Tufts
UNIVERSITY

FIRST-ORDER LOGIC 2

ARTIFICIAL INTELLIGENCE | COMP 131

TODAY ON AI

- First-order Logic inference
- Resolution-based inference
- Forward chaining
- Backward chaining
- Questions?

The **simplest possible** approach is FOL inference to use what we know about Propositional Logic inference.

- Resolution-based inference
  - Use **Refutation** to confirm or refute a sentence p (but not to generate all entailed sentences)
  - Requires FOL KB to be reduced to CNF
- Forward chaining
  - Uses **Generalize Modus Ponens** to add new atomic sentences
  - Useful for systems that make inferences as information streams in
  - Requires KB to be in form of first-order definite clauses
- Backward chaining
  - Works backwards from a query to try to construct a proof
  - Can suffer from repeated states and incompleteness
  - Useful for query-driven inference

SECTION 01

Reduction to Propositional form

Herbrand (1930) postulated that if a sentence p is entailed by a FOL knowledge base, then it is also **entailed** but a finite subset of the propositionalized version.

Every FOL KB can be propositionalized so that entailment is preserved.

Three problems in applying PL algorithms to FOL sentences:

1. The **Existential quantifier** ∃
2. The **Universal quantifier** ∀
3. Ground **terms of functions**

Get rid of the existential quantifiers: in an **Existential instantiation** the variable is replaced by a new constant symbol (not in the domain):

CONSTANTS

$\{\text{Robot}, \text{Sq12}, \text{Sq23}, \text{Sq21}\}$

PREDICATES

$\{\exists x: \text{radioactive}(x)\}$

RESULT

$\text{radioactive}(\text{C1})$

The constant C1 is called **Skolem constant**.

Get rid of the universal quantifiers: in a **Universal instantiation** k copies of the universally quantified sentences are added:

CONSTANTS

$\{\text{Robot}, \text{Sq12}, \text{Sq23}, \text{Sq21}\}$

PREDICATES

$\{\forall x: \text{radioactive}(x) \rightarrow \text{unsafe}(x)\}$

RESULT

$\text{radioactive}(\text{Robot}) \rightarrow \text{unsafe}(\text{Robot})$ $\quad$ $\text{radioactive\_robot} \rightarrow \text{unsafe\_robot}$

$\text{radioactive}(\text{Sq12}) \rightarrow \text{unsafe}(\text{Sq12})$ $\quad$ $\text{radioactive\_sq12} \rightarrow \text{unsafe\_sq12}$

$\text{radioactive}(\text{Sq23}) \rightarrow \text{unsafe}(\text{Sq23})$ $\quad$ $\text{radioactive\_sq23} \rightarrow \text{unsafe\_sq23}$

$\text{radioactive}(\text{Sq21}) \rightarrow \text{unsafe}(\text{Sq21})$ $\quad$ $\text{radioactive\_sq21} \rightarrow \text{unsafe\_sq21}$

An issue raises with function symbols, ground terms are infinitely many, e.g., $\text{father}(\text{father}(\text{father}(\text{John})))$.

For $n = 0$ to ∞, create a propositional KB by instantiating with **depth-n** terms see if is entailed by this KB.

BAD

The problem is that it works if the sentence is **entailed**; it does not work if is **not entailed**

SECTION 02

Resolution-based inference

A **resolution-based inference** uses the same PL refutation method:

- It does not generate all entailed sentences (all the new facts)
- It only confirms or refute the query
- It requires to:
  - Propositionalize the KB from a FOL form to a PL form (with specified depth)
  - The PL form of the KB must be reduced to a CNF form

SECTION 03

Forward chaining

Generalized Modus Ponens (GMP) combines And-Introduction, Universal-Elimination, and Modus Ponens when the Knowledge Base contains only **Implications clauses**:

For $\{p_i, p_i', q\}$, a substitution θ such that $\texttt{Substitution}(\theta, p_i') = \texttt{Substitution}(\theta, p_i)$ for all i, then:

$$\frac{p_1', p_2', \ldots, p_n', (p_1 \wedge p_2 \wedge \cdots \wedge p_n \rightarrow q)}{\texttt{Substitution}(\theta, q)}$$

CONSTANTS

$\{\text{Robot}, \text{Sq12}, \text{Sq23}, \text{Sq21}\}$

PREDICATES

$\{\forall x: \text{radioactive}(x) \wedge \text{empty}(x) \rightarrow \text{unsafe}(x)\}$

$\text{radioactive}(\text{Sq12})$

$\text{empty}(\text{Sq12})$

RESULT

$\text{radioactive}(\text{Sq12}), \text{empty}(\text{Sq12})$

$(\text{radioactive}(x) \wedge \text{empty}(x) \rightarrow \text{unsafe}(x))$

$\text{unsafe}(\text{Sq12})$

There is an implicit assumption that all variables are universally quantified.

Unification is a pattern matching procedure that takes two atomic sentences and returns a failure if they do not match and a substitution list if they do.

The substitution list is called the **most general unifier**.

CONSTANTS

$\{\text{Robot}, \text{Sq12}, \text{Sq23}, \text{Sq21}\}$

PREDICATES

$\{\forall x: \text{radioactive}(x) \rightarrow \text{unsafe}(x)\}$

$\text{Radioactive}(\text{Sq12})$

$\text{windy}(\text{Sq12})$

$\text{empty}(\text{Sq21})$

RESULT

$\text{radioactive}(x) \cup \text{radioactive}(\text{Sq12})$	$\{x/\text{Sq12}\}$
$\text{radioactive}(x) \cup \text{windy}(\text{Sq12})$	FAILURE
$\text{radioactive}(x) \cup \text{empty}(\text{Sq21})$	FAILURE

```
1  function Unify(p, q, θ) return a solution, or FAILURE
2  scan p and q left-to-right to find where p and q are not equal
3  if there is no disagreement
4    return θ
5  let r and s be the different terms
6  if Variable(r) then
7    θ = Unify-var(θ, {r/s})
8    return Unify(Substitution(θ, p), Substitution(θ, q), θ)
9  else if Variable(s) then
10   θ = Unify-var(θ, {s/r})
11   return Unify(Substitution(θ, p), Substitution(θ, q), θ)
12 else return FAILURE
```

EXAMPLES

adjacent(Sq12, x) ∪ adjacent(Sq12, Sq13)
adjacent(Sq12, x) ∪ adjacent(y, Sq13)
adjacent(Sq12, x) ∪ adjacent(y, free(Sq13))
adjacent(Sq12, x) ∪ adjacent(x, Sq13)

RESULT

$\{x/\text{Sq13}\}$
$\{x/\text{Sq13}, y/\text{Sq12}\}$
$\{y/\text{Sq12}, x/\text{free(Sq13)}\}$
FAILURE

Standardizing sentences means renaming the variables in a sentence to avoid some unnecessary failures:

EXAMPLES	RESULT
adjacent(**Sq12**, x) U adjacent(x, **Sq13**)	
adjacent(**Sq12**, x) U adjacent(x_{23}, **Sq13**)	$\{x/\mathbf{Sq13}, x_{23}/\mathbf{Sq12}\}$

Like in **Propositional Logic** inference, the algorithm answers queries using the KB to determine new facts until it finds that the query is **true**, or until we've run out of new facts to generate.

Forward chaining works very much like **Breath-first Search**.

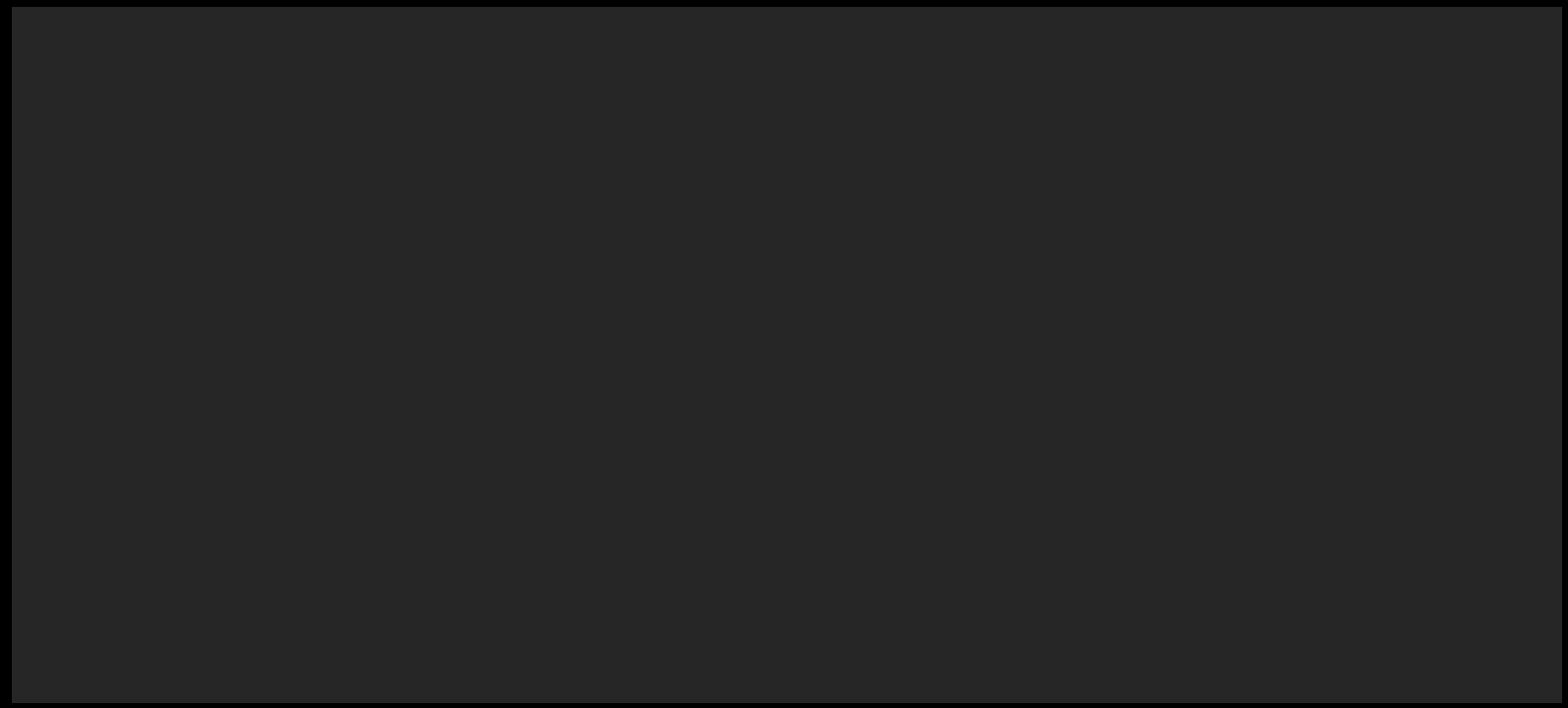
```
1  function Forward-Chaining(KB, q) return a substitution, or FAILURE
2    repeat until new is empty
3      new = {}
4      for each (p1 ∧ p2 ∧ ⋯ ∧ pn → c) in KB
5        for each θ such that Substitution(θ, p1 ∧ ⋯ ∧ pn)=Substitution(θ, p'1 ∧ ⋯ ∧ p'n)
6                    for some p'1,…,p'n in KB do
7          c' = Substitution(θ,c)
8          if c' does not unify with any sentence in KB + new then
9            new = new + c'
10           ϕ = Unify(c', q)
11           if ϕ is not failure then
12             return ϕ
13     KB = KB + new
14   return FAILURE
```

NL STORY

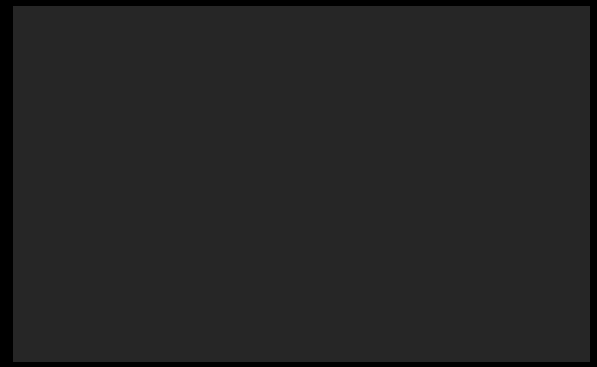
The law says that it is a crime for an American to sell weapons to hostile nations.
The country Nono, an enemy of America, has some missiles, and all its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE



NEW FACTS



First-order Logic inference
EXAMPLE

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\forall x\ \forall y\ \forall z$: $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$

NEW FACTS

First-order Logic inference

EXAMPLE

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

5 $\exists x\colon \text{owns}(\textbf{Nono}, x) \wedge \text{missile}(x)$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West**, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\forall x: \text{missile}(x) \land \text{owns}(\textbf{Nono}, x) \rightarrow \textbf{sells}(\textbf{West}, x, \textbf{Nono})$

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West**, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\forall x\colon \text{missile}(x) \rightarrow \text{weapon}\ (x)$

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}\ (x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}\ (x)$ ...

4 $\forall x\colon \text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}\ (x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

NEW FACTS

NL STORY

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 its missiles were sold to it by **Colonel West, who is American.**

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

7 $\text{american}(\text{West})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}\ (x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

7 $\text{american}(\text{West})$

8 $\text{enemy}(\textbf{Nono}, \textbf{America})$

NEW FACTS

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is **Colonel West a criminal**?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}\ (x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

7 $\text{american}(\text{West})$

8 $\text{enemy}(\text{Nono}, \text{America})$

NEW FACTS

$\text{Criminal}(\text{West})$?

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\textbf{Nono}, x) \rightarrow \text{sells}(\textbf{West}, x, \textbf{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\textbf{Nono}, \textbf{M1})$

6 $\textbf{missile}(\text{M1})$

7 $\text{american}(\textbf{West})$

8 $\text{enemy}(\textbf{Nono}, \textbf{America})$

NEW FACTS

$\text{weapon}(\text{M1})$

$\text{Criminal}(\text{West})$?

First-order Logic inference
EXAMPLE

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

7 $\text{american}(\text{West})$

8 $\text{enemy}(\text{Nono}, \text{America})$

NEW FACTS

$\text{weapon}(\text{M1})$

$\text{hostile}(\text{Nono})$

$\text{Criminal}(\text{West})?$

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 **missile(x) ∧ owns(Nono, x) → sells(West, x, Nono) ...**

3 $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 **owns(Nono, M1)**

6 **missile(M1)**

7 american(West)

8 enemy(Nono, America)

NEW FACTS

weapon(M1)

hostile(Nono)

sell(West, M1, Nono)

Criminal(West)?

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

7 $\text{american}(\text{West})$

8 $\text{enemy}(\text{Nono}, \text{America})$

NEW FACTS

$\text{weapon}(\text{M1})$

$\text{hostile}(\text{Nono})$

$\text{sell}(\text{West}, \text{M1}, \text{Nono})$

$\text{Criminal}(\text{West})$:

NL STORY

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 its missiles were sold to it by Colonel West, who is American.

Is Colonel West a criminal?

KNOWLEDGE BASE

1 $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...

2 $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...

3 $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...

4 $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...

5 $\text{owns}(\text{Nono}, \text{M1})$

6 $\text{missile}(\text{M1})$

7 $\text{american}(\text{West})$

8 $\text{enemy}(\text{Nono}, \text{America})$

NEW FACTS

$\text{weapon}(\text{M1})$

$\text{hostile}(\text{Nono})$

$\text{sell}(\text{West}, \text{M1}, \text{Nono})$

$\text{Criminal}(\text{West})$: **YES**

SECTION 04

Backward chaining

Like in Propositional Logic, the basic idea behind **Backward chaining** is to work backward from the goal to the facts that must be asserted for the goal to hold.

Backward chaining proceeds in a **Depth-first Search**.

```
1  function Backward-chaining(KB, goals, θ) return substitution
2    if goals is empty then
3      return θ
4    goal = pop from goals
5    q'= Substitution(θ, goal)
6    θ'' = {}
7    for each r in KB such that (p1 ∧ p2 ∧ ··· ∧ pn -> q) do
8      r' = Standardize(r)
9      θ' = Unify(q, q')
10     if θ' succeded then
11       θ'' = θ'' + Backward-chaining(KB, (p1 ... pn) + goals, Compose(θ,θ'))
12    return θ''
```

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

QUERY

Is Colonel West a criminal?

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

KNOWLEDGE BASE

1. $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \wedge \text{owns}(\textbf{Nono}, x) \rightarrow \text{sells}(\textbf{West}, x, \textbf{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}\ (x)$ ...
4. $\text{enemy}(x, \textbf{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\textbf{Nono}, \textbf{M1})$
6. $\text{missile}(\textbf{M1})$
7. $\text{american}(\textbf{West})$
8. $\text{enemy}(\textbf{Nono}, \textbf{America})$

First-order Logic inference

EXAMPLE

Criminal(West)

QUERY

Is Colonel West a criminal?

Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\text{Nono}, \text{M1})$
6. $\text{missile}(\text{M1})$
7. $\text{american}(\text{West})$
8. $\text{enemy}(\text{Nono}, \text{America})$

First-order Logic inference

EXAMPLE

$\text{Criminal}(\text{West})$ $\{x/\text{West}\}$

QUERY

Is Colonel West a criminal?

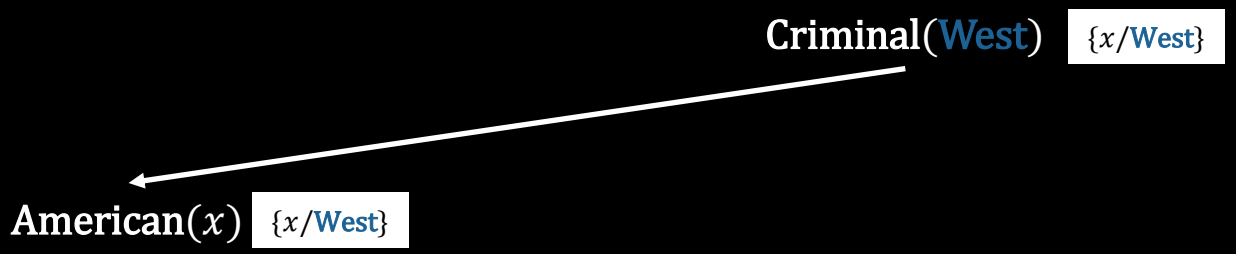
$\text{Criminal}(\text{West})$

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\text{Nono}, \text{M1})$
6. $\text{missile}(\text{M1})$
7. $\text{american}(\text{West})$
8. $\text{enemy}(\text{Nono}, \text{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

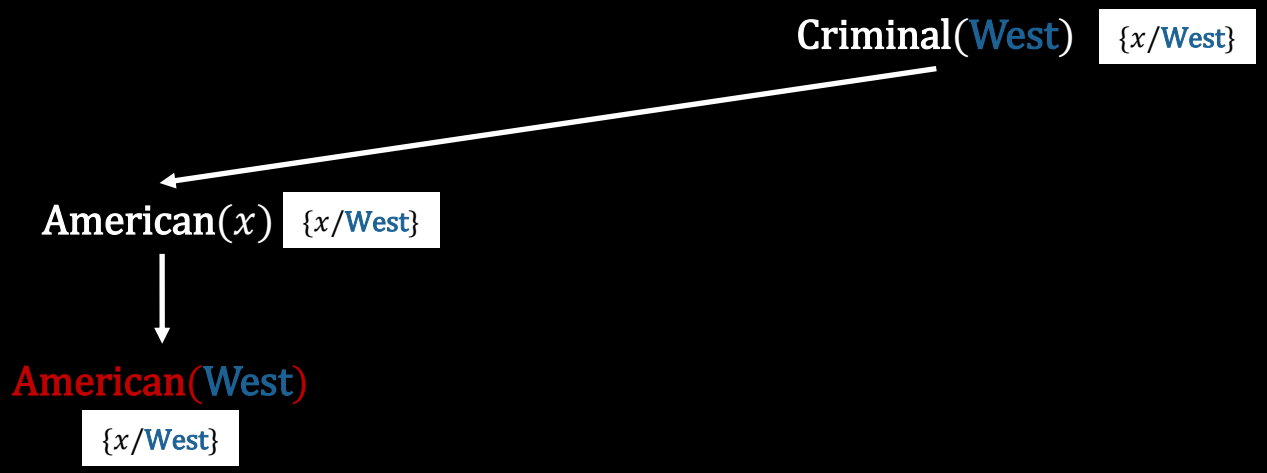
Criminal(West)

KNOWLEDGE BASE

1. american(x) ∧ weapon(y) ∧ sells(x, y, z) ∧ hostile(z) → criminal(x) ...
2. missile(x) ∧ owns(Nono, x) → sells(West, x, Nono) ...
3. missile(x) → weapon (x) ...
4. enemy(x, America) → hostile(x) ...
5. owns(Nono, M1)
6. missile(M1)
7. american(West)
8. enemy(Nono, America)

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

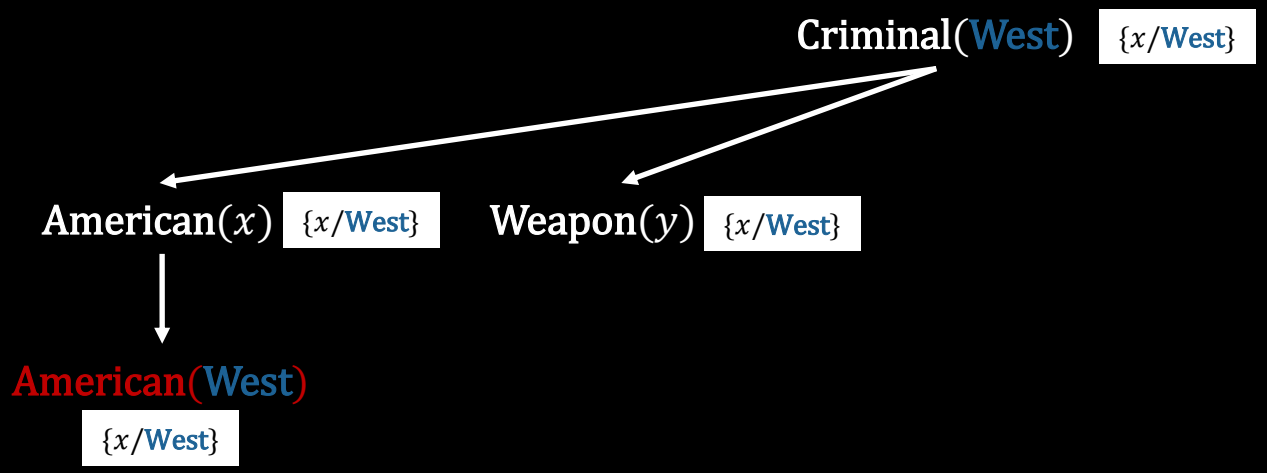
Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\text{Nono}, \text{M1})$
6. $\text{missile}(\text{M1})$
7. $\text{american}(\text{West})$
8. $\text{enemy}(\text{Nono}, \text{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

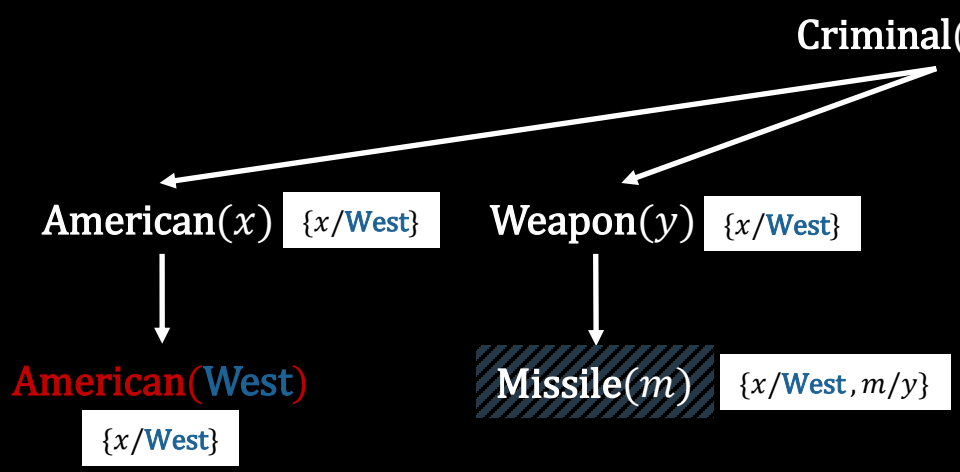
Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \wedge \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\text{Nono}, \text{M1})$
6. $\text{missile}(\text{M1})$
7. $\text{american}(\text{West})$
8. $\text{enemy}(\text{Nono}, \text{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

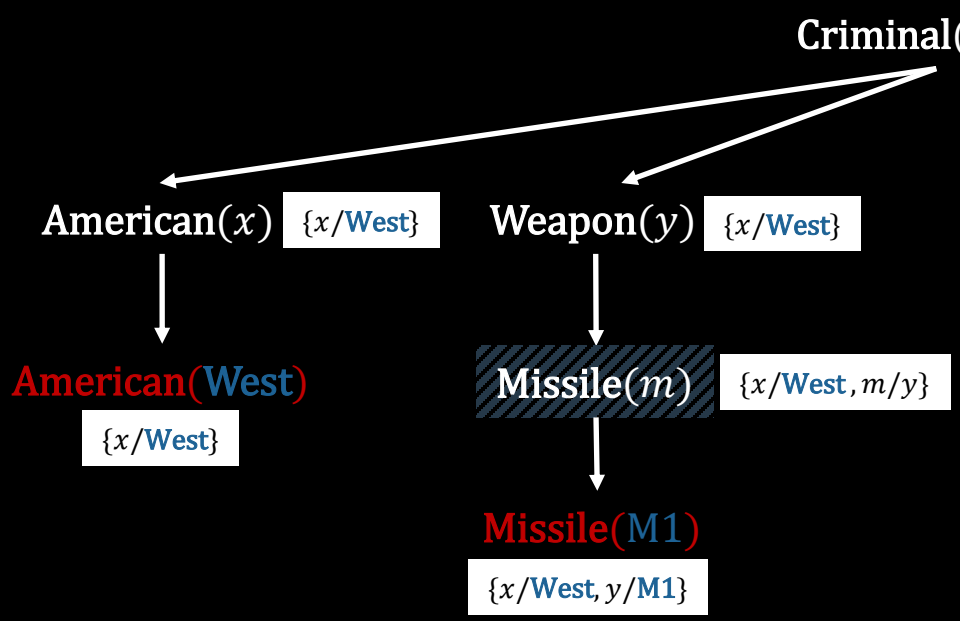
Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \wedge \text{owns}(\textbf{Nono}, x) \rightarrow \text{sells}(\textbf{West}, x, \textbf{Nono})$ ...
3. **$\text{missile}(x) \rightarrow \text{weapon}(x)$ ...**
4. $\text{enemy}(x, \textbf{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\textbf{Nono}, \textbf{M1})$
6. $\text{missile}(\textbf{M1})$
7. $\text{american}(\textbf{West})$
8. $\text{enemy}(\textbf{Nono}, \textbf{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

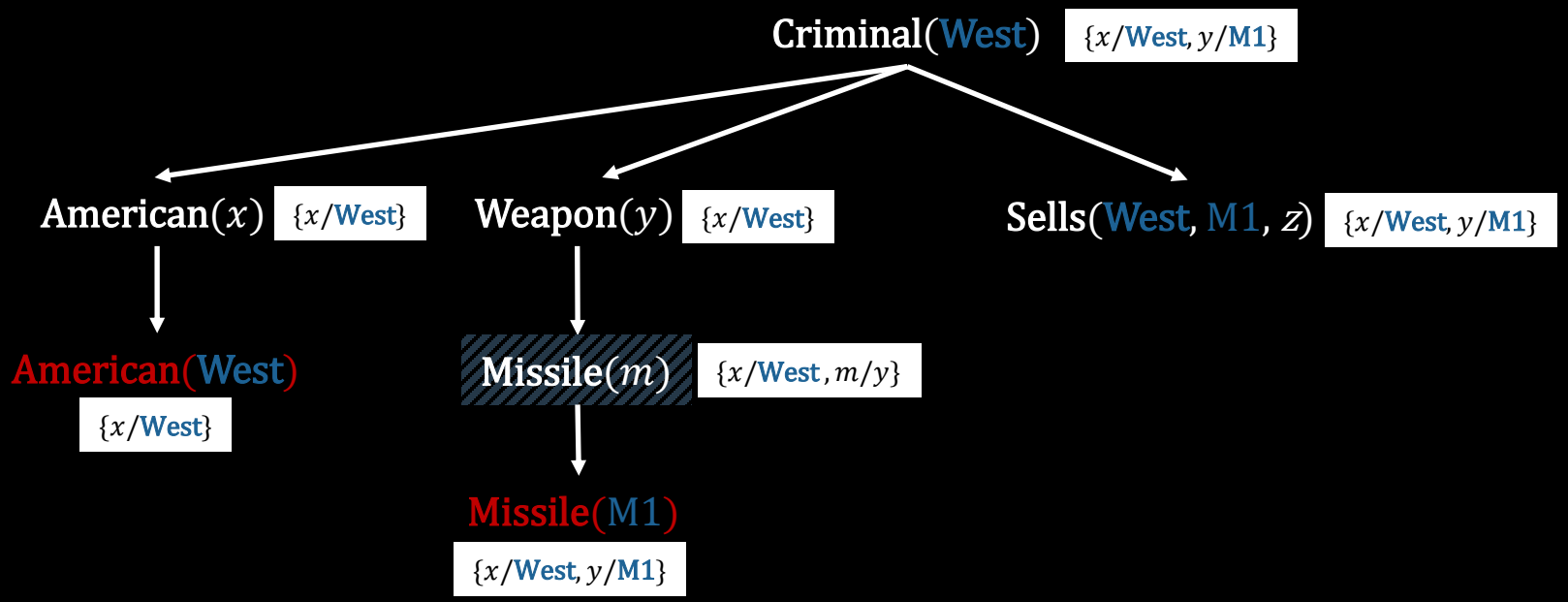
Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \wedge \text{owns}(\textbf{Nono}, x) \rightarrow \text{sells}(\textbf{West}, x, \textbf{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \textbf{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\textbf{Nono}, \text{M1})$
6. $\textbf{missile}(\text{M1})$
7. $\text{american}(\textbf{West})$
8. $\text{enemy}(\textbf{Nono}, \textbf{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

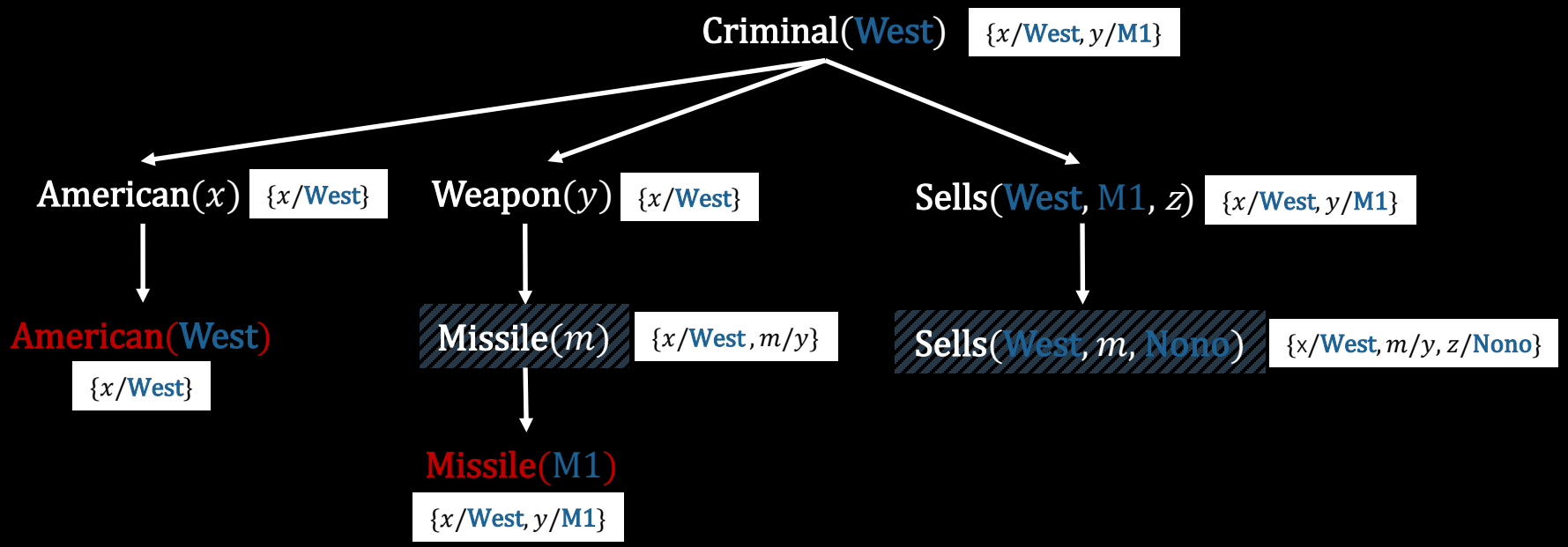
Criminal(West)

KNOWLEDGE BASE

1. $\mathbf{american}(x) \wedge \mathbf{weapon}(y) \wedge \mathbf{sells}(x, y, z) \wedge \mathbf{hostile}(z) \rightarrow \mathbf{criminal}(x)$ ...
2. $\mathrm{missile}(x) \wedge \mathrm{owns}(\mathbf{Nono}, x) \rightarrow \mathrm{sells}(\mathbf{West}, x, \mathbf{Nono})$ ...
3. $\mathrm{missile}(x) \rightarrow \mathrm{weapon}\ (x)$ ...
4. $\mathrm{enemy}(x, \mathbf{America}) \rightarrow \mathrm{hostile}(x)$ ...
5. $\mathrm{owns}(\mathbf{Nono}, \mathbf{M1})$
6. $\mathrm{missile}(\mathbf{M1})$
7. $\mathrm{american}(\mathbf{West})$
8. $\mathrm{enemy}(\mathbf{Nono}, \mathbf{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

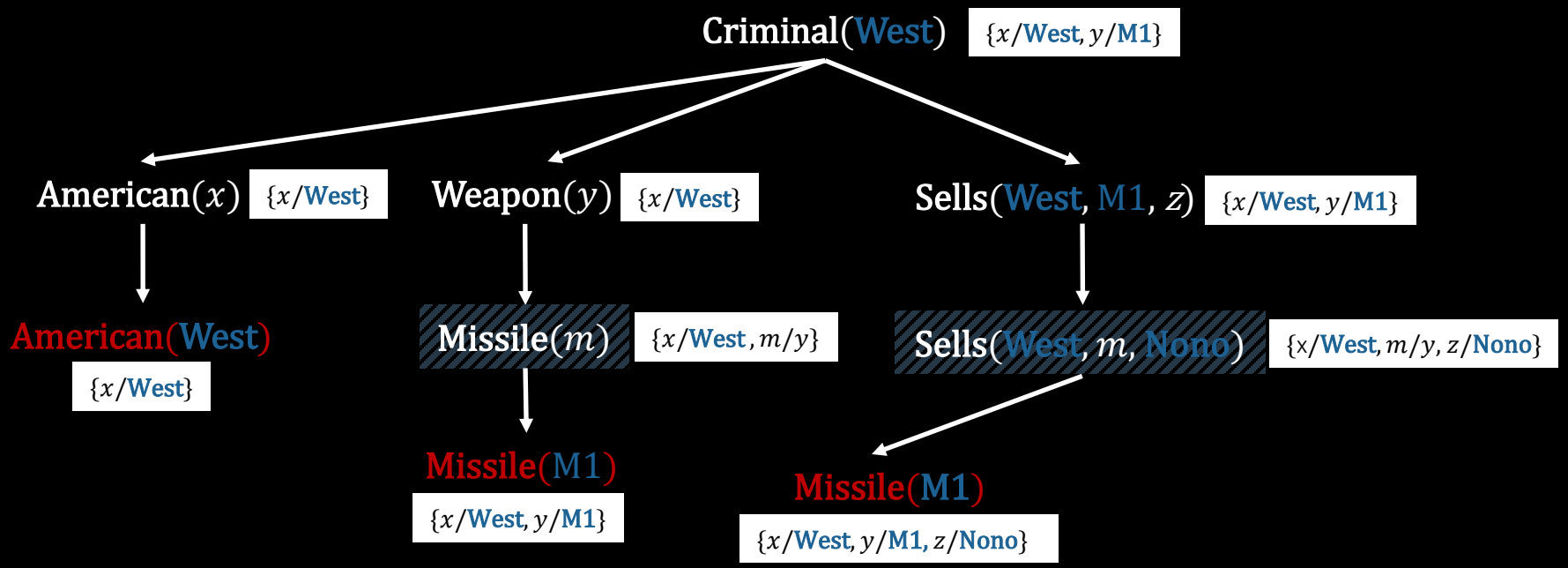
Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. **$\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...**
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\text{Nono}, \text{M1})$
6. $\text{missile}(\text{M1})$
7. $\text{american}(\text{West})$
8. $\text{enemy}(\text{Nono}, \text{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \land \text{owns}(\textbf{Nono}, x) \rightarrow \text{sells}(\textbf{West}, x, \textbf{Nono})$ ...
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \textbf{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\textbf{Nono}, \text{M1})$
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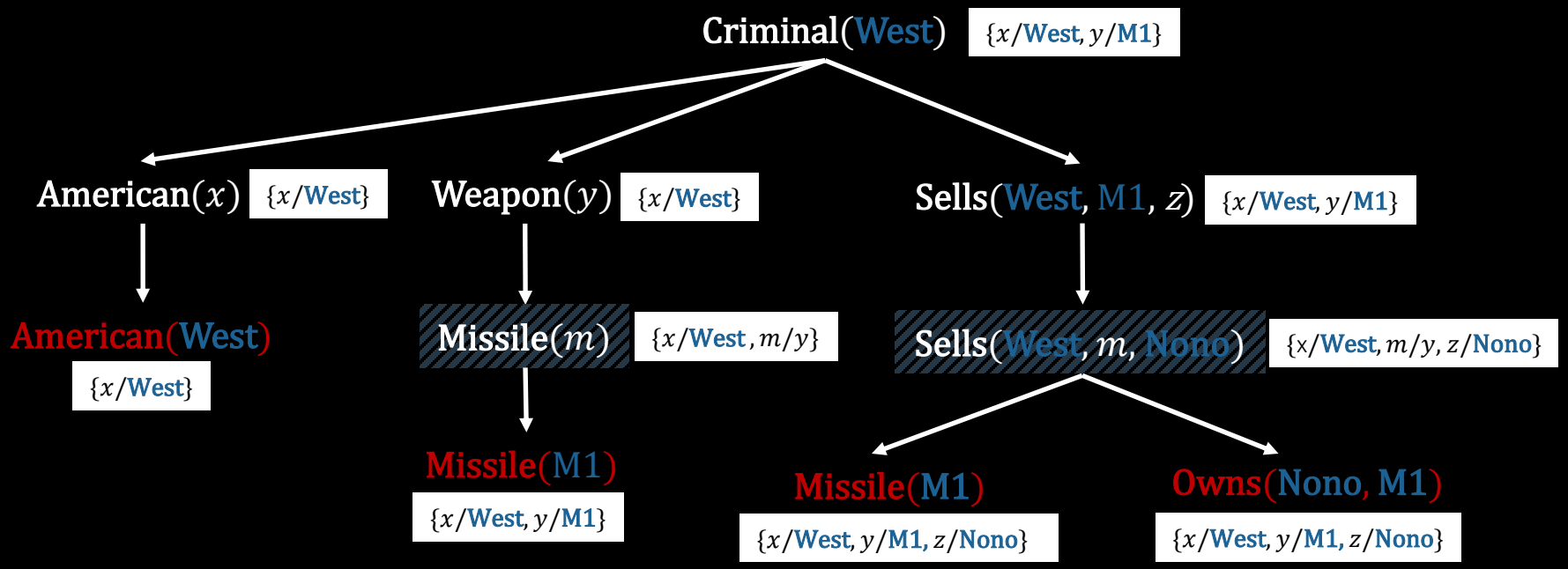
7. $\text{american}(\textbf{West})$
8. $\text{enemy}(\textbf{Nono}, \textbf{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
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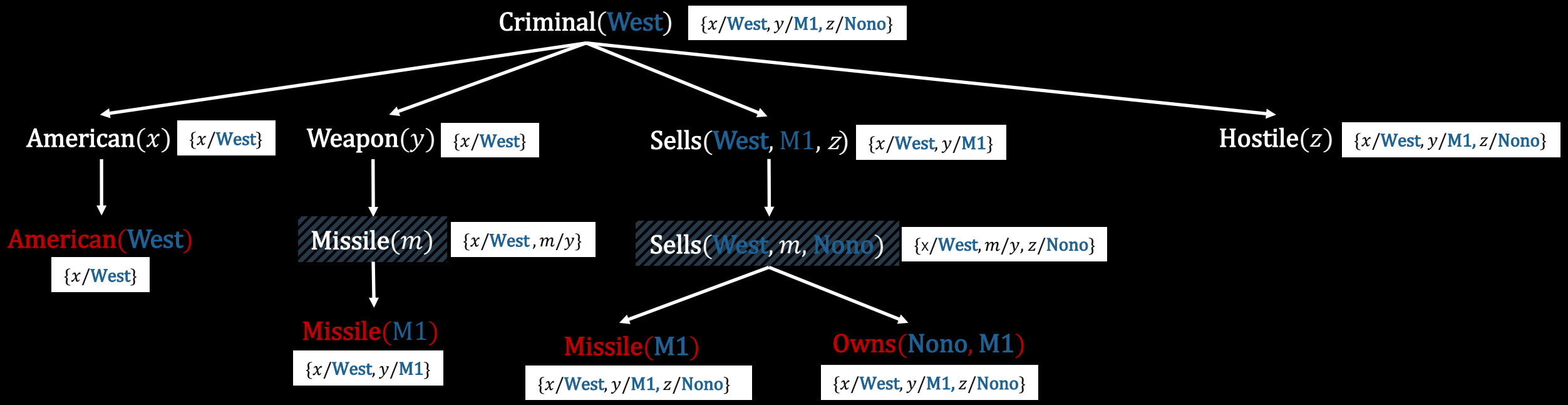
8. $\text{enemy}(\textbf{Nono}, \textbf{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...
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7. $\text{american}(\text{West})$
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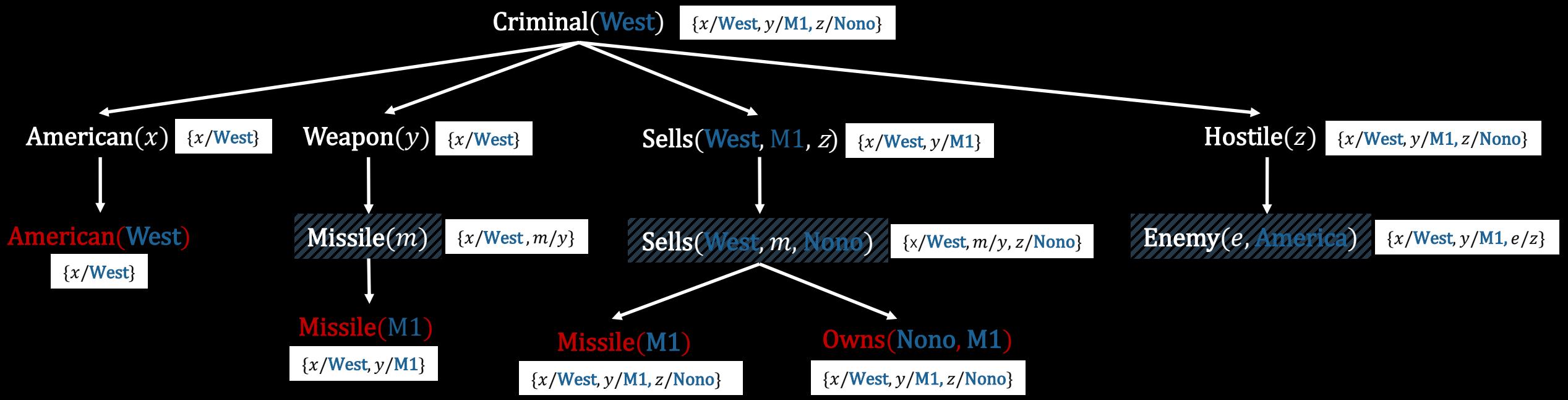
First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \land \text{owns}(\text{Nono}, x) \rightarrow \text{sells}(\text{West}, x, \text{Nono})$ ...
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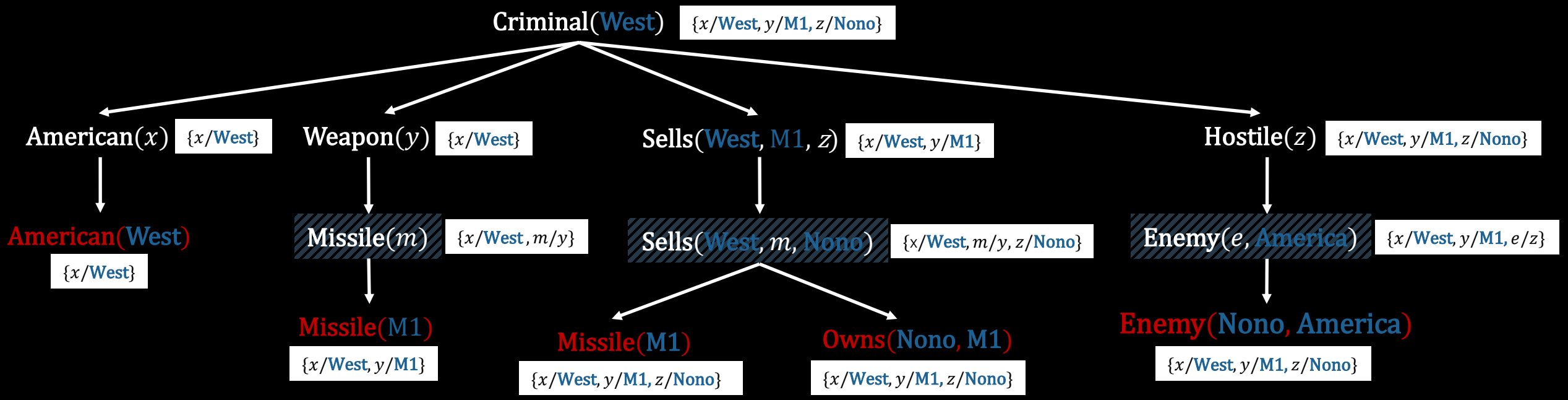
First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

Criminal(West)

KNOWLEDGE BASE

1. $\text{american}(x) \land \text{weapon}(y) \land \text{sells}(x, y, z) \land \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
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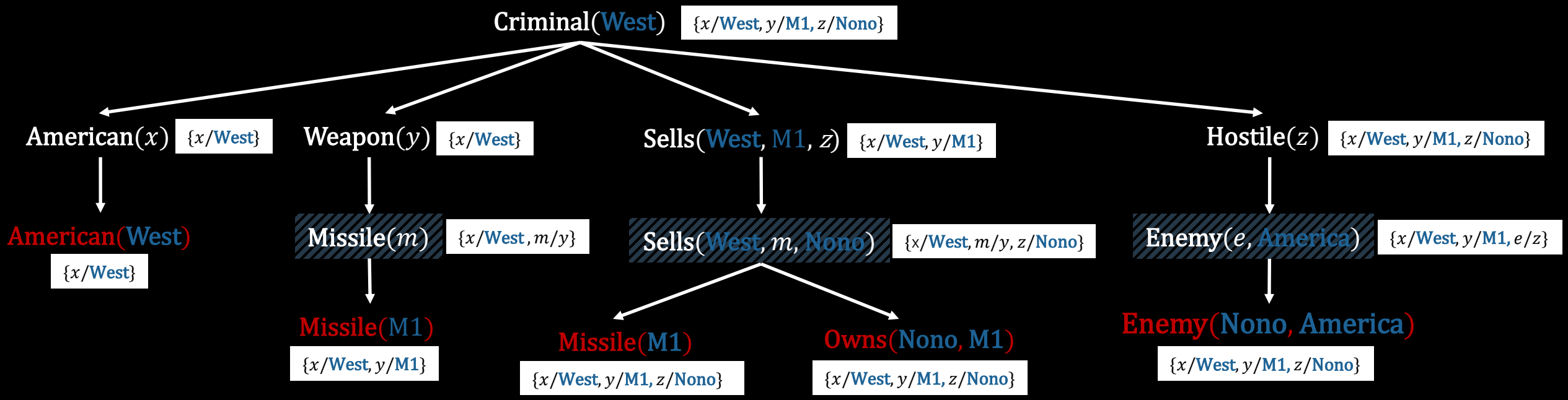
3. $\text{missile}(x) \rightarrow \text{weapon}(x)$ ...
4. $\text{enemy}(x, \text{America}) \rightarrow \text{hostile}(x)$ ...
5. $\text{owns}(\text{Nono}, \text{M1})$
6. $\text{missile}(\text{M1})$
7. $\text{american}(\text{West})$
8. $\text{enemy}(\text{Nono}, \text{America})$

First-order Logic inference

EXAMPLE



QUERY

Is Colonel West a criminal?

Criminal(West)

{x/West, y/M1, z/Nono}

KNOWLEDGE BASE

1. $\text{american}(x) \wedge \text{weapon}(y) \wedge \text{sells}(x, y, z) \wedge \text{hostile}(z) \rightarrow \text{criminal}(x)$ ...
2. $\text{missile}(x) \wedge \text{owns}(\textbf{Nono}, x) \rightarrow \text{sells}(\textbf{West}, x, \textbf{Nono})$ ...
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6. $\text{missile}(\textbf{M1})$
7. $\text{american}(\textbf{West})$
8. $\text{enemy}(\textbf{Nono}, \textbf{America})$

First-order Logic inference

EXAMPLE

READINGS

Chapters 8

QUESTIONS ?

Tufts
UNIVERSITY

ARTIFICIAL INTELLIGENCE

COMP 131

FABRIZIO SANTINI

VERSION 4.2