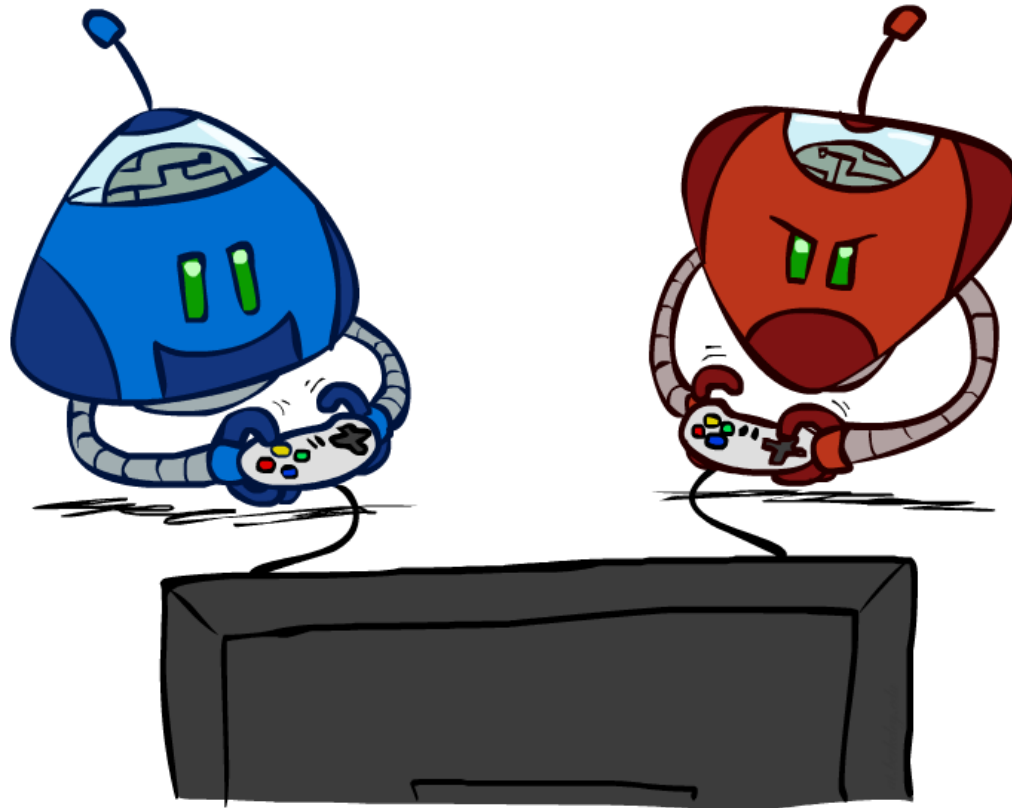


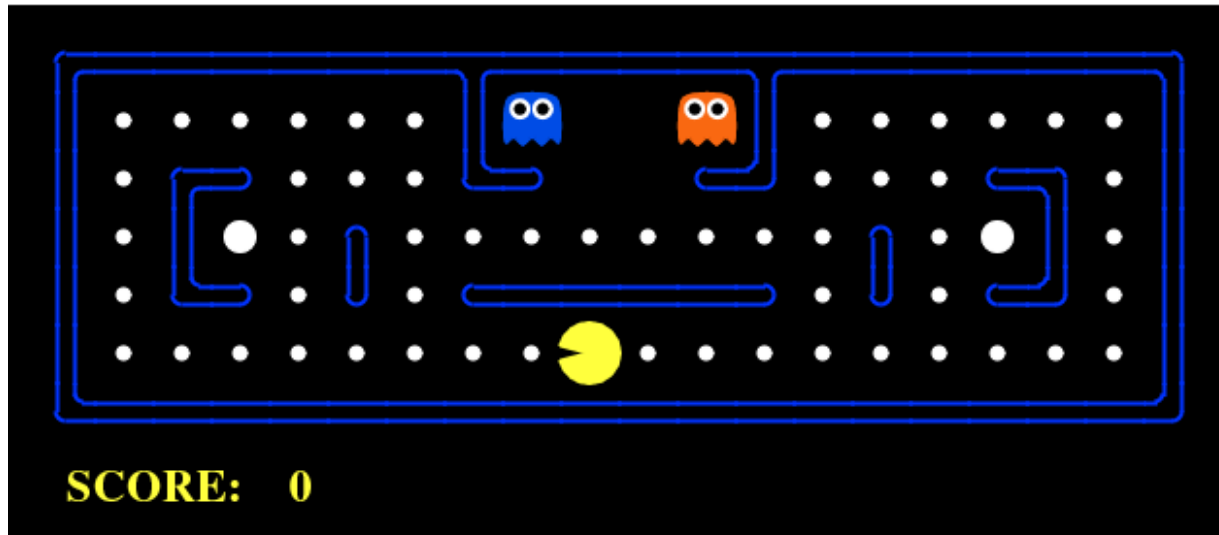
# Adversarial Search



# Why Multiple Agents?

- AI agents that work with humans (or other AI agents)
  - Robot helpers, AI tutors, self-driving cars
- Multiple agents compete against each other to improve
  - Examples: AlphaGo
- Play multi-agent Pacman! (and other games)

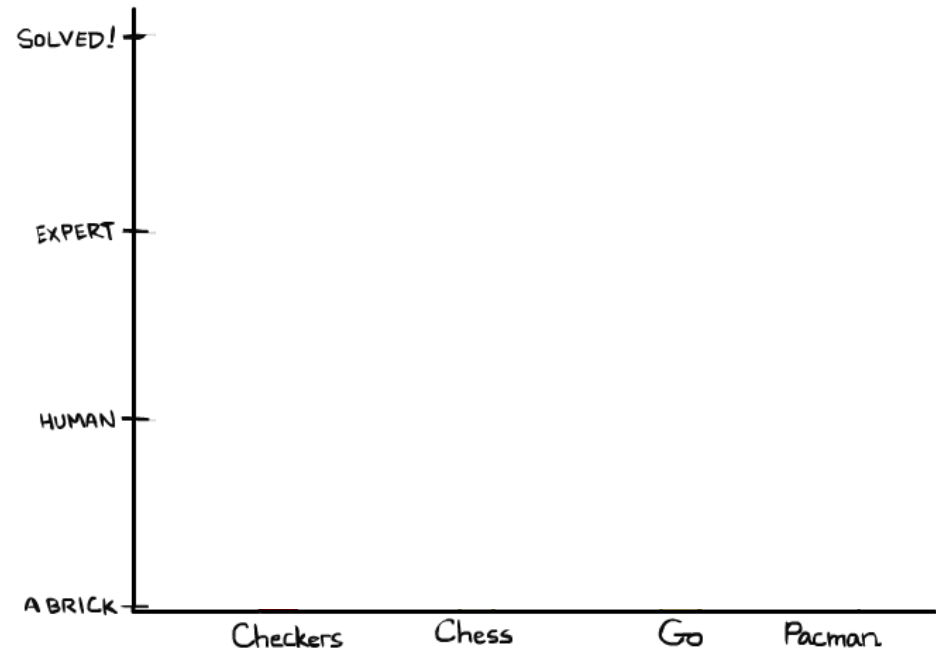
# Multi-Agent Pacman



We'll focus on games in this class, but multi-agent ideas come up in many areas of AI

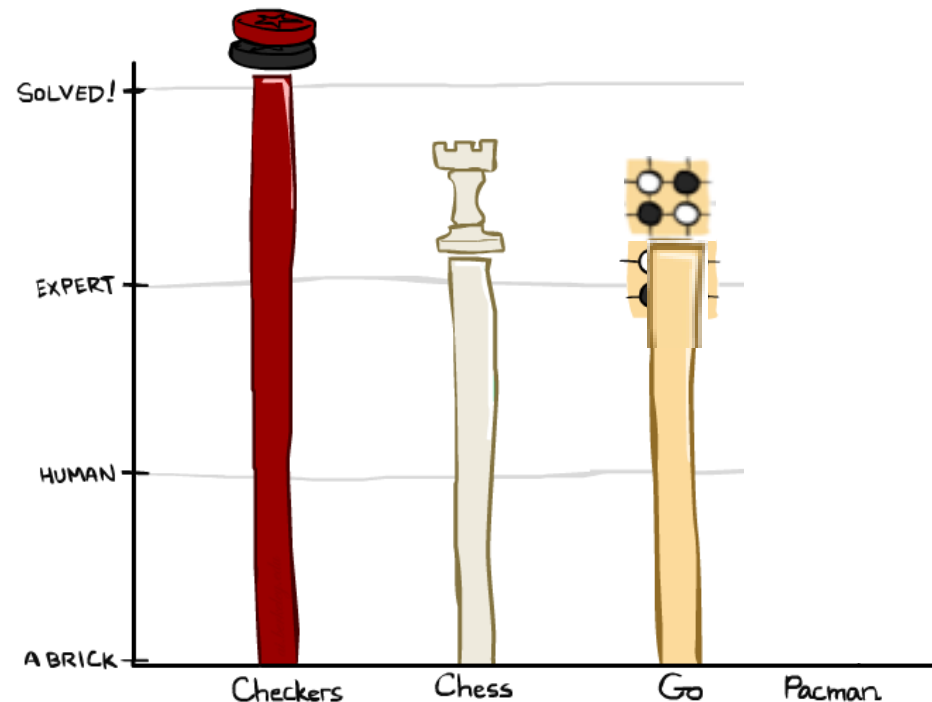
# Game Playing State-of-the-Art

- **Checkers:** 1950: First computer player. 1994: First computer champion: Chinook ended 40-year-reign of human champion Marion Tinsley using complete 8-piece endgame. 2007: Checkers solved!
- **Chess:** 1997: Deep Blue defeats human champion Gary Kasparov in a six-game match. Deep Blue examined 200M positions per second, used very sophisticated evaluation and undisclosed methods for extending some lines of search up to 40 ply. Current programs are even better, if less historic.
- **Go:** Human champions are now starting to be challenged by machines. In go,  $b > 300$ ! Classic programs use pattern knowledge bases, but big recent advances use Monte Carlo (randomized) expansion methods.

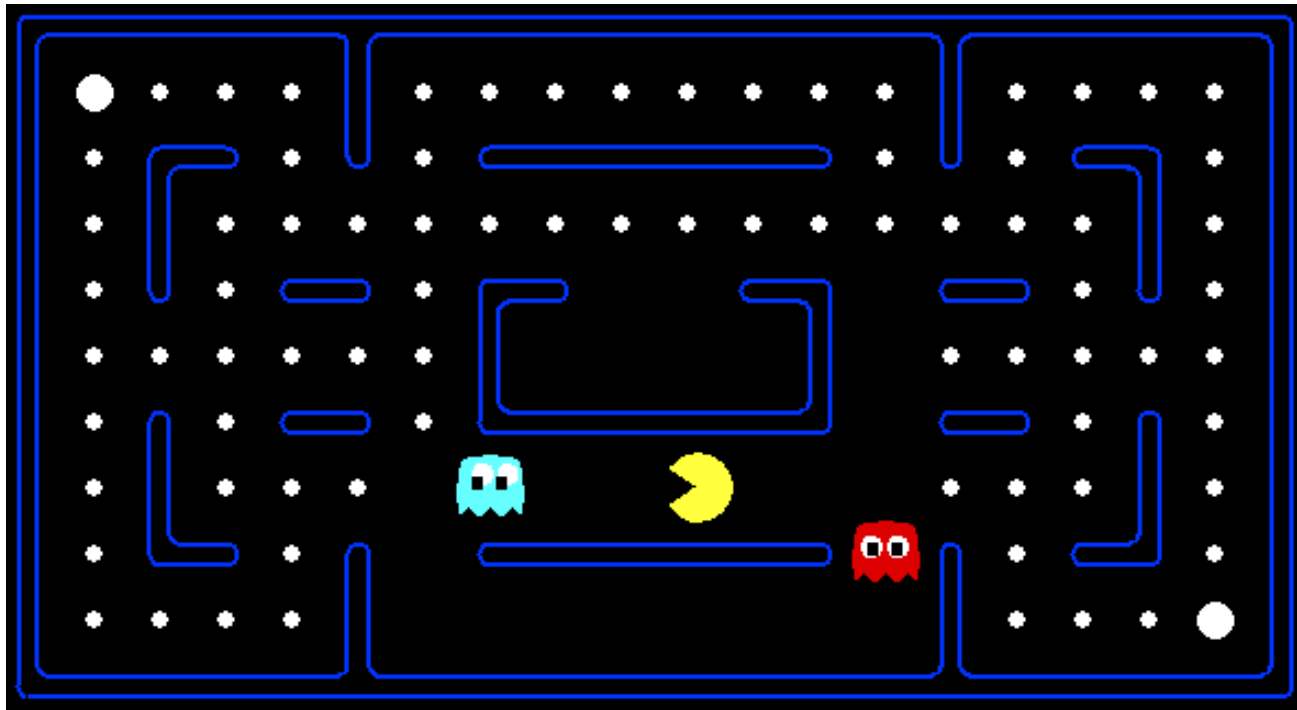


# Game Playing State-of-the-Art

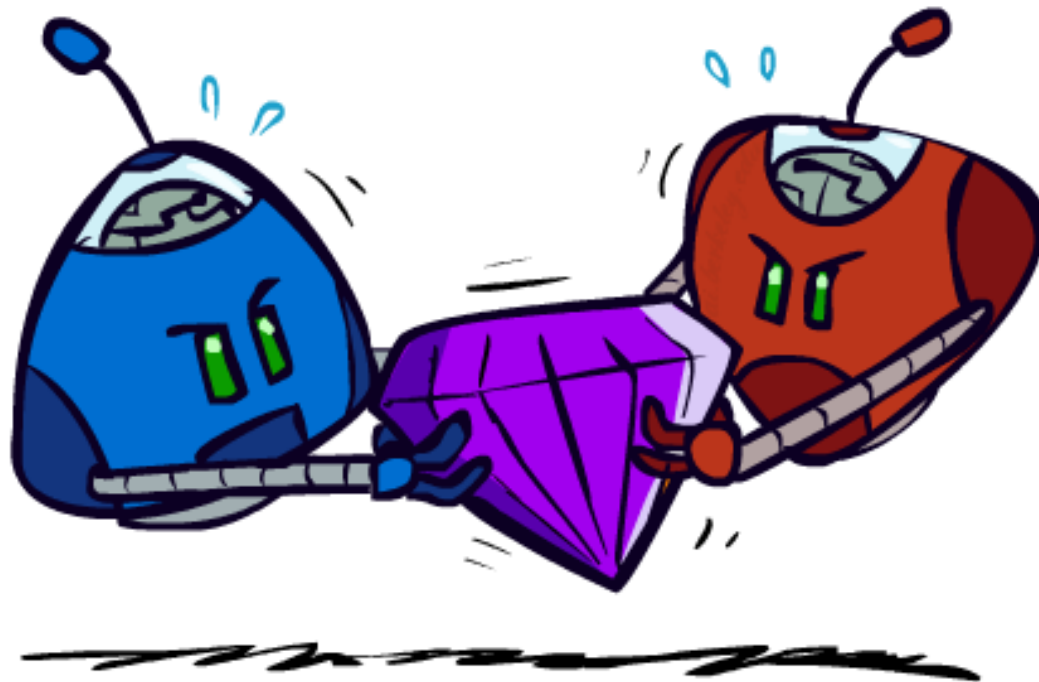
- **Checkers:** 1950: First computer player. 1994: First computer champion: Chinook ended 40-year-reign of human champion Marion Tinsley using complete 8-piece endgame. 2007: Checkers solved!
- **Chess:** 1997: Deep Blue defeats human champion Gary Kasparov in a six-game match. Deep Blue examined 200M positions per second, used very sophisticated evaluation and undisclosed methods for extending some lines of search up to 40 ply. Current programs are even better, if less historic.
- **Go:** 2016: Alpha GO defeats human champion. Uses Monte Carlo Tree Search, learned evaluation function.
- **Pacman**



# Behavior from Computation

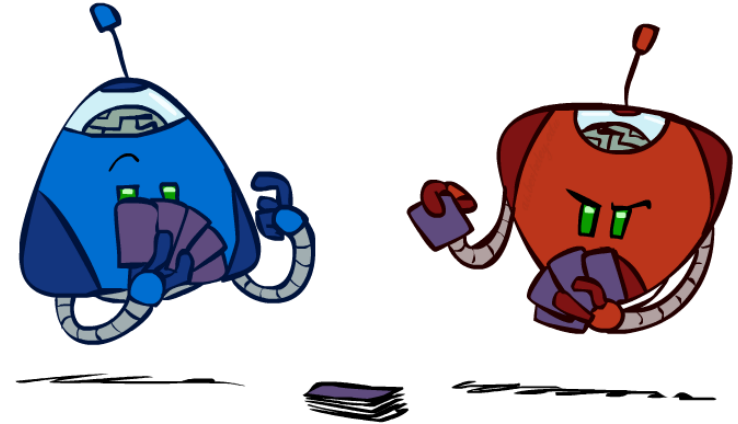


# Adversarial Games



# Types of Games

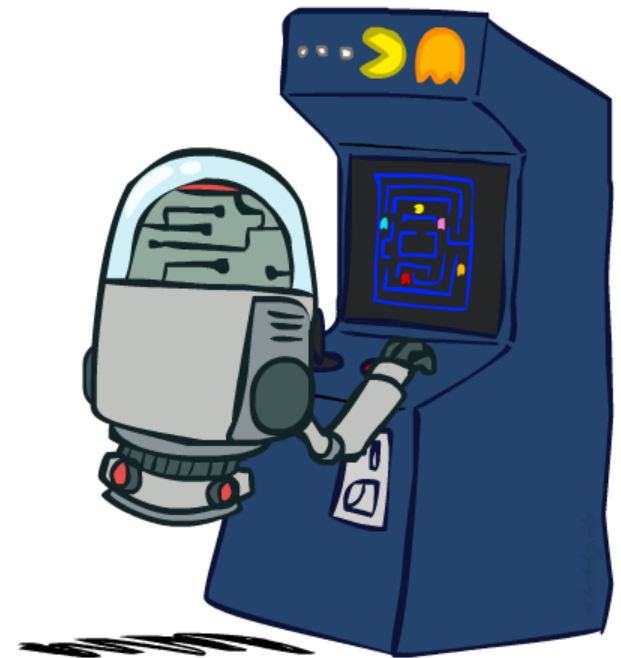
- Many different kinds of games!
- Axes:
  - Deterministic or stochastic?
  - One, two, or more players?
  - Zero sum?
  - Perfect information (can you see the state)?
- Want algorithms for calculating a **strategy (policy)** which recommends a move from each state



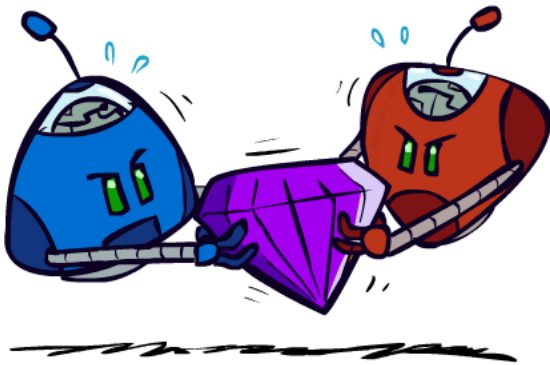


# Deterministic Games

- Many possible formalizations, one is:
  - States:  $S$  (start at  $s_0$ )
  - Players:  $P=\{1\dots N\}$  (usually take turns)
  - Actions:  $A$  (may depend on player / state)
  - Transition Function:  $S \times A \rightarrow S$
  - Terminal Test:  $S \rightarrow \{t, f\}$
  - Terminal Utilities:  $S \times P \rightarrow R$
- Solution for a player is a **policy**:  $S \rightarrow A$



# Zero-Sum Games



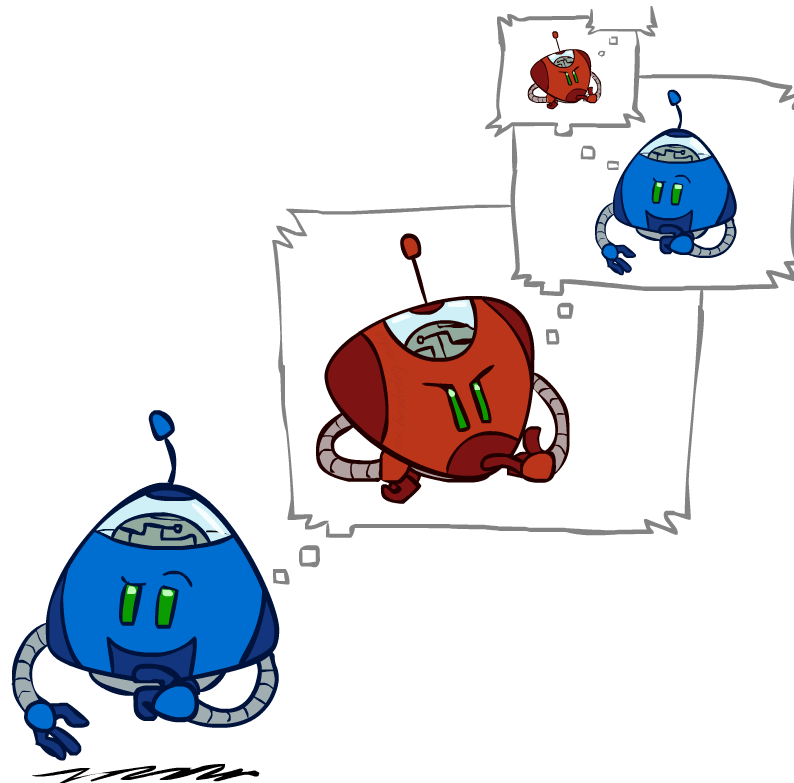
## ■ Zero-Sum Games

- Agents have opposite utilities (values on outcomes)
- Lets us think of a single value that one maximizes and the other minimizes
- Adversarial, pure competition

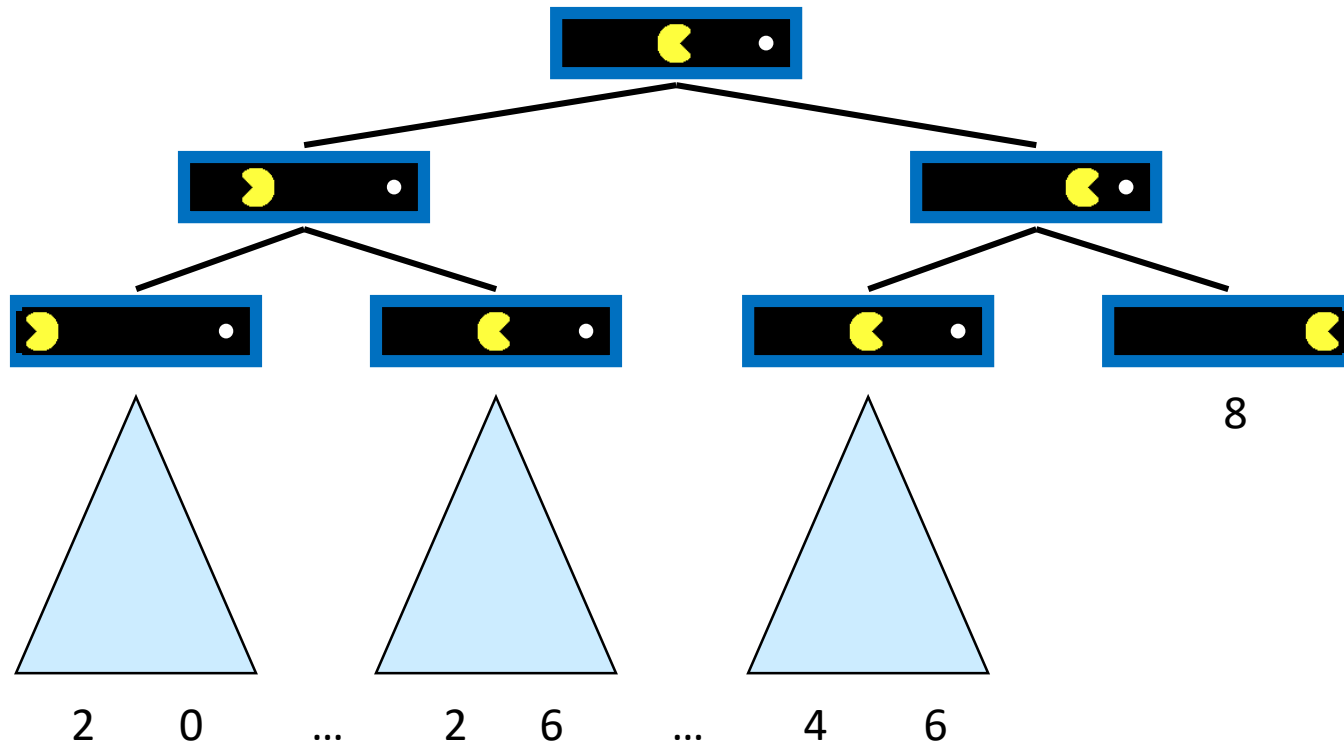
## ■ General Games

- Agents have independent utilities (values on outcomes)
- Cooperation, indifference, competition, and more are all possible
- More later on non-zero-sum games

# Adversarial Search

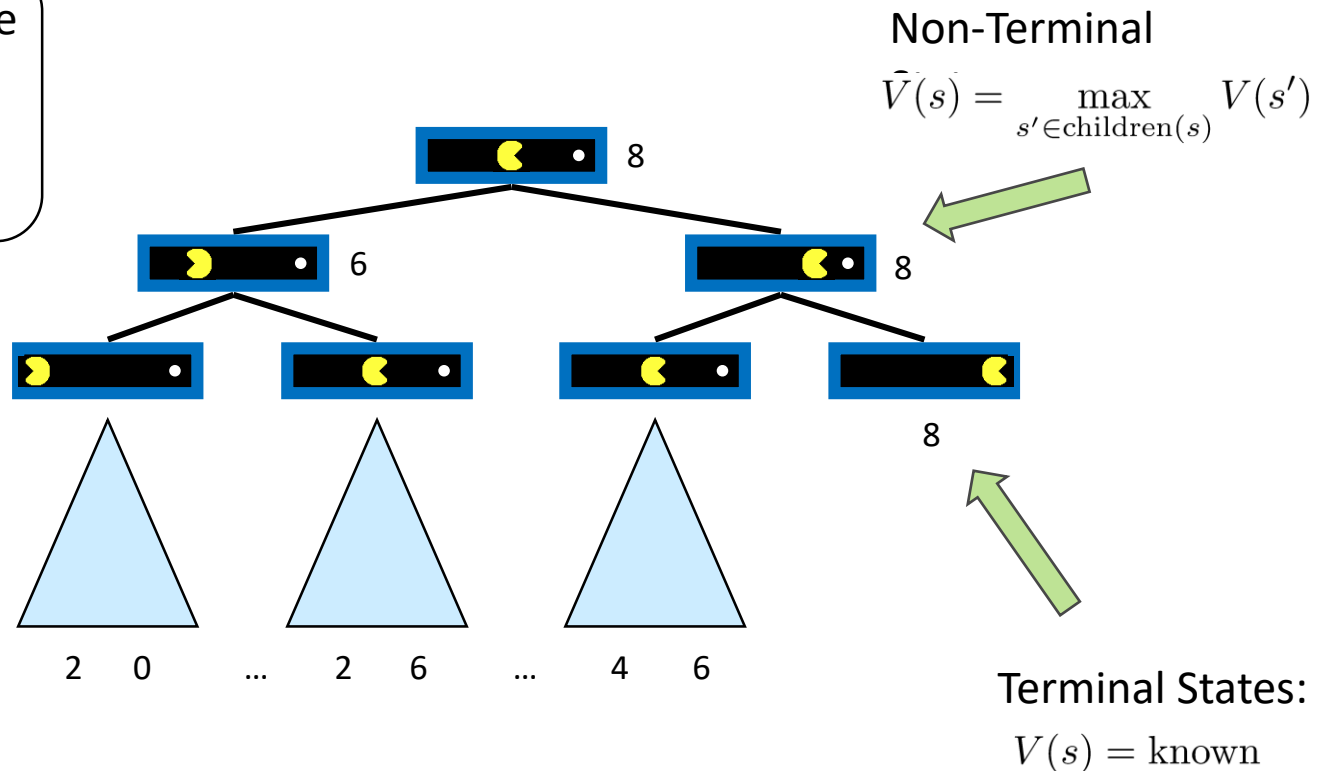


# Single-Agent Trees

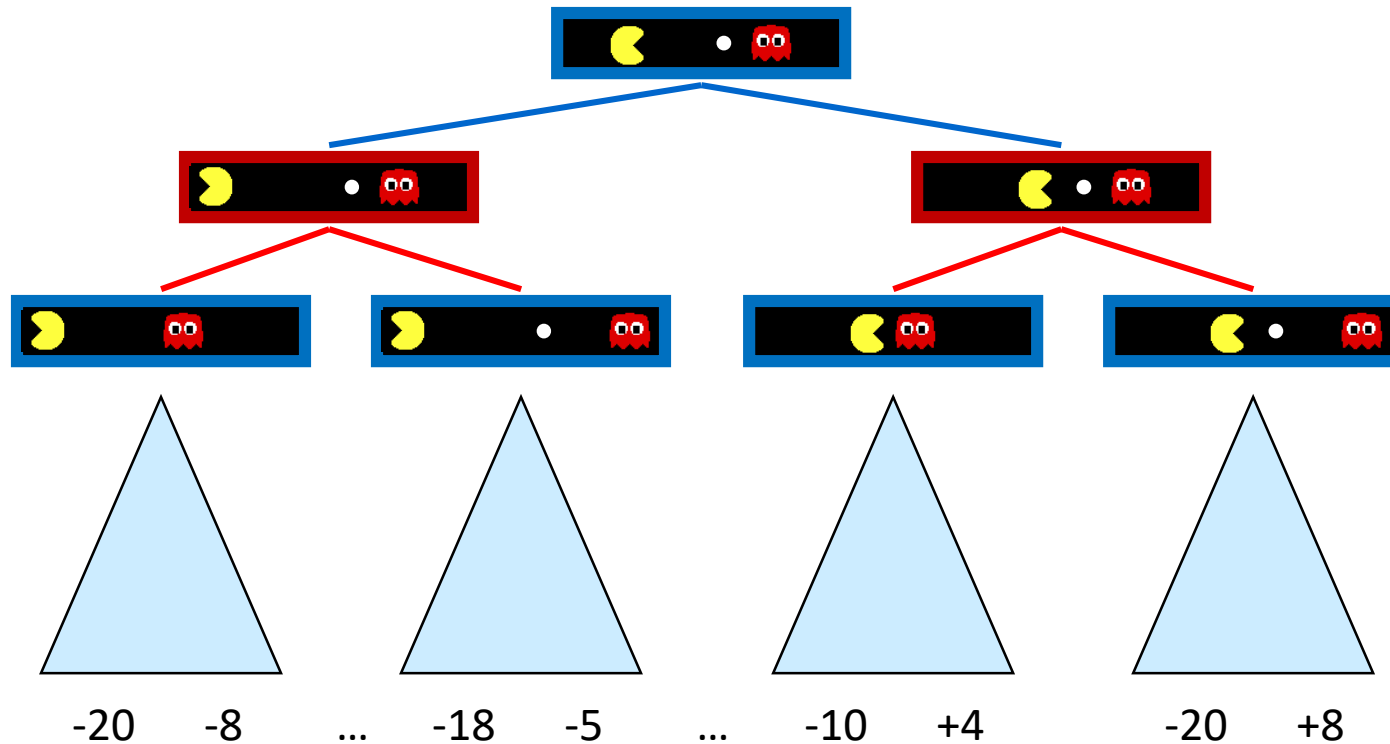


# Value of a State

Value of a state: The best achievable outcome (utility) from that state



# Adversarial Game Trees



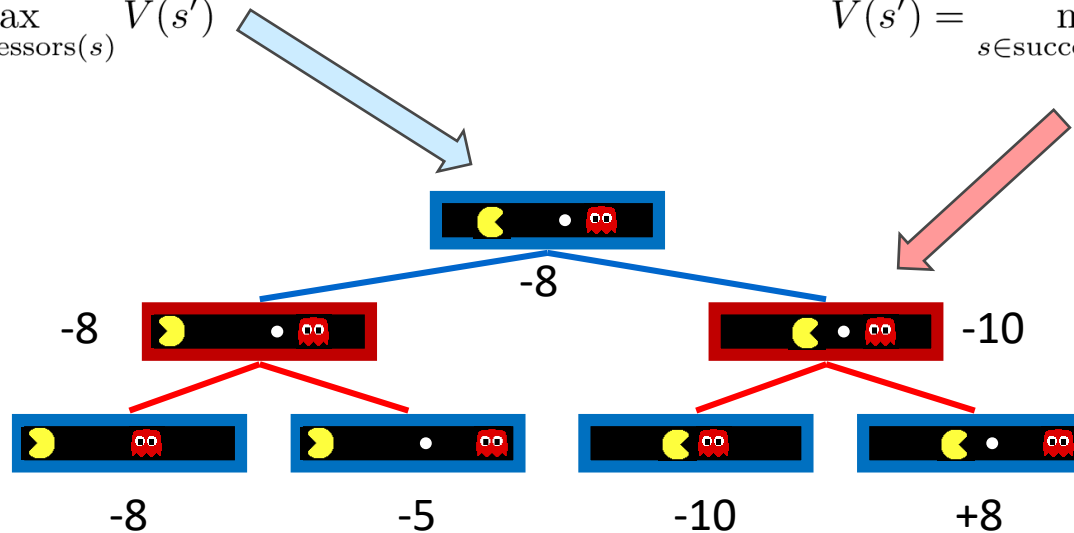
# Minimax Values

States Under Agent's Control:

$$V(s) = \max_{s' \in \text{successors}(s)} V(s')$$

States Under Opponent's Control:

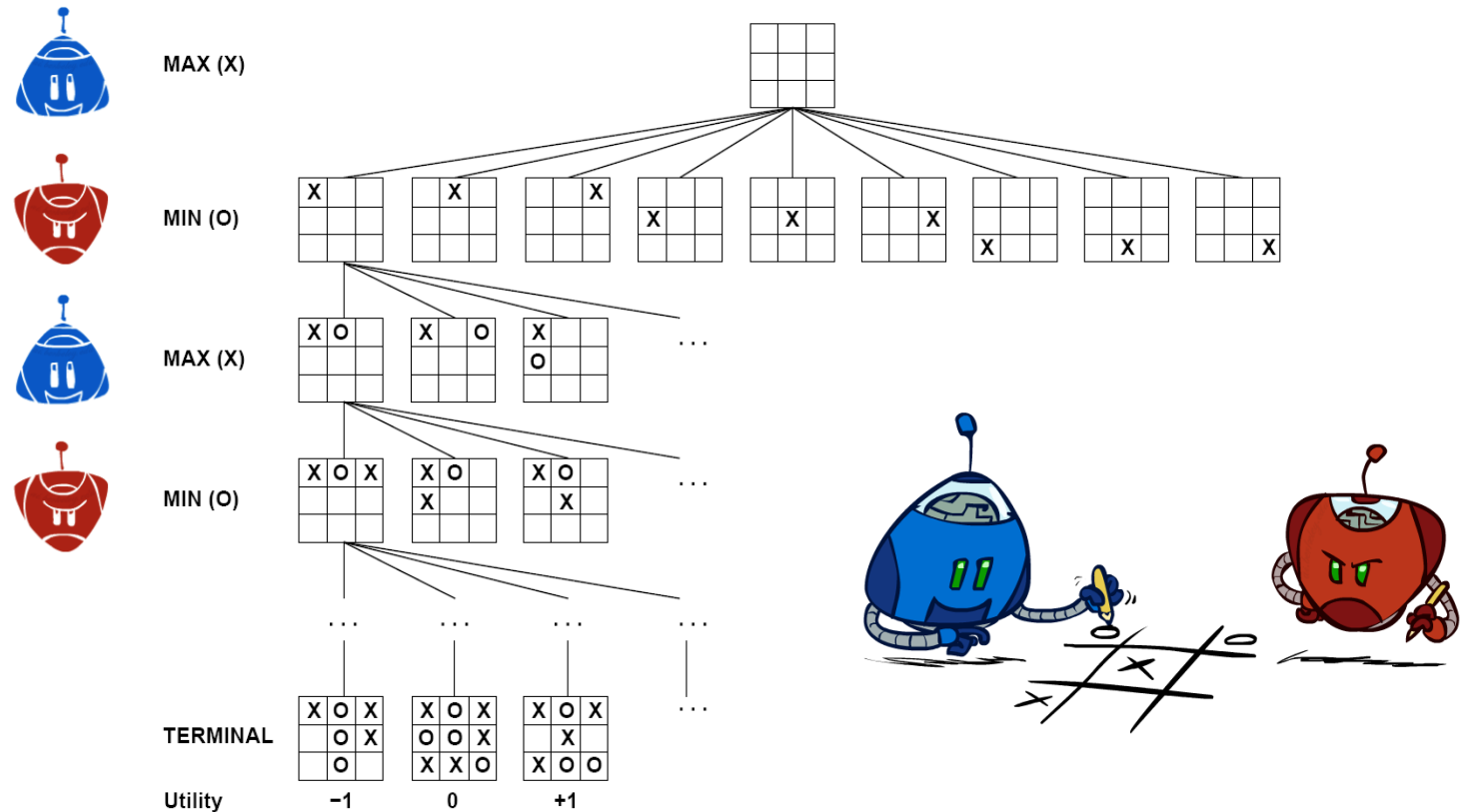
$$V(s') = \min_{s \in \text{successors}(s')} V(s)$$



Terminal States:

$$V(s) = \text{known}$$

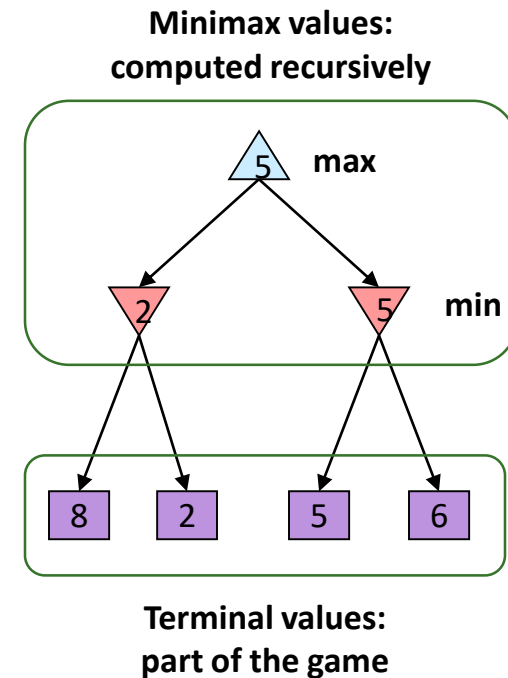
# Tic-Tac-Toe Game Tree





# Adversarial Search (Minimax)

- Deterministic, zero-sum games:
  - Tic-tac-toe, chess, checkers
  - One player maximizes result
  - The other minimizes result
- Minimax search:
  - A state-space search tree
  - Players alternate turns
  - Compute each node's **minimax value**: the best achievable utility against a rational (optimal) adversary



# Minimax Implementation

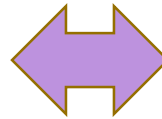
def max-value(state):

  initialize  $v = -\infty$

  for each successor of state:

$v = \max(v, \text{min-value}(\text{successor}))$

  return  $v$



def min-value(state):

  initialize  $v = +\infty$

  for each successor of state:

$v = \min(v, \text{max-value}(\text{successor}))$

  return  $v$

$$V(s) = \max_{s' \in \text{successors}(s)} V(s')$$

$$V(s') = \min_{s \in \text{successors}(s')} V(s)$$

# Minimax Implementation (Dispatch)

def value(state):

if the state is a terminal state: return the state's utility

if the next agent is MAX: return max-value(state)

if the next agent is MIN: return min-value(state)

def max-value(state):

initialize  $v = -\infty$

for each successor of state:

$v = \max(v, \text{value}(\text{successor}))$

return v

def min-value(state):

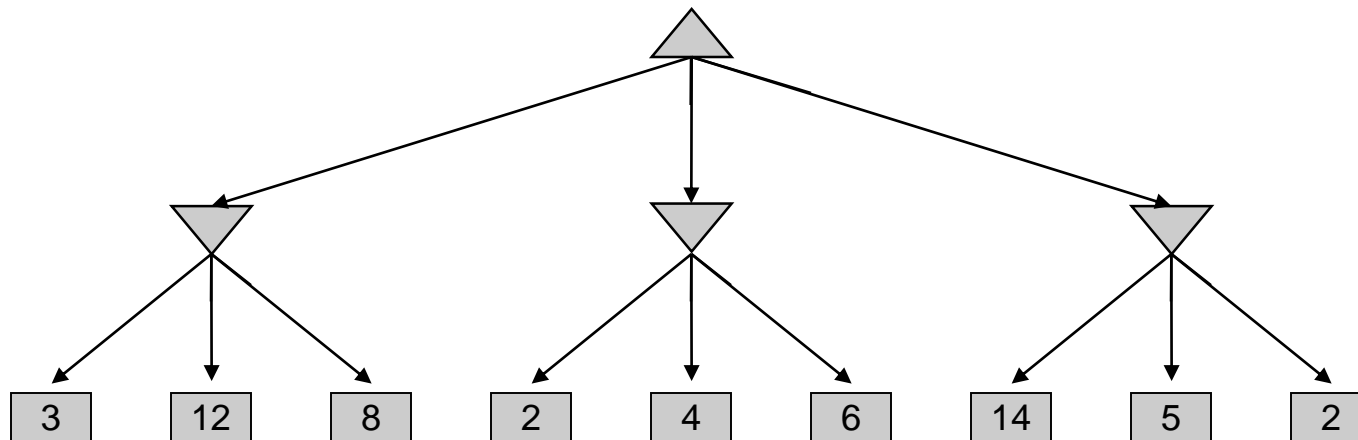
initialize  $v = +\infty$

for each successor of state:

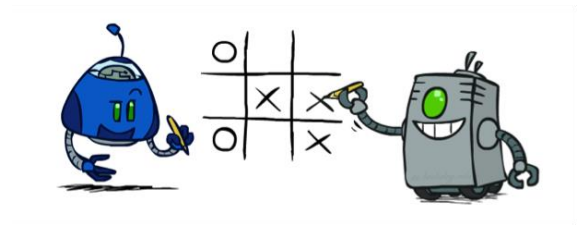
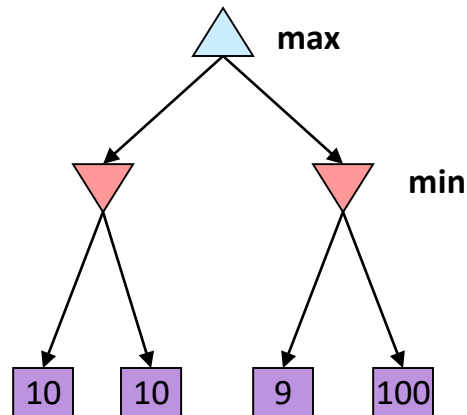
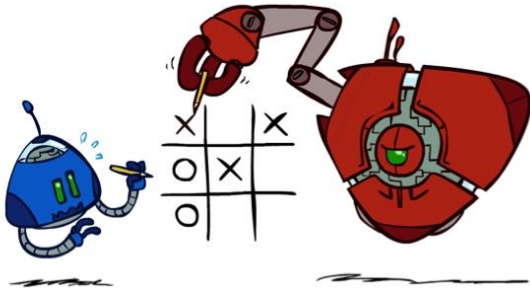
$v = \min(v, \text{value}(\text{successor}))$

return v

# Minimax Example

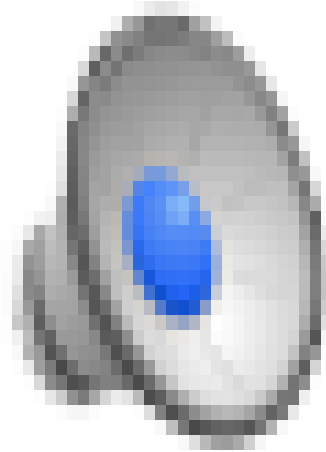


# Minimax Properties

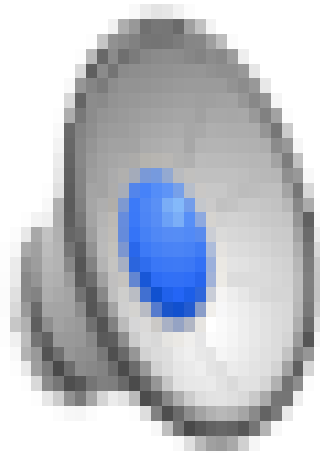


Optimal against a perfect player. Otherwise?

# Video of Demo Min vs. Exp (Min)

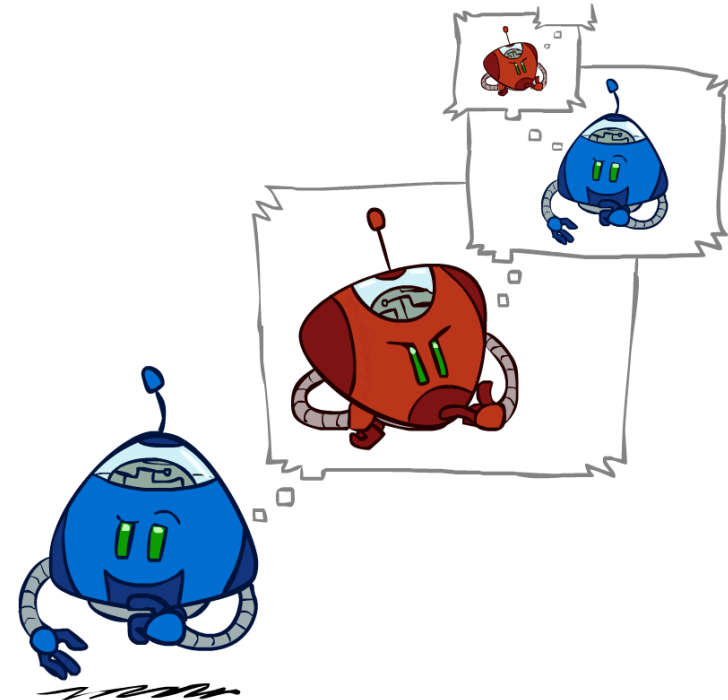


# Video of Demo Min vs. Exp (Exp)



# Minimax Efficiency

- How efficient is minimax?
  - Just like (exhaustive) DFS
  - Time:  $O(b^m)$
  - Space:  $O(bm)$
- Example: For chess,  $b \approx 35$ ,  $m \approx 100$ 
  - Exact solution is completely infeasible
  - But, do we need to explore the whole tree?

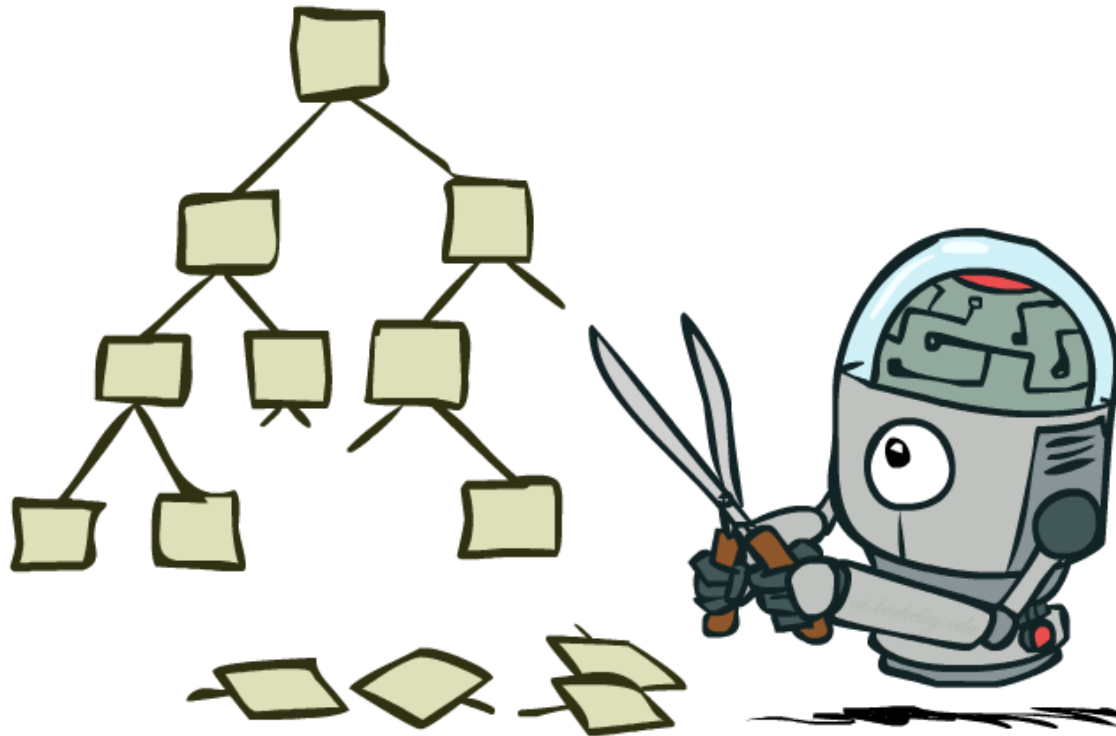




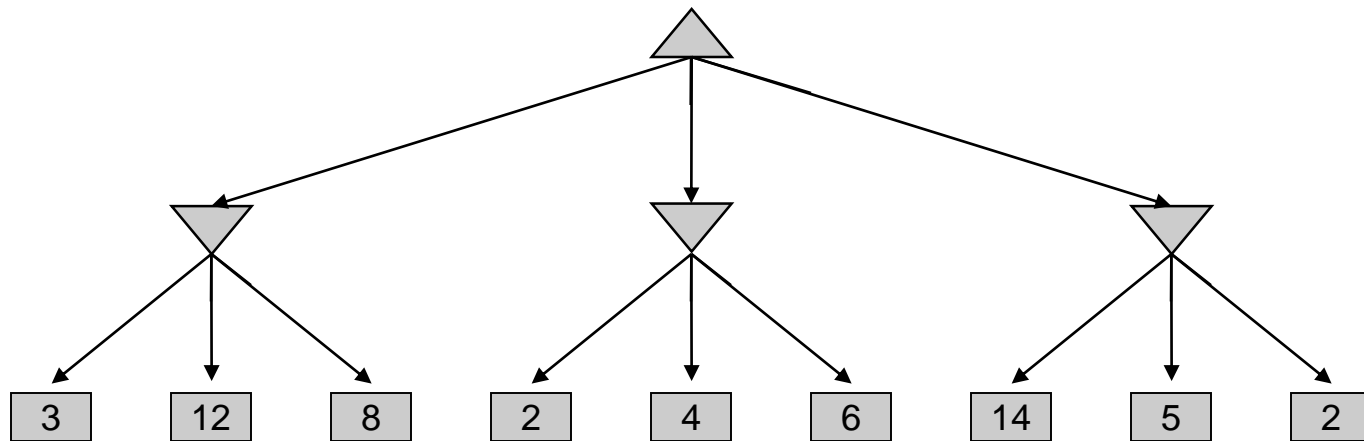
# Overcoming Resource Limits



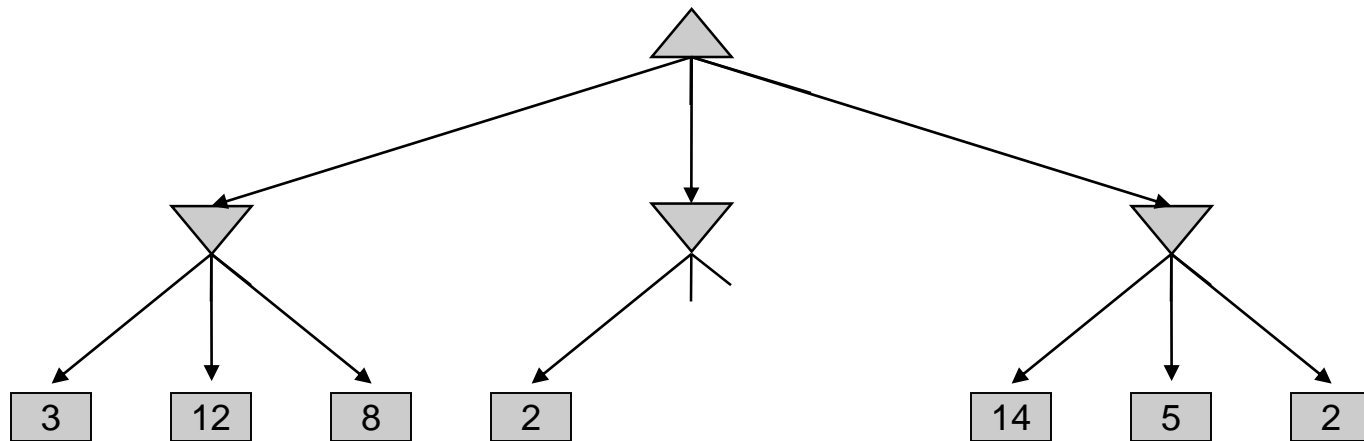
# Game Tree Pruning



# Minimax Example

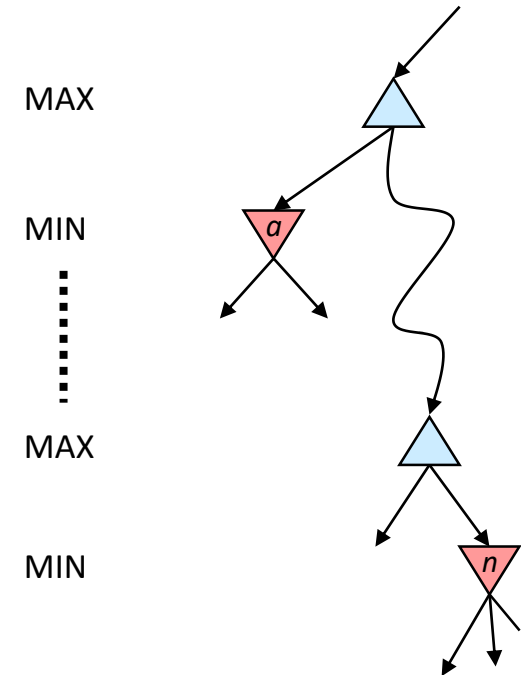


# Minimax Pruning



# Alpha-Beta Pruning

- General configuration (MIN version)
  - We're computing the MIN-VALUE at some node  $n$
  - We're looping over  $n$ 's children
  - $n$ 's estimate of the childrens' min is dropping
  - Who cares about  $n$ 's value? MAX
  - Let  $a$  be the best value that MAX can get at any choice point along the current path from the root
  - If  $n$  becomes worse than  $a$ , MAX will avoid it, so we can stop considering  $n$ 's other children (it's already bad enough that it won't be played)
  
- MAX version is symmetric



# Alpha-Beta Implementation

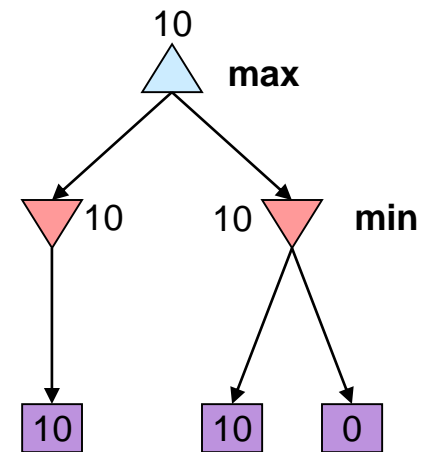
$\alpha$ : MAX's best option on path to root  
 $\beta$ : MIN's best option on path to root

```
def max-value(state,  $\alpha$ ,  $\beta$ ):  
    initialize  $v = -\infty$   
    for each successor of state:  
         $v = \max(v, \text{value}(\text{successor}, \alpha, \beta))$   
        if  $v \geq \beta$  return  $v$   
         $\alpha = \max(\alpha, v)$   
    return  $v$ 
```

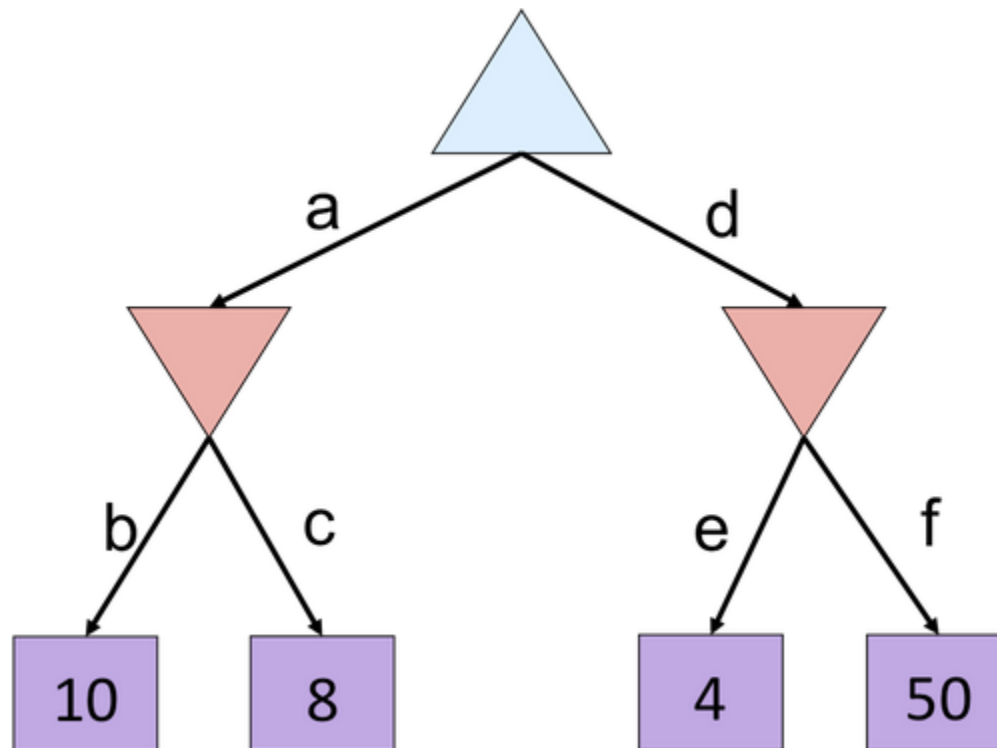
```
def min-value(state,  $\alpha$ ,  $\beta$ ):  
    initialize  $v = +\infty$   
    for each successor of state:  
         $v = \min(v, \text{value}(\text{successor}, \alpha, \beta))$   
        if  $v \leq \alpha$  return  $v$   
         $\beta = \min(\beta, v)$   
    return  $v$ 
```

# Alpha-Beta Pruning Properties

- This pruning has **no effect** on minimax value computed for the root!
- Values of intermediate nodes might be wrong
  - Important: children of the root may have the wrong value
  - So the most naïve version won't let you do action selection
- Good child ordering improves effectiveness of pruning
- With “perfect ordering”:
  - Time complexity drops to  $O(b^{m/2})$
  - Doubles solvable depth!
  - Full search of, e.g. chess, is still hopeless...
- This is a simple example of **metareasoning** (computing about what to compute)

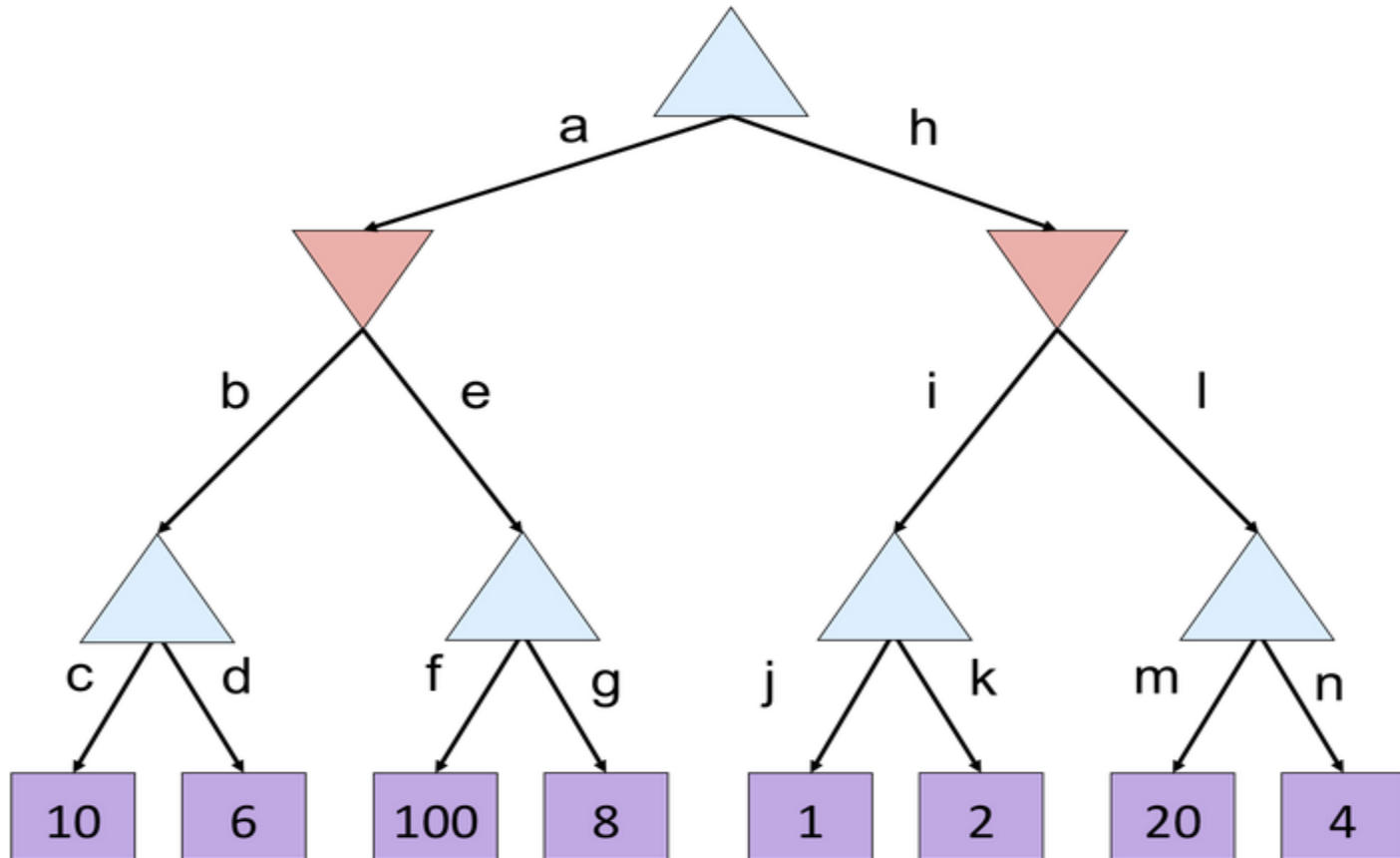


# Alpha-Beta Quiz

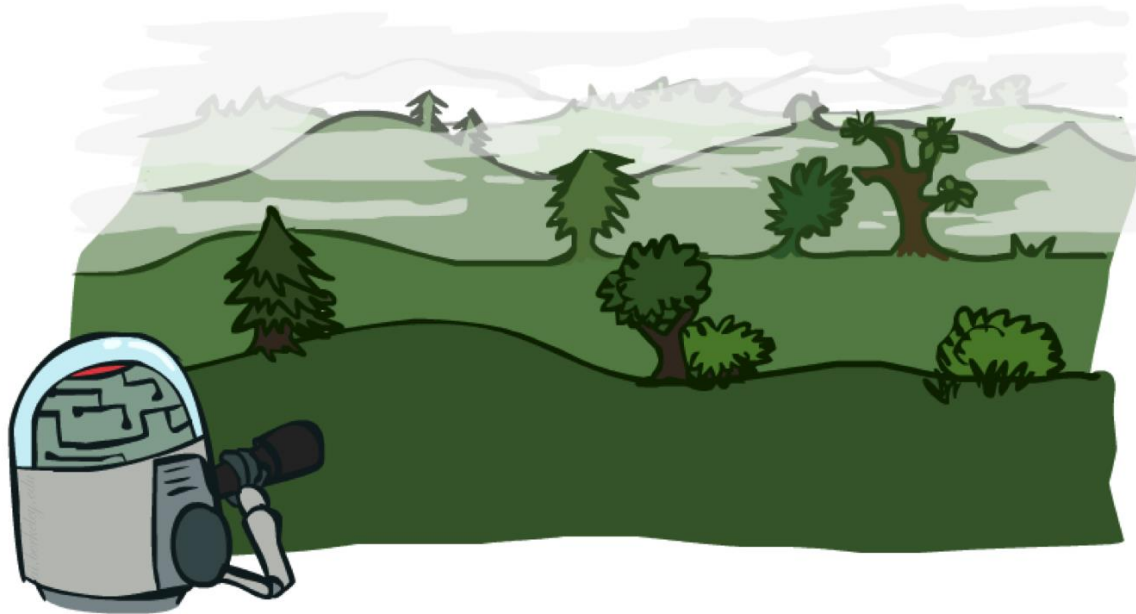




# Alpha-Beta Quiz 2

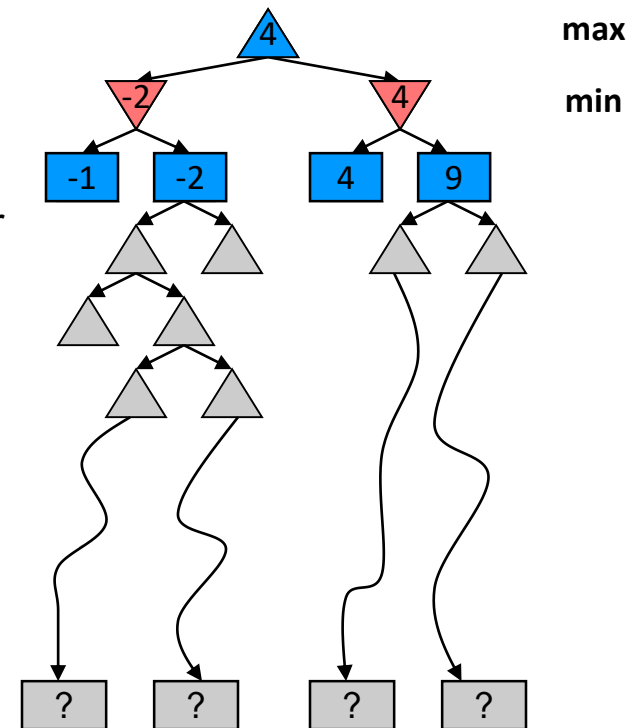


# Overcoming Resource Limits

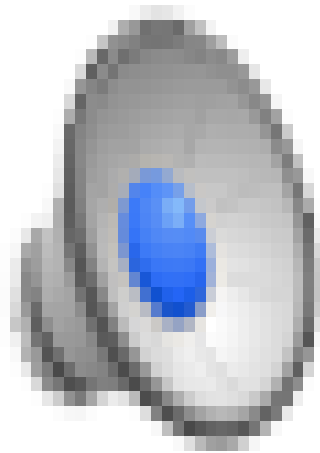


# Limiting Depth

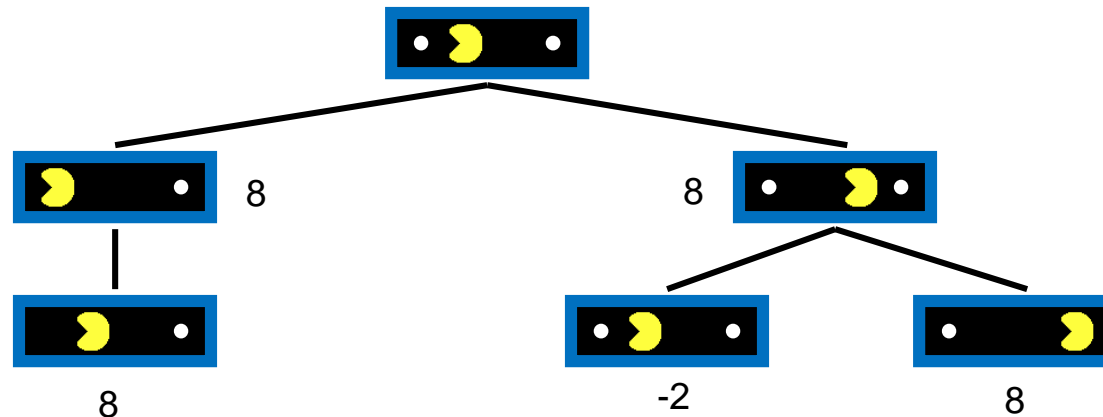
- Problem: In realistic games, cannot search to leaves!
- Solution: Depth-limited search
  - Instead, search only to a limited depth in the tree
  - Replace terminal utilities with an evaluation function for non-terminal positions
- Example:
  - Suppose we have 100 seconds, can explore 10K nodes / sec
  - So can check 1M nodes per move
  - $\alpha$ - $\beta$  reaches about depth 8 – decent chess program
- Guarantee of optimal play is gone
- More plies makes a BIG difference
- Use iterative deepening for an anytime algorithm



# Video of Demo Thrashing (d=2)

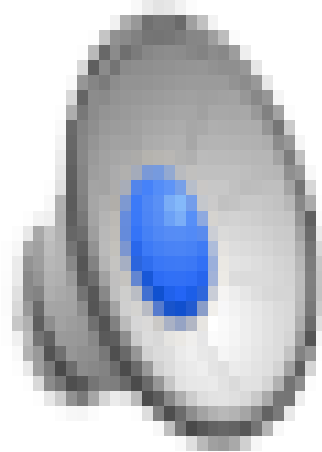


# Why Pacman Starves (d=2)

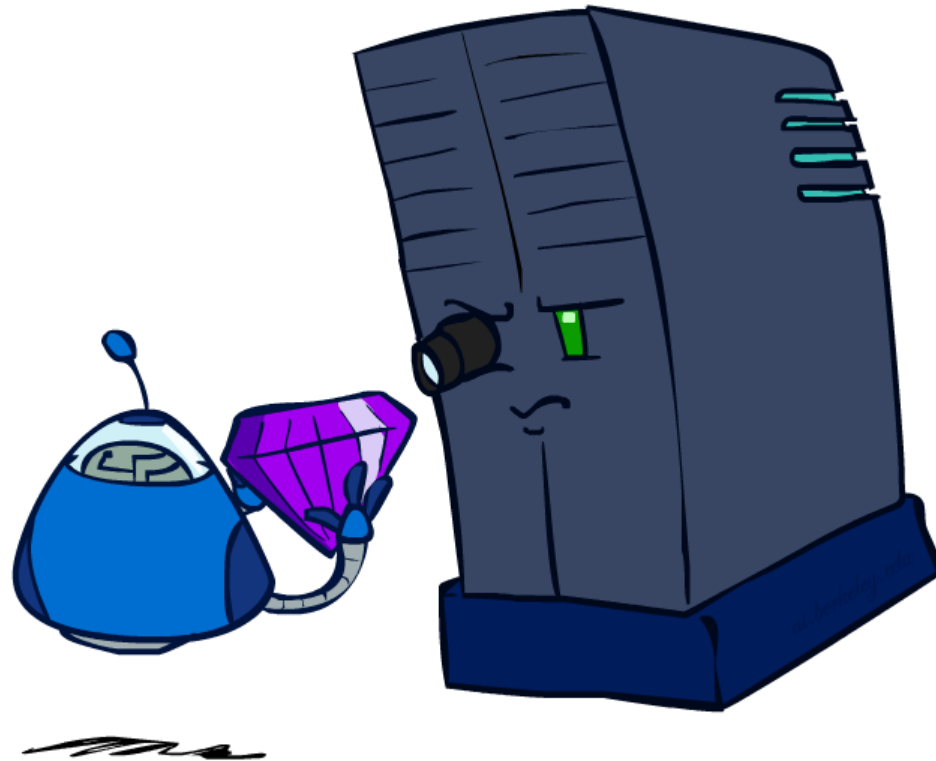


- A danger of replanning agents!
  - He knows his score will go up by eating the dot now (west, east)
  - He knows his score will go up just as much by eating the dot later (east, west)
  - There are no point-scoring opportunities after eating the dot (within the horizon, two here)
  - Therefore, waiting seems just as good as eating: he may go east, then back west in the next round of replanning!

# Video of Demo Thrashing -- Fixed ( $d=2$ )

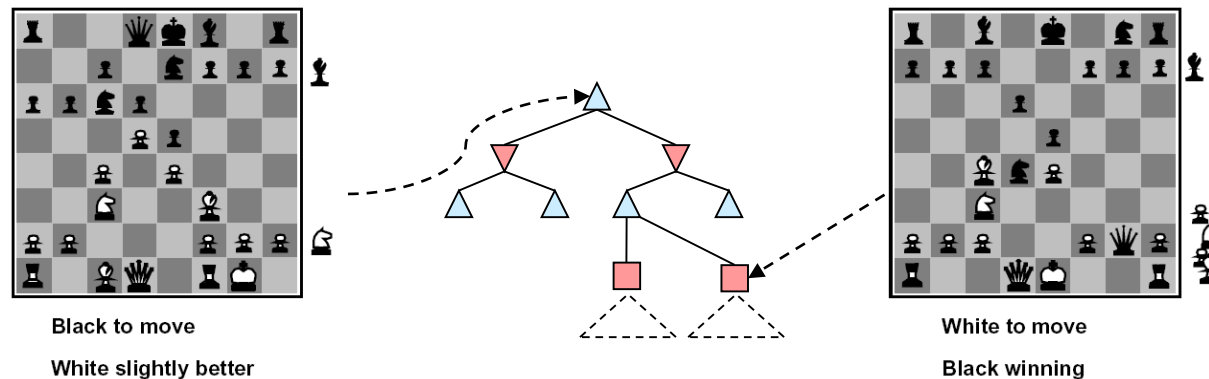


# Evaluation Functions



# Evaluation Functions

- Evaluation functions score non-terminals in depth-limited search



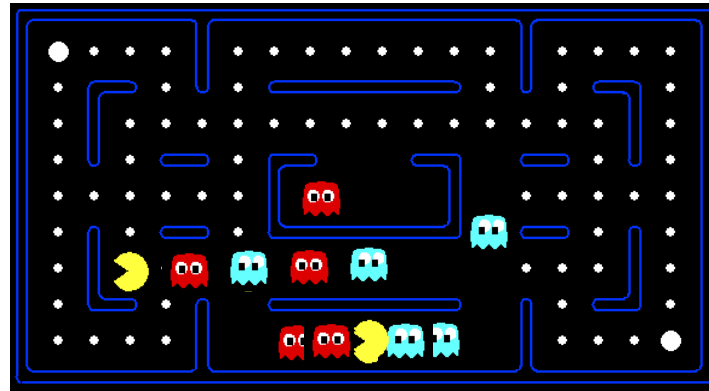
- Ideal function: returns the actual minimax value of the position
- In practice: typically weighted linear sum of features:

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

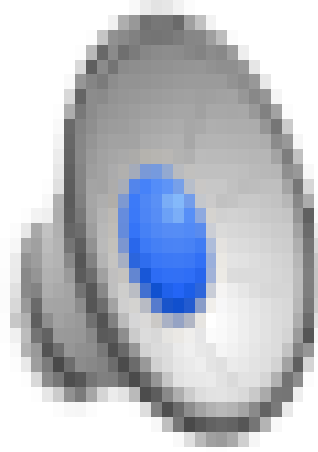
- e.g.  $f_1(s) = (\text{num white queens} - \text{num black queens})$ , etc.



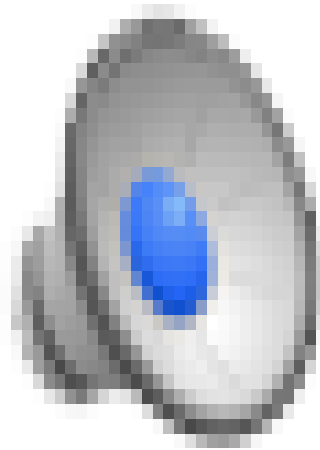
# Evaluation for Pacman



# Video of Demo Smart Ghosts (Coordination)

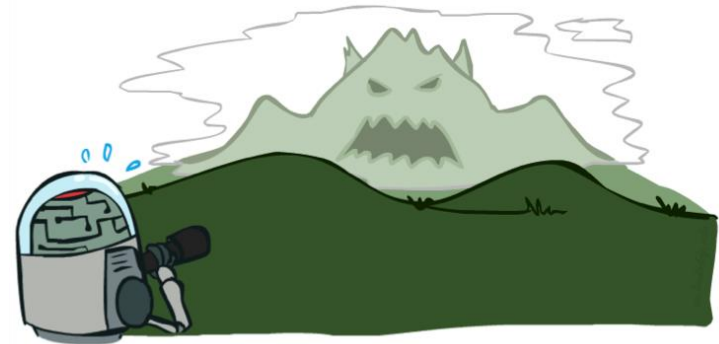


# Video of Demo Smart Ghosts (Coordination) – Zoomed In

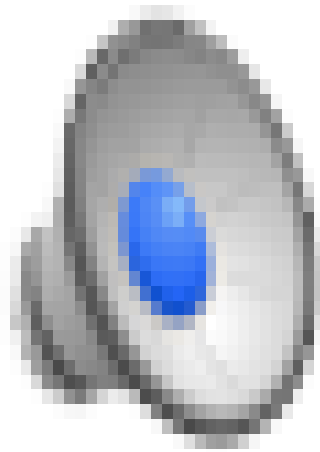


# Depth Matters

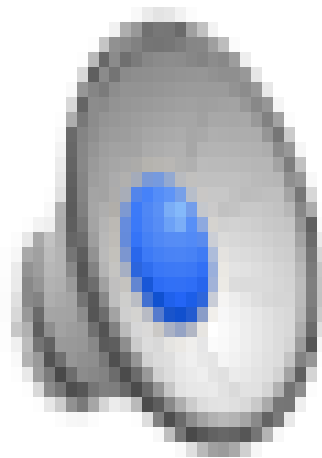
- Evaluation functions are always imperfect
- The deeper in the tree the evaluation function is buried, the less the quality of the evaluation function matters
- An important example of the tradeoff between complexity of features and complexity of computation



# Video of Demo Limited Depth (2)



# Video of Demo Limited Depth (10)



# Synergies between Evaluation Function and Alpha-Beta?

- Alpha-Beta: amount of pruning depends on expansion ordering
  - Evaluation function can provide guidance to expand most promising nodes first (which later makes it more likely there is already a good alternative on the path to the root)
    - (somewhat similar to role of A\* heuristic, CSPs filtering)
- Alpha-Beta: (similar for roles of min-max swapped)
  - Value at a min-node will only keep going down
  - Once value of min-node lower than better option for max along path to root, can prune
  - Hence: IF evaluation function provides upper-bound on value at min-node, and upper-bound already lower than better option for max along path to root  
THEN can prune

# What we did today

- Introduced multi-agent games
  - Come up in many places in AI
  - Different types of games (focused on *zero-sum* today)
- Reviewed single-agent search trees (from previous lectures)
  - *Value* of a state is an important concept that will come up in the future
- Modified search trees to include opponent actions
  - Assumed opponent acts in a way that is worst for you
  - Called this *Minimax Search*
- Looked at efficiency (not good) and suggested two ways to improve it
  - Alpha-Beta pruning (exact, some gains but not huge)
  - Limiting tree depth (big gains, but not exact and needs heuristics)