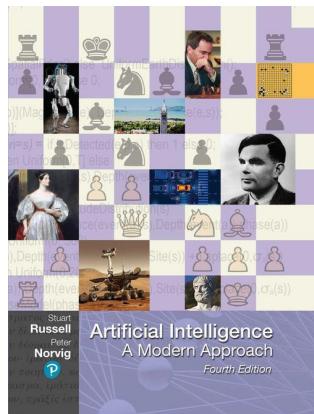


Artificial Intelligence: A Modern Approach

Fourth Edition



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Chapter 6

Constraint Satisfaction Problems

Outline

- ◆ Defining Constraint Satisfaction Problems (CSP)
- ◆ CSP examples
- ◆ Backtracking search for CSPs
- ◆ Local search for CSPs
- ◆ Problem structure and problem decomposition



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Chapter 6 2

Defining Constraint Satisfaction Problems

A constraint satisfaction problem (CSP) consists of three components, X , D , and C :

- X is a set of variables, $\{X_1, \dots, X_n\}$.
- D is a set of domains, $\{D_1, \dots, D_n\}$, one for each variable
- C is a set of constraints that specify allowable combination of values

CSPs deal with assignments of values to variables.

- A complete assignment is one in which every variable is assigned a value, and a solution to a CSP is a consistent, complete assignment.
- A partial assignment is one that leaves some variables unassigned.
- Partial solution is a partial assignment that is consistent



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Chapter 6 3

Constraint satisfaction problems (CSPs)

Standard search problem:

state is a “black box”—any old data structure
that supports goal test, eval, successor

CSP:

state is defined by variables X_i with values from domain D_i

goal test is a set of constraints specifying
allowable combinations of values for subsets of
variables

Simple example of a formal representation language

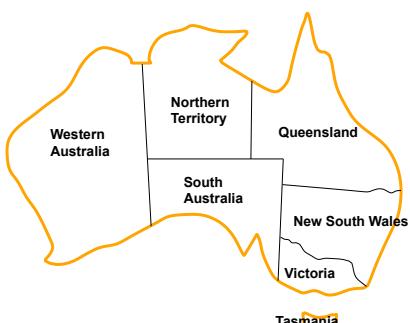
Allows useful general-purpose algorithms with more
power than standard search algorithms



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Chapter 6 4

Example: Map-Coloring



Variables WA, NT, Q, NSW, V, SA, T

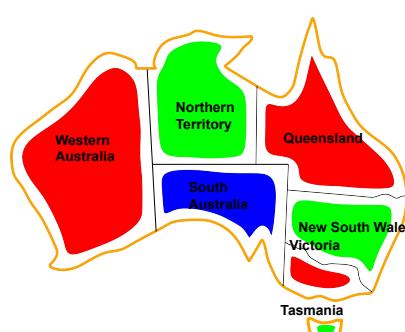
Domains $D_i = \{\text{red, green, blue}\}$

Constraints: adjacent regions must have different
colors e.g., $WA \neq NT$ (if the language allows
this), or

$\{A, NT\} \in \{\text{(red, green), (red, blue), (green, red), (green, blue), ...}\}$

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Example: Map-Coloring contd.



Solutions are assignments satisfying all constraints, e.g.,

$\{WA = \text{red}, NT = \text{green}, Q = \text{red}, NSW = \text{green}, V = \text{red}, SA = \text{blue}, T = \text{green}\}$



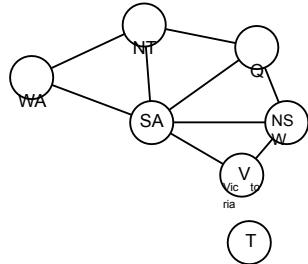
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Chapter 6 6

Constraint graph

Binary CSP: each constraint relates at most two variables

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!

Varieties of CSPs

Discrete variables

- finite domains; size $d \Rightarrow O(d^n)$ complete assignments
- ◆ e.g., Boolean CSPs, incl. Boolean satisfiability (NP-complete)
- infinite domains (integers, strings, etc.)
- ◆ e.g., job scheduling, variables are start/end days for each job
- ◆ need a constraint language, e.g., $StartJob_1 + 5 \leq StartJob_3$
- ◆ linear constraints solvable, nonlinear undecidable

Continuous variables

- ◆ e.g., start/end times for Hubble Telescope observations
- ◆ linear constraints solvable in poly time by LP methods

Varieties of constraints

Unary constraints involve a single variable, e.g., $SA \neq green$

Binary constraints involve pairs of variables, e.g., $SA \neq WA$

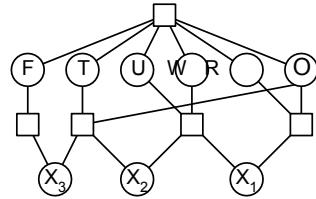
Higher-order constraints involve 3 or more variables, e.g., cryptarithmetic column constraints

Preferences (soft constraints), e.g., *red* is better than *green*

often representable by a cost for each variable assignment
→ constrained optimization problems

Example: Cryptarithmetic

$$\begin{array}{r}
 T \quad W \\
 O \\
 + I \quad W \\
 \hline
 O \quad F \quad O \\
 \hline
 U \quad R
 \end{array}$$



Variables: $F, T, U, W, R, O, X_1, X_2, X_3$

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

Constraints

$$\begin{aligned}
 & \text{alldiff}(F, T, U, W, R, O) \\
 & O + O = R + 10 \cdot X_1 \text{ etc.}
 \end{aligned}$$

Real-world CSPs

Assignment problems

e.g., who teaches what class

Timetabling problems

e.g., which class is offered when and where?

Hardware configuration

Spreadsheets

Transportation

scheduling

Factory

scheduling

Floorplanning

Notice that many real-world problems involve real-valued variables

Standard search formulation (incremental)

Let's start with the 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 that does not conflict with current assignment.
⇒ fail if no legal assignments (not fixable!)
- ◆ **Goal test:** the current assignment is complete

- 1) This is the same for all CSPs! 😊
- 2) Every solution appears at depth n with n variables
⇒ use depth-first search
- 3) Path is irrelevant, so can also use complete-state formulation
- 4) $b = (n - \epsilon)d$ at depth ϵ , hence $n!d^n$ leaves!!!!

Backtracking search

Variable assignments are **commutative**, i.e.,
 $[WA = \text{red} \text{ then } NT = \text{green}]$ same as $[NT = \text{green} \text{ then } WA = \text{red}]$

Only need to consider assignments to a single variable at each node
 $\Rightarrow b = d$ and there are d^n leaves

Depth-first search for CSPs with single-variable assignments is called **backtracking** search
Backtracking search is the basic uninformed algorithm for
CSPs Can solve n -queens for $n \approx 25$

Backtracking search

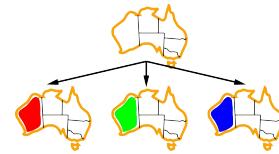
```

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  $\leftarrow$  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  $\{ \text{var} = \text{value} \}$  to assignment
            result  $\leftarrow$  Recursive-Backtracking(assignment, csp)
            if result  $\neq$  failure then return result
            remove  $\{ \text{var} = \text{value} \}$  from assignment
    return failure
  
```

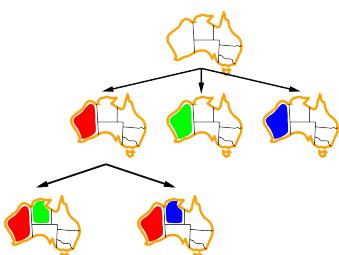
Backtracking example



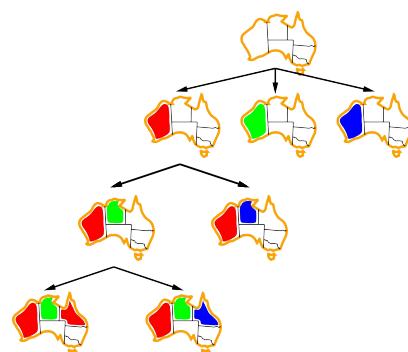
Backtracking example



Backtracking example



Backtracking example



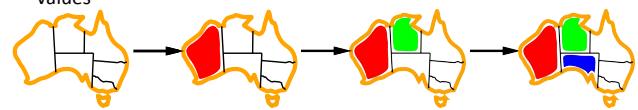
Improving backtracking efficiency

General-purpose methods can give huge gains in speed:

1. Which variable should be assigned next?
2. In what order should its values be tried?
3. Can we detect inevitable failure early?
4. Can we take advantage of problem structure?

Minimum remaining values

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

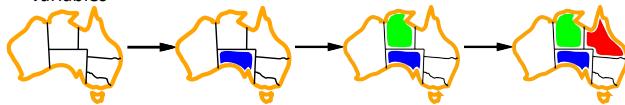


Degree heuristic

Tie-breaker among MRV variables

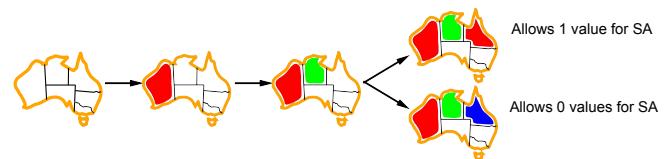
Degree heuristic:

choose the variable with the most constraints on remaining variables



Least constraining value

Given a variable, choose the least constraining value:
the one that rules out the fewest values in the remaining variables



Combining these heuristics makes 1000 queens feasible

Forward checking

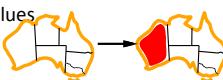
Idea: Keep track of remaining legal values for unassigned variables
Terminate search when any variable has no legal values



WA	NT	Q	NSW	V	SA	T
Red	Green	Blue	Red	Green	Blue	Red

Forward checking

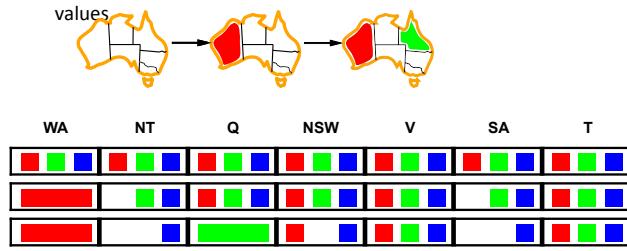
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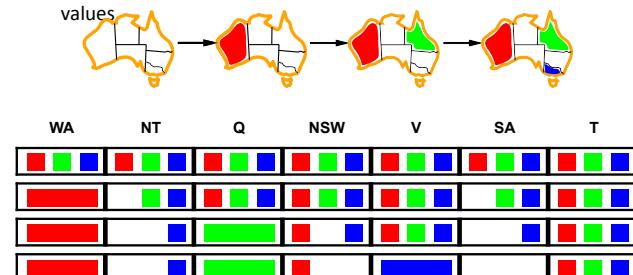
Forward checking

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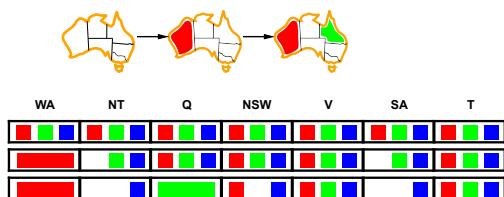
Forward checking

Idea: Keep track of remaining legal values for unassigned variables. Terminate search when any variable has no legal values



Constraint propagation

Forward checking propagates information from assigned to unassigned variables, but doesn't provide early detection for all failures:



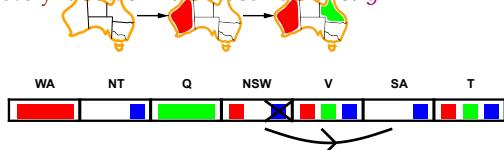
NT and SA cannot both be blue!

Constraint propagation repeatedly enforces constraints locally

Arc consistency

Simplest form of propagation makes each arc consistent

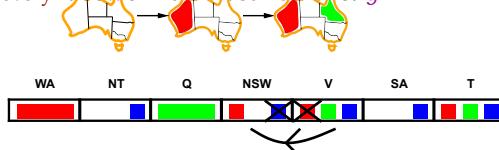
$X \rightarrow Y$ is consistent iff
for every value x of X there is some allowed y



Arc consistency

Simplest form of propagation makes each arc consistent

$X \rightarrow Y$ is consistent iff
for every value x of X there is some allowed y



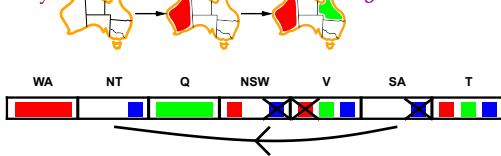
If X loses a value, neighbors of X need to be rechecked

Arc consistency

Simplest form of propagation makes each arc consistent

$X \rightarrow Y$ is consistent iff

for every value x of 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 Can be run as a preprocessor or after each assignment

Arc consistency algorithm

function **AC-3**(*csp*) returns the CSP, possibly with reduced domains

inputs: *csp*, a binary CSP with variables $\{X_1, X_2, \dots, X_n\}$

local variables: *queue*, a queue of arcs, initially all the arcs in *csp*

while *queue* is not empty do

$(X_i, X_j) \leftarrow \text{Remove-First}(\text{queue})$

if *Remove-Inconsistent-Values*(X_i, X_j) then for

each X_k in *Neighbors*[X_j] do

add (X_k, X_j) to *queue*

function **Remove-Inconsistent-Values**(X_i, X_j) returns true iff succeeds

removed \leftarrow false

for each x in *Domain*[X_i] do

if no value y in *Domain*[X_j] allows (x, y) to satisfy the constraint $X_i \leftrightarrow X_j$

then delete x from *Domain*[X_i]; *removed* \leftarrow true

return *removed*

$O(n^2 d^3)$, can be reduced to $O(n^2 d^2)$ (but detecting all is NP-hard)

Local Search for CSPs

Local search algorithms can be very effective in solving many CSPs.

Local search algorithms use a complete-state formulation where each state assigns a value to every variable, and the search changes the value of one variable at a time.

Min-conflicts heuristic: value that results in the **minimum number of conflicts** with other variables that **brings us closer to a solution**.
• Usually has a series of **plateaus**

Plateau search: allowing sideways moves to another state with the same score.
• can help local search find its way off the plateau.

Constraint weighting aims to concentrate the search on the important constraints

- Each constraint is given a numeric weight, initially all 1.
- weights adjusted by incrementing when it is violated by the current assignment

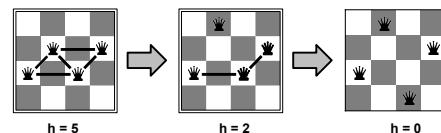
Example: 4-Queens

States: 4 queens in 4 columns ($4^4 = 256$ states)

Operators: move queen in

column Goal test: no attacks

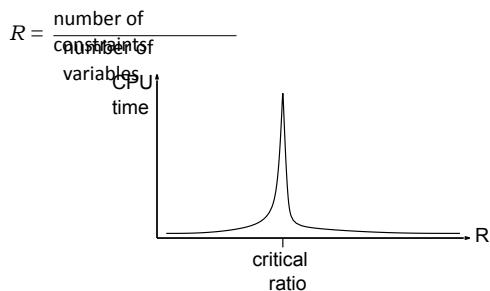
Evaluation: $h(n)$ = number of attacks



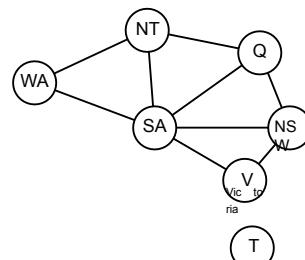
Performance of min-conflicts

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



Problem structure



Tasmania and mainland are **independent subproblems**

Identifiable as **connected components** of constraint graph

Problem structure contd.

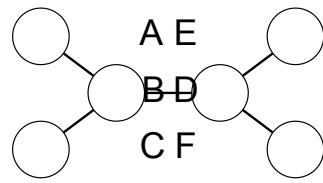
Suppose each subproblem has c variables out of n total

Worst-case solution cost is $n/c \cdot d^c$, linear in n

E.g., $n = 80, d = 2, c = 20$

$2^{80} = 4$ billion years at 10 million nodes/sec
 $4 \cdot 2^{20} = 0.4$ seconds at 10 million nodes/sec

Tree-structured CSPs



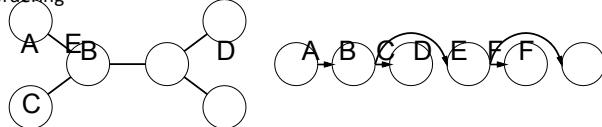
Theorem: if the constraint graph has no loops, the CSP can be solved in $O(n d^c)$ time

Compare to general CSPs, where worst-case time is $O(d^n)$

This property also applies to logical and probabilistic reasoning: an important example of the relation between syntactic restrictions and the complexity of reasoning.

Algorithm for tree-structured CSPs

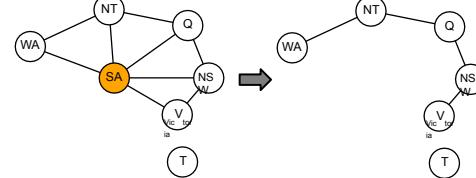
1. Choose a variable as root, order variables from root to leaves such that every node's parent precedes it in the ordering



2. For j from n down to 2, apply RemoveInconsistent($\text{Parent}(X_j), X_j$)
3. For j from 1 to n , assign X_j consistently with $\text{Parent}(X_j)$

Nearly tree-structured CSPs

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 $c \Rightarrow$ runtime $O(d^c \cdot (n - c)d^c)$, very fast for small c

Iterative algorithms for CSPs

Hill-climbing, simulated annealing 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., hillclimb with $h(n) =$ total number of violated constraints

Summary

CSPs are a special kind of 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 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

Local search using the min-conflicts heuristic has also been applied to constraint satisfaction problems with great success

The CSP representation allows analysis of problem