Title: Logical Agents
AIMA: Chapter 7 (Sections 7.4 and 7.5)

Introduction to Artificial Intelligence
CSCE 476-876, Spring 2005
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Outline
• Login in general: models and entailment
• Propositional (Boolean) logic
• Equivalence, validity and satisfiability
• Inference:
  – By model checking
  – Using inference rules
  – Resolution algorithm: Conjunctive Normal form
  – Horn theories: forward and backward chaining
A logic consists of:

1. A formal representation system:
   (a) Syntax: how to make sentences
   (b) Semantics: systematics constraints on how sentences relate to the states of affairs

2. Proof theory: a set of rules for deducing the entailment of a set of sentences

Example:
✓ Propositional logic (or Boolean logic)
✓ First-order logic FOL

Models (I)

A model is a world in which a sentence is true under a particular interpretation

Logicians typically think in terms of models, which are formally structured worlds with respect to which truth can be evaluated

We say $m$ is a model of a sentence $\alpha$ if $\alpha$ is true in $m$

Typically, a sentence can be true in many models
Models (II)

$M(\alpha)$ is the set of all models of $\alpha$

**Entailment:** A sentence $\alpha$ is entailed by a KB if the models of the KB are all models of $\alpha$

$KB \models \alpha$ iff all models of KB are models of $\alpha$ (i.e., $M(KB) \subseteq M(\alpha)$)

Then $KB \models \alpha$ if and only if $M(KB) \subseteq M(\alpha)$

Inference

- Example of inference procedure: deduction
- Validity of a sentence: always true (i.e., under all possible interpretations)
  - The Earth is round or not round
  - $\rightarrow$ Tautology
- Satisfiability of a sentence: sometimes true (i.e., $\exists$ some interpretation(s) where it holds)
  - Alex is on campus
- Insatisfiability of a sentence: never true (i.e., $\not\exists$ any interpretation where it holds)
  - The Earth is round and the earth is not round
    - $\rightarrow$ useful for refutation, as we will see later

**Beauty of inference:**

Formal inference allows the computer to derive **valid** conclusions even when the computer does not know the interpretation you are using
Syntax of Propositional Logic

Propositional logic is the simplest logic—illustrates basic ideas

- Symbols represent whole propositions, sentences
  - D says the Wumpus is dead
  The proposition symbols $P_1$, $P_2$, etc. are sentences
- Boolean connectives: $\land, \lor, \neg, \Rightarrow$ (alternatively, $\rightarrow, \supset$), $\Leftrightarrow$, connect sentences
  If $S_1$ and $S_2$ are sentences, the following are sentences too:
  $\neg S_1$, $\neg S_2$, $S_1 \land S_2$, $S_1 \lor S_2$, $S_1 \Rightarrow S_2$, $S_1 \Leftrightarrow S_2$

Formal grammar of Propositional Logic: Backus-Naur Form, check Figure 7.7 page 205 in AIMA

Terminology

Atomic sentence: single symbol

Complex sentence: contains connectives, parentheses

Literal: atomic sentence or its negation (e.g., $P$, $\neg Q$)

Sentence $(P \land Q) \Rightarrow R$ is an implication, conditional, rule, if-then statement

$(P \land Q)$ is a premise, antecedent

$R$ is a conclusion, consequence

Sentence $(P \land Q) \Leftrightarrow R$ is an equivalence, biconditional

Precedence order resolves ambiguity (highest to lowest):

$\neg, \land, \lor, \Rightarrow, \Leftrightarrow$

E.g., $((\neg P) \lor (Q \land R)) \Rightarrow S$ Careful: $A \land B \land C$ and $A \Rightarrow B \Rightarrow C$
Syntax of First-order logic

First-Order Logic (FOL) is expressive enough to say almost anything of interest and has a sound and complete inference procedure

- Logical symbols:
  - parentheses
  - connectives (¬, ⇒, the rest can be regenerated)
  - variables
  - equality symbol (optional)
- Parameters:
  - quantifier ∀
  - predicate symbols
  - constant symbols
  - function symbols

Semantics of Propositional Logic

Semantics is defined by specifying:
— Interpretation of a proposition symbols and constants (T/F)
— Meaning of logical connectives

Proposition symbol means what ever you want:

D says the Wumpus is dead
Breeze says the agent is feeling a breeze
Stench says the agent is perceiving an unpleasant smell

Connectives are functions: complex sentences meaning derived from the meaning of its parts

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<th>Q</th>
<th>¬P</th>
<th>P ∧ Q</th>
<th>P ∨ Q</th>
<th>P ⇒ Q</th>
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Note:
P ⇒ Q: if P is true, Q is true, otherwise I am making no claim
Models in propositional logic

- A model is a mapping from proposition symbols directly to truth or falsehood
- The models of a sentence are the mappings that make the sentence true

Example:

\[ \alpha: \text{obj}1 \land \text{obj}2 \]
\[ \checkmark \text{ Model1: } \text{obj}1 = 1 \text{ and } \text{obj}2 = 1 \]
\[ \times \text{ Model2: } \text{obj}1 = 0 \text{ and } \text{obj}2 = 1 \]

Wumpus world in Propositional Logic

- \( P_{i,j} \): there is a pit in \([i, j]\)
- \( B_{i,j} \): there is a breeze in \([i, j]\)

- \( R_1 : \neg P_{1,1} \)
- “Pits cause breezes in adjacent squares”
  - \( R_2 : B_{1,1} \leftrightarrow (P_{1,2} \lor P_{2,1}) \)
  - \( R_3 : B_{2,1} \leftrightarrow (P_{1,1} \lor P_{2,2} \lor P_{3,1}) \)
- Percepts:
  - \( R_4 : \neg B_{1,1} \)
  - \( R_5 : B_{2,1} \)
- KB: \( R_1 \land R_2 \land R_3 \land R_4 \land R_5 \)
- Questions: KB \( \models \neg P_{1,2} \)? KB \( \not\models P_{2,2} \)?
**umpus world** in Propositional Logic

Given KB: \( R_1 \land R_2 \land R_3 \land R_4 \land R_5 \)

Number of symbols: 7
Number of models: \( 2^7 = 128 \)

<See Figure 7.9, page 209>

KB is true in only 3 models

\( P_{1,2} \) is false but \( \neg P_{1,2} \) holds in all 3 models of the KB, thus KB \( \models \neg P_{1,2} \)

\( P_{2,2} \) is true in 2 models, false in third, thus KB \( \not\models P_{2,2} \)

---

**Enumeration method** in Propositional Logic

Let \( \alpha = A \lor B \) and KB = \( (A \lor C) \land (B \lor \neg C) \)

Is it the case that KB \( \models \alpha \)?

Check all possible models—\( \alpha \) must be true wherever KB is true

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Complexity? Inference is exponential in propositional logic
Inference by enumeration

- Algorithm: TT-ENTAILS?(KB, α), Figure 209
  - Identifies all the symbols in kb
  - Performs a recursive enumeration of all possible assignments (T/F) to symbols
  - In a depth-first manner
- It terminates: there is only a finite number of models
- It is sound: because it implements definition of entailment
- It is complete, and works for any KB and α
- Time complexity: $O(2^n)$, for a KB with $n$ symbols
- Alert: Entailment in Propositional Logic is co-NP-Complete

Important concepts

- Logical equivalence
- Validity
  - Deduction theorem: links validity to entailment
- Satisfiability
  - Refutation theorem: links satisfiability to entailment
Logical equivalence

Two sentences are logically equivalent $\alpha \leftrightarrow \beta$ iff true in same models

$\alpha \equiv \beta$ if and only if $\alpha \models \beta$ and $\beta \models \alpha$

\[
\begin{align*}
(\alpha \land \beta) & \equiv (\beta \land \alpha) \quad \text{commutativity of } \land \\
(\alpha \lor \beta) & \equiv (\beta \lor \alpha) \quad \text{commutativity of } \lor \\
((\alpha \land \beta) \land \gamma) & \equiv (\alpha \land (\beta \land \gamma)) \quad \text{associativity of } \land \\
((\alpha \lor \beta) \lor \gamma) & \equiv (\alpha \lor (\beta \lor \gamma)) \quad \text{associativity of } \lor \\
\neg(\neg \alpha) & \equiv \alpha \quad \text{double-negation elimination} \\
(\alpha \implies \beta) & \equiv (\neg \beta \implies \neg \alpha) \quad \text{contraposition} \\
(\alpha \implies \beta) & \equiv (\neg \alpha \lor \beta) \quad \text{implication elimination} \\
(\alpha \iff \beta) & \equiv ((\alpha \implies \beta) \land (\beta \implies \alpha)) \quad \text{biconditional elimination} \\
\neg(\alpha \land \beta) & \equiv (\neg \alpha \lor \neg \beta) \quad \text{de Morgan} \\
\neg(\alpha \lor \beta) & \equiv (\neg \alpha \land \neg \beta) \quad \text{de Morgan} \\
(\alpha \land (\beta \lor \gamma)) & \equiv ((\alpha \land \beta) \lor (\alpha \land \gamma)) \quad \text{distributivity of } \land \text{ over } \lor \\
(\alpha \lor (\beta \land \gamma)) & \equiv ((\alpha \lor \beta) \land (\alpha \lor \gamma)) \quad \text{distributivity of } \lor \text{ over } \land
\end{align*}
\]

Validity

A sentence is valid if it is true in all models

e.g., $P \lor \neg P$, \quad $P \Rightarrow P$, \quad $(P \land (P \Rightarrow H)) \Rightarrow H$

To establish validity, use truth tables:

<table>
<thead>
<tr>
<th>$P$</th>
<th>$H$</th>
<th>$P \lor H$</th>
<th>$(P \lor H) \land \neg H$</th>
<th>$((P \lor H) \land \neg H) \Rightarrow P$</th>
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If every row is true, then then the conclusion, $P$, is entailed by the premises, $((P \lor H) \land \neg H)$

Use of validity: Deduction Theorem:

$KB \models \alpha$ iff $(KB \Rightarrow \alpha)$ is valid

$\text{TT-ENTAILS?(KB, } \alpha) \text{ checks the validity of } (KB \Rightarrow \alpha)$
Satisfiability

A sentence is *satisfiable* if it is true in *some* model
\[ e.g., A \lor B, \quad C \]

Satisfiability can be checked by enumerating the possible models until one is found that satisfies the sentence (e.g., SAT!)
A sentence is *unsatisfiable* if it is true in **no** models
\[ e.g., A \land \neg A \]

Satisfiability and validity are connected:
\( \alpha \) valid iff \( \neg \alpha \) is unsatisfiable and \( \alpha \) satisfiable iff \( \neg \alpha \) is not valid

Use of satisfiability: refutation
\[ KB \models \alpha \iff (KB \land \neg \alpha) \text{ is unsatisfiable} \]
i.e., prove \( \alpha \) by *reductio ad absurdum*

---

Proof methods

Proof methods divide into (roughly) two kinds
Model checking
- Truth-table enumeration (sound & complete but exponential)
- Backtrack search in model space (sound & complete)
  \[ e.g., \text{Davis-Putnam Algorithm (DPLL) (Section 7.6)} \]
- Heuristic search in model space (sound but incomplete)
  \[ e.g., \text{the GSAT algorithm, the WalkSat algorithm (Section 7.6)} \]

Application of inference rules
- Legitimate (sound) generation of new sentences from old
- **Proof** = a sequence of inference rule applications, can use inference rules as operators in a standard search algorithm
- Typically require translation of sentences into a normal form
Inference rules for Propositional Logic (I)

Reasoning patterns

- **Modus Ponens (Implication-Elimination)**
  \[
  \alpha \Rightarrow \beta, \ \alpha \\
  \frac{}{\beta}
  \]

- **And-Elimination**
  \[
  \alpha_1 \land \alpha_2 \land \ldots \land \alpha_n \\
  \frac{}{\alpha_i}
  \]

- We can also use all logical equivalences as inference rules:
  \[
  \frac{\alpha \Leftrightarrow \beta}{(\alpha \Rightarrow \beta) \land (\beta \Rightarrow \alpha)} \quad \text{and} \quad \frac{(\alpha \Rightarrow \beta) \land (\beta \Rightarrow \alpha)}{\alpha \Leftrightarrow \beta}
  \]

**Soundness** of an inference rule can be verified by building a truth table

---

Inference rules and equivalences in the wumpus world

Given KB: \( R_1 \land R_2 \land R_3 \land R_4 \land R_5 \)
Prove: \( \neg P_{1,2} \)

- Biconditional elimination to \( R_2 : B_{1,1} \Leftrightarrow (P_{1,2} \lor P_{2,1}) \)
  \( R_6 : (B_{1,1} \Rightarrow (P_{1,2} \lor P_{2,1})) \land ((P_{1,2} \lor P_{2,1}) \Rightarrow B_{1,1}) \)

- And elimination to \( R_6 \):
  \( R_7 : ((P_{1,2} \lor P_{2,1}) \Rightarrow B_{1,1}) \)

- Logical equivalence of contrapositives:
  \( R_8 : (\neg B_{1,1} \Rightarrow \neg (P_{1,2} \lor P_{2,1})) \)

- Modus ponens on \( R_8 \) and \( R_4 : \neg B_{1,1} \)
  \( R_8 : \neg (P_{1,2} \lor P_{2,1}) \)

- De Morgan’s rules: \( R_9 : \neg P_{1,2} \land \neg P_{2,1} \)
The job of an inference procedure is to construct proofs by finding appropriate sequences of applications of inference rules starting with sentences initially in KB and culminating in the generation of the sentence whose proof is desired.

Complexity of propositional inference

Truth-table: Sound and complete.
\[ 2^n \text{ rows: exponential, thus impractical} \]
Entailment is co-NP-Complete in Propositional Logic

Inference rules: sound (resolution gives completeness)
NP-complete in general
However, we can focus on the sentences and propositions of interest: The truth values of all propositions need not be considered
Monotonicity

the set of entailed sentences can only increase as information (new sentences) is added to the KB:
if $\text{KB} \models \alpha$ then $(\text{KB} \land \beta) \models \alpha$

Monotonicity allows us to apply inference rules whenever suitable premises appear in the KB: the conclusion of the rule follow regardless of what else is in the KB

PL, FOL are monotonic, probability theory is not

Monotonicity essential for soundness of inference

Resolution for completeness of inference rules

- Unit resolution:

  \[
  \begin{array}{c}
  l_1 \lor l_2, \quad \neg l_2 \\
  \hline
  l_1
  \end{array}
  \]

  More generally:

  \[
  \begin{array}{c}
  l_1 \lor \cdots \lor l_k, \quad m \\
  \hline
  l_1 \lor \cdots \lor l_{i-1} \lor l_{i+1} \lor \cdots \lor l_k
  \end{array}
  \]

  where $l_i$ and $m$ are complementary literals

- Resolution:

  \[
  \begin{array}{c}
  l_1 \lor l_2, \quad \neg l_2 \lor l_3 \\
  \hline
  l_1 \lor l_3
  \end{array}
  \]

  More generally:

  \[
  \begin{array}{c}
  l_1 \lor \cdots \lor l_k, \quad m_1 \lor \cdots \lor m_n \\
  \hline
  l_1 \lor \cdots \lor l_{i-1} \lor l_{i+1} \lor \cdots \lor l_k \lor m_1 \lor \cdots \lor m_{j-1} \lor m_{j+1} \lor \cdots \lor m_n
  \end{array}
  \]

  where $l_i$ and $m_j$ are complementary literals
Resolution in the wumpus world

Agent goes [1, 1], [2, 1], [1, 1], [1, 2]

Agent perceives a stench but no breeze: \( R_{11} : \neg B_{1,2} \)
But \( R_{12} : B_{1,2} \iff (P_{1,1} \lor P_{2,2} \lor P_{1,3}) \)

Applying biconditional elimination to \( R_{12} \), followed by
and-elimination, contraposition, and finally modus ponens with
\( R_{11} \), we get:

\( R_{13} : \neg P_{2,2} \) and \( R_{14} : \neg P_{1,3} \)

\( R_{3} : B_{2,1} \iff (P_{1,1} \lor P_{2,2} \lor P_{3,1}) \)

\( R_{5} : B_{2,1} \)

Now, applying biconditional elimination too \( R_{3} \) and modus ponens
with \( R_{5} \), we get:

\( R_{15} : P_{1,1} \lor P_{2,2} \lor P_{3,1} \)

Resolving \( R_{13} \) and \( R_{15} : R_{16} : P_{1,1} \lor P_{3,1} \)

Resolving \( R_{16} \) and \( R_{1} : R_{17} : P_{3,1} \)

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Soundness of the resolution rule

Resolution rule: \( \frac{\alpha \lor \beta, \neg \beta \lor \gamma}{\alpha \lor \gamma} \) or

equivalently \( \frac{\neg \alpha \Rightarrow \beta, \beta \Rightarrow \gamma}{\alpha \Rightarrow \gamma} \)

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**Resolution** for completeness of inference rules

- Inference rules can be used as successor functions in a search-based agent

- Any complete search algorithm, applying only the resolution rule, can derive any conclusion entailed by any knowledge base in propositional logic.

- Refutation completeness:
  Resolution can always be used to either prove or refute a sentence
  \[ \rightarrow \text{Resolution algorithm on CNF} \]

- Caveat:
  Resolution cannot be used to enumerate true sentences.
  Given $A$ is true, resolution cannot generate $A \lor B$

---

**Conjunctive Normal Form**

- Resolution applies only to disjunctions of literals

- We can transform any sentence in PL in CNF

- A $k$-CNF has exactly $k$ literals per clause:
  \[(l_{1,1} \lor \cdots \lor l_{1,k}) \land \cdots \land (l_{n,1} \lor \cdots \lor l_{n,k})\]

Conversion procedure:

- Eliminate $\leftrightarrow$ using biconditional elimination

- Eliminate $\Rightarrow$ using implication elimination

- Move $\neg$ inwards using (repeatedly) double-negation elimination and de Morgan rules

- Apply distributivity law, distributing $\lor$ over $\land$ whenever possible

Finally, the KB can be used as input to a resolution procedure
**Example** of conversion to CNF

\[ R_2 : B_{1,1} \iff (P_{1,2} \lor P_{2,1}) \]

- Eliminate \( \Rightarrow \) using biconditional elimination
  \[ (B_{1,1} \Rightarrow (P_{1,2} \lor P_{2,1})) \land ((P_{1,2} \lor P_{2,1}) \Rightarrow B_{1,1}) \]

- Eliminate \( \Rightarrow \) using implication elimination
  \[ (\neg B_{1,1} \lor (P_{1,2} \lor P_{2,1})) \land ((P_{1,2} \lor P_{2,1}) \lor B_{1,1}) \]

- Move \( \neg \) inwards using (repeatedly) double-negation elimination and de Morgan rules
  \[ (\neg B_{1,1} \lor (P_{1,2} \lor P_{2,1})) \land (\neg P_{1,2} \land \neg P_{2,1}) \lor B_{1,1} \]

- Apply distributivity law, distributing \( \lor \) over \( \land \) whenever possible
  \[ (\neg B_{1,1} \lor P_{1,2} \lor P_{2,1}) \land (\neg P_{1,2} \lor B_{1,1}) \land (\neg P_{2,1} \lor B_{1,1}) \]

---

**Resolution algorithm**

- \( KB \models \alpha \) iff \( (KB \land \neg \alpha) \) is unsatisfiable

- \( (KB \land \neg \alpha) \) is converted to CNF
  then we apply resolution rule repeatedly, until:
  - no clause can be added (i.e., \( KB \models \neg \alpha \))
  - we derive the empty clause (i.e., \( KB \models \alpha \))

  \(<\text{PL-ResOLUTION}(KB, \alpha), \text{Fig 7.12, page 216}>\)

- Ground resolution theorem:
  If a set of clauses is unsatisfiable, then the resolution closure of those clauses contains the empty clause.
Example of applying resolution algorithm to wumpus world

With KB = R2 ∧ R4, prove that ¬P1,2

R2 : B1,1 ⇔ (P1,2 ∨ P2,1)
R4 : ¬B1,1

Note that many steps are pointless and could be avoided, example:

B1,1 ∨ P2,1 ∨ ¬B1,1 = True ∨ P2,1 = True

Restriction to Horn clauses: a subset of PL

- Disjunctive form: disjunction of literals of which at most one is positive
  Example: ¬P1 ∨ ¬P2 ∨ ... ∨ ¬Pn ∨ Q where Pi and Q are non-negated atoms

- Implicative form: an implication whose premise is a conjunction of literals and whose conclusion is a single positive literal
  Example: P1 ∧ P2 ∧ ... Pn ⇒ Q, where Pi and Q are non-negated atoms

Significance of Horn clauses:

- Real-world KB’s are easy to write in implicative form
- Inference can be done with Forward and Backward chaining (easy to trace and understand) PL-FC-ENTAILS?(KB, q)
- Deciding entailment with Horn clauses is linear time
**Forward chaining** PL-FC-ENTAILS? (KB, q)

- determines whether \( p \) is entailed by a KB of Horn clauses
- begins with known facts
- asserts the conclusion (head) of an implication whose premises hold
- continues until the query \( q \) is added to KB (success) or no further inferences can be made (failure)

Forward chaining terminates (reaches a fixed point), is sound and complete

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**Execution example** of Forward chaining

KB: \((P \Rightarrow Q) \land (L \land M \Rightarrow P) \land (B \land L \Rightarrow M) \land (A \land P \Rightarrow L) \land (A \land B \Rightarrow L) \land A \land B\)
Inference in Horn theories

Runs in linear time

- Forward chaining:
  - data-driven
  - infers every possible conclusion
  - may do lots of work that is irrelevant to the goal

- Backward chaining:
  - goal-directed reasoning
  - works back from q, tries to find known facts that support the query
  - touches only relevant facts, often cost much less than linear in the size of KB

Problems with Propositional Logic

- good vehicle for introducing what logic / inference is

- too weak to even handle the Wumpus world
  ‘Don’t go forward when Wumpus is in front of you’ requires 64 rules (16 squares x 4 orientations for agent)

- Problem: generating rules, handling truth tables ($2^n$ rows for $n$ symbols)!

- Important problem: How to represent change when agent moves from [1, 1] to [1, 2]? Solution: Time-stamp symbols :-(

  But (1) length of game is not known in advance, (2) rewrite a time-dependent version of each rule.

Problem: PL only allows propositions, no relations, no objects
Summary

Logical agents apply inference to a knowledge base to derive new information and make decisions.

Basic concepts of logic:
— **Syntax:** formal structure of sentences
— **Semantics:** truth of sentences WRT models
— **Entailment:** necessary truth of one sentence given another
— **Inference:** deriving sentences from other sentences
— **Soundness:** derivations produce only entailed sentences
— **Completeness:** derivations can produce all entailed sentences

- Truth-table method is sound and complete for propositional logic
- Forward and backward chaining are linear-time, sound and complete for Horn clauses
- Resolution is complete for propositional logic

→ Propositional logic suffices for some of these tasks, not all