Logical Agents

Chapter 7
Outline

- Knowledge-based agents
- Wumpus world
- Logic in general - models and entailment
- Propositional (Boolean) logic
- Equivalence, validity, satisfiability
- Inference rules and theorem proving
  - forward chaining
  - backward chaining
  - resolution
Knowledge bases

- Knowledge base = set of sentences in a formal language

- **Declarative** approach to building an agent (or other system):
  - **Tell** it what it needs to know

- Then it can **Ask** itself what to do - answers should follow from the KB

- Agents can be viewed at the **knowledge level**
  - i.e., what they know, regardless of how implemented

- Or at the **implementation level**
  - i.e., data structures in KB and algorithms that manipulate them
A simple knowledge-based agent

The agent must be able to:

- Represent states, actions, etc.
- Incorporate new percepts
- Update internal representations of the world
- Deduce hidden properties of the world

```plaintext
function KB-AGENT( percept ) returns an action
    static: KB, a knowledge base
    t, a counter, initially 0, indicating time
    TELL(KB, MAKE-PERCEPT-SENTENCE( percept, t ))
    action ← ASK( KB, MAKE-ACTION-QUERY(t ) )
    TELL(KB, MAKE-ACTION-SENTENCE( action, t ))
    t ← t + 1
    return action
```
Wumpus World PEAS description

- **Performance measure**
  - gold +1000, death -1000
  - -1 per step, -10 for using the arrow

- **Environment**
  - Squares adjacent to wumpus are smelly
  - Squares adjacent to pit are breezy
  - Glitter iff gold is in the same square
  - Shooting kills wumpus if you are facing it
  - Shooting uses up the only arrow
  - Grabbing picks up gold if in same square
Wumpus world characterization

- **Fully Observable** No – only local perception
- **Deterministic** Yes – outcomes exactly specified
- **Episodic** No – sequential at the level of actions
- **Static** Yes – Wumpus and Pits do not move
- **Discrete** Yes
- **Single-agent?** Yes – Wumpus is essentially a
  natural feature
Exploring a wumpus world
Exploring a wumpus world
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Exploring a wumpus world

P

B

A

A

OK

OK

S

W
Exploring a wumpus world
Exploring a wumpus world
Logic in general

- **Logics** are formal languages for representing information such that conclusions can be drawn.

- **Syntax** defines the sentences in the language.

- **Semantics** define the "meaning" of sentences;
  - i.e., define **truth** of a sentence in a world.

- E.g., the language of arithmetic
  - $x+2 \geq y$ is a sentence; $x^2+y > \{\}$ is not a sentence
  - $x+2 \geq y$ is true iff the number $x+2$ is no less than the number $y$.
Entailment

- **Entailment** means that one thing follows from another:

  \[
  \text{KB } \models \alpha
  \]

- Knowledge base \( KB \) entails sentence \( \alpha \) if and only if \( \alpha \) is true in all worlds where \( KB \) is true
  - E.g., the KB containing “the Giants won” and “the Reds won” entails “Either the Giants won or the Reds won”
  - E.g., \( x+y = 4 \) entails \( 4 = x+y \)
  - Entailment is a relationship between sentences (i.e., syntax) that is based on semantics
Models

- 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 \( m \).

- \( M(\alpha) \) is the set of all models of \( \alpha \).

- Then \( KB \models \alpha \) iff \( M(KB) \subseteq M(\alpha) \).

- E.g. \( KB = \) Giants won and Reds won \( \alpha = \) Giants won.
Entailment in the wumpus world

Situation after detecting nothing in [1,1], moving right, breeze in [2,1]

Consider possible models for $KB$ assuming only pits

3 Boolean choices $\Rightarrow$ 8 possible models
Wumpus models
Wumpus models

- $KB = \text{wumpus-world rules} + \text{observations}$
Wumpus models

- $KB = \text{wumpus-world rules} + \text{observations}$
- $\alpha_1 = \text{"[1,2] is safe"}$, $KB \models \alpha_1$, proved by model checking
Wumpus models

- $KB = \text{wumpus-world rules + observations}$
Wumpus models

- $KB = \text{wumpus-world rules} + \text{observations}$
- $\alpha_2 = \text{"[2,2] is safe"}$, $KB \not\models \alpha_2$
Inference

- Define: $KB \vdash_i \alpha = \text{sentence } \alpha \text{ can be derived from } KB \text{ by procedure } i$

- **Soundness:** $i$ is sound if whenever $KB \vdash_i \alpha$, it is also true that $KB \not\models \alpha$

- **Completeness:** $i$ is complete if whenever $KB \models \alpha$, it is also true that $KB \vdash_i \alpha$

- Preview: we will define a logic (first-order logic) which is expressive enough to say almost anything of interest, and for which there exists a sound and complete inference procedure.

That is, the procedure will answer any question whose answer is contained in $KB$. 
Propositional logic: Syntax

- Propositional logic is the simplest logic – illustrates basic ideas

- The proposition symbols $P_1$, $P_2$ etc are sentences
  - If $S$ is a sentence, $\neg S$ is a sentence (negation)
  - If $S_1$ and $S_2$ are sentences, $S_1 \land S_2$ is a sentence (conjunction)
  - If $S_1$ and $S_2$ are sentences, $S_1 \lor S_2$ is a sentence (disjunction)
  - If $S_1$ and $S_2$ are sentences, $S_1 \Rightarrow S_2$ is a sentence (implication)
  - If $S_1$ and $S_2$ are sentences, $S_1 \Leftrightarrow S_2$ is a sentence (biconditional)
Propositional logic: Semantics

Each model specifies true/false for each proposition symbol

E.g. \( P_{1,2} \) \( P_{2,2} \) \( P_{3,1} \)
false true false

With these symbols, 8 possible models, can be enumerated automatically.

Rules for evaluating truth with respect to a model \( m \):

\[
\begin{align*}
\neg S & \quad \text{is true iff} \quad S \text{ is false} \\
S_1 \land S_2 & \quad \text{is true iff} \quad S_1 \text{ is true and } S_2 \text{ is true} \\
S_1 \lor S_2 & \quad \text{is true iff} \quad S_1 \text{ is true or } S_2 \text{ is true} \\
S_1 \Rightarrow S_2 & \quad \text{is true iff} \quad S_1 \text{ is false or } S_2 \text{ is true} \\
\text{i.e.,} & \quad \text{is false iff} \quad S_1 \text{ is true and } S_2 \text{ is false} \\
S_1 \iff S_2 & \quad \text{is true iff} \quad S_1 \Rightarrow S_2 \text{ is true and } S_2 \Rightarrow S_1 \text{ is true}
\end{align*}
\]

Simple recursive process evaluates an arbitrary sentence, e.g.,

\[
\neg P_{1,2} \land (P_{2,2} \lor P_{3,1}) = true \land (true \lor false) = true \land true = true
\]
**Truth tables for connectives**

<table>
<thead>
<tr>
<th>$P$</th>
<th>$Q$</th>
<th>$\neg P$</th>
<th>$P \land Q$</th>
<th>$P \lor Q$</th>
<th>$P \Rightarrow Q$</th>
<th>$P \Leftrightarrow Q$</th>
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Wumpus world sentences

Let $P_{i,j}$ be true if there is a pit in $[i, j]$. Let $B_{i,j}$ be true if there is a breeze in $[i, j]$.

\[-P_{1,1}\]
\[-B_{1,1}\]
$B_{2,1}$

"Pits cause breezes in adjacent squares"

$B_{1,1} \iff (P_{1,2} \lor P_{2,1})$
$B_{2,1} \iff (P_{1,1} \lor P_{2,2} \lor P_{3,1})$
### Truth tables for inference

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<th>$B_{1,1}$</th>
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<th>$P_{2,2}$</th>
<th>$P_{3,1}$</th>
<th>$KB$</th>
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Inference by enumeration

- Depth-first enumeration of all models is sound and complete

```
function TT-ENTAILS?(KB, α) returns true or false
    symbols ← a list of the proposition symbols in KB and α
    return TT-CHECK-ALL(KB, α, symbols, [])

function TT-CHECK-ALL(KB, α, symbols, model) returns true or false
    if EMPTY?(symbols) then
        if PL-TRUE?(KB, model) then return PL-TRUE?(α, model)
        else return true
    else do
        P ← FIRST(symbols); rest ← REST(symbols)
        return TT-CHECK-ALL(KB, α, rest, EXTEND(P, true, model) and TT-CHECK-ALL(KB, α, rest, EXTEND(P, false, model))
```

- For $n$ symbols, time complexity is $O(2^n)$, space complexity is $O(n)$
Logical equivalence

- Two sentences are **logically equivalent** iff true in same models: $\alpha \equiv \beta$ iff $\alpha \models \beta$ and $\beta \models \alpha$

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

A sentence is **valid** if it is true in **all** models,

- e.g., $True$, $A \lor \neg A$, $A \Rightarrow A$, $(A \land (A \Rightarrow B)) \Rightarrow B$

Validity is connected to inference via the **Deduction Theorem**:

$KB \models \alpha$ if and only if $(KB \Rightarrow \alpha)$ is valid

A sentence is **satisfiable** if it is true in **some** model

- e.g., $A \lor B$, $C$

A sentence is **unsatisfiable** if it is true in **no** models

- e.g., $A \land \neg A$

Satisfiability is connected to inference via the following:

$KB \models \alpha$ if and only if $(KB \land \neg \alpha)$ is unsatisfiable
Proof methods

Proof methods divide into (roughly) two kinds:

- **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 transformation of sentences into a normal form

- **Model checking**
  - truth table enumeration (always exponential in \( n \))
  - improved backtracking, e.g., Davis--Putnam-Logemann-Loveland (DPLL)
Resolution

Conjunctive Normal Form (CNF)

conjunction of disjunctions of literals

clauses

E.g., \((A \lor \neg B) \land (B \lor \neg C \lor \neg D)\)

- **Resolution** inference rule (for CNF):

\[
\begin{align*}
\ell_i \lor \ldots \lor \ell_k, & \quad m_1 \lor \ldots \lor m_n \\
\ell_i \lor \ldots \lor \ell_{i-1} \lor \ell_{i+1} \lor \ldots \lor \ell_k \lor m_1 \lor \ldots \lor m_{j-1},
\end{align*}
\]

where \(\ell_i\) and \(m_j\) are complementary literals.

E.g., \(P_{1,3} \lor P_{2,2}, \quad \neg P_{2,2}\)

\(P_{1,3}\)

- Resolution is sound and complete for propositional logic.
Resolution

Soundness of resolution inference rule:

\[
\neg (l_i \lor \ldots \lor l_{i-1} \lor l_{i+1} \lor \ldots \lor l_k) \Rightarrow l_i
\]

\[
\neg m_j \Rightarrow (m_1 \lor \ldots \lor m_{j-1} \lor m_{j+1} \lor \ldots \lor m_n)
\]

\[
\neg (l_i \lor \ldots \lor l_{i-1} \lor l_{i+1} \lor \ldots \lor l_k) \Rightarrow (m_1 \lor \ldots \lor m_{j-1} \lor m_{j+1} \lor \ldots \lor m_n)
\]

where \(l_i\) and \(m_j\) are complementary literals.
Conversion to CNF

1. Eliminate \( \iff \), replacing \( \alpha \iff \beta \) with \((\alpha \implies \beta) \land (\beta \implies \alpha)\).

\[
(B_{1,1} \implies (P_{1,2} \lor P_{2,1})) \land ((P_{1,2} \lor P_{2,1}) \implies B_{1,1})
\]

2. Eliminate \( \implies \), replacing \( \alpha \implies \beta \) with \( \neg \alpha \lor \beta \).

\[
(\neg B_{1,1} \lor P_{1,2} \lor P_{2,1}) \land (\neg (P_{1,2} \lor P_{2,1}) \lor B_{1,1})
\]

3. Move \( \neg \) inwards using de Morgan's rules and double-negation:

\[
(\neg B_{1,1} \lor P_{1,2} \lor P_{2,1}) \land ((\neg P_{1,2} \lor \neg P_{2,1}) \lor B_{1,1})
\]
Resolution algorithm

- Proof by contradiction, i.e., show $KB \land \neg \alpha$ unsatisfiable

```plaintext
function PL-RESOLUTION(KB, \alpha) returns true or false

clauses ← the set of clauses in the CNF representation of $KB \land \neg \alpha$
new ← {}

loop do
    for each $C_i, C_j$ in clauses do
        resolvents ← PL-RESOLVE($C_i, C_j$)
        if resolvents contains the empty clause then return true
        new ← new ∪ resolvents
    if new ⊆ clauses then return false
    clauses ← clauses ∪ new
```
Resolution example

- $KB = (B_{1,1} \iff (P_{1,2} \lor P_{2,1})) \land \neg B_{1,1}$
- $\alpha = \neg P_{1,2}$ (negate the premise for proof by refutation)

To think about: what does an empty proposition mean?
Forward and backward chaining

- **Horn Form (restricted)**
  
  \[ KB = \text{conjunction of Horn clauses} \]

  - Horn clause =
    - proposition symbol; or
    - (conjunction of symbols) \(\Rightarrow\) symbol

  - E.g., \(C \land (B \Rightarrow A) \land (C \land D \Rightarrow B)\)

- **Modus Ponens (for Horn Form): complete for Horn KBs**

  \[
  \begin{align*}
  \alpha_1, \ldots, \alpha_n, & \quad a_1 \land \ldots \land a_n \Rightarrow \beta \\
  \beta & 
  \end{align*}
  \]

- Can be used with **forward chaining** or **backward chaining**.
- These algorithms are very natural and run in **linear time**
Forward chaining

- Idea: fire any rule whose premises are satisfied in the $KB$, add its conclusion to the $KB$, until query is found

\[ P \Rightarrow Q \]
\[ L \land M \Rightarrow P \]
\[ B \land L \Rightarrow M \]
\[ A \land P \Rightarrow L \]
\[ A \land B \Rightarrow L \]
\[ A \]
\[ B \]
Forward chaining algorithm

function PL-FC-ENTAILS?(KB, q) returns true or false

  local variables: count, a table, indexed by clause, initially the number of premises
  inferred, a table, indexed by symbol, each entry initially false
  agenda, a list of symbols, initially the symbols known to be true

  while agenda is not empty do
      p ← POP(agenda)
      unless inferred[p] do
          inferred[p] ← true
          for each Horn clause c in whose premise p appears do
              decrement count[c]
              if count[c] = 0 then do
                  if HEAD[c] = q then return true
              PUSH(HEAD[c], agenda)
      return false

Forward chaining is sound and complete for Horn KB
Forward chaining example
Forward chaining example
Forward chaining example
Forward chaining example
Forward chaining example
Forward chaining example
Forward chaining example
Forward chaining example

[Diagram of a network with nodes labeled Q, P, M, L, A, B, showing a forward chaining process.]
Proof of completeness

- FC derives every atomic sentence that is entailed by $KB$

1. FC reaches a **fixed point** where no new atomic sentences are derived

2. Consider the final state as a model $m$, assigning true/false to symbols

3. Every clause in the original $KB$ is true in $m$

   $$a_1 \land \ldots \land a_k \Rightarrow b$$

4. Hence $m$ is a model of $KB$
Backward chaining

Idea: work backwards from the query $q$:

to prove $q$ by BC,
check if $q$ is known already, or
prove by BC all premises of some rule concluding $q$

Avoid loops: check if new subgoal is already on the goal stack

Avoid repeated work: check if new subgoal
has already been proved true, or
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Backward chaining example
Forward vs. backward chaining

- FC is data-driven, automatic, unconscious processing,
  - e.g., object recognition, routine decisions

- May do lots of work that is irrelevant to the goal

- BC is goal-driven, appropriate for problem-solving,
  - e.g., Where are my keys? How do I get into a PhD program?

- Complexity of BC can be much less than linear in size of KB
Efficient propositional inference

Two families of efficient algorithms for propositional inference:

Complete backtracking search algorithms
- DPLL algorithm (Davis, Putnam, Logemann, Loveland)

Incomplete local search algorithms
- WalkSAT algorithm
The DPLL algorithm

Determine if an input propositional logic sentence (in CNF) is satisfiable.

Improvements over truth table enumeration:

1. **Early termination**
   A clause is true if any literal is true.
   A sentence is false if any clause is false.

2. **Pure symbol heuristic**
   Pure symbol: always appears with the same "sign" in all clauses.
   e.g., In the three clauses \((A \lor \neg B), (\neg B \lor \neg C), (C \lor A)\), \(A\) and \(B\) are pure, \(C\) is impure.
   Make a pure symbol literal true.

3. **Unit clause heuristic**
   Unit clause: only one literal in the clause
   The only literal in a unit clause must be true.
The DPLL algorithm

```plaintext
function DPLL-SATISFIABLE?(s) returns true or false
  inputs: s, a sentence in propositional logic
  clauses ← the set of clauses in the CNF representation of s
  symbols ← a list of the proposition symbols in s
  return DPLL(clauses, symbols, [])

function DPLL(clauses, symbols, model) returns true or false
  if every clause in clauses is true in model then return true
  if some clause in clauses is false in model then return false
  P, value ← FIND-PURE-SYMBOL(symbols, clauses, model)
  if P is non-null then return DPLL(clauses, symbols−P, [P = value|model])
  P, value ← FIND-UNIT-CLAUSE(clauses, model)
  if P is non-null then return DPLL(clauses, symbols−P, [P = value|model])
  P ← FIRST(symbols); rest ← REST(symbols)
  return DPLL(clauses, rest, [P = true|model]) or
         DPLL(clauses, rest, [P = false|model])
```
The \textit{WalkSAT} algorithm

- Incomplete, local search algorithm

- Evaluation function: The min-conflict heuristic of minimizing the number of unsatisfied clauses

- Balance between greediness and randomness
The WalkSAT algorithm

function WalkSAT(clauses, p, max-flips) returns a satisfying model or failure

inputs: clauses, a set of clauses in propositional logic
p, the probability of choosing to do a "random walk" move
max-flips, number of flips allowed before giving up

model ← a random assignment of true/false to the symbols in clauses
for i = 1 to max-flips do
    if model satisfies clauses then return model
    clause ← a randomly selected clause from clauses that is false in model
    with probability p flip the value in model of a randomly selected symbol
    from clause
    else flip whichever symbol in clause maximizes the number of satisfied clauses
return failure
Hard satisfiability problems

Consider random 3-CNF sentences. e.g.,

$$(\neg D \lor \neg B \lor C) \land (B \lor \neg A \lor \neg C) \land (\neg C \lor \neg B \lor E) \land (E \lor \neg D \lor B) \land (B \lor E \lor \neg C)$$

$m = \text{number of clauses}$
$n = \text{number of symbols}$

Hard problems seem to cluster near $m/n = 4.3$
Hard satisfiability problems
Hard satisfiability problems

- Median runtime for 100 satisfiable random 3-CNF sentences, $n = 50$
Inference-based agents in the wumpus world

A wumpus-world agent using propositional logic:

\[
\begin{align*}
\neg P_{1,1} \\
\neg W_{1,1} \\
B_{x,y} &\iff (P_{x,y+1} \lor P_{x,y-1} \lor P_{x+1,y} \lor P_{x-1,y}) \\
S_{x,y} &\iff (W_{x,y+1} \lor W_{x,y-1} \lor W_{x+1,y} \lor W_{x-1,y}) \\
W_{1,1} \lor W_{1,2} \lor \ldots \lor W_{4,4} \\
\neg W_{1,1} \lor \neg W_{1,2} \\
\neg W_{1,1} \lor \neg W_{1,2} \\
\ldots
\end{align*}
\]

⇒ 64 distinct proposition symbols, 155 sentences
function PL-WUMPUS-AGENT(\text{percept}) \text{ returns an action}
  \text{inputs: percept, a list, [stench,breeze,glitter]}
  \text{static: KB, initially containing the “physics” of the wumpus world}
  \hspace{1em} x, y, \text{orientation, the agent’s position (init. [1,1]) and orient. (init. right)}
  \hspace{1em} \text{visited, an array indicating which squares have been visited, initially false}
  \hspace{1em} \text{action, the agent’s most recent action, initially null}
  \hspace{1em} \text{plan, an action sequence, initially empty}
  \text{update } x,y,\text{orientation, visited based on action}
  \text{if stench then TELL(KB, } S_{x,y} \text{) else TELL(KB, } \neg S_{x,y} \text{)}
  \text{if breeze then TELL(KB, } B_{x,y} \text{) else TELL(KB, } \neg B_{x,y} \text{)}
  \text{if glitter then action} \leftarrow \text{grab}
  \text{else if plan is nonempty then action} \leftarrow \text{POP(plan)}
  \text{else if for some fringe square } [i,j], \text{ ASK(KB, } \neg P_{i,j} \land \neg W_{i,j} \text{) is true or}
  \hspace{1em} \text{for some fringe square } [i,j], \text{ ASK(KB, } P_{i,j} \lor W_{i,j} \text{) is false then do}
  \hspace{1em} \text{plan} \leftarrow \text{A*-GRAPH-SEARCH(Route-PB([x,y, orientation, [i,j], visited])}
  \hspace{1em} \text{action} \leftarrow \text{POP(plan)}
  \text{else action} \leftarrow \text{a randomly chosen move}
\text{return action}
Expressiveness limitation of propositional logic

- KB contains "physics" sentences for every single square

- For every time $t$ and every location $[x,y]$,
  
  $$L_{x,y} \land \text{FacingRight}^t \land \text{Forward}^t \Rightarrow L_{x+1,y}$$

- Rapid proliferation of clauses
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

Wumpus world requires the ability to represent partial and negated information, reason by cases, etc.

Resolution is complete for propositional logic.