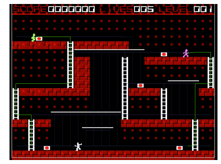
Advanced Pathfinding

IMGD 4000

With material from: Millington and Funge, *Artificial Intelligence for Games*, Morgan Kaufmann 2009 (Chapter 4) and Buckland, *Programming Game AI by Example*, Wordware 2005 (Chapter 5, 8).

Finding a Path

- Often seems obvious and natural in real life
  - e.g., Get from point A to B → go around lake
- For computer controlled player, may be difficult
  - e.g., Going from A to B goes through enemy base!
- Want to pick "best" path
- Need to do it in real-time

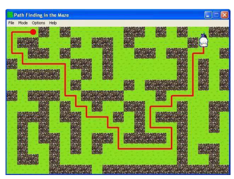


http://www.rocket5studios.com/tutorials/make-a-2d-game-with-unity3d-using-only-free-tools-beginning-enemy-ai-with-a-pathfinding/

http://www.codeofhonor.com/blog/the-starcraft-path-finding-hack

Finding a Path

- Path – a list of cells, points or nodes that agent must traverse to get to from start to goal
  - Some paths are better than others → measure of quality
- A* is commonly used heuristic search
  - *Complete* algorithm in that if there is path, will find
  - Using "distance" as heuristic measure, then guaranteed optimal



http://www.cognaxon.com/index.php?page=educational

A* Pathfinding Search

- Covered in detail in IMGD 3000

  http://web.cs.wpi.edu/~imgd4000/d16/slides/imgd3000-astar.pdf
- Basic A* is a *minimal requirement* for solo project
  - You may use any reference code as a guide, but not copy and paste (cf. academic honesty policies)
- An advanced pathfinding feature will be optional, but required for an A
  - This slide deck

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Practical Path Planning

- Sometimes, basic A* is not enough
- Also, often need:
  - Navigation graphs
    - Points of visibility (pov) – lines connecting visible nodes
    - Navigation mesh (navmesh) – models traversable areas of virtual map
  - Path smoothing
  - Compute-time optimizations
  - Hierarchical pathfinding
  - Special case methods
- Some of these count as optional requirement

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Tile-Based Navigation Graphs

- Common, especially if environment already designed in squares or hexagons
- Node center of cell; edges to adjacent cells
- Each cell already labeled with material (mud, river, etc.)
- *Downside:*
  - Can burden CPU and memory
    - e.g., Modest 100x100 cell map has 10,000 nodes and 78,000 edges!
  - Especially if multiple AI's calling at same time

*Most of slide deck is **survey** about how to do better...*

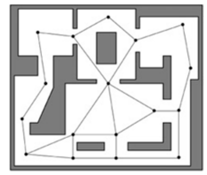
http://opinionatedgamers.com/2011/12/07/review-of-kingdom-builder/

http://forum.cocos2d-objc.org/t/tilemapkit-complete-tiled-tmx-tilemap-support-including-hex-staggered-iso/17313

Outline

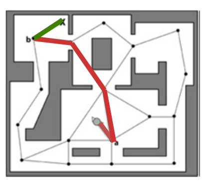
- Introduction (done)
- Navigation Graphs (next)
- Navigation Mesh
- Pathfinding Tuning
- Pathfinding in UE4

Point of Visibility (POV) Navigation Graph



- Place graph nodes (usually by hand) at *important points* in environment
- Such that *each node has line of sight to at least one other node*

POV Navigation

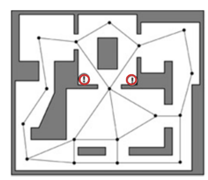


- Find closest *visible* node (a) to current location
- Find closest *visible* node (b) to target location
- Search for least cost path from (a) to (b), e.g. A*
- Move to (a)
- Follow path to (b)
- Move to target location

Note, some "backtracking"

DEMO (COARSE)

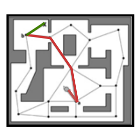
Blind Spots in POV



- No POV point is visible from red spots!
- Easy to fix manually in small graphs
- A problem in larger graphs

DEMO (COARSE)

POV Navigation



- Advantage
  - Obvious how to build and expand
- Disadvantages
  - Can have "blind spots"
  - Can have "jerky" (backtracking) paths
  - Can take a lot of developer time, especially if design is rapidly evolving
  - Problematic for random or user generated maps
- Solutions
  1. Automatically generate POV graphs
  2. Make finer grained graphs
  3. Path smoothing

Automatic POV by Expanded Geometry

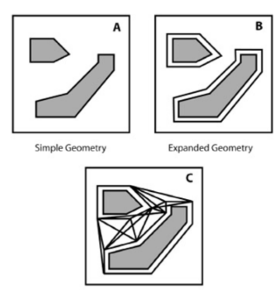
(A) Expand geometry
- By amount proportional to bounding radius of moving agents

(B) Connect all vertices

(C) Prune non-line of sight points

→ Avoids objects hitting edges when pathing

Note: works best if bounding radius similar for all units

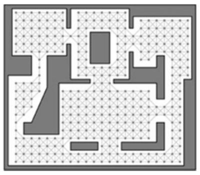


Simple Geometry

Expanded Geometry

The finished POV graph

Finely Grained Graphs



- Upside? Improves blind spots and path smoothness
- Downside? Back to similar performance issues as tiled graphs
- Upside? Can often generate automatically using “flood fill” (next slide)

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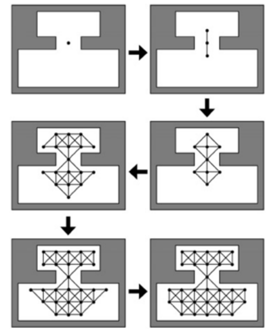
Flood Fill to Produce Finely Grained Graph

- Place “seed” in graph
- Expand outward
  - e.g., 8 directions
  - Making sure nodes and edges passable by bounding radius
- Continue until covered

→ Produces a finely grained graph

- Note, same algorithm used by “paint” programs to flood fill color



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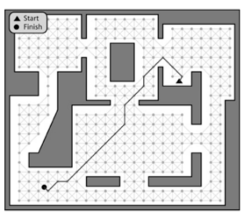
Path Finding in Finely Grained Graph



- Use A* or Dijkstra depending on whether looking for specific or multiple general targets
  - e.g., Find exit? A* typically faster than Dijkstra’s since latter is exhaustive
  - e.g., Find one of many rocket launchers? A* would need to be re-run for each, then chose minimum.

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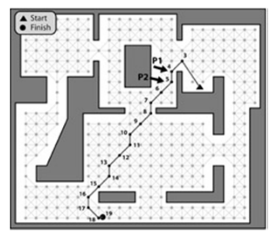
Problem: Kinky Paths

Problem: Path chosen “kinky”, not natural



Solution? Path smoothing.
- Simple fix to “penalize” change in direction
- Others work better (next)

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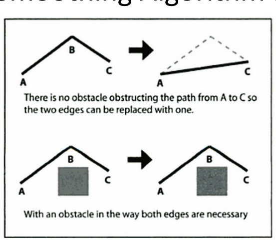
Simple Smoothing Algorithm (1 of 2)



- Check for “passability” between *adjacent* edges
- Also known as “ray-cast” since if can cast a ray between A and C then waypoint B is not needed

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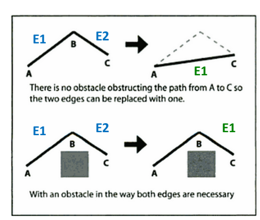
Simple Smoothing Algorithm (2 of 2)

1. Grab source E1
2. Grab destination E2
3. If agent can move between,
   a) Assign destination E1 to destination E2
   b) Remove E2
   c) Advance E2
4. If agent cannot move
   a) Assign E2 to E1
   b) Advance E2
5. Repeat until destination E1 or destination E2 is endpoint



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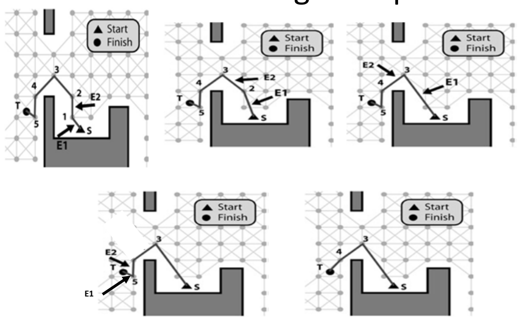
Path Smoothing Example



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DEMO (SMOOTH)

Outline

- Introduction (done)
- Navigation Graphs (done)
- Navigation Mesh (next)
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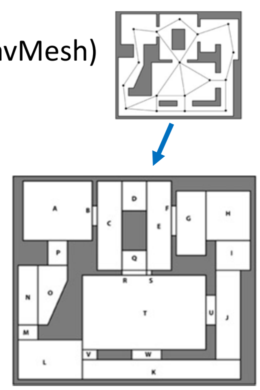
Navigation Mesh (NavMesh)

- Partition open space into network of *convex* polygons
  - Why convex? → guaranteed path from any point to any point inside
- Instead of network of points, have network of polygons
- Can be automatically generated from arbitrary polygons
- Becoming very popular (e.g., UE4)



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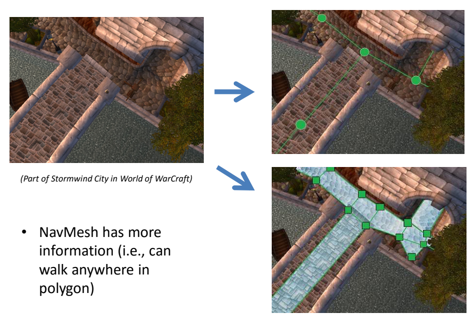
NavMesh Example (1 of 3)



Waypoint

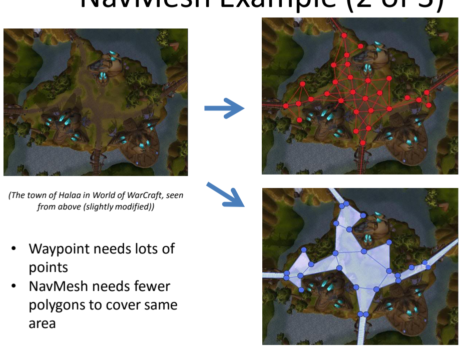
NavMesh

(Part of Stormwind City in World of WarCraft)

- NavMesh has more information (i.e., can walk anywhere in polygon)

http://www.ai-blog.net/archives/000152.html

NavMesh Example (2 of 3)



Waypoint

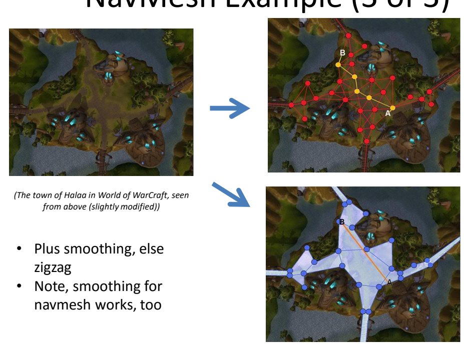
NavMesh

(The town of Halaa in World of WarCraft, seen from above (slightly modified))

- Waypoint needs lots of points
- NavMesh needs fewer polygons to cover same area

http://www.ai-blog.net/archives/000152.html

NavMesh Example (3 of 3)



Waypoint

NavMesh

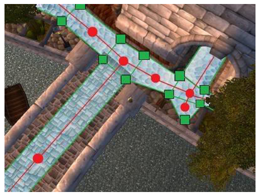
(The town of Halaa in World of WarCraft, seen from above (slightly modified))

- Plus smoothing, else zigzag
- Note, smoothing for navmesh works, too

http://www.ai-blog.net/archives/000152.html

NavMesh Performance

- *But isn't it slower to do pathfinding on NavMesh?*
- No. NavMesh is also a graph, just like waypoints.
- Difference? Navmesh has polygon at each graph node
- A* runs on any graph
  - Square grid
  - Waypoint
  - Navmesh



(Illustration of graph (red) underlying a navigation mesh)

http://www.ai-blog.net/archives/000152.html

NavMesh with other Paths

- NavMesh can be used *with* waypoints
- Use waypoints for higher-order locations
  - E.g.,
    - Soldiers need patrol path
    - Old man needs fishing path
    - Cover points for hiding
- NavMesh to get there

(Various terrain markers (AI hints) and NavMesh)

http://www.ai-blog.net/archives/000152.html

Outline

- Introduction (done)
- Navigation Graphs (done)
- Navigation Mesh
  - Generating a NavMesh (next)
- Pathfinding Tuning
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Generating NavMesh

- Can be generated by hand
  - e.g., lay out polygons (e.g., squares) to cover terrain for map
  - Takes a few hours for typical FPS map
- Can be generated automatically
  - Various algorithm choices
  - One example [Leo14]

[Leo14] Timothy Leonard. "Procedural Generation of Navigation Meshes in Arbitrary 2D Environments", *Open Journal Systems Game Behavior*, Volume 1, Number 1, 2014. Online: http://computing.derby.ac.uk/ojs/index.php/gb/article/view/13

Generating NavMesh – Walkable Area

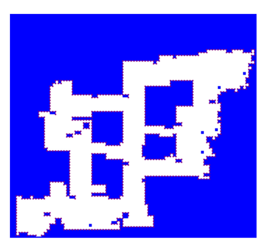
Base background (just for show)

Walkable area (white)

- Use collision grid to compute walkable area
  - Prepare 2d array, one for each pixel
  - Sample each pixel → if collide, then black else white

Generating NavMesh – Contour

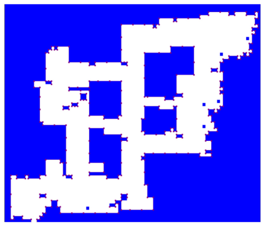
- Run marching squares to get contour
  - "marching squares" is graphics algorithm that generates contours for 2d field
  - Parallelizes really well
- Contour points used as vertices for triangles for NavMesh



After running marching squares. Purple dots show contour of walkable area.

Generating NavMesh – Simplified Contour

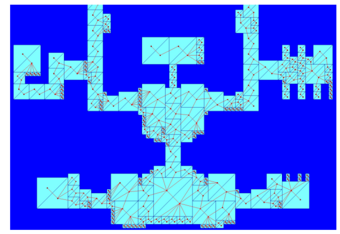
- Simplify contour by removing points along same horizontal/vertical line
- Don't remove all redundant points to avoid super-long edges (can produce odd navigation) in triangles
  - Define max distance between points



Simplifying contour points, max distance 128

Generating NavMesh – Triangles

- Fit squares → Loop
  - Find point not in mesh
  - Create square at point
  - Expand until hits edge or other square
  - Done when no more points
- Split squares into triangles
- Connect triangle to all other triangles in neighbor squares
- Now have graph for pathfinding (e.g., A*)



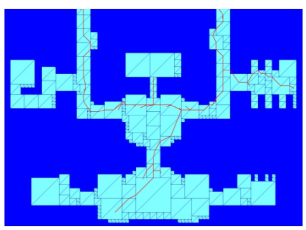
NavMesh generated using rectangle expansion. Red lines show neighbors.

Generating NavMesh – Path

- Using mid-points, path will *zig-zag* (see right)

Solution? → Path smoothing

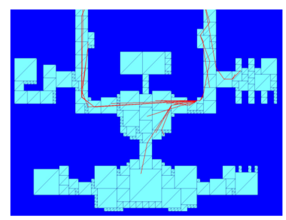
A. Simple ray-cast
B. Funnel



Path generated using midpoints of triangles

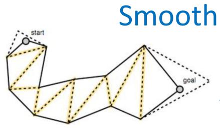
Generating NavMesh – Path Smoothing by Ray-cast

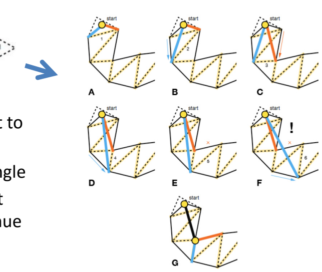
- Ray-cast as for "simple" smoothing shown earlier (see right)



Path generated using ray-cast to remove unnecessary points

Generating Navmesh – Path Smoothing by Funnel





- Smooth path from start to goal
- Move edges along triangle
- If can ray-cast, then not path "corner" so continue
- If cannot, then found "corner"

Outline

- Introduction (done)
- Navigation Graphs (done)
- Navigation Mesh (done)
- Pathfinding Tuning (next)
- Pathfinding in UE4

Possible Pathfinding Load Spikes

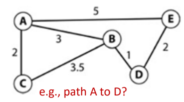
- Could be many AI agents, all moving to different destinations
- Each queries and computes independent paths
- Can lead to spikes in processing time

→ Game loop can't keep up!

- Solution? Reduce CPU load by:
  1) Pre-compute paths
  2) Hierarchical pathfinding
  3) Grouping
  4) Time slice

(Talk about each briefly, next)

Reduce CPU Overhead – Precompute



e.g., path A to D?

If static paths, pre-generate paths and costs (e.g., using Djikstra's)
Time/space tradeoff

	A	B	C	D	E
A	A	B	C	B	E
B	A	B	C	D	D
C	A	B	C	B	B
D	B	B	B	D	E
E	A	D	D	D	E

Shortest path table (next node)

	A	B	C	D	E
A	0	3	2	4	5
B	3	0	3.5	1	3
C	2	3.5	0	4.5	6.5
D	4	1	4.5	0	2
E	5	3	6.5	2	0

Path cost table

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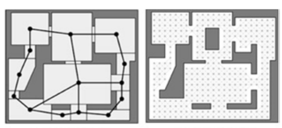
Reduce CPU Overhead – Hierarchical



High-Level Graph Low-Level Graph

- Typically two levels, but can be more
- First plan in high-level, then refine in low-level
- E.g., Navigate (by car) Atlanta to Richmond
  - States Georgia and Virginia
  - State navigation: Georgia → South Carolina → North Carolina → Virginia
  - Fine grained pathfinding within state

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Reduce CPU Overhead – Grouping

- In many cases, individuals do not need to independently plan path
  - E.g., military has leader
- So, only have leader plan path
  - Normal A*
- Other units then follow leader
  - Using steering behaviors (*later slide deck*)

(Sketch of how next)

Reduce CPU Overhead – Time Slice (1 of 3)

- Evenly divide fixed CPU pathfinding budget between all current callers
  - Must be able to divide up searches over multiple steps
- Considerable work required!
  - But can be worth it since makes pathfinding load constant

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Reduce CPU Overhead – Time Slice (2 of 3)

- Pathfinding generalized
  - Grab next node from priority queue
  - Add node to shortest paths tree
  - Test to see if target
  - If not target, examine adjacent nodes, placing in tree as needed
- Call above a "cycle"
- Create generalized class so can call one cycle

(next slide)

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Generalized Search Class

```
enum SearchType {Astar, Dijkstra};
enum SearchResult {found, not_found, incomplete};

class GraphSearch {

private:
  SearchType search_type;
  Position target;

public:
  GraphSearch(SearchType type, Position target);

  // Go through one search cycle.  Indicate if found.
  virtual SearchResult cycleOnce()=0;

  virtual double getCost() const=0;

  // Return list if edges (path) to target.
  virtual std::list<PathEdge> getPath() const=0;
};
```

- Derive specific search classes (A*, Dijkstra)
- Each game loop, PathManager calls cycleOnce()
- (If enough time, could call more than once)

Reduce CPU Overhead – Time Slice (2 of 3)

- Create PathPlanner for Obj
- Create PathManager to <u>allocate cycles</u>
- PathPlanner registers with PathManager
  – Gets instance of path
- Each tick, PathManager distributes cycles among all
- When path complete, send message (event) to PathPlanner, which notifies Object
- Objects to use for pathing

(See example next slide)

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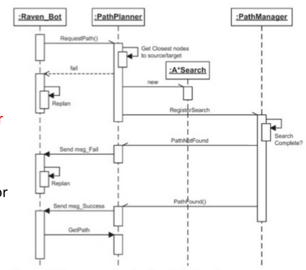
Time Slice Example

- Object requests path to target
- PathPlanner
  – Provides closest node
  – Creates search (A*, also could be Djikstra)
  – Registers with PathManager
- PathManager
  – Allocates cycles among all searches
  – When done, returns path (or path not found)
- PathPlanner
  – Notifies Object
  – Object requests path



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Reduce CPU Overhead – Time Slice (3 of 3)

- Note "time slicing" implies that caller may have to wait for answer
  – Wait time proportional to size of graph (number of cycles needed) and number of other Objects pathing
- What should Object do while waiting for path?
  – *Stand still* → but often looks bad (e.g., player expects unit to move)
  – So, *start moving*, preferably in "general direction" of target
    - "Seek" as behavior (*see later slide deck*)
    - "Wander" as behavior (*ditto*)
  – When path returns, "smooth" to get to target (example next slide)

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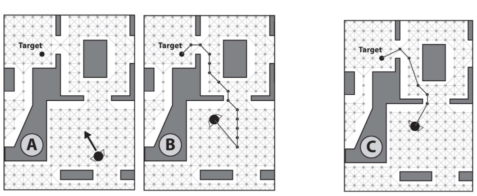
Time Slicing needs Smoothing

- Object registers pathfinding to target
- Starts seeking towards target
- When path returns, Object will backtrack. Bad!
- Solution? → Simple smoothing described earlier to remove



Without smoothing   Smoothed

DEMO (TIME-SLICING)

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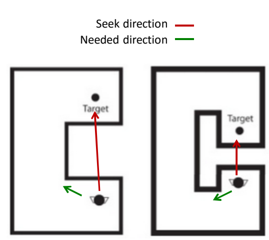
Time Slicing with Seek Fail

- When waiting for path, head "wrong" direction
  – May even hit walls!
  – Looks stoopid
- Alternative can be to return path to node closer to Object
  – Modify A* to return answer after *X* cycles/depth
  – Start moving along that path
  – Request rest of path
- When complete path returned, adjust



Seek heads in obvious (to player) wrong direction

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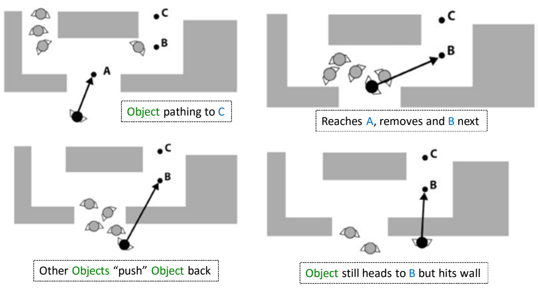
Getting Out of Stuck Situations



DEMO (STUCK)

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Getting Out of Stuck Situations

- Calculate distance to Object's next waypoint each update step
- If this distance remains about same or consistently increases
  - →Probably *stuck*
  - →Replan
- Alternatively – estimate arrival time at next waypoint
  - If takes longer, probably *stuck*
  - → Replan

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Advanced Pathfinding Summary

- Not necessar to use *all* techniques in *one* game
- Only use whatever game demands and *no more*
- An advanced pathfinding feature is an optional project requirement
- For reference C++ code see
  http://samples.jbpub.com/9781556220784/Buckland_SourceCode.zip
  (Chapter 8 folder)

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- Introduction (done)
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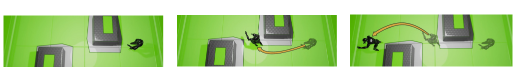
Navigation in UE4



- Has NavMesh
  - Auto generated initially
  - Tweaked by hand
- NavLinkProxy to allow "jumping"
- Auto re-generates when static objects move

(More in upcoming slides)

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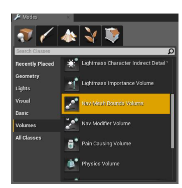
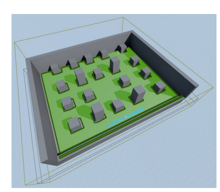
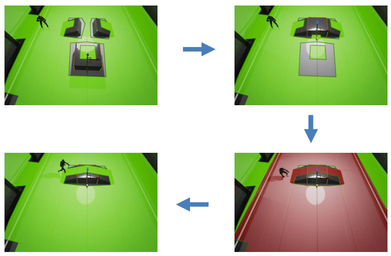
UE4 NavMesh



- *Modes Panel* → *Create* → *Volumes*
- Translate/scale to encapsulate walkable area
- Press "P" to view
  - Green shows mesh



Automatic Update as Design Level

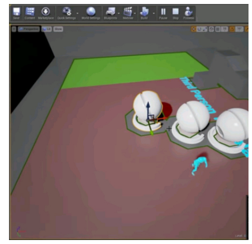


Move static mesh (bridge)

NavMesh automatic update

Automatic Update at Runtime

- *Edit → Project Settings → Navigation Settings → Rebuild at Runtime*



Unreal Engine 4 Tutorial - NavMesh Rebuild Realtime
https://www.youtube.com/watch?v=UpbaCHTcNPA

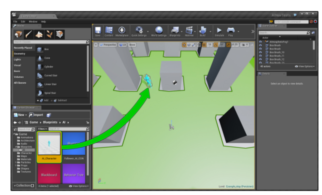
NavLinkProxy

- Tell Pawns where can temporarily leave NavMesh (e.g., to jump off edges)

https://docs.unrealengine.com/latest/INT/Resources/ContentExamples/NavMesh/1_2/index.html

Use NavMesh with Character

- Setup AI Character and AI Controller Blueprint
- Place character in scene
- "Move to location"
  - E.g., waypoints
- "Move to actor"
  - E.g., follow or attach character



Unreal Engine 4 Tutorial - Basic AI Navigation
https://www.youtube.com/watch?v=KDazrBx6lY