



GAM250: Advanced Games Programming

8: AI

Learning outcomes

- ▶ **Understand** navigation in Video Games
- ▶ **Implement** Finite State Machines in Unity
- ▶ **Implement** Behaviour Trees in Unity

Pathfinding



The problem

- We have a **graph**

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses
 - ▶ Edges = roads

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses
 - ▶ Edges = roads
- ▶ E.g. a tile-based 2D game

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses
 - ▶ Edges = roads
- ▶ E.g. a tile-based 2D game
 - ▶ Nodes = grid squares

The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses
 - ▶ Edges = roads
- ▶ E.g. a tile-based 2D game
 - ▶ Nodes = grid squares
 - ▶ Edges = connections between adjacent squares

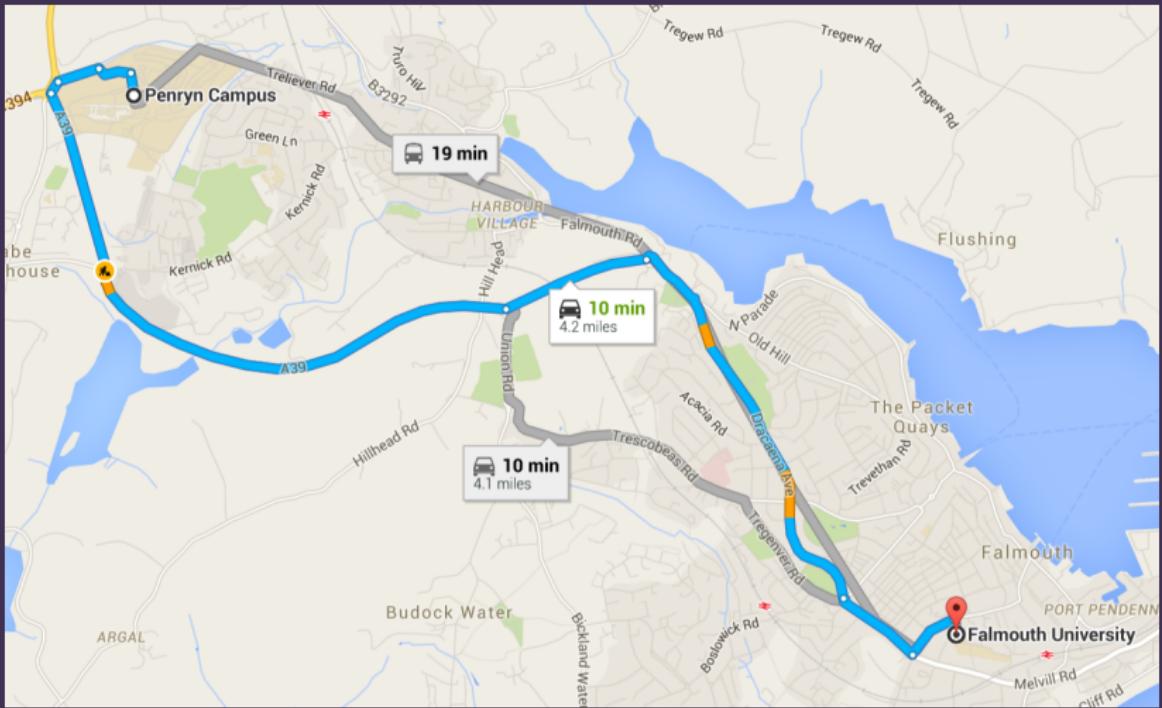
The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses
 - ▶ Edges = roads
- ▶ E.g. a tile-based 2D game
 - ▶ Nodes = grid squares
 - ▶ Edges = connections between adjacent squares
- ▶ Given two nodes *A* and *B*, find the **shortest path** from *A* to *B*

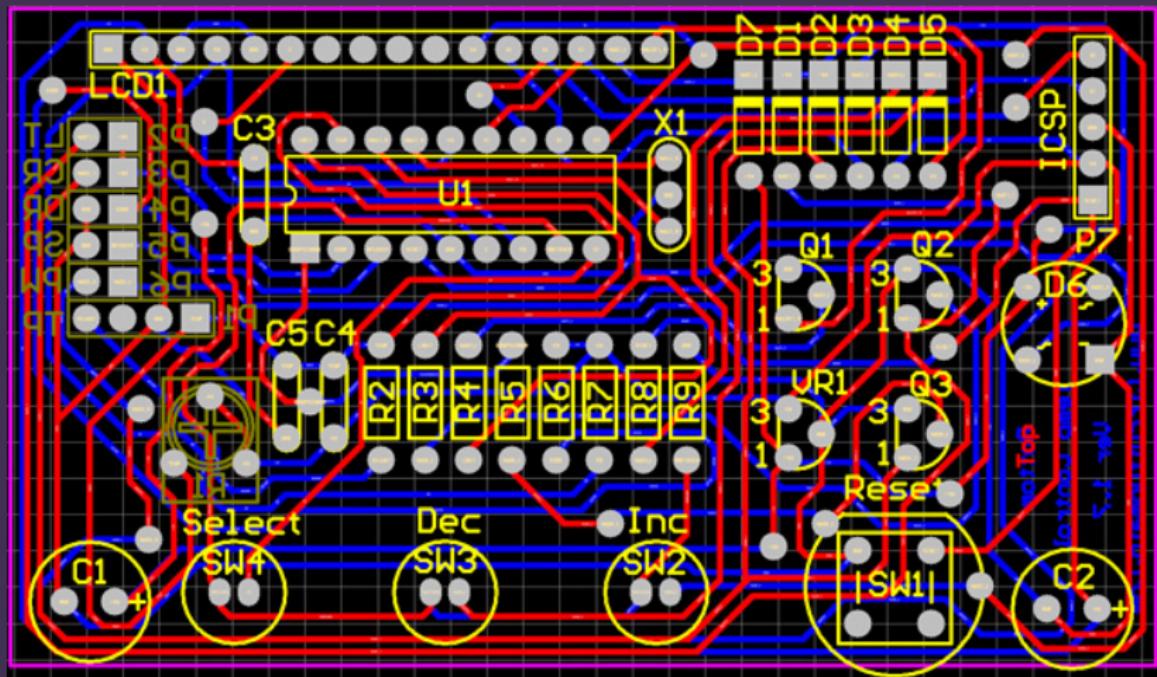
The problem

- ▶ We have a **graph**
 - ▶ **Nodes** (points)
 - ▶ **Edges** (lines between points, each with a **length**)
- ▶ E.g. a road map
 - ▶ Nodes = addresses
 - ▶ Edges = roads
- ▶ E.g. a tile-based 2D game
 - ▶ Nodes = grid squares
 - ▶ Edges = connections between adjacent squares
- ▶ Given two nodes *A* and *B*, find the **shortest path** from *A* to *B*
 - ▶ “Shortest” in terms of edge lengths — could be distance, time, fuel cost, ...

Applications of pathfinding



Applications of pathfinding



Applications of pathfinding

Many applications in game AI

Applications of pathfinding

Many applications in game AI

- ▶ Non-player character AI

Applications of pathfinding

Many applications in game AI

- ▶ Non-player character AI
- ▶ Mouse-based movement (e.g. strategy games)

Applications of pathfinding

Many applications in game AI

- ▶ Non-player character AI
- ▶ Mouse-based movement (e.g. strategy games)
- ▶ Maze navigation

Applications of pathfinding

Many applications in game AI

- ▶ Non-player character AI
- ▶ Mouse-based movement (e.g. strategy games)
- ▶ Maze navigation
- ▶ Puzzle solving

Aside: data structures

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front
 - ▶ “First in, first out”

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front
 - ▶ “First in, first out”
- ▶ **Priority queue**: maintains its elements in **sorted** order

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front
 - ▶ “First in, first out”
- ▶ **Priority queue**: maintains its elements in **sorted** order
 - ▶ **Enqueue** automatically puts the element in the correct position according to its priority

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front
 - ▶ “First in, first out”
- ▶ **Priority queue**: maintains its elements in **sorted** order
 - ▶ **Enqueue** automatically puts the element in the correct position according to its priority
 - ▶ **Dequeue** gives the highest priority element currently in the queue

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front
 - ▶ “First in, first out”
- ▶ **Priority queue**: maintains its elements in **sorted** order
 - ▶ **Enqueue** automatically puts the element in the correct position according to its priority
 - ▶ **Dequeue** gives the highest priority element currently in the queue
 - ▶ Usually implemented as a **heap** or a **balanced tree**...

Aside: data structures

- ▶ **Stack**: can **push** to the top and **pop** from the top
 - ▶ “Last in, first out”
- ▶ **Queue**: can **enqueue** to the back and **dequeue** to the front
 - ▶ “First in, first out”
- ▶ **Priority queue**: maintains its elements in **sorted** order
 - ▶ **Enqueue** automatically puts the element in the correct position according to its priority
 - ▶ **Dequeue** gives the highest priority element currently in the queue
 - ▶ Usually implemented as a **heap** or a **balanced tree**...
 - ▶ ... but implementations are available for all popular programming languages

Graph traversal

Graph traversal

- ▶ Depth-first or breadth-first

Graph traversal

- ▶ **Depth-first** or **breadth-first**
- ▶ Recall: can be implemented with a **stack** or a **queue** respectively

Graph traversal

- ▶ **Depth-first** or **breadth-first**
- ▶ Recall: can be implemented with a **stack** or a **queue** respectively
- ▶ Inefficient — generally has to explore the **entire map**

Graph traversal

- ▶ **Depth-first** or **breadth-first**
- ▶ Recall: can be implemented with a **stack** or a **queue** respectively
- ▶ Inefficient — generally has to explore the **entire map**
- ▶ Finds a path, but probably not the **shortest**

Greedy search

Greedy search

- ▶ Always try to move **closer** to the goal

Greedy search

- ▶ Always try to move **closer** to the goal
- ▶ Can be implemented with a **priority queue**

Greedy search

- ▶ Always try to move **closer** to the goal
- ▶ Can be implemented with a **priority queue**
- ▶ Doesn't handle **dead ends** well

Greedy search

- ▶ Always try to move **closer** to the goal
- ▶ Can be implemented with a **priority queue**
- ▶ Doesn't handle **dead ends** well
- ▶ Not guaranteed to find the **shortest** path

A* search

A* search

- ▶ Let $h(x)$ be an estimate of the distance from x to the goal

A* search

- ▶ Let $h(x)$ be an estimate of the distance from x to the goal
- ▶ Let $g(x)$ be the distance of the path found from the start to x

A* search

- ▶ Let $h(x)$ be an estimate of the distance from x to the goal
- ▶ Let $g(x)$ be the distance of the path found from the start to x
- ▶ Choose a node that minimises $g(x) + h(x)$

A* search

- ▶ Let $h(x)$ be an estimate of the distance from x to the goal
- ▶ Let $g(x)$ be the distance of the path found from the start to x
- ▶ Choose a node that minimises $g(x) + h(x)$
 - ▶ Contrast with greedy search, which just minimises $h(x)$

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**
 - ▶ E.g. straight line Euclidean distance is clearly an underestimate for actual travel distance

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**
 - ▶ E.g. straight line Euclidean distance is clearly an underestimate for actual travel distance
- ▶ The more accurate $h(x)$ is, the more efficient the search

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**
 - ▶ E.g. straight line Euclidean distance is clearly an underestimate for actual travel distance
- ▶ The more accurate $h(x)$ is, the more efficient the search
 - ▶ E.g. $h(x) = 0$ is admissible, but not very helpful

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**
 - ▶ E.g. straight line Euclidean distance is clearly an underestimate for actual travel distance
- ▶ The more accurate $h(x)$ is, the more efficient the search
 - ▶ E.g. $h(x) = 0$ is admissible, but not very helpful
- ▶ $h(x)$ is a **heuristic**

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**
 - ▶ E.g. straight line Euclidean distance is clearly an underestimate for actual travel distance
- ▶ The more accurate $h(x)$ is, the more efficient the search
 - ▶ E.g. $h(x) = 0$ is admissible, but not very helpful
- ▶ $h(x)$ is a **heuristic**
 - ▶ In AI, a heuristic is an estimate based on human intuition

Properties of A* search

- ▶ A* is **guaranteed** to find the shortest path if the distance estimate $h(x)$ is **admissible**
- ▶ Essentially, **admissible** means it must be an **underestimate**
 - ▶ E.g. straight line Euclidean distance is clearly an underestimate for actual travel distance
- ▶ The more accurate $h(x)$ is, the more efficient the search
 - ▶ E.g. $h(x) = 0$ is admissible, but not very helpful
- ▶ $h(x)$ is a **heuristic**
 - ▶ In AI, a heuristic is an estimate based on human intuition
 - ▶ Heuristics are often used to prioritise search, i.e. explore the most promising options first

Tweaking A*

Tweaking A*

- ▶ Can change how $g(x)$ is calculated

Tweaking A*

- ▶ Can change how $g(x)$ is calculated
 - ▶ Increased movement cost for rough terrain, water, lava...

Tweaking A*

- ▶ Can change how $g(x)$ is calculated
 - ▶ Increased movement cost for rough terrain, water, lava...
 - ▶ Penalty for changing direction

Tweaking A*

- ▶ Can change how $g(x)$ is calculated
 - ▶ Increased movement cost for rough terrain, water, lava...
 - ▶ Penalty for changing direction
- ▶ Different $h(x)$ can lead to different paths (if there are multiple “shortest” paths)

String pulling

String pulling

- ▶ Paths restricted to edges can look unnatural

String pulling

- ▶ Paths restricted to edges can look unnatural
- ▶ Intuition: visualise the path as a string, then pull both ends to make it taut

String pulling

- ▶ Paths restricted to edges can look unnatural
- ▶ Intuition: visualise the path as a string, then pull both ends to make it taut
- ▶ Simple algorithm:

String pulling

- ▶ Paths restricted to edges can look unnatural
- ▶ Intuition: visualise the path as a string, then pull both ends to make it taut
- ▶ Simple algorithm:
 - ▶ Found path is $p[0], p[1], \dots, p[n]$

String pulling

- ▶ Paths restricted to edges can look unnatural
- ▶ Intuition: visualise the path as a string, then pull both ends to make it taut
- ▶ Simple algorithm:
 - ▶ Found path is $p[0], p[1], \dots, p[n]$
 - ▶ If the line from $p[i]$ to $p[i + 2]$ is unobstructed, remove point $p[i + 1]$

String pulling

- ▶ Paths restricted to edges can look unnatural
- ▶ Intuition: visualise the path as a string, then pull both ends to make it taut
- ▶ Simple algorithm:
 - ▶ Found path is $p[0], p[1], \dots, p[n]$
 - ▶ If the line from $p[i]$ to $p[i + 2]$ is unobstructed, remove point $p[i + 1]$
 - ▶ Repeat until there are no more points that can be removed

Navigation meshes



Pathfinding in videogames

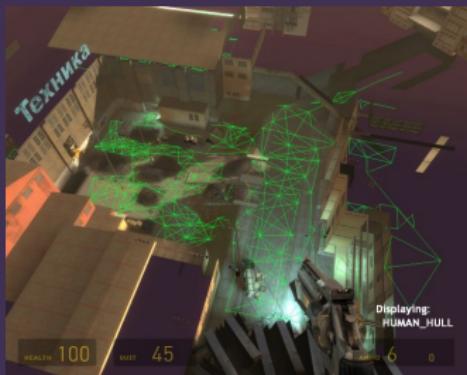
Pathfinding in videogames

- ▶ A* works on any **graph**

Pathfinding in videogames

- ▶ A* works on any **graph**
- ▶ But what if the game world is not a graph? E.g. complex 3D environments

Waypoint navigation



Waypoint navigation

- ▶ Manually place graph nodes in the world



Waypoint navigation

- ▶ Manually place graph nodes in the world
- ▶ Place them at key points, e.g. in doorways, around obstacles

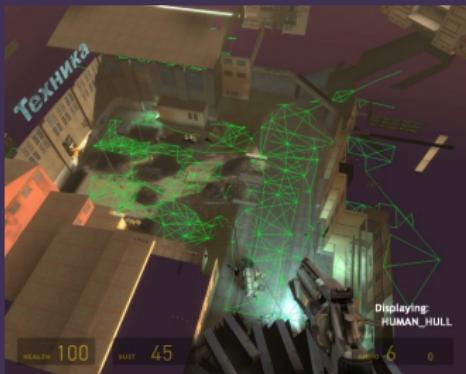


Waypoint navigation

- ▶ Manually place graph nodes in the world
- ▶ Place them at key points, e.g. in doorways, around obstacles
- ▶ Works, but...



Waypoint navigation



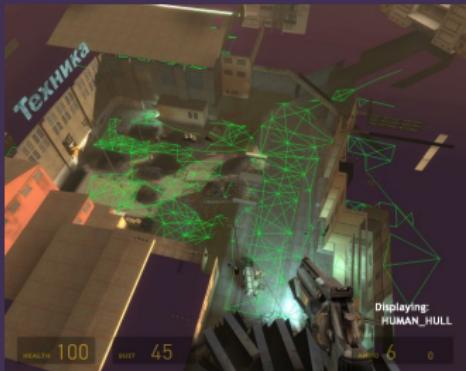
- ▶ Manually place graph nodes in the world
- ▶ Place them at key points, e.g. in doorways, around obstacles
- ▶ Works, but...
 - ▶ More work for level designers

Waypoint navigation



- ▶ Manually place graph nodes in the world
- ▶ Place them at key points, e.g. in doorways, around obstacles
- ▶ Works, but...
 - ▶ More work for level designers
 - ▶ Requires lots of testing and tweaking to get natural-looking results

Waypoint navigation



- ▶ Manually place graph nodes in the world
- ▶ Place them at key points, e.g. in doorways, around obstacles
- ▶ Works, but...
 - ▶ More work for level designers
 - ▶ Requires lots of testing and tweaking to get natural-looking results
 - ▶ No good for dynamic environments

Navigation meshes



Navigation meshes

- ▶ Automatically generate navigation graph from level geometry



Navigation meshes



- ▶ Automatically generate navigation graph from level geometry
- ▶ Basic idea:

Navigation meshes



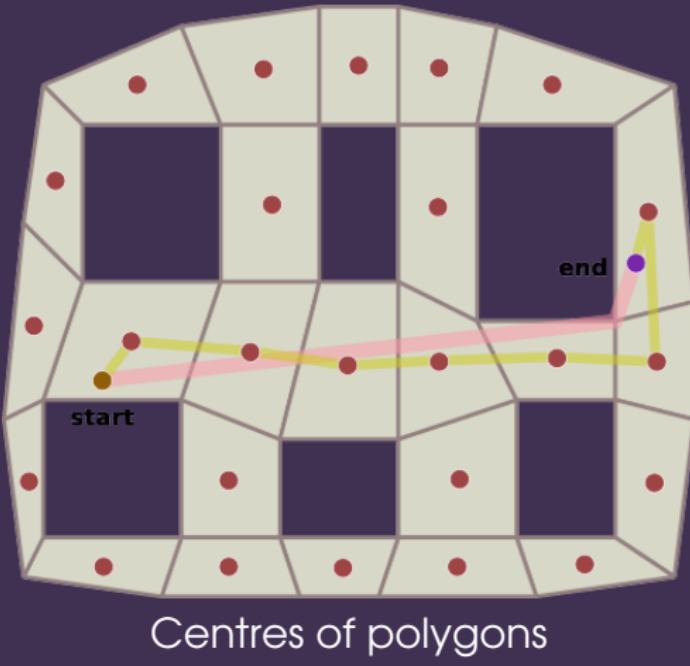
- ▶ Automatically generate navigation graph from level geometry
- ▶ Basic idea:
 - ▶ Filter level geometry to those polygons which are **passable** (i.e. floors, not walls/ceilings/obstacles)

Navigation meshes

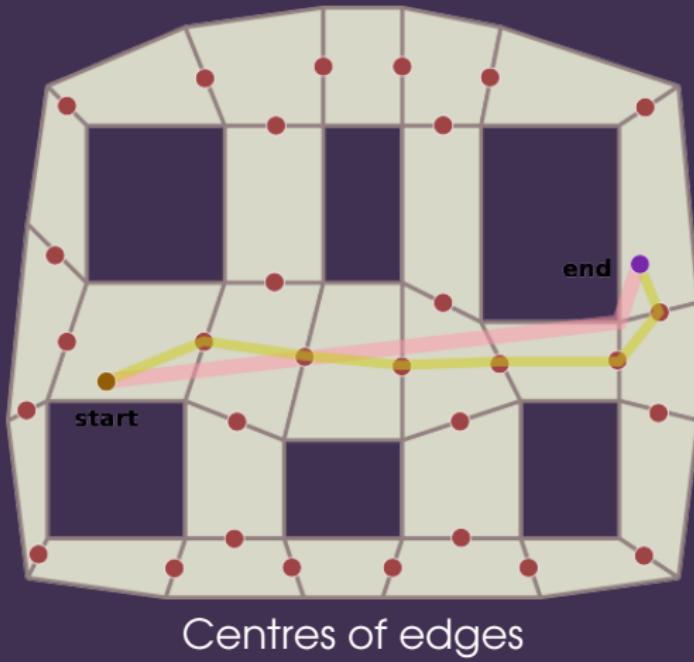


- ▶ Automatically generate navigation graph from level geometry
- ▶ Basic idea:
 - ▶ Filter level geometry to those polygons which are **passable** (i.e. floors, not walls/ceilings/obstacles)
 - ▶ Generate graph from polygons

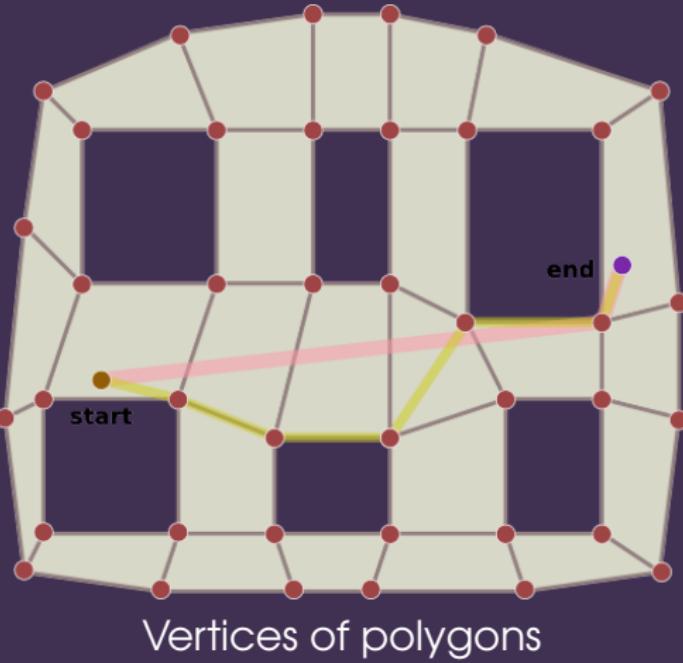
Meshes to graphs



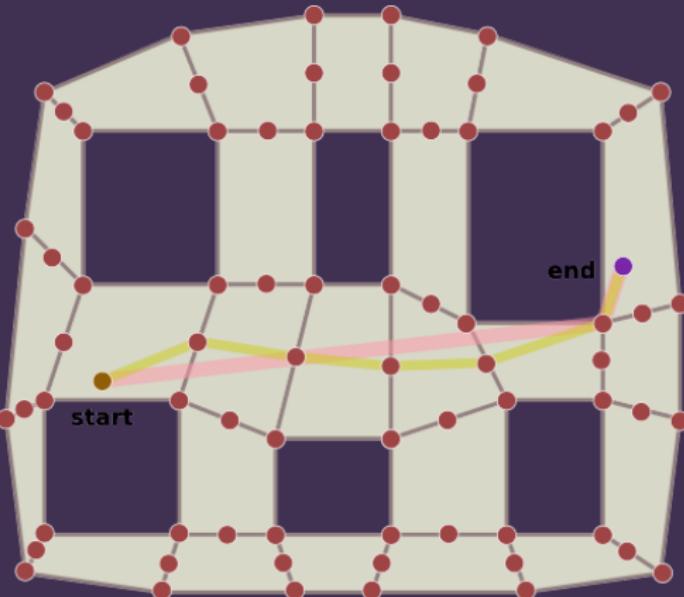
Meshes to graphs



Meshes to graphs



Meshes to graphs



Hybrid approach: edges and vertices

Following the path

Following the path

- ▶ **Funnelling:** like string pulling but for navigation meshes

Following the path

- ▶ **Funnelling:** like string pulling but for navigation meshes
 - ▶ <http://digestingduck.blogspot.co.uk/2010/03/simple-stupid-funnel-algorithm.html>
 - ▶ <http://jceipek.com/Olin-Coding-Tutorials/pathing.html>

Following the path

- ▶ **Funnelling:** like string pulling but for navigation meshes
 - ▶ <http://digestingduck.blogspot.co.uk/2010/03/simple-stupid-funnel-algorithm.html>
 - ▶ <http://jceipek.com/Olin-Coding-Tutorials/pathing.html>
- ▶ **Steering:** don't have your AI agent follow the path exactly, but instead try to stay close to it

Following the path

- ▶ **Funnelling:** like string pulling but for navigation meshes
 - ▶ <http://digestingduck.blogspot.co.uk/2010/03/simple-stupid-funnel-algorithm.html>
 - ▶ <http://jceipek.com/Olin-Coding-Tutorials/pathing.html>
- ▶ **Steering:** don't have your AI agent follow the path exactly, but instead try to stay close to it
- ▶ **Dynamic environments:** may need to re-run pathfinder if environment changes (e.g. movable obstacles, destructible terrain)

Finite state machines



Finite state machines

- ▶ A **finite state machine (FSM)** consists of:

Finite state machines

- ▶ A **finite state machine (FSM)** consists of:
 - ▶ A set of **states**; and

Finite state machines

- ▶ A **finite state machine (FSM)** consists of:
 - ▶ A set of **states**; and
 - ▶ **Transitions** between states

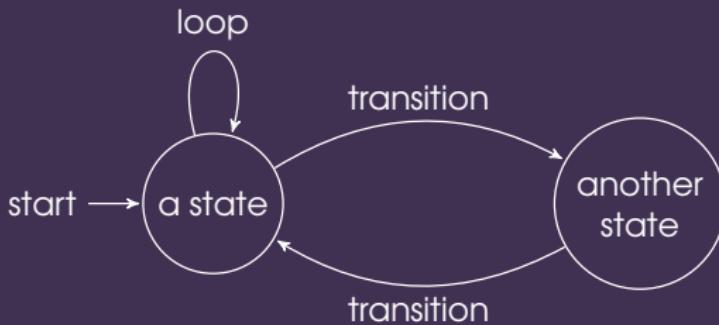
Finite state machines

- ▶ A **finite state machine (FSM)** consists of:
 - ▶ A set of **states**; and
 - ▶ **Transitions** between states
- ▶ At any given time, the FSM is in a **single state**

Finite state machines

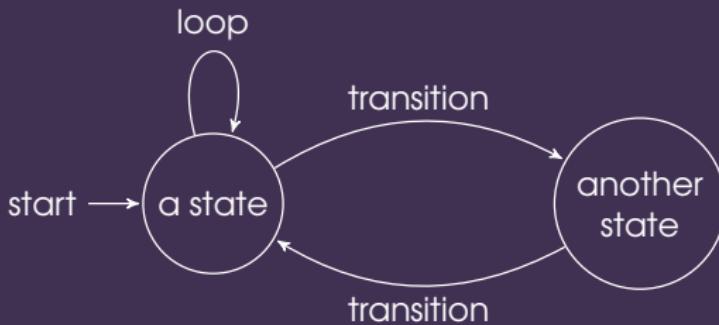
- ▶ A **finite state machine (FSM)** consists of:
 - ▶ A set of **states**; and
 - ▶ **Transitions** between states
- ▶ At any given time, the FSM is in a **single state**
- ▶ **Inputs** or **events** can cause the FSM to transition to a different state

State transition diagrams



- ▶ FSMs are often drawn as **state transition diagrams**
- ▶ Reminiscent of **flowcharts** and certain types of **UML diagram**

State transition diagrams



- ▶ FSMs are often drawn as **state transition diagrams**
- ▶ Reminiscent of **flowcharts** and certain types of **UML diagram**

FSMs for AI behaviour

The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

FSMs for AI behaviour

The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

- ▶ By default, patrol (e.g. along a preset route)

FSMs for AI behaviour

The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

- ▶ By default, patrol (e.g. along a preset route)
- ▶ If the player is spotted, attack them

FSMs for AI behaviour

The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

- ▶ By default, patrol (e.g. along a preset route)
- ▶ If the player is spotted, attack them
- ▶ If the player is no longer visible, resume patrolling

FSMs for AI behaviour

The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

- ▶ By default, patrol (e.g. along a preset route)
- ▶ If the player is spotted, attack them
- ▶ If the player is no longer visible, resume patrolling
- ▶ If you are low on health, run away and find a medikit.
Then resume patrolling

FSMs for AI behaviour

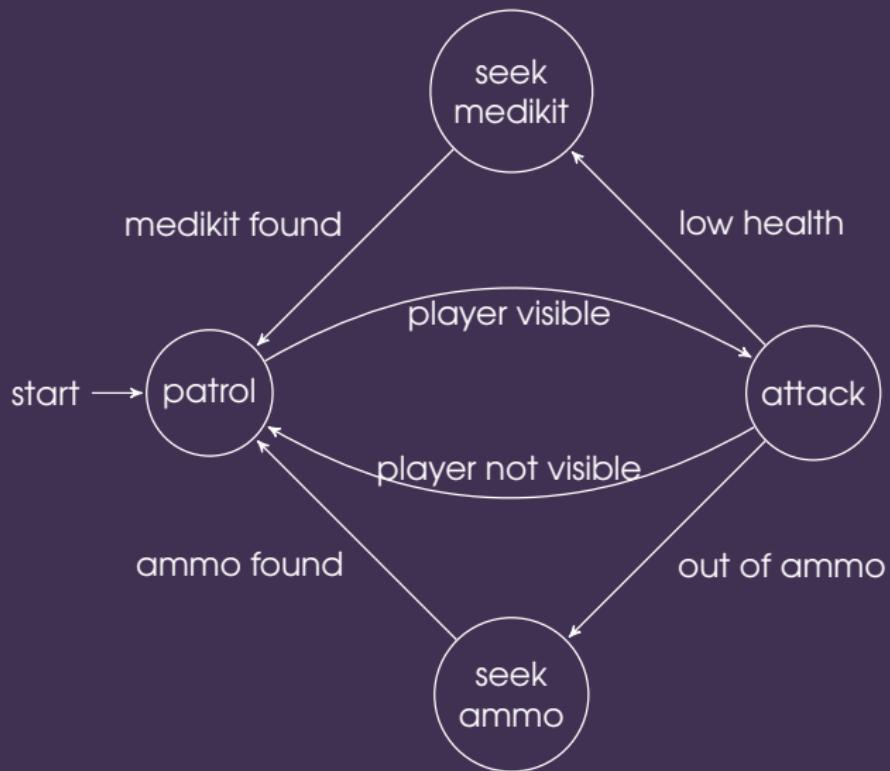
The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

- ▶ By default, patrol (e.g. along a preset route)
- ▶ If the player is spotted, attack them
- ▶ If the player is no longer visible, resume patrolling
- ▶ If you are low on health, run away and find a medikit.
Then resume patrolling
- ▶ If you are low on ammo, run away and find ammo.
Then resume patrolling

FSMs for AI behaviour

The next slide shows a simple FSM for the following AI behaviour, for an enemy NPC in a shooter game:

- ▶ By default, patrol (e.g. along a preset route)
- ▶ If the player is spotted, attack them
- ▶ If the player is no longer visible, resume patrolling
- ▶ If you are low on health, run away and find a medikit.
Then resume patrolling
- ▶ If you are low on ammo, run away and find ammo.
Then resume patrolling



Other uses of FSMs

As well as AI behaviours, FSMs may also be used for:

Other uses of FSMs

As well as AI behaviours, FSMs may also be used for:

- ▶ UI menu systems

Other uses of FSMs

As well as AI behaviours, FSMs may also be used for:

- ▶ UI menu systems
- ▶ Dialogue trees

Other uses of FSMs

As well as AI behaviours, FSMs may also be used for:

- ▶ UI menu systems
- ▶ Dialogue trees
- ▶ Token parsing

Other uses of FSMs

As well as AI behaviours, FSMs may also be used for:

- ▶ UI menu systems
- ▶ Dialogue trees
- ▶ Token parsing
- ▶ ...

Beyond FSMs

Some topics for you to research, for when plain old FSMs aren't enough...

Beyond FSMs

Some topics for you to research, for when plain old FSMs aren't enough...

- ▶ Hierarchical FSMs
- ▶ Nested FSMs
- ▶ Stack-based FSMs
- ▶ Hierarchical task networks
- ▶ ...

Plus the topic we will be looking at today: **behaviour trees**

Behaviour Trees



Behaviour trees (BTs)

Behaviour trees (BTs)

- ▶ A **hierarchical** model of decision making

Behaviour trees (BTs)

- ▶ A **hierarchical** model of decision making
- ▶ Allow **complex behaviours** to be built up from **simple components**

Behaviour trees (BTs)

- ▶ A **hierarchical** model of decision making
- ▶ Allow **complex behaviours** to be built up from **simple components**
- ▶ Allow for **more complex** behaviours than FSMs

Behaviour trees (BTs)

- ▶ A **hierarchical** model of decision making
- ▶ Allow **complex behaviours** to be built up from **simple components**
- ▶ Allow for **more complex** behaviours than FSMs
- ▶ First used in Halo 2 (2005), now used extensively

Behaviour trees (BTs)

- ▶ A **hierarchical** model of decision making
- ▶ Allow **complex behaviours** to be built up from **simple components**
- ▶ Allow for **more complex** behaviours than FSMs
- ▶ First used in Halo 2 (2005), now used extensively
- ▶ Also used in robotics and other non-game AI applications

Using BTs

Using BTs

- ▶ Fairly easy to implement; plenty of resources online

Using BTs

- ▶ Fairly easy to implement; plenty of resources online
- ▶ Some engines (e.g. Unreal) have BTs built in

Using BTs

- ▶ Fairly easy to implement; plenty of resources online
- ▶ Some engines (e.g. Unreal) have BTs built in
- ▶ We will be using the free **Behaviour Machine** library for Unity

BT basics

BT basics

- ▶ A BT is a **tree** of **nodes**

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well
 - ▶ So ticks propagate down the tree from the root

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well
 - ▶ So ticks propagate down the tree from the root
- ▶ A ticked node returns one of three **statuses**:

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well
 - ▶ So ticks propagate down the tree from the root
- ▶ A ticked node returns one of three **statuses**:
 - ▶ Success

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well
 - ▶ So ticks propagate down the tree from the root
- ▶ A ticked node returns one of three **statuses**:
 - ▶ Success
 - ▶ Running

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well
 - ▶ So ticks propagate down the tree from the root
- ▶ A ticked node returns one of three **statuses**:
 - ▶ Success
 - ▶ Running
 - ▶ Failure

BT basics

- ▶ A BT is a **tree** of **nodes**
- ▶ On each game update (i.e. each frame), the root node is **ticked**
 - ▶ When a node is ticked, it might cause some or all of its **children** to tick as well
 - ▶ So ticks propagate down the tree from the root
- ▶ A ticked node returns one of three **statuses**:
 - ▶ Success
 - ▶ Running
 - ▶ Failure
- ▶ “Running” status allows nodes to represent operations that **last multiple frames**

Node types

Node types

- ▶ There are **three main types** of BT node

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children
 - ▶ Represent actions (i.e. the AI agent actually doing something)

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children
 - ▶ Represent actions (i.e. the AI agent actually doing something)
- ▶ **Decorator** nodes

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children
 - ▶ Represent actions (i.e. the AI agent actually doing something)
- ▶ **Decorator** nodes
 - ▶ One child

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children
 - ▶ Represent actions (i.e. the AI agent actually doing something)
- ▶ **Decorator** nodes
 - ▶ One child
 - ▶ Modify the execution of the child

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children
 - ▶ Represent actions (i.e. the AI agent actually doing something)
- ▶ **Decorator** nodes
 - ▶ One child
 - ▶ Modify the execution of the child
- ▶ **Composite** nodes

Node types

- ▶ There are **three main types** of BT node
- ▶ **Leaf** nodes
 - ▶ No children
 - ▶ Represent actions (i.e. the AI agent actually doing something)
- ▶ **Decorator** nodes
 - ▶ One child
 - ▶ Modify the execution of the child
- ▶ **Composite** nodes
 - ▶ Control which of the children are executed on each tick

Leaf nodes

Leaf nodes

- ▶ Represent **atomic actions**

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"
 - ▶ Failure means "the action cannot be done"

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"
 - ▶ Failure means "the action cannot be done"
 - ▶ Running means "the action is still in progress"

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"
 - ▶ Failure means "the action cannot be done"
 - ▶ Running means "the action is still in progress"
- ▶ Leaf nodes can also be used to represent **conditions**

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"
 - ▶ Failure means "the action cannot be done"
 - ▶ Running means "the action is still in progress"
- ▶ Leaf nodes can also be used to represent **conditions**
 - ▶ E.g. "is my health below 10%?"

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"
 - ▶ Failure means "the action cannot be done"
 - ▶ Running means "the action is still in progress"
- ▶ Leaf nodes can also be used to represent **conditions**
 - ▶ E.g. "is my health below 10%?"
 - ▶ Returns success for true, failure for false

Leaf nodes

- ▶ Represent **atomic actions**
 - ▶ I.e. actions which can't sensibly be broken down into smaller actions
- ▶ E.g. walk to, crouch, attack, open door
- ▶ Status:
 - ▶ Success means "the action is done"
 - ▶ Failure means "the action cannot be done"
 - ▶ Running means "the action is still in progress"
- ▶ Leaf nodes can also be used to represent **conditions**
 - ▶ E.g. "is my health below 10%?"
 - ▶ Returns success for true, failure for false
- ▶ Leaf nodes often have **parameters** to allow for reuse in different situations

Leaf node example

```
using UnityEngine;
using System.Collections;
using BehaviourMachine;

public class GoTo : ActionNode
{
    public GameObjectVar objectToMove;
    public Vector3Var target;
    public FloatVar speed;

    public override Status Update()
    {
        float distance = (objectToMove.Value.transform.position - target.Value).magnitude;
        float step = speed.Value * Time.deltaTime;
        if (distance < step)
        {
            objectToMove.Value.transform.position = target.Value;
            return Status.Success;
        }
        else
        {
            objectToMove.Value.transform.position = Vector3.MoveTowards(
                objectToMove.Value.transform.position, target.Value, step);
            return Status.Running;
        }
    }
}
```

Composite nodes: sequence

Composite nodes: sequence

- ▶ Run each child, in order

Composite nodes: sequence

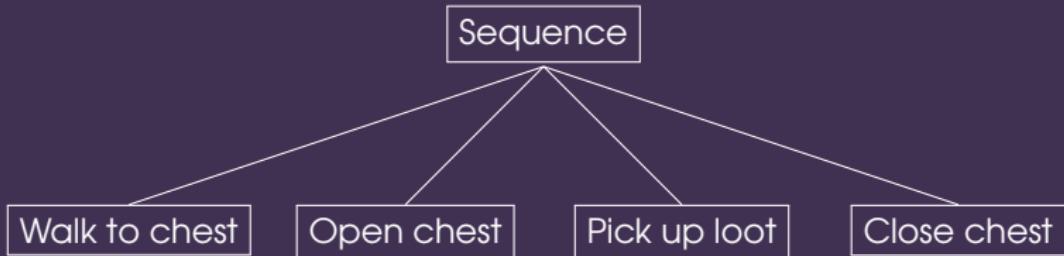
- ▶ Run each child, in order
- ▶ If **any** child returns failure, stop and return failure

Composite nodes: sequence

- ▶ Run each child, in order
- ▶ If **any** child returns failure, stop and return failure
- ▶ If **all** children return success, stop and return success

Composite nodes: sequence

- ▶ Run each child, in order
- ▶ If **any** child returns failure, stop and return failure
- ▶ If **all** children return success, stop and return success



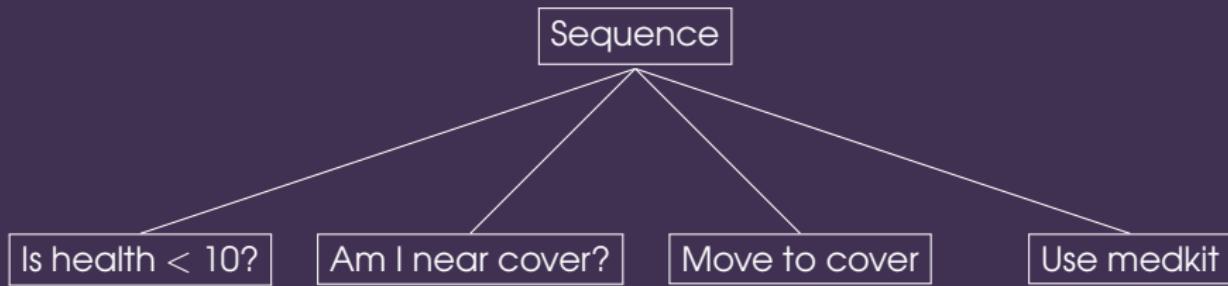
Sequence nodes and conditions

Sequence nodes and conditions

- ▶ A sequence node can be used like an **if** (cond1 && cond2) statement

Sequence nodes and conditions

- ▶ A sequence node can be used like an **if** (cond1 && cond2) statement



Composite nodes: selector

Composite nodes: selector

- ▶ Run each child, in order

Composite nodes: selector

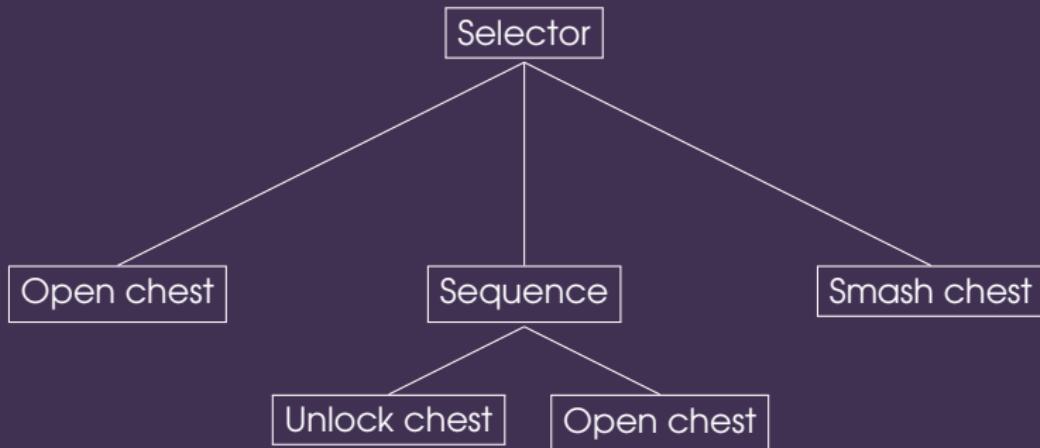
- ▶ Run each child, in order
- ▶ If a child returns failure, move onto the next one

Composite nodes: selector

- ▶ Run each child, in order
- ▶ If a child returns failure, move onto the next one
- ▶ If **any** child returns success, stop and return success

Composite nodes: selector

- ▶ Run each child, in order
- ▶ If a child returns failure, move onto the next one
- ▶ If **any** child returns success, stop and return success



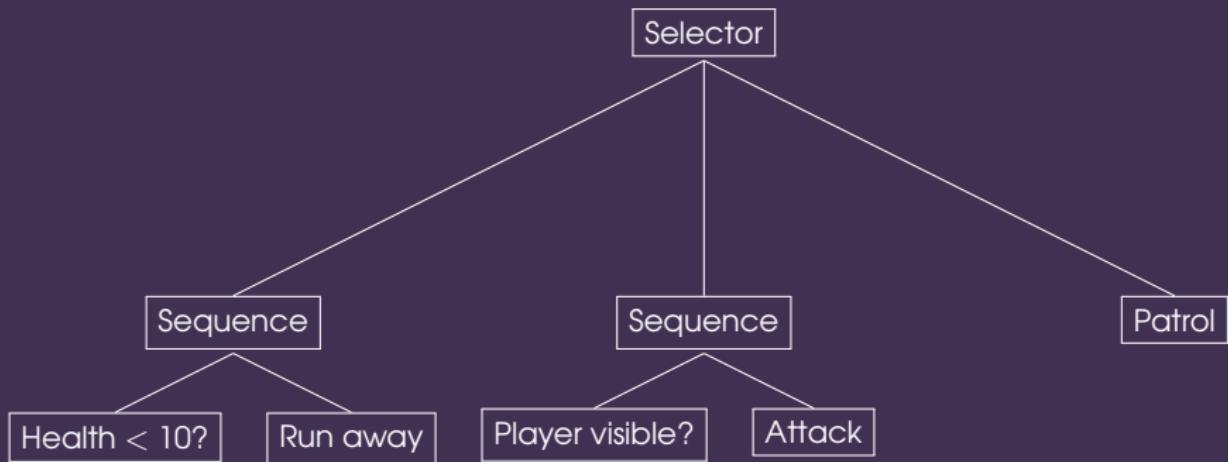
Selectors and priority

Selectors and priority

- ▶ Order of selector children represents the **priority** of different alternatives

Selectors and priority

- ▶ Order of selector children represents the **priority** of different alternatives



Sequence vs selector

Sequence vs selector

- ▶ Sequence: perform a list of actions; if one of them fails then abandon the task

Sequence vs selector

- ▶ Sequence: perform a list of actions; if one of them fails then abandon the task
- ▶ Selector: try a list of alternatives; stop once you find one that works

Sequence vs selector

- ▶ Sequence: perform a list of actions; if one of them fails then abandon the task
- ▶ Selector: try a list of alternatives; stop once you find one that works
- ▶ Sequence works like **and**, selector works like **or**

Other composite nodes

Other composite nodes

- ▶ Execute children in **random** order

Other composite nodes

- ▶ Execute children in **random** order
- ▶ Execute children in **parallel**

Other composite nodes

- ▶ Execute children in **random** order
- ▶ Execute children in **parallel**
- ▶ Most BT frameworks allow programmers to create custom composite nodes

Decorator nodes

Decorator nodes

- ▶ **Inverter:** if child returns success then return failure, and vice versa

Decorator nodes

- ▶ **Inverter:** if child returns success then return failure, and vice versa
- ▶ **Repeater:** run the child a number of times, or forever

Decorator nodes

- ▶ **Inverter**: if child returns success then return failure, and vice versa
- ▶ **Repeater**: run the child a number of times, or forever
- ▶ Most BT frameworks allow programmers to create custom decorator nodes

Blackboard

Blackboard

- ▶ It is often useful to **share** data between nodes

Blackboard

- ▶ It is often useful to **share** data between nodes
- ▶ A **blackboard** (sometimes called a **data context**) allows this

Blackboard

- ▶ It is often useful to **share** data between nodes
- ▶ A **blackboard** (sometimes called a **data context**) allows this
- ▶ Blackboard defines **variables**, which can be **read** and **written** by nodes

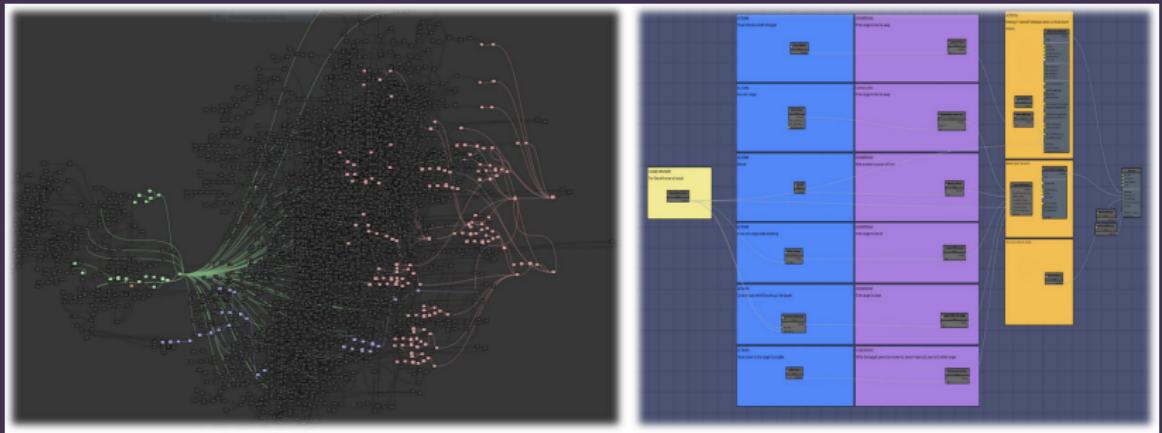
Blackboard

- ▶ It is often useful to **share** data between nodes
- ▶ A **blackboard** (sometimes called a **data context**) allows this
- ▶ Blackboard defines **variables**, which can be **read** and **written** by nodes
- ▶ Blackboard can be **local** to the AI agent, **shared** between several agents, or **global** to all agents

Blackboard

- ▶ It is often useful to **share** data between nodes
- ▶ A **blackboard** (sometimes called a **data context**) allows this
- ▶ Blackboard defines **variables**, which can be **read** and **written** by nodes
- ▶ Blackboard can be **local** to the AI agent, **shared** between several agents, or **global** to all agents
- ▶ (Shared blackboards mean that your AI has “telepathy” — this may or may not be desirable!)

BTs in The Division



[http://www.gdcvault.com/play/1023382/
AI-Behavior-Editing-and-Debugging](http://www.gdcvault.com/play/1023382/AI-Behavior-Editing-and-Debugging)

Exercise

- ▶ Using FSM or Behaviour Trees, create an AI agent which does the following
 - ▶ Navigates a series of waypoints
 - ▶ Shoots at the player when in range
 - ▶ When low on health it attempts to heal by collecting an item
- ▶ Stretch Goal: Make an AI Agent to replace the player!

Further Reading

- ▶ Finite State AI in Unity -

<https://unity3d.com/learn/tutorials/topics/navigation/finite-state-ai-delegate-pattern>

- ▶ Using Unity Animator as an FSM - <https://medium.com/the-unity-developers-handbook/dont-re-invent-finite-state-machines-how-to-rep>

- ▶ Behaviour Machine (FSM for Unity) -

<http://www.behaviourmachine.com/>

- ▶ Unity Behavior Library - <https://github.com/listentorick/UnityBehaviorLibrary/>

- ▶ Unity Crystal AI -

<https://igiagkiozis.github.io/CrystalAI/>