

CS 380: Artificial Intelligence

Lecture 6: Adversarial Search

Recall: Problem Solving

- Idea: represent the problem we want to solve as:
 - State space
 - Actions
 - Goal check
 - Cost function
- If this is possible, we can use search methods to solve any problem:
 - Systematic Search:
 - BFS, DFS, ID, Greedy Search, A*
 - Local Search:
 - Hill Climbing, Simulated Annealing, Local Beam Search (e.g., GAs)

Games vs. search problems

“Unpredictable” opponent \Rightarrow solution is a **strategy** specifying a move for every possible opponent reply

Time limits \Rightarrow unlikely to find goal, must approximate

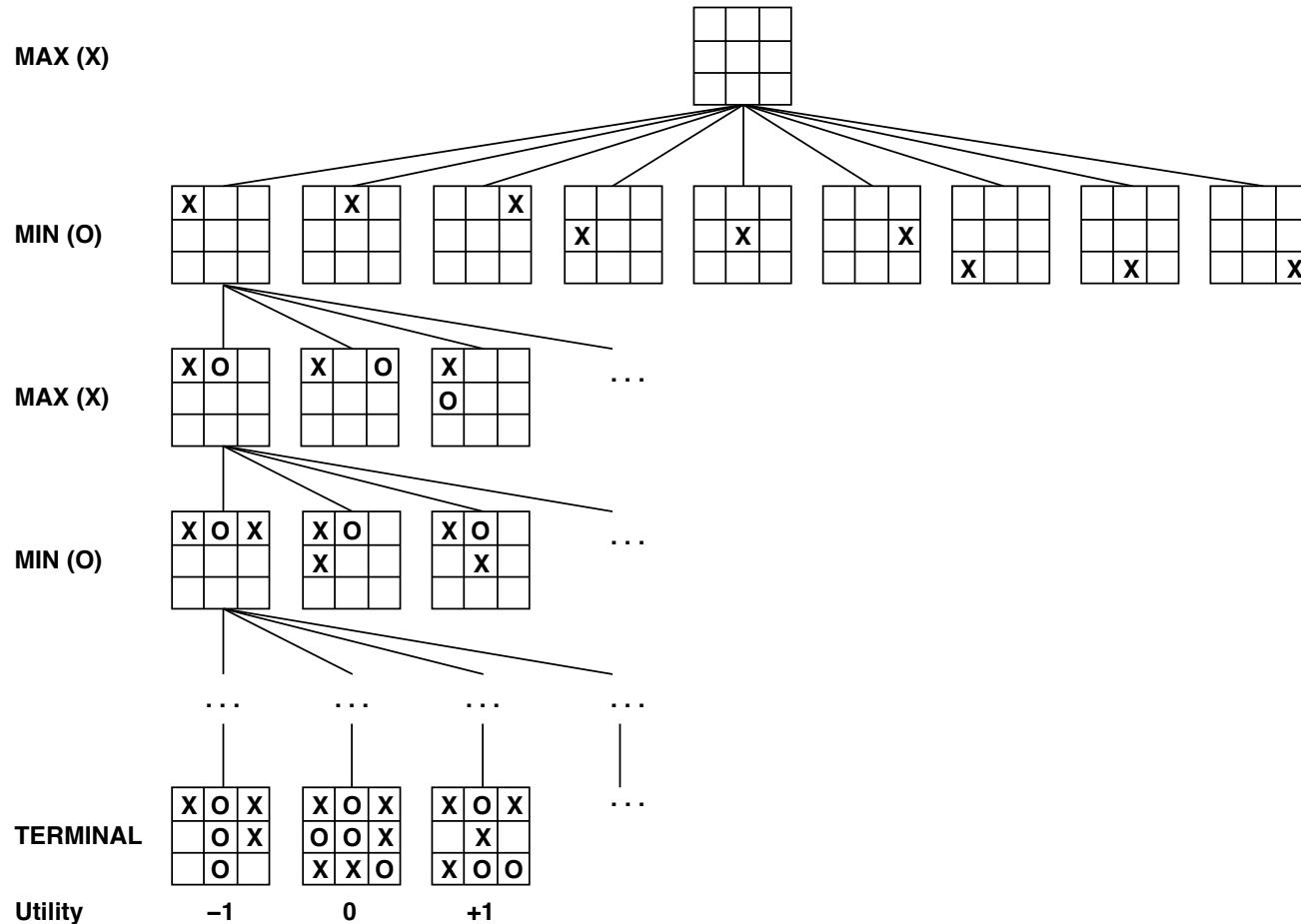
Plan of attack:

- Computer considers possible lines of play (Babbage, 1846)
- Algorithm for perfect play (Zermelo, 1912; Von Neumann, 1944)
- Finite horizon, approximate evaluation (Zuse, 1945; Wiener, 1948; Shannon, 1950)
- First chess program (Turing, 1951)
- Machine learning to improve evaluation accuracy (Samuel, 1952–57)
- Pruning to allow deeper search (McCarthy, 1956)

Types of games

	deterministic	chance
perfect information	chess, checkers, go, othello	backgammon monopoly
imperfect information	battleships, blind tictactoe	bridge, poker, scrabble nuclear war

Game tree (2-player, deterministic, turns)

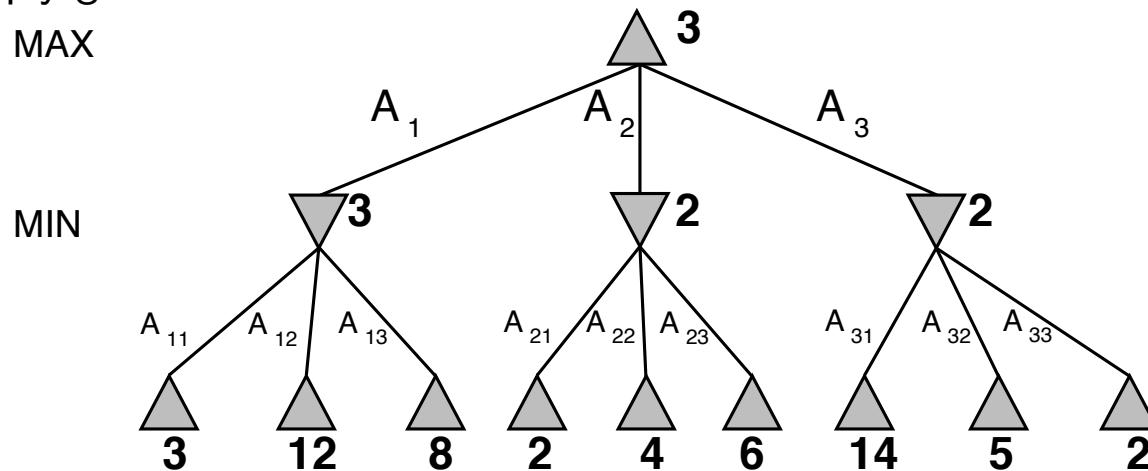


Minimax

Perfect play for deterministic, perfect-information games

Idea: choose move to position with highest **minimax value**
= best achievable payoff against best play

E.g., 2-ply game:



Minimax algorithm

```
function MINIMAX-DECISION(state) returns an action
    inputs: state, current state in game
    return the a in ACTIONS(state) maximizing MIN-VALUE(RESULT(a, state))
```

```
function MAX-VALUE(state) returns a utility value
    if TERMINAL-TEST(state) then return UTILITY(state)
    v  $\leftarrow -\infty$ 
    for a, s in SUCCESSORS(state) do v  $\leftarrow \text{MAX}(\text{MIN-VALUE}(\text{RESULT}(\text{ACTION}(\iota), \text{state})), \text{v})$ 
    return v
```

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```

Properties of minimax

Complete??

Properties of minimax

Complete?? Only if tree is finite (chess has specific rules for this).

NB a finite strategy can exist even in an infinite tree!

Optimal??

Properties of minimax

Complete?? Yes, if tree is finite (chess has specific rules for this)

Optimal?? Yes, against an optimal opponent. Otherwise??

Time complexity??

Properties of minimax

Complete?? Yes, if tree is finite (chess has specific rules for this)

Optimal?? Yes, against an optimal opponent. Otherwise??

Time complexity?? $O(b^m)$

Space complexity??

Properties of minimax

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Optimal?? Yes, against an optimal opponent. Otherwise??

Time complexity?? $O(b^m)$

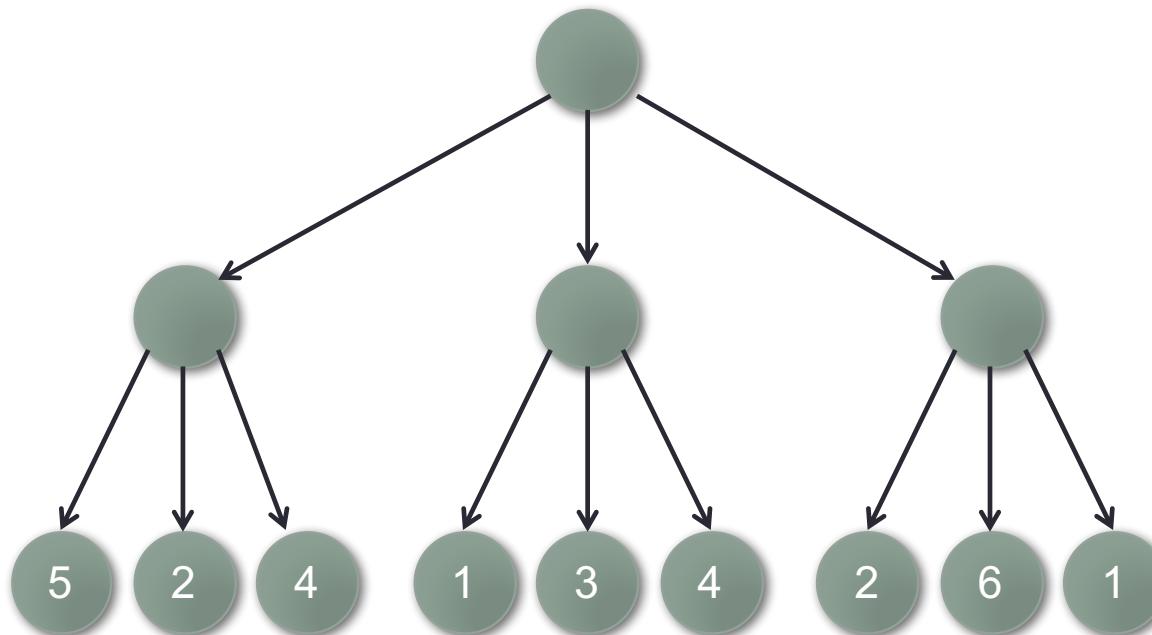
Space complexity?? $O(bm)$ (depth-first exploration)

For chess, $b \approx 35$, $m \approx 100$ for “reasonable” games
⇒ exact solution completely infeasible

But do we need to explore every path?

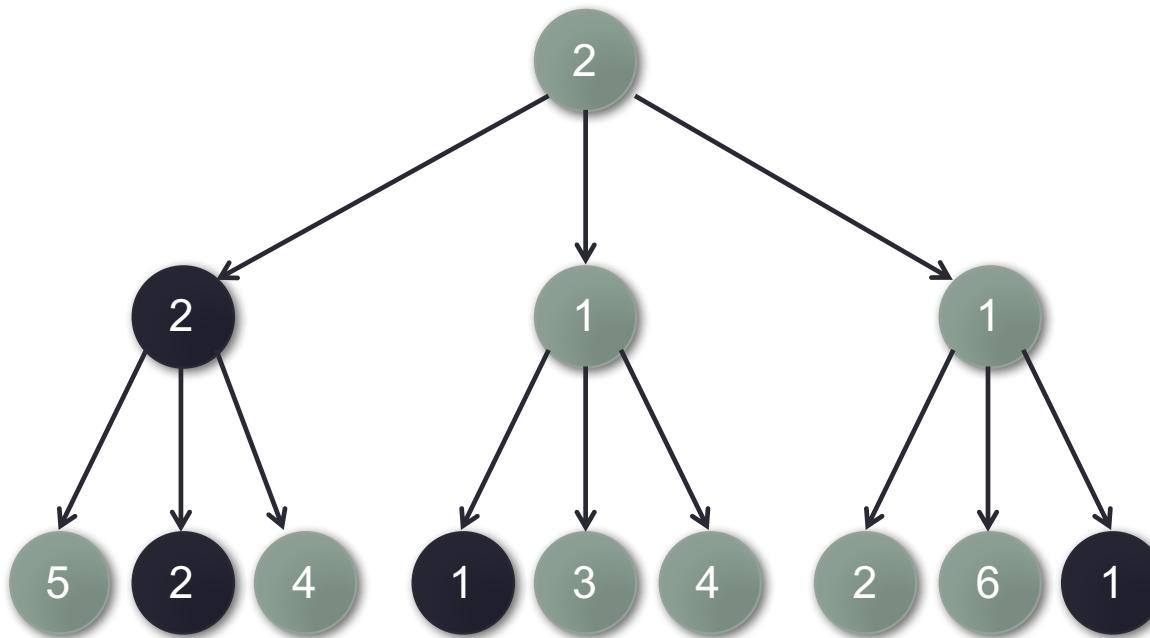
Alpha-Beta Pruning

- Not all the nodes in the search tree are relevant for deciding the next move



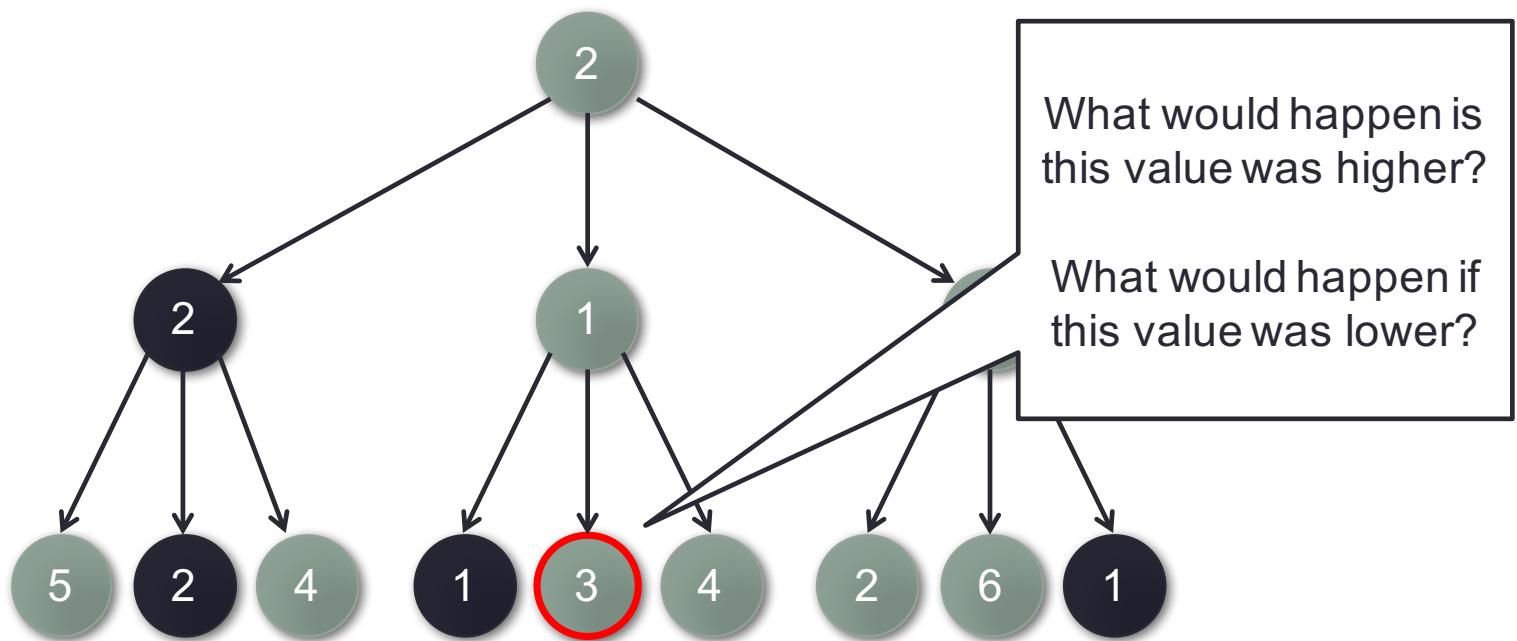
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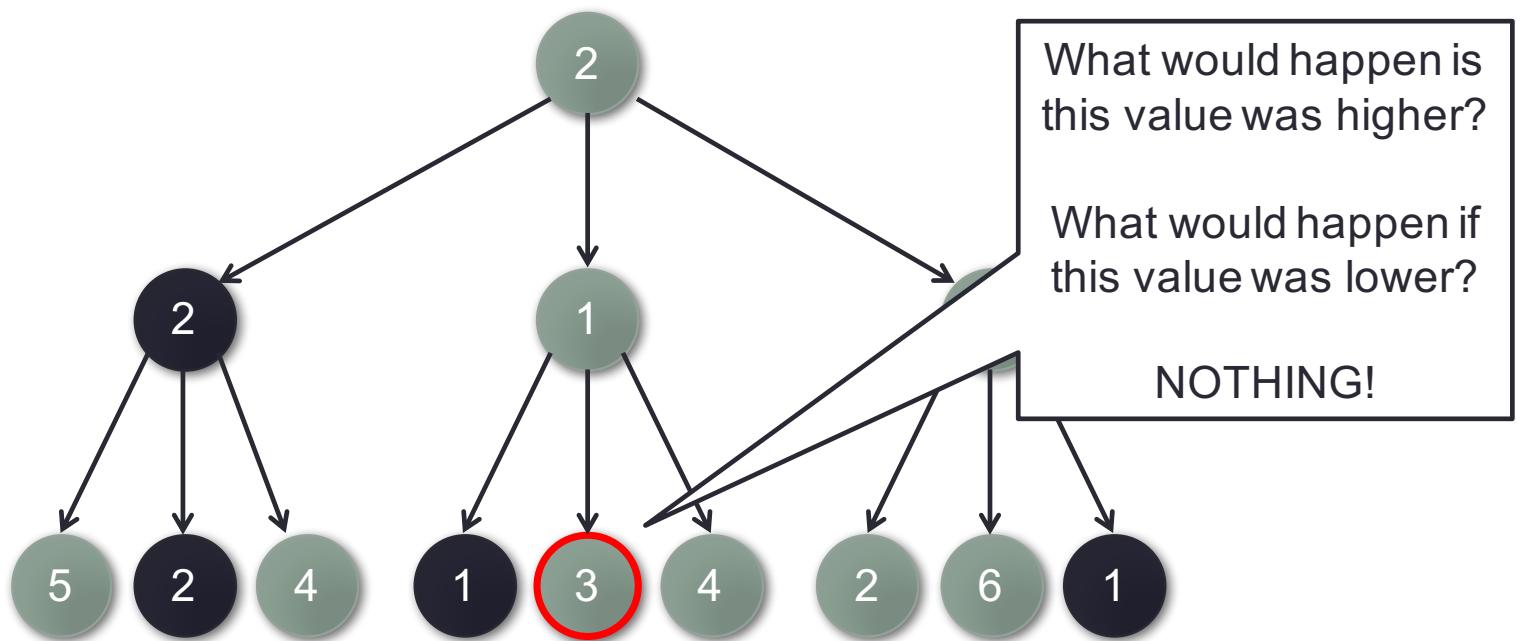
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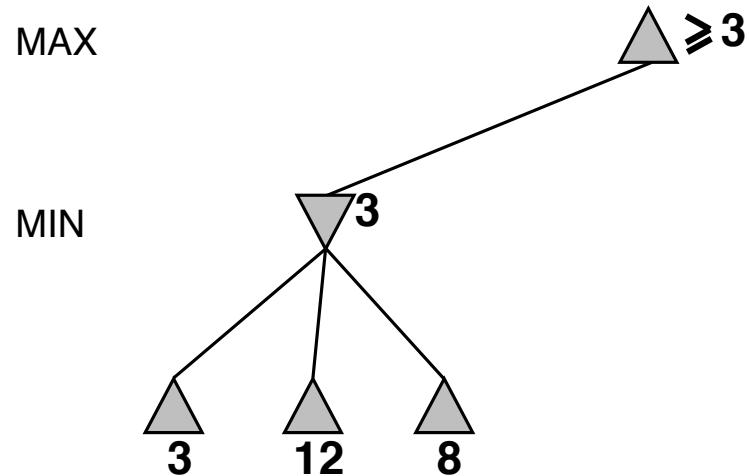


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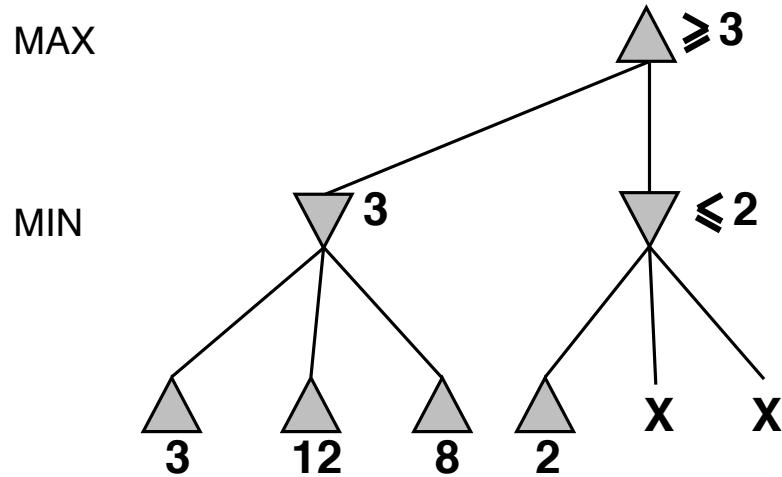
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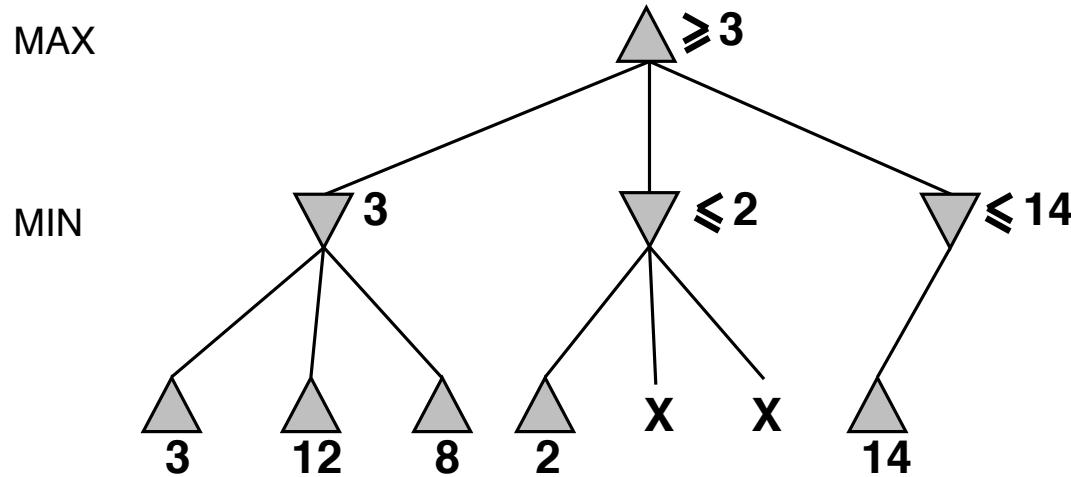
α - β pruning example



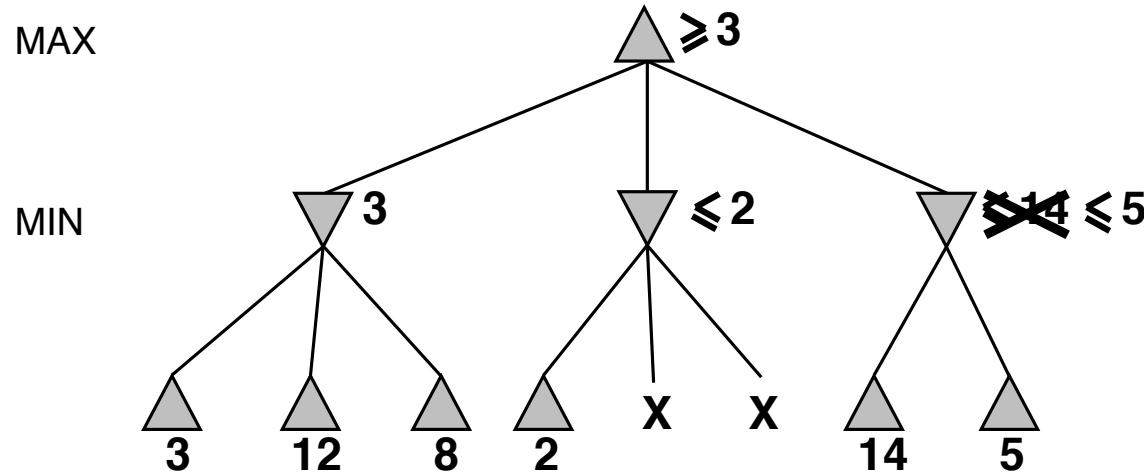
$\alpha-\beta$ pruning example



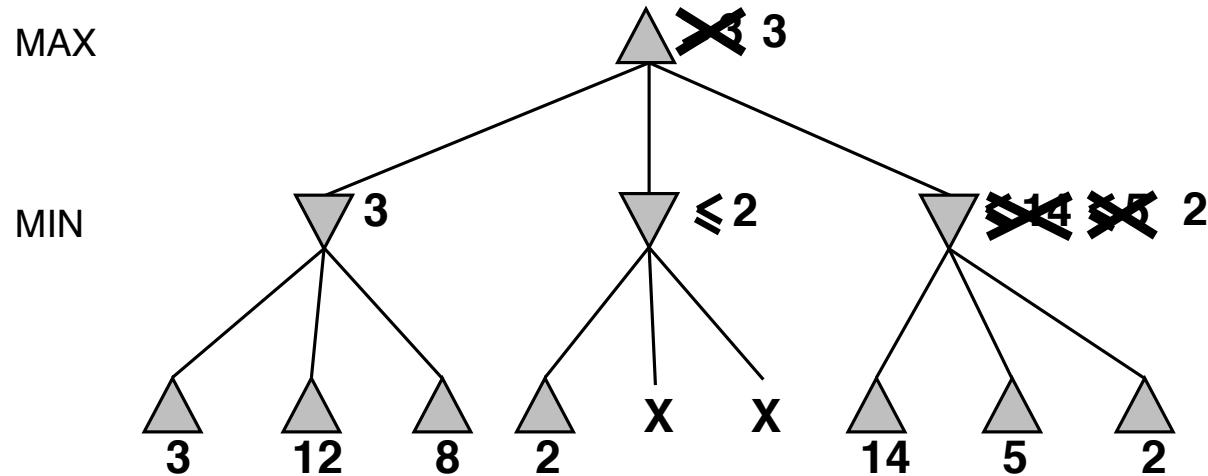
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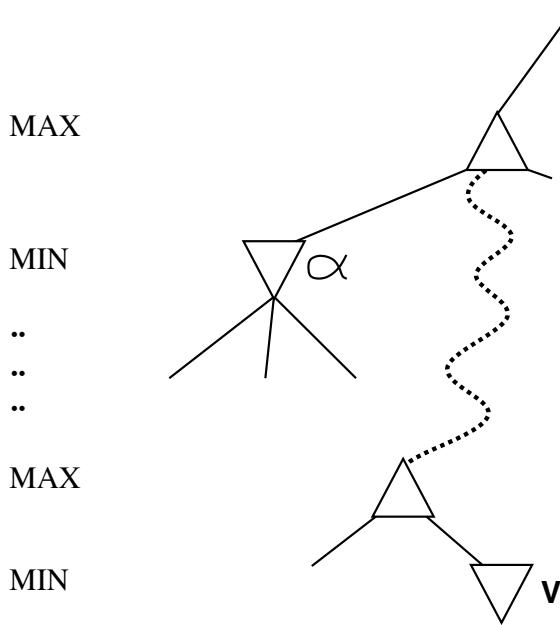
$\alpha-\beta$ pruning example



$\alpha-\beta$ pruning example



Why is it called α - β ?



α is the best value (to MAX) found so far off the current path

If V is worse than α , MAX will avoid it \Rightarrow prune that branch

Define β similarly for MIN

The α - β algorithm

```
function ALPHA-BETA-DECISION(state) returns an action
    return the a in ACTIONS(state) maximizing MIN-VALUE(RESULT(a, state))
```

```
function MAX-VALUE(state, α, β) returns a utility value
```

inputs: *state*, current state in game

α , the value of the best alternative for MAX along the path to *state*

β , the value of the best alternative for MIN along the path to *state*

```
if TERMINAL-TEST(state) then return UTILITY(state)
```

$v \leftarrow -\infty$

```
for a, s in SUCCESSORS(state) do
```

$v \leftarrow \text{MAX}(v, \text{MIN-VALUE}(s, \alpha, \beta))$

```
    if  $v \geq \beta$  then return v
```

$\alpha \leftarrow \text{MAX}(\alpha, v)$

```
return v
```

```
function MIN-VALUE(state, α, β) returns a utility value
```

same as MAX-VALUE but with roles of α, β reversed

Properties of α - β

Pruning **does not** affect final result

Good move ordering improves effectiveness of pruning

With “perfect ordering,” time complexity = $O(b^{m/2})$
⇒ **doubles** solvable depth

A simple example of the value of reasoning about which computations are relevant (a form of **metareasoning**)

Unfortunately, 35^{50} is still impossible!

Resource limits

Standard approach:

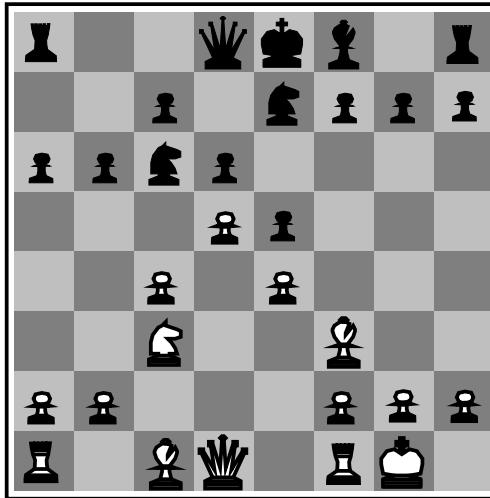
- Use CUTOFF-TEST instead of TERMINAL-TEST
 - e.g., depth limit (perhaps add quiescence search)
- Use EVAL instead of UTILITY
 - i.e., evaluation function that estimates desirability of position

Suppose we have 100 seconds, explore 10^4 nodes/second

$$\Rightarrow 10^6 \text{ nodes per move} \approx 35^{8/2}$$

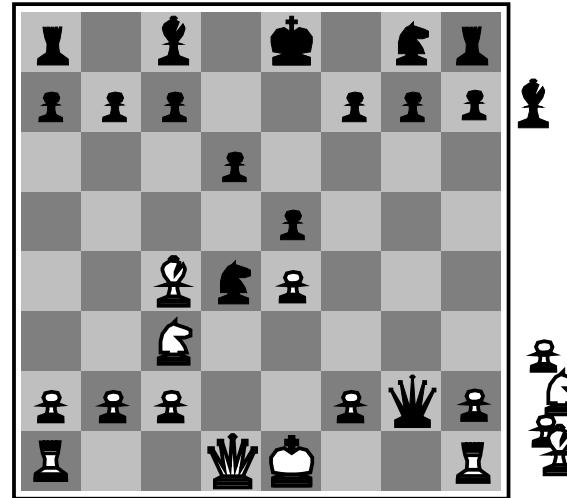
$\Rightarrow \alpha-\beta$ reaches depth 8 \Rightarrow pretty good chess program

Evaluation functions



Black to move

White slightly better



White to move

Black winning

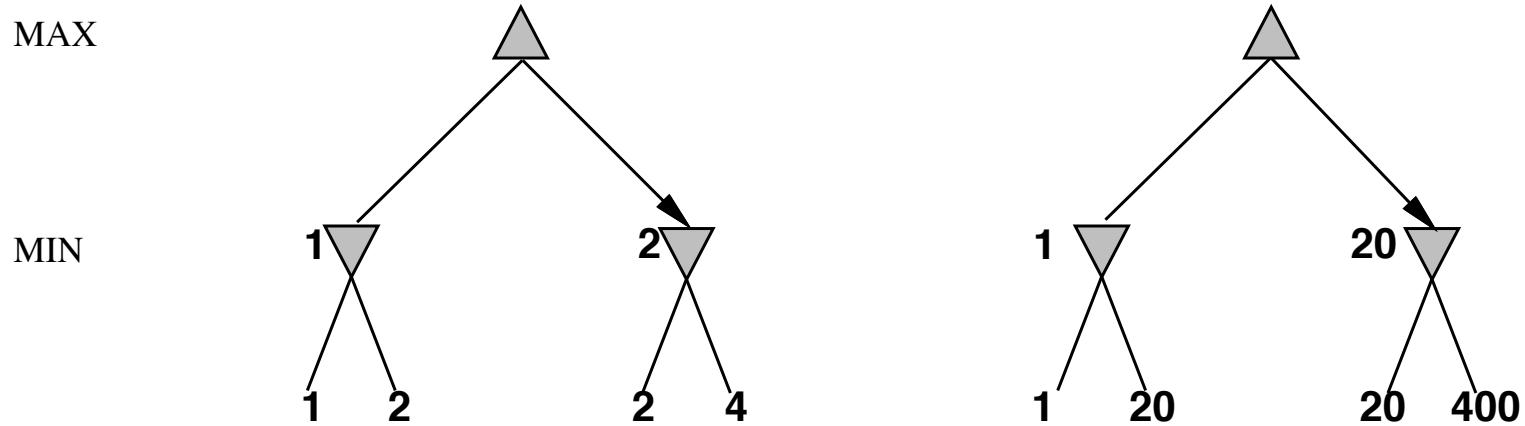
For chess, typically **linear** weighted sum of **features**

$$Eval(s) = w_1 f_1(s) + w_2 f_2(s) + \dots + w_n f_n(s)$$

e.g., $w_1 = 9$ with

$f_1(s) = (\text{number of white queens}) - (\text{number of black queens}),$ etc.

Digression: Exact values don't matter



Behaviour is preserved under any **monotonic** transformation of EVAL

Only the order matters:

payoff in deterministic games acts as an **ordinal utility** function

Deterministic games in practice

Checkers: Chinook ended 40-year-reign of human world champion Marion Tinsley in 1994. Used an endgame database defining perfect play for all positions involving 8 or fewer pieces on the board, a total of 443,748,401,247 positions.

Chess: Deep Blue defeated human world champion Gary Kasparov in a six-game match in 1997. Deep Blue searches 200 million positions per second, uses very sophisticated evaluation, and undisclosed methods for extending some lines of search up to 40 ply.

Othello: human champions refuse to compete against computers, who are too good.

Go: human champions refuse to compete against computers, who are too bad. In go, $b > 300$, so most programs use pattern knowledge bases to suggest plausible moves.

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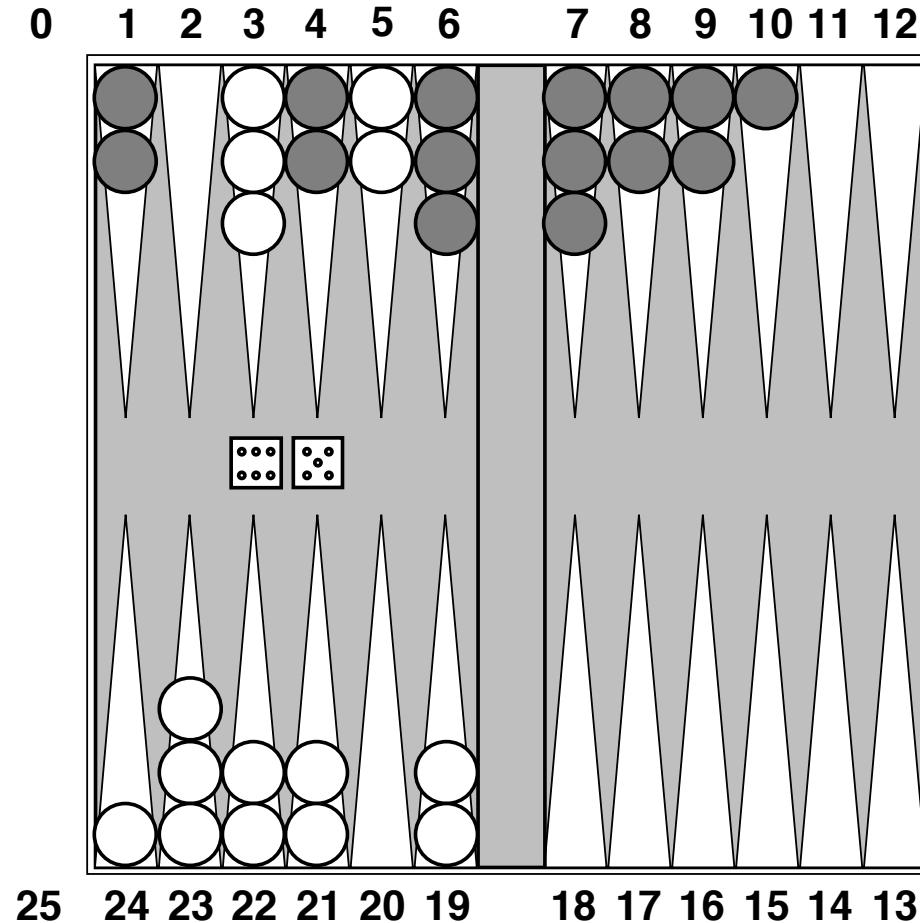
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AlphaGo

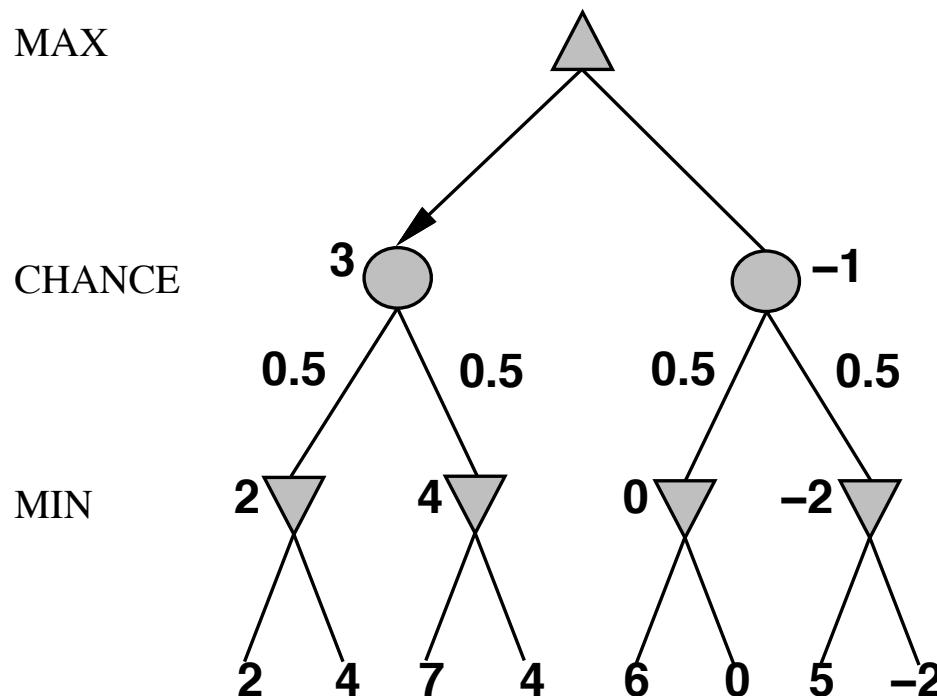
Nondeterministic games: backgammon



Nondeterministic games in general

In nondeterministic games, chance introduced by dice, card-shuffling

Simplified example with coin-flipping:



Algorithm for nondeterministic games

EXPECTIMINIMAX gives perfect play

Just like MINIMAX, except we must also handle chance nodes:

...

```
if state is a MAX node then
    return the highest EXPECTIMINIMAX-VALUE of SUCCESSORS(state)
if state is a MIN node then
    return the lowest EXPECTIMINIMAX-VALUE of SUCCESSORS(state)
if state is a chance node then
    return average of EXPECTIMINIMAX-VALUE of SUCCESSORS(state)
...
```

Nondeterministic games in practice

Dice rolls increase b : 21 possible rolls with 2 dice

Backgammon ≈ 20 legal moves (can be 6,000 with 1-1 roll)

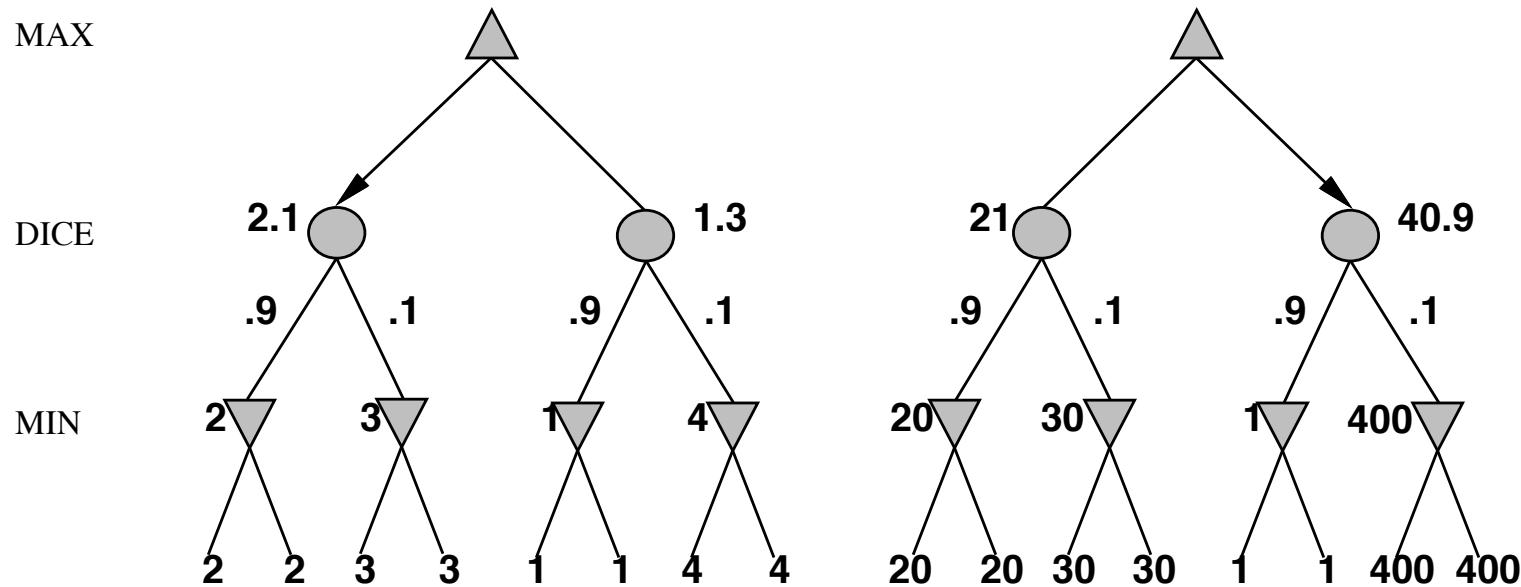
$$\text{depth 4} = 20 \times (21 \times 20)^3 \approx 1.2 \times 10^9$$

As depth increases, probability of reaching a given node shrinks
⇒ value of lookahead is diminished

α - β pruning is much less effective

TDGAMMON uses depth-2 search + very good EVAL
 \approx world-champion level

Digression: Exact values DO matter



Behaviour is preserved only by **positive linear transformation** of EVAL

Hence EVAL should be proportional to the expected payoff

Games of imperfect information

E.g., card games, where opponent's initial cards are unknown

Typically we can calculate a probability for each possible deal

Seems just like having one big dice roll at the beginning of the game^{*}

Idea: compute the minimax value of each action in each deal,
then choose the action with highest expected value over all deals^{*}

Special case: if an action is optimal for all deals, it's optimal.^{*}

GIB, current best bridge program, approximates this idea by

- 1) generating 100 deals consistent with bidding information
- 2) picking the action that wins most tricks on average

Proper analysis

* Intuition that the value of an action is the average of its values in all actual states is **WRONG**

With partial observability, value of an action depends on the **information state** or **belief state** the agent is in

Can generate and search a tree of information states

Leads to rational behaviors such as

- ◊ Acting to obtain information
- ◊ Signalling to one's partner
- ◊ Acting randomly to minimize information disclosure

Coming up...

- What if the game is too complex for minimax and related searches?
- Can we do reasonably well using some other approach?
 - Monte Carlo methods