COMP 4752
Computational Intelligence

Lecture 9

Heuristic Search Improvements

Depth-First Branch and Bound

Starcraft AI

A* Search – Memory

- A* search stores nodes in the search tree, so the memory required may far exceed the number of states in the problem
- Worst-Case Memory Required: $O(b^m)$
  - Heuristic may guide us to bad parts of tree
- A* not used in practice for large problems
- How can we reduce memory usage?

Iterative Deepening A* (IDA*)

- Iterative deepening used in DFS to ensure the search was complete
- Instead of using a depth limit like DFS, IDA* uses an increasing f-value cutoff
- But memory / CPU usage still high due to storing and sorting the entire open list

Recursive Best-First Search (RBFS)

- Recall DFS can be implemented using the Tree-Search algorithm with a fringe stack
- However, a better implementation of DFS was using a recursive function
- Similarly, we can implement Best-First Search algorithms as recursive functions
- Mimics the operations of standard BeFS, but only uses linear space

Recursive Best-First Search (RBFS)

- Keeps track of the f-value of the best alternative path from any ancestor of the current node
- If the current node exceeds this limit, recursion unwinds back to the alternative path
- As recursion unwinds, RBFS replaces the f value of each node along the path with the best f-value of its children
- RBGS retains the f-value of the best leaf in the forgotten subtree and can decide whether it should reexpand that subtree at a later time

Recursive Best-First Search (RBFS)

```
1.  Function RBFS(problem, node, f_limit)
2.      if (node.state == goal) return node
3.      successors = Expand(node, problem)
4.      if (successors.empty()) return (failure, infinity)
5.      for s in successors:
6.          s.f = max(s.g + h(s), node.f)
7.      repeat:
8.          best_node = min_f_node(successors)
9.          if (best_node.f > f_limit) return (falure, best.f)
10.         alt_node = second_lowest_f(successors)
11.         result, best_node.f = RBFS(problem, best_node, min(f_limit, alt_node))
12.         if (result != failure) return result
```

RBFS Performance

- Like A*, RBFS is optimal if the heuristic function h(n) is admissible
- Memory usage is linear in search depth O(d)
- Time complexity is difficult to analyze
  - Accuracy of heuristics?
  - How often does the best path change?

Memory-Bounded A*

- Simple Memory-Bounded A* (SMA*)
- Use all available system memory
- When all memory used and we need to add a node, erase the highest f-value node
- SMA* then backs up the value of the forgotten node to its parent
- The ancestor of a forgotten subtree knows the quality of the best path in that subtree
- In case of ties, SMA* selects the newest node generated, and deletes the oldest node generated
- SMA* is complete/optimal only if depth of shallowest goal < memory

Branch and Bound

Branch & Bound Algorithms

- “Any-time” search algorithm
  - Will continue to find increasingly better solutions until the you stop the algorithm
  - If run to completion, will find optimal solution
- Choose an initial search cutoff bound and search all solutions up to that bound, when a solution is found, update the bound to the cost of that solution

Depth-First Branch and Bound (DFBB)

```
best_path = []
bound = infinity
Function DFBB(problem, node, bound)
        if (node.state == goal)
            best_path = reconstruct_path(node)
            bound = path_cost(best_path)
        children = Expand(node, problem)
        sort(children, h())                          # optional move-ordering
        for child in Expand(node, problem):
            if (child.g + h(child) > bound) continue   # h must be admissible
            DFBB(problem, child, bound)
```

DFBB Example: Starcraft

Real-Time Strategy

- War-like Simulation
- Single / Multiplayer Games

- Most RTS Games:
  - Gather Resources
  - Build Town / Army
  - Combat With Enemies

Properties of RTS

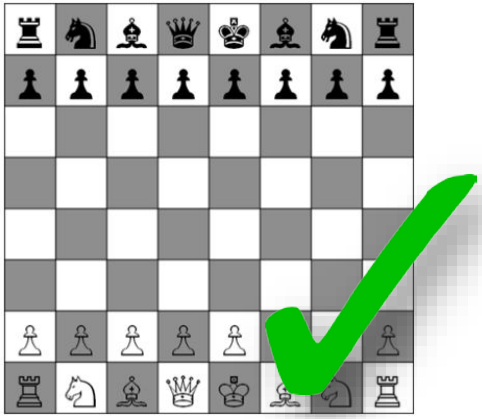
- Real-Time
- Simultaneous Move
- Non-Deterministic
- Imperfect Information
- Multi-Unit Control
- Unknown Game Engine
- Action / State Space

Benefits of RTS AI

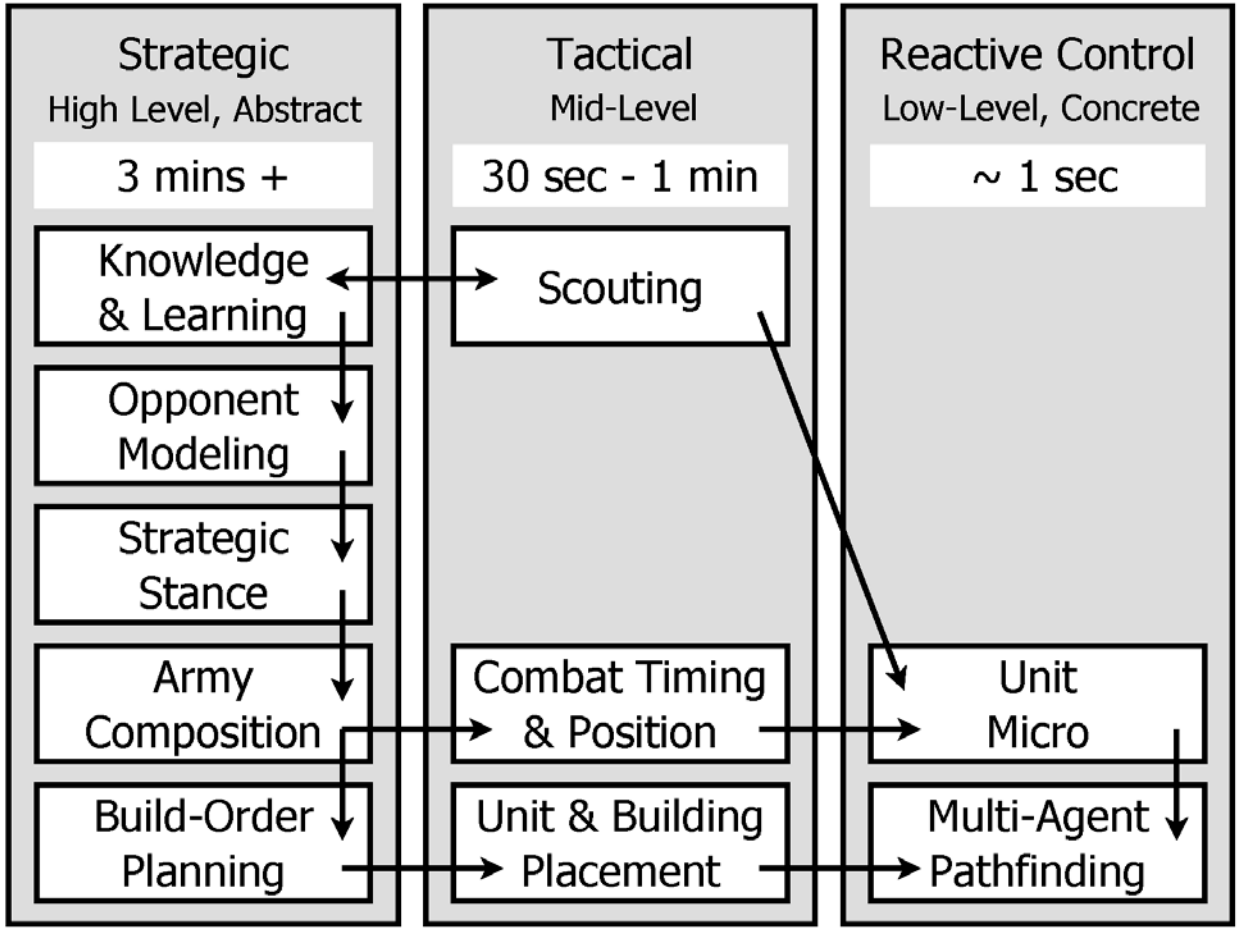
- Better In-Game AI
  - More intelligent NPCs
  - Better single player
- Create Offline Tools
  - Game balancing
  - Reduce human testing
- Apply to any game

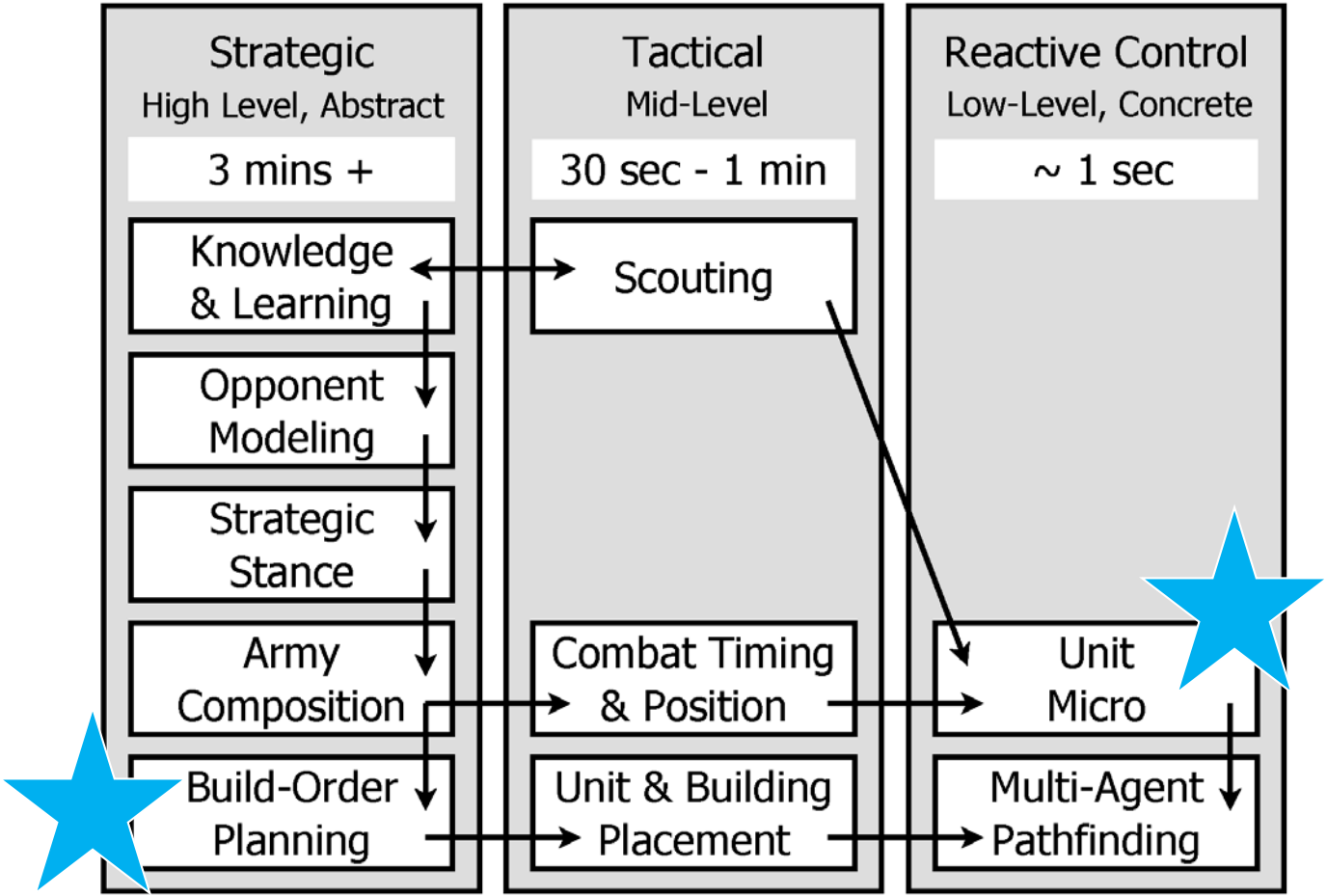
eSports

Human vs. Machine



StarCraft (Huge)


Strategic
High Level, Abstract
3 mins +
Tactical
Mid-Level
30 sec - 1 min
Reactive Control
Low-Level, Concrete
~ 1 sec
Knowledge & Learning
Scouting
Opponent Modeling
Strategic Stance
Army Composition
Combat Timing & Position
Unit Micro
Build-Order Planning
Unit & Building Placement
Multi-Agent Pathfinding


Strategic
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30 sec - 1 min
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Reactive Control
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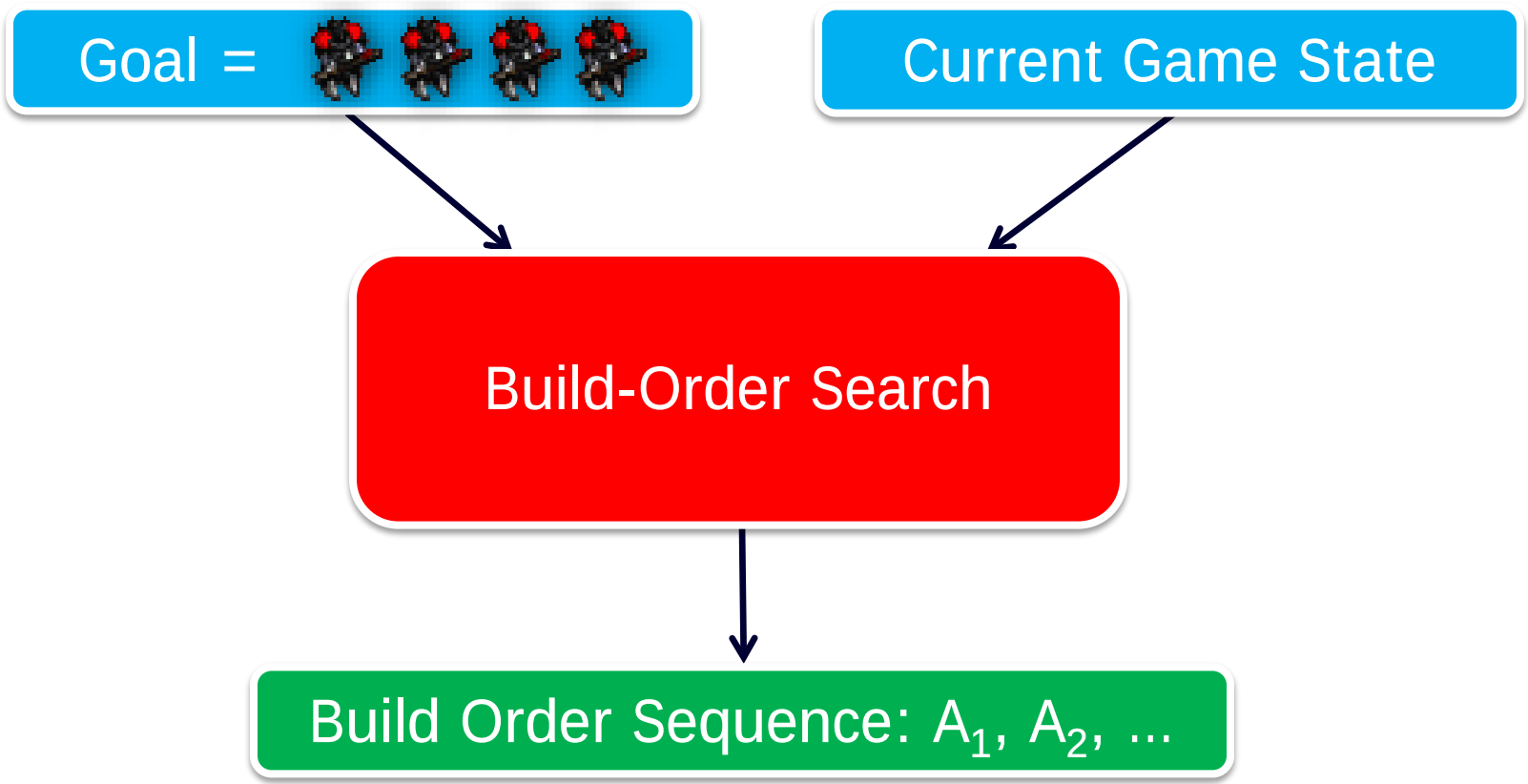
~ 1 sec
Unit Micro
Multi-Agent Pathfinding

Build-Order Planning and Optimization

What is a Build-Order?

- Sequence of economic actions
- List of buildings / units to build in order
- Players memorize ‘opening books’


Goal =
Current Game State
Build-Order Search
Build Order Sequence: A_1, A_2, ...

Algorithm - DFBB

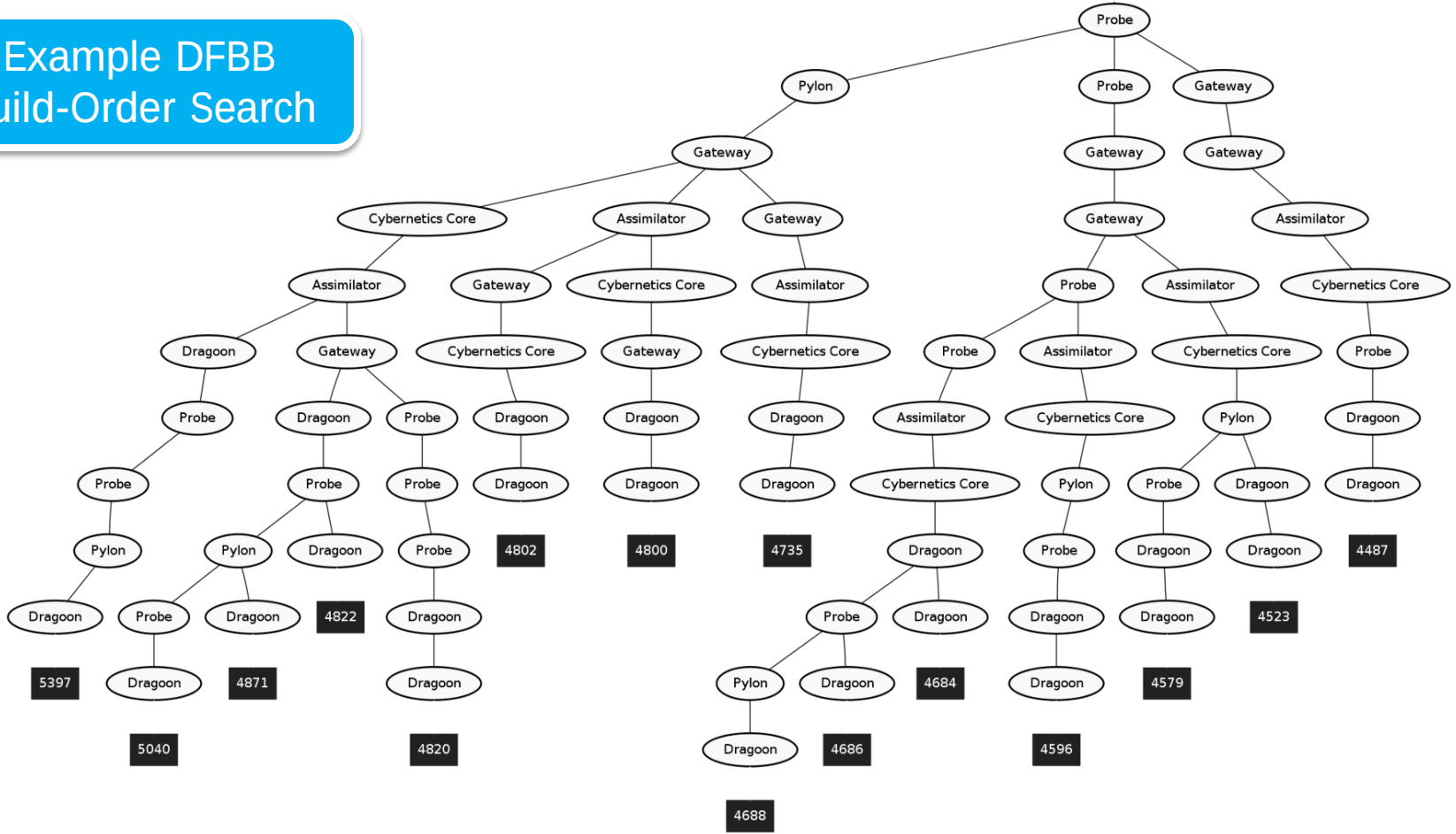
- Depth-First Branch and Bound
- Optimize: Build-Order Makespan

Algorithm - DFBB

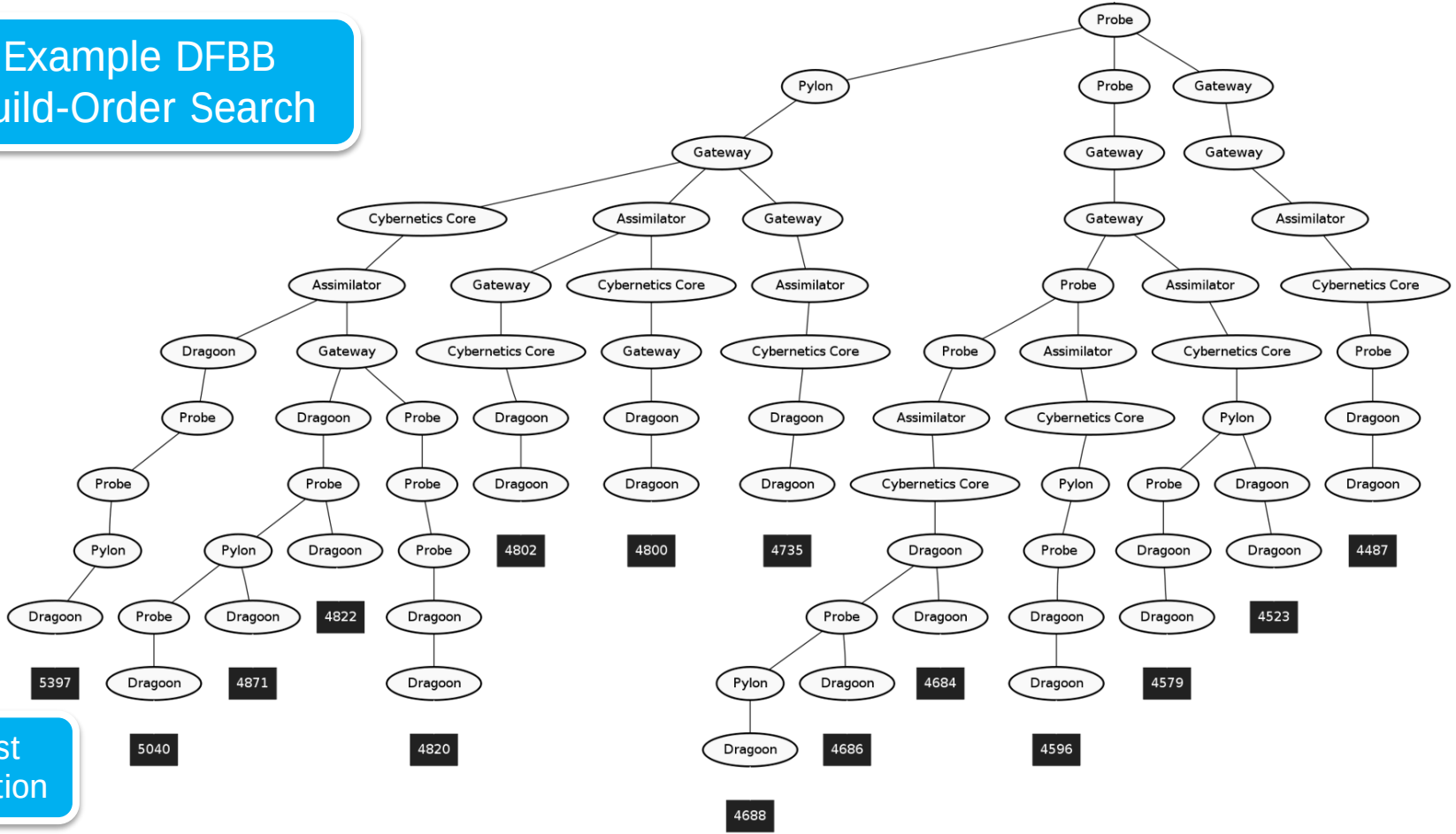
- Depth-First Branch and Bound
- Optimize: Build-Order Makespan

- Low Memory Usage
- Any-Time
- Save / Load Search
- Upper + Lower Bound Heuristics

Example DFBB Build-Order Search

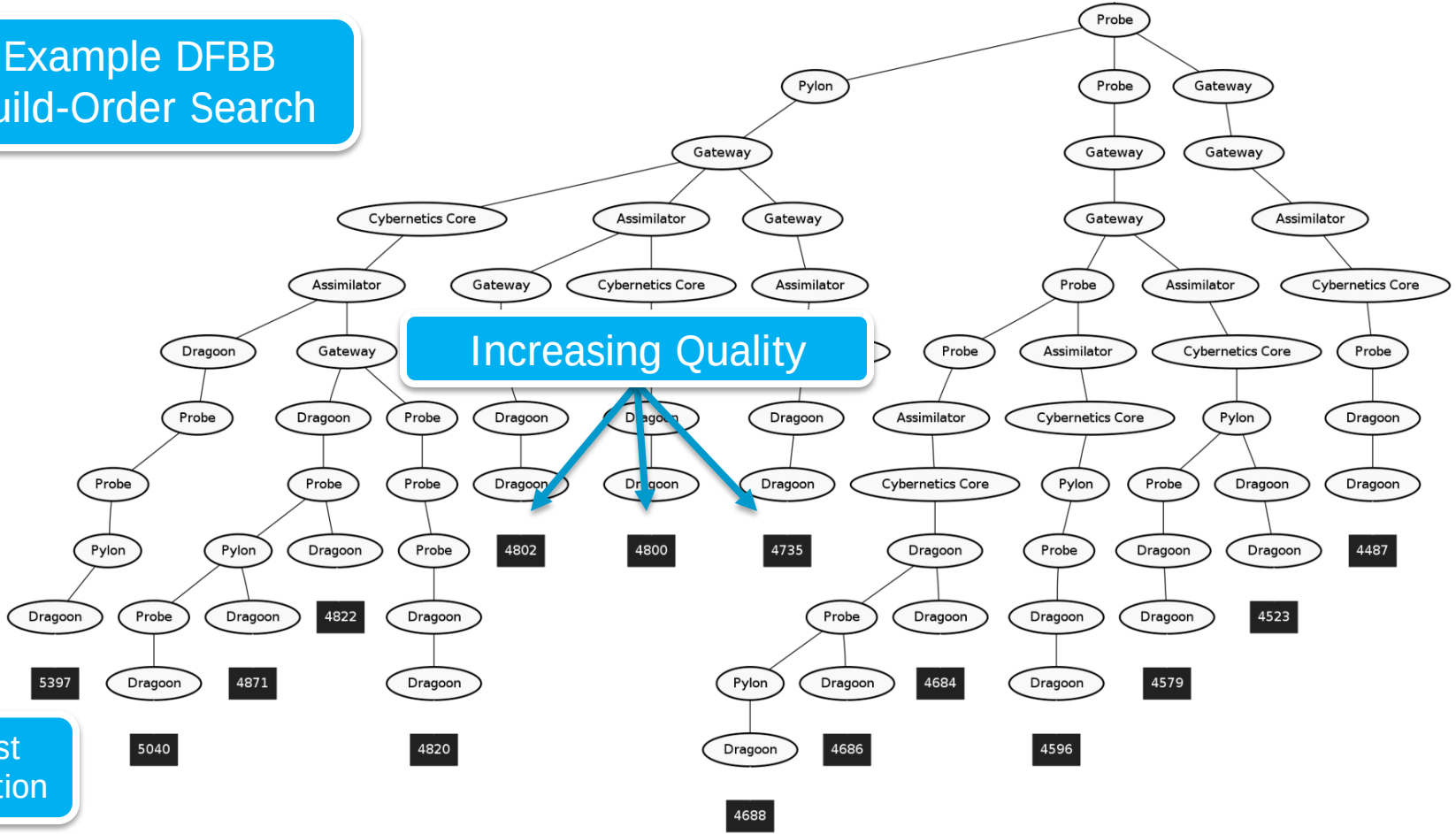


Example DFBB Build-Order Search

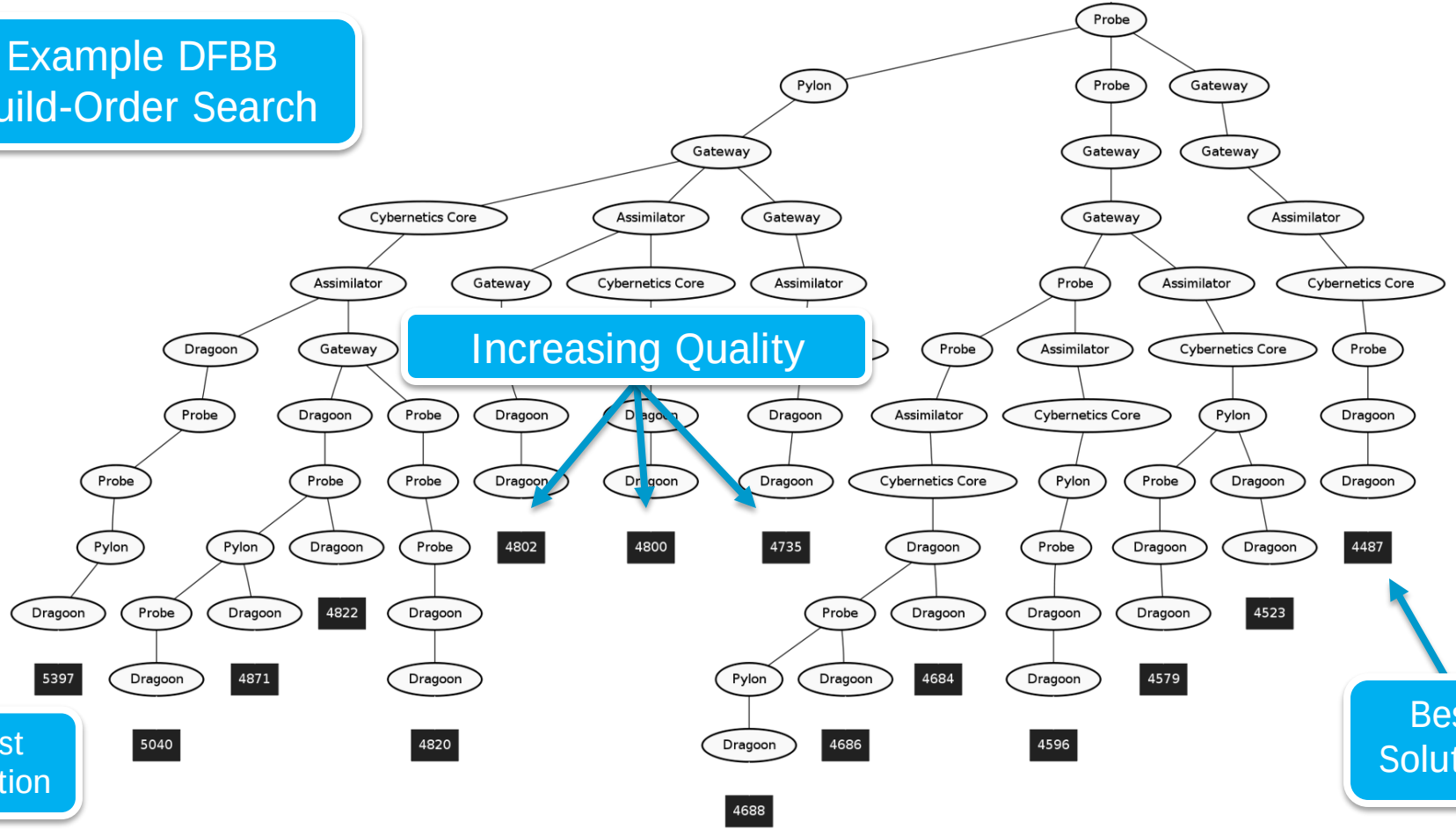


First Solution

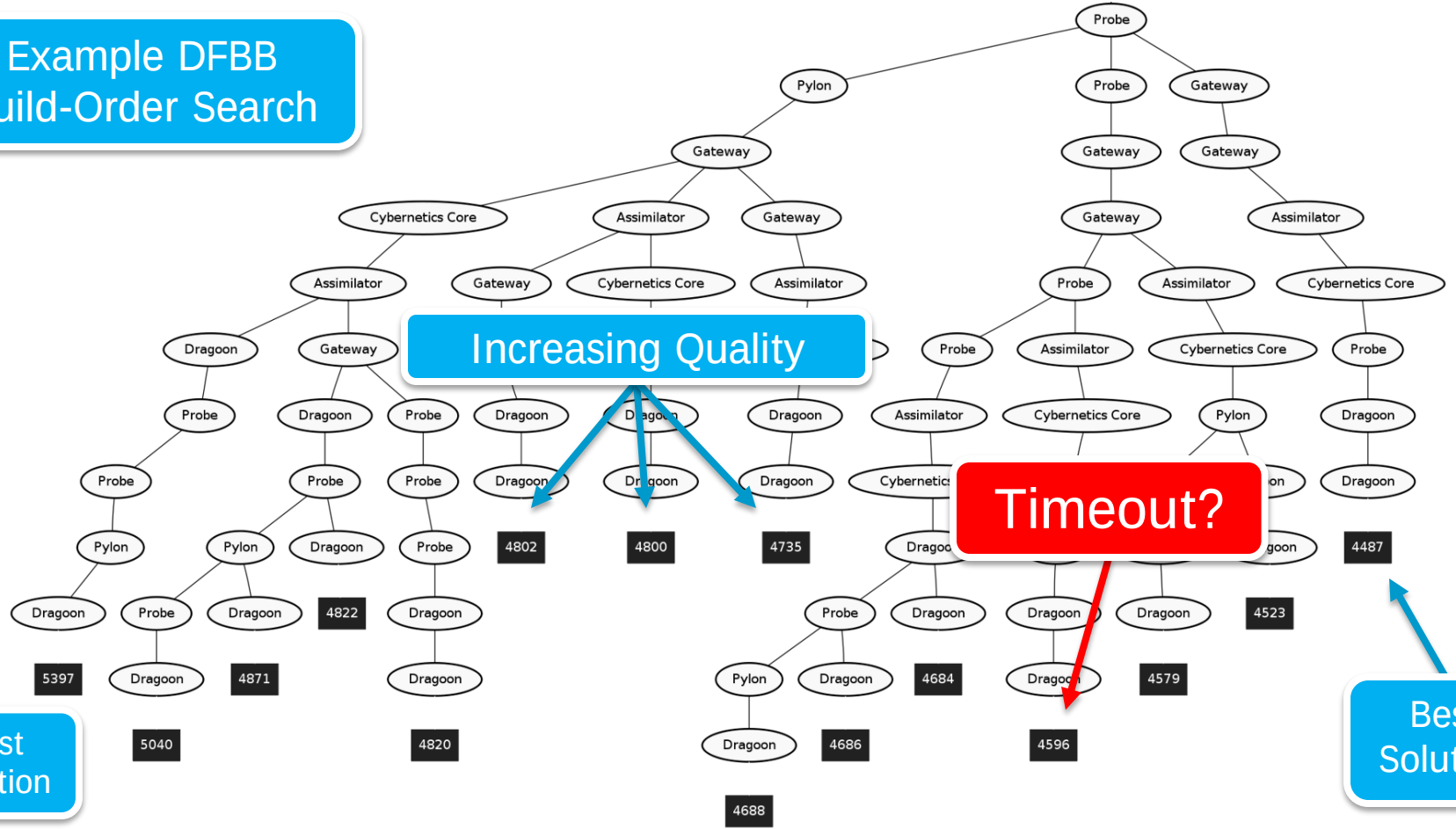
Example DFBB Build-Order Search



Example DFBB Build-Order Search



Example DFBB Build-Order Search



Pro Human Results

- Extract Pro Build-Orders
- Re-plan with BOSS
- Compare to original

- Results:
  - 100% of build orders solved
  - Faster than humans
  - Solve Time: 4% of makespan

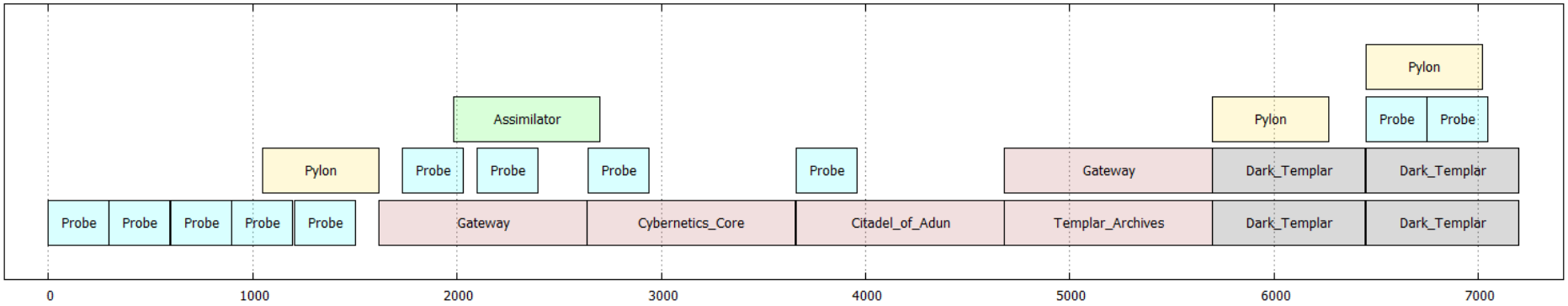
Build-Order Heuristics

- Resource Gathering Bound
- Landmark Heuristic

- Macro Actions
  - Repeat actions common in pro build orders

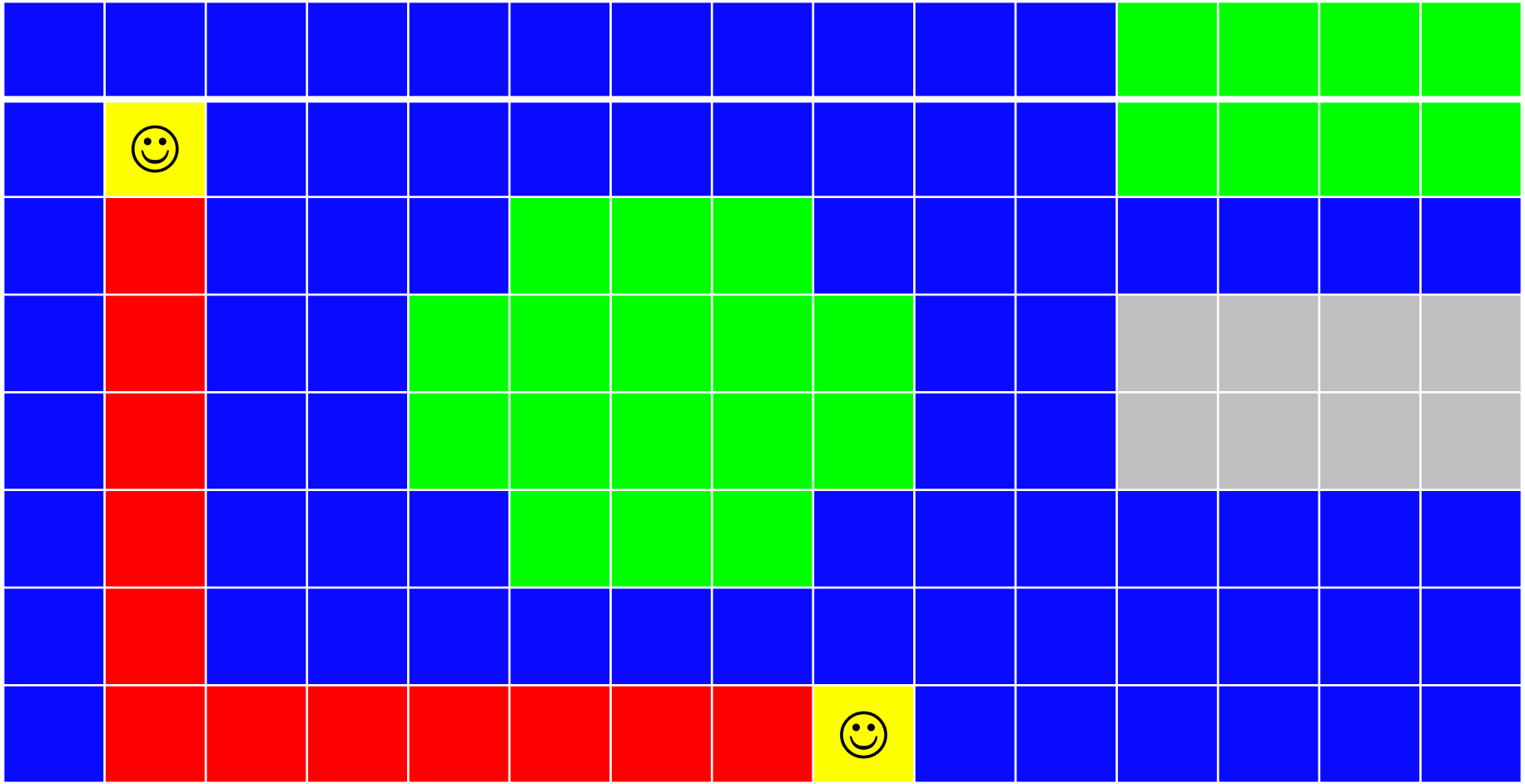
Landmark Heuristic

- How long do we need to build the sequential prerequisites of an action



Macro Actions

- Some problems have common sequences of actions that appear in optimal paths
- These commonly repeated action sequences are called “macro actions”
- Adding macro actions to the search can sometimes help us “shortcut” to better nodes further down the optimal path

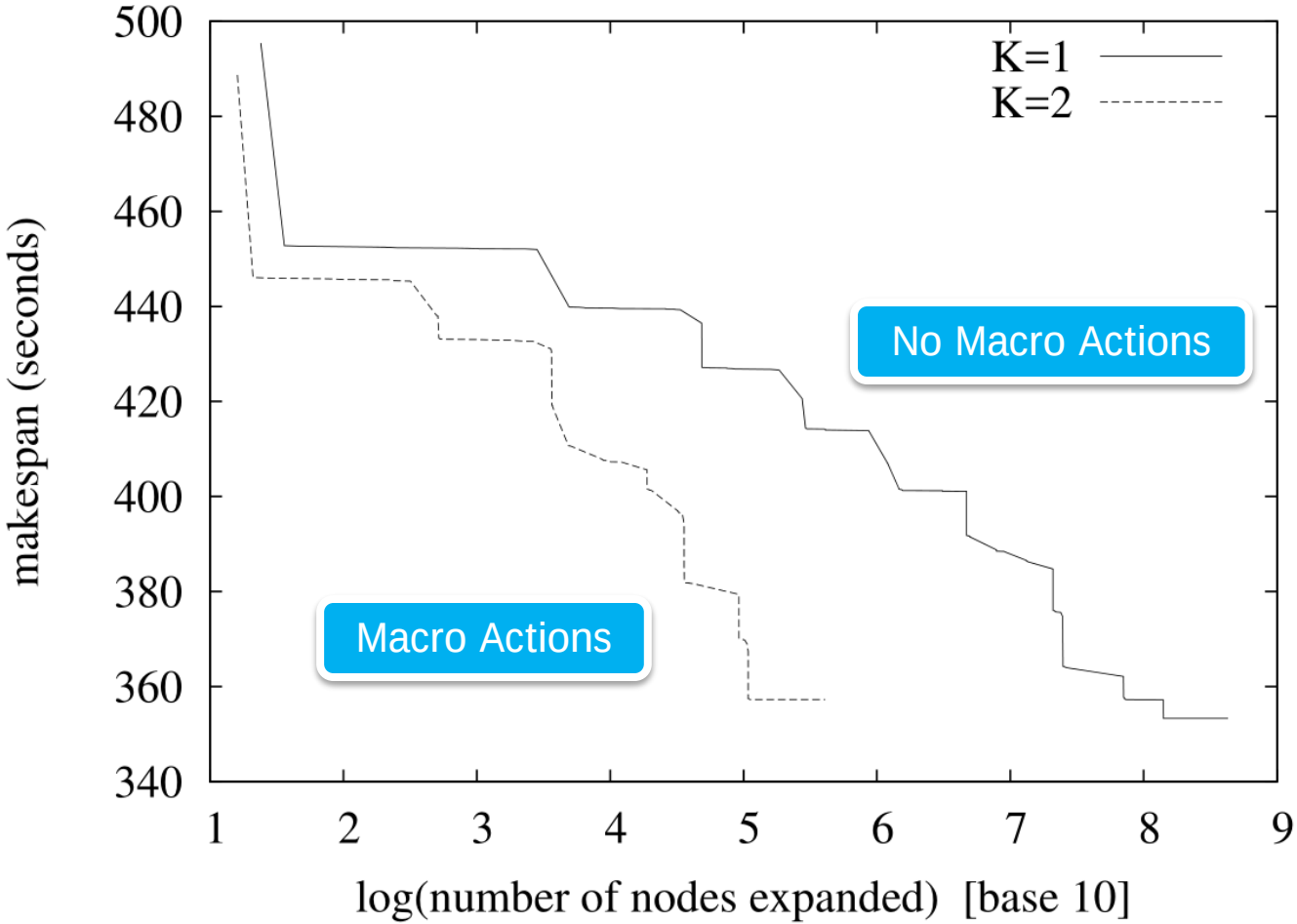


Macro Actions

- Macro actions are built of atomic actions
- They have cost equal to the sum of the actions contained within them
- Example: > > ^
  - Built From: Right Right Up
  - Cost: 100 + 100 + 141 = 341

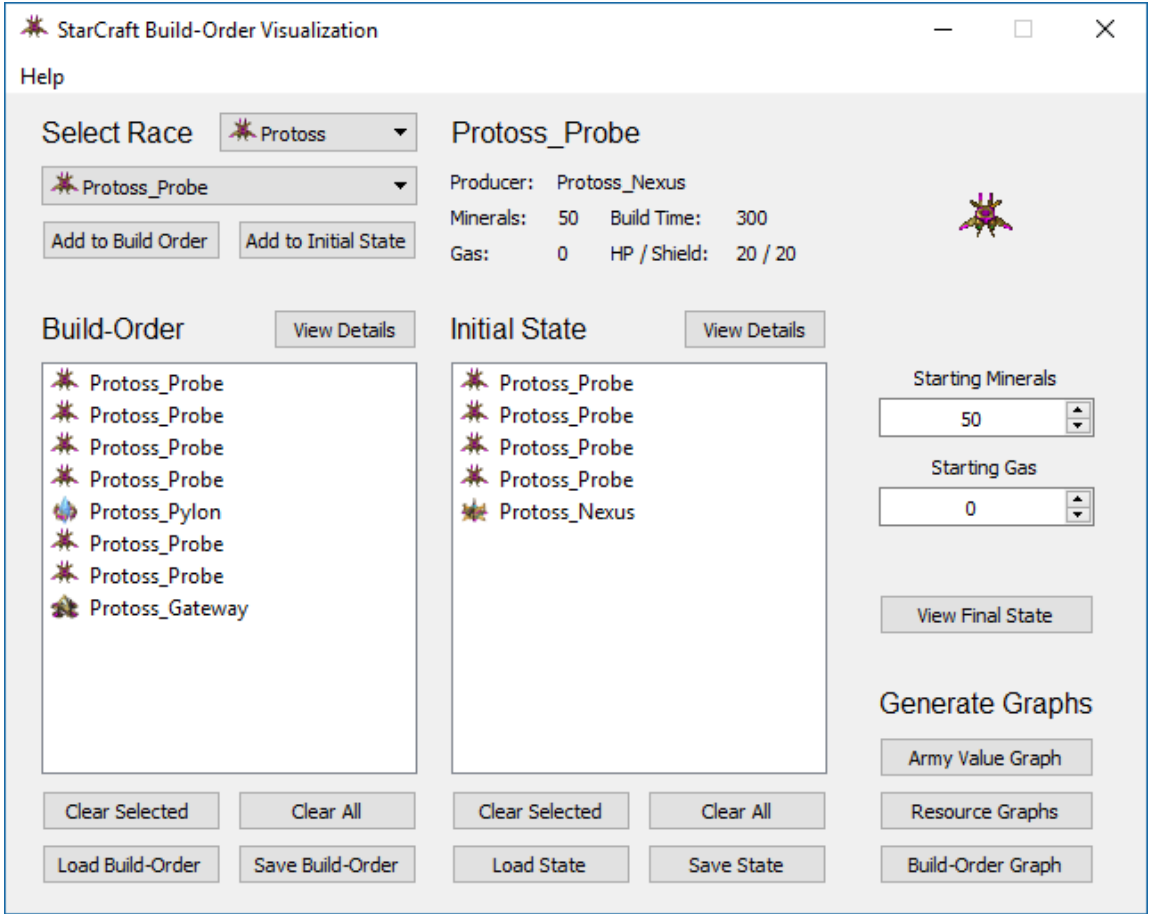
Macro Actions

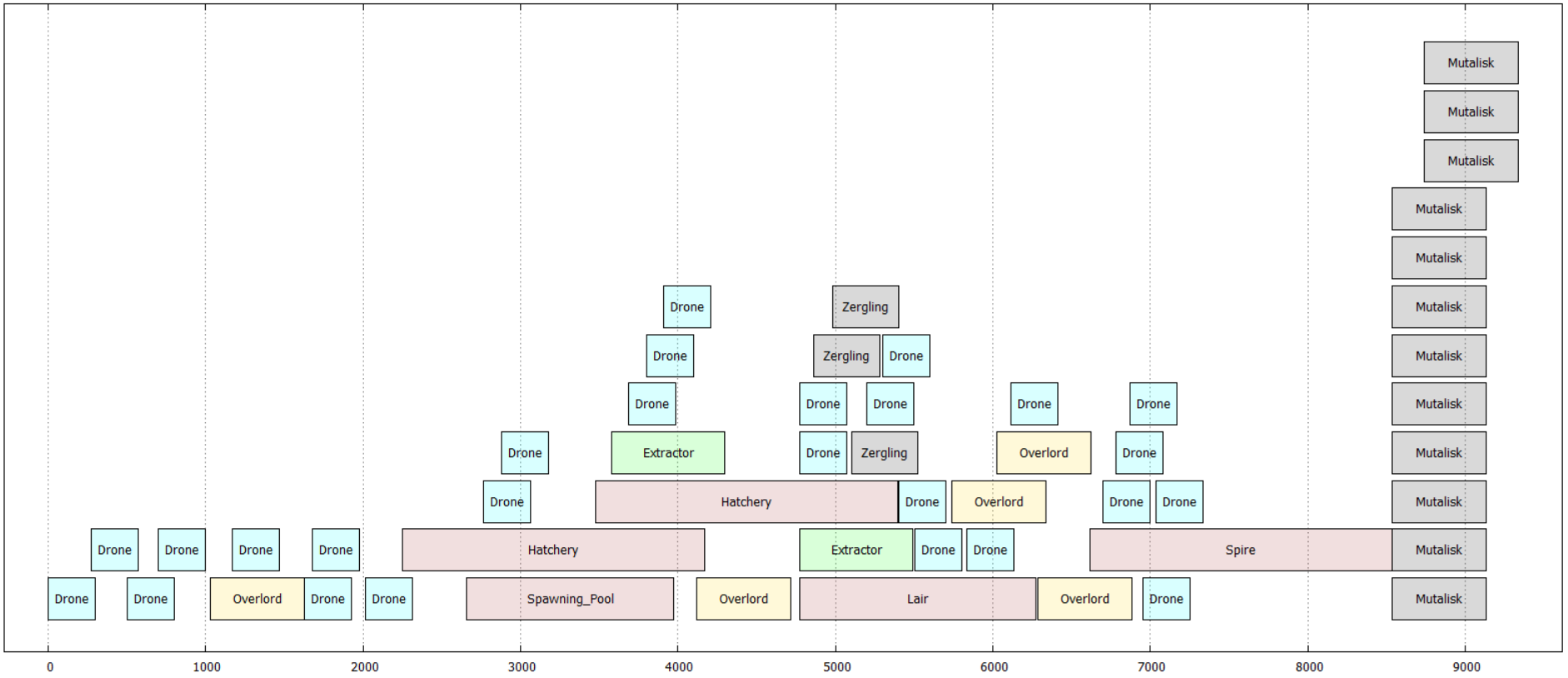
- Trade-off: branching factor vs. depth
- We must keep all atomic actions to ensure that the optimal solution is still found
- Macro actions search deeper into the tree with a single transition, but increase the branching factor of a given node
- They may speed up the search, but a poor choice of macro action can also slow down the search


500
480
460
440
420
400
380
360
340
makespan (seconds)
1
2
3
4
5
6
7
8
9
log(number of nodes expanded) [base 10]
K=1
K=2
No Macro Actions
Macro Actions

Build-Order Planning Impact

- Implemented into UAlbertaBot
  - Used in other bots in past few years
- All build-orders planned in real-time
  - First real-time planning solution
- Ran in real time with no time-outs
- UAlbertaBot placed 2nd when implemented


StarCraft Build-Order Visualization
Help
Select Race
Protoss
Protoss_Probe
Add to Build Order
Add to Initial State
Protoss_Probe
Producer: Protoss_Nexus
Minerals: 50
Build Time: 300
Gas: 0
HP / Shield: 20 / 20
Build-Order
View Details
Protoss_Probe
Protoss_Probe
Protoss_Probe
Protoss_Probe
Protoss_Pylon
Protoss_Probe
Protoss_Probe
Protoss_Gateway
Initial State
View Details
Protoss_Probe
Protoss_Probe
Protoss_Probe
Protoss_Probe
Protoss_Nexus
Starting Minerals
50
Starting Gas
0
View Final State
Generate Graphs
Army Value Graph
Resource Graphs
Build-Order Graph
Clear Selected
Clear All
Load Build-Order
Save Build-Order
Clear Selected
Clear All
Load State
Save State


Mutalisk
Mutalisk
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Drone
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Zergling
Overlord
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Extractor
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Spire
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Drone
Overlord
Drone
Drone
Spawning_Pool
Overlord
Lair
Overlord
Drone
Mutalisk
0
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9000