CSE 473

Lecture 14

FOL Wrap-Up
and
Midterm Review

Resolution: Summary

- FOL resolution rule:

$$\frac{l_1 \vee \cdots \vee l_k, \qquad m_1 \vee \cdots \vee m_n}{(l_1 \vee \cdots \vee l_{i-1} \vee l_{i+1} \vee \cdots \vee l_k \vee m_1 \vee \cdots \vee m_{j-1} \vee m_{j+1} \vee \cdots \vee m_n)\theta}$$

  where `Unify`$(l_i, \neg m_j) = \theta$.

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

- Example:

$$\frac{\neg Rich(x) \vee HasSwissBankAccount(x) \qquad Rich(Willard)}{HasSwissBankAccount(Willard)}$$

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

Resolution: Conversion to CNF

Everyone who loves all animals is loved by someone:

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

1. Eliminate biconditionals and implications

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

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

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

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

Conversion to CNF contd.

3. Standardize variables: Each quantifier uses a different variable

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

4. Skolemize: 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 $\wedge$ to get CNF (clauses connected by $\wedge$):

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

Example: Nono and West again

- It is a crime for an American to sell weapons to hostile nations. The country Nono, an enemy of America, has some missiles. All of its missiles were sold to it by Colonel West, who is American.
- Is Col. West a criminal?
- FOL representation:

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

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KB in CNF and Resolution

- KB in CNF (variables not standardized):

$\neg$*American(x)* $\vee$ $\neg$ *Weapon(y)* $\vee$ $\neg$ *Sells(x,y,z)* $\vee$ $\neg$ *Hostile(z)* $\vee$ *Criminal(x)*
Owns(Nono,M_1) [*Skolem constant M_1*]
Missile(M_1)
$\neg$ *Missile(x)* $\vee$ $\neg$ *Owns(Nono,x)* $\vee$ *Sells(West,x,Nono)*
$\neg$ *Missile(x)* $\vee$ *Weapon(x)*
$\neg$ *Enemy(x,America)* $\vee$ *Hostile(x)*
American(West)
Enemy(Nono,America)

- Resolution: Uses "proof by contradiction"
  Show KB $\models \alpha$ by showing KB $\wedge \neg\alpha$ unsatisfiable
- To prove Col. West is a criminal, add $\neg$Criminal(West) to KB and derive empty clause

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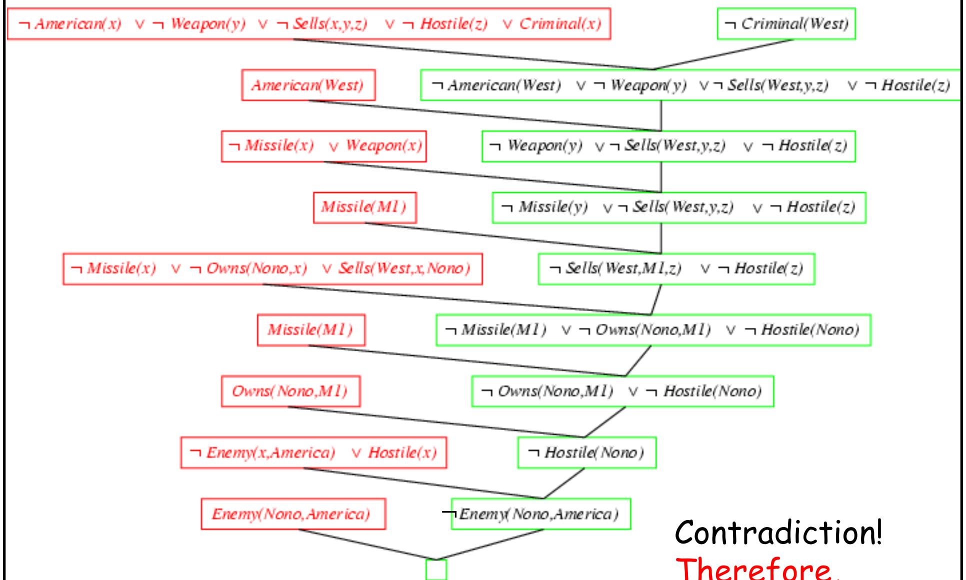
FOL Resolution Example



Contradiction!
Therefore,
Criminal(West)

FOL Resolution Example 2

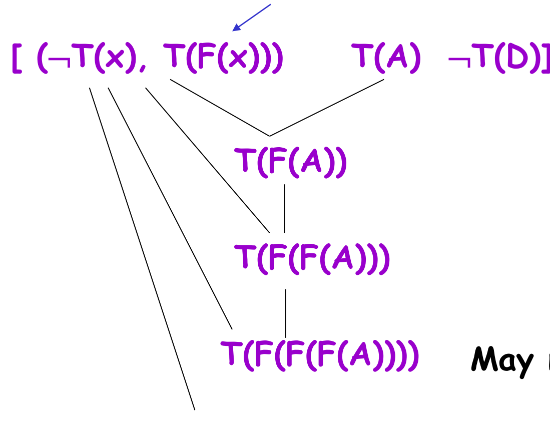
Given

∀x ∃y Twin(x) ⇒ Twin(y)
Twin(Ashley)

∀x Twin(x) ⇒ Twin(F(x)) **Skolemization**

Prove

Twin(Diddy)



May not terminate!

Inference Technique IV: Compilation to Prop. Logic

- Sentence S:

  $\forall_{city}\ a,b$ Connected(a,b)
- Universe

  Cities: seattle, tacoma, enumclaw
- Equivalent propositional formula?

  Cst ∧ Cse ∧ Cts ∧ Cte ∧ Ces ∧ Cet

∀ converted to a bunch of ∧'s

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Compilation to Prop. Logic (cont)

- Sentence S:

  $\exists_{city}\ c$ Biggest(c)
- Universe

  Cities: seattle, tacoma, enumclaw
- Equivalent propositional formula?

  Bs ∨ Bt ∨ Be

∃ converted to a bunch of ∨'s

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Compilation to Prop. Logic (cont again)

- Universe
  - Cities: seattle, tacoma, enumclaw
  - Firms: IBM, Microsoft, Boeing
- First-Order formula

  $\forall_{firm}\, f \;\; \exists_{city}\, c \quad \text{HeadQuarters}(f, c)$
- Equivalent propositional formula

  $$[\ (HQis \vee HQit \vee HQie) \wedge (HQms \vee HQmt \vee HQme) \wedge (HQbs \vee HQbt \vee HQbe)\ ]$$

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Hey!

- You said FO Inference is semi-decidable
- But you compiled it to SAT

  Which is NP Complete
- So now we can always do the inference?!?

  (might take exponential time but still decidable?)
- Something seems wrong here....????

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Compilation to Prop. Logic: The Problem

- Universe
  - People: homer, bart, marge
- First-Order formula

  $\forall_{people}\, p \quad Male(FatherOf(p))$
- Equivalent propositional formula?

  [$(M_{father-homer} \wedge M_{father-bart} \wedge M_{father-marge} \wedge$
  $(M_{father-father-homer} \wedge M_{father-father-bart} \wedge \ldots$
  $(M_{father-father-father-homer} \wedge \ldots$
  …]

  Not a finite formula

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Restricted Forms of FO Logic

- Known, Finite Universes

  Compile to SAT
- Function-Free Definite Clauses (exactly one positive literal, no functions)

  Aka **Datalog** knowledge bases
- Definite clauses + Inference Process

  E.g., Logic programming using Prolog (uses depth-first backward chaining but may not terminate in some cases)

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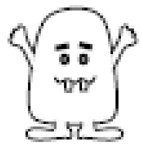
Hurray! We've reached the Midterm mark



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Midterm Exam Logistics

- When: Monday, class time
- Where: Here
- What to read: Lecture slides, your notes, Chapters 1-3, 4.1, 5, and 7-9, and practice problems
- Format: Closed book, closed notes except for one 8½" x 11" sheet of notes (double-sided ok)

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Friday Class: TA Help Session

- No lecture
- TA Jenn Hanson will be in class 9:30-10:20am to go over some practice problems and answer questions on project or midterm

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Midterm Review: Chapters 1 & 2 Agents and Environments

- Browse Chapter 1
- Chapter 2: Definition of an Agent
  Sensors, actuators, environment of agent, performance measure, rational agents
- Task Environment for an Agent = PEAS description
  E.g., automated taxi driver, medical expert
  Know how to write PEAS description for a given task environment

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Review: Chapter 2
Agents and Environments

- Properties of Environments
  Full *vs.* partial observability, deterministic *vs.* stochastic, episodic *vs.* sequential, static *vs.* dynamic, discrete *vs.* continuous, single *vs.* multiagent
- *Agent Function vs. Agent Program*
  State space graph for an agent
- Types of agent programs:
  Simple reflex agents, reflex agent with internal state, goal-based agents, utility-based agents, learning agents

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Review: Chapter 3
Search

- State-Space Search Problem
  Start state, goal state, successor function
- Tree representation of search space
  Node, parent, children, depth, path cost *g*(n)
- General tree search algorithm
- Evaluation criteria for search algorithms
  Completeness, time and space complexity, optimality
  Measured in terms of b, d, and m

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Review: Chapter 3
Uninformed Search Strategies

- Know how the following work:
  - Breadth first search
  - Uniform cost search
  - Depth first search
  - Depth limited search
  - Iterative deepening search
- Implementation using FIFO/LIFO
- Completeness (or not), time/space complexity, optimality (or not) of each
- Bidirectional search
- Repeated states and Graph Search algorithm

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Review: Chapter 3
Informed Search

- Best-First Search algorithm
  - Evaluation function f(n)
  - Implementation with priority queue
- Greedy best-first search
  - f(n) = heuristic function h(n) = estimate of cost from n to goal
  - E.g, $h_{SLD}(n)$ = straight-line distance to goal from n
  - Completeness, time/space complexity, optimality

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Review: Chapter 3
A* Search

- A* search =
  best-first search with f(n) = g(n) + h(n)
- Know the definition of *admissible* heuristic function h(n)
- Relationship between admissibility and optimality of A*
- Consistent heuristic function
- Completeness, time/space complexity, optimality of A*
- Comparing heuristics: Dominance
- Iterative-deepening A*

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Review: Chapter 3 and 4.1
Heuristics & Local Search

- Relaxed versions of problems and deriving heuristics from them
- Combining multiple heuristic functions
- Pattern Databases
- Disjoint pattern databases
- Local search:
  Hill climbing, global vs. local maxima
  - Stochastic hill climbing
  - Random Restart hill climbing

  Simulated Annealing
  Local Beam Search
  Genetic Algorithms

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Review: Chapter 5 Adversarial Search

- Games as search problems
- MAX player, MIN player
- Game Tree, n-Ply tree
- Minimax search for finding best move
  - Computing minimax values for nodes in a game tree
  - Completeness, time/space complexity, optimality
- Minimax for multiplayer games

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Review: Chapter 5 Adversarial Search

- Alpha Beta Pruning
  - Know how to prune trees using alpha-beta
  - Time complexity
- Fixed Depth (cutoff) search
  - Evaluation functions
- Iterative deepening game tree search
- Transposition tables (what? why?)
- Game trees with chance nodes
  - Expectiminimax algorithm

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Review: Chapter 7
Logical Agents

- What is a Knowledge Base (KB)?
  ASK, TELL
- Wumpus world as an example domain
- Syntax vs. Semantics for a language
- Definition of Entailment
  $KB \models \alpha$ *if and only if* α is true in all worlds where KB is true.
- Models and relationship to entailment
- Soundness vs. Completeness of inference algorithms

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Review: Chapter 7
Logical Agents

- Propositional Logic
  Syntax and Semantics, Truth tables
  Evaluating whether a statement is true/false
- Inference by Truth Table Enumeration
- Logical equivalence of sentences
  Commutativity, associativity, etc.
- Definition of validity and relation to entailment
- Definition of satisfiability, unsatisfiability and relation to entailment

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Review: Chapter 7 Logical Agents

- Inference Techniques
  Model checking vs. using inference rules
- Resolution
  Know the definition of literals, clauses, CNF
  Converting a sentence to CNF
  General Resolution inference rule
- Using Resolution for proving statements
  To show $KB \models \alpha$, show $KB \wedge \neg\alpha$ is unsatisfiable by deriving the empty clause via resolution

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Review: Chapter 7 Logical Agents

- Forward and Backward chaining
  Know definition of Horn clauses
  AND-OR graph representation
  Modus ponens inference rule
  Know how forward & backward chaining work
- DPLL algorithm
  How is it different from TT enumeration?
- WalkSAT: Know how it works
  Evaluation function, 3-CNF
  m/n ratio and relation to hardness of SAT

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Review: Chapter 8
First-Order Logic (FOL)

- First-Order Logic syntax and semantics
  - Constants, variables, functions, terms, relations (or predicates), atomic sentences
  - Logical connectives: and, or, not, ⇒, ⇔
  - Quantifiers: ∀ and ∃
- Know how to express facts in FOL
  - Interaction between quantifiers and connectives
  - Nesting of quantifiers
- Interpretations, validity, satisfiability, and entailment

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Review: Chapter 9
Inference in FOL

- FOL Inference Techniques
  - Universal instantiation
  - Existential instantiation
    - Skolemization: Skolem constants, Skolem functions
  - Unification
    - Know how to compute most general unifier (MGU)
  - Generalized Modus Ponens (GMP) and Lifting
  - Forward chaining using GMP
  - Backward chaining using GMP
  - Resolution in FOL
    - Standardizing apart variables, converting to CNF
  - Compilation to Propositional Logic and using SAT solvers

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STAR TREK
Good luck on the midterm!
Midterm?! I got binders full of wumpuses!
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