Constraint Satisfaction Problems

Chapter 5

Sections 1 – 3

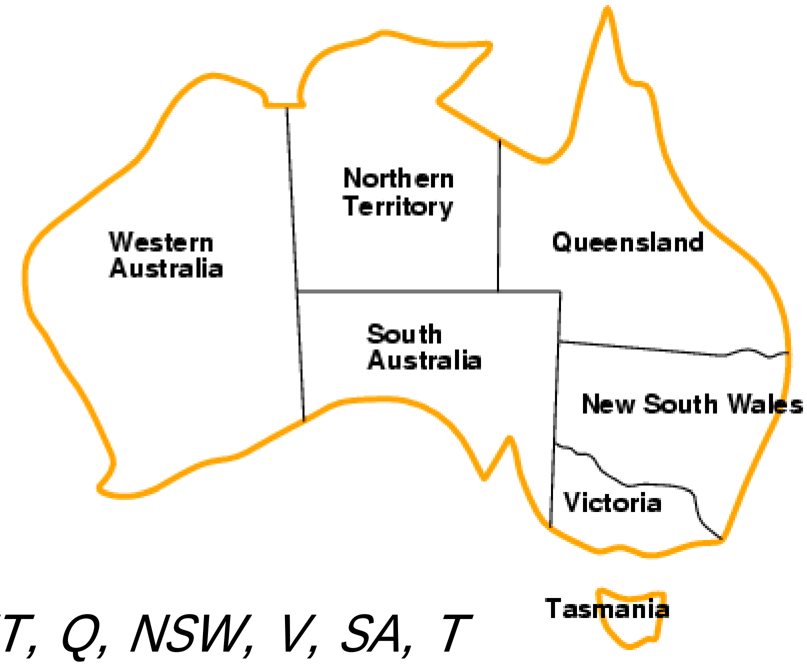
Outline

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

Constraint satisfaction problems (CSPs)

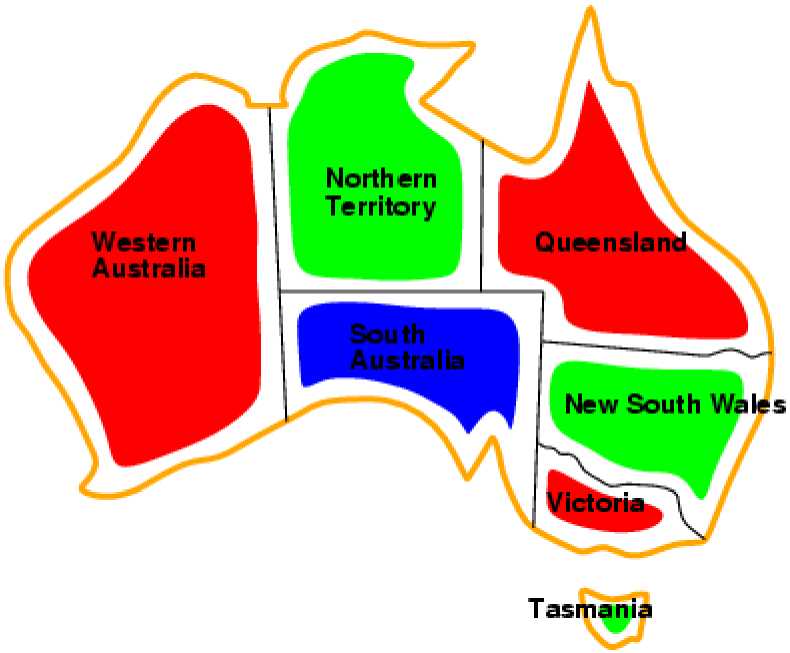
- Standard search problem:
  - state is a “black box” – any data structure that supports successor function, heuristic function, and goal test
- CSP:
  - state is defined by variables X_i with values from domain D_i
  - goal test is a set of constraints specifying allowable combinations of values for subsets of variables
- Simple example of a formal representation language
- Allows useful general-purpose algorithms with more power than standard search algorithms

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)}

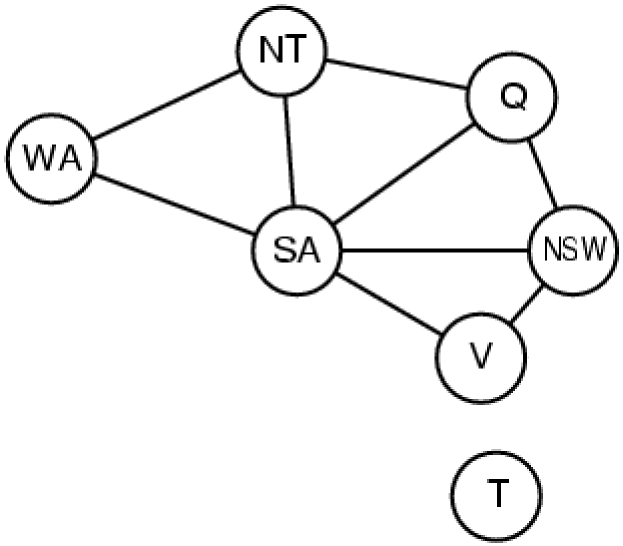
Example: Map-Coloring



- 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 graph: nodes are variables, arcs are constraints



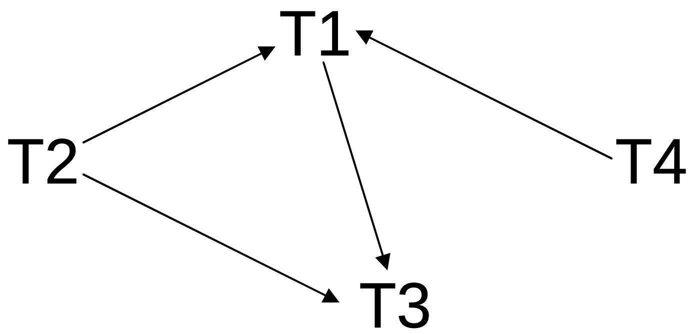
Varieties of CSPs

- Discrete variables
  - finite domains:
    - *n* variables, domain size *d* → $O(d^n)$ 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

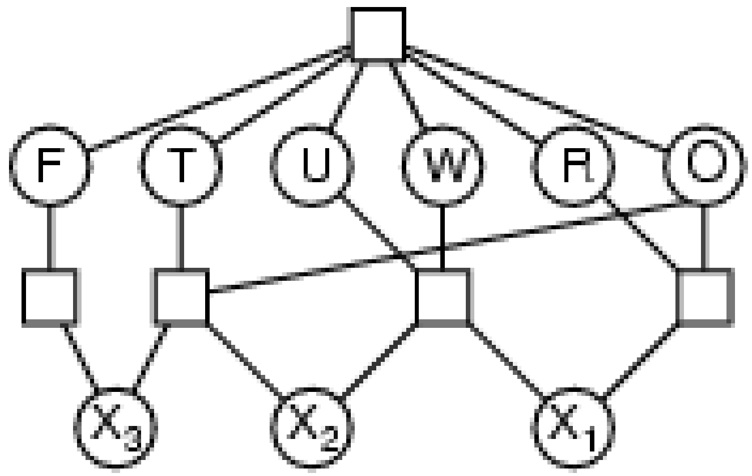
Example: Task Scheduling



T1 must be done during T3
T2 must be achieved before T1 starts
T2 must overlap with T3
T4 must start after T1 is complete

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-valued variables

Standard search formulation (incremental)

Let's start with the straightforward approach, then fix it

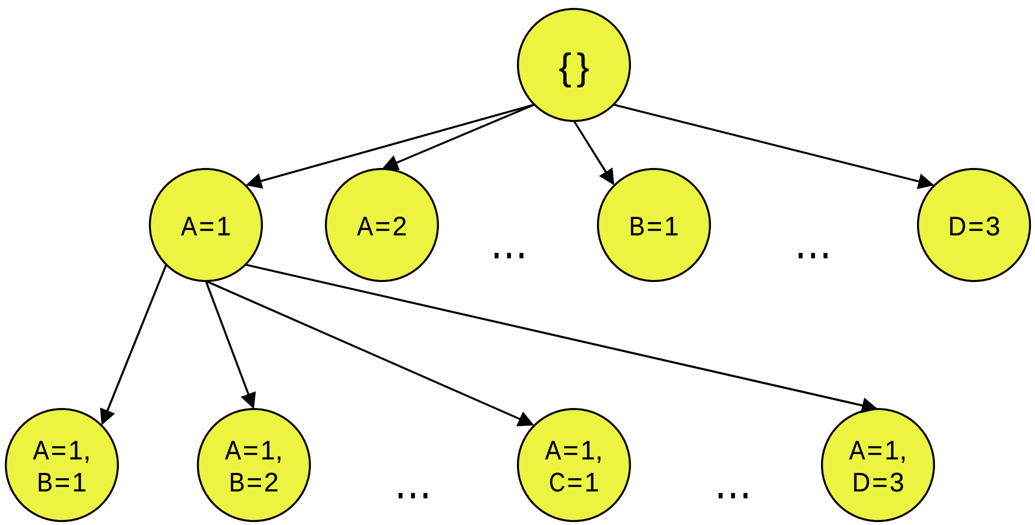
States are defined by the values assigned so far

- 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

CSP Search tree size

b = (n - l)d at depth l, hence n! · d^n leaves



Variables: A,B,C,D
Domains: 1,2,3

Depth 1: 4 variables x 3 domains = 12 states

Depth 2: 3 variables x 3 domains = 9 states

Depth 3: 2 variables x 3 domains = 6 states

Depth 4: 1 variable x 3 domains = 3 states (leaf level)

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
  - Fix an order in which we'll examine the variables

  → b = d and there are d^n leaves

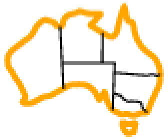
- Depth-first search for CSPs with single-variable assignments is called backtracking search
  - Is the basic uninformed algorithm for CSPs
  - Can solve *n*-queens for $n \approx 25$

Backtracking search

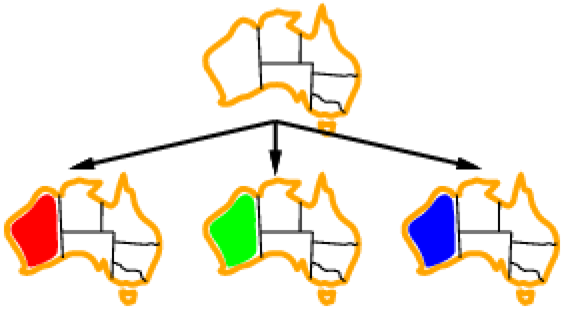
```
function Backtracking-Search(csp) returns a solution, or failure
   return Recursive-Backtracking({}, csp)

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
```

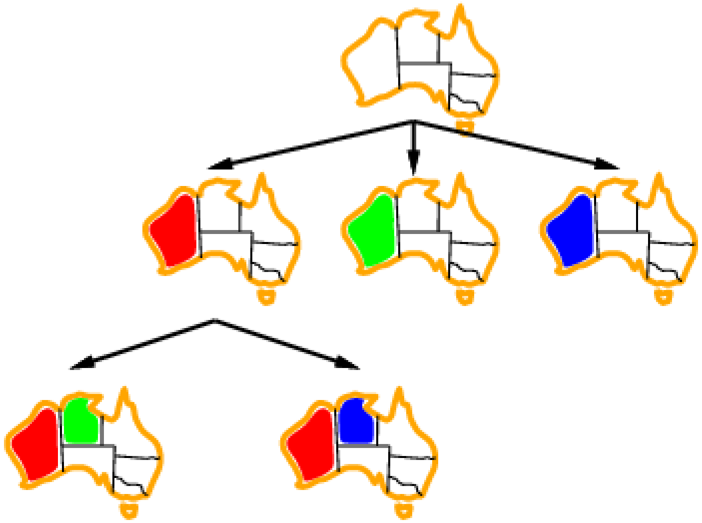
Backtracking example



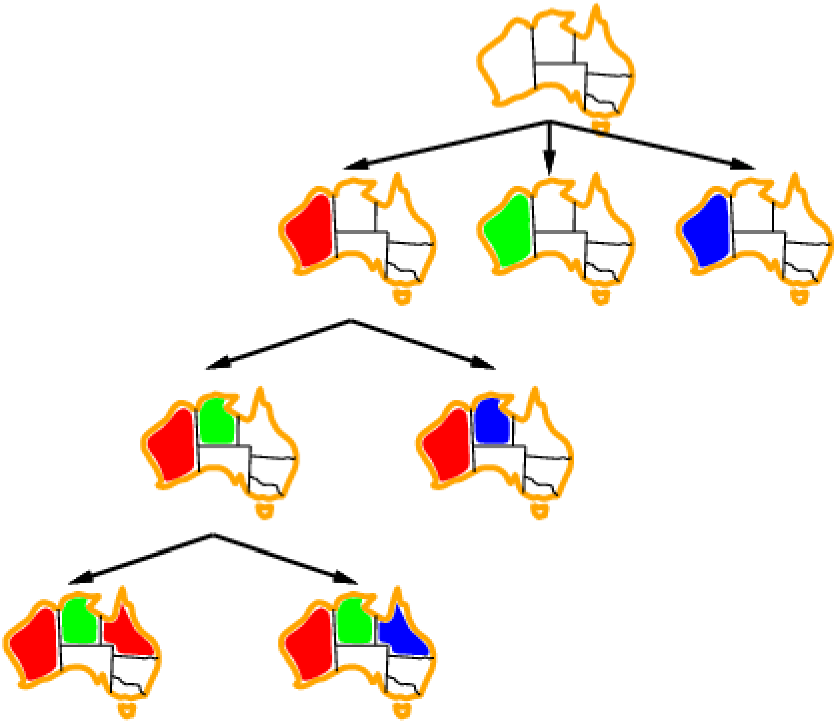
Backtracking example



Backtracking example



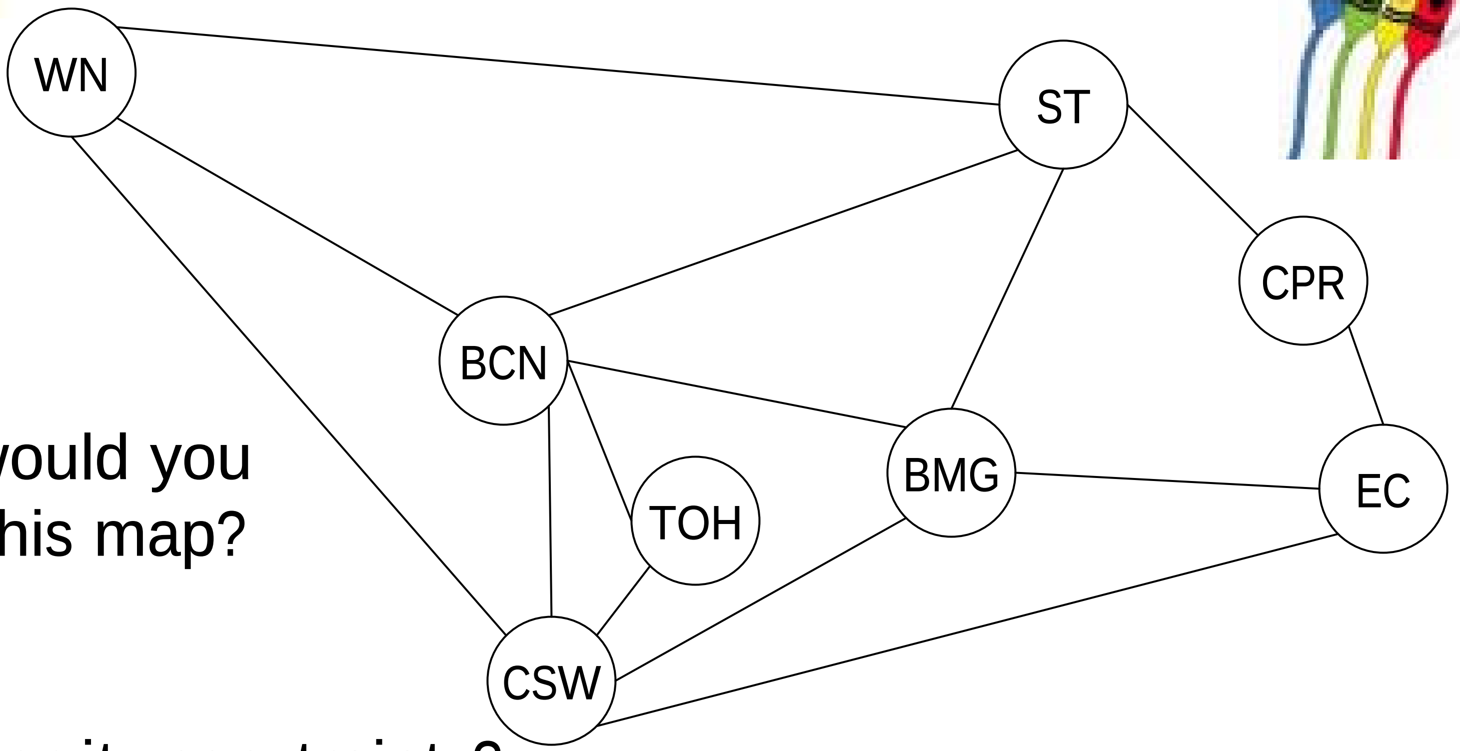
Backtracking example



Exercise - paint the town!

- Districts across corners can be colored using the same color.

Constraint Graph



How would you color this map?

Consider its constraints?
Can you do better than blind search?

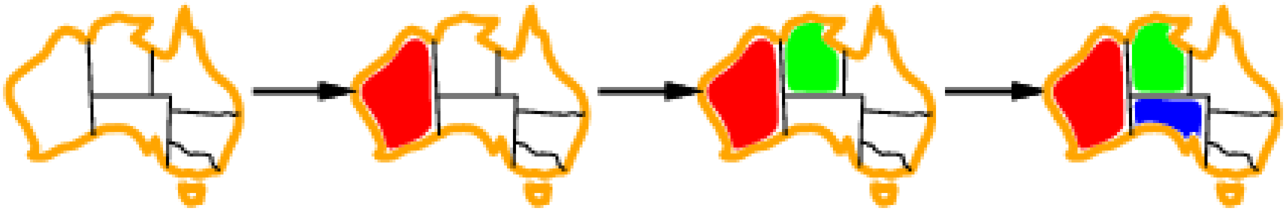
Improving backtracking efficiency

- 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:

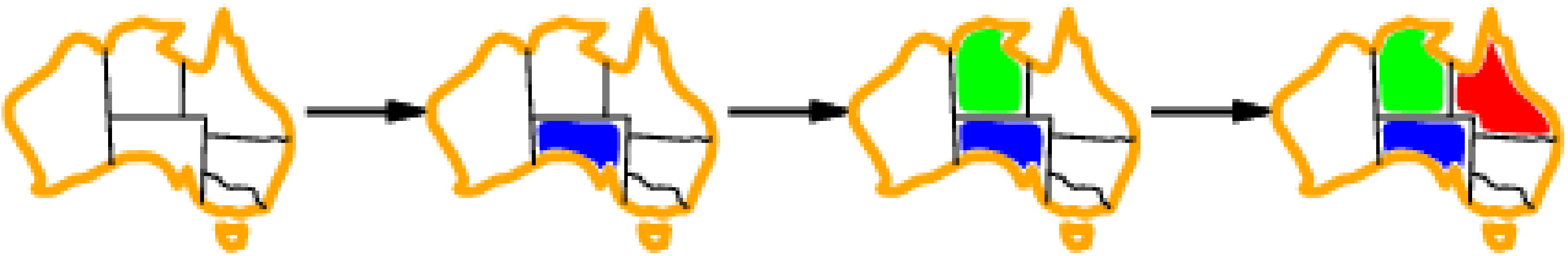
  choose the variable with the fewest legal values



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

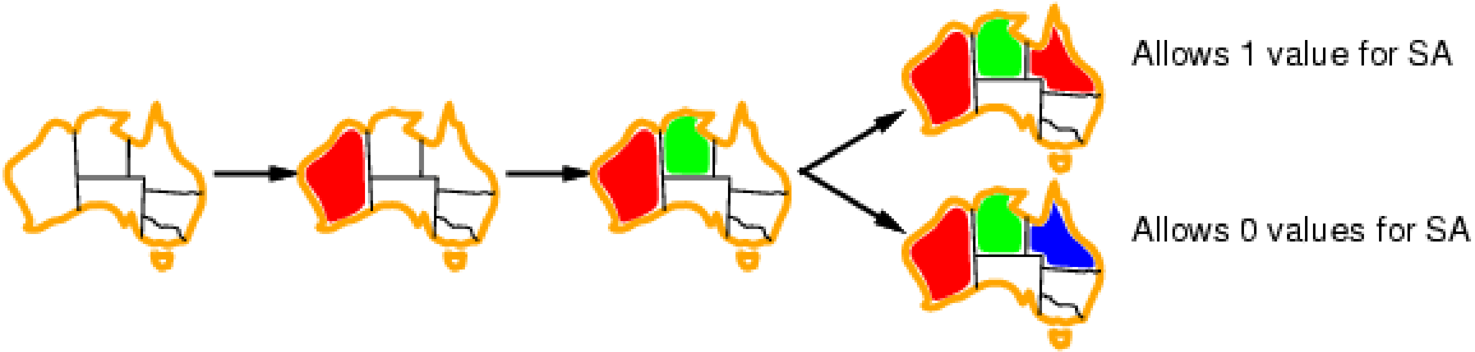
Most constraining variable

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



Least constraining value

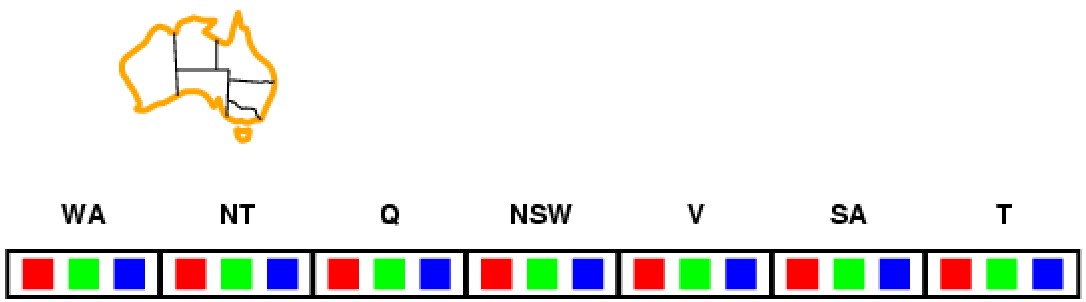
- Given a variable, choose the least constraining value:
  - the one that rules out the fewest values in the remaining variables



- 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



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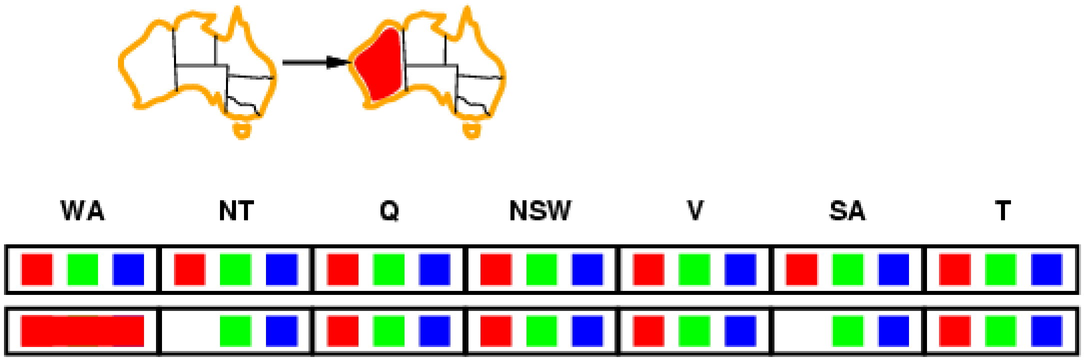

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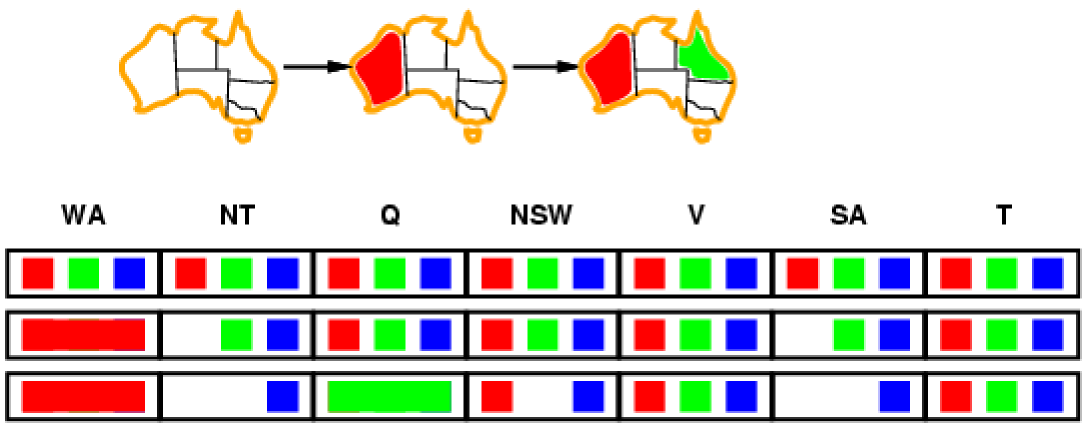

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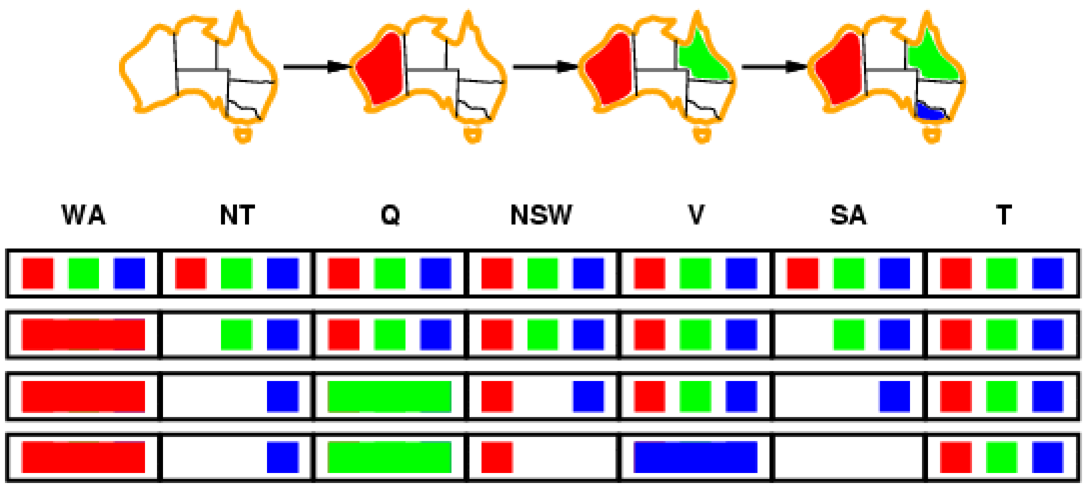
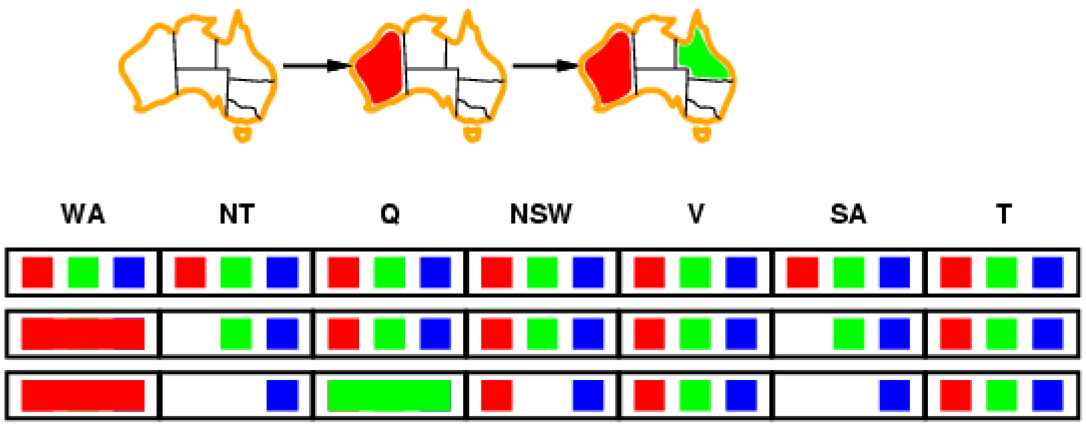


Constraint propagation

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

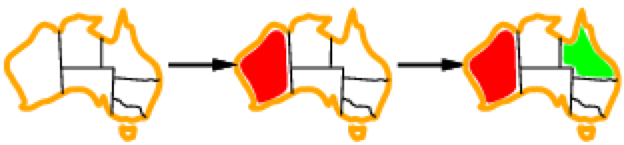


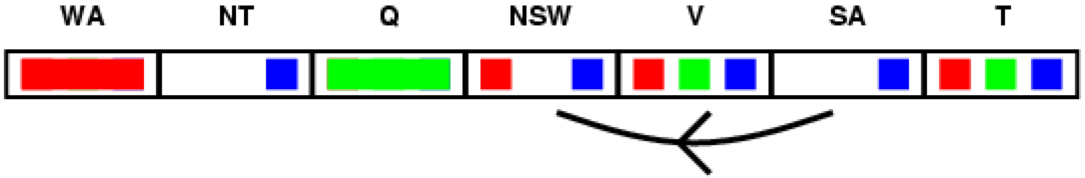
- NT and SA cannot both be blue!
- Constraint propagation repeatedly enforces constraints locally

Arc consistency

- Simplest form of propagation makes each arc consistent
- $X \rightarrow Y$ is consistent iff

  for every value x of X there is some allowed y





More on arc consistency

- Arc consistency is based on a very simple concept
  - if we can look at just one constraint and see that x=v is impossible ...
  - obviously we can remove the value x=v from consideration
- How do we know a value is impossible?
- If the constraint provides ***no support*** for the value
- e.g. if D_x = {1,4,5} and D_y = {1, 2, 3}
  - then the constraint x > y provides no support for x=1
  - we can remove x=1 from D_x

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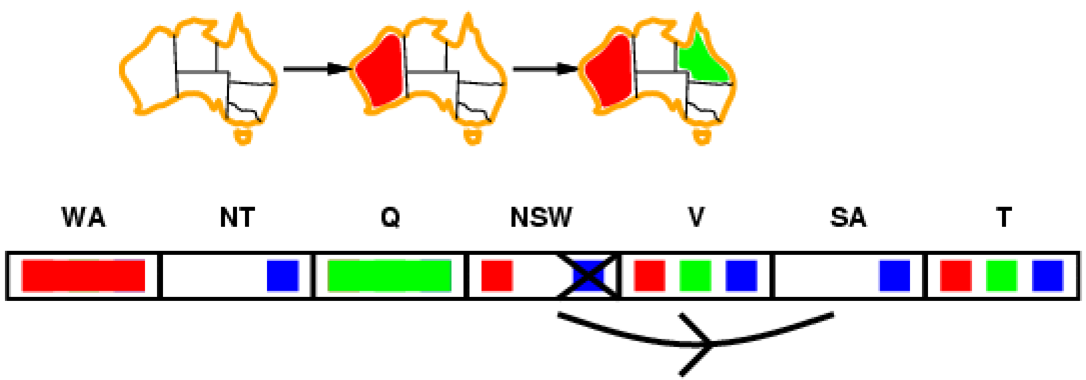

- Arcs are directed, a binary constraint becomes two arcs
- NSW $\Rightarrow$ SA arc originally not consistent, is consistent after deleting blue

Arc consistency

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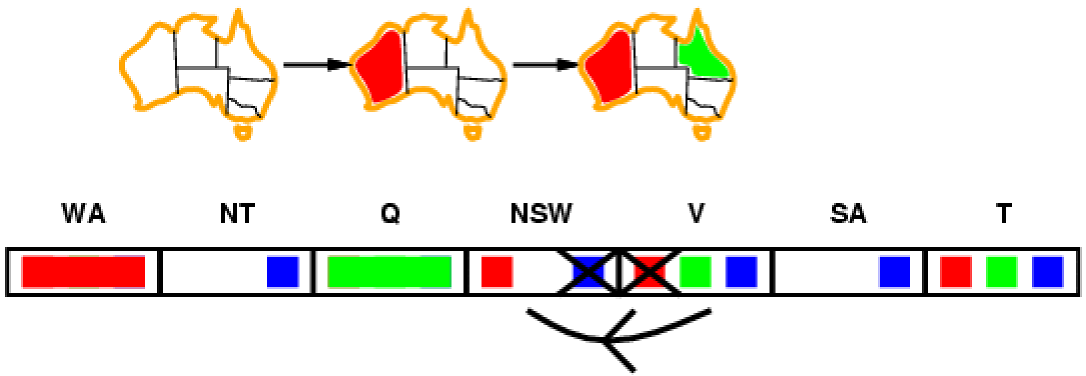

- If X loses a value, neighbors of X need to be (re)checked

Arc Consistency Propagation

- When we remove a value from D_x, we may get new removals because of it
- E.g. $D_x = \{1,4,5\}$, $D_y = \{1, 2, 3\}$, $D_z = \{2, 3, 4, 5\}$
  - $x > y$, $z > x$
  - As before we can remove 1 from D_x, so $D_x = \{4,5\}$
  - But now there is no support for $D_z = 2,3,4$
  - So we can remove those values, $D_z = \{5\}$, so $z=5$
  - Before AC applied to y-x, we could not change D_z
- This can cause a chain reaction

Arc consistency

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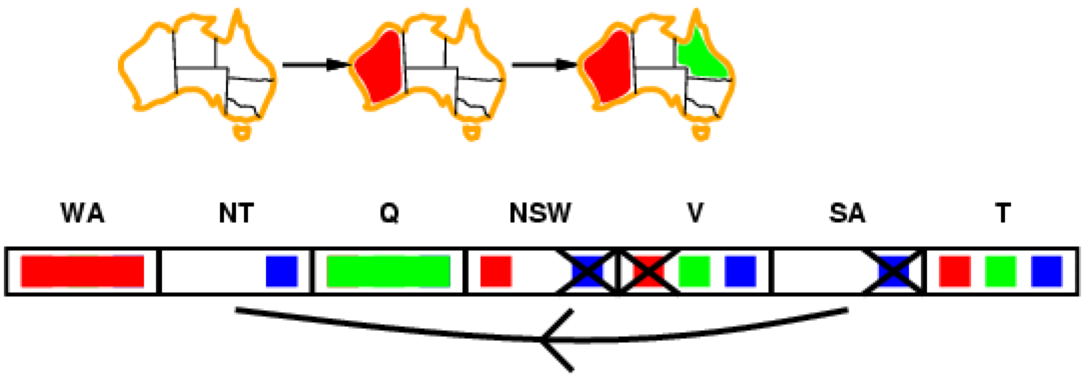

- If X loses a value, neighbors of X need to be (re)checked
- Arc consistency detects failure earlier than forward checking
- Can be run as a preprocessor or after each assignment

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: $O(n^2d^3)$

Time complexity of AC-3

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   return removed
```

- CSP has n^2 directed arcs
- Each arc X_i,X_j has d possible values. For each value we can reinsert the neighboring arc X_k,X_i at most d times because X_i has d values
- Checking an arc requires at most d^2 time

- $O(n^2 * d * d^2) = O(n^2d^3)$

Maintaining AC (MAC)

- Like any other propagation, we can use AC in search
- i.e. search proceeds as follows:
  - establish AC at the root
  - when AC3 terminates, choose a new variable/value
  - re-establish AC given the new variable choice (i.e. maintain AC)
  - repeat;
  - backtrack if AC gives domain wipe out
- The hard part of implementation is undoing effects of AC

Special kinds of Consistency

- Some kinds of constraint lend themselves to special kinds of arc-consistency
- Consider the all-different constraint
  - the named variables must all take different values
  - not a binary constraint
  - can be expressed as n(n-1)/2 not-equals constraints
- We can apply (e.g.) AC3 as usual
- But there is a much better option

All Different

- Suppose $D_x = \{2,3\} = D_y$, $D_z = \{1,2,3\}$
- All the constraints $x \neq y$, $y \neq z$, $z \neq x$ are all arc consistent
  - e.g. $x=2$ supports the value $z = 3$
- The single ternary constraint AllDifferent(x,y,z) is not!
  - We must set $z = 1$
- A special purpose algorithm exists for All-Different to establish GAC in efficient time
  - Special purpose propagation algorithms are vital

K-consistency

- Arc Consistency (2-consistency) can be extended to k-consistency

- 3-consistency (path consistency): any pair of adjacent variables can always be extended to a third neighbor.
  - Catches problem with D_x, D_y and D_z, as assignment of Dz = 2 and Dx = 3 will lead to domain wipe out.
  - But is expensive, exponential time
- *n*-consistency means the problem is solvable in linear time
  - As any selection of variables would lead to a solution
- In general, need to strike a balance between consistency and search.
  - This is usually done by experimentation.

Local search for CSPs

- Hill-climbing, simulated annealing typically work with "complete" states, i.e., all variables assigned

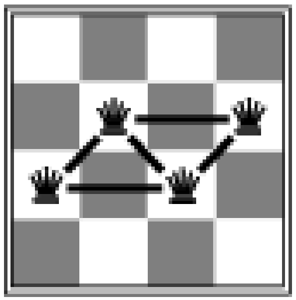
- To apply to CSPs:
  - allow states with unsatisfied constraints
  - operators reassign variable values

- Variable selection: randomly select any conflicted variable

- Value selection by min-conflicts heuristic:
  - choose value that violates the fewest constraints
  - i.e., hill-climb with *h(n)* = total number of violated constraints

Example: 4-Queens

- States: 4 queens in 4 columns (4^4 = 256 states)
- Actions: move queen in column
- Goal test: no attacks
- Evaluation: *h(n)* = number of attacks



h = 5

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

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
- Iterative min-conflicts is usually effective in practice

Midterm test

- Five questions, first hour of class (be on time!)
- Topics to be covered (**CSP** is not on the midterm):
  - Chapter 2 – Agents
  - Chapter 3 – Uninformed Search
  - Chapter 4 – Informed Search
    - Not including the parts of 4.1 (memory-bounded heuristic search) and 4.5
  - Chapter 6 – Adversarial Search
    - Not including 6.5 (games with chance)

Homework #1

- Due today by 23:59:59 in the IVLE workbin.
- Late policy given on website. Only one submission will be graded, whichever one is latest.
- Your tagline is used to generate the ID to identify your agent on the scoreboard.
- If you don't have an existing account fill out: https://mysoc.nus.edu.sg/~eform/new and send me e-mail ASAP.

Checklist for HW #1

- **Does it compile?**
- Is my code in a single file?
- Did I comment my code so that it's understandable to the reader?
- Is the main class appropriately named?
- Did I place a unique tagline so I can identify my player on the scoreboard?