

## Artificial Intelligence

### *Games (adversarial search)*

**Reading:** AIMA chapter 5.

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## Solving problems by search: playing games

How might an agent act when *the outcomes of its actions are not known* because an *adversary is trying to hinder it*?

- This is essentially a more realistic kind of search problem because we do not know the exact outcome of an action.
- This is a common situation when *playing games*: in chess, draughts, and so on an opponent *responds* to our moves.

Game playing has been of interest in AI because it provides an *idealisation* of a world in which two agents act to *reduce* each other's well-being.

We now look at:

- How game-playing can be modelled as *search*.
- The *minimax algorithm* for game-playing.
- Some problems inherent in the use of minimax.
- The concept of  *$\alpha - \beta$  pruning*.

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## Playing games: search against an adversary

Despite the fact that games are an idealisation, game playing can be an excellent source of hard problems. For instance with chess:

- The average branching factor is roughly 35.
- Games can reach 50 moves per player.
- So a rough calculation gives the search tree  $35^{100}$  nodes.
- Even if only different, legal positions are considered it's about  $10^{40}$ .

*So: in addition* to the uncertainty due to the opponent:

- We can't make a complete search to find the best move...
- ... so we have to act even though we're not sure about the best thing to do.

And chess isn't even very hard: *Go* is *much* harder...

*Note:* yes, more advanced learning-based methods have conquered chess and Go, but that's an entirely different approach with its own pros and cons.

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## Perfect decisions in a two-person game

Say we have two players. Traditionally, they are called *Max* and *Min* for reasons that will become clear.

- We'll use *noughts and crosses* as an initial example.
- *Max* moves first.
- The players alternate until the game ends.
- At the end of the game, prizes are awarded. (Or punishments administered—**EVIL ROBOT** is starting up his favourite chainsaw...)

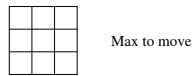
This is exactly the same game format as chess, Go, draughts and so on.

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### Perfect decisions in a two-person game

Games like this can be modelled as search problems as follows:

- There is an *initial state*.



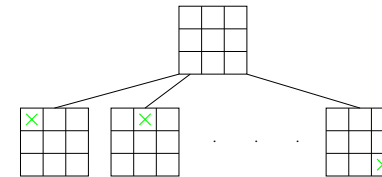
- There is a set of *operators*. Here, *Max* can place a cross in any empty square, or *Min* a nought.
- There is a *terminal test*. Here, the game ends when three noughts or three crosses are in a row, or there are no unused spaces.
- There is a *utility* or *payoff* function. This tells us, numerically, what the outcome of the game is.

This is enough to model the entire game.

### Perfect decisions in a two-person game

We can *construct a tree* to represent a game.

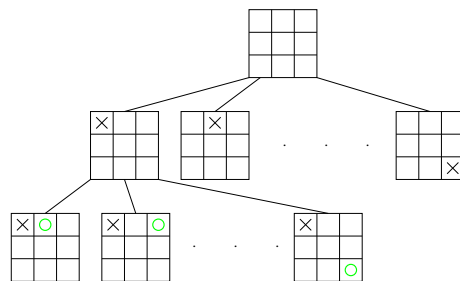
From the initial state *Max* can make nine possible moves:



Then it's *Min's* turn...

### Perfect decisions in a two-person game

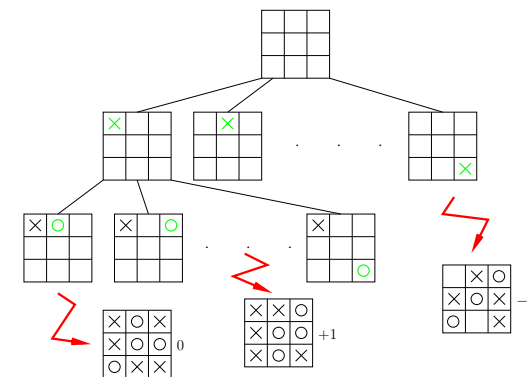
For each of *Max's* opening moves *Min* has eight replies:



And so on...

This can be continued to represent *all* possibilities for the game.

### Perfect decisions in a two-person game

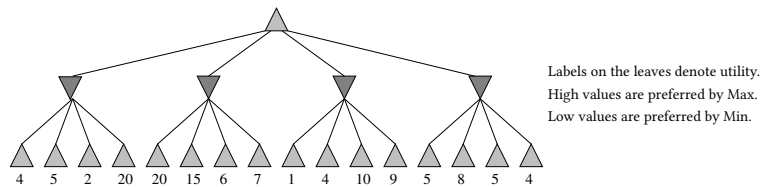


At the leaves a player has won or there are no spaces. Leaves are *labelled* using the utility function.

## Perfect decisions in a two-person game

How can *Max* use this tree to decide on a first move?

Consider a much simpler tree:



If *Max* is rational he will play to reach a position with the *biggest utility possible*

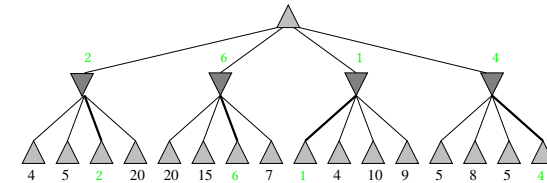
But if *Min* is rational she will play to *minimise* the utility available to *Max*.

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## The minimax algorithm

There are two moves: *Max* then *Min*. Game theorists would call this one move, or two *ply* deep.

The *minimax algorithm* allows us to infer the best move that the current player can make, given the utility function, by working backward from the leaves.

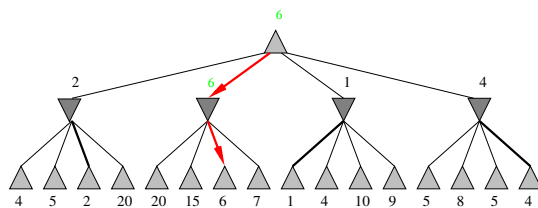


As *Min* plays the last move, she *minimises* the utility available to *Max*.

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## The minimax algorithm

Moving one further step up the tree:



We can see that *Max*'s best opening move is move *2*, as this leads to the node with highest utility.

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## The minimax algorithm

*In general:*

- Generate the complete tree and label the leaves according to the utility function.
- Working from the leaves of the tree upward, label the nodes depending on whether *Max* or *Min* is to move.
- If *Min* is to move label the current node with the *minimum* utility of any descendant.
- If *Max* is to move label the current node with the *maximum* utility of any descendant.

If the game is  $p$  ply and at each point there are  $q$  available moves then this process has (surprise, surprise)  $O(q^p)$  time complexity and space complexity linear in  $p$  and  $q$ .

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### Making imperfect decisions

We need to avoid searching all the way to the end of the tree.

So:

- We generate only part of the tree: instead of testing whether a node is a leaf we introduce a *cut-off* test telling us when to stop.
- Instead of a utility function we introduce an *evaluation function* for the evaluation of positions for an incomplete game.

The evaluation function attempts to measure the expected utility of the current game position.

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### Making imperfect decisions

How can this be justified?

- This is a strategy that humans clearly sometimes make use of.
- For example, when using the concept of *material value* in chess.
- The effectiveness of the evaluation function is *critical*...
- ... but it must be computable in a reasonable time.
- (In principle it could just be done using minimax.)

The importance of the evaluation function can not be understated—it is probably the most important part of the design.

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### The evaluation function

Designing a good evaluation function can be extremely tricky:

- Let's say we want to design one for chess by giving each piece its material value: pawn = 1, knight/bishop = 3, rook = 5 and so on.
- Define the evaluation of a position to be the difference between the material value of black's and white's pieces

$$\text{eval}(\text{position}) = \sum_{\text{black's pieces } p_i} \text{value of } p_i - \sum_{\text{white's pieces } q_i} \text{value of } q_i$$

This seems like a reasonable first attempt. Why might it go wrong?

- Until the first capture the evaluation function gives 0, so in fact we have a *category* containing many different game positions with equal estimated utility.
- For example, all positions where white is one pawn ahead.

So in fact this seems highly naïve ...

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### The evaluation function

We can try to *learn* an evaluation function.

- For example, using material value, construct a *weighted linear evaluation function*

$$\text{eval}(\text{position}) = \sum_{i=1}^n w_i f_i$$

where the  $w_i$  are *weights* and the  $f_i$  represent *features* of the position—in this case, the value of the  $i$ th piece.

- Weights can be chosen by allowing the game to play itself and using *learning* techniques to adjust the weights to improve performance.

However in general

- Here we probably want to give *different evaluations* to *individual positions*.
- The design of an evaluation function can be highly *problem dependent* and might require significant *human input and creativity*.

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### $\alpha - \beta$ pruning

Even with a good evaluation function and cut-off test, the time complexity of the minimax algorithm makes it impossible to write a good chess program without some further improvement.

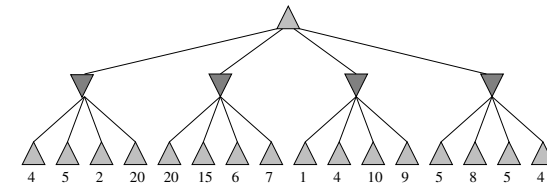
- Assuming we have 150 seconds to make each move, for chess we would be limited to a search of about 3 to 4 ply whereas...
- ...even an average human player can manage 6 to 8.

Luckily, it is possible to prune the search tree *without affecting the outcome* and *without having to examine all of it*.

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### $\alpha - \beta$ pruning

Returning for a moment to the earlier, simplified example:

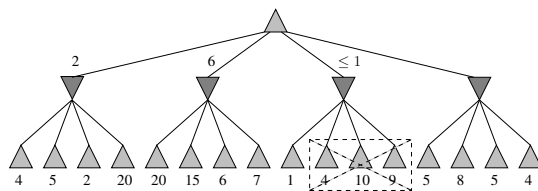


The search is depth-first and left to right.

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### $\alpha - \beta$ pruning

The search continues as previously for the first 8 leaves.



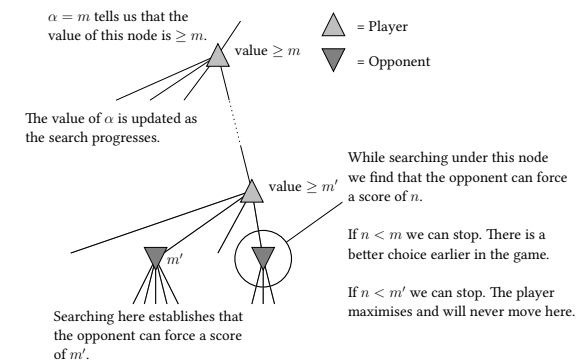
Then we note: if *Max* plays move 3 then *Min* can reach a leaf with utility at most 1.

So: *we don't need to search any further under Max's opening move 3*. This is because the search has *already established* that *Max* can do better by making opening move 2.

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### $\alpha - \beta$ pruning in general

Remember that this search is *depth-first*. We're only going to use knowledge of *nodes on the current path*.



So: once you've established that *n* is sufficiently small, you don't need to explore any more of the corresponding node's children.

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### $\alpha - \beta$ pruning in general

The situation is exactly analogous if we *swap player and opponent* in the previous diagram.

The search is depth-first, so we're only ever looking at *one path through the tree*.

We need to keep track of the values  $\alpha$  and  $\beta$  where

$\alpha$  = the *highest* utility seen so far on the path for *Max*

$\beta$  = the *lowest* utility seen so far on the path for *Min*

Assume *Max begins*. Initial values for  $\alpha$  and  $\beta$  are

$$\alpha = -\infty$$

and

$$\beta = +\infty.$$

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### $\alpha - \beta$ pruning in general

So: we start with the function call

$\text{player}(-\infty, +\infty, \text{root})$

The following function implements the procedure suggested by the previous diagram:

```
1 function player( $\alpha, \beta, n$ )
2   if cutoff( $n$ ) then
3     return eval( $n$ );
4   value =  $-\infty$ ;
5   for each successor  $n'$  of  $n$  do
6     value = max(value, opponent( $\alpha, \beta, n'$ ));
7     if value >  $\beta$  then
8       return value;
9     if value >  $\alpha$  then
10       $\alpha$  = value;
11  return value;
```

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### $\alpha - \beta$ pruning in general

The function *opponent* is exactly analogous:

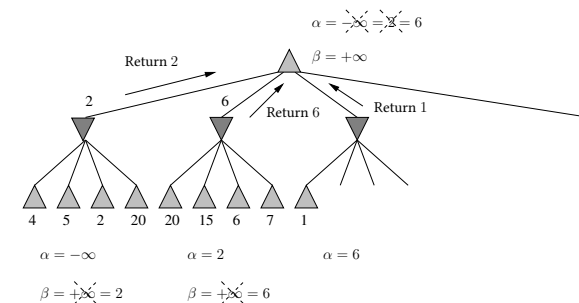
```
1 function opponent( $\alpha, \beta, n$ )
2   if cutoff( $n$ ) then
3     return eval( $n$ );
4   value =  $\infty$ ;
5   for each successor  $n'$  of  $n$  do
6     value = min(value, player( $\alpha, \beta, n'$ ));
7     if value <  $\alpha$  then
8       return value;
9     if value <  $\beta$  then
10       $\beta$  = value;
11  return value;
```

*Note:* the semantics here is that parameters are passed to functions *by value*.

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### $\alpha - \beta$ pruning in general

Applying this to the earlier example and keeping track of the values for  $\alpha$  and  $\beta$  you should obtain:



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### How effective is $\alpha - \beta$ pruning?

(Warning: the theoretical results that follow are somewhat idealised.)

A quick inspection should convince you that the *order* in which moves are arranged in the tree is critical.

So, it seems sensible to try good moves first:

- If you were to have a perfect move-ordering technique then  $\alpha - \beta$  pruning would be  $O(q^{p/2})$  as opposed to  $O(q^p)$ .
- Consequently the branching factor would effectively be  $\sqrt{q}$  instead of  $q$ .
- We would therefore expect to be able to search ahead *twice as many moves as before*.

However, this is not realistic: if you had such an ordering technique you'd be able to play perfect games!

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### How effective is $\alpha - \beta$ pruning?

If moves are arranged at random then  $\alpha - \beta$  pruning is:

- $O((q/\log q)^p)$  asymptotically when  $q > 1000$  or...
- ...about  $O(q^{3p/4})$  for reasonable values of  $q$ .

In practice *simple ordering techniques* can get *close to the best case*. For example, if we try captures, then threats, then moves forward etc.

Alternatively, we can implement an *iterative deepening* approach and use the order obtained at one iteration to drive the next.

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### A further optimisation: the transposition table

Finally, note that many games correspond to *graphs* rather than *trees* because the same state can be arrived at in different ways.

- This is essentially the same effect we saw in heuristic search: recall *graph search* versus *tree search*.
- It can be addressed in a similar way: store a state with its evaluation in a hash table—generally called a *transposition table*—the first time it is seen.

The transposition table is essentially equivalent to the *closed list* introduced as part of graph search.

This can vastly increase the effectiveness of the search process, because we don't have to evaluate a single state multiple times.

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### Artificial Intelligence

*Constraint satisfaction problems (CSPs)*

**Reading:** AIMA chapter 6.

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## Constraint satisfaction problems (CSPs)

The search scenarios examined so far seem in some ways unsatisfactory.

- States were represented using an *arbitrary* and *problem-specific* data structure.
- Heuristics were also *problem-specific*.
- It would be nice to be able to *transform* general search problems into a *standard format*.

CSPs *standardise* the manner in which states and goal tests are represented. By standardising like this we benefit in several ways:

- We can devise *general purpose* algorithms and heuristics.
- We can look at general methods for exploring the *structure* of the problem.
- Consequently it is possible to introduce techniques for *decomposing* problems.
- We can try to understand the relationship between the *structure* of a problem and the *difficulty of solving it*.

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## Introduction to constraint satisfaction problems

We now return to the idea of problem solving by search and examine it from this new perspective.

*Aims:*

- To introduce the idea of a constraint satisfaction problem (CSP) as a general means of representing and solving problems by search.
- To look at a *backtracking algorithm* for solving CSPs.
- To look at some *general heuristics* for solving CSPs.
- To look at *more intelligent ways of backtracking*.

Another method of interest in AI that allows us to do similar things involves transforming to a *propositional satisfiability* problem.

We'll see an example of this—and of the application of CSPs—when we discuss *planning*.

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## Constraint satisfaction problems

We have:

- A set of  $n$  variables  $V_1, V_2, \dots, V_n$ .
- For each  $V_i$  a *domain*  $D_i$  specifying the values that  $V_i$  can take.
- A set of  $m$  constraints  $C_1, C_2, \dots, C_m$ .

Each constraint  $C_i$  involves a set of variables and specifies an *allowable collection of values*.

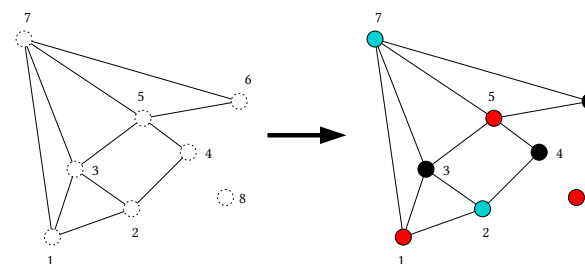
- A *state* is an assignment of specific values to some or all of the variables.
- An assignment is *consistent* if it violates no constraints.
- An assignment is *complete* if it gives a value to every variable.

A *solution* is a consistent and complete assignment.

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## Example

We will use the problem of *colouring the nodes of a graph* as a running example.



Each node corresponds to a *variable*. We have three colours and directly connected nodes should have different colours.

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### Example

This translates easily to a CSP formulation:

- The variables are the nodes

$$V_i = \text{node } i$$

- The domain for each variable contains the values black, red and cyan

$$D_i = \{B, R, C\}$$

- The constraints enforce the idea that directly connected nodes must have different colours. For example, for variables  $V_1$  and  $V_2$  the constraints specify

$$(B, R), (B, C), (R, B), (R, C), (C, B), (C, R)$$

- Variable  $V_8$  is unconstrained.

### Different kinds of CSP

This is an example of the simplest kind of CSP: it is *discrete* with *finite domains*. We will concentrate on these.

We will also concentrate on *binary constraints*; that is, constraints between *pairs of variables*.

- Constraints on single variables—*unary constraints*—can be handled by adjusting the variable's domain. For example, if we don't want  $V_i$  to be *red*, then we just remove that possibility from  $D_i$ .
- Higher-order constraints* applying to three or more variables can certainly be considered, but...
- ...when dealing with finite domains they can always be converted to sets of binary constraints by introducing extra *auxiliary variables*.

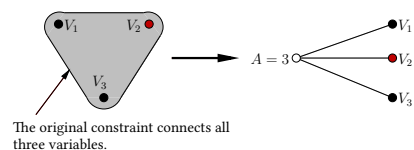
How does that work?

### Auxiliary variables

*Example:* three variables each with domain  $\{B, R, C\}$ .

A single constraint

$$(C, C, C), (R, B, B), (B, R, B), (B, B, R)$$



New, binary constraints:

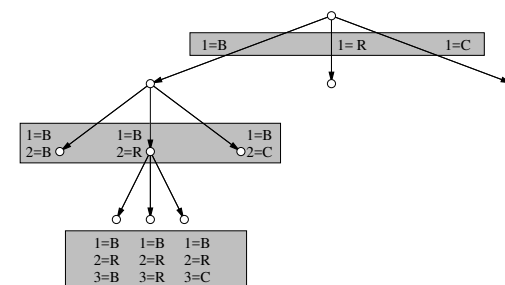
$$\begin{aligned} &(A = 1, V_1 = C), (A = 1, V_2 = C), (A = 1, V_3 = C) \\ &(A = 2, V_1 = R), (A = 2, V_2 = B), (A = 2, V_3 = B) \\ &(A = 3, V_1 = B), (A = 3, V_2 = R), (A = 3, V_3 = B) \\ &(A = 4, V_1 = B), (A = 4, V_2 = B), (A = 4, V_3 = R) \end{aligned}$$

Introducing auxiliary variable  $A$  with domain  $\{1, 2, 3, 4\}$  allows us to convert this to a set of binary constraints.

### Backtracking search

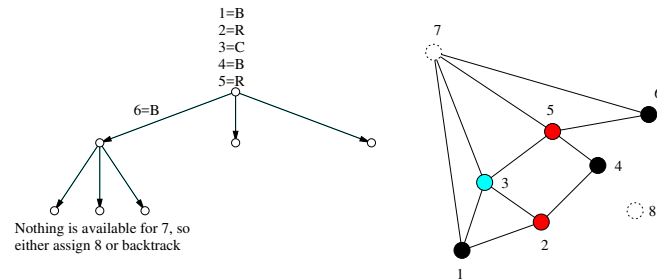
*Backtracking search* now takes on a very simple form: search depth-first, assigning a single variable at a time, and backtrack if no valid assignment is available.

Using the graph colouring example, the search now looks something like this...



...and new possibilities appear.

## Backtracking search



Rather than using problem-specific heuristics to try to improve searching, we can now explore heuristics applicable to *general* CSPs.

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## Backtracking search

Starting with:

`backtrack([], problemDescription)`

```

1 function backtrack (assignmentList, problemDescription)
2   if assignmentList is complete then
3     return SOME assignmentList;
4   nextVar = getNextVariable (assignmentList, problemDescription);
5   for each v in orderValues (nextVar, assignmentList, problemDescription) do
6     if v is consistent with assignmentList then
7       add "nextVar = v" to assignmentList;
8       solution = backtrack (assignmentList, problemDescription);
9       if solution is not FAIL then
10        return solution;
11      remove "nextVar = v" from assignmentList;
12  return FAIL;
  
```

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## Backtracking search: possible heuristics

There are several points we can examine in an attempt to obtain general CSP-based heuristics:

- In what order should we try to *assign variables*?
- In what order should we try to *assign possible values* to a variable?

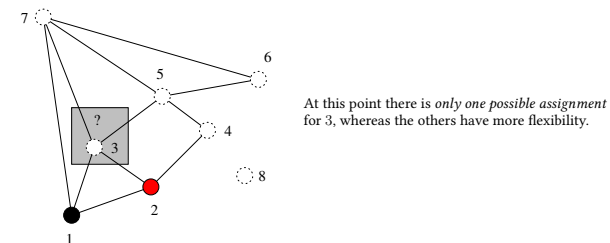
Or being a little more subtle:

- What *effect* might the *values assigned so far* have on *later attempted assignments*?
- When *forced to backtrack*, is it possible to *avoid the same failure later on*?
- Can we try to force the search in a successful direction (remember the use of *heuristics*)?
- Can we try to force *failures/backtracks* to occur quickly?

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## Heuristics I: Choosing the order of variable assignments and values

Say we have  $1 = B$  and  $2 = R$



Assigning such variables *first* is called the *minimum remaining values (MRV)* heuristic.

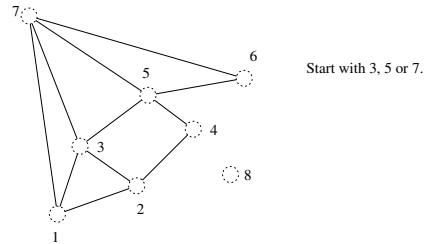
(Alternatively, the *most constrained variable* or *fail first* heuristic.)

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## Heuristics I: Choosing the order of variable assignments and values

How do we choose a variable to begin with?

The *degree heuristic* chooses the variable involved in the most constraints on as yet unassigned variables.

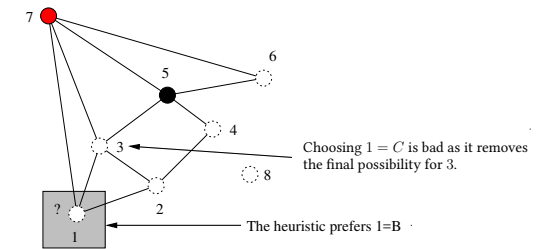


MRV is usually better but the degree heuristic is a good tie breaker.

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## Heuristics I: Choosing the order of variable assignments and values

Once a variable is chosen, in *what order should values be assigned?*

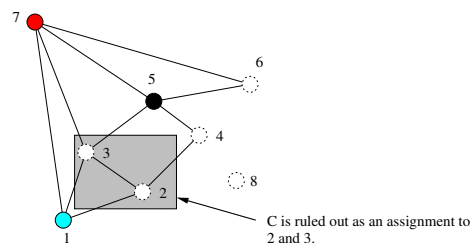


The *least constraining value* heuristic chooses first the value that leaves the maximum possible freedom in choosing assignments for the variable's neighbours.

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## Heuristics II: forward checking and constraint propagation

Continuing the previous slide's progress, now add  $1 = C$ .



Each time we assign a value to a variable, it makes sense to delete that value from the collection of *possible assignments to its neighbours*.

This is called *forward checking*. It works nicely in conjunction with MRV.

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## Heuristics II: forward checking and constraint propagation

We can visualise this process as follows:

|       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| Start | BRC | BRC | BRC | BRC | BRC | BRC | BRC | BRC |
| 2 = B | RC  | = B | RC  | RC  | BRC | BRC | BRC | BRC |
| 3 = R | C   | = B | = R | RC  | BC  | BRC | BC  | BRC |
| 6 = B | C   | = B | = R | RC  | C   | = B | C   | BRC |
| 5 = C | C   | = B | = R | R   | = C | = B | !   | BRC |

At the fourth step 7 has *no possible assignments left*.

However, we could have detected a problem a little earlier...

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## Heuristics II: forward checking and constraint propagation

...by looking at step three.

|       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| Start | BRC | BRC | BRC | BRC | BRC | BRC | BRC | BRC |
| 2 = B | RC  | = B | RC  | RC  | BRC | BRC | BRC | BRC |
| 3 = R | C   | = B | = R | RC  | BC  | BRC | BC  | BRC |
| 6 = B | C   | = B | = R | RC  | C   | = B | C   | BRC |
| 5 = C | C   | = B | = R | R   | = C | = B | !   | BRC |

- At step three, 5 can be C only and 7 can be C only.
- But 5 and 7 are connected.
- So we can't progress, but this hasn't been detected.
- Ideally we want to do *constraint propagation*.

*Trade-off*: time to do the search, against time to explore constraints.

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## Constraint propagation

### Arc consistency:

Consider a constraint as being *directed*. For example  $4 \rightarrow 5$ .

In general, say we have a constraint  $i \rightarrow j$  and currently the domain of  $i$  is  $D_i$  and the domain of  $j$  is  $D_j$ .

$i \rightarrow j$  is *consistent* if

$$\forall d \in D_i, \exists d' \in D_j \text{ such that } i \rightarrow j \text{ is valid}$$

### Example:

In step three of the table,  $D_4 = \{R, C\}$  and  $D_5 = \{C\}$ .

- $5 \rightarrow 4$  in step three of the table *is consistent*.
- $4 \rightarrow 5$  in step three of the table *is not consistent*.

$4 \rightarrow 5$  can be made consistent by deleting C from  $D_4$ .

Or in other words, regardless of what you assign to  $i$  you'll be able to find something valid to assign to  $j$ .

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## Enforcing arc consistency

We can enforce arc consistency each time a variable  $i$  is assigned.

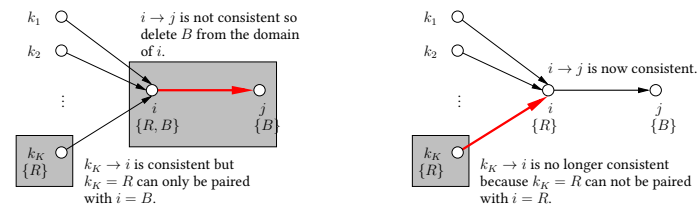
- We need to maintain a *collection of arcs to be checked*.
- Each time we alter a domain, we may have to include further arcs in the collection.

This is because if  $i \rightarrow j$  is inconsistent resulting in a deletion from  $D_j$  we may as a consequence make some arc  $k \rightarrow i$  inconsistent.

Why is this?

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## Enforcing arc consistency



- $i \rightarrow j$  inconsistent means removing a value from  $D_j$ .
- $\exists d \in D_i$  such that there is no valid  $d' \in D_j$  so delete  $d \in D_i$ .

However some  $d'' \in D_k$  may only have been pairable with  $d$ .

We need to continue until all consequences are taken care of.

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## The AC-3 algorithm

```

1 function AC-3 (problemDescription)
2   Queue toCheck = [ all arcs  $i \rightarrow j$  ];
3   while toCheck is not empty do
4      $i \rightarrow j$  = next (toCheck);
5     if removeInconsistencies ( $D_i, D_j$ ) then
6       for each  $k$  that is a neighbour of  $i$  do
7         add  $k \rightarrow i$  to toCheck;

```

```

1 function removeInconsistencies ( $D_1, D_2$ )
2   Bool result = FALSE;
3   for each  $d \in D_1$  do
4     if no  $d' \in D_2$  valid with  $d$  then
5       remove  $d$  from  $D_1$ ;
6       result = TRUE;
7   return result;

```

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## Enforcing arc consistency

### Complexity:

- A binary CSP with  $n$  variables can have  $O(n^2)$  directional constraints  $i \rightarrow j$ .
- Any  $i \rightarrow j$  can be considered at most  $d$  times where  $d = \max_k |D_k|$  because only  $d$  things can be removed from  $D_i$ .
- Checking any single arc for consistency can be done in  $O(d^2)$ .

So the complexity is  $O(n^2 d^3)$ .

*Note:* this setup includes 3SAT.

*Consequence:* we can't check for consistency in polynomial time, which suggests this doesn't guarantee to find all inconsistencies.

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## A more powerful form of consistency

We can define a stronger notion of consistency as follows:

- *Given:* any  $k - 1$  variables and any consistent assignment to these.
- *Then:* We can find a consistent assignment to any  $k$ th variable.

This is known as *k-consistency*.

*Strong k-consistency* requires the we be  $k$ -consistent,  $k - 1$ -consistent *etc* as far down as 1-consistent.

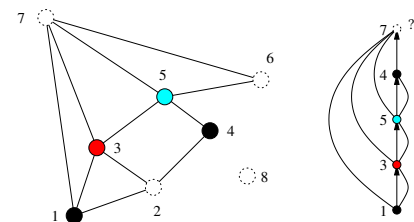
If we can demonstrate strong  $n$ -consistency (where as usual  $n$  is the number of variables) then an assignment can be found in  $O(nd)$ .

Unfortunately, demonstrating strong  $n$ -consistency will be *worst-case exponential*.

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## Backjumping

The basic backtracking algorithm backtracks to the *most recent assignment*. This is known as *chronological backtracking*. It is not always the best policy:



Say we've assigned  $1 = B$ ,  $3 = R$ ,  $5 = C$  and  $4 = B$  and now we want to assign something to 7. This isn't possible so we backtrack, however re-assigning 4 clearly doesn't help.

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## Backjumping

With some careful bookkeeping it is often possible to *jump back multiple levels* without sacrificing the ability to find a solution.

We need some definitions:

- When we set a variable  $V_i$  to some value  $d \in D_i$  we refer to this as the *assignment*  $A_i = (V_i \leftarrow d)$ .
- A *partial instantiation*  $I_k = \{A_1, A_2, \dots, A_k\}$  is a *consistent* set of assignments to the first  $k$  variables...
- ... where *consistent* means that no constraints are violated.
- Conversely,  $I_k$  *conflicts* with some variable  $V$  if no value for  $V$  is consistent with  $I_k$ .

Henceforth we shall assume that variables are assigned in the order  $V_1, V_2, \dots, V_n$  when formally presenting algorithms.

## Gaschnig's algorithm

*Gaschnig's algorithm* works as follows. Say we have a partial instantiation  $I_k$ :

- When choosing a value for  $V_{k+1}$  we need to check that any candidate value  $d \in D_{k+1}$ , is consistent with  $I_k$ .
- When testing potential values for  $d$ , we will generally discard one or more possibilities, because they conflict with some member of  $I_k$ .
- We keep track of the *most recent assignment*  $A_j$  for which this has happened.

Finally, if *no* value for  $V_{k+1}$  is consistent with  $I_k$  then we backtrack to  $V_j$ .

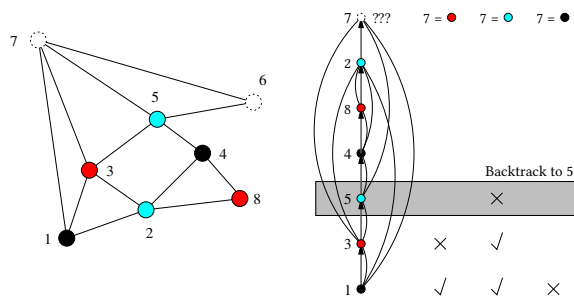
More formally: if  $I_k$  conflicts with  $V_{k+1}$  we backtrack to  $V_j$  where

$$j = \min\{j \leq k \mid I_j \text{ conflicts with } V_{k+1}\}.$$

If there are no possible values left to try for  $V_j$  then we backtrack *chronologically*.

## Gaschnig's algorithm

*Example:*



If there's no value left to try for 5 then backtrack to 3 and so on.

## Graph-based backjumping

This allows us to jump back multiple levels *when we initially detect a conflict*.

Can we do better than chronological backtracking *thereafter*?

Some more definitions:

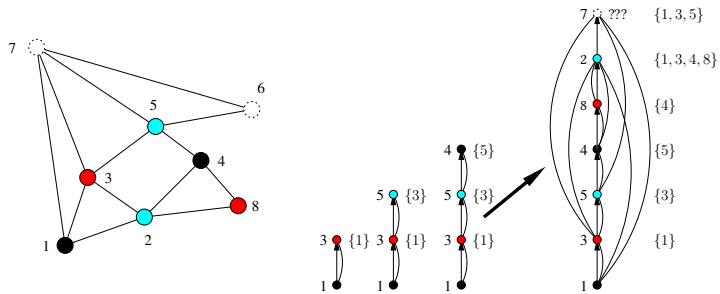
- We assume an ordering  $V_1, V_2, \dots, V_n$  for the variables.
- Given  $V' = \{V_1, V_2, \dots, V_k\}$  where  $k < n$  the *ancestors* of  $V_{k+1}$  are the members of  $V'$  connected to  $V_{k+1}$  by a constraint.
- The *parent*  $P(V_{k+1})$  of  $V_{k+1}$  is its most recent ancestor.

The ancestors for each variable can be accumulated as assignments are made.

*Graph-based backjumping* backtracks to the *parent* of  $V_{k+1}$ .

*Note:* Gaschnig's algorithm uses *assignments* whereas graph-based backjumping uses *constraints*.

### Graph-based backjumping



At this point, backjump to the *parent* for 7, which is 5.

### Backjumping and forward checking

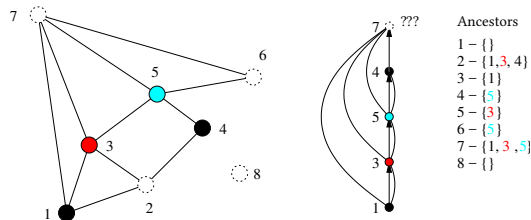
If we use *forward checking*: say we're assigning to  $V_{k+1}$  by making  $V_{k+1} = d$ :

- Forward checking removes  $d$  from the  $D_i$  of *all*  $V_i$  connected to  $V_{k+1}$  by a constraint.
- When doing graph-based backjumping, we'd also add  $V_{k+1}$  to the ancestors of  $V_j$ .

In fact, use of forward checking can make some forms of backjumping *redundant*.

*Note*: there are in fact many ways of combining *constraint propagation* with *backjumping*, and we will not explore them in further detail here.

### Backjumping and forward checking

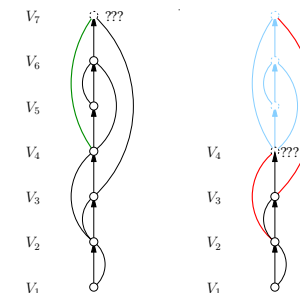


|       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| Start | BRC | BRC | BRC | BRC | BRC | BRC | BRC | BRC |
| 1 = B | = B | RC  | RC  | BRC | BRC | BRC | RC  | BRC |
| 3 = R | = B | C   | = R | BRC | BC  | BRC | C   | BRC |
| 5 = C | = B | C   | = R | BR  | = C | BR  | !   | BRC |
| 4 = B | = B | C   | = R | BR  | = C | BR  | !   | BRC |

Forward checking finds the problem *before backtracking does*.

### Graph-based backjumping

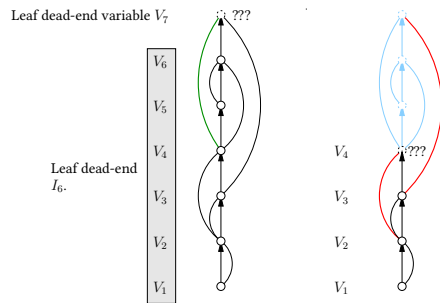
We're not quite done yet though. What happens when *there are no assignments left for the parent we just backjumped to*?



Backjumping from  $V_7$  to  $V_4$  is fine. However we shouldn't then just backjump to  $V_2$ , because changing  $V_3$  could fix the problem at  $V_7$ .

### Graph-based backjumping

To describe an algorithm in this case is a little involved.

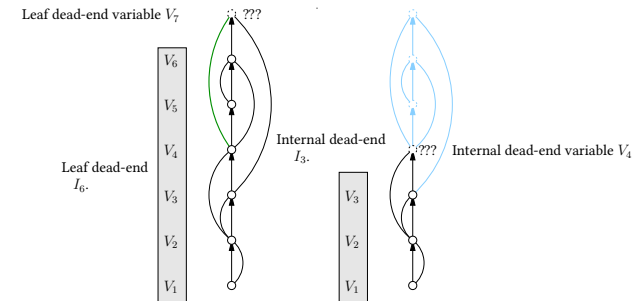


Given an instantiation  $I_k$  and  $V_{k+1}$ , if there is no consistent  $d \in D_{k+1}$  we call  $I_k$  a *leaf dead-end* and  $V_{k+1}$  a *leaf dead-end variable*.

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### Graph-based backjumping

Also



If  $V_i$  was backtracked to from a later leaf dead-end and there are no more values to try for  $V_i$  then we refer to it as an *internal dead-end variable* and call  $I_{i-1}$  an *internal dead-end*.

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### Graph-based backjumping

To keep track of exactly where to jump to we also need the definitions:

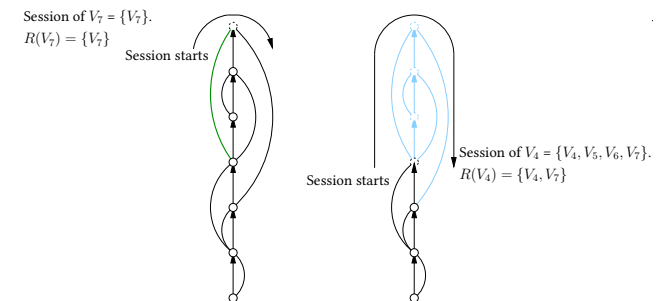
- The *session* of a variable  $V$  begins when the search algorithm visits it and ends when it backtracks through it to an earlier variable.
- The *current session* of a variable  $V$  is the set of all variables visited during its session.
- In particular, the current session for any  $V$  contains  $V$ .
- The *relevant dead-ends for the current session*  $R(V)$  for a variable  $V$  are:
  1.  $R(V)$  is initialized to  $\{V\}$  when  $V$  is first visited.
  2. If  $V$  is a leaf dead-end variable then  $R(V) = \{V\}$ .
  3. If  $V$  was backtracked to from a dead-end  $V'$  then  $R(V) = R(V) \cup R(V')$ .

And we're not done yet...

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### Graph-based backjumping

*Example:*



As expected, the relevant dead-ends for  $V_4$  are  $\{V_4\}$  and  $\{V_7\}$ .

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## Graph-based backjumping

One more bunch of definitions before the pain stops. Say  $V_k$  is a dead-end:

- The *induced ancestors*  $\text{ind}(V_k)$  of  $V_k$  are defined as

$$\text{ind}(V_k) = \{V_1, V_2, \dots, V_{k-1}\} \cap \left( \bigcup_{V \in R(V_k)} \text{ancestors}(V) \right)$$

- The *culprit* for  $V_k$  is the most recent  $V' \in \text{ind}(V_k)$ .

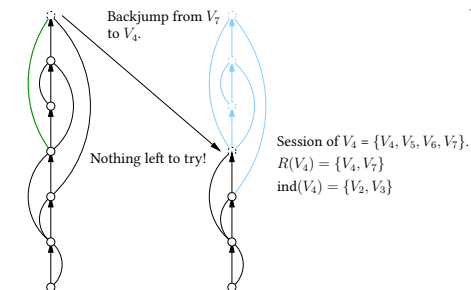
Note that these definitions depend on  $R(V_k)$ .

*FINALLY:* graph-based backjumping *backjumps to the culprit*.

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## Graph-based backjumping

*Example:*



As expected, we back jump to  $V_3$  instead of  $V_2$ . Hooray!

Gaschnig's algorithm and graph-based backjumping can be *combined* to produce *conflict-directed backjumping*.

We will not explore conflict-directed backjumping in this course.

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## Varieties of CSP

We have only looked at *discrete* CSPs with *finite domains*. These are the simplest. We could also consider:

1. Discrete CSPs with *infinite domains*:

- We need a *constraint language*. For example

$$V_3 \leq V_{10} + 5$$

- Algorithms are available for integer variables and linear constraints.
- There is *no algorithm* for integer variables and nonlinear constraints.

2. Continuous domains—using linear constraints defining convex regions we have *linear programming*. This is solvable in polynomial time in  $n$ .
3. We can introduce *preference constraints* in addition to *absolute constraints*, and in some cases an *objective function*.

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