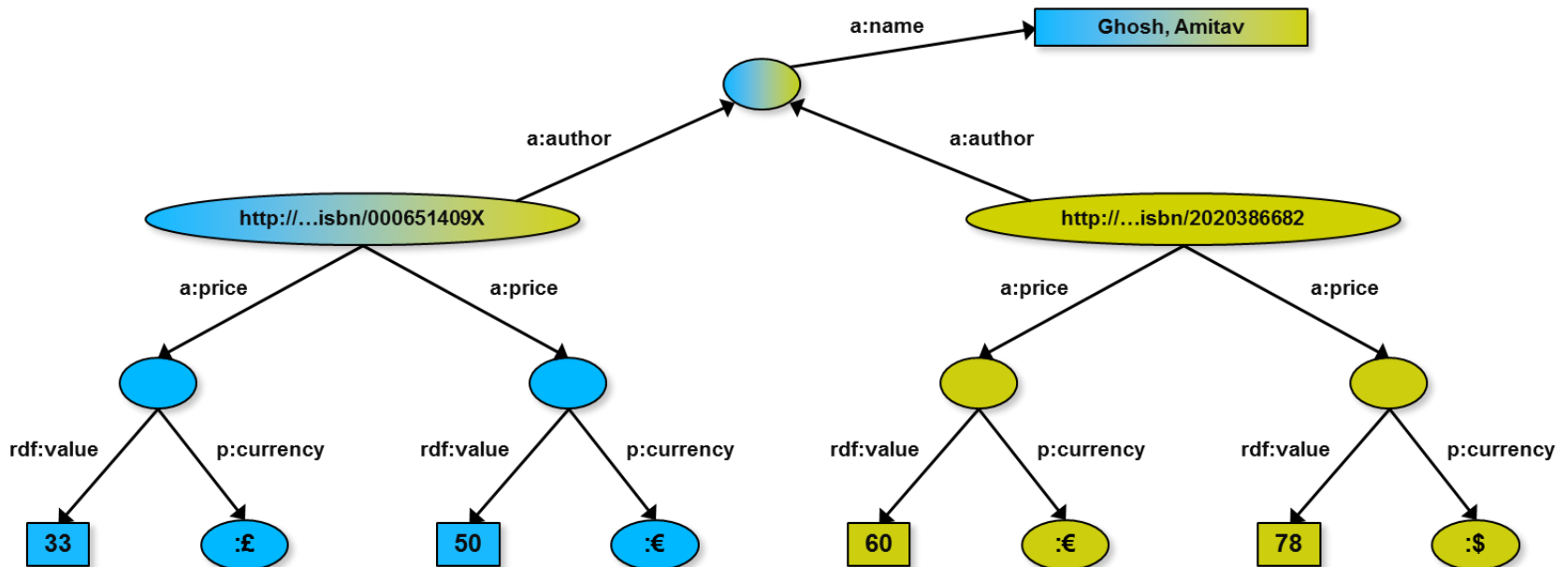
Querying RDF data

- In practice, complex queries into RDF data are needed
 - ▶ E.g., “give me (a,b) pairs for which there is an x such that (x parent a) and (b brother x) holds” (i.e., return the uncles)
- SPARQL (SPARQL Protocol and RDF Query Language)
 - Analogous to SQL for relational database

Example

```
SELECT ?isbn ?price ?currency
WHERE {
    ?isbn a:price ?x.
    ?x rdf:value ?price.
    ?x p:currency ?currency. }
```

- Returns: [<...409X>,33,:£], [<...409X>,50,:€]
[<...6682>,60,:€], [<...6682>,78,:\$]



[http://www.bbc.co.uk/nature/life/Equus_\(genus\)](http://www.bbc.co.uk/nature/life/Equus_(genus))

BBC News Sport Weather Shop Earth Travel More Search

NATURE WILDLIFE

Home | News | Features | Video collections | **Wildlife** | Prehistoric life | Places | FAQs

Life > Animals > Mammals > Horses, donkeys and zebras

Horses, donkeys and zebras

From our own domestic horses to the iconic black and white striped zebras that roam wild on **plains and savannahs**, horses, asses and zebras are familiar to most of us. There are three species of zebra and three species of wild ass. There is just one species of **horse**, and that encompasses the domestic horse.

They all have a robust and sturdy appearance, long necks and a mane. Their long heads have moveable ears that the animals can turn towards and effectively localise sound. Each of their limbs ends in a vitally important hoof that encases and protects a single toe. Horses, asses and zebras are usually **social** animals, living in either permanent or temporary herds on open terrains.


Scientific name: Equus
Rank: **Genus**



Carol Walker / naturepl.com1



Introduction



Sheriff's office
Africa
A solitary Grevy's zebra stallion sees off a posse of young males.

Explore this group



Classification

Life
Animals
Vertebrates
Mammals
Odd-toed ungulates
Equidae

Find wildlife

Search for your favourite wildlife

Elsewhere on the web

• [Animal Diversity Web](#)

[http://www.bbc.co.uk/nature/life/Equus_\(genus\).rdf](http://www.bbc.co.uk/nature/life/Equus_(genus).rdf)

```

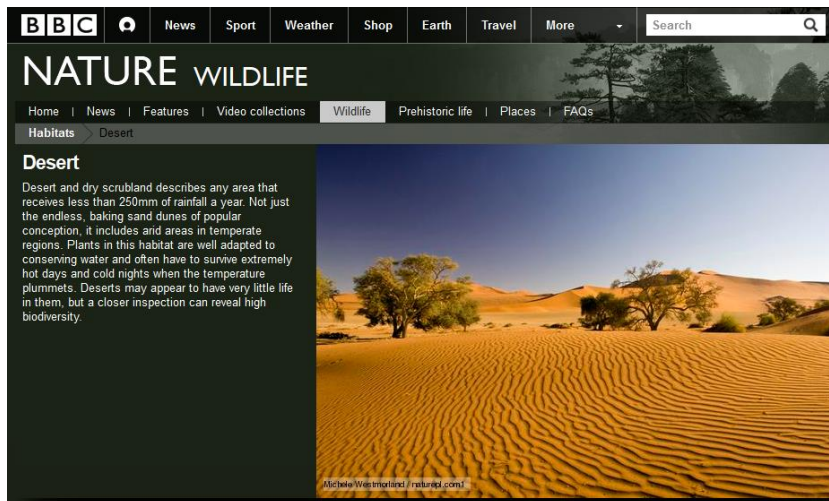
- <rdf:RDF>
- <rdf:Description rdf:about="/nature/genus/Equus_(genus)">
  <foaf:primaryTopic rdf:resource="/nature/genus/Equus_(genus)#genus"/>
  <rdfs:seeAlso rdf:resource="/nature/genus"/>
</rdf:Description>
- <wo:Genus rdf:about="/nature/life/Equus_(genus)#genus">
  <rdfs:label>Horses, donkeys and zebras</rdfs:label>
  <wo:name rdf:resource="http://www.bbc.co.uk/nature/genus/Equus_(genus)#name"/>
  <foaf:depiction rdf:resource="http://ichef.bbci.co.uk/naturelibrary/images/ic/640x360/e/eq/equus_genus/equus_genus_1.jpg"/>
- <dc:description>
  From our own domestic horses to the iconic black and white striped zebras that roam wild on
  <a href="/nature/habitats/Temperate_grasslands%2C_savannas%2C_and_shrublands">plains and savannahs</a>
  , horses, asses and zebras are familiar to most of us. There are three species of zebra and three species of
  wild ass. There is just one species of
  <a href="/nature/life/Wild_horse">horse</a>
  , and that encompasses the domestic horse.
  <br/>
  <br/>
  They all have a robust and sturdy appearance, long necks and a mane. Their long heads have moveable ears
  that the animals can turn towards and effectively localise sound. Each of their limbs ends in a vitally
  important hoof that encases and protects a single toe. Horses, asses and zebras are usually
  <a href="/nature/adaptations/Presociality">social</a>
  animals, living in either permanent or temporary herds on open terrains.
</dc:description>
<owl:sameAs rdf:resource="http://dbpedia.org/resource/Equus_(genus)"/>
<wo:adaptation rdf:resource="/nature/adaptations/Hearing_(sense)#adaptation"/>
<wo:adaptation rdf:resource="/nature/adaptations/Herbivore#adaptation"/>
<wo:adaptation rdf:resource="/nature/adaptations/Parental_investment#adaptation"/>
<wo:adaptation rdf:resource="/nature/adaptations/Presociality#adaptation"/>

```

[http://www.bbc.co.uk/nature/life/Equus_\(genus\).rdf](http://www.bbc.co.uk/nature/life/Equus_(genus).rdf)

- Connects to other resources in the dataset

`Equus_(genus) wo:livesIn Deserts_and_xeric_shrublands`



www.bbc.co.uk/nature/habitats/Deserts_and_xeric_shrublands

Habitats

The following **habitats** are found across the Horses, donkeys and zebras distribution range. Find out more about these environments, what it takes to live there and what else inhabits them.



Desert



Temperate grassland

[www.bbc.co.uk/nature/life/Equus_\(genus\)](http://www.bbc.co.uk/nature/life/Equus_(genus))

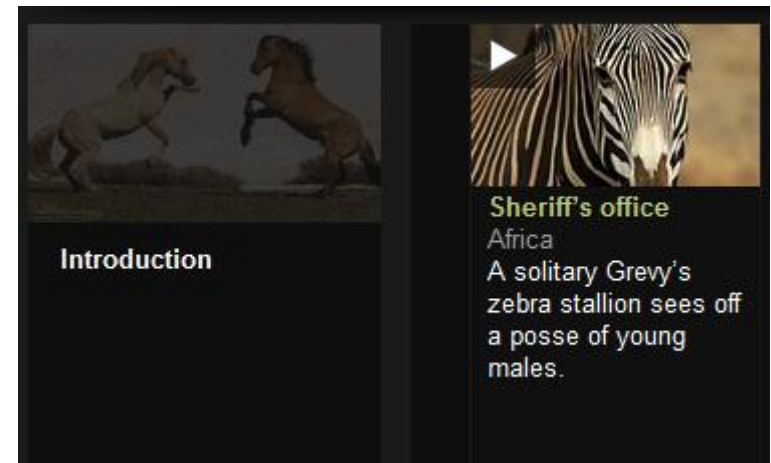
[http://www.bbc.co.uk/nature/life/Equus_\(genus\).rdf](http://www.bbc.co.uk/nature/life/Equus_(genus).rdf)

- Connects to resources in other BBC datasets

`Equus_(genus) po:Clip programmes/p014dcrj`



<http://www.bbc.co.uk/programmes/p014dcrj>

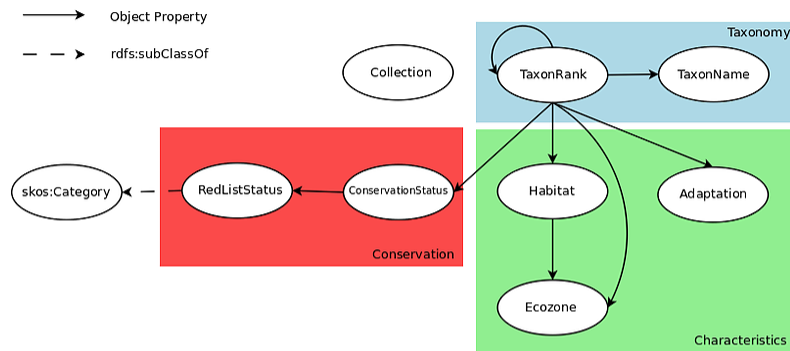


[www.bbc.co.uk/nature/life/Equus_\(genus\)](http://www.bbc.co.uk/nature/life/Equus_(genus))

BBC Wildlife Ontology

Ontology Diagram

The following diagram illustrates the relationships between the key classes in the ontology. A number of classes, e.g. sub classes of TaxonRank, Habitat and Adaptation have been omitted for clarity.



Ontology Terms

Automatically generated documentation for the ontology terms.

Classes

Adaptation	
URI	http://purl.org/ontology/wo/Adaptation
Description	An adaptation is any feature of an animal or plant which makes it better suited for a particular habitat or to do a particular task. For instance, being streamlined is an adaptation to swimming fast and being able to survive on very little water is an adaptation to life in the desert.
Subclasses	ExtremesAdaptation , BehaviouralPattern , CommunicationAdaptation , EcosystemRole , FeedingHabit , LifeCycle , LocomotionAdaptation , MorphologyAdaptation , PredationStrategy , ReproductionStrategy , SocialBehaviour , SurvivalStrategy
Properties	adaptation

Adapted to Extremes

Adapted to Extremes	
URI	http://purl.org/ontology/wo/ExtremesAdaptation
Description	Organisms that are adapted to extremes (known as Extremophiles) are organisms that thrives in and even may require physically or geochemically extreme conditions that are detrimental to the majority of life on Earth.
Superclasses	Adaptation

Animal Intelligence	
URI	http://purl.org/ontology/wo/AnimalIntelligence
Description	Animal Intelligence or animal cognition is the title given to a modern approach to the mental capacities of non-human animals. It has developed out of comparative psychology, but has also been strongly influenced by the approach of ethology, behavioral ecology, and evolutionary psychology.

Behavioural Pattern	
URI	http://purl.org/ontology/wo/BehaviouralPattern
Description	Behavioural pattern describes an animal's dominant way of life. Arboreal animals, for example, live in trees and nocturnal animals are active at night.
Superclasses	Adaptation

Class	
URI	http://purl.org/ontology/wo/Class
Description	A class is a scientific way to group related organisms together, some examples of classes being jellyfish, reptiles and sea urchins. Classes are big groups and contain within them smaller groupings called orders, families, genera and species.
Superclasses	TaxonRank
Properties	class

Collection	
URI	http://purl.org/ontology/wot/Collection
Description	A collection of resources, including documents, multimedia files, programme clips and their associated taxa, which aims to showcase a particular aspect of natural history film-making, or illustrate aspects of the natural world. A collection provides an alternate way to organize content over and above the basic taxonomic hierarchy.
Superclasses	http://purl.org/dc/dcmitype/Collection
Properties	collection

Communication Adaptation	
URI	http://purl.org/ontology/wo/CommunicationAdaptation

http://www.bbc.co.uk/ontologies

- 14 domain ontologies
 - Core Concepts Ontology
 - Programmes Ontology
 - Business News Ontology
 - Politics Ontology
 - Food Ontology
 - Sport Ontology
 - Wildlife Ontology
 -



The screenshot shows the BBC Ontologies website. At the top is the BBC logo and a navigation bar with links for News, Sport, Weather, Shop, Capital, Travel, and More. A search bar is located on the right. Below the navigation bar is a blue header with the word "ONTOLOGIES" in white. The main content area has a "Welcome" section followed by a paragraph explaining that the site provides access to ontologies used by BBC for its audience-facing applications, such as BBC Sport, BBC Education, BBC Music, and News projects. It mentions that these ontologies form the basis of the Linked Data Platform. Below this, there are two paragraphs: one stating that if you want to access an RDF Turtle version of an ontology, you should add .ttl to the end of the URL, and another stating that if you want to get in touch, you should email linkeddata@bbc.co.uk. The next section is titled "Basic Concepts" and explains that the ontologies are built incrementally according to current business requirements and are expected to evolve. It mentions that the BBC produces a plethora of rich and diverse content about the things that matter to its audiences, and that Linked Data gives an opportunity to connect content together through those topics. It also states that they use ontologies to describe the world around them, the content they create, and the management, storage, and sharing of these data within the Linked Data Platform. The final section is titled "Creative Works".

BBC

News Sport Weather Shop Capital Travel More

Search

ONTOLOGIES

Welcome

This site provides access to the ontologies the BBC is using to support its audience facing applications such as [BBC Sport](#), [BBC Education](#), [BBC Music](#), [News projects](#) and more. These ontologies form the basis of our Linked Data Platform.

If you would like to access an [RDF Turtle](#) version of an ontology, simply add .ttl to the end of an ontology URL.

If you would like to get in touch with us, please email linkeddata@bbc.co.uk.

You can also access the [mappings](#) of the terms we have defined in our ontologies to other, well known open vocabularies.

Basic Concepts

The ontologies are built incrementally according to current business requirements. They are all expected to evolve as our requirements evolve. The BBC produces a plethora of rich and diverse content about the things that matter to our audiences. Linked Data gives us an opportunity to connect content together through those topics. We use ontologies to describe the world around us, content the BBC creates, and the management, storage and sharing of these data within the Linked Data Platform.

Creative Works

Google Knowledge Graph

- Google uses a knowledge base to enhance its
 - search engine
 - personal assistant
 - smart speaker
- KB size
 - (2012) over 570 million objects and more than 18 billion facts
 - (2016) over 70 billion facts.



Thomas Jefferson
3rd U.S. President

Thomas Jefferson was an American Founding Father, the principal author of the Declaration of Independence, and the third President of the United States. [Wikipedia](#)

Born: April 13, 1743, Shadwell, VA
Died: July 4, 1826, Charlottesville, VA
Presidential term: March 4, 1801 – March 4, 1809
Spouse: [Martha Jefferson](#) (m. 1772–1782)
Party: [Democratic-Republican Party](#)
Awards: AIA Gold Medal

Get updates about Thomas Jefferson

People also search for [View 15+ more](#)

 John Adams	 George Washington	 Benjamin Franklin	 James Madison	 Alexander Hamilton
---	--	--	--	---

Summary

- First-order logic:
 - objects and relations are semantic primitives
 - syntax: constants, functions, predicates, quantifiers
- Inference
 - Unification
 - Forward/backward chaining
 - Resolution
- Semantic web
 - Application of predicate logic to WWW