Constraint Satisfaction Problems

Chapter 5

Section 1 – 3

Outline

- Constraint Satisfaction Problems (CSP)
- Backtracking search for CSPs
- Local search for CSPs

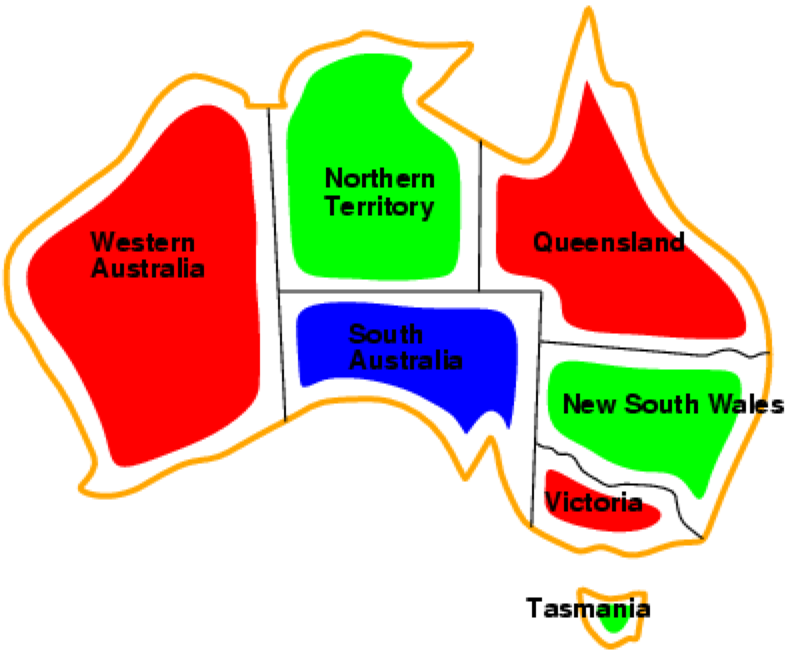
Constraint satisfaction problems (CSPs)

- Standard search problem:
-
  - state is a "black box" – any data structure that supports successor function, heuristic function, and goal test
  -
- 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

Example: Map-Coloring

- Variables *WA, NT, Q, NSW, V, SA, T*
- Domains D_i = {red,green,blue}
- Constraints: adjacent regions must have different colors
-
- e.g., WA ≠ NT, or (WA,NT) in {(red,green),(red,blue),(green,red), (green,blue),(blue,red),(blue,green)}
-

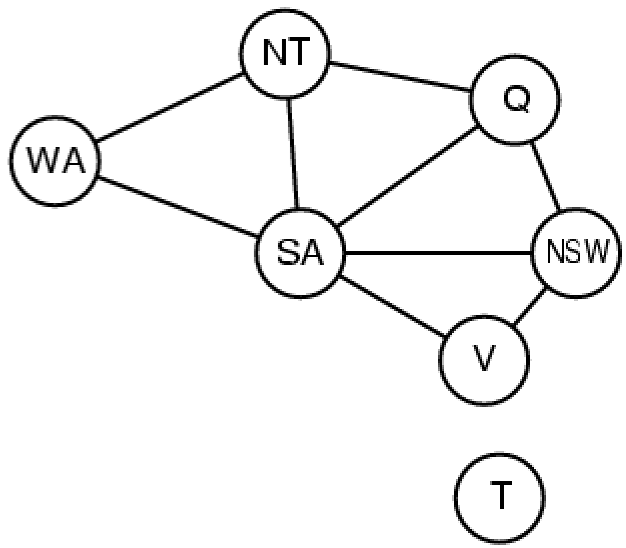
Example: Map-Coloring



- Solutions are complete and consistent assignments, e.g., WA = red, NT = green,Q = red,NSW = green,V = red,SA = blue,T = green
-

Constraint graph

- Binary CSP: each constraint relates two variables
-
- Constraint grap[illegible]s are constraints
-



Varieties of CSPs

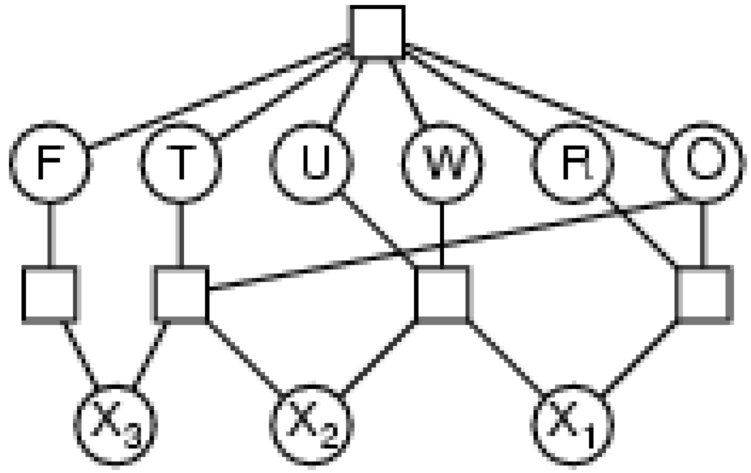
- Discrete variables
-
  - finite domains:
    - n variables, domain size $d \rightarrow O(d^n)$ complete assignments
    - e.g., Boolean CSPs, incl.~Boolean satisfiability (NP-complete)
  - infinite domains:
    - integers, strings, etc.
    - e.g., job scheduling, variables are start/end days for each job
    - need a constraint language, e.g., $StartJob_1 + 5 \leq StartJob_3$
- Continuous variables
-
  - e.g., start/end times for Hubble Space Telescope observations
  - linear constraints solvable in polynomial time by linear programming

Varieties of constraints

- Unary constraints involve a single variable,
  - e.g., SA ≠ green
  -
- Binary constraints involve pairs of variables,
  - e.g., SA ≠ WA
  -
- Higher-order constraints involve 3 or more variables,
  - e.g., cryptarithmetic column constraints

Example: Cryptarithmetic

```
    T W O
  + T W O
  -------
  F O U R
```



- 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: *Alldiff (F,T,U,W,R,O)*
-
  - $O + O = R + 10 \cdot X_1$
  -
  - $X_1 + W + W = U + 10 \cdot X_2$
  -
  - $X_2 + T + T = O + 10 \cdot X_3$
  - $X_3 = F, T \neq 0, F \neq 0$

Real-world CSPs

- Assignment problems
  - e.g., who teaches what class
- Timetabling problems
  - e.g., which class is offered when and where?
- Transportation scheduling
- Factory scheduling
- Notice that many real-world problems involve real-

Standard search formulation (incremental)

Let's start with the straightforward 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
- 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. $b = (n - \ell)d$ at depth ℓ, hence $n! \cdot d^n$ leaves

Backtracking search

- Variable assignments are commutative}, 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 node
  → b = d and there are \$d^n\$ leaves

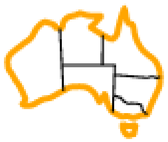
- Depth-first search for CSPs with single-variable assignments is called backtracking search
-
- Backtracking search is the basic uninformed algorithm for CSPs
-
- Can solve *n*-queens for $n \approx 25$
-

Backtracking search

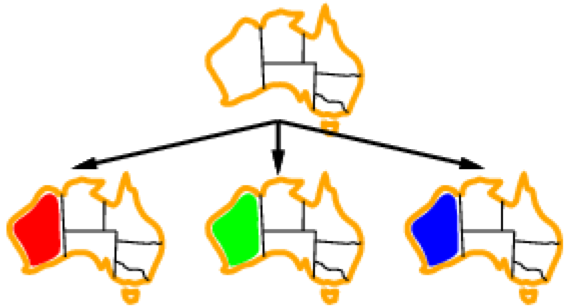
function BACKTRACKING-SEARCH(*csp*) **returns** a solution, or failure
  return RECURSIVE-BACKTRACKING({}, *csp*)

function RECURSIVE-BACKTRACKING(*assignment, csp*) **returns** a solution, or 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* according to Constraints[*csp*] **then**
      add { *var* = *value* } to *assignment*
      result ← RECURSIVE-BACKTRACKING(*assignment, csp*)
      if *result* ≠ *failue* **then return** *result*
      remove { *var* = *value* } from *assignment*
  return *failure*

Backtracking example



Backtracking example



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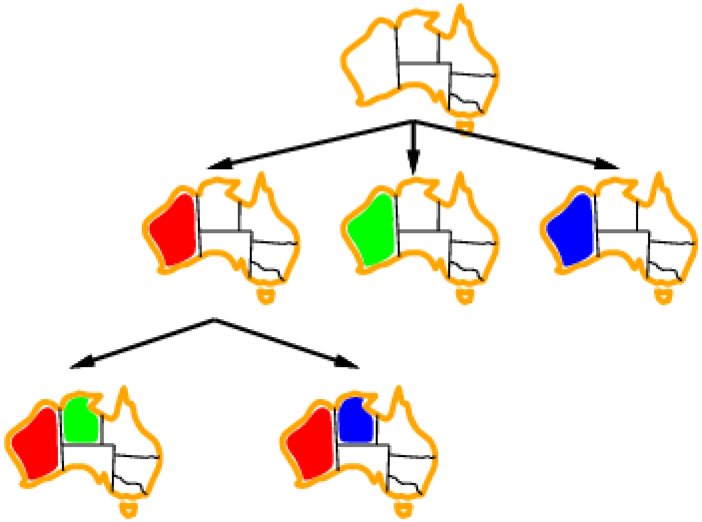

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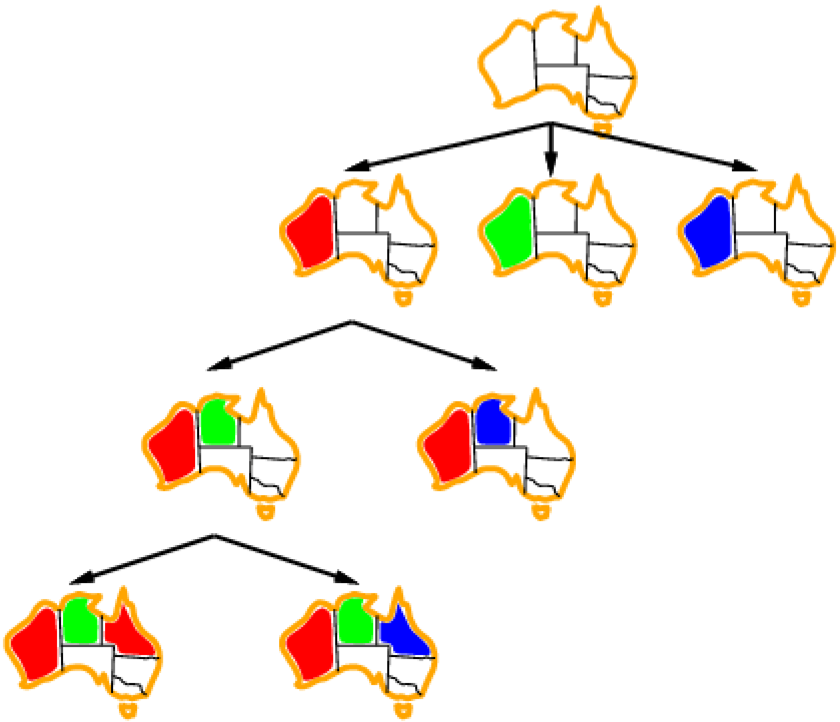
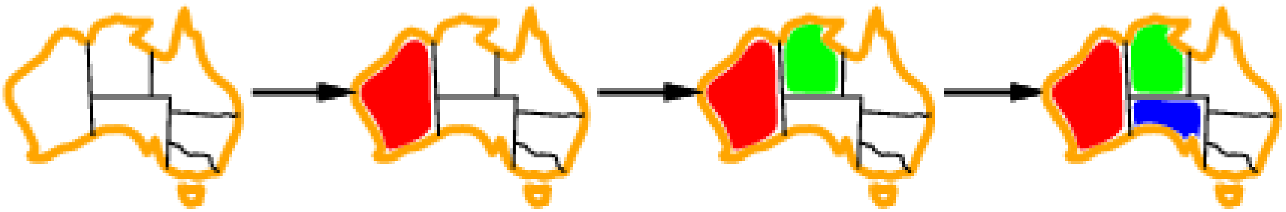


Improving backtracking efficiency

- General-purpose methods can give huge gains in speed:
-
  - Which variable should be assigned next?
  -
  - In what order should its values be tried?
  -
  - Can we detect inevitable failure early?
  -

Most constrained variable

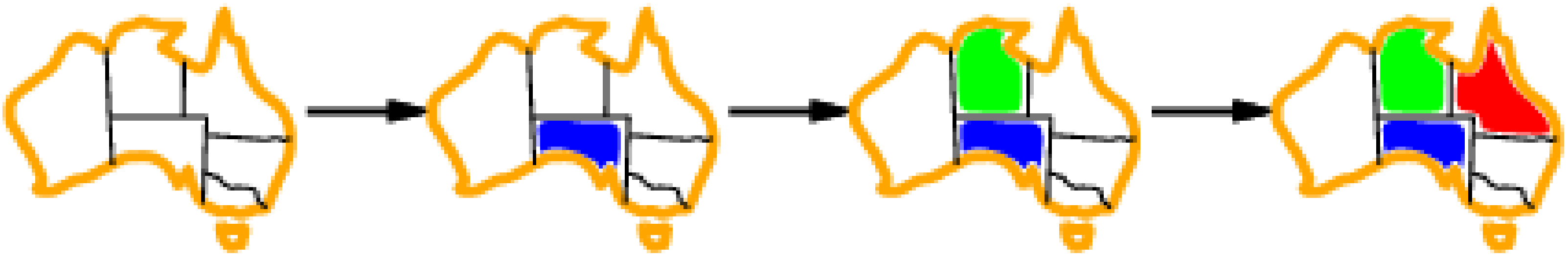
- Most constrained variable:
  choose the variable with the fewest legal values



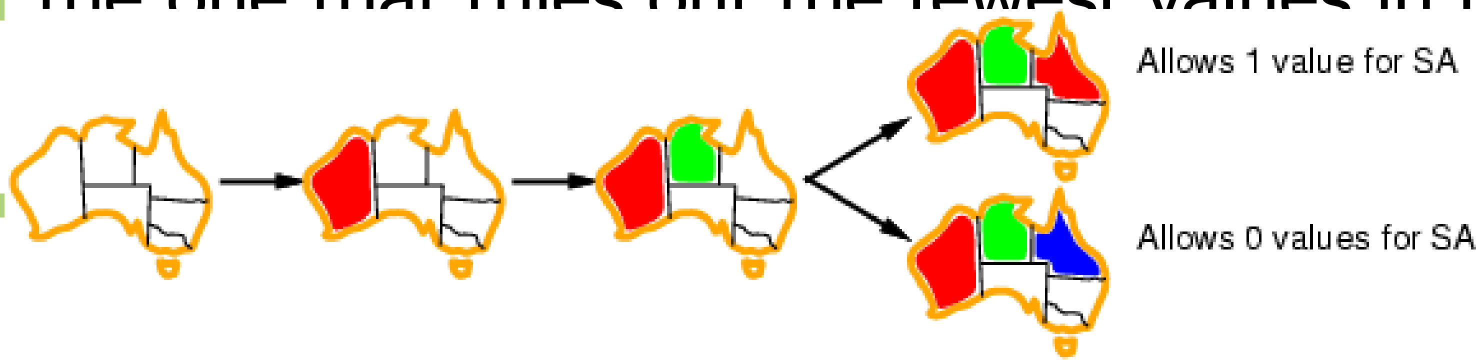
- a.k.a. minimum remaining values (MRV) heuristic
-

Most constraining variable

- Tie-breaker among most constrained variables
- Most constraining variable:
-
  - choose the variable with the most constraints on



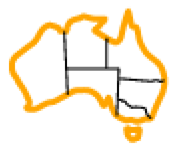
Least constraining value

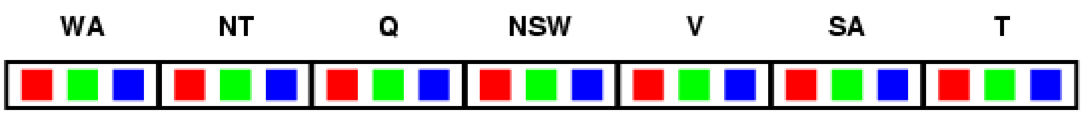
- Given a variable, choose the least constraining value:
-
  - the one that rules out the fewest values in the
  - 

- Combining these heuristics makes 1000

Forward checking

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





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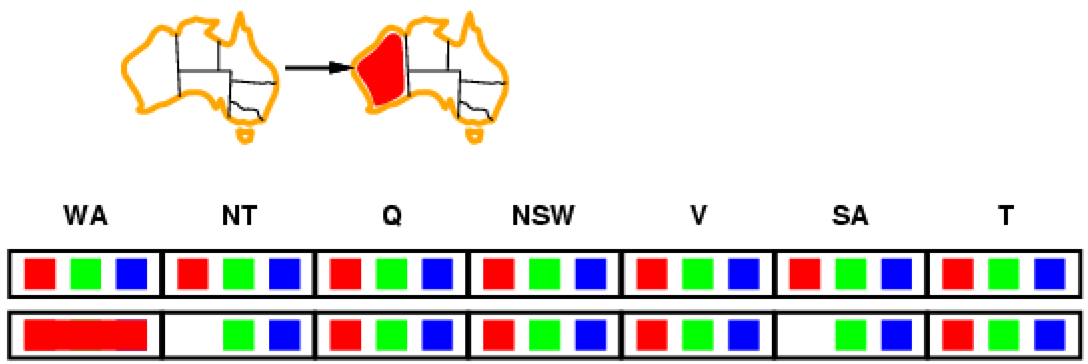

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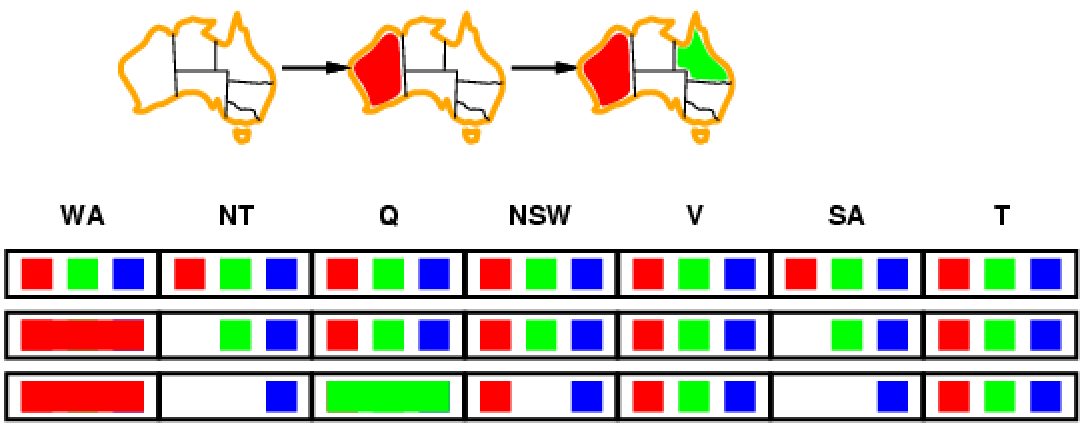

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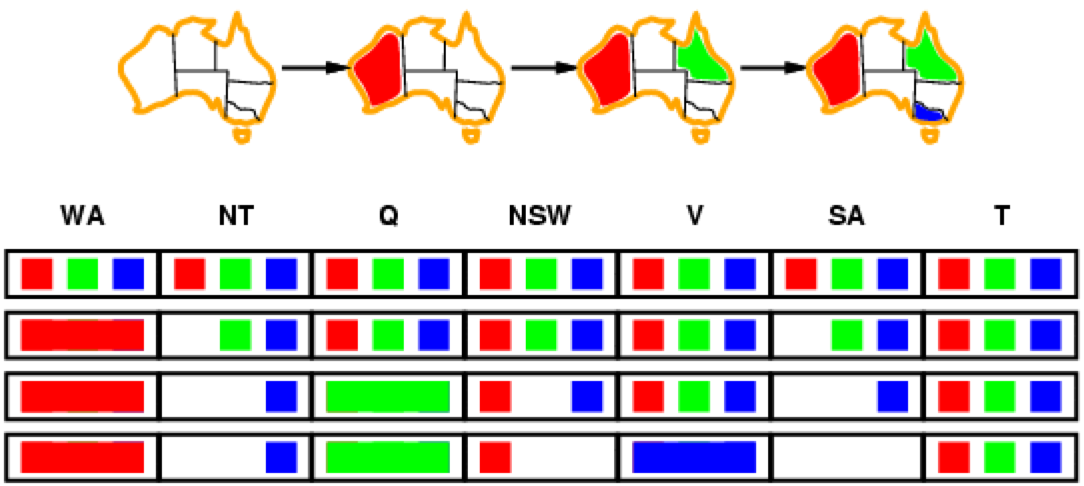
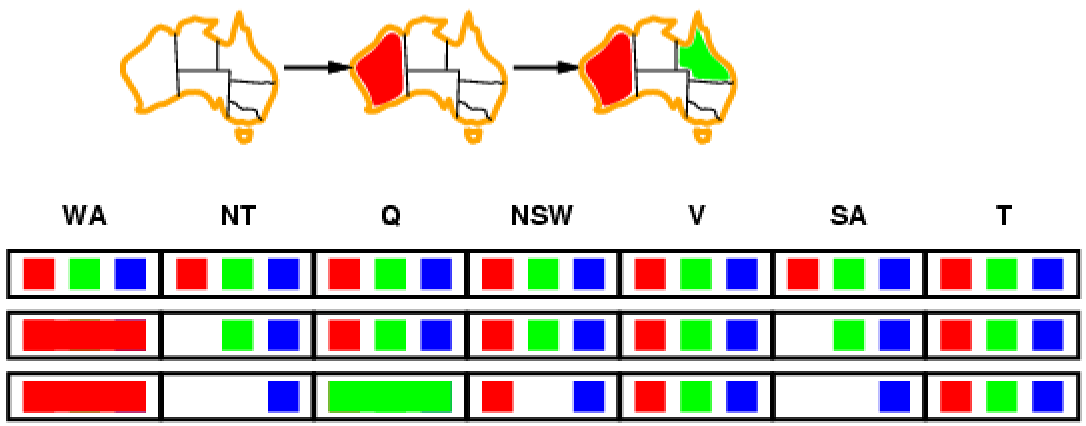


Constraint propagation

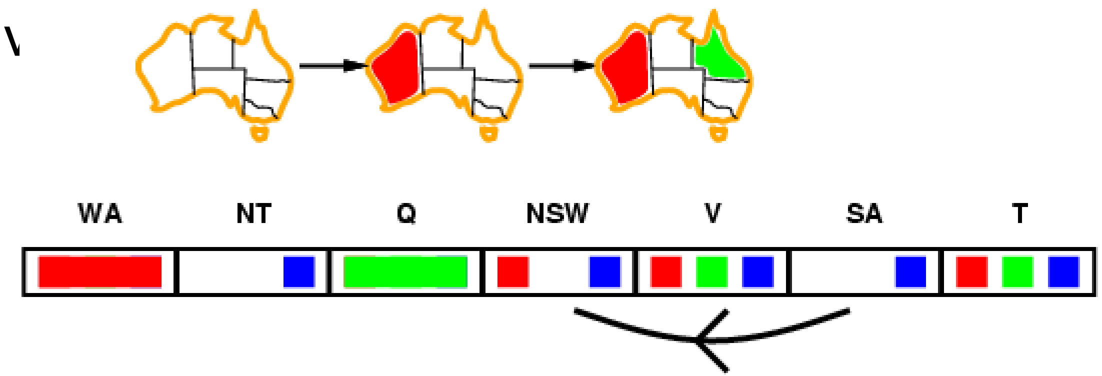
- Forward checking propagates information from assigned to unassigned variables, but doesn't provide early detection for all failures:
- 

- 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 v



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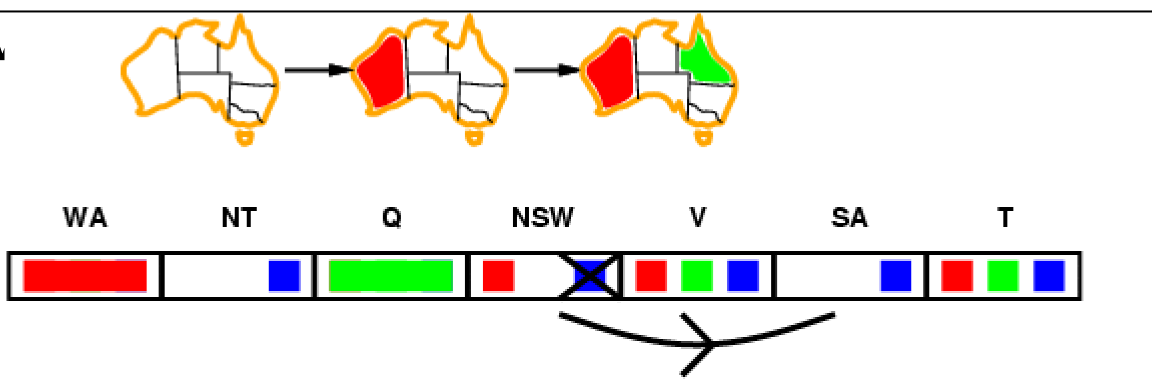

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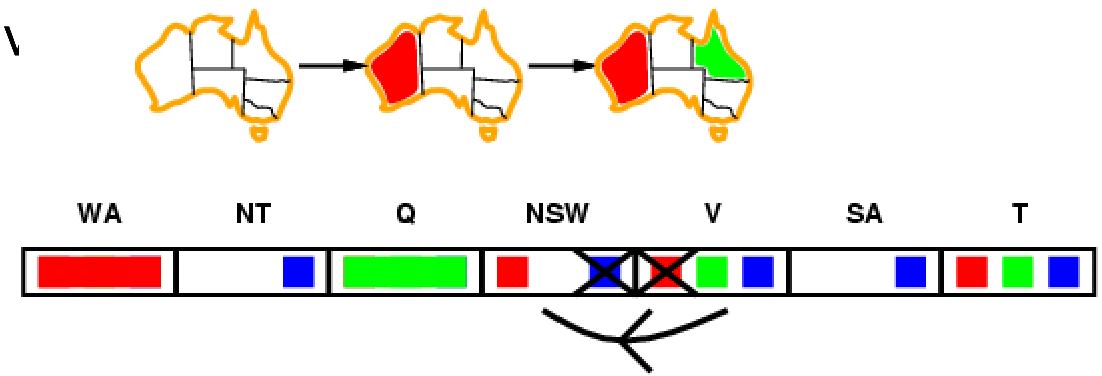

- If X loses a value, neighbors of X need to be rechecked
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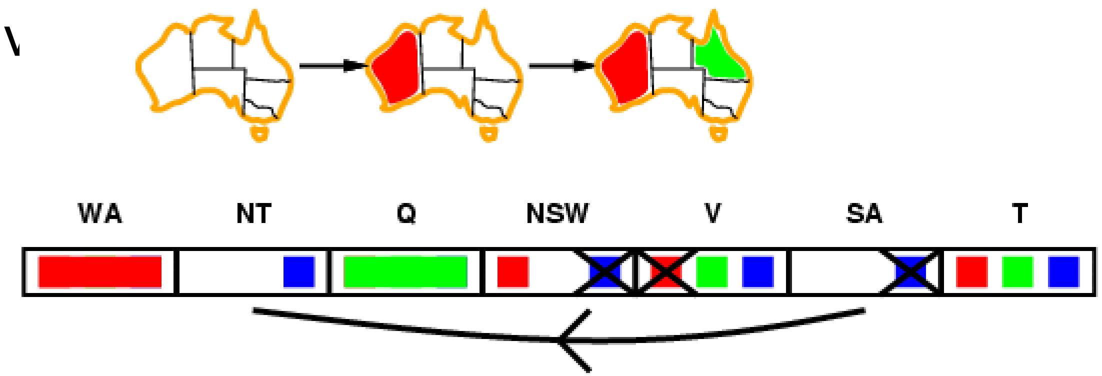


- If X loses a value, neighbors of X need to be rechecked
- Arc consistency detects failure earlier than forward checking
-

- Can be run as a preprocessor or after each assignment

Arc consistency algorithm AC-3

```
function AC-3(csp) returns the CSP, possibly with reduced domains
   inputs: csp, a binary CSP with variables {X1, X2, ..., Xn}
   local variables: queue, a queue of arcs, initially all the arcs in csp

   while queue is not empty do
      (Xi, Xj) ← REMOVE-FIRST(queue)
      if RM-INCONSISTENT-VALUES(Xi, Xj) then
         for each Xk in NEIGHBORS[Xi] do
            add (Xk, Xi) to queue
```

```
function RM-INCONSISTENT-VALUES(Xi, Xj) returns true iff remove a value
   removed ← false
   for each x in DOMAIN[Xi] do
      if no value y in DOMAIN[Xj] allows (x,y) to satisfy constraint(Xi, Xj)
         then delete x from DOMAIN[Xi];  removed ← true
   return removed
```

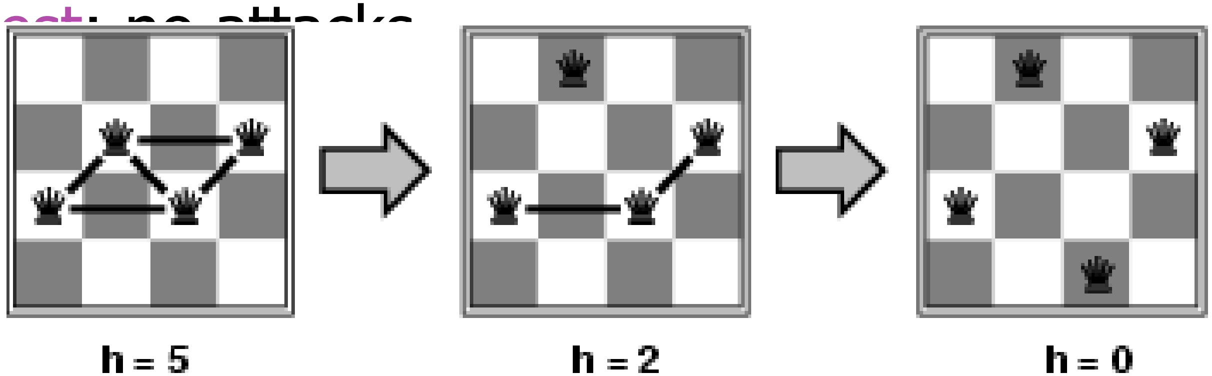
- Time complexity: $O(n^2d^3)$

Local search 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:

Example: 4-Queens

- States: 4 queens in 4 columns (4^4 = 256 states)
-
- Actions: move queen in column
-
- Goal test: no attacks
-
- Evalua
-



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

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