CSE 473: Artificial Intelligence

Constraint Satisfaction

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Multiple slides adapted from Dan Klein, Stuart Russell, Andrew Moore
What is Search For?

- Models of the world: single agent, deterministic actions, fully observed state, discrete state space

- Planning: sequences of actions
  - The path to the goal is the important thing
  - Paths have various costs, depths
  - Heuristics to guide, fringe to keep backups

- Identification: assignments to variables
  - The goal itself is important, not the path
  - All paths at the same depth (for some formulations)
  - CSPs are specialized for identification problems
Commitment Satisfaction Problems

- **Standard search problems:**
  - State is a “black box”: arbitrary data structure
  - Goal test: any function over states
  - Successor function can be anything

- **Constraint satisfaction problems (CSPs):**
  - A special subset of search problems
  - State is defined by variables $X_i$ with values from a domain $D$ (sometimes $D$ depends on $i$)
  - Goal test is a set of constraints specifying allowable combinations of values for subsets of variables

- Simple example of a formal representation language
- Allows useful general-purpose algorithms with more power than standard search algorithms
Example: N-Queens

- **Formulation 1:**
  - Variables: $X_{ij}$
  - Domains: $\{0, 1\}$
  - Constraints

\[
\begin{align*}
\forall i, j, k & \quad (X_{ij}, X_{ik}) \in \{(0, 0), (0, 1), (1, 0)\} \\
\forall i, j, k & \quad (X_{ij}, X_{kj}) \in \{(0, 0), (0, 1), (1, 0)\} \\
\forall i, j, k & \quad (X_{ij}, X_{i+k, j+k}) \in \{(0, 0), (0, 1), (1, 0)\} \\
\forall i, j, k & \quad (X_{ij}, X_{i+k, j-k}) \in \{(0, 0), (0, 1), (1, 0)\}
\end{align*}
\]

\[
\sum_{i,j} X_{ij} = N
\]
Example: N-Queens

- **Formulation 2:**
  - **Variables:** $Q_k$
  - **Domains:** $\{1, 2, 3, \ldots N\}$
  - **Constraints:**
    - Implicit: $\forall i, j$ non-threatening($Q_i, Q_j$)
    - or-
    - Explicit: $(Q_1, Q_2) \in \{(1, 3), (1, 4), \ldots\}$
Example: Map-Coloring

- **Variables**: \( WA, NT, Q, NSW, V, SA, T \)
- **Domain**: \( D = \{\text{red, green, blue}\} \)
- **Constraints**: adjacent regions must have different colors
  \[
  WA \neq NT
  \]
  \[
  (WA, NT) \in \{(\text{red, green}), (\text{red, blue}), (\text{green, red}), \ldots\}
  \]
- **Solutions** are assignments satisfying all constraints, e.g.:
  \[
  \{WA = \text{red}, NT = \text{green}, Q = \text{red}, NSW = \text{green}, V = \text{red}, SA = \text{blue}, T = \text{green}\}
  \]
Constraint Graphs

- Binary CSP: each constraint relates (at most) two variables
- Binary constraint graph: nodes are variables, arcs show constraints
- General-purpose CSP algorithms use the graph structure to speed up search. E.g., Tasmania is an independent subproblem!
Example: Cryptarithmetic

- **Variables (circles):**
  \[ F \quad T \quad U \quad W \quad R \quad O \quad X_1 \quad X_2 \quad X_3 \]

- **Domains:**
  \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}

- **Constraints (boxes):**
  \[
  \text{alldiff}(F, T, U, W, R, O) \\
  O + O = R + 10 \cdot X_1 \\
  \ldots
  \]

\[ \begin{array}{c}
  T \quad W \quad O \\
  + \quad T \quad W \quad O \\
  \hline \\
  F \quad O \quad U \quad R
  \end{array} \]
Example: Sudoku

- **Variables:**
  - Each (open) square

- **Domains:**
  - \{1,2,...,9\}

- **Constraints:**
  9-way alldiff for each column
  9-way alldiff for each row
  9-way alldiff for each region
Example: The Waltz Algorithm

- The Waltz algorithm is for interpreting line drawings of solid polyhedra
- An early example of a computation posed as a CSP
  - Look at all intersections
  - Adjacent intersections impose constraints on each other
Waltz on Simple Scenes

- Assume all objects:
  - Have no shadows or cracks
  - Three-faced vertices
  - “General position”: no junctions change with small movements of the eye.

- Then each line on image is one of the following:
  - Boundary line (edge of an object) (→) with right hand of arrow denoting “solid” and left hand denoting “space”
  - Interior convex edge (+)
  - Interior concave edge (−)
Legal Junctions

- Only certain junctions are physically possible
- How can we formulate a CSP to label an image?
- Variables: vertices
- Domains: junction labels
- Constraints: both ends of a line should have the same label

\[(x, y) \text{ in } \{\ldots\}\]
Varieties of CSPs

- **Discrete Variables**
  - Finite domains
    - Size $d$ means $O(d^n)$ complete assignments
    - E.g., Boolean CSPs, including Boolean satisfiability (NP-complete)
  - Infinite domains (integers, strings, etc.)
    - E.g., job scheduling, variables are start/end times for each job
    - Linear constraints solvable, nonlinear undecidable

- **Continuous variables**
  - E.g., start/end times for Hubble Telescope observations
  - Linear constraints solvable in polynomial time by LP methods (see cs170 for a bit of this theory)
Varieties of Constraints

- **Varieties of Constraints**
  - Unary constraints involve a single variable (equiv. to shrinking domains):
    \[ SA \neq \text{green} \]
  - Binary constraints involve pairs of variables:
    \[ SA \neq WA \]
  - Higher-order constraints involve 3 or more variables:
    e.g., cryptarithmetic column constraints

- **Preferences (soft constraints):**
  - E.g., red is better than green
  - Often representable by a cost for each variable assignment
  - Gives constrained optimization problems
  - (We’ll ignore these until we get to Bayes’ nets)
Real-World CSPs

- Assignment problems: e.g., who teaches what class
- Timetabling problems: e.g., which class is offered when and where?
- Hardware configuration
- Transportation scheduling
- Factory scheduling
- Floorplanning
- Fault diagnosis
- … lots more!

- Many real-world problems involve real-valued variables…
Standard Search Formulation

- Standard search formulation of CSPs (incremental)

- Let's start with a straightforward, dumb approach, then fix it

- States are defined by the values assigned so far
  - Initial state: the empty assignment, {} 
  - Successor function: assign a value to an unassigned variable 
  - Goal test: the current assignment is complete and satisfies all constraints
Search Methods

- What does BFS do?
- What does DFS do?
DFS - and BFS would be much worse!
Backtracking Search

- Idea 1: Only consider a single variable at each point
  - Variable assignments are commutative, so fix ordering
  - I.e., [WA = red then NT = green] same as [NT = green then WA = red]
  - Only need to consider assignments to a *single variable at each step*
  - How many leaves are there now?

- Idea 2: Only allow legal assignments at each point
  - I.e. consider only values which do not conflict previous assignments
  - Might have to do some computation to figure out whether a value is ok
  - “Incremental goal test”

- Depth-first search for CSPs with these two improvements is called *backtracking search*
  - Backtrack when there’s no legal assignment for the next variable

- Backtracking search is the basic uninformed algorithm for CSPs
Backtracking Search

function Backtracking-Search(csp) returns solution/failure
    return Recursive-Backtracking({}, csp)

function Recursive-Backtracking(assignment, csp) returns soln/failure
    if assignment is complete then return assignment
    var ← Select-Unassigned-Variable(VARIABLES[csp], assignment, csp)
    for each value in Order-Domain-Values(var, assignment, csp) do
        if value is consistent with assignment given CONSTRAINTS[csp] then
            add \{var = value\} to assignment
            result ← Recursive-Backtracking(assignment, csp)
            if result \neq failure then return result
            remove \{var = value\} from assignment
        return failure

- What are the choice points?
Backtracking Example
Are we done?
Improving Backtracking

- General-purpose ideas give huge gains in speed

- Ordering:
  - Which variable should be assigned next?
  - In what order should its values be tried?

- Filtering: Can we detect inevitable failure early?

- Structure: Can we exploit the problem structure?
Forward Checking

- Idea: Keep track of remaining legal values for unassigned variables (using immediate constraints)
- Idea: Terminate when any variable has no legal values
Forward Checking
Are We Done?
Constraint Propagation

- Forward checking propagates information from assigned to adjacent unassigned variables, but doesn't detect more distant failures:

- NT and SA cannot both be blue!
- Why didn’t we detect this yet?
- *Constraint propagation* repeatedly enforces constraints (locally)
Arc Consistency

- Simplest form of propagation makes each arc consistent
  - $X \rightarrow Y$ is consistent iff for every value $x$ there is some allowed $y$

If $X$ loses a value, neighbors of $X$ need to be rechecked!
- Arc consistency detects failure earlier than forward checking
- What’s the downside of arc consistency?
- Can be run as a preprocessor or after each assignment
Arc Consistency

function **AC-3**( csp) **returns** the CSP, possibly with reduced domains
inputs: csp, a binary CSP with variables \{X_1, X_2, \ldots, X_n\}
local variables: queue, a queue of arcs, initially all the arcs in csp

while queue is not empty do

(X_i, X_j) ← REMOVE-FIRST(queue)

if REMOVE-INCONSISTENT-VALUES(X_i, X_j) then

for each X_k in NEIGHBORS[X_i] do

add (X_k, X_i) to queue


function **REMOVE-INCONSISTENT-VALUES**(X_i, X_j) **returns** true iff succeeds

removed ← false

for each x in DOMAIN[X_i] do

if no value y in DOMAIN[X_j] allows (x,y) to satisfy the constraint X_i ← X_j

then delete x from DOMAIN[X_i]; removed ← true

return removed

- Runtime: O(n^2d^3), can be reduced to O(n^2d^2)
- ... but detecting all possible future problems is NP-hard – why?
  [demo: arc consistency animation]
Constraint Propagation
Are We Done?
Limitations of Arc Consistency

- After running arc consistency:
  - Can have one solution left
  - Can have multiple solutions left
  - Can have no solutions left (and not know it)

What went wrong here?
**K-Consistency**

- Increasing degrees of consistency
- 1-Consistency (Node Consistency): Each single node’s domain has a value which meets that node’s unary constraints
- 2-Consistency (Arc Consistency): For each pair of nodes, any consistent assignment to one can be extended to the other
- K-Consistency: For each k nodes, any consistent assignment to k-1 can be extended to the k\(^{th}\) node.

- Higher k more expensive to compute
- (You need to know the k=2 algorithm)
What Were Choice Points?

- At each step we have to decide...
  - What variable to assign next
  - What order to explore its assignments
Ordering: Minimum Remaining Values

- Minimum remaining values (MRV):
  - Choose the variable with the fewest legal values

- Why min rather than max?
- Also called “most constrained variable”
- “Fail-fast” ordering
Ordering: Degree Heuristic

- **Tie-breaker among MRV variables**
  - What do we color first? (All have 3 choices)

- **Degree heuristic:**
  - Choose the variable participating in the most constraints on remaining variables

- Why most rather than fewest constraints?
Domain Ordering: Least Constraining Value

- Given a choice of variable:
  - Choose the least constraining assignment value
  - The one that rules out the fewest values in the remaining variables
  - Note that it may take some computation to determine this!

- Why least rather than most?

- Combining these heuristics makes 1000 queens feasible
Propagation with Ordering
Problem Structure

- Tasmania and mainland are independent subproblems
- Identifiable as connected components of constraint graph
- Suppose each subproblem has $c$ variables out of $n$ total
- Worst-case solution cost is $O((n/c)(d^c))$ - linear in $n$
  - E.g., $n = 80$, $d = 2$, $c = 20$
  - $2^{80} = 4$ billion years at 10 million nodes/sec
  - $(4)(2^{20}) = 0.4$ seconds at 10 million nodes/sec
Tree-Structured CSPs

- Choose a variable as root, order variables from root to leaves such that every node's parent precedes it in the ordering (so now every node has exactly 1 parent)

- For $i = n \rightarrow 2$, apply RemoveInconsistent(\text{Parent}(X_i), X_i)
  - (i.e., apply arc consistency from each parent to child)

- For $i = 1 \rightarrow n$, assign $X_i$ consistently with Parent($X_i$)

- Runtime: $O(n \ d^2)$
Nearly Tree-Structured CSPs

- **Cycle cutset:** a set of variables whose removal makes a graph into a tree
- **Conditioning:** instantiate a variable, prune its neighbors' domains
- **Cutset conditioning:** instantiate (in all ways) a set of variables such that the remaining constraint graph is a tree
- Cutset size $c$ gives runtime $O\left( (d^c)(n-c) \cdot d^2 \right)$, very fast for small $c$
Iterative Algorithms for CSPs

- Greedy and local methods typically work with “complete” states, i.e., all variables assigned

- To apply to CSPs:
  - Allow states with unsatisfied constraints
  - Operators *reassign* variable values

- Variable selection: randomly select any conflicted variable

- Value selection by min-conflicts heuristic:
  - Choose value that violates the fewest constraints
  - I.e., hill climb with $h(n) = \text{total number of violated constraints}$
Example: 4-Queens

- States: 4 queens in 4 columns \( (4^4 = 256 \text{ states}) \)
- Operators: move queen in column
- Goal test: no attacks
- Evaluation: \( h(n) = \text{number of attacks} \)
Performance of Min-Conflicts

- Given random initial state, can solve n-queens in almost constant time for arbitrary n with high probability (e.g., n = 10,000,000)

- The same appears to be true for any randomly-generated CSP except in a narrow range of the ratio

\[ R = \frac{\text{number of constraints}}{\text{number of variables}} \]
CSPs are a special kind of search problem:
- States defined by values of a fixed set of variables
- Goal test defined by constraints on variable values

Backtracking = depth-first search with one legal variable assigned per node

Variable ordering and value selection heuristics help significantly

Forward checking prevents assignments that guarantee later failure

Constraint propagation (e.g., arc consistency) does additional work to constrain values and detect inconsistencies

The constraint graph representation allows analysis of problem structure

Tree-structured CSPs can be solved in linear time