First-Order Logic
Semantics & Inference

Review Chapters 8.3-8.5,

Read 9.1-9.2 (optional: 9.5)

Next Lecture

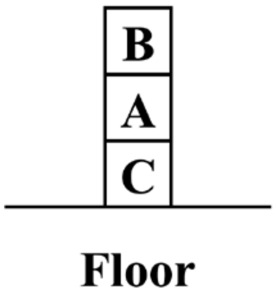
Read Chapters 13, 14.1-14.5

Semantics: Worlds

- The **world** consists of **objects** that have **properties**.
  - There are **relations** and **functions** between these objects
  - Objects in the world, individuals: people, houses, numbers, colors, baseball games, wars, centuries
    - Clock A, John, 7, the-house in the corner, Tel-Aviv
  - Functions on individuals:
    - father-of, best friend, third inning of, one more than
  - Relations:
    - brother-of, bigger than, inside, part-of, has color, occurred after
  - Properties (a relation of arity 1):
    - red, round, bogus, prime, multistoried, beautiful

Semantics: Interpretation

- An interpretation of a sentence (wff) is an assignment that maps
  - Object constants to objects in the worlds,
  - n-ary function symbols to n-ary functions in the world,
  - n-ary relation symbols to n-ary relations in the world
- Given an interpretation, an atomic sentence has the value "true" if it denotes a relation that holds for those individuals denoted in the terms. Otherwise it has the value "false"
  - Example: Block world:
    - A,B,C,floor, On, Clear
  - World:
  - On(A,B) is false, Clear(B) is true, On(C,Floor) is true…



Truth in first-order logic

- Sentences are true with respect to a model and an interpretation
- Model contains objects (domain elements) and relations among them
- Interpretation specifies referents for

  constant symbols → objects

  predicate symbols → relations

  function symbols → functional relations

- An atomic sentence *predicate*$(term_1, \ldots, term_n)$ is true iff the objects referred to by $term_1, \ldots, term_n$ are in the relation referred to by *predicate*

Review: Models (and in FOL, Interpretations)

- Models are formal worlds within which truth can be evaluated
- Interpretations map symbols in the logic to the world
  - Constant symbols in the logic map to objects in the world
  - n-ary functions/predicates map to n-ary functions/predicates in the world

- We say <u>*m* is a model given an interpretation i</u> of a sentence α if and only if α is true in the world *m* under the mapping *i.*

- *M(α)* is the set of all models of α

- Then KB $\models$ α iff $M(KB) \subseteq M(\alpha)$
  - E.g. *KB,* = "Mary is Sue's sister and Amy is Sue's daughter."
  - α = "Mary is Amy's aunt." (Must Tell it about mothers/daughters)

- <u>Think of KB and α as constraints, and models as states.</u>
- M(KB) are the solutions to KB and M(α) the solutions to α.
- Then, KB $\models$ α, i.e., $\models$ (KB $\Rightarrow$ a) ,
  when all solutions to KB are also solutions to α.

Semantics: Models and Definitions

- An interpretation and possible world **satisfies** a wff (sentence) if the wff has the value “true” under that interpretation in that possible world.

- Model: A domain and an interpretation that satisfies a wff is a **model** of that wff

- Validity: Any wff that has the value “true” in all possible worlds and under all interpretations is **valid.**

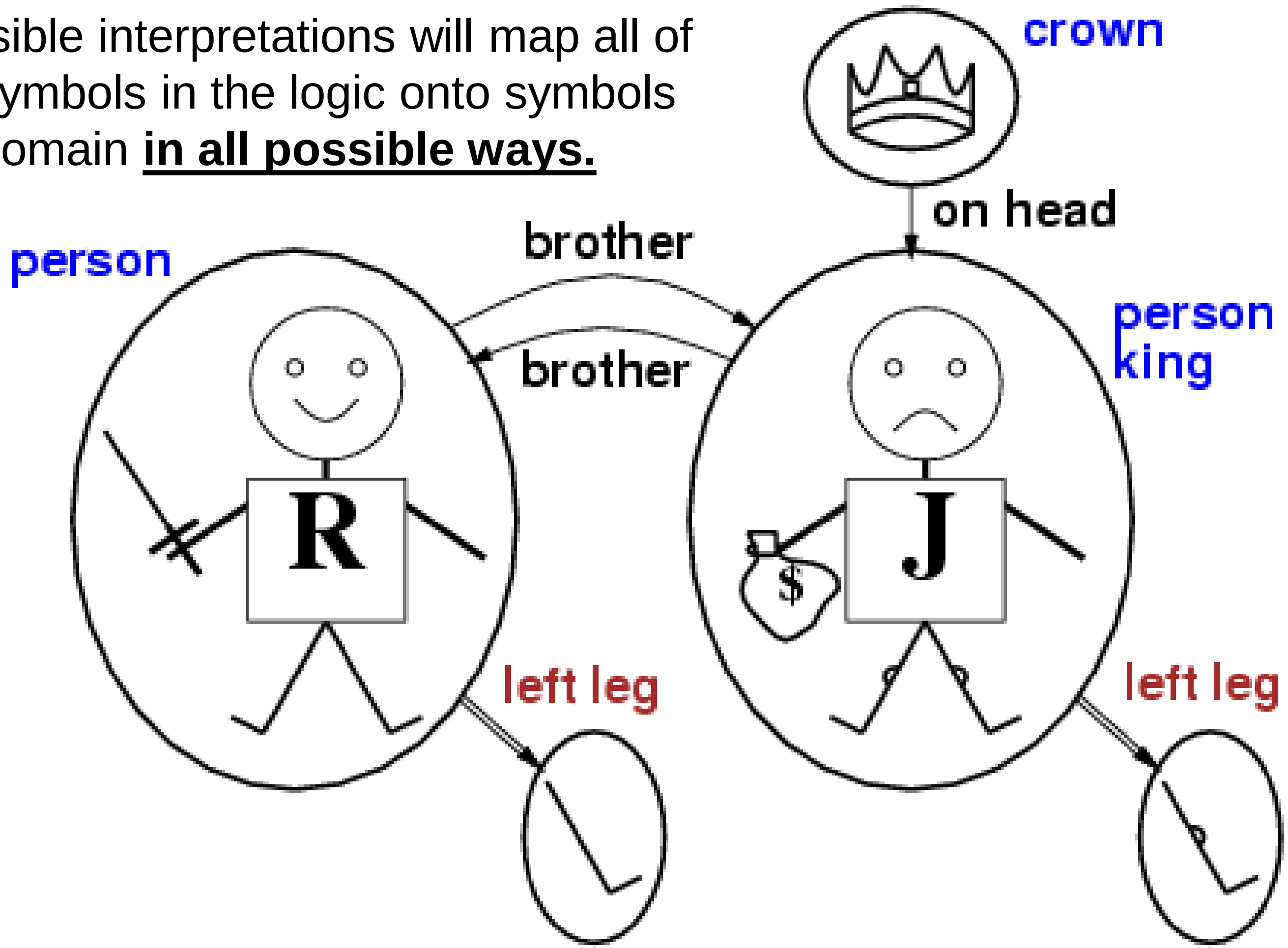
- Any wff that does not have a model under any interpretation is inconsistent or **unsatisfiable.**

- Any wff that is true in at least one possible world under at least one interpretation is **satisfiable**.

- If a wff w has a value true under all the models of a set of sentences KB then KB logically **entails** w.

Models for FOL: Example

All possible interpretations will map all of these symbols in the logic onto symbols in the domain **<u>in all possible ways.</u>**



An interpretation maps all symbols in KB onto matching symbols in a possible world. All possible interpretations gives a combinatorial explosion of mappings. Your job, as a Knowledge Engineer, is to write the axioms in KB so **<u>they are satisfied only under the intended interpretation in your own real world.</u>**

Summary of FOL Semantics

- A well-formed formula ("wff") FOL is true or false with respect to a world and an interpretation (a model).
- The world has objects, relations, functions, and predicates.
- The interpretation maps symbols in the logic to the world.
- The wff is true if and only if (iff) its assertion holds among the objects in the world under the mapping by the interpretation.
- Your job, as a Knowledge Engineer, is to write sufficient KB axioms that ensure that KB is true in your own real world under your own intended interpretation.
  - **The KB axioms must rule out other worlds and interpretations.**

Conversion to CNF

- Everyone who loves all animals is loved by someone:

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

1. Eliminate biconditionals and implications

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

2. Move $\neg$ inwards:

$$\neg\forall x\ p \equiv \exists x\ \neg p,\quad \neg\exists x\ p \equiv \forall x\ \neg p$$

$$\forall x\ [\exists y\ \neg(\neg\mathit{Animal}(y) \lor \mathit{Loves}(x,y))] \lor [\exists y\ \mathit{Loves}(y,x)]$$
$$\forall x\ [\exists y\ \neg\neg\mathit{Animal}(y) \land \neg\mathit{Loves}(x,y)] \lor [\exists y\ \mathit{Loves}(y,x)]$$
$$\forall x\ [\exists y\ \mathit{Animal}(y) \land \neg\mathit{Loves}(x,y)] \lor [\exists y\ \mathit{Loves}(y,x)]$$

Conversion to CNF contd.

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

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

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

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

5. Drop universal quantifiers:

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

6. Distribute $\vee$ over $\wedge$:

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

Unification

- Recall: Subst(θ, p) = result of substituting θ into sentence p

- Unify algorithm: takes 2 sentences p and q and returns a unifier if one exists

  Unify(p,q) = θ   where Subst(θ, p) = Subst(θ, q)

- Example:
  p = Knows(John,x)
  q = Knows(John, Jane)

  Unify(p,q) = {x/Jane}

Unification examples

- simple example: query = Knows(John,x), i.e., who does John know?

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}

- Last unification fails: only because x can’t take values John and OJ at the same time
  - But we know that if John knows x, and everyone (x) knows OJ, we should be able to infer that John knows OJ

- Problem is due to use of same variable x in both sentences

- Simple solution: Standardizing apart eliminates overlap of variables, e.g., Knows(z,OJ)

Unification

- To unify *Knows(John,x)* and *Knows(y,z)*,

  θ = {y/John, x/z } or θ = {y/John, x/John, z/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.

  MGU = { y/John, x/z }

- General algorithm in Figure 9.1 in the text

Unification Algorithm

function UNIFY(x, y, θ) **returns** a substitution to make x and y identical
  inputs: x, a variable, constant, list, or compound expression
    y, a variable, constant, list, or compound expression
    θ, the substitution built up so far (optional, defaults to empty)

  if θ = failure **then return** failure
  else if $x = y$ **then return** θ
  else if VARIABLE?(x) **then return** UNIFY-VAR(x, y, θ)
  else if VARIABLE?(y) **then return** UNIFY-VAR(y, x, θ)
  else if COMPOUND?(x) **and** COMPOUND?(y) **then**
    return UNIFY(x.ARGS, y.ARGS, UNIFY(x.OP, y.OP, θ))
  else if LIST?(x) **and** LIST?(y) **then**
    return UNIFY(x.REST, y.REST, UNIFY(x.FIRST, y.FIRST, θ))
  else return failure

---

function UNIFY-VAR(var, x, θ) **returns** a substitution

  if $\{var/val\} \in \theta$ **then return** UNIFY(val, x, θ)
  else if $\{x/val\} \in \theta$ **then return** UNIFY(var, val, θ)
  else if OCCUR-CHECK?(var, x) **then return** failure
  else return add $\{var/x\}$ to θ

Figure 9.1 The unification algorithm. The algorithm works by comparing the structures of the inputs, element by element. The substitution θ that is the argument to UNIFY is built up along the way and is used to make sure that later comparisons are consistent with bindings that were established earlier. In a compound expression such as $F(A, B)$, the OP field picks out the function symbol F and the ARGS field picks out the argument list (A, B).

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    if θ = failure **then return** failure
    else if $x = y$ **then return** θ

If we have failed or succeeded, then fail or succeed.

    else if VARIABLE?(x) **then return** UNIFY-VAR(x, y, θ)
    else if VARIABLE?(y) **then return** UNIFY-VAR(y, x, θ)
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If we can unify a variable then do so.

---

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   else return add {var/x} to θ
```

If we already have bound variable *var* to a value, try to continue on that basis.

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There is an implicit assumption that “{var/val} ∈ θ”, if it succeeds, binds val to the value that allowed it to succeed,

that were established earlier. In a compound expression such as $F(A, B)$, the OP field picks out the function symbol F and the ARGS field picks out the argument list (A, B).

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If *var* occurs anywhere within *x*, then no substitution will succeed.

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Else, try to bind *var* to *x*, and recurse.

Figure 9.1 The unification algorithm. The algorithm works by comparing the structures of the inputs, element by element. The substitution θ that is the argument to UNIFY is built up along the way and is used to make sure that later comparisons are consistent with bindings that were established earlier. In a compound expression such as $F(A, B)$, the OP field picks out the function symbol F and the ARGS field picks out the argument list (A, B).

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  else if LIST?(x) **and** LIST?(y) **then**
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If a predicate/function, unify the arguments.

---

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   else return failure
```

If unifying arguments, unify the remaining arguments.

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function UNIFY-VAR(var, x, θ) returns a substitution

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  else if LIST?(x) and LIST?(y) then
     return UNIFY(x.REST, y.REST, UNIFY(x.FIRST, y.FIRST, θ))
  else return failure
```

Otherwise, fail.

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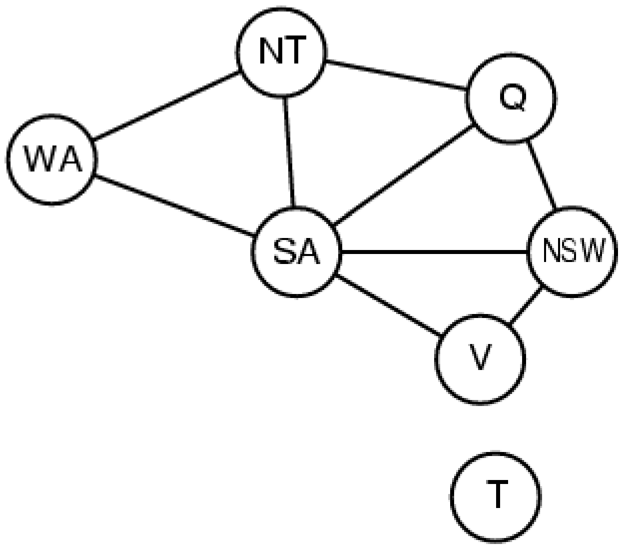
Hard matching example



$Diff(wa,nt) \wedge Diff(wa,sa) \wedge Diff(nt,q) \wedge$
$Diff(nt,sa) \wedge Diff(q,nsw) \wedge Diff(q,sa) \wedge$
$Diff(nsw,v) \wedge Diff(nsw,sa) \wedge Diff(v,sa) \Rightarrow$
$Colorable()$

Diff(Red,Blue) *Diff (Red,Green)*
Diff(Green,Red) *Diff(Green,Blue)*
Diff(Blue,Red) *Diff(Blue,Green)*

- To unify the grounded propositions with premises of the implication you need to solve a CSP!
- *Colorable*() is inferred iff the CSP has a solution
- CSPs include 3SAT as a special case, hence matching is NP-hard

Resolution: brief summary

- Full first-order version:

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

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

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

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

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

- Apply resolution steps to CNF(KB $\wedge \neg\alpha$); complete for FOL

Example knowledge base

- The 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 (Horn clauses)

... 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):

$Owns(Nono,M_1) \wedge Missile(M_1)$

... 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)*

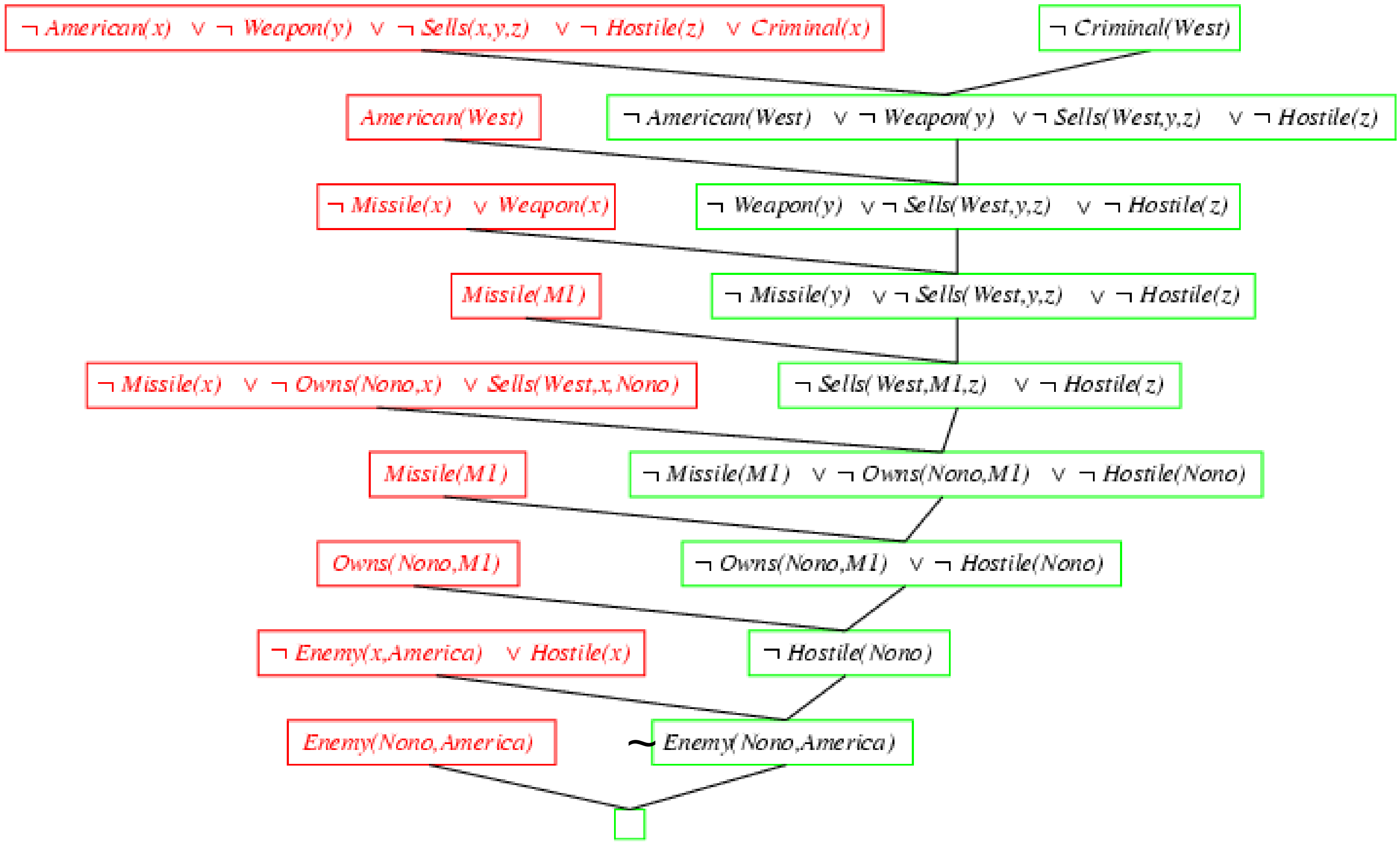
West, who is American ...

American(West)

The country Nono, an enemy of America ...

Enemy(Nono,America)

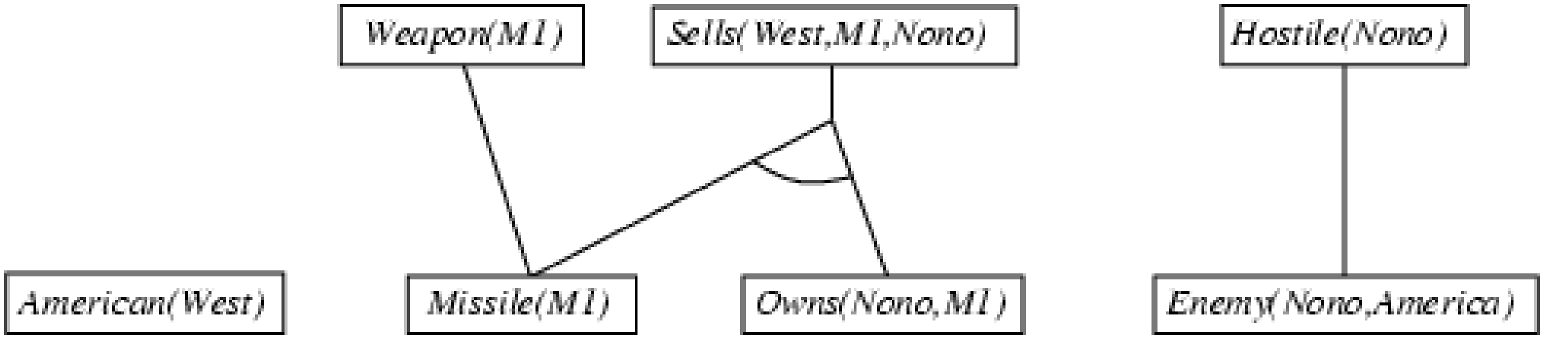
Resolution proof:



Forward chaining proof: (Horn clauses)

American(West)   *Missile(M1)*   *Owns(Nono,M1)*   *Enemy(Nono,America)*

Forward chaining proof (Horn clauses)

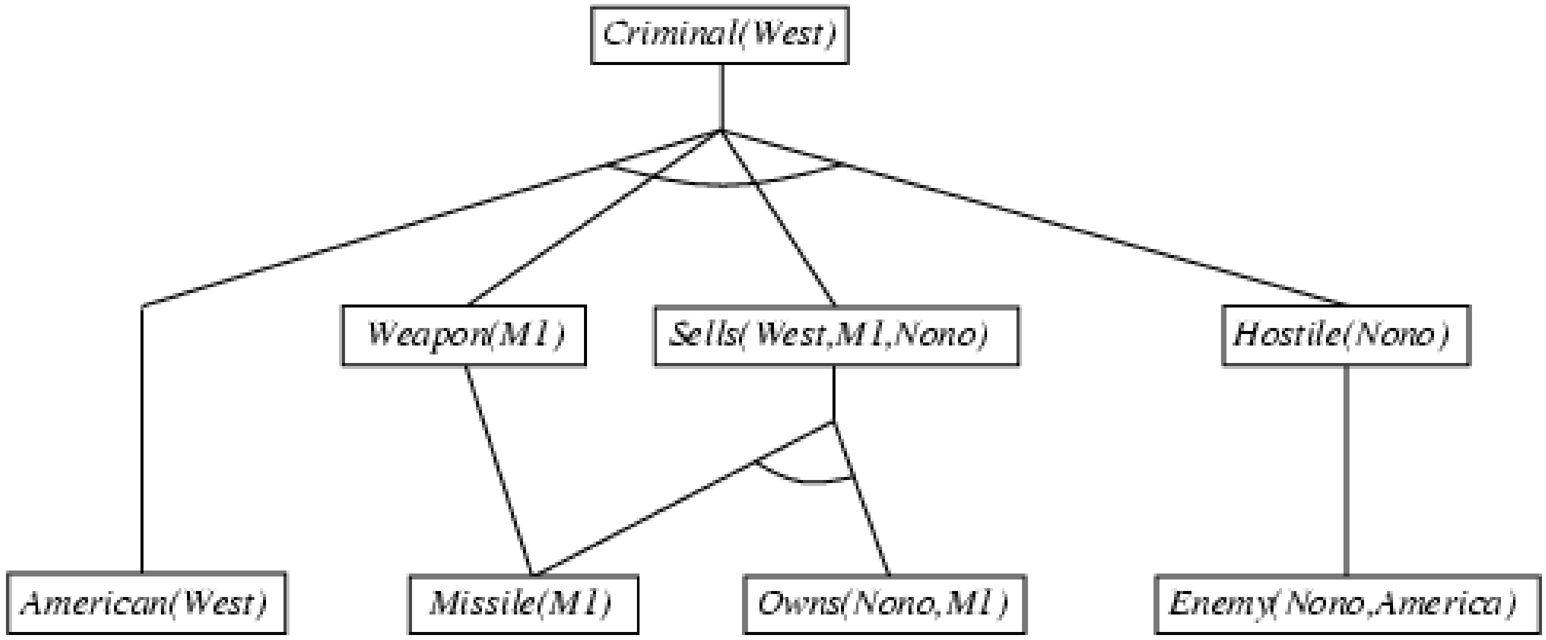


Enemy(x,America) $\Rightarrow$ *Hostile(x)*

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

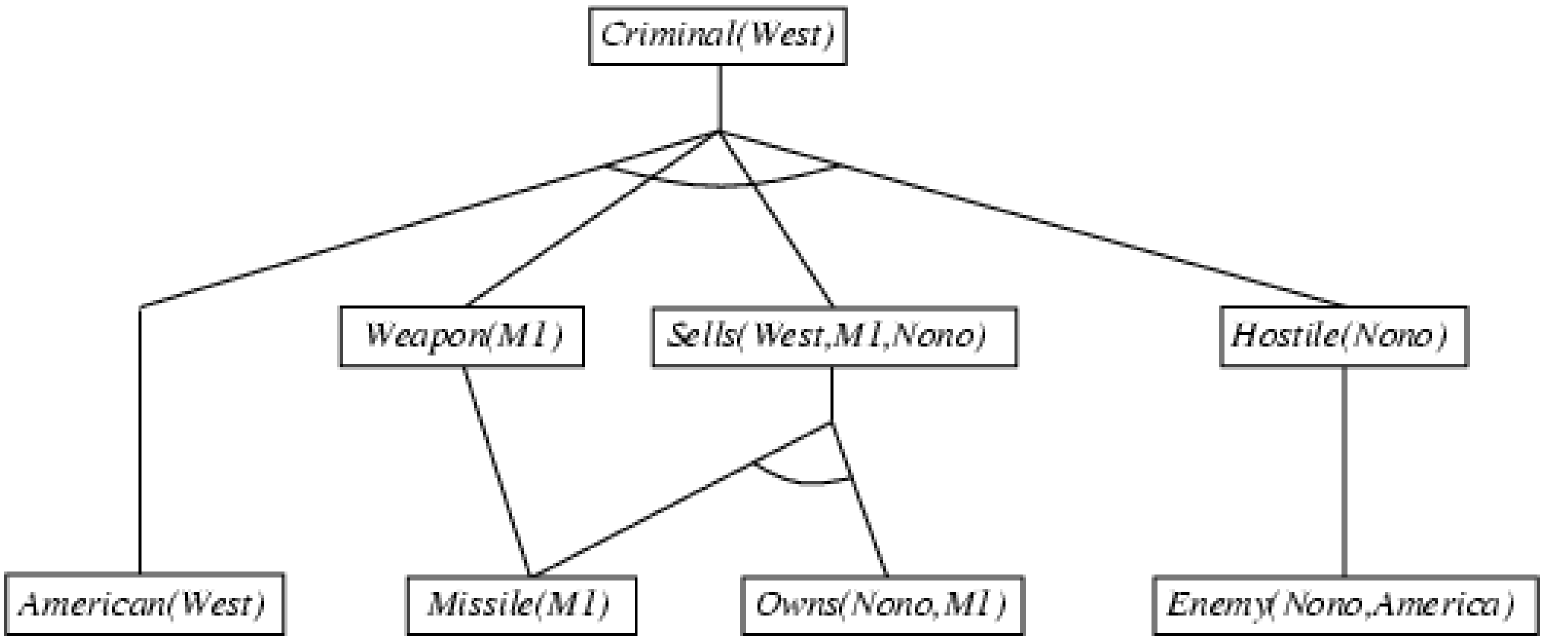
Missile(x) $\Rightarrow$ *Weapon(x)*

Forward chaining proof (Horn clauses)



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

Forward chaining proof (Horn clauses)

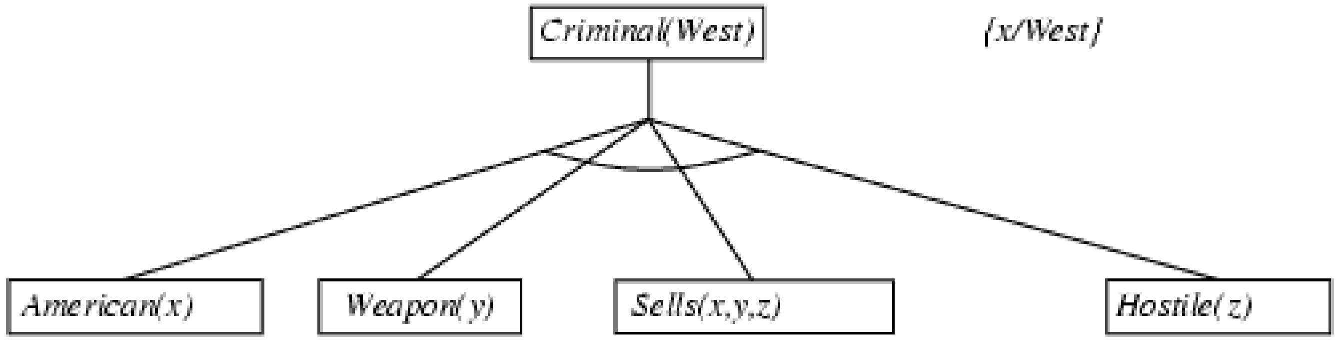


*American(x) $\wedge$ Weapon(y) $\wedge$ Sells(x,y,z) $\wedge$ Hostile(z) $\Rightarrow$ Criminal(x)
*Owns(Nono,M1) and Missile(M1)
*Missile(x) $\wedge$ Owns(Nono,x) $\Rightarrow$ Sells(West,x,Nono)
*Missile(x) $\Rightarrow$ Weapon(x)
*Enemy(x,America) $\Rightarrow$ Hostile(x)
*American(West)
*Enemy(Nono,America)

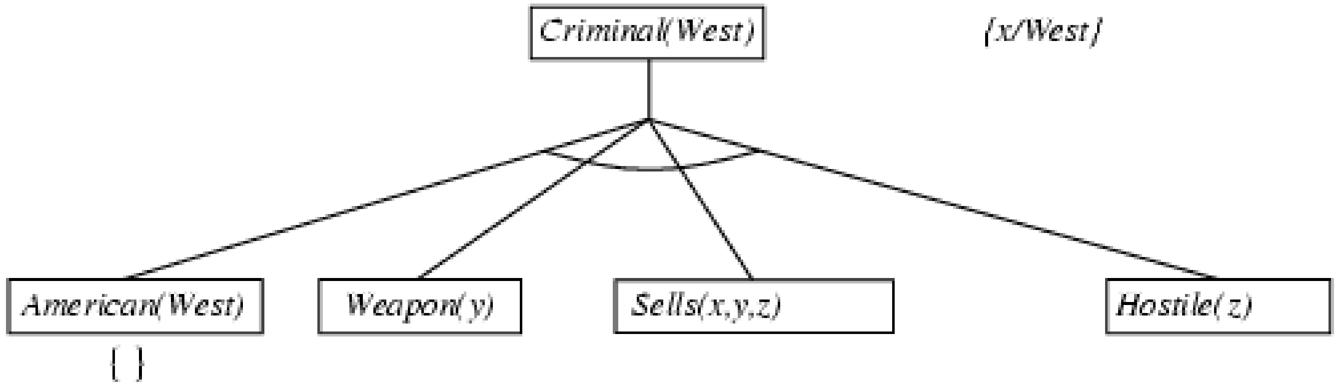
Backward chaining example (Horn clauses)

$$\boxed{Criminal(West)}$$

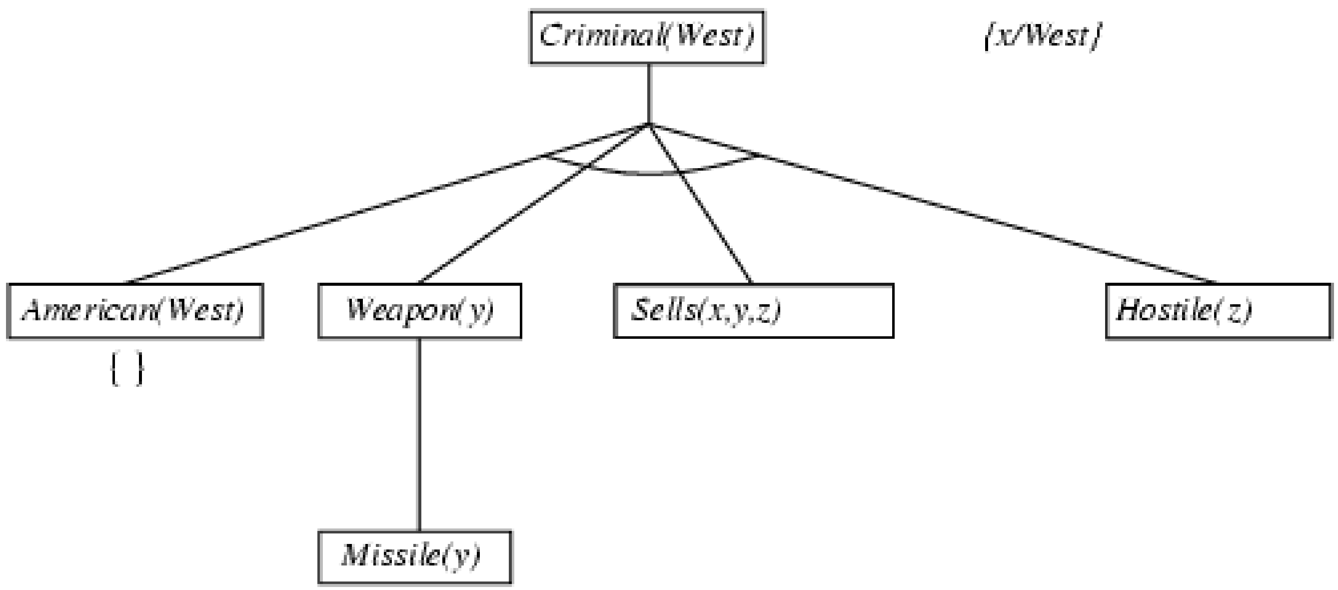
Backward chaining example (Horn clauses)



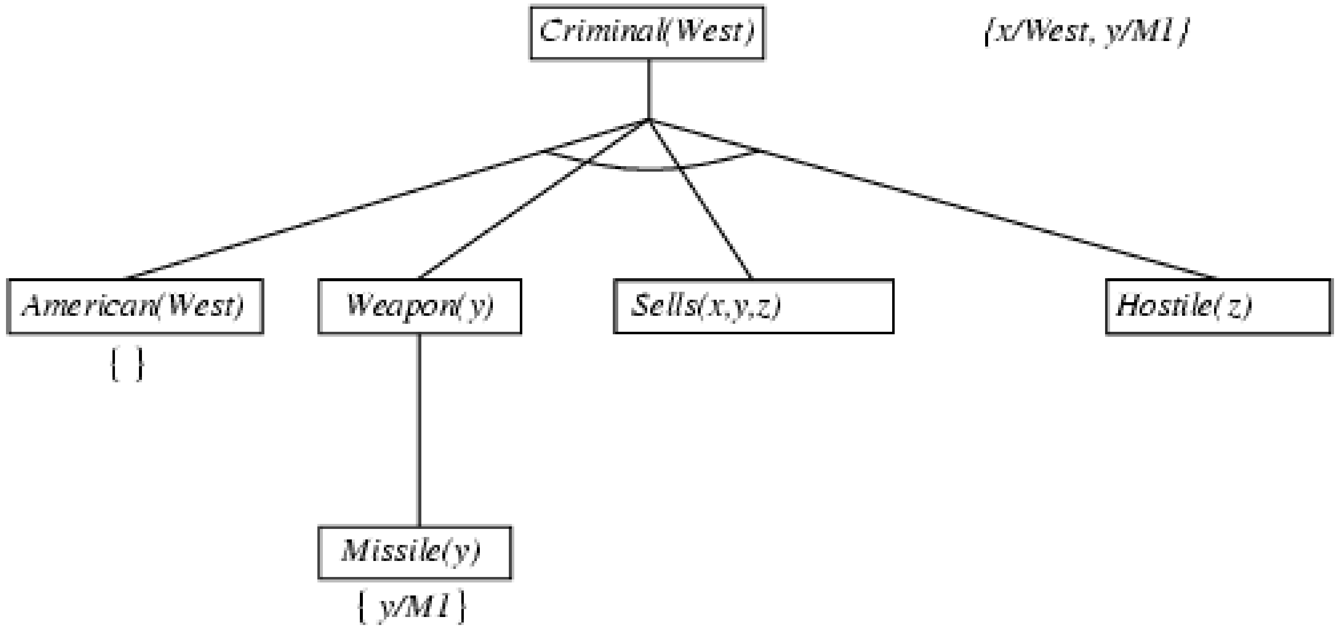
Backward chaining example (Horn clauses)



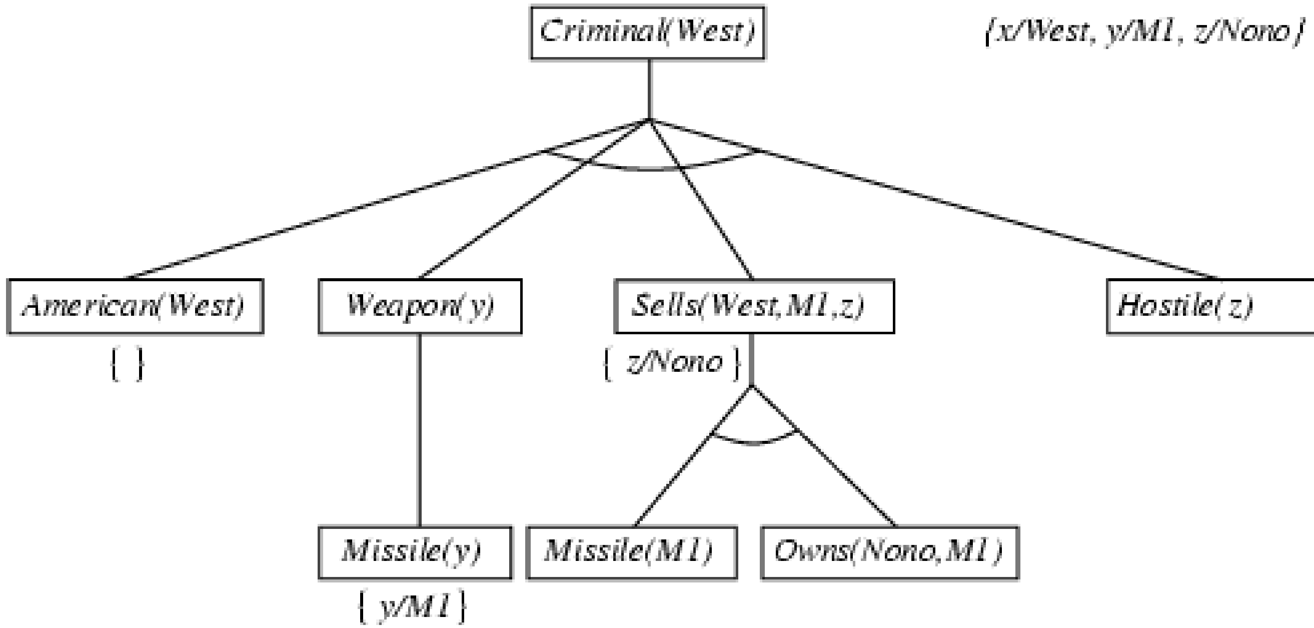
Backward chaining example (Horn clauses)



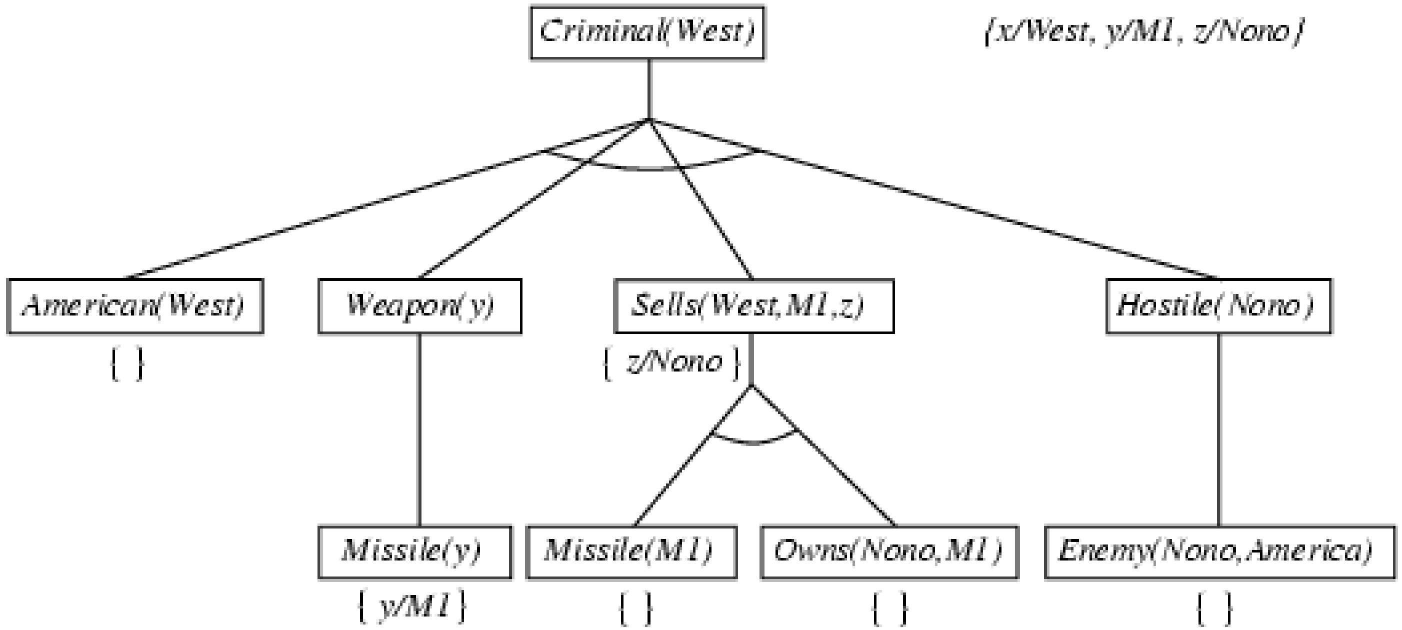
Backward chaining example (Horn clauses)



Backward chaining example (Horn clauses)



Backward chaining example (Horn clauses)



Summary

- First-order logic:
  - Much more expressive than propositional logic
  - Allows objects and relations as semantic primitives
  - Universal and existential quantifiers
- Syntax: constants, functions, predicates, equality, quantifiers
- Nested quantifiers
- Translate simple English sentences to FOPC and back
- Semantics: correct under any interpretation and in any world
- Unification: Making terms identical by substitution
  - The terms are universally quantified, so substitutions are justified.