Beyond A*: Speeding up pathfinding through hierarchical abstraction

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Motivation

• Myth: Pathfinding is a solved problem.
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  Reality: Pathfinding is not solved!
Motivation

• Myth: Pathfinding is a solved problem.
  • Reality: Pathfinding is not solved!
    • A* underlies many pathfinding systems but...
    • Many open problems persist!
Problem: Efficient pathfinding in very large environments

Image: World of Warcraft (Blizzard Entertainment)
Problem: Dynamic terrain

Image: Company of Heroes (Relic Entertainment)
Problem: Different unit classes

Image: Red Alert 3 (Electronic Arts)
Problem: Cooperative Pathfinding

Image: Settlers: Heritage of Kings (Blue Byte Software)
Rest of this talk

- Some background on A*
- Then, a story in 3 parts:
  - Part 1: Hierarchical pathfinding
  - Part 2: Dealing with diversity
  - Part 3: Probabilistic roadmaps
Background
A* In Brief

- [Hart, Nilsson & Raphael, 1968]
- Heuristic search
- $f(n) = g(n) + h(n)$, where:
  - $g(n) =$ distance so far
  - $h(n) =$ estimate remaining distance
- Complete + Optimal
A* example

Diagram:

- S
- 1.5
- 1
- 1
- 1.5 +3
- 1+5
- 1+5
A* example
A* example
A* example
A* example
The problem with A*

- Time complexity (nodes expanded)
- Memory overhead (stuff to remember)
- Good heuristics not enough.
A* Example
A* Example

An optimal path (straight-line movement only)
A* Example

Another optimal path
A* Example

Lots of optimal paths (and many more exist!)

Cost = 18
**A* Example**

A* expands: all green tiles + some white
Part I: Hierarchical pathfinding
Hierarchical pathfinding

- Build a smaller, approximate search space.
- Area-based vs. Tile-based pathfinding.
- Factored problems are easy!
- Faster + lower memory requirements.
HPA* Overview

• [Botea, Müller & Schaeffer, 2004]

• Pre-processing:
  • Build abstract graph (Clusters and Entrances)

• Run-time processing:
  • Insert start and goal into abstract graph
  • Find abstract solution
  • Refine if necessary (or use cached info)
Map: Temple Prime (Red Alert 3)
Split map into square clusters (e.g. 10x10)

Image: Adi Botea
Identify entrances between adjacent clusters

Image: Adi Botea
Small entrance (length < 6)

- 1 central transition point

Large entrance (length >= 6)

- 2 perimeter transition points
Transition point =
2 abstract nodes + 1 abstract (inter) edge

Abstract graph

Entrance
Select transition points for each entrance

Image: Adi Botea
Connect abstract nodes inside the same cluster

Image: Adi Botea
Intra-edges (cost = path length) added to abstract graph
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Runtime processing

- Insert start + goal into abstract graph.
- Find an abstract path connecting them.
- Refine each abstract step using a small A* search to traverse each cluster (free if we cache intra-edge paths).
Add Start + Goal as (temp.) abstract nodes

Image: Adi Botea
Insert temp. edges to connect Start + Goal

Image: Adi Botea
Run A* to find an abstract path

Image: Adi Botea
Refine the abstract path before execution. Each step is independent (and fast!)

Images: Adi Botea
HPA* Advantages

- Easy to understand + implement
- Very fast (Beats A* by 10x)
- Low memory overhead (vs. A*)
- Complete
HPA* Disadvantages

- Non-optimal (but very close!).
- Assumes fixed-size 1x1 units.
- Only supports single terrain type.
- Insertion effort.
Part 2:
Dealing with diversity
Assumptions in pathfinding literature
Assumptions in pathfinding literature

Assumption #1: all units are the same size.
Assumptions in pathfinding literature

- Assumption #1: all units are the same size.
- Assumption #2: any terrain traversable for one unit is traversable for all.
Assumptions in pathfinding literature

- Assumption #1: all units are the same size.
- Assumption #2: any terrain traversable for one unit is traversable for all.
- Pathfinding breaks when either assumption is lifted.
HPA* Tank Fail

HPA* loses information (like sizes of entrances)
Challenging pathfinding

Unit sizes: Small, Medium, Large
Terrains: Snow, Road, Water, Ground

Images: Red Alert 3 (Electronic Arts)
HAA* Overview

- [Harabor, Botea, 2008]
- HPA*-style abstraction & search.
- Combined with clearance-based pathfinding.
- Caters for different terrains and unit sizes.
- Constructs complete abstractions.
Modeling diversity

Example Map

- Ground (white tiles)
- Water (blue tiles)
- Obstacles (black tiles)

Agent Sizes

- Small
- Big

Movement rules

- OK
- OK
- Not OK

Terrain traversal Capabilities

- {Ground}
- {Water}
- {Ground or Water}
Clearance-based pathfinding

• Intuition:
  • Calculate how much clearance (traversable space) exists at a given tile (t) on the map.
  • A tile (t) is traversable by an agent (a) if:
    1. terrain(t) is in capability(a)
    2. clearance(t, capability(a)) >= size(a)
Example

Agent size = 1
Capability = \{Ground\}

Each tile on the path is traversable for the agent
Computing clearance

Initial Clearance. Capability = \{\text{Ground}\} (white tiles)
Computing clearance

1
Initial Clearance.
Capability = \{\text{Ground}\}
(white tiles)

2
First Expansion
OK
Computing clearance

1. Initial Clearance. Capability = \{Ground\} (white tiles)
2. First Expansion OK
3. Second Expansion OK
Computing clearance

1.

Initial Clearance.
Capability = \{Ground\}
(white tiles)

2.

First Expansion
OK

3.

Second Expansion
OK

3.

Third Expansion
Fail
Maps with multiple terrain types

- Easy! Each tile has a clearance-value for each possible capability.
Maps with multiple terrain types

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Maps with multiple terrain types

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Clearances for {Ground} Capability

Clearances for {Water} Capability

Clearances for {Ground, Water} Capability
Dealing with large agents

Each 2x2 agent occupies 4 tiles. Which clearance value do we consider?

Agent size = 2, Capability = {Ground}
Problem reduction

Theorem: Any pathfinding problem can be reduced into a canonical problem (agent size = 1, capability = 1 terrain)
Problem reduction

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Annotated A*

- Search process:
  - Similar to A*.
  - Extra parameters: Agent's size and capability.
  - Only expand nodes with clearance > agent size.
- Works great!
- For small problem sizes...
Abstraction Process

• Similar to HPA*:
  • Divide map into N x N clusters.
  • Identify entrances for all capabilities.
  • Using AA*, find intra-edges for all agent sizes and capabilities.
  • Reduce the graph using dominance
Clusters

C1

C2

C3

C4
Identifying entrances

Transition points

Abstract graph

Entrances

E1 \{\text{Ground, 2}\}

E2 \{\text{Water, 1}\}

E3 \{\text{Ground, Water, 5}\}
Intra-edges

• Use AA* to find all possible ways (sizes/capabilities) to traverse across each cluster.

• For each path found, add a new abstract edge.

Edge Annotations
{Terrain, Clearance}:
E1 = {Ground, 2}
E2 = {Ground, 1}
E3 = {Ground, Water, 2}
E4 = {Ground, Water, 2}
E3 = {Ground, Water, 1}
E4 = {Ground, Water, 1}
Initial abstraction
Compacting the abstract graph

• Method produces a representationally complete graph but can get rather large.

• Solutions:
  • Strong dominance
  • Weak dominance
Strong dominance

Initial graph

High Quality graph

Edge Annotations
[Capability, Clearance, Length]:
E1 = [{Ground}, 2, 7.5]
E2 = [{Ground}, 1, 4.5]
E3 = [{Ground, Water}, 2, 3.0]
E4 = [{Ground, Water}, 2, 3.0]
E5 = [{Ground, Water}, 2, 3.0]
E6 = [{Ground, Water}, 1, 3.0]

Edge Annotations
[Capability, Clearance, Length]:
E1 = [{Ground}, 2, 7.5]
E2 = [{Ground}, 1, 4.5]
E3 = [{Ground, Water}, 2, 3.0]
E4 = [{Ground, Water}, 2, 3.0]

Remove edges with smaller clearance (all else being identical)
Weak dominance

Retain only edges traversable by largest number of agents (aka. prefer freeways where possible)

Two places of interest: U and X.
Path p = \{E1, E2, E3\}. Length: 15, Max Size = 1, Capability: \{Ground, Water\}
Path q = \{E4, E5, E6\}. Length: 17, Max Size = 2, Capability: \{Ground\}
Weak dominance is applied to transitions between adjacent clusters (inter-edges).
HAA*

- Similar search process to HPA*
  - Insert Start + Goal
  - Find + refine abstract path
- Differences:
  - Add a node to open list only if reachable according to edge annotations.
Initial problem
Size = 2, Capability = \{Ground\}

Inserting Start + Goal

Reducing the problem

Solution
HAA* Advantages

• Works for units with different sizes and capabilities.

• Complete and near-optimal (within 4-8% from optimal on average)

• Fast (similar performance to HPA*)

• Low overhead (storing abstract graph requires little memory in practice)
HAA* Disadvantages

- Only works on grids.
- Need to model units using square bounding volumes.
- Insertion effort.
Part 3: Probabilistic Roadmaps
Limitations of grid methods

• Coarse coverage of underlying terrain.
• Restricted movement (fixed angles)
• Paths don’t look realistic
• Often need to apply smoothing
• Not very useful in 3D spaces
vs.
Probabilistic Road Maps

• PRM: Robotics inspired method from mid 90s.
  e.g. see [Choset et al, 2004].
• Pick a robot configuration.
• Build a graph by taking lots of sample points.
Select non-obstacle sample points from the map.
Retain collision-free points for some configuration of an agent
Connect nearby points to form a graph
Pathfinding: Connect start and goal to rest of roadmap
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Most PRMs are only useful for agent/configuration used during construction.
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2 options to fix this problem:

- Create a PRM for each unit type
- Opt for a (generalised) Voronoi-based PRM
Voronoi diagram: Each point on the medial axis maximises clearance.
Intuition: retract PRM (nodes and edges) to the medial axis.
Identify the closest obstacle then retract the point to a position equidistant to 2 obstacles.
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Edge retraction

Edges too close to obstacles are retracted by splitting.
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Edges too close to obstacles are retracted by splitting.
• Other improvements:
  • Remove overlapping edges (similar idea to weak dominance)
  • Smooth edges using circular blends
Other improvements

Remove overlapping edges
(similar to weak dominance)

Apply circular blends
PRM Advantages

- Fast to construct.
- Low overhead (especially Voronoi PRMs)
- Facilitate pathfinding in n-dimensional spaces
- Generalisable to different unit sizes (Voronoi PRMs only)
- Nice alternative to navigation meshes
PRM Disadvantages

- Only probabilistically complete*
- Might need several PRMs (to support units with different capabilities).
- Non Voronoi PRMs produce ugly paths.
Conclusion

- There’s more to pathfinding than A*!
- Many open problems; some with nice solutions
  - HPA*, HAA*, Roadmaps
- Pathfinding with abstraction is very effective.
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Questions?