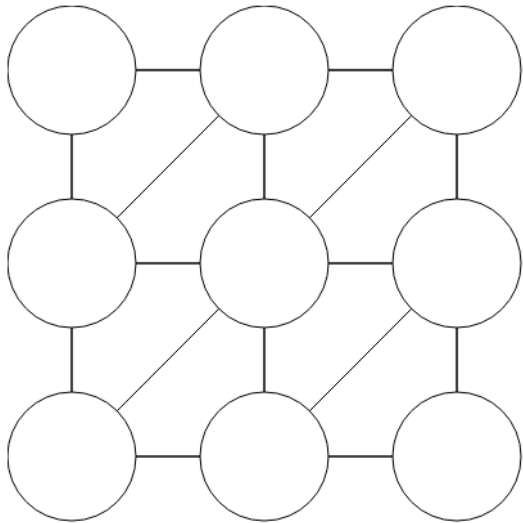


Warm-up as You Walk In

Assign Red, Green, or Blue
Neighbors must be different



Sudoku

1			
	2	1	
		3	
			4

- 1) What is your brain doing to solve these?
- 2) How would you solve these with search (BFS, DFS, etc.)?

Plan

Last Time

- A* search
- Adversarial search
 - Minimax
 - Evaluation functions
 - Pruning

Today

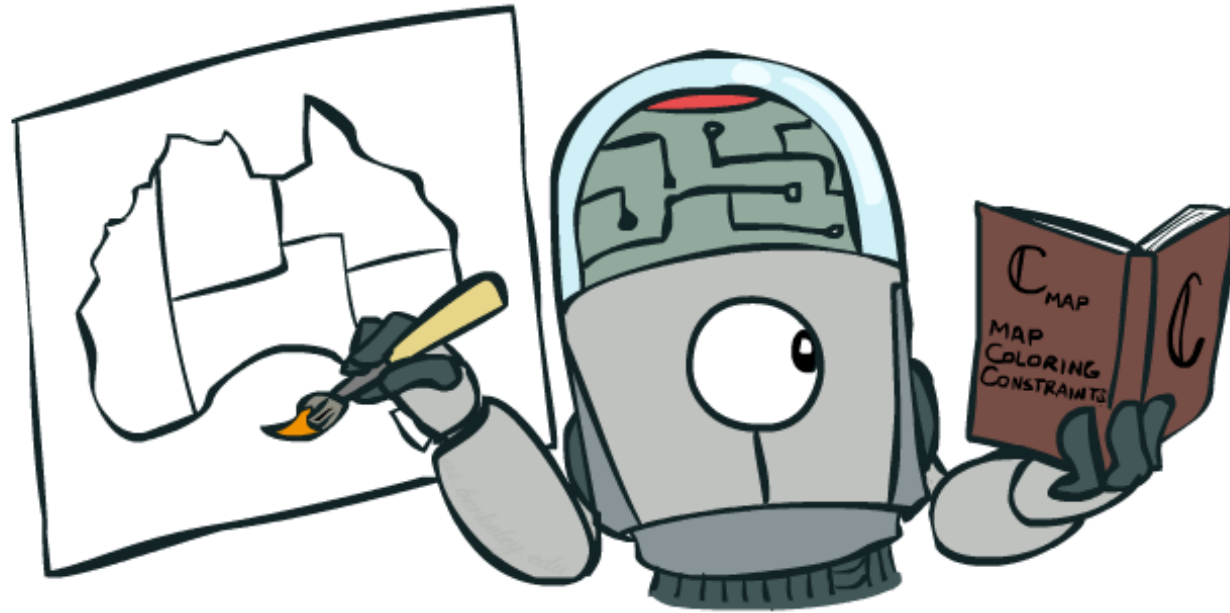
- Adversarial search: Expectimax
- Constraint Satisfaction Problems

Expectimax

Adversarial search slides

AI: Representation and Problem Solving

Constraint Satisfaction Problems (CSPs)

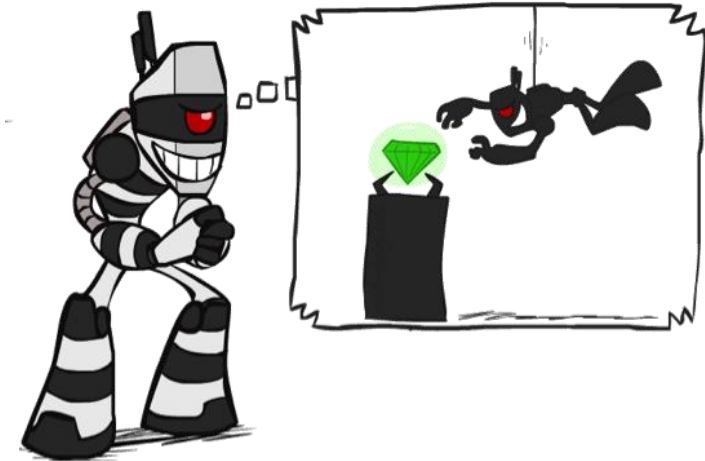


Instructor: Pat Virtue

Slide credits: CMU AI, <http://ai.berkeley.edu>

What is Search For?

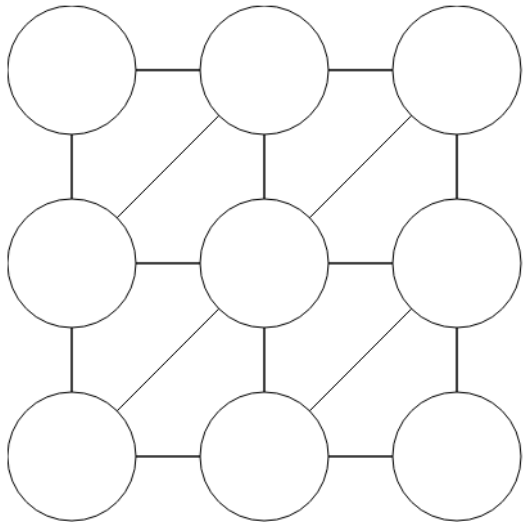
- Planning: sequences of actions
 - The path to the goal is the important thing
 - Paths have various costs, depths
 - Heuristics give problem-specific guidance
- Identification: assignments to variables
 - The goal itself is important, not the path
 - All paths at the same depth (for some formulations)



Are the warm-up assignments
planning or identification problems?

Warm-up as You Walk In

Assign Red, Green, or Blue
Neighbors must be different



Sudoku

1			
	2	1	
		3	
			4

Constraint Satisfaction Problems

CSP is a special class of search problems

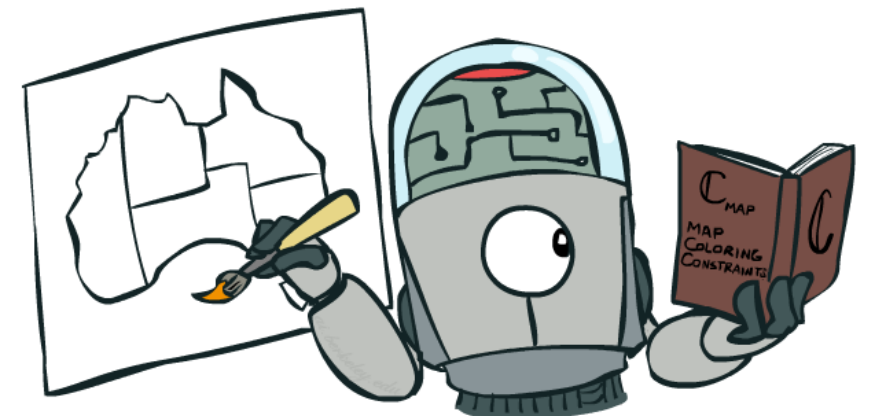
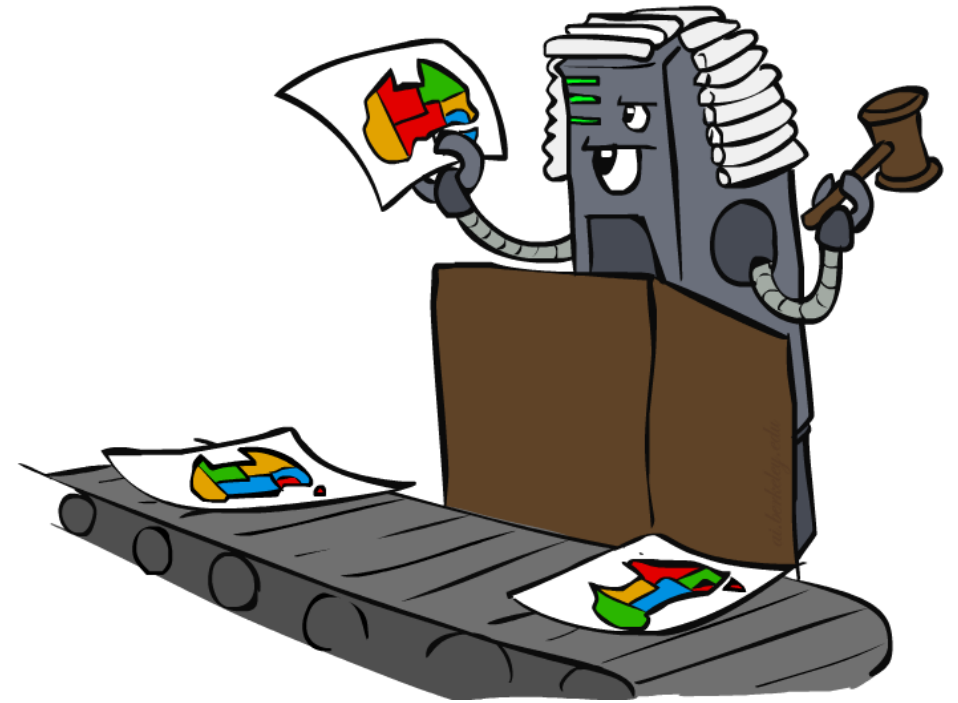
- Mostly identification problems
- Have specialized algorithms for them

Standard search problems:

- State is an arbitrary data structure
- Goal test can be any function over states

Constraint satisfaction problems (CSPs):

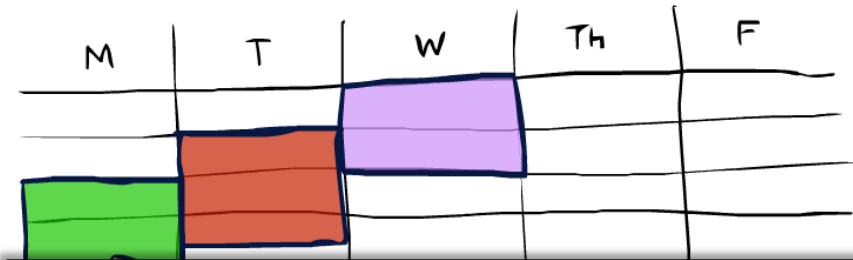
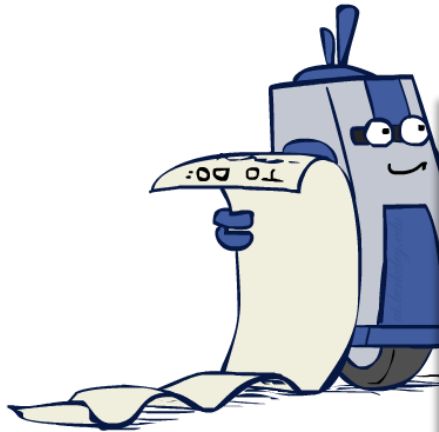
- State is defined by **variables X_i** with values from a **domain D** (sometimes D depends on i)
- Goal test is a **set of constraints** specifying allowable combinations of values for subsets of variables



Why study CSPs?

Many real-world problems can be formulated as 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
- Circuit layout
- Fault diagnosis
- ... lots more!
- Sometimes involve real-valued variables...



Stephanie Rosenthal (She/Her) • 1st

Artificial Intelligence and Human-Computer Interaction

5mo • 🌐

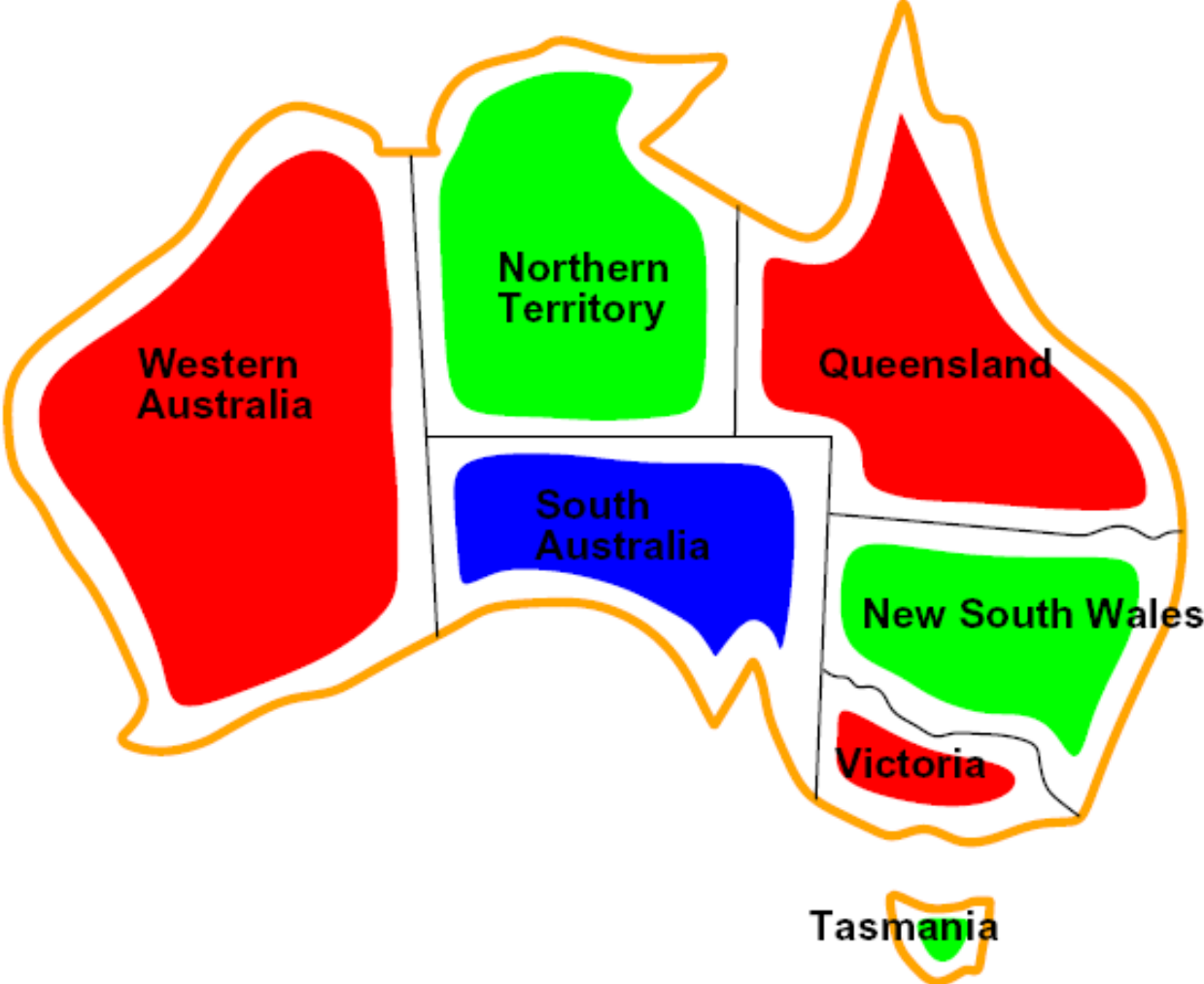
Hi Everyone. My amazing team at Microsoft is hiring a Scheduling/OR specialist to help with our efforts to create an automated scheduling service. Do you know anyone who fits the bill? Have them reach out to me for more information.

[Search Jobs | Microsoft Careers](#)

jobs.careers.microsoft.com



CSP Examples



Example: Map Coloring

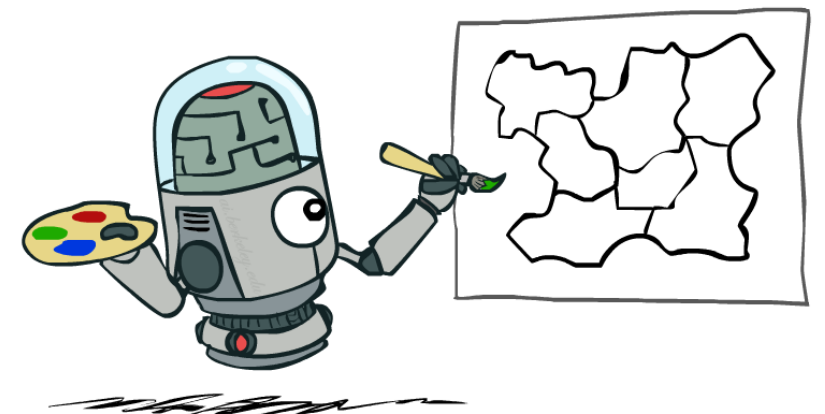
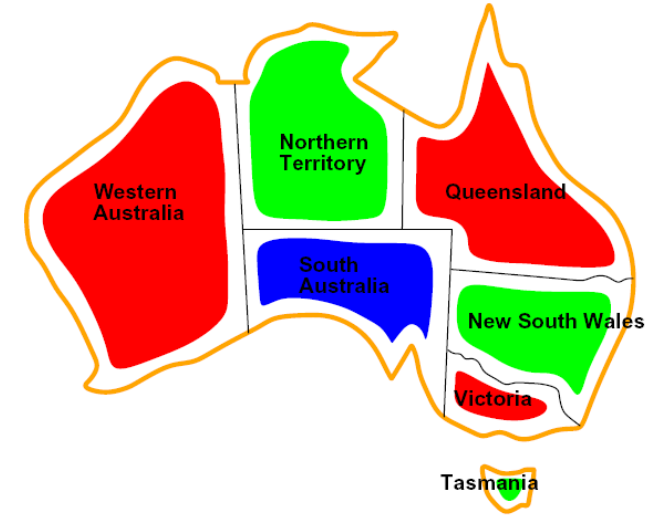
- Variables: WA, NT, Q, NSW, V, SA, T
- Domains: $D = \{\text{red, green, blue}\}$
- Constraints: adjacent regions must have different colors

Implicit: $WA \neq NT$

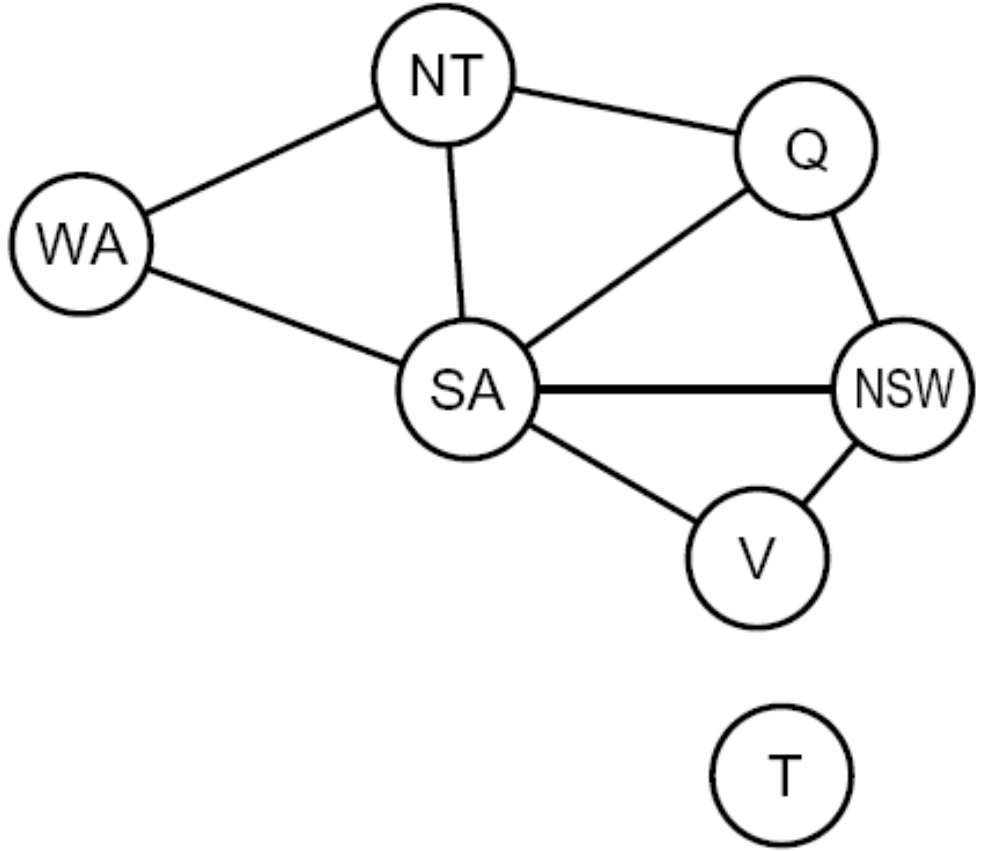
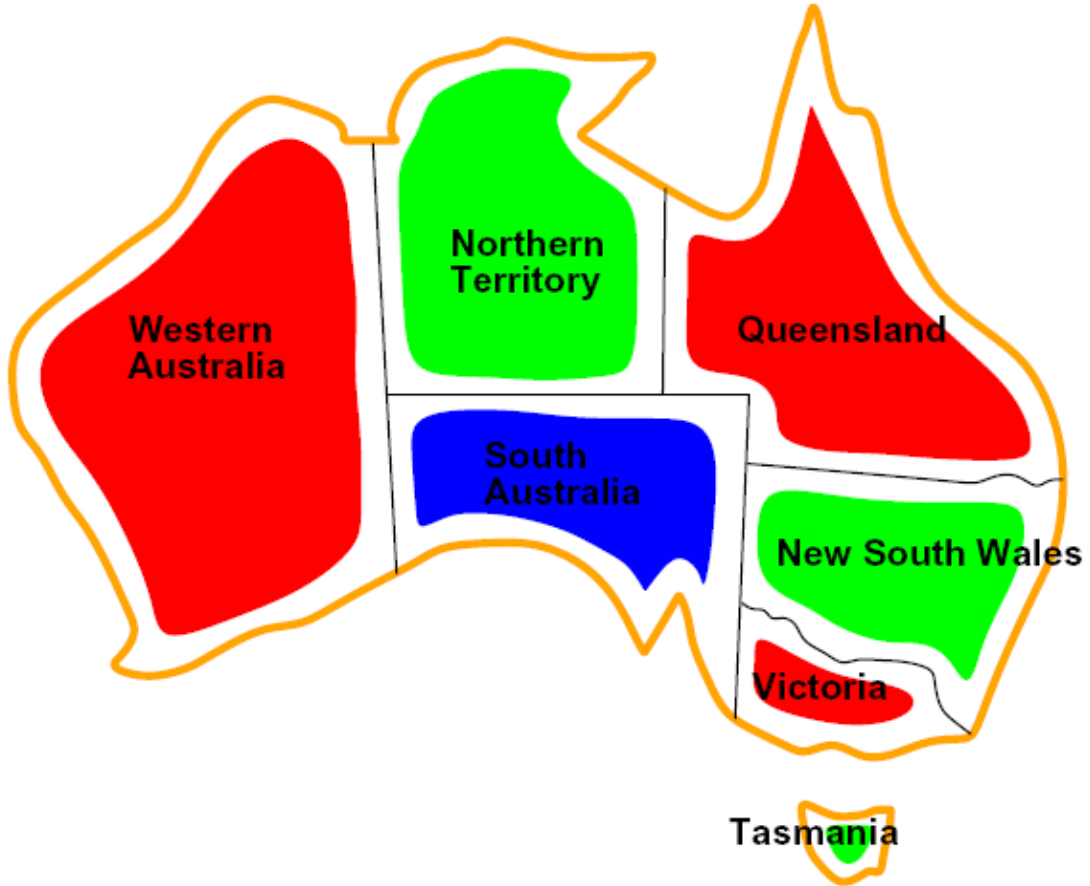
Explicit: $(WA, NT) \in \{(\text{red, green}), (\text{red, blue}), \dots\}$

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

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

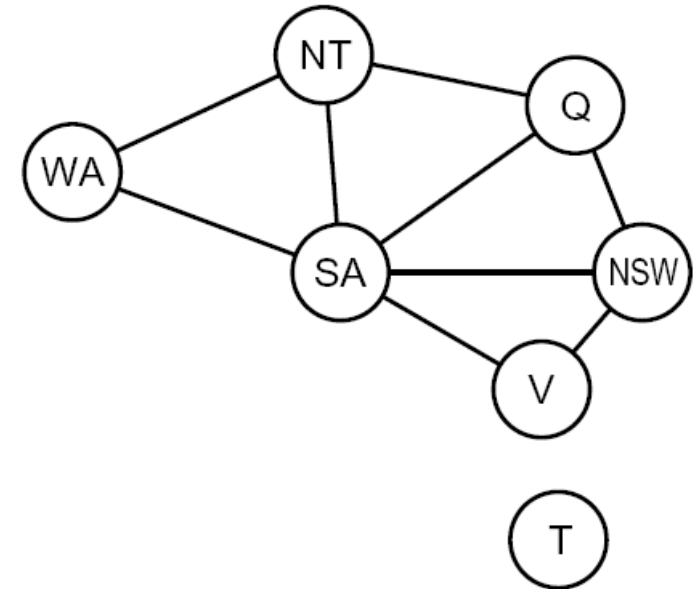


Constraint Graphs

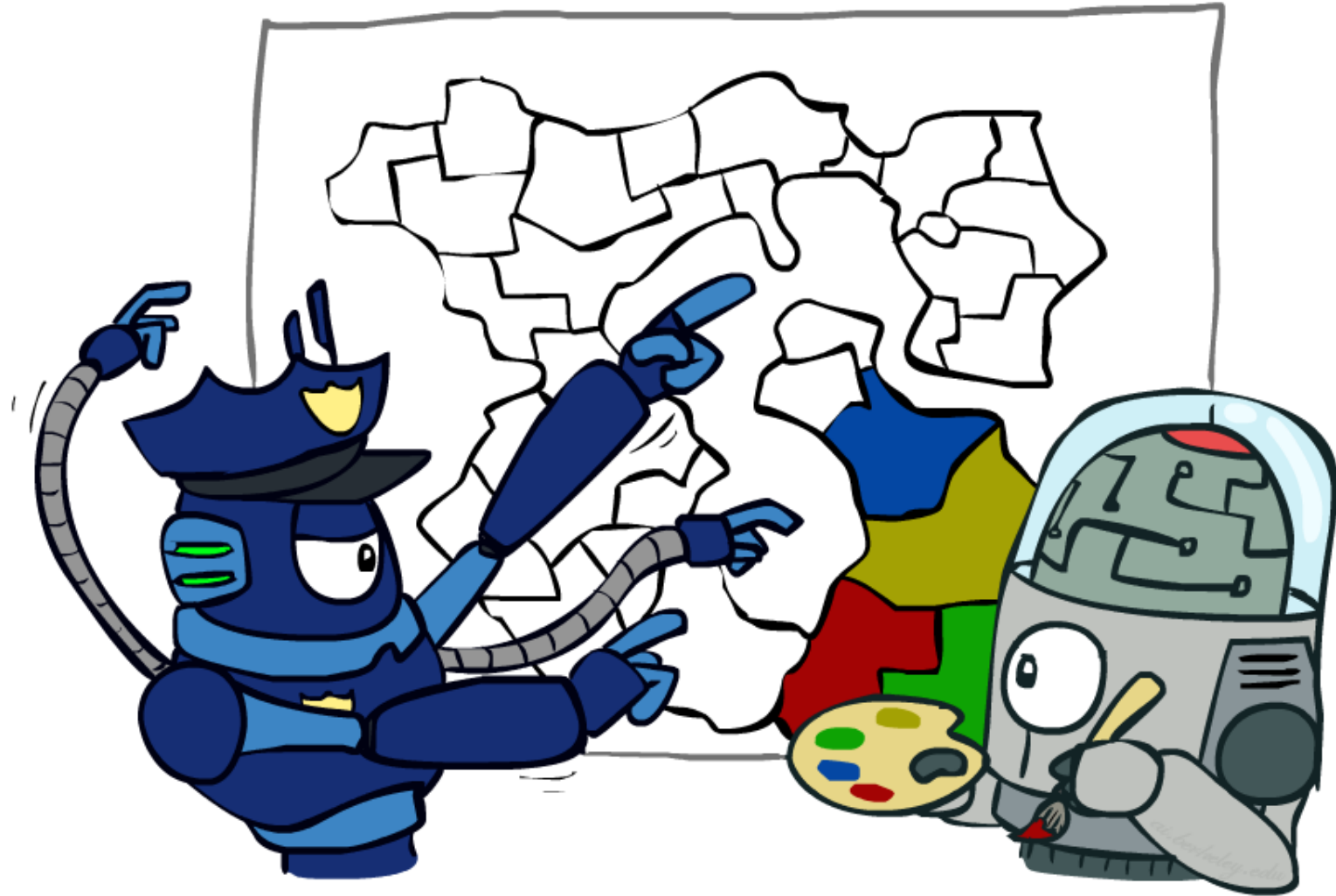


Constraint Graphs

- 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!



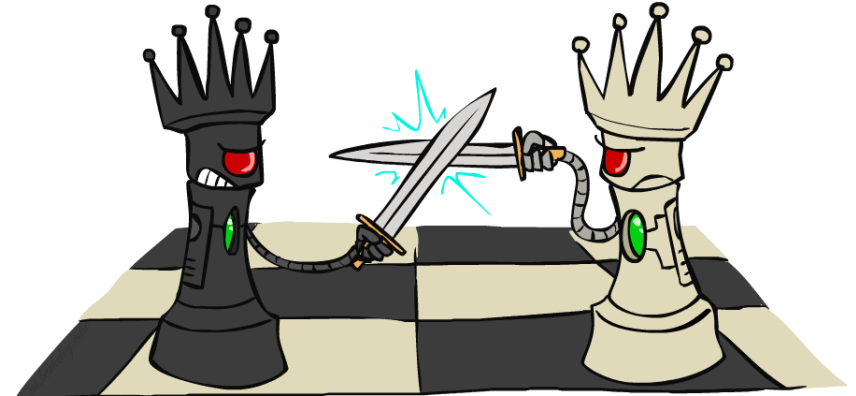
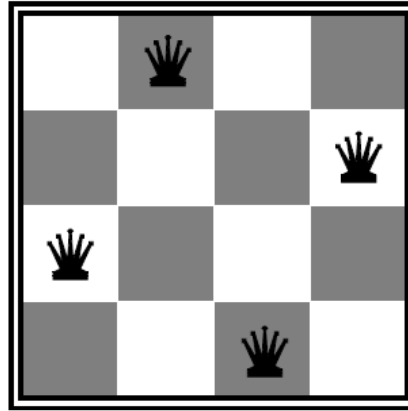
Varieties of CSPs and Constraints



Example: N-Queens

- Formulation 1:

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



$$\forall i, j, k \quad (X_{ij}, X_{ik}) \in \{(0, 0), (0, 1), (1, 0)\}$$

$$\forall i, j, k \quad (X_{ij}, X_{kj}) \in \{(0, 0), (0, 1), (1, 0)\}$$

$$\forall i, j, k \quad (X_{ij}, X_{i+k, j+k}) \in \{(0, 0), (0, 1), (1, 0)\}$$

$$\forall i, j, k \quad (X_{ij}, X_{i+k, j-k}) \in \{(0, 0), (0, 1), (1, 0)\}$$

$$\sum_{i,j} X_{ij} = N$$

Example: N-Queens

- Formulation 2:

- Variables: Q_k

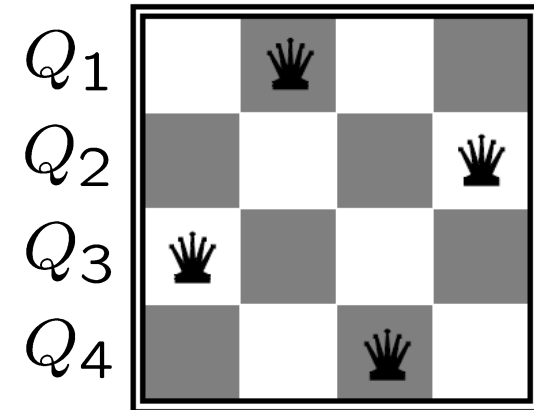
- Domains: $\{1, 2, 3, \dots, N\}$

- Constraints:

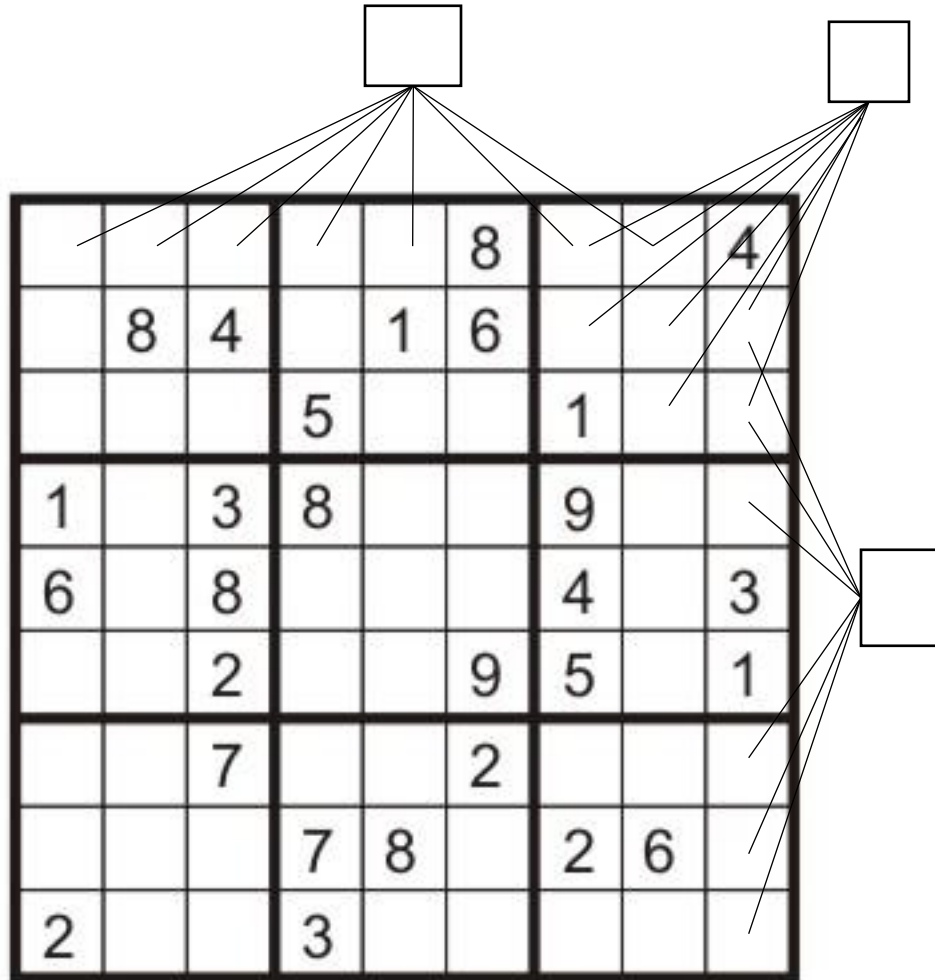
Implicit: $\forall i, j$ non-threatening(Q_i, Q_j)

Explicit: $(Q_1, Q_2) \in \{(1, 3), (1, 4), \dots\}$

• • •



Example: Sudoku



- Variables: Each (open) square
- Domains: $\{1,2,\dots,9\}$
- Constraints:
 - 9-way alldiff for each column
 - 9-way alldiff for each row
 - 9-way alldiff for each region
 - (or can have a bunch of pairwise inequality constraints)

Varieties of CSPs

- Discrete Variables

We will cover today

- Finite domains

- Size d means $O(d^n)$ complete assignments
 - E.g., Boolean CSPs, including Boolean satisfiability (NP-complete)

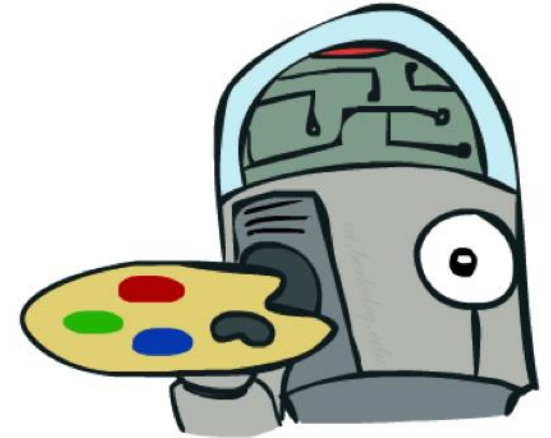
- Infinite domains (integers, strings, etc.)

- E.g., job scheduling, variables are start/end times for each job
 - Linear constraints solvable, nonlinear undecidable

We will cover in a later lecture (linear programming)

- Continuous variables

- E.g., start/end times for Hubble Telescope observations
 - Linear constraints solvable in polynomial time



Varieties of Constraints

- Varieties of Constraints

- Unary constraints involve a single variable (equivalent to reducing domains), e.g.:

$$SA \neq \text{green}$$

Focus of today

- Binary constraints involve pairs of variables, e.g.:

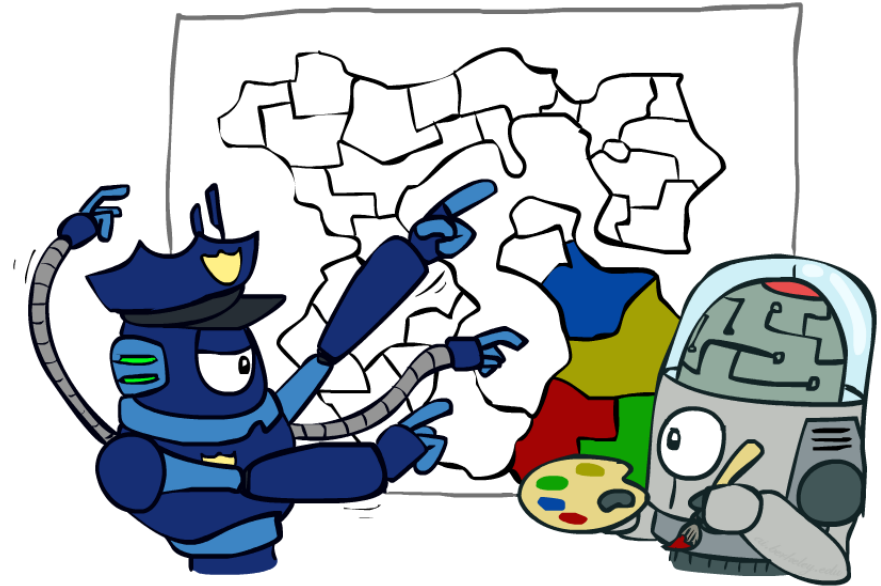
$$SA \neq WA$$

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

$$O + O = R + 10 \cdot X_1$$

- Preferences (soft constraints):

- E.g., red is better than green
- Often representable by a cost for each variable assignment
- Gives constrained optimization problems

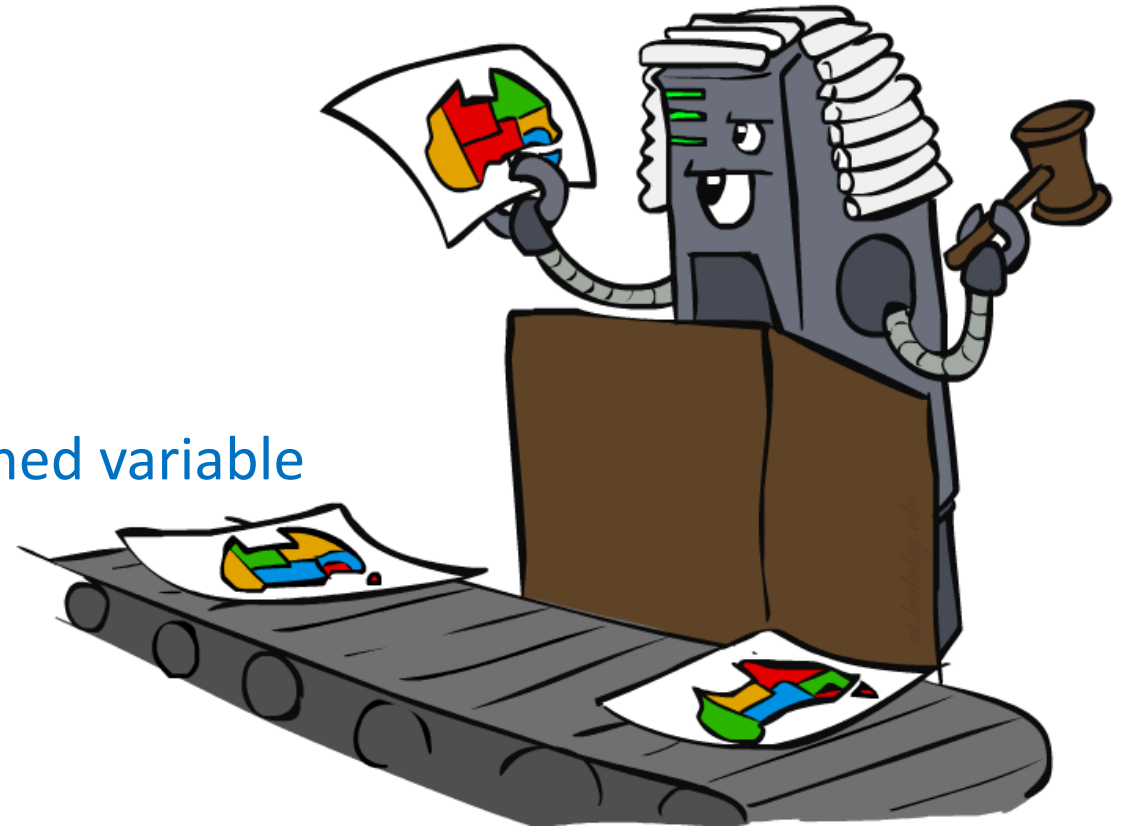


Solving CSPs



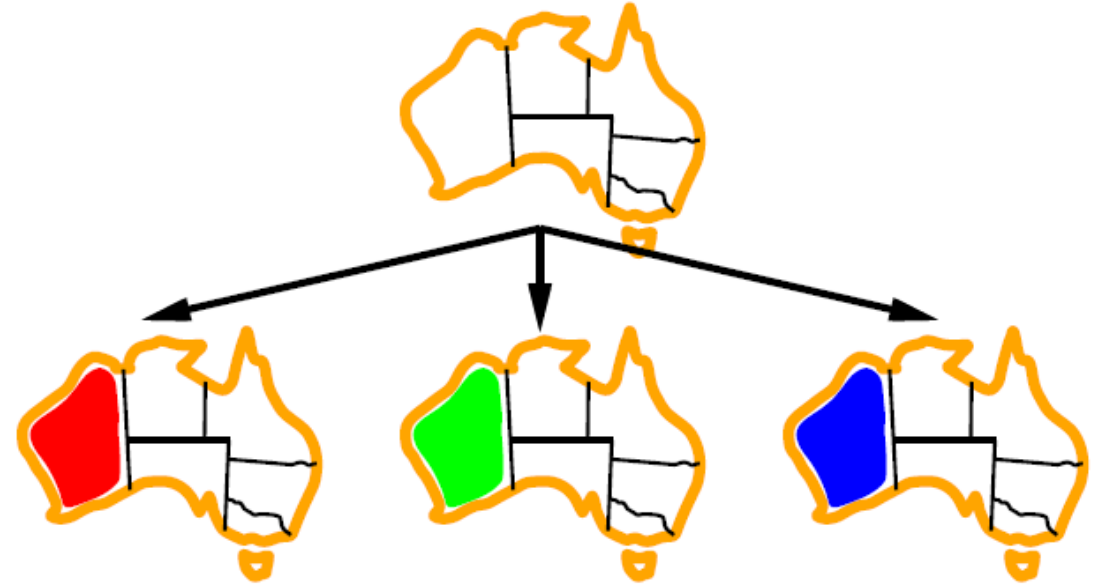
Standard Search Formulation

- Standard search formulation of CSPs
- States defined by the values assigned so far (partial assignments)
 - Initial state: the empty assignment, $\{\}$
 - Successor function: assign a value to an **unassigned variable** → Can be any unassigned variable
 - Goal test: the current assignment is **complete** and **satisfies all constraints**
- We'll start with the straightforward, naïve approach, then improve it



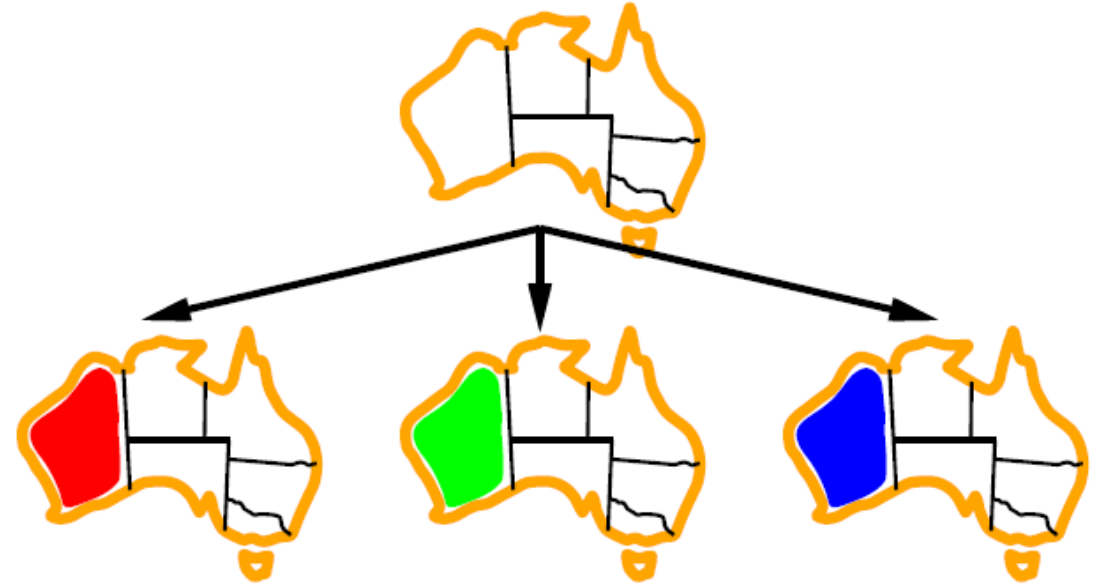
Poll 1: Search for CSPs

Should we use BFS or DFS?

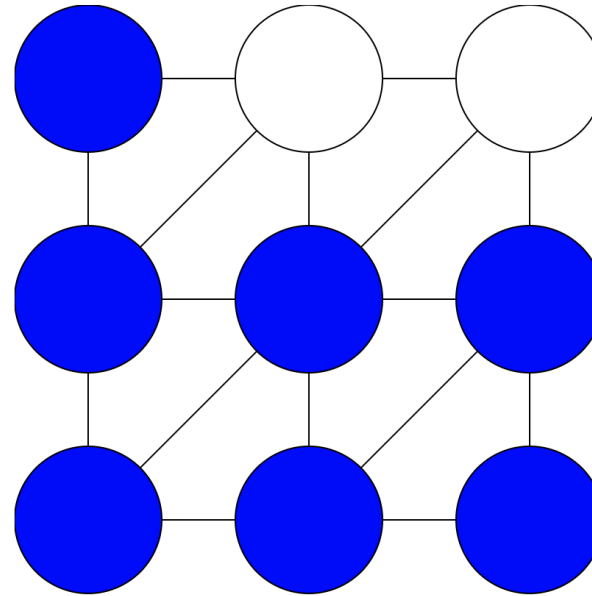
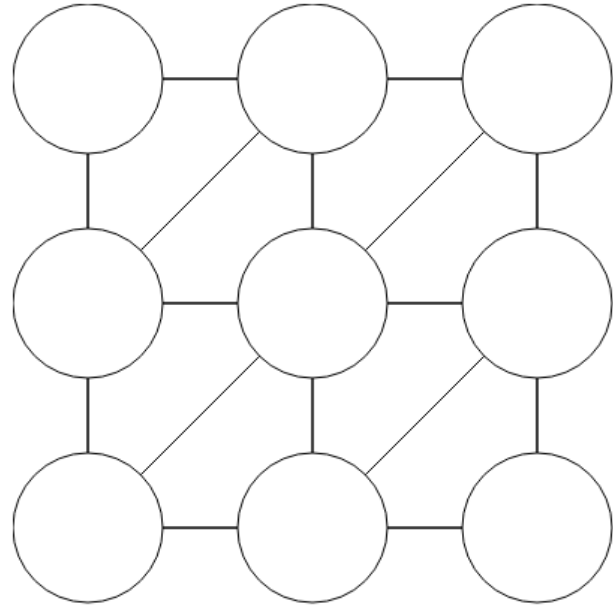


Depth First Search

- At each node, assign a value from the domain to the variable
- Check feasibility (constraints) when the assignment is complete



Demo – Naïve Search



15-281: Artificial Intelligence

OH

Schedule

Recitations

Exams

Assignments

Policies

Course Notes

9/5 Thu

Adversarial Search

AIMA Ch. 5.1-2, 5.5

[pptx \(inked\)](#) [pdf \(inked\)](#)

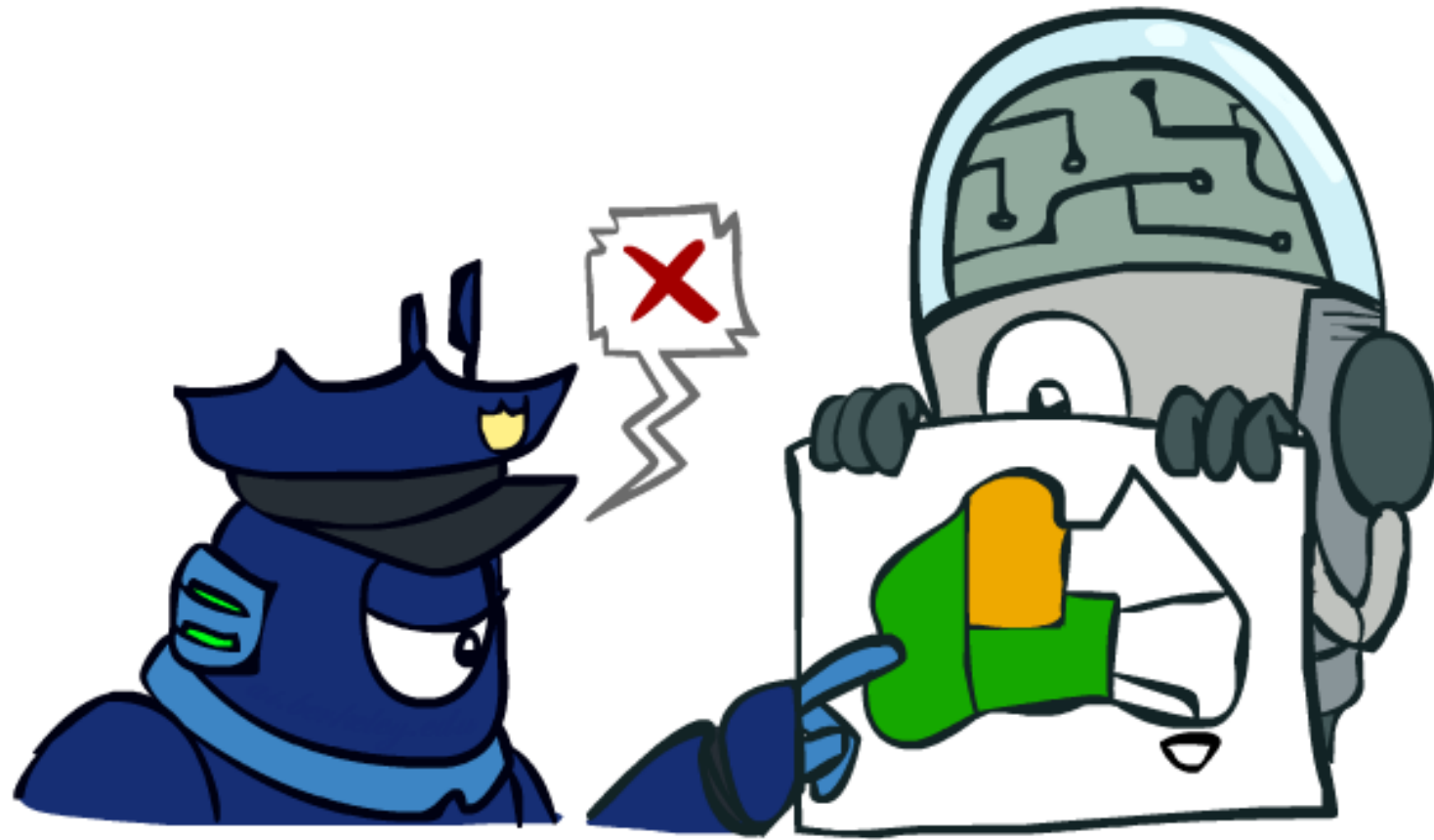
9/10 Tue

Constraint Satisfaction Problems

AIMA Ch. 6.1-3, 6.5

[CSP Demo](#)

Backtracking Search



Backtracking Search

Backtracking search is the basic uninformed algorithm for solving CSPs

Backtracking search = DFS + two improvements

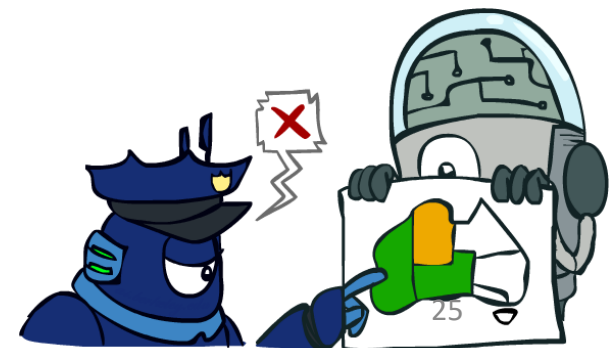
Idea 1: One variable at a time

- Variable assignments are commutative
 - [WA = red then NT = green] same as [NT = green then WA = red]
- Only need to consider assign value to a single variable at each step

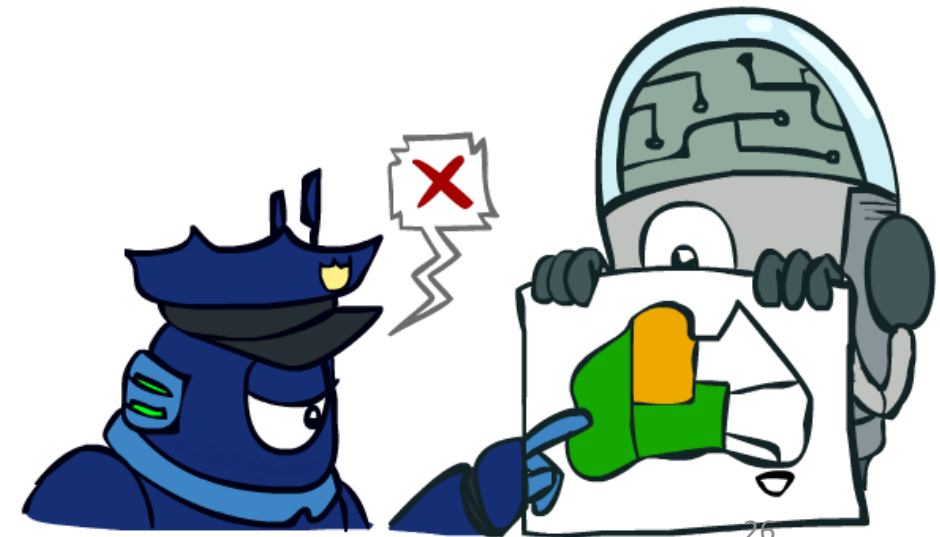
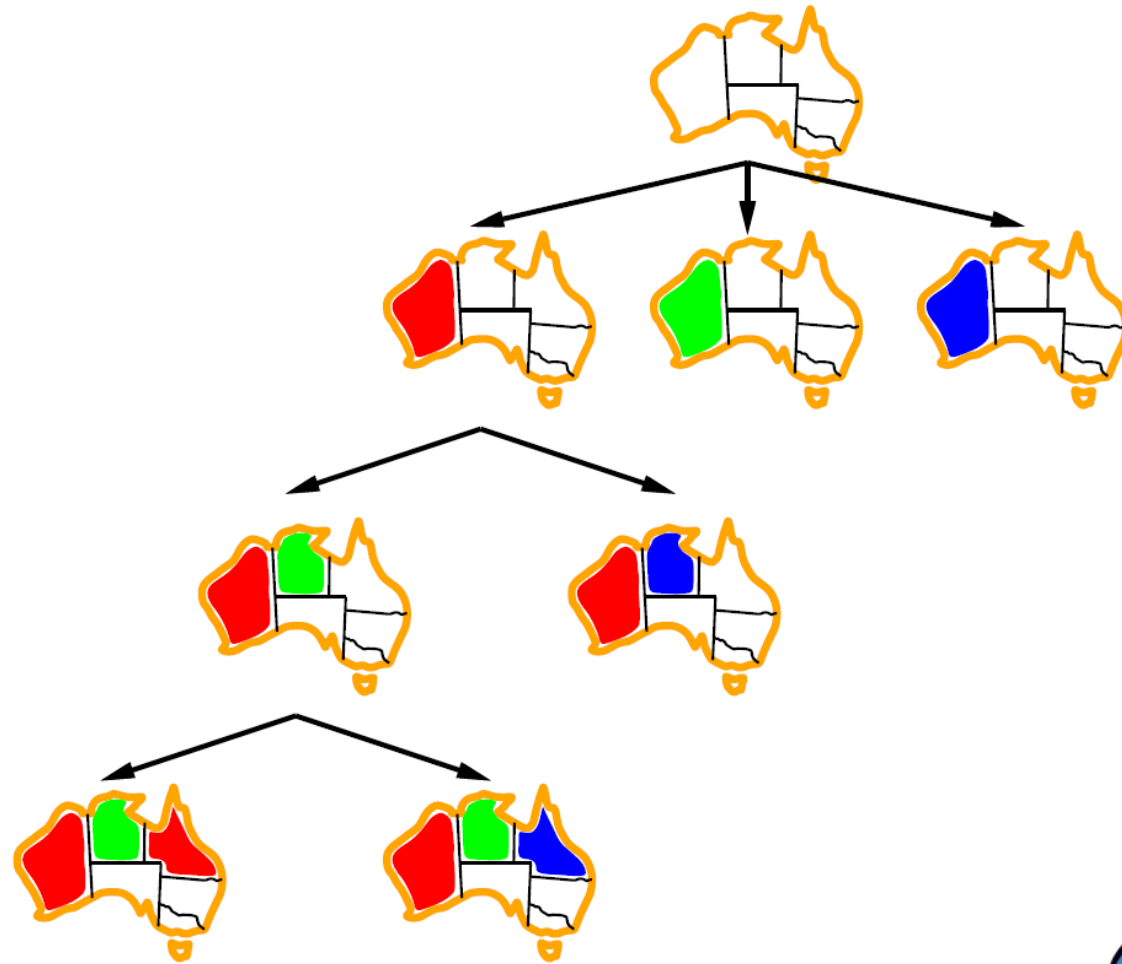
Idea 2: Check constraints as you go

- Consider only values which do not conflict previous assignments
- May need some computation to check the constraints
- “Incremental goal test”

Can solve n-queens for $n \approx 25$



Backtracking Example



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 ≠ failure then return result
      remove {var = value} from assignment
  return failure
```

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      remove {var = value} from assignment
  return failure
```

No need to check constraints for a complete assignment

Backtracking Search

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  return RECURSIVE-BACKTRACKING({ }, csp)

function RECURSIVE-BACKTRACKING(assignment, csp) returns soln/failure
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      remove {var = value} from assignment
  return failure
```

Checks consistency at each assignment

Backtracking Search

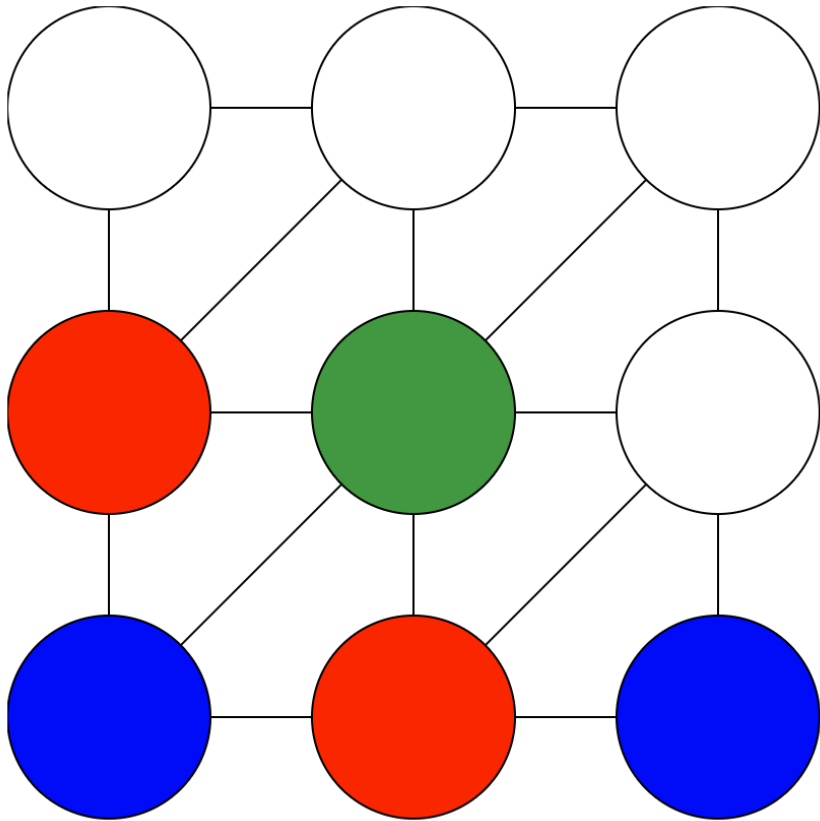
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```

- Backtracking = DFS + variable-ordering + fail-on-violation
- What are the decision points?

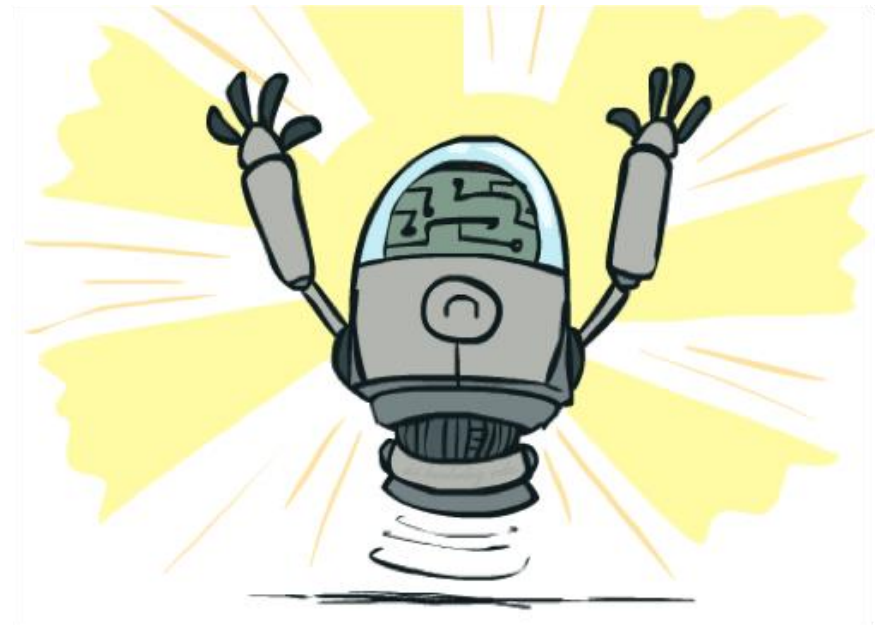
Demo – Backtracking

https://www.cs.cmu.edu/~15281/demos/csp_backtracking



Improving Backtracking

- General-purpose ideas give huge gains in speed
- Filtering: Can we detect inevitable failure early?
- Ordering:
 - Which variable should be assigned next?
 - In what order should its values be tried?
- Structure: Can we exploit the problem structure?



Filtering



Filtering: Forward Checking

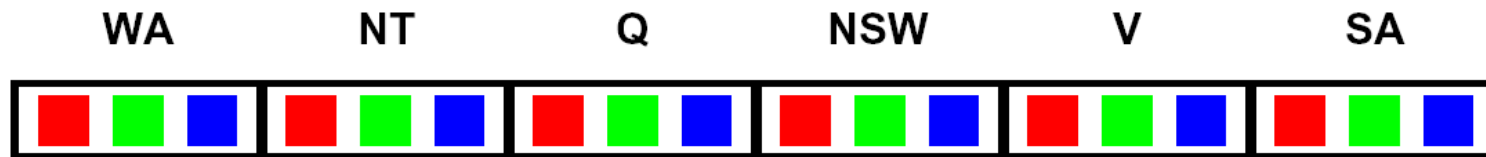
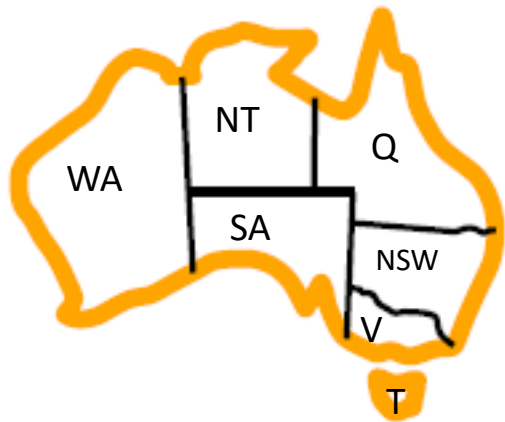
Filtering: Keep track of domains for unassigned variables and cross off bad options

Forward checking: A simple way for filtering

- After a variable is assigned a value, check related constraints and cross off values of unassigned variables which violate the constraints
- Failure detected if some variables have no values remaining

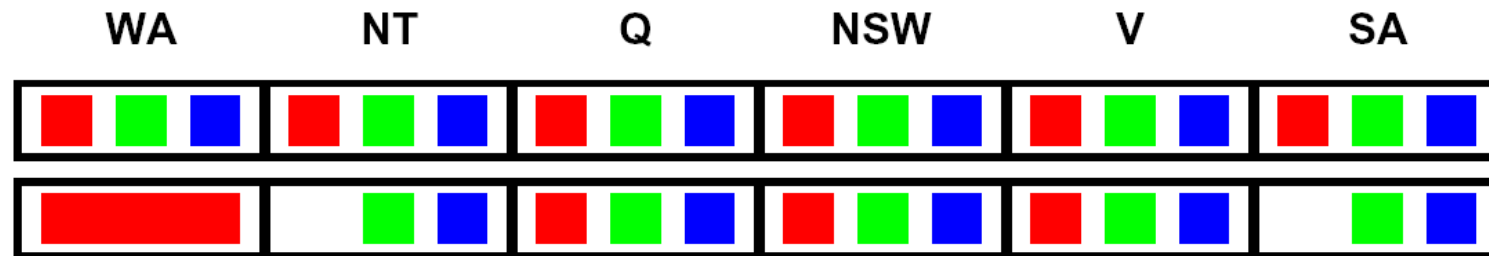
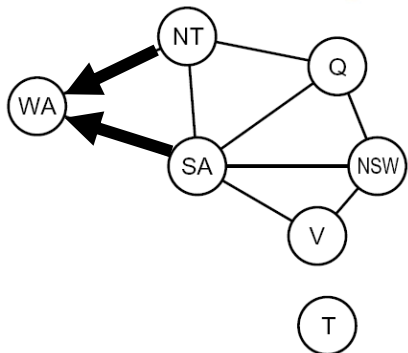
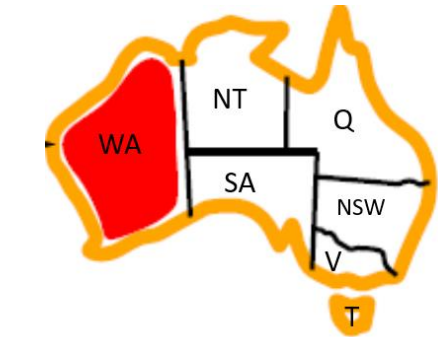
Filtering: Forward Checking

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Filtering: Forward Checking

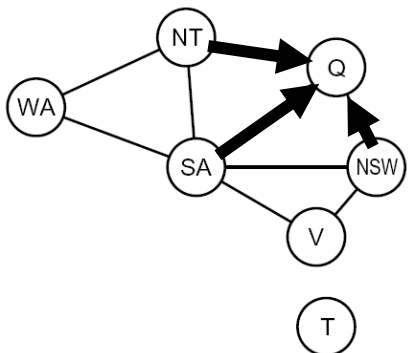
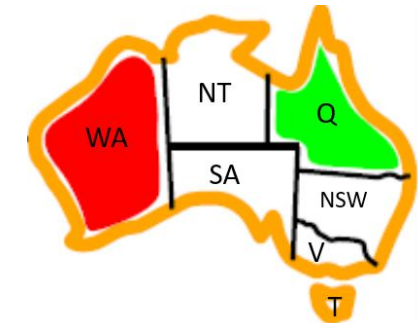
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- Forward checking: A simple way for filtering
 - After a variable is assigned a value, check related constraints and cross off values of unassigned variables which violate the constraints
 - Failure detected if some variables have no values remaining



Recall: Binary constraint graph for a binary CSP (i.e., each constraint has most two variables): nodes are variables, edges show constraints

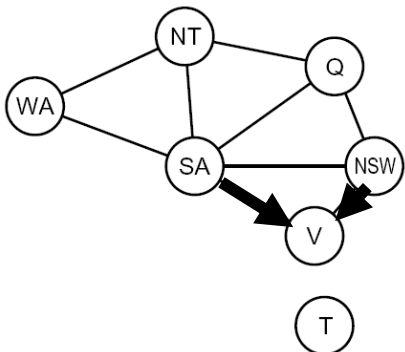
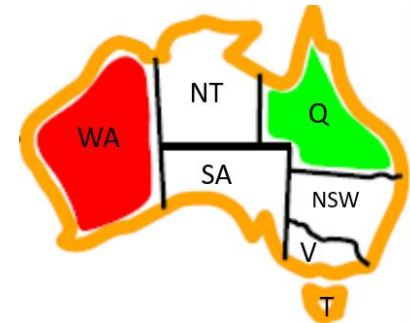
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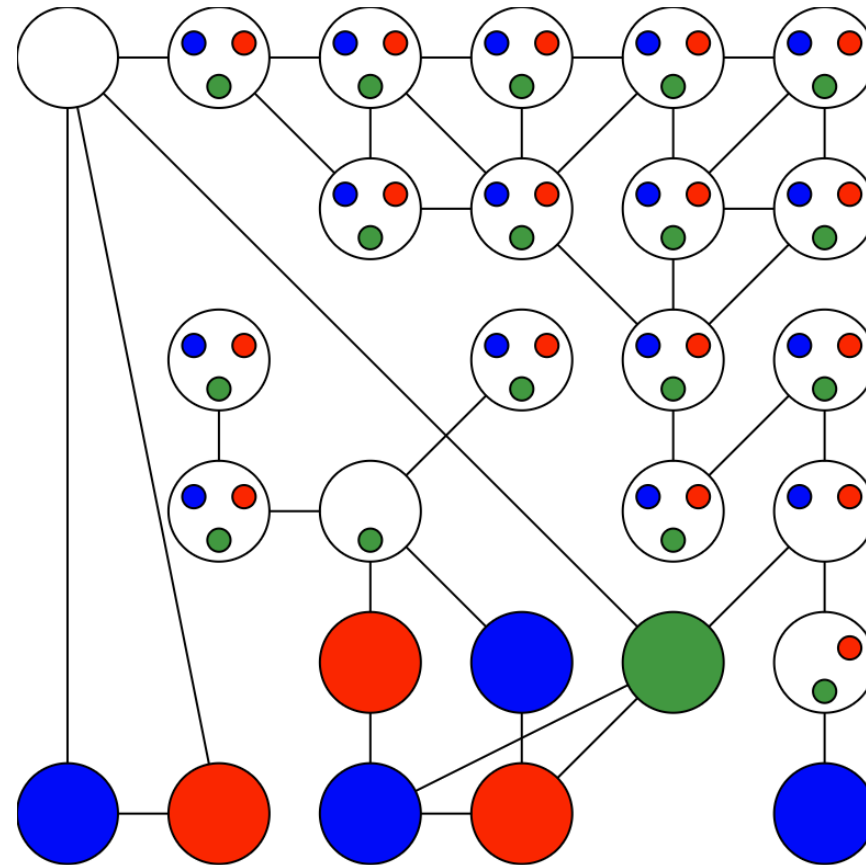
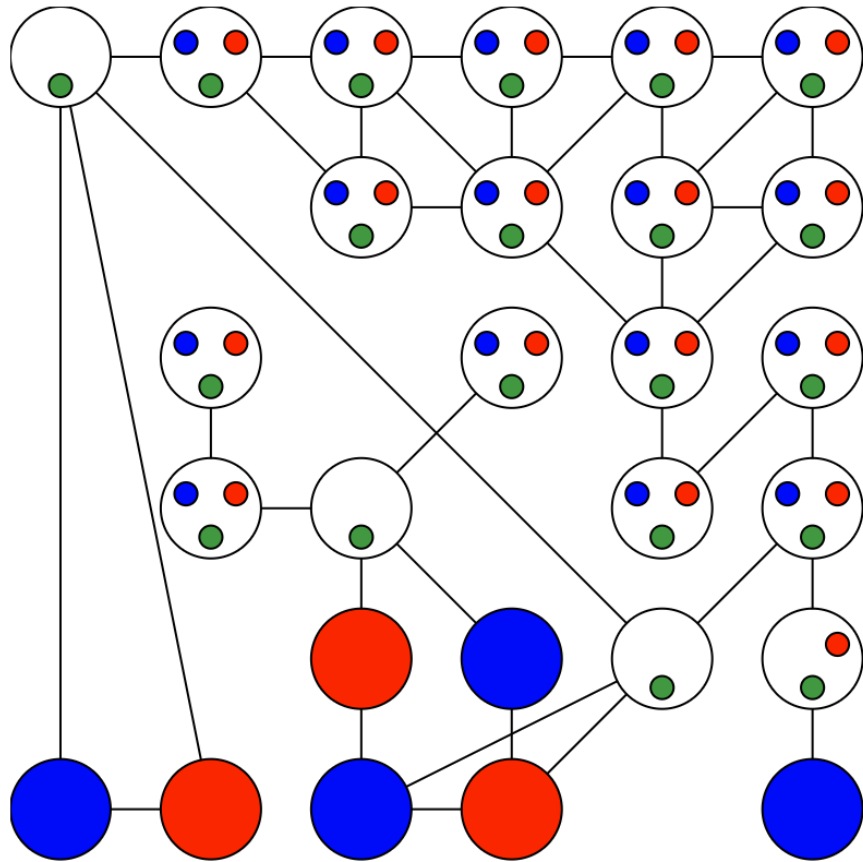


WA	NT	Q	NSW	V	SA
Red, Green, Blue	Red, Green, Blue	Red, Green, Blue	Red, Green, Blue	Red, Green, Blue	Red, Green, Blue
Red	Green, Blue	Red, Green, Blue	Red, Green, Blue	Red, Green, Blue	Green, Blue
Red	Blue	Green	Red, Blue	Red, Green, Blue	Blue
Red	Blue	Green	Red	Blue	

FAIL – variable with no possible values

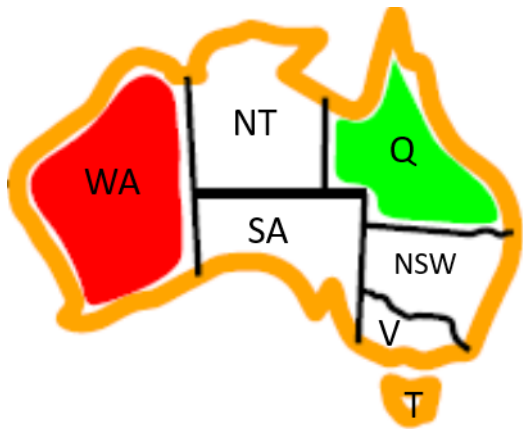
Demo – Backtracking with Forward Checking

https://www.cs.cmu.edu/~15281/demos/csp_backtracking



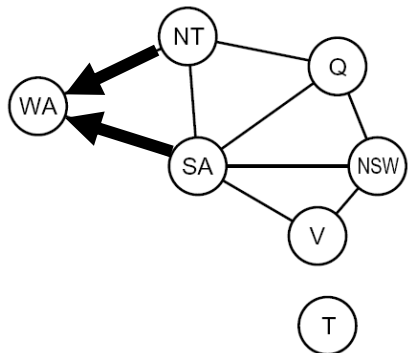
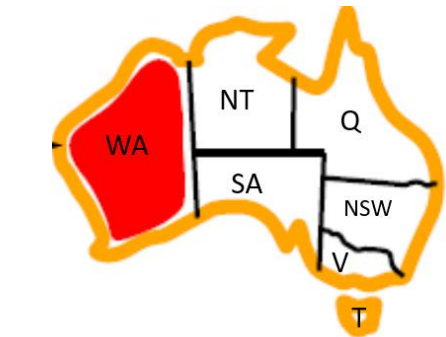
Filtering: Constraint Propagation

- Limitations of simple 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! Why didn't we detect this yet?
- *Constraint propagation*: reason from constraint to constraint

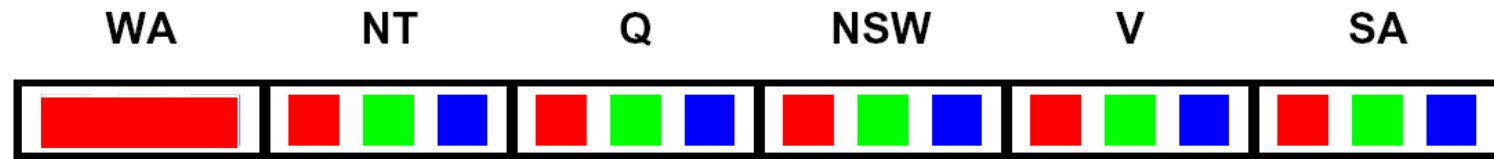


Consistency of A Single Arc

- An arc $X \rightarrow Y$ is consistent iff for **every** x in the tail there is **some** y in the head which could be assigned without violating a constraint
- Enforce arc consistency: Remove values in domain of X if no corresponding legal Y exists
- Forward checking: Only enforce $X \rightarrow Y, \forall (X, Y) \in E$ and Y newly assigned



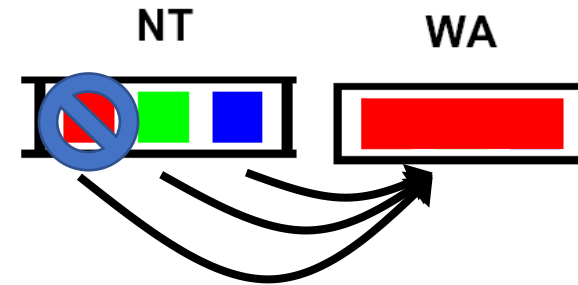
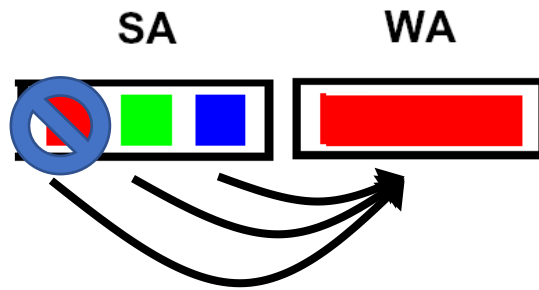
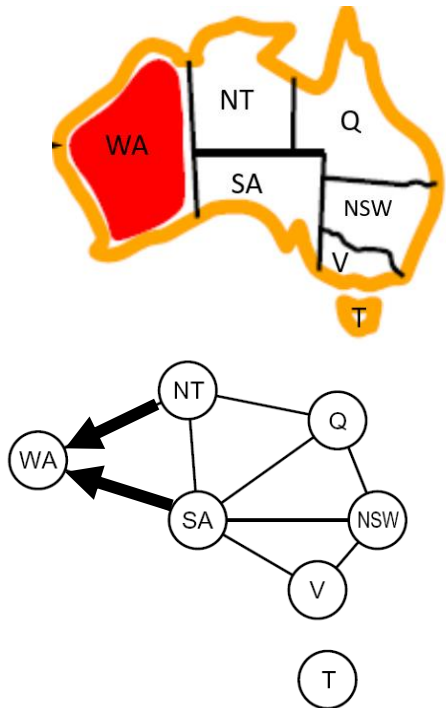
(Remove values from the tail!)



Recall: Binary constraint graph for a binary CSP (i.e., each constraint has most two variables): nodes are variables, edges show constraints

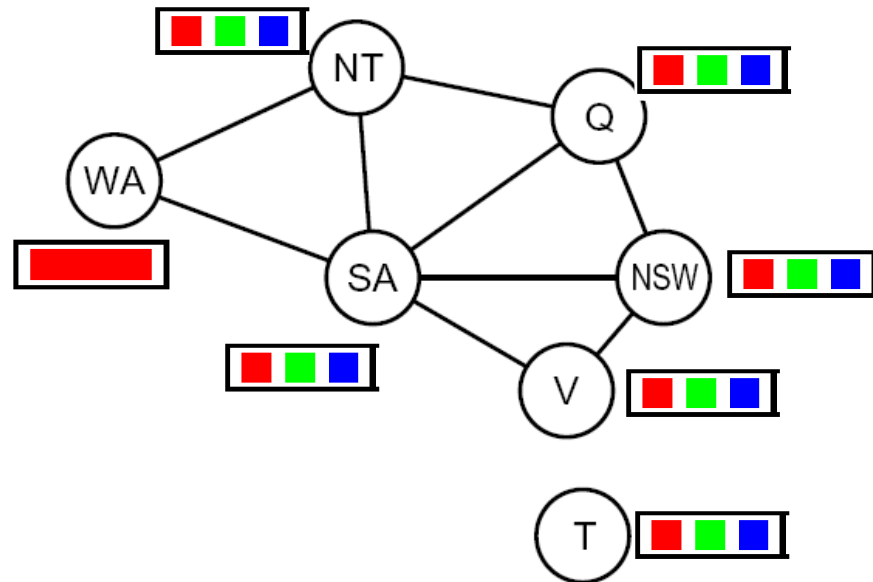
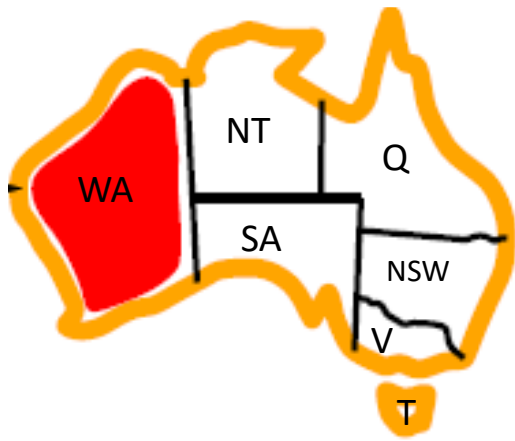
Consistency of A Single Arc

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How to Enforce Arc Consistency of Entire CSP

- A simplistic algorithm: Cycle over the pairs of variables, enforcing arc-consistency, repeating the cycle until no domains change for a whole cycle
- AC-3 (short for Arc Consistency Algorithm #3): A more efficient algorithm ignoring constraints that have not been modified since they were last analyzed



AC-3: Enforce Arc Consistency of Entire CSP

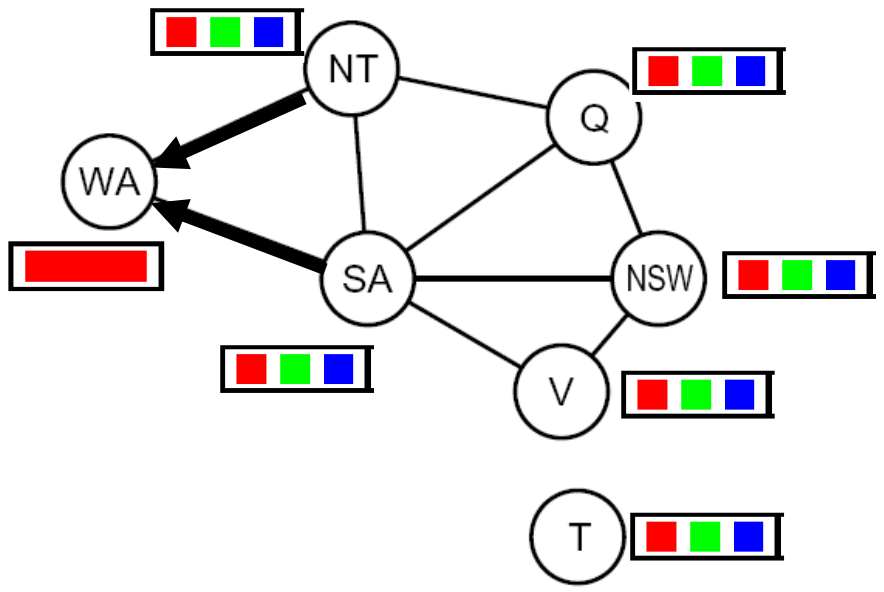
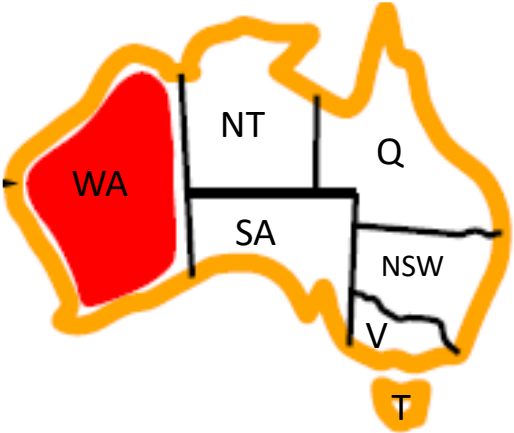
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inputs: csp, a binary CSP with variables  $\{X_1, X_2, \dots, X_n\}$ 
local variables: queue, a queue of arcs, initially all the arcs in csp
while queue is not empty do
     $(X_i, X_j) \leftarrow \text{REMOVE-FIRST}(\textit{queue})$ 
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        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  $\leftarrow$  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
```

Constraint Propagation!

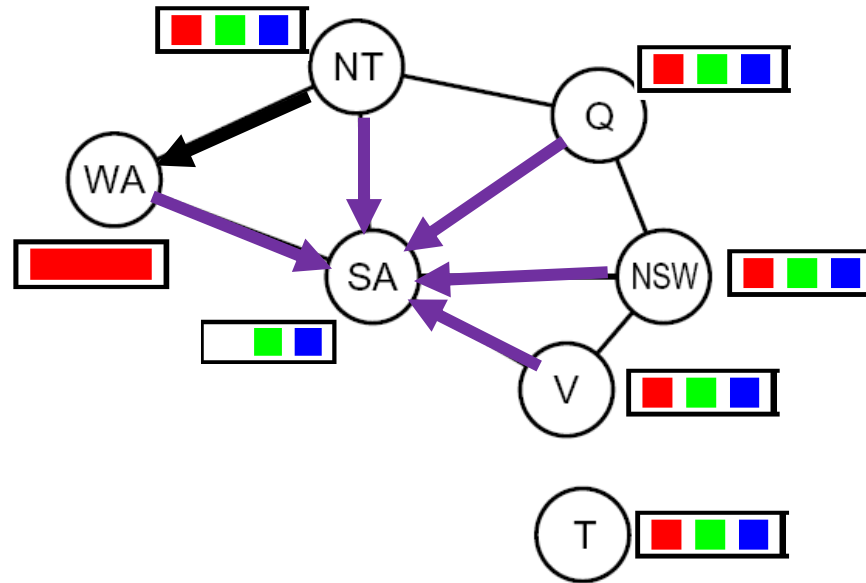
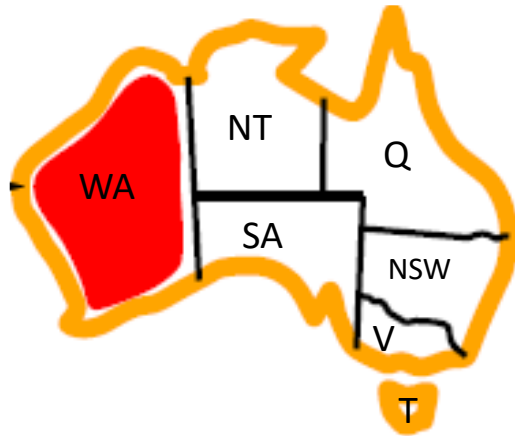
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
SA->WA
NT->WA

Remember: Delete from the tail!

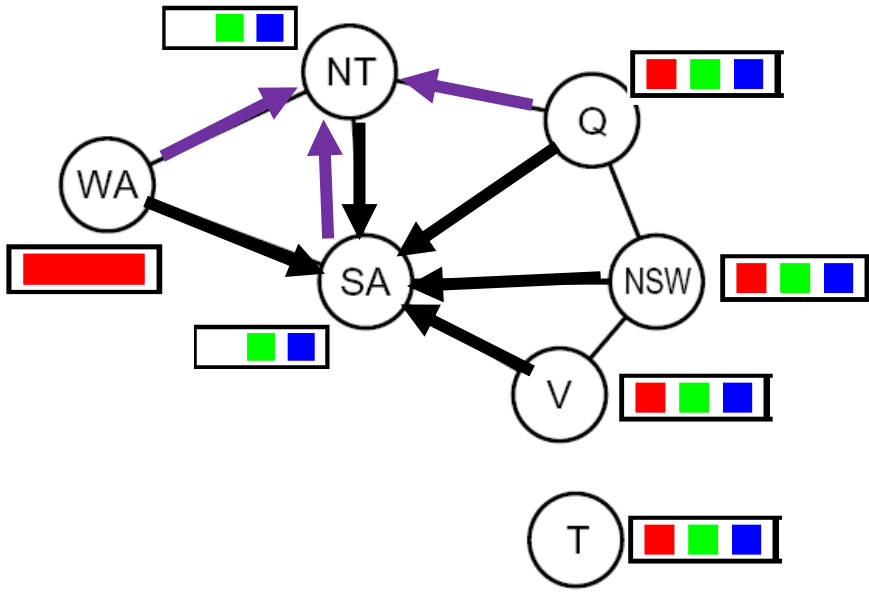
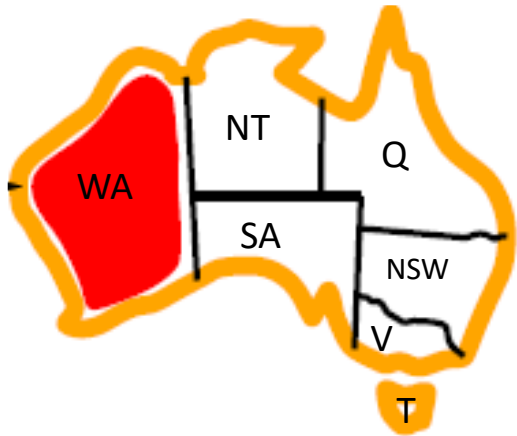
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
NT->WA
WA->SA
NT->SA
Q->SA
NSW->SA
V->SA

Remember: Delete from the tail!

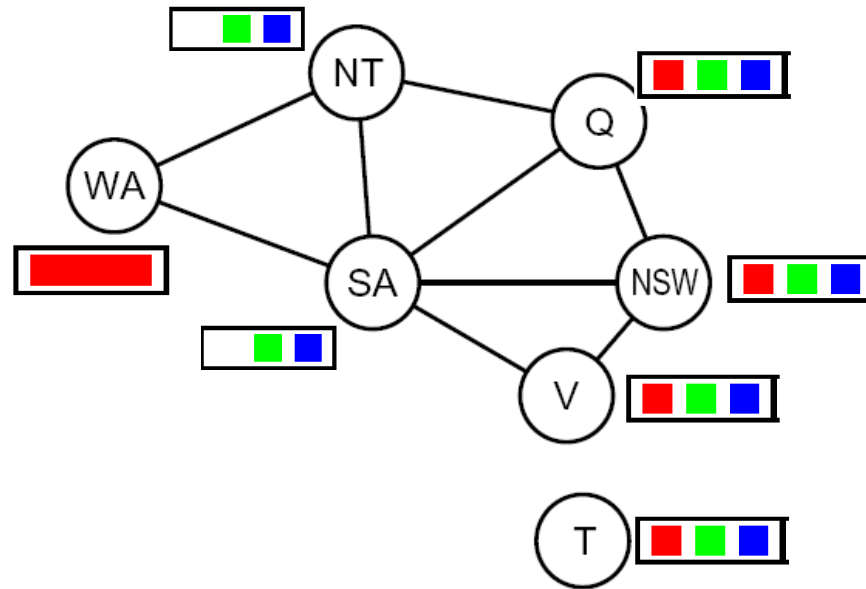
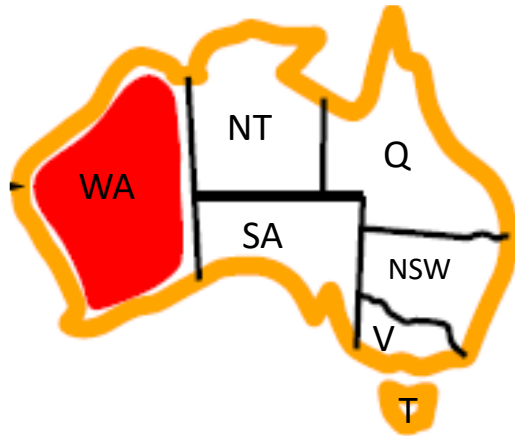
AC-3: Enforce Arc Consistency of Entire CSP



- Queue:
- WA->SA
 - NT->SA
 - Q->SA
 - NSW->SA
 - V->SA
 - WA->NT
 - SA->NT
 - Q->NT

Remember: Delete from the tail!

AC-3: Enforce Arc Consistency of Entire CSP



Queue:

WA->SA

NT->SA

Q->SA

NSW->SA

V->SA

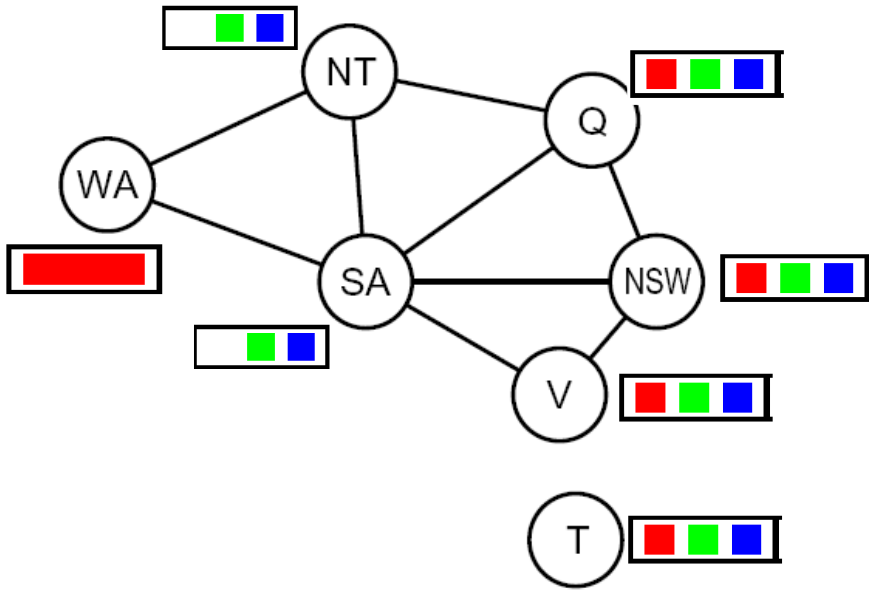
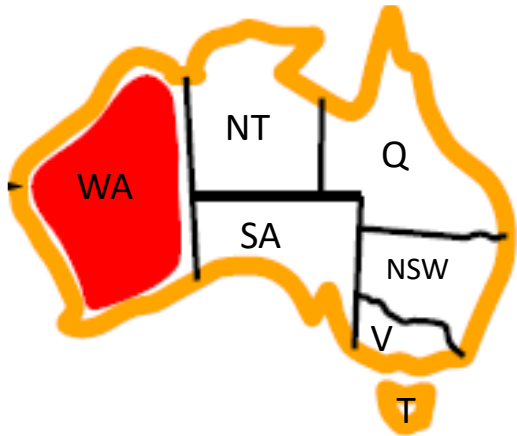
WA->NT

SA->NT

Q->NT

Remember: Delete from the tail!

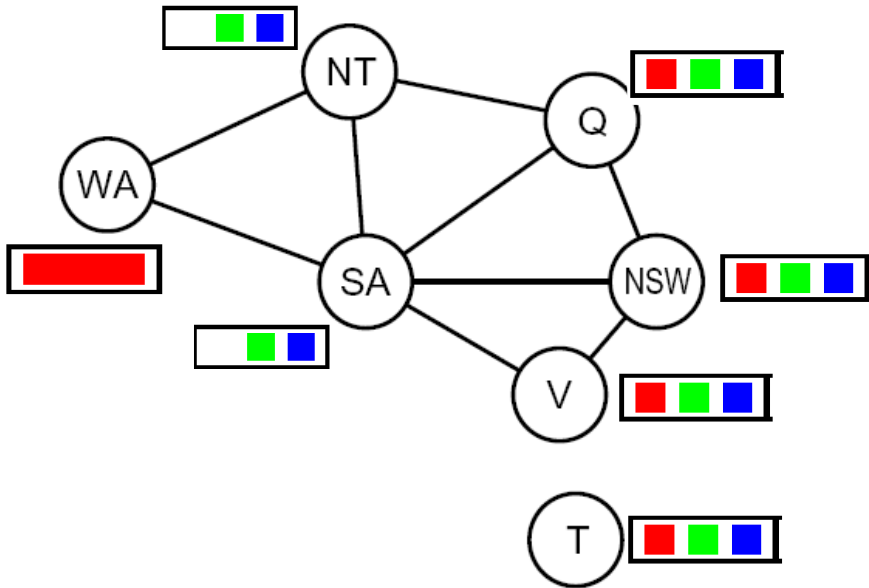
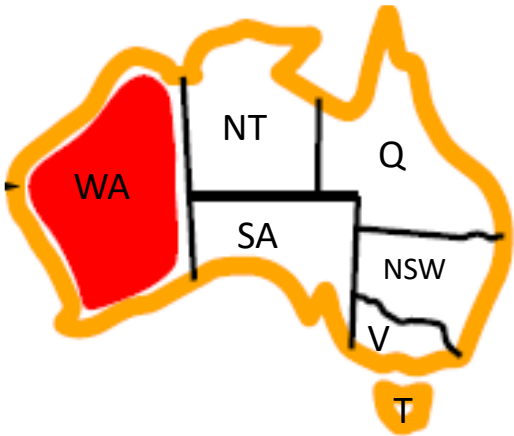
AC-3: Enforce Arc Consistency of Entire CSP



- Queue:
NT->SA
Q->SA
NSW->SA
V->SA
WA->NT
SA->NT
Q->NT

Remember: Delete from the tail!

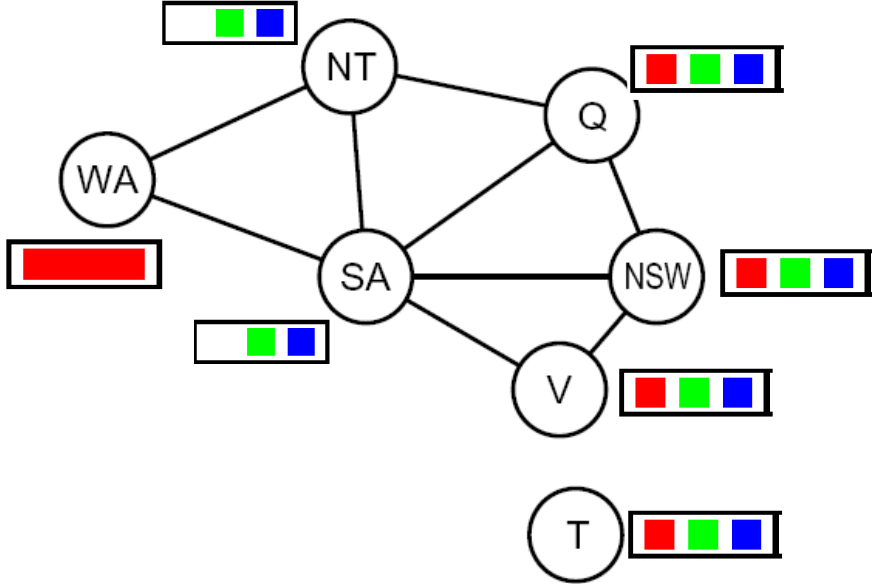
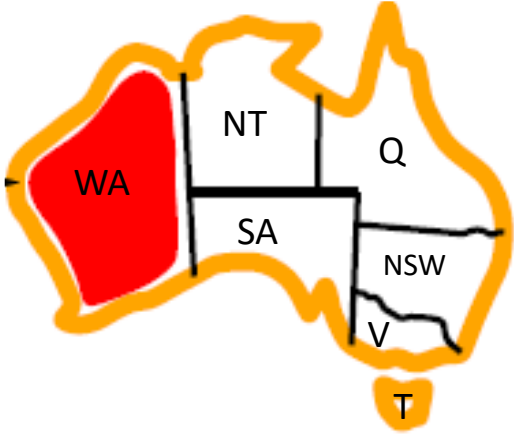
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
Q->SA
NSW->SA
V->SA
WA->NT
SA->NT
Q->NT

Remember: Delete from the tail!

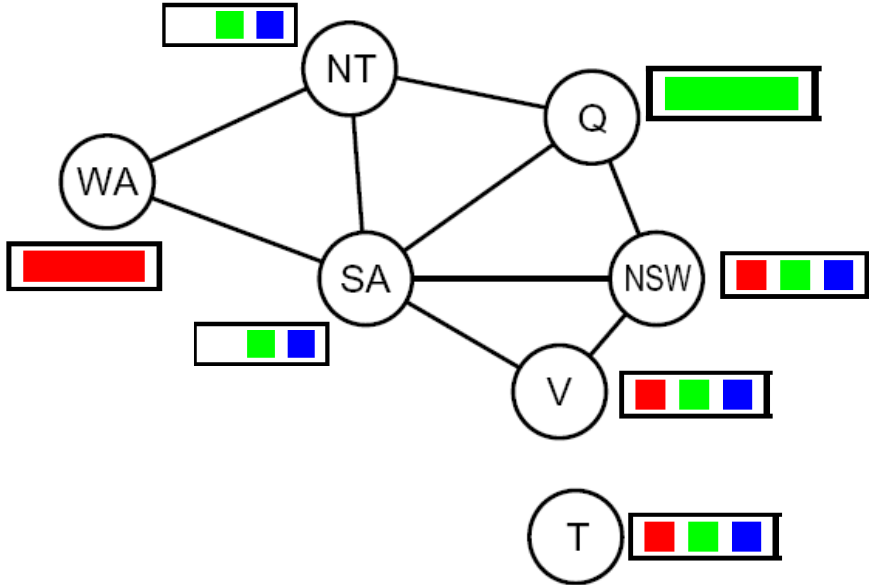
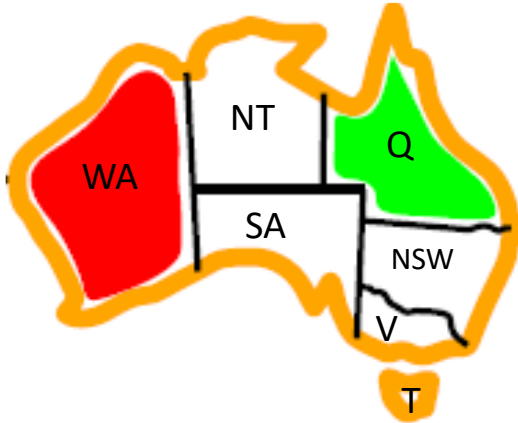
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
NSW->SA
V->SA
WA->NT
SA->NT
Q->NT

Remember: Delete from the tail!

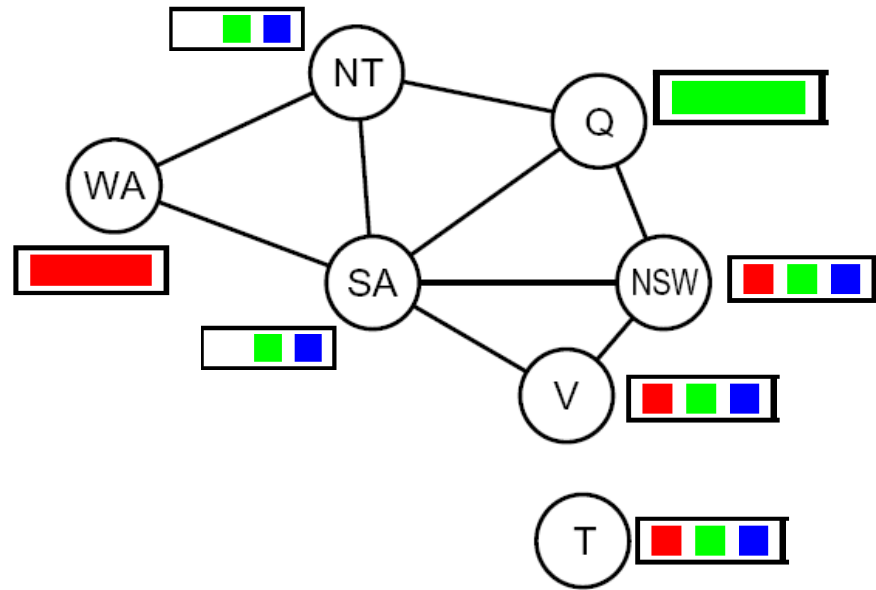
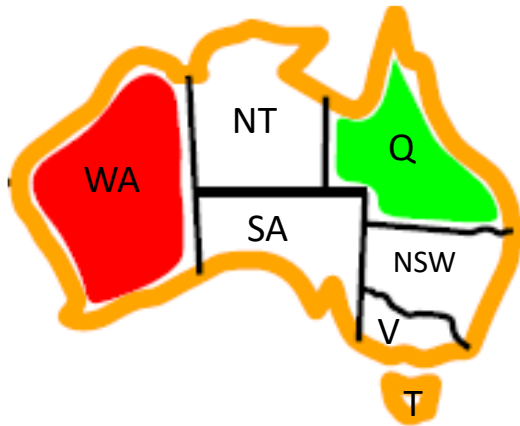
AC-3: Enforce Arc Consistency of Entire CSP



Queue:

Remember: Delete from the tail!

Poll 2: After assigning Q to Green, what gets added to the Queue?

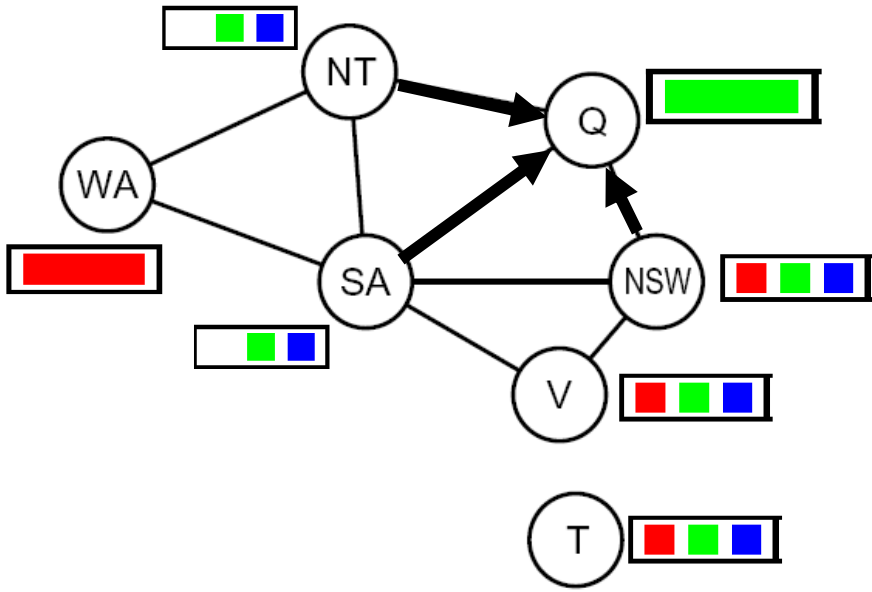
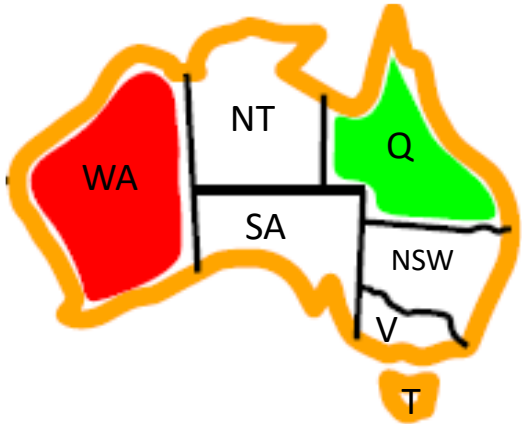


Queue:

A: NSW->Q, SA->Q, NT->Q

B: Q->NSW, Q->SA, Q->NT

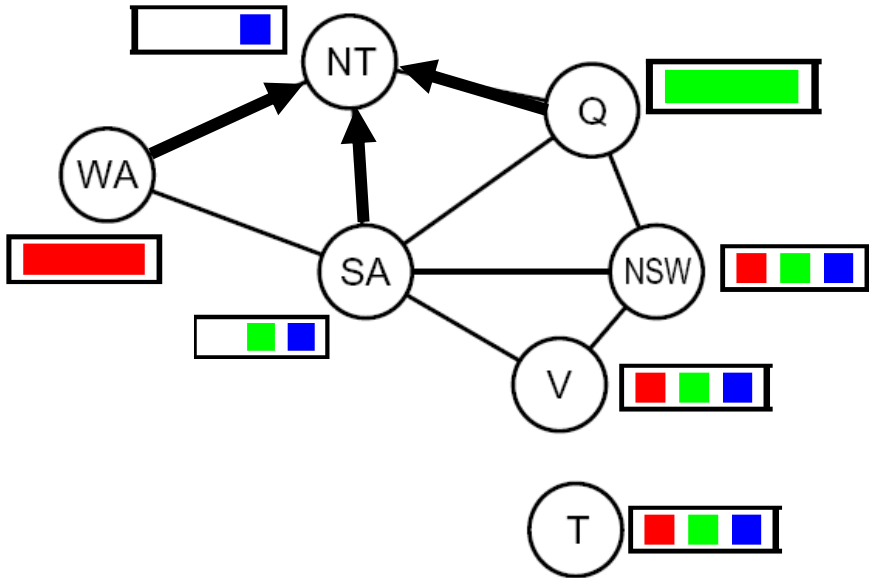
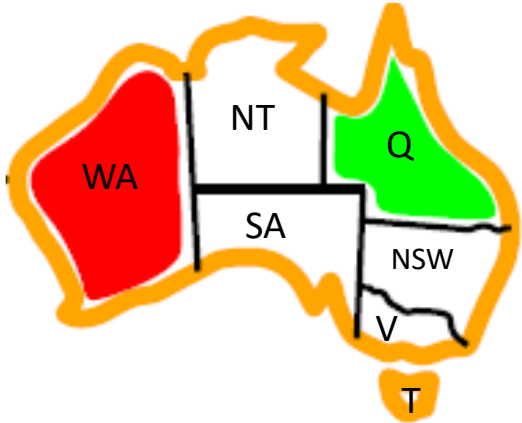
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
NT->Q
SA->Q
NSW->Q

Remember: Delete from the tail!

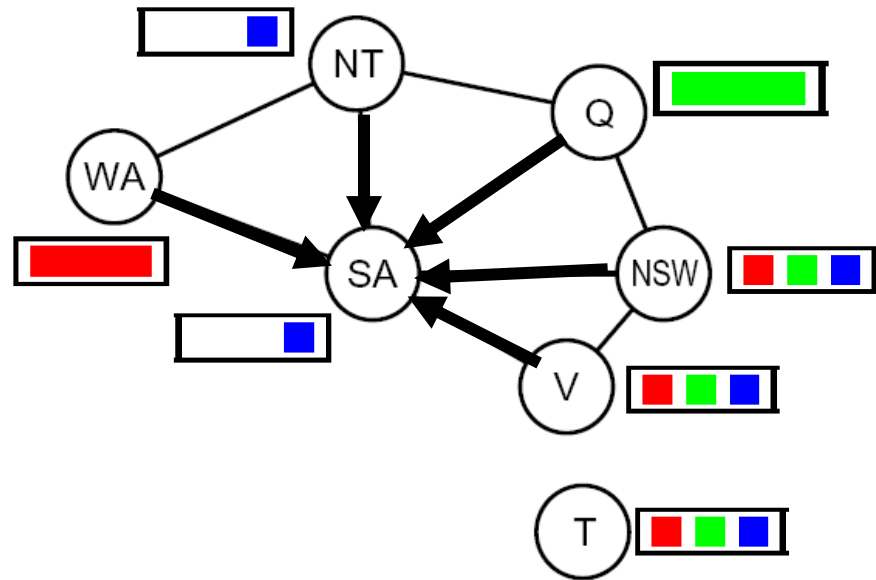
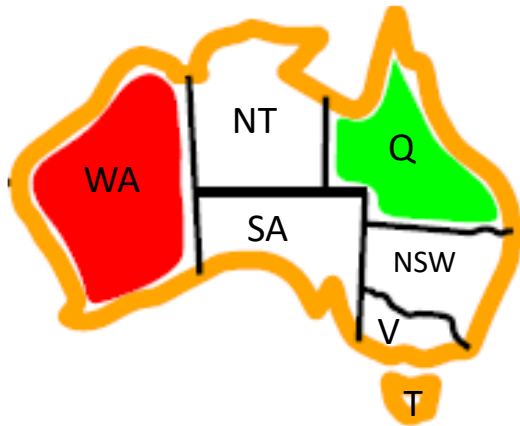
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
 SA->Q
 NSW->Q
 WA->NT
 SA->NT
 Q->NT

Remember: Delete from the tail!

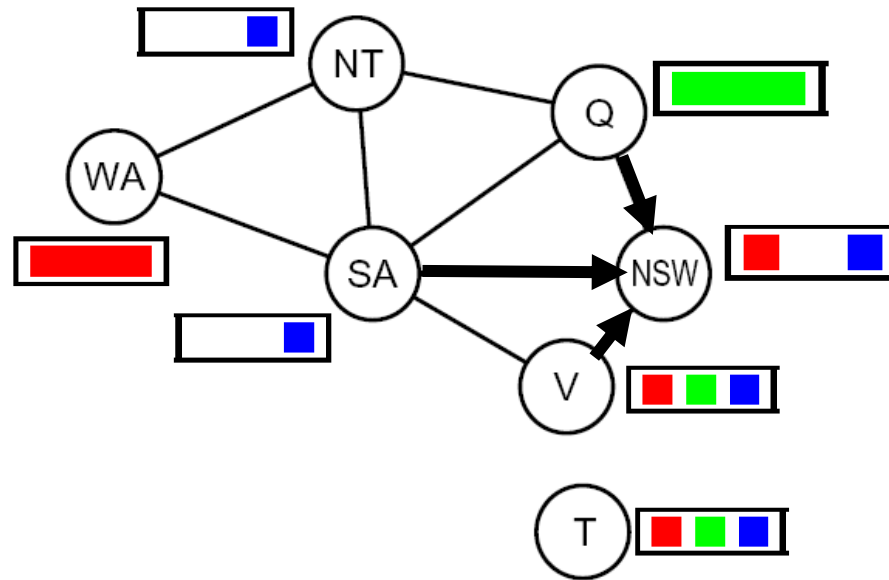
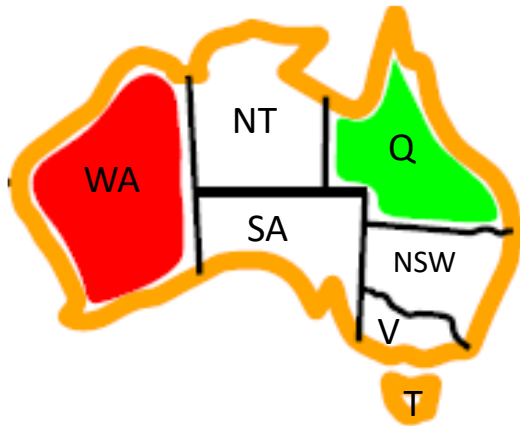
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
NSW->Q
WA->NT
SA->NT
Q->NT
WA->SA
NT->SA
Q->SA
NSW->SA
V->SA

Remember: Delete from the tail!

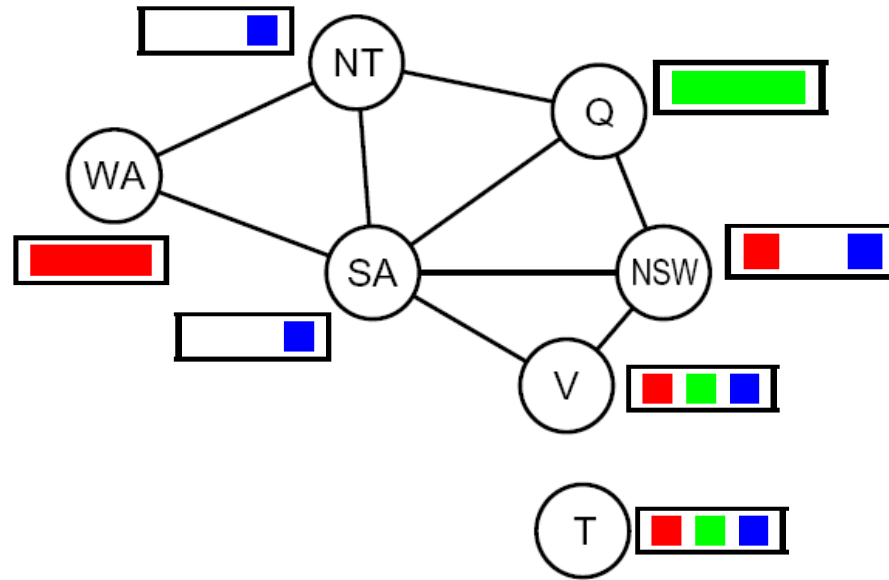
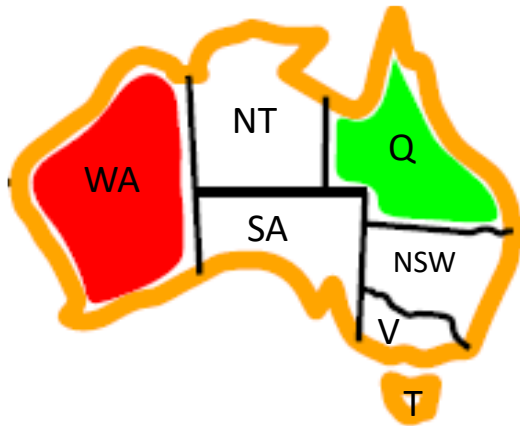
AC-3: Enforce Arc Consistency of Entire CSP



Queue:
WA->NT
SA->NT
Q->NT
WA->SA
NT->SA
Q->SA
NSW->SA
V->SA
V->NSW
Q->NSW
SA->NSW

Remember: Delete from the tail!

AC-3: Enforce Arc Consistency of Entire CSP



Queue:

WA->NT

SA->NT

Q->NT

WA->SA

NT->SA

Q->SA

NSW->SA

V->SA

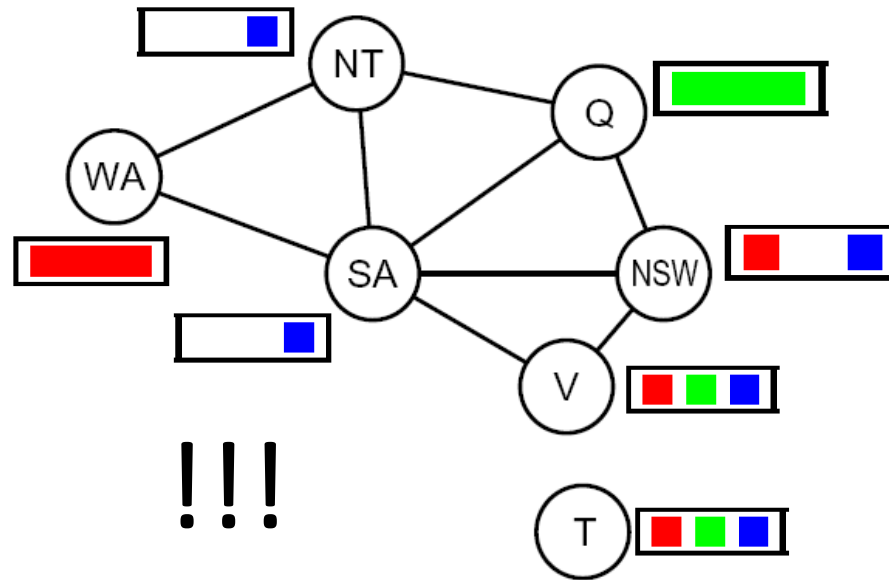
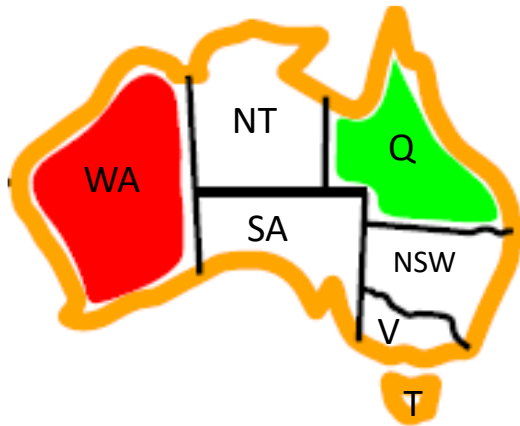
V->NSW

Q->NSW

SA->NSW

Remember: Delete from the tail!

AC-3: Enforce Arc Consistency of Entire CSP



Queue:

SA->NT

Q->NT

WA->SA

NT->SA

Q->SA

NSW->SA

V->SA

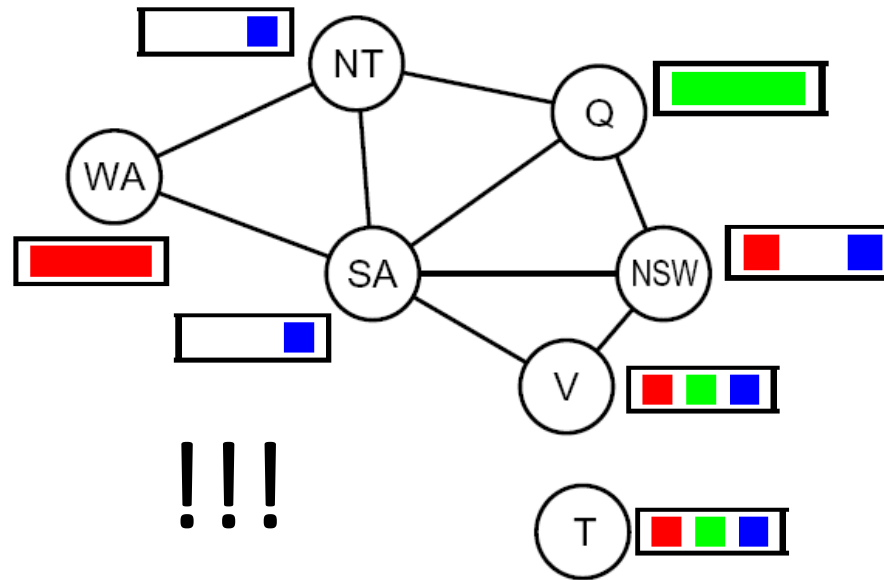
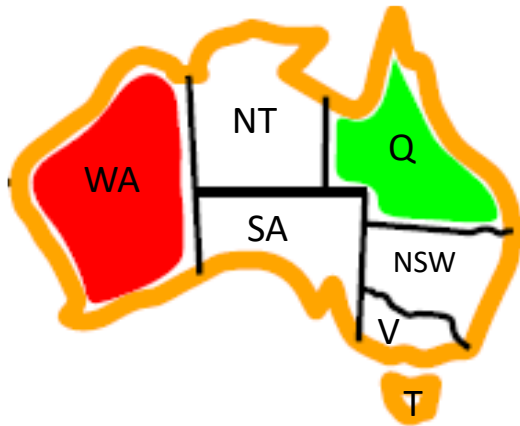
V->NSW

Q->NSW

SA->NSW

Remember: Delete from the tail!

AC-3: Enforce Arc Consistency of Entire CSP



Queue:

SA->NT

Q->NT

WA->SA

NT->SA

Q->SA

NSW->SA

V->SA

V->NSW

Q->NSW

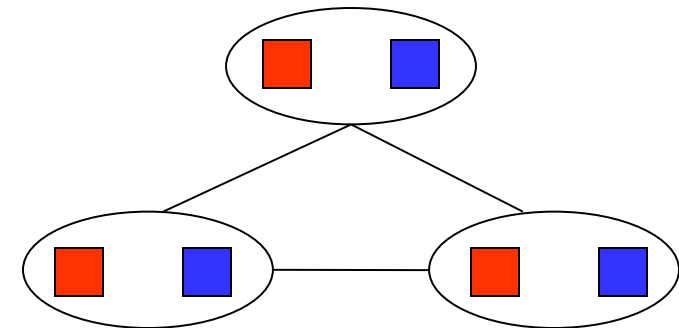
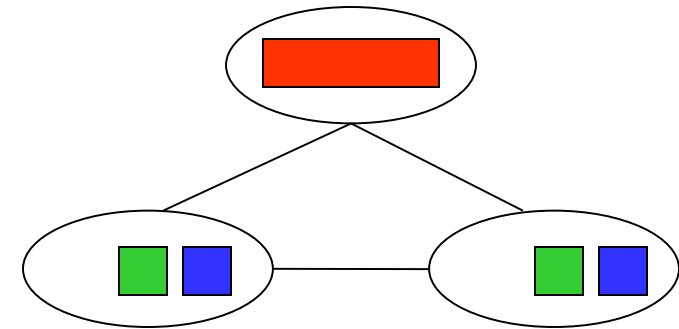
SA->NSW

- Backtrack on the assignment of Q
- Arc consistency detects failure earlier than forward checking
- Can be run as a preprocessor or after each assignment
- What's the downside of enforcing arc consistency?

Remember: Delete from the tail!

Limitations of Arc Consistency

- After enforcing arc consistency:
 - Can have one solution left
 - Can have multiple solutions left
 - Can have no solutions left (and not know it)
- Arc consistency only checks local consistency conditions
- Arc consistency still runs inside a backtracking search!



What went wrong here?

Backtracking Search with AC-3

```
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 AC-3(csp)
      result ← RECURSIVE-BACKTRACKING(assignment, csp)
      if result ≠ failure then return result
      remove {var = value} from assignment
  return failure
```

- Where do you run AC-3?

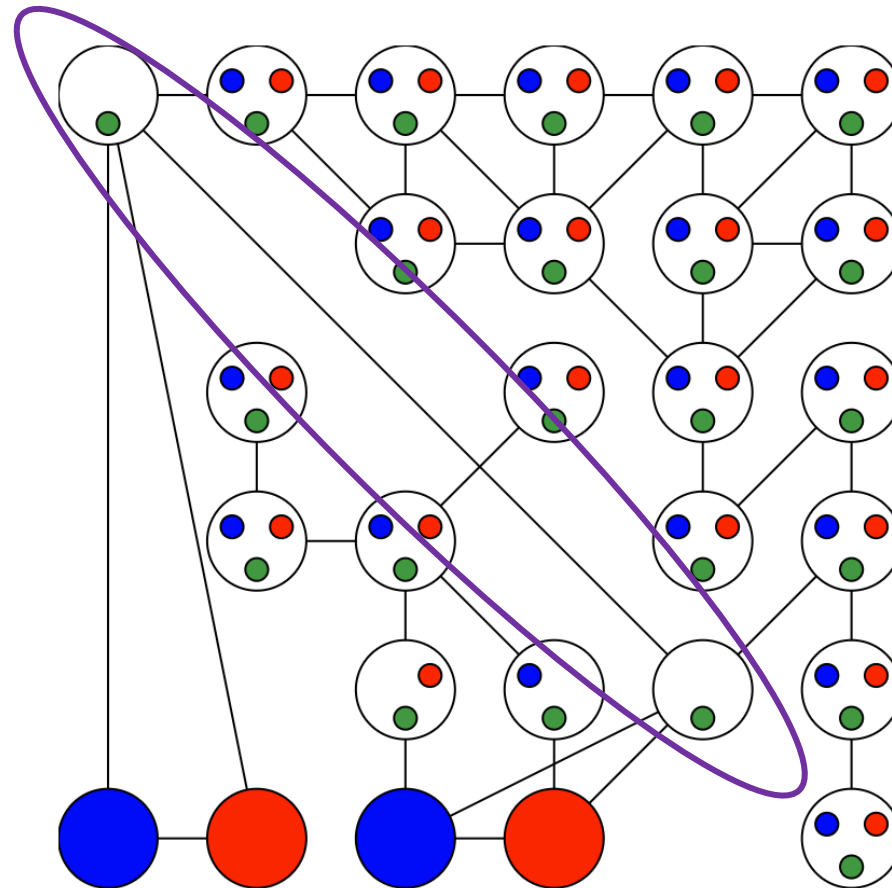
Demo – Backtracking with AC-3

Compare

- Backtracking with Forward Checking
- Backtracking with AC-3

Forward checking only check arcs connecting variables a variable that we just assigned.

With AC-3, we can find existing problems, such as the arc between these two variables with only green left.



Complexity of a single run of AC-3

```
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
     $(X_i, X_j) \leftarrow \text{REMOVE-FIRST}(\textit{queue})$ 
    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  $\leftarrow$  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
```

Recall that the whole backtracking algorithm with AC-3 will call AC-3 many times

Complexity of a single run of AC-3

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    return removed
```

- An arc is added after a removal of value at a node
- n node in total, each has $\leq d$ values
- Total times of removal: $O(nd)$

Complexity of a single run of AC-3

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```

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- n node in total, each has $\leq d$ values
- Total times of removal: $O(nd)$
- After a removal, $\leq n$ arcs added
- Total times of adding arcs: $O(n^2d)$

Complexity of a single run of AC-3

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- n node in total, each has $\leq d$ values
- Total times of removal: $O(nd)$
- After a removal, $\leq n$ arcs added
- Total times of adding arcs: $O(n^2d)$
- Check arc consistency per arc: $O(d^2)$

Complexity of a single run of AC-3 is at most $O(n^2d^3)$

(Not required) Zhang&Yap (2001) show that its complexity is $O(n^2d^2)$

Ordering

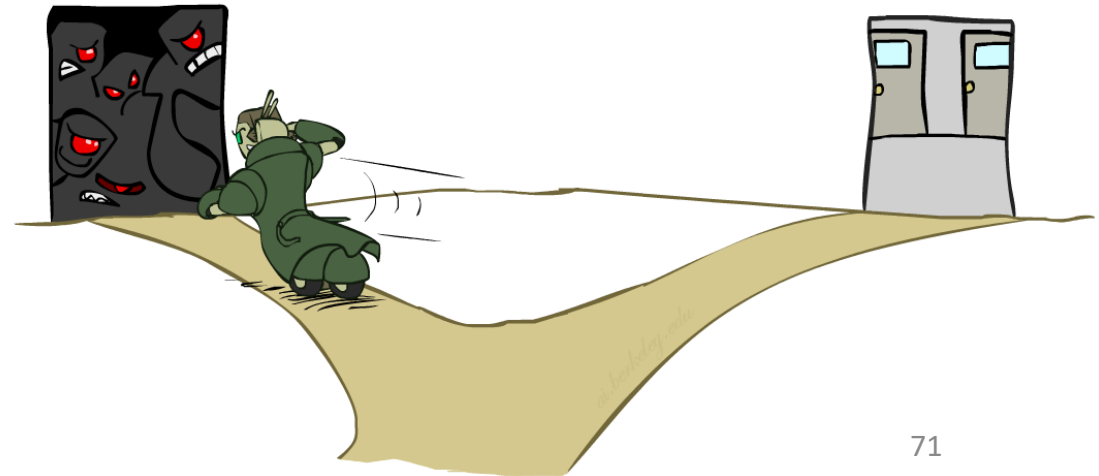


Ordering: Minimum Remaining Values

- Variable Ordering: Minimum remaining values (MRV):
 - Choose the variable with the fewest legal left values in its domain



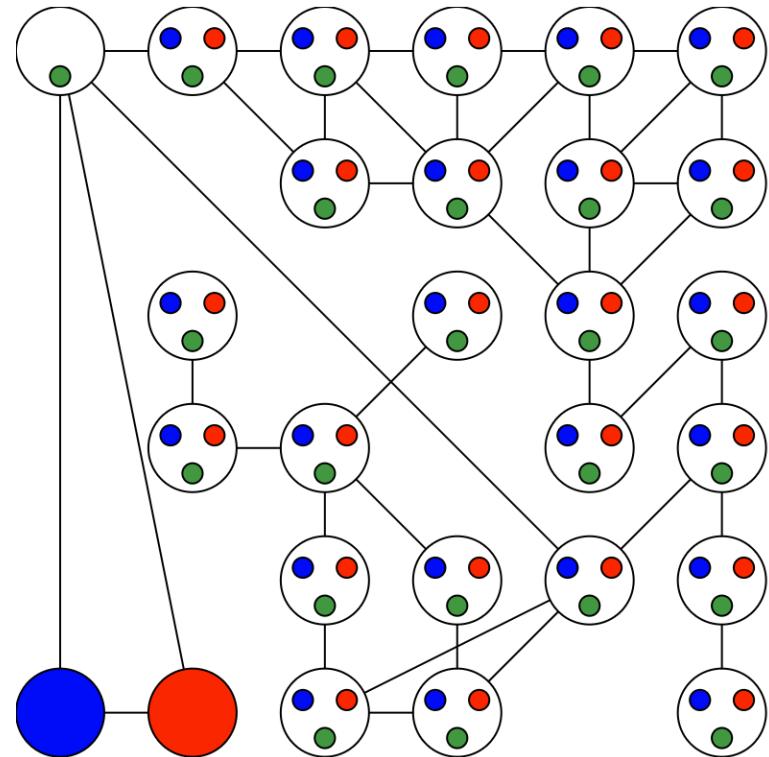
- Why min rather than max?
- Also called “most constrained variable”
- “Fail-fast” ordering



Demo – Coloring with a Complex Graph

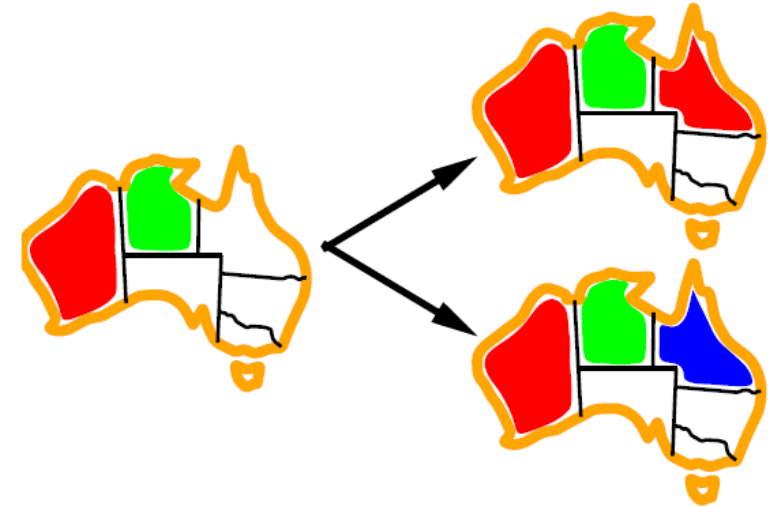
Compare

- Backtracking with Forward Checking
- Backtracking with AC-3
- **Backtracking + Forward Checking + Minimum Remaining Values (MRV)**



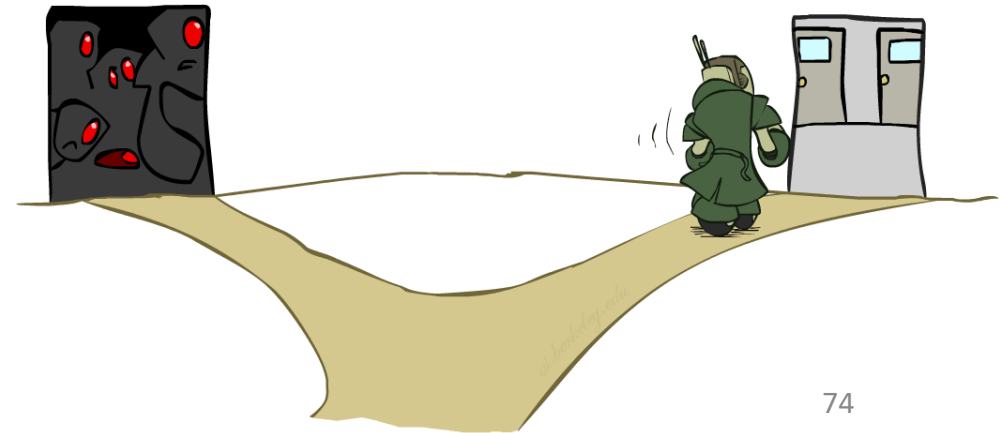
Ordering: Least Constraining Value

- Value Ordering: Least Constraining Value
 - Given a choice of variable, choose the *least constraining value*
 - i.e., the one that rules out the fewest values in the remaining variables
 - Note that it may take some computation to determine this! (E.g., rerunning filtering)



Ordering: Least Constraining Value

- Value Ordering: Least Constraining Value
 - Given a choice of variable, choose the *least constraining value*
 - i.e., the one that rules out the fewest values in the remaining variables
 - Note that it may take some computation to determine this! (E.g., rerunning filtering)
- Why least rather than most?
- Combining these ordering ideas makes 1000 queens feasible



Demo – Coloring with a Complex Graph

Compare

- Backtracking with Forward Checking
- Backtracking with AC-3
- Backtracking + Forward Checking + Minimum Remaining Values (MRV)
- Backtracking + AC-3 + MRV + LCV

Summary: CSPs

- CSPs are a special kind of search problem:
 - States are partial assignments
 - Goal test defined by constraints
- Basic solution: backtracking search
- Speed-ups:
 - Ordering
 - Filtering
 - (Structure)

