AlphaGO

- Tic-Tac-Toe — PhD project @ Cambridge 1952
- Chess — Deep Blue 1997
- Jeopardy — Watson 2011
- Atari Games from raw pixels (Google) — 2014
- AlphaGo — Deepmind — 2016
  - GO game search space?
    - more than a GooGol larger than Chess!!
      - greater than #atoms in universe

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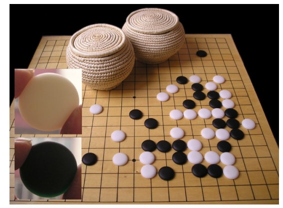
Search Space

- 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,0 possible positions



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AlphaGo

- Monte Carlo Tree Search
  - **Policy Network** — suggest moves
  - **Value Network** — estimates eventual winner
- Deep Neural Networks
  - 12 layers (supervised and reinforcement learning)
  - millions of connections
  - trained with 30 million of moves (human experts)
  - predicted 57%
  - networks by itself defeat state-of-the-art programs (based on trees)

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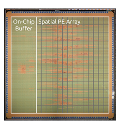
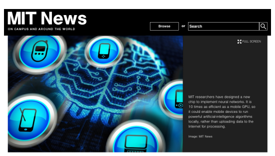
Deep Learning Chip

- "On our chip we bring the data as close as possible to the processing units, and move the data as little as possible,"
- "Whereas many of the cores in a GPU share a single, large memory bank, each of the Eyeriss cores has its own memory"



Eyeriss has 168 processing elements (PE), each with its own memory.



Energy-friendly chip can perform powerful artificial-intelligence tasks

Advance could enable mobile devices to implement "neural networks" modeled on the human brain.

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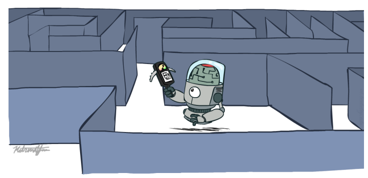
CS 188: Artificial Intelligence

A* Analysis



Instructor: Marco Alvarez

University of Rhode Island

[These slides were created by Dan Klein and Pieter Abbeel for CS188 Intro to AI at UC Berkeley (ai.berkeley.edu)]

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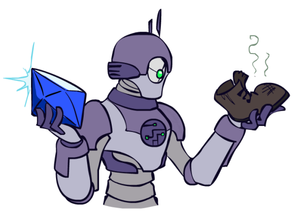
Today

- Informed Search
  - A* Search (Analysis)
- Graph Search



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A* Search

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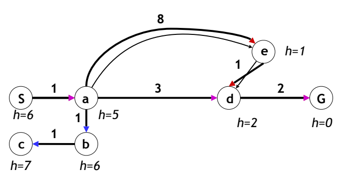
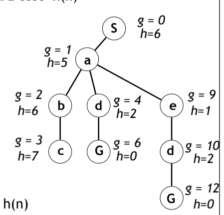
Combining UCS and Greedy

- Uniform-cost orders by path cost, or *backward cost* g(n)
- Greedy orders by goal proximity, or *forward cost* h(n)





- A* Search orders by the sum: f(n) = g(n) + h(n)

Example: Teg Grenager

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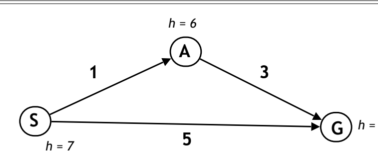
Is A* Optimal?



- What went wrong?
- Actual bad goal cost < estimated good goal cost
- We need estimates to be less than actual costs!

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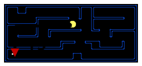
Admissible Heuristics

- A heuristic h is *admissible* (optimistic) if:

$$0 \leq h(n) \leq h^*(n)$$

where $h^*(n)$ is the true cost to a nearest goal

- Example:



- Coming up with admissible heuristics is most of what's involved in using A* in practice.

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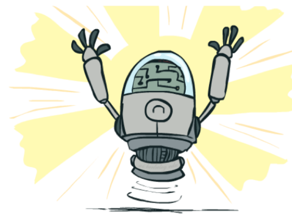
Optimality of A* Tree Search



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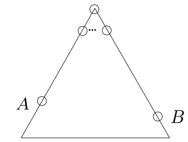
Optimality of A* Tree Search

Assume:
- A is an optimal goal node
- B is a suboptimal goal node
- h is admissible

Claim:
- A will exit the fringe before B



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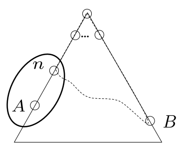
Optimality of A* Tree Search: Blocking

Proof:
- Imagine B is on the fringe
- Some ancestor n of A is on the fringe, too (maybe A!)
- Claim: n will be expanded before B
  1. f(n) is less or equal to f(A)



$f(n) = g(n) + h(n)$	Definition of f-cost
$f(n) \leq g(A)$	Admissibility of h
$g(A) = f(A)$	h = 0 at a goal

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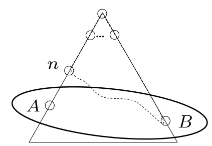
Optimality of A* Tree Search: Blocking

Proof:
- Imagine B is on the fringe
- Some ancestor n of A is on the fringe, too (maybe A!)
- Claim: n will be expanded before B
  1. f(n) is less or equal to f(A)
  2. f(A) is less than f(B)



$g(A) < g(B)$	B is suboptimal
$f(A) < f(B)$	h = 0 at a goal

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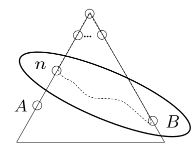
Optimality of A* Tree Search: Blocking

Proof:
- Imagine B is on the fringe
- Some ancestor n of A is on the fringe, too (maybe A!)
- Claim: n will be expanded before B
  1. f(n) is less or equal to f(A)
  2. f(A) is less than f(B)
  3. n expands before B
- All ancestors of A expand before B
- A expands before B
- A* search is optimal



$$f(n) \leq f(A) < f(B)$$

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Semi-Lattice of Heuristics

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Trivial Heuristics, Dominance

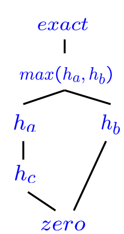
- Dominance: $h_a \geq h_c$ if

$$\forall n : h_a(n) \geq h_c(n)$$

- Heuristics form a semi-lattice:
  - Max of admissible heuristics is admissible

$$h(n) = max(h_a(n), h_b(n))$$

- Trivial heuristics
  - Bottom of lattice is the zero heuristic (what does this give us?)
  - Top of lattice is the exact heuristic



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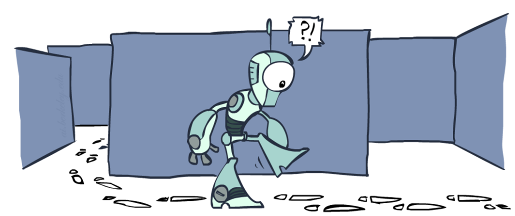
Graph Search



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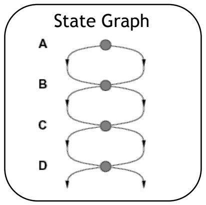
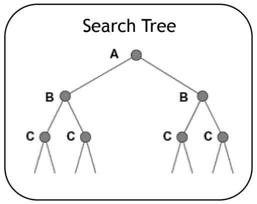
Tree Search: Extra Work!

- Failure to detect repeated states can cause exponentially more work.





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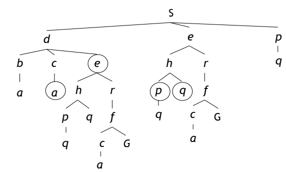
Graph Search

- In BFS, for example, we shouldn't bother expanding the circled nodes (why?)



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Graph Search

states (Graph)
nodes (Tree)

- Idea: never expand a state twice
- How to implement:
  - Tree search + set of expanded **states** ("closed set")
  - Expand the search tree **node**-by-**node**, but…
  - Before expanding a **node**, check to make sure its **state** has never been expanded before
  - If not new, skip it, if new add to closed set
- Important: store the closed set as a set, not a list
- Can graph search wreck completeness? Why/why not?
- How about optimality?

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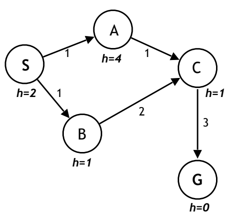
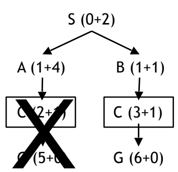
A* Graph Search Gone Wrong?

State space graph



Search tree



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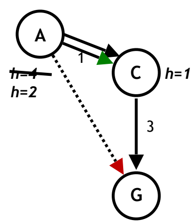
Consistency of Heuristics



- Main idea: estimated heuristic costs ≤ actual costs
  - Admissibility: heuristic cost ≤ actual cost to goal

    h(A) ≤ actual cost from A to G
  - Consistency: heuristic "arc" cost ≤ actual cost for each arc

    h(A) – h(C) ≤ cost(A to C)
- Consequences of consistency:
  - The f value along a path never decreases

    h(A) ≤ cost(A to C) + h(C)
  - A* graph search is optimal

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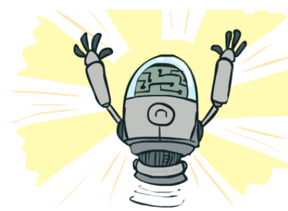
Optimality of A* Graph Search



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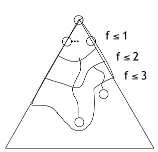
Optimality of A* Graph Search

- Sketch: consider what A* does with a consistent heuristic:
  - Fact 1: In tree search, A* expands nodes in increasing total f value (f-contours)
  - Fact 2: For every state s, nodes that reach s optimally are expanded before nodes that reach s suboptimally
  - Result: A* graph search is optimal



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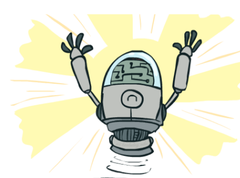
Optimality

- Tree search:
  - A* is optimal if heuristic is admissible
  - UCS is a special case (h = 0)
- Graph search:
  - A* optimal if heuristic is consistent
  - UCS optimal (h = 0 is consistent)
- Consistency implies admissibility
- In general, most natural admissible heuristics tend to be consistent, especially if from relaxed problems



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A*: Summary

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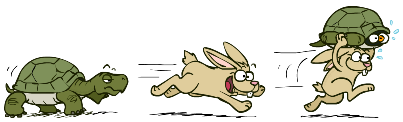
A*: Summary

- A* uses both backward costs and (estimates of) forward costs
- A* is optimal with admissible / consistent heuristics
- Heuristic design is key: often use relaxed problems



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Tree Search Pseudo-Code

```
function TREE-SEARCH(problem, fringe) return a solution, or failure
    fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)
    loop do
        if fringe is empty then return failure
        node ← REMOVE-FRONT(fringe)
        if GOAL-TEST(problem, STATE[node]) then return node
        for child-node in EXPAND(STATE[node], problem) do
            fringe ← INSERT(child-node, fringe)
        end
    end
```

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Graph Search Pseudo-Code

```
function GRAPH-SEARCH(problem, fringe) return a solution, or failure
    closed ← an empty set
    fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)
    loop do
        if fringe is empty then return failure
        node ← REMOVE-FRONT(fringe)
        if GOAL-TEST(problem, STATE[node]) then return node
        if STATE[node] is not in closed then
            add STATE[node] to closed
            for child-node in EXPAND(STATE[node], problem) do
                fringe ← INSERT(child-node, fringe)
            end
    end
```

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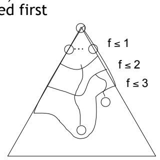
Optimality of A* Graph Search

- Consider what A* does:
  - Expands nodes in increasing total f value (f-contours)
    Reminder: f(n) = g(n) + h(n) = cost to n + heuristic
  - Proof idea: the optimal goal(s) have the lowest f value, so it must get expanded first

There's a problem with this argument. What are we assuming is true?



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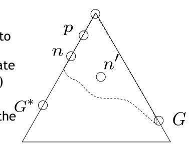
Optimality of A* Graph Search

Proof:

- New possible problem: some *n* on path to G* isn't in queue when we need it, because some worse *n'* for the same state dequeued and expanded first (disaster!)
- Take the highest such *n* in tree
- Let *p* be the ancestor of *n* that was on the queue when *n'* was popped
- *f(p)* < *f(n)* because of consistency
- *f(n)* < *f(n')* because *n'* is suboptimal
- *p* would have been expanded before *n'*
- Contradiction!



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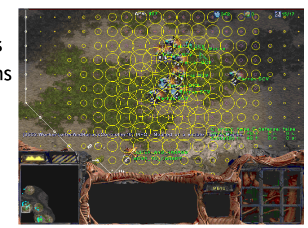
A* Applications

- Video games
- Pathing / routing problems
- Resource planning problems
- Robot motion planning
- Language analysis
- Machine translation
- Speech recognition
- …



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