
Class 6
Pathfinding and AI

Game A.I.

- Artificial Intelligence is what makes computer-controlled entities in a game behave reasonably
- Can be used to control enemy entities, or used to support the human player
- Usually, we want AI-controlled entities to behave as if a human is controlling them
- The goal of game AI is to provide a fun challenge, not necessarily to make optimal decisions

Pathfinding

- Pathfinding is the most common primitive used in game AI
- A path is a list of instructions for getting from one location to another
  - Not just locations: instructions could include “jump” or “climb ladder”
- A hard problem!
  - Bad path planning breaks the immersive experience
  - Many games get it wrong

3D world representation

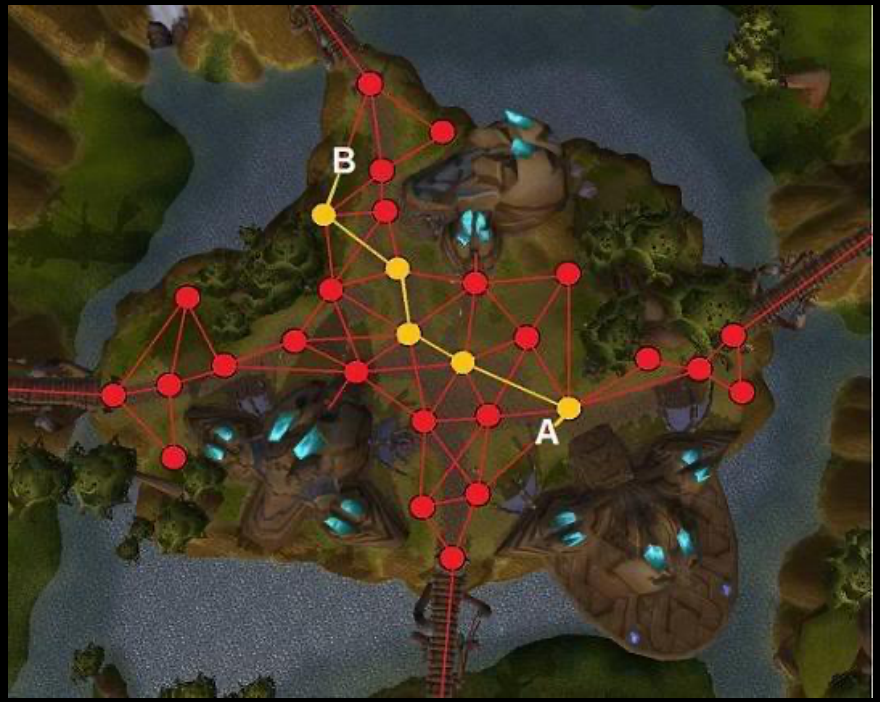
- Need an efficient encoding of relevant information in the world
  - Navigable space
  - Important locations (health, safety, bases, mission objective)
- Graph-based approaches
  - Waypoints
  - Navigation meshes

Decision Making

- World is represented as a graph
  - Nodes represent open space
  - Edges represent ways to travel between nodes
  - Use graph search algorithms to find paths
- Two common types
  - Waypoint graphs
  - Navigation meshes

Waypoint graphs

- Represents a fixed set of paths through the world
- Nodes are waypoints
- Edges represent a path between adjacent nodes



Disadvantages of waypoint graphs

- Optimal path is likely not in the graph
  - Paths will zig-zag to destination
  - Good paths require huge numbers of waypoints and/or connections, which can be expensive
- No model of space in between waypoints
  - No way of going around dynamic objects without recomputing the graph
- Awkward to handle entities with different radii
  - Have to turn off certain edges and add more waypoints

Navigation meshes

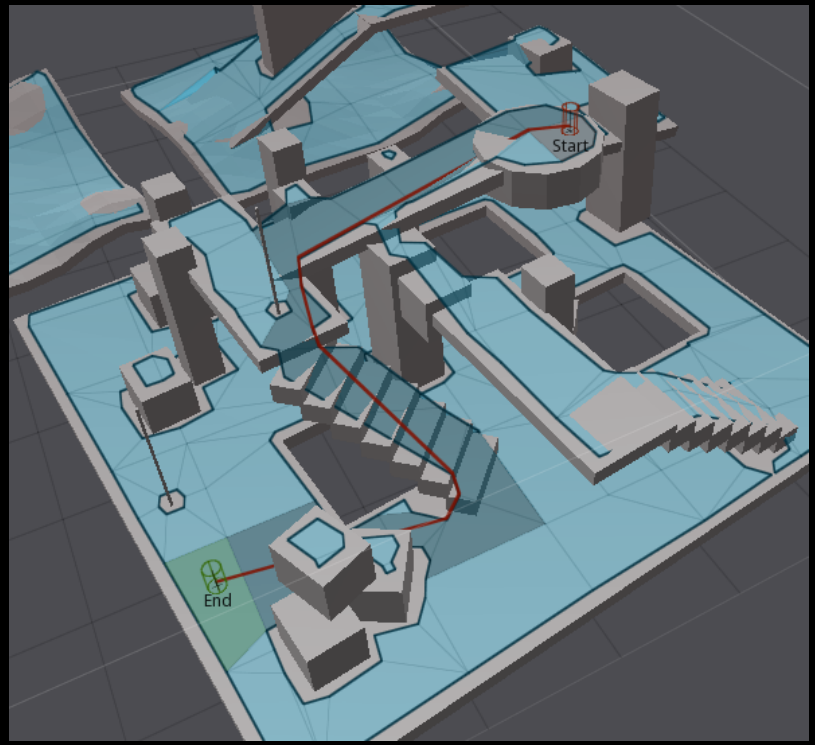
- Convex polygons as navigable space
- Nodes are polygons
- Edges show which polygons share a side

Advantages of navigation meshes

- More efficient and compact representation
  - Equivalent waypoint graph would have many more nodes and would take longer to traverse
- Models entire navigable space
  - Can plan path from anywhere inside nav mesh
  - Paths can be planned around dynamic obstacles
  - Zig-zagging can be avoided
- Naturally handles entities of different radii
  - Don't go through edges less than 2 * radius long
  - Leave at least a distance of radius when moving around nav mesh vertices

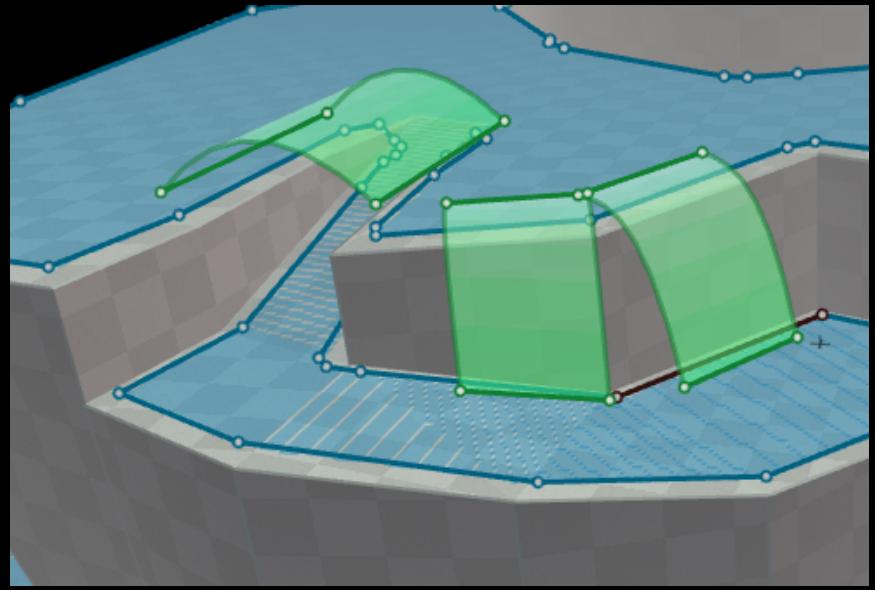
Navigation meshes

- Different from collision mesh
  - Only contains walkable faces
  - Stairs become a single, rectangular polygon
  - Polygons are usually smaller to account for player radius



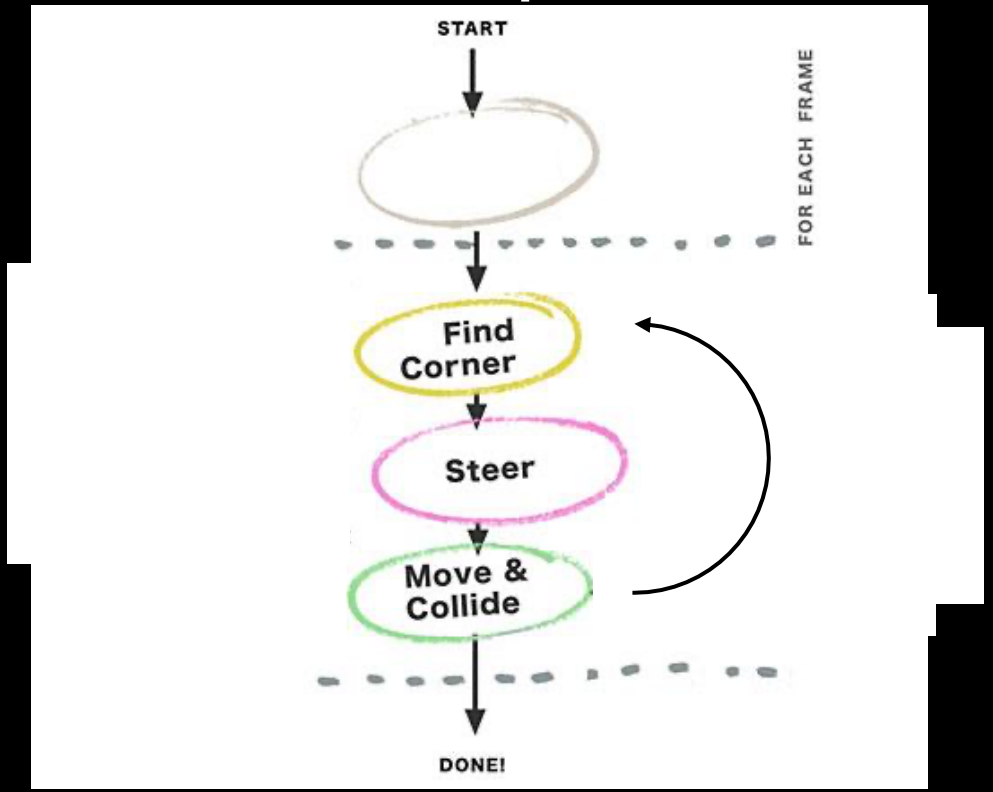
Navigation meshes

- Annotate special regions
  - Can have regions for jumping across, falling down, crouching behind, climbing up, …
  - Regions are usually computed automatically



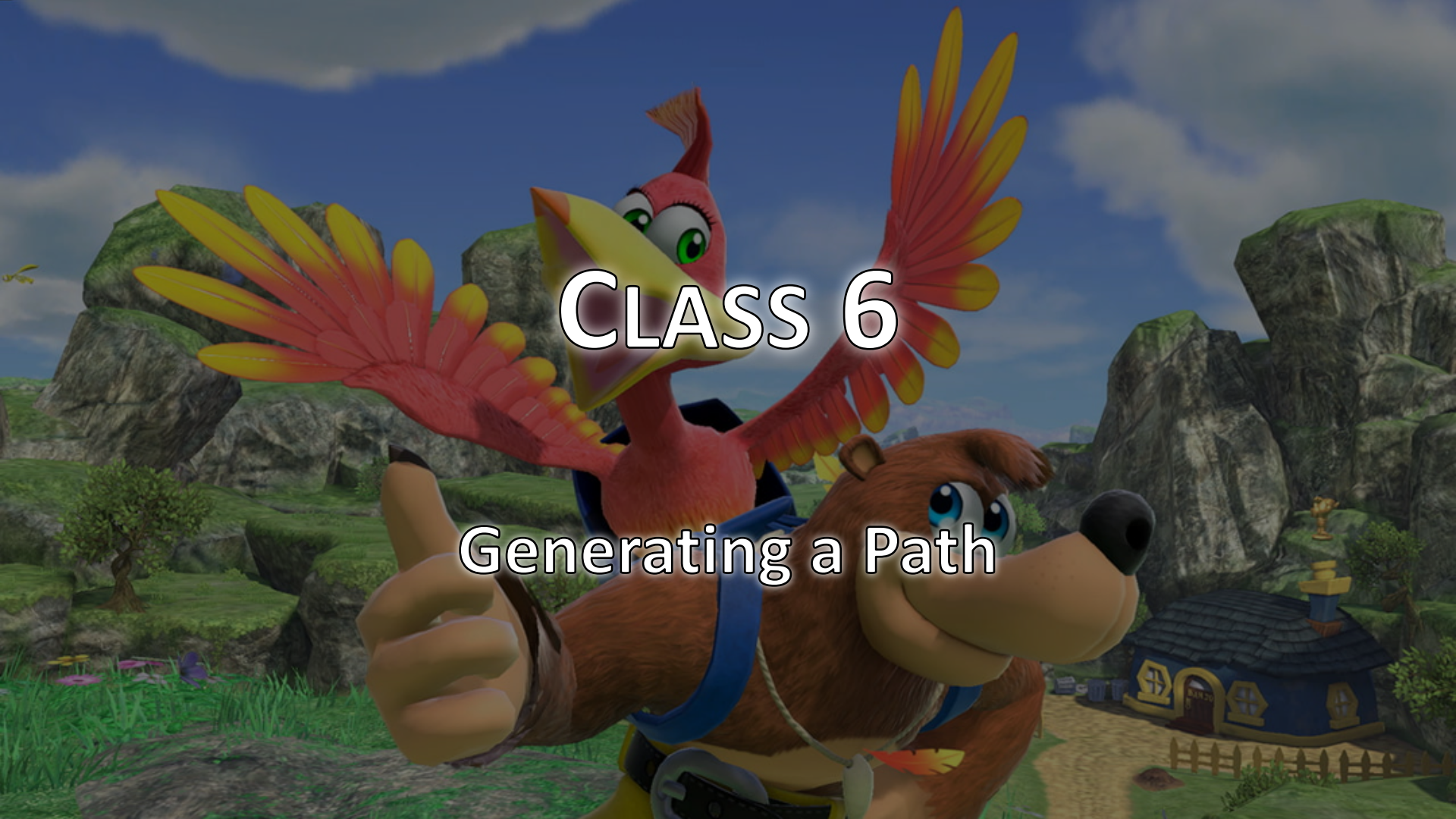
Navigation loop

- Process for robust path navigation on a navigation mesh:
  - Find sequence of polygons (corridor) using graph algorithm
  - Find corner using string pulling (funnel algorithm)
  - Steer using smoothing
  - Actually move/collide entity



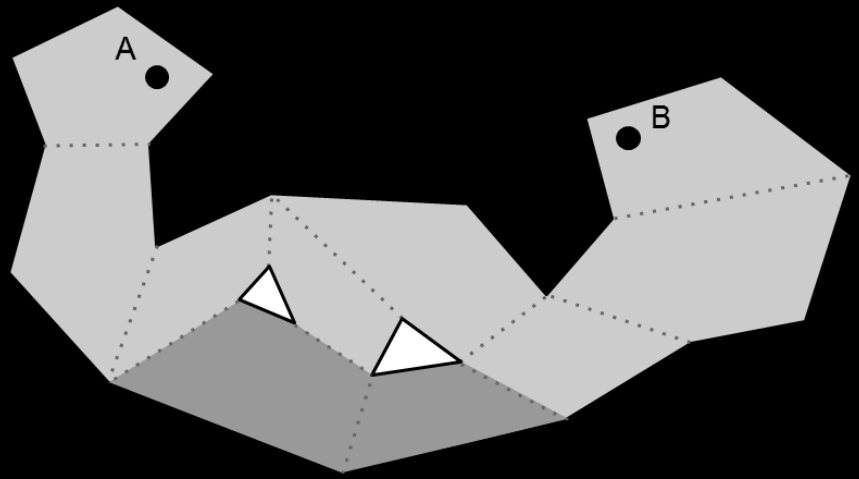
Graph search

- First step in finding a path
- Graph search problem statement
  - Given starting point A, target point B and a nav mesh
  - Generate a list of nav mesh nodes from A to B (called a corridor)
- Simplest approach: Breadth-first search
  - Keep searching until target point is reached
  - Each edge has equal weight
- Most common approach: A-star
  - Variable edge weights (mud or steep surfaces may have higher cost)
  - Uses a heuristic to arrive at an answer faster


Class 6
Generating a Path

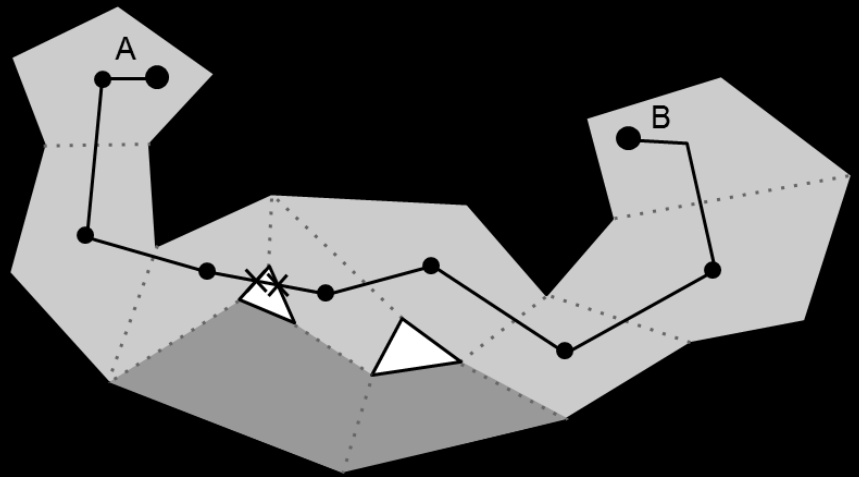
Path generation: problem statement

- Given a list of polygons (output of a graph search)
  - The light polygons
- Construct the shortest path for the agent
  - Where a path is a sequence of connected segments
  - The path must lie entirely in the list of polygons



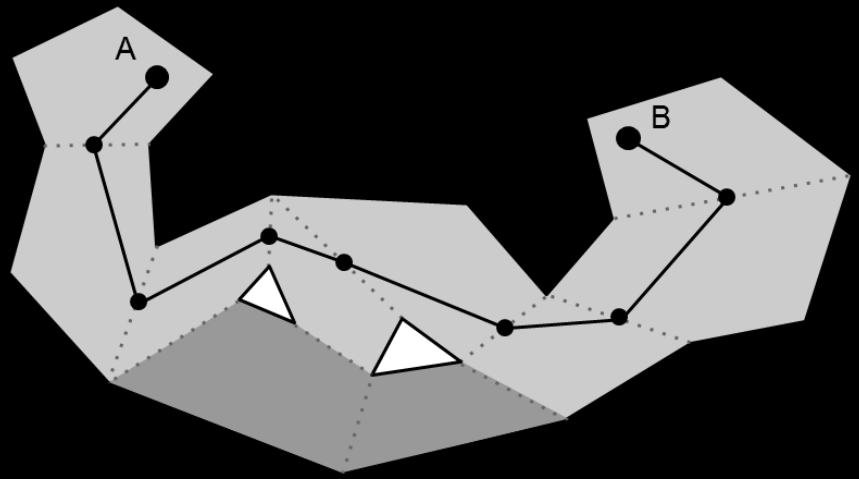
Path generation: first attempt

- Can we just connect polygon centers?
- No: the path might not even be within the polygons
- Polygons' convexity only tells us that any 2 points in a single polygon can be connected with a segment



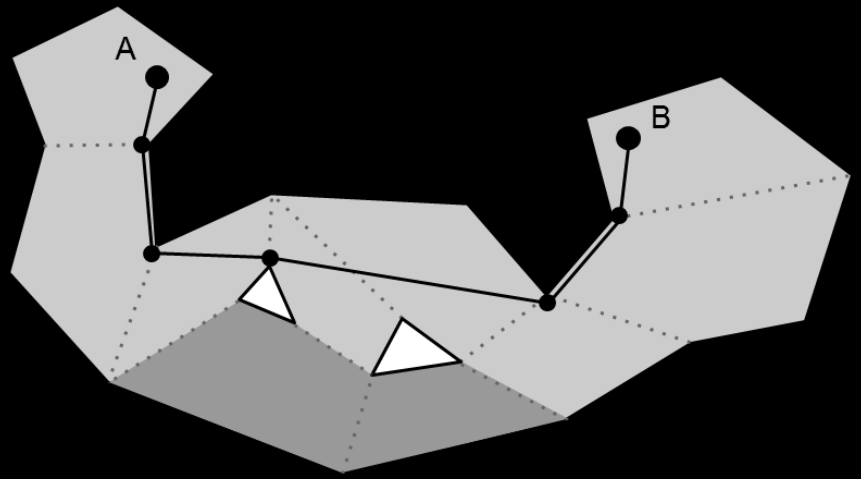
Path generation: second attempt

- Can we just connect centers of polygon sides?
- This always produces a valid path (within the polygons)
- But not always the optimal path (zig-zagging)
- This is just a waypoint graph!



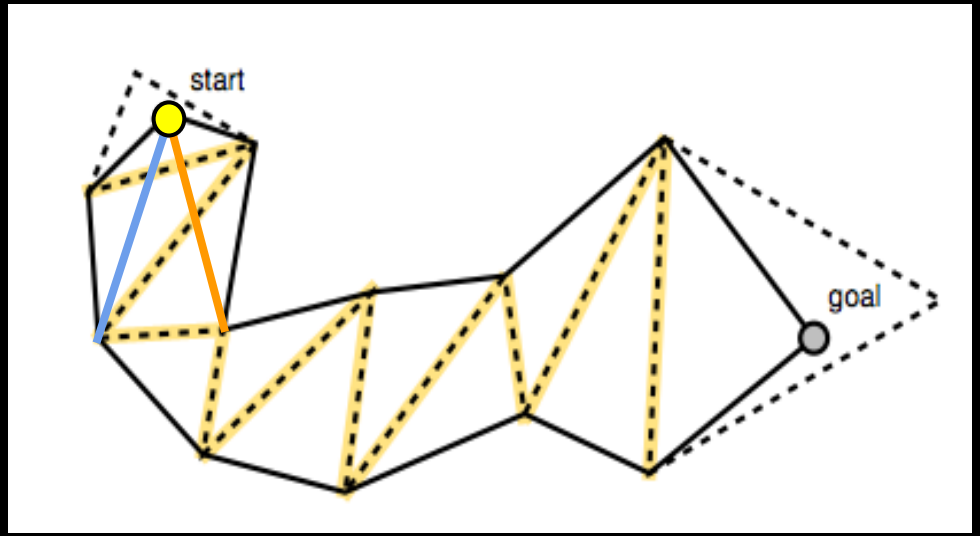
Path generation: third attempt

- The Funnel algorithm finds the optimal path
- Hugs corners
- Is like “pulling a string” that connects A and B until it is taut

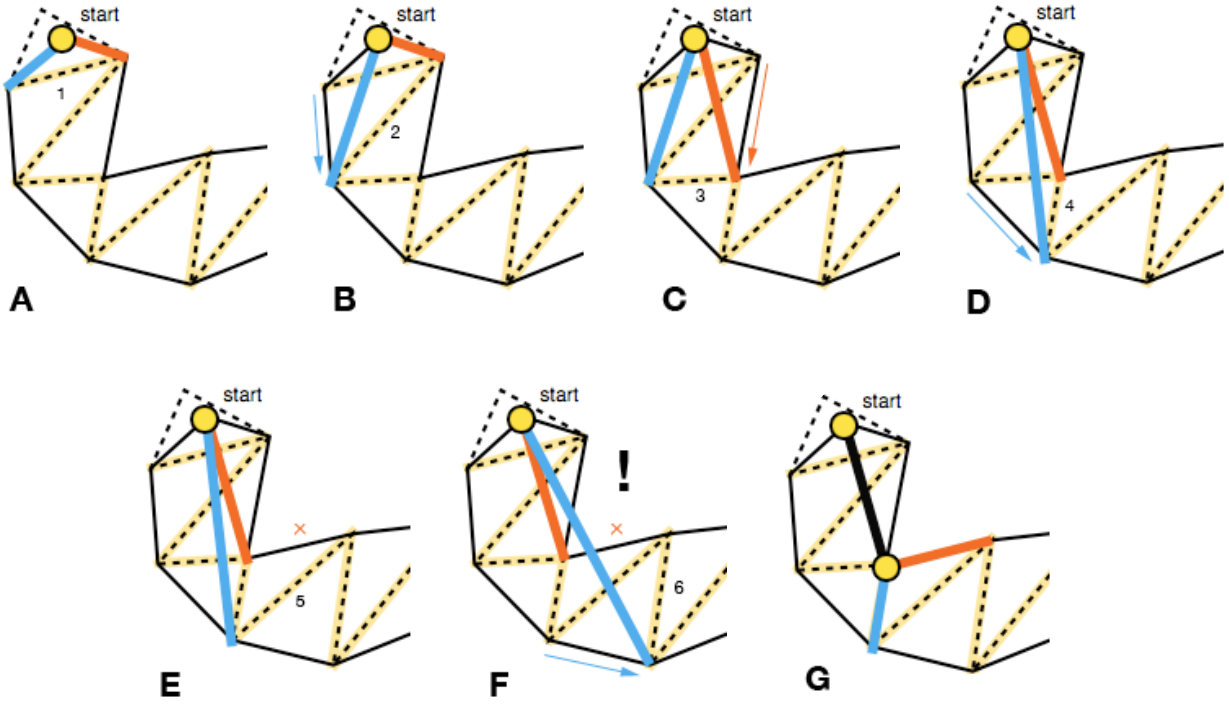


Funnel algorithm

- Traverses through a list of polygons connected by shared edges (portals)
- Keeps track of the leftmost and rightmost sides of the "funnel" along the way
- Alternates updating the left and right sides, making the funnel narrower and narrower
- Add a new point to the path when they cross



Funnel Algorithm



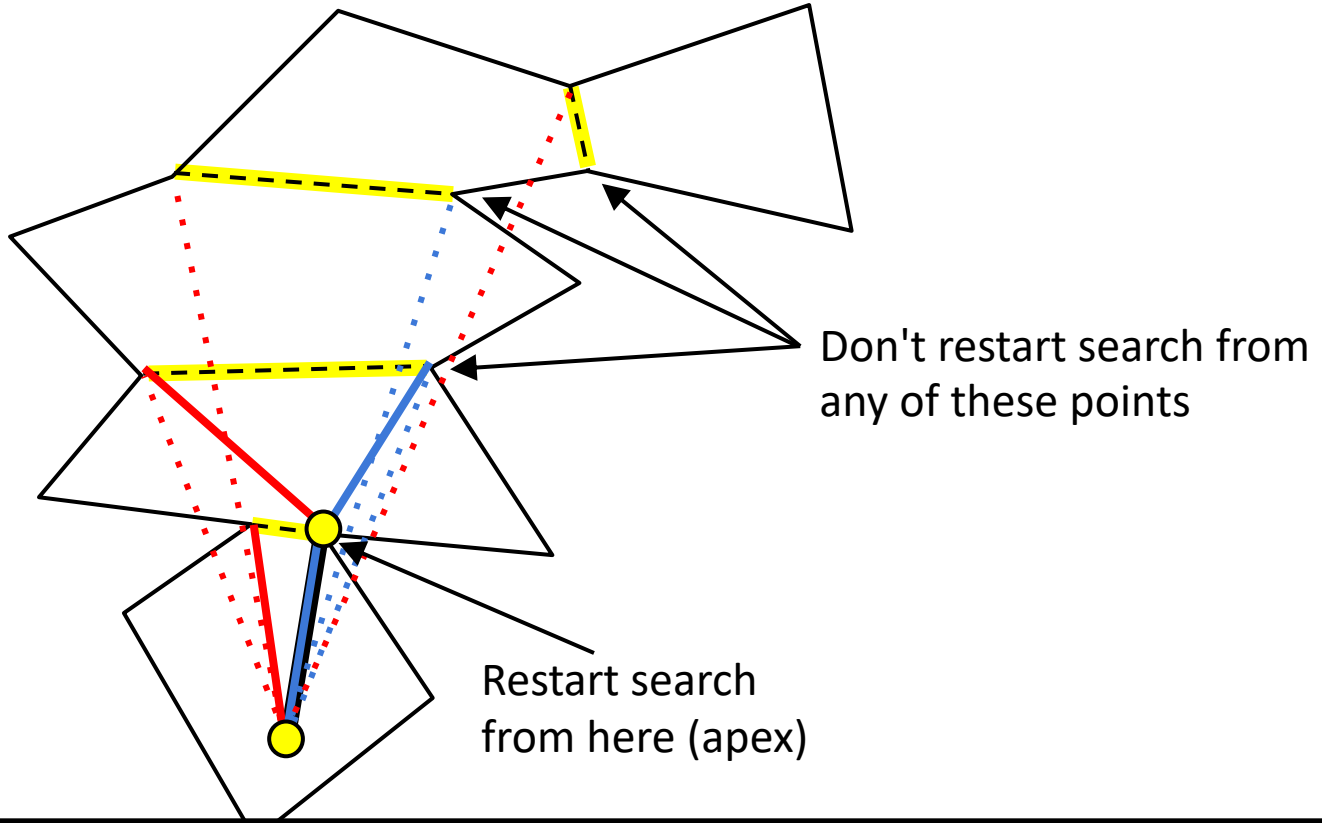
Funnel Algorithm

- Start
  - Apex point = start of path
  - Left and right points = left and right vertices of first portal
- Step
  - Advance to the next portal
  - Try to move left point to left vertex of next portal
    - If inside the funnel, narrow the funnel (C-D in previous slide)
    - If past the right side of the funnel, turn a corner (E-G in previous slide)
      - Add right point to path
      - Set apex point to right point
      - Restart at portal where right point came from
  - Try to move right point to right vertex of next portal
    - Similar to left point

Edge cases

- Zero-length funnel side (portals that share a vertex)
  - Always use left*0.99+right*0.01 for the left and left*0.01+right*0.99 for the right (shrinks portal slightly)
- End iteration of the funnel algorithm
  - End point is portal of size 0, need to check for potential restart like other portals

Funnel algorithm example



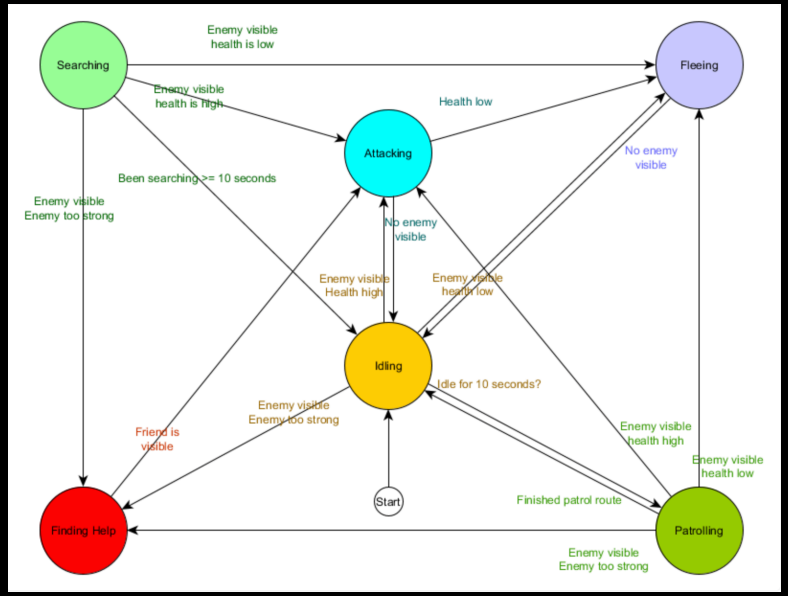

Class 6
Finite/Hierarchical State Machines

Decision Making

- NPC’s should do something, but what?
- Could hardcode the logic
  - Game-specific
  - Likely involves copied code
- We want a structured way for NPC’s to make decisions
  - Based on game state, unit state, random values, etc…

Finite State Machines

- A finite state machine (FSM) defines a set of states for an entity and the conditions that cause the entity to change states
- The FSM can be represented by a directed graph where the nodes are states and the edges are transitions between states
- At every tick, we check whether we need to move to a different state given the state we are currently in and the transitions to other states that we have defined



Finite State Machine Example

- This is an FSM for a patrolling guard AI
- Note how a lot of logic is copied between the edges in the graph
- To implement this FSM, we would have to do a lot of copy-and-pasting and hardcoding
- Can we formulate a better approach that creates the same behavior?

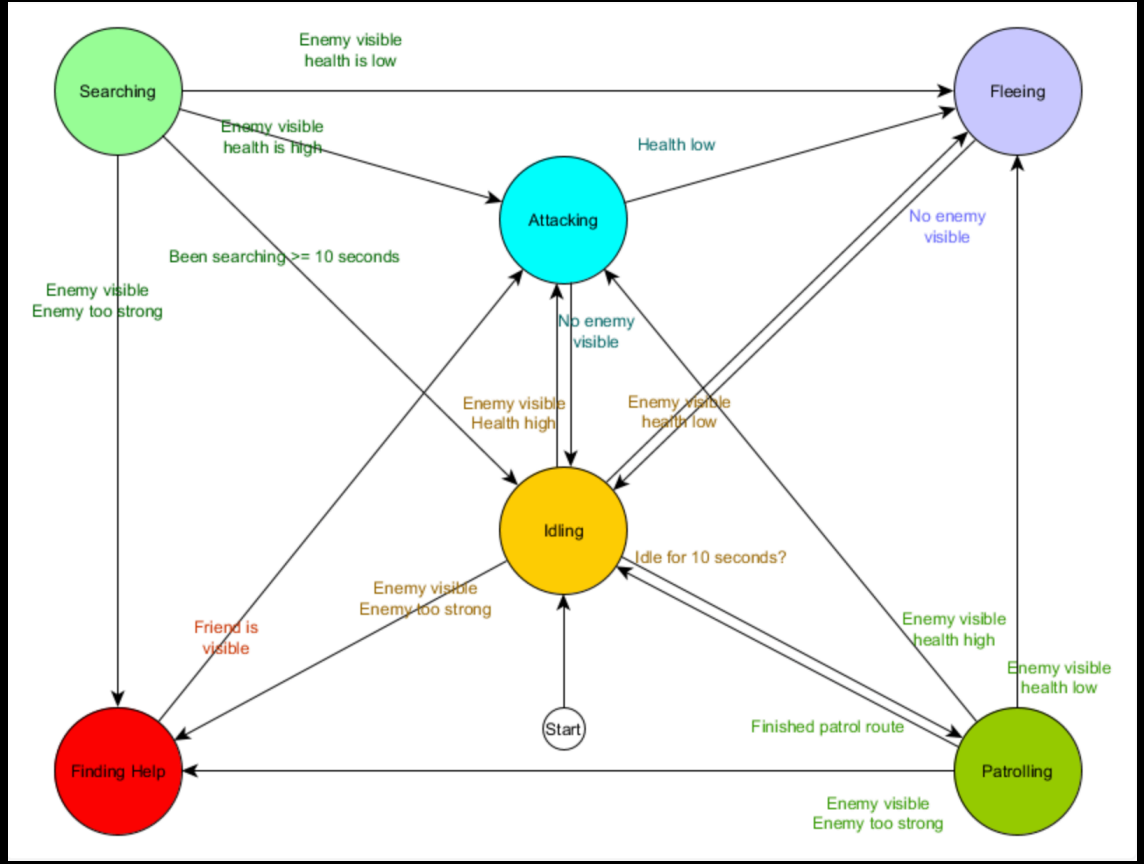
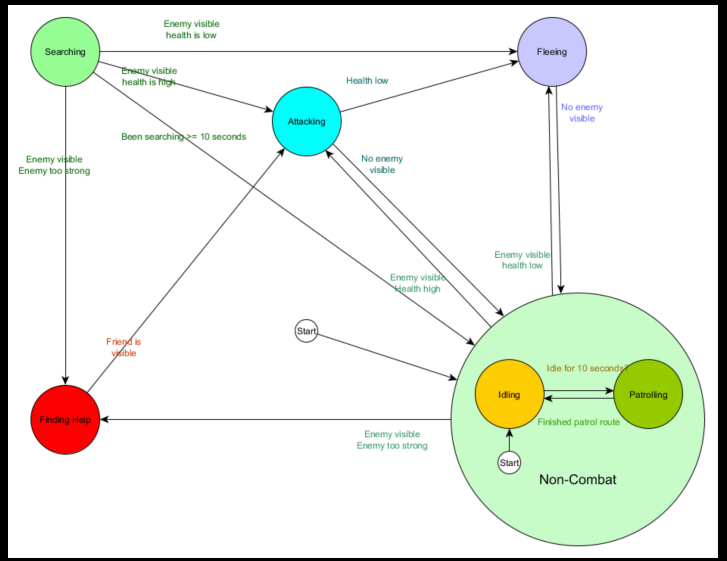


Image from:
https://www.gamedev.net/tutorials/programming/artificial-intelligence/the-total-beginners-guide-to-game-ai-r4942/

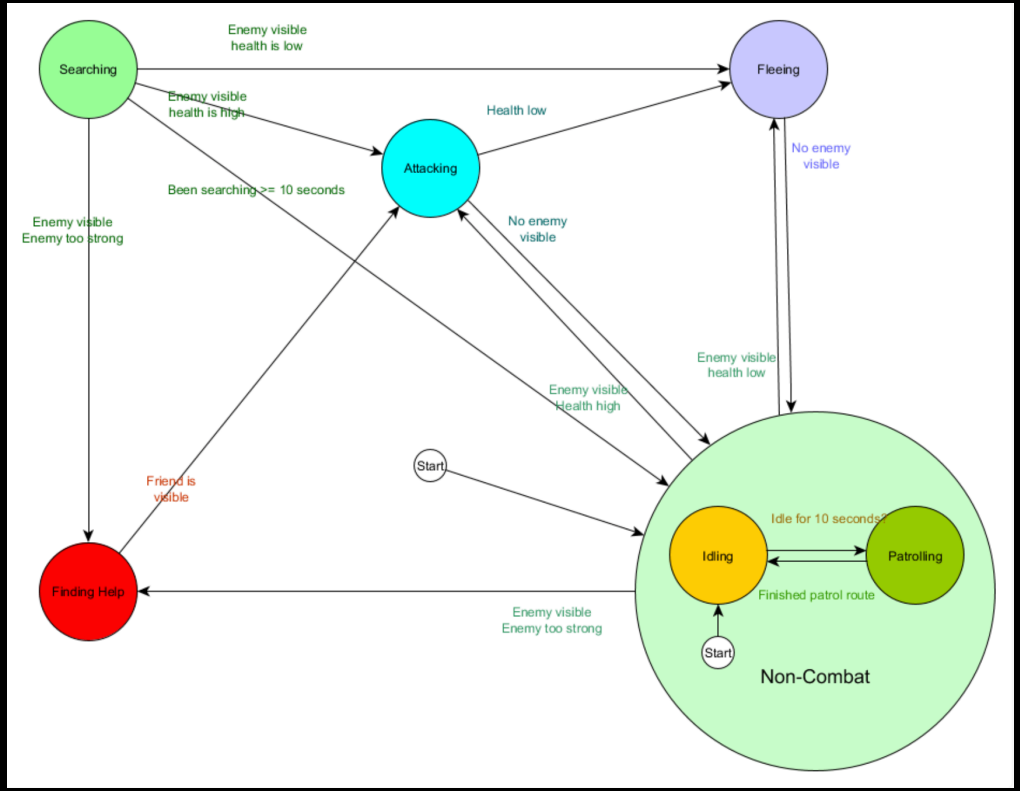
Hierarchical State Machines

- A hierarchical state machine (HSM) defines a state hierarchy
- States may have substates within them, (which also may have substates within them)
- Transitions between states are defined between nodes in the hierarchy (non-combat) as well as leaf substates (attacking, idling)
- It is easier to have an entity perform two behaviors at once if we use an HSM rather than a FSM



Hierarchical State Machine Example

- The is an HSM describing the same functionality as the FSM for the patrolling guard
- Notice how using an HSM simplifies the transitions in the graph
- We still would have to define a lot of functionality game-side to make this work



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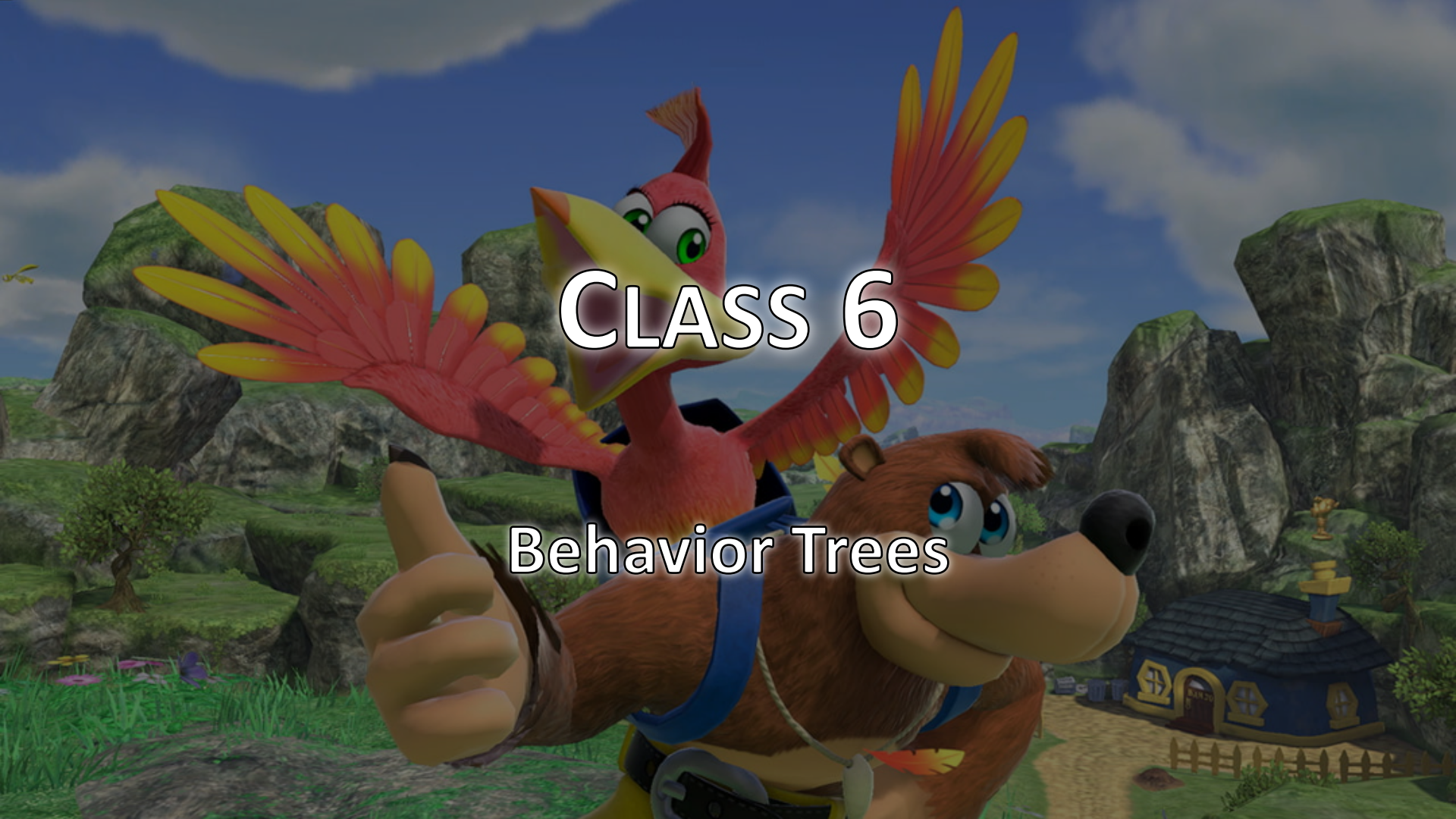
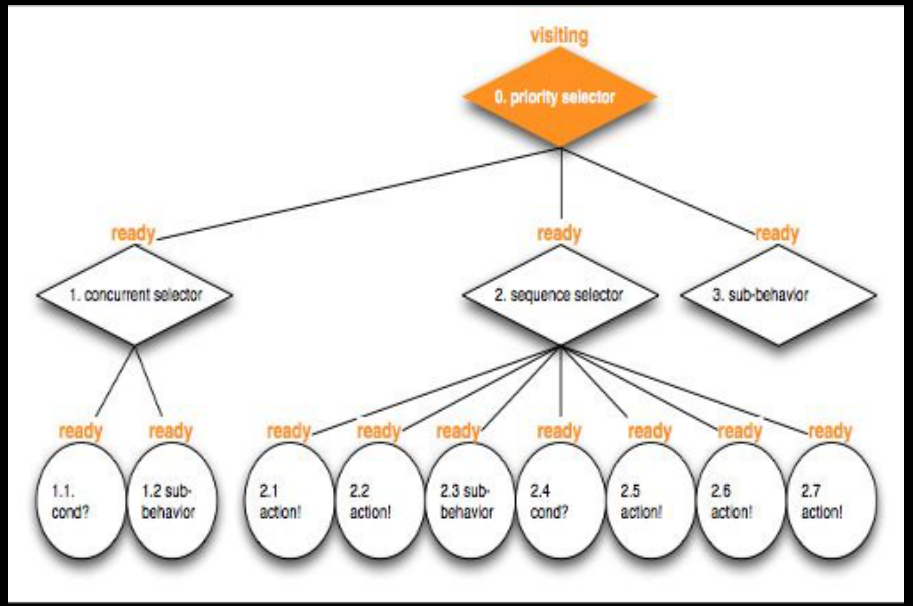

Class 6
Behavior Trees

Behavior Trees

- Popularized by Halo 2
- Core functionality is engine-general!

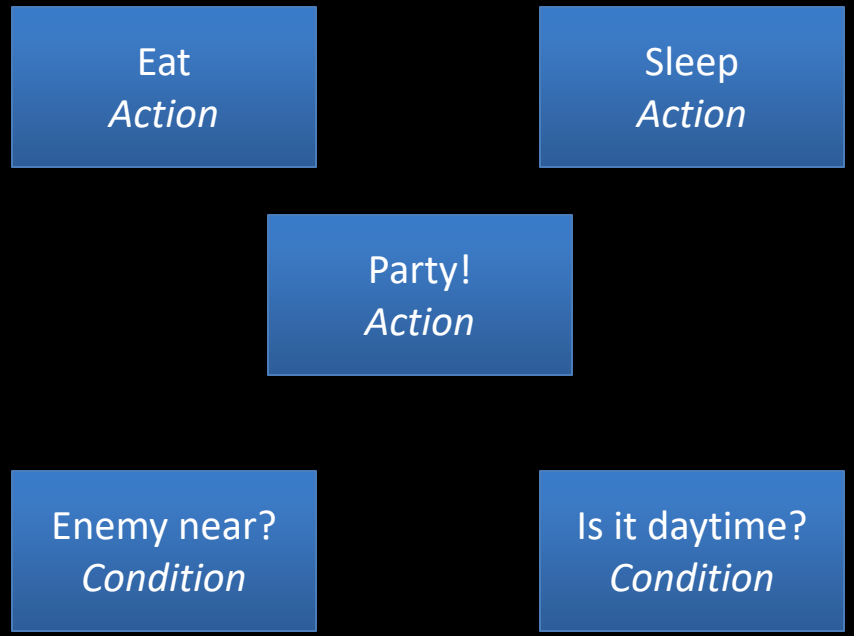
Structure

- It's a tree!
- Every tick, the root node is updated
- Each node returns a status when it's updated
  - SUCCESS, FAIL, RUNNING
- Nodes will update their children and return a status based on responses



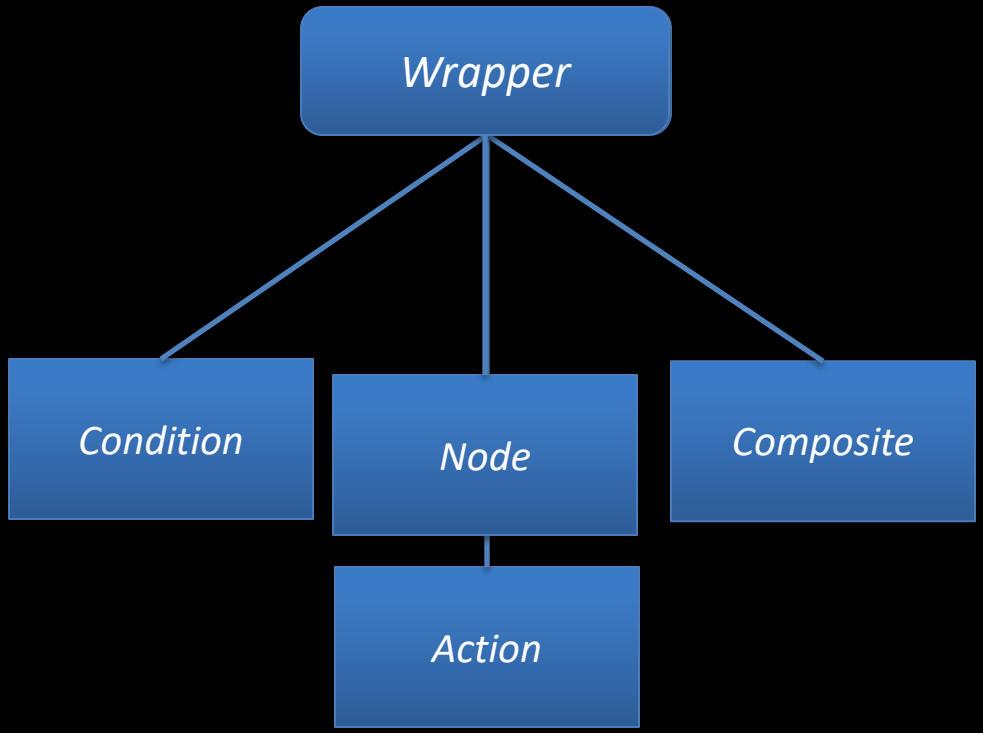
The Leaves

- Leaf nodes of the tree are Actions and Conditions
- Actions do things
  - Make a unit move or attack
  - Return SUCCESS or FAIL based on result of Action
  - Return RUNNING if Action is still if progress
- Conditions check some game state
  - Returns SUCCESS if the condition is true, or FAIL if the condition is false



The Internal Nodes

- Internal nodes are Composites and Wrappers/Decorators
- Composites have multiple children nodes
- Wrappers wrap a single child node and execute their child if they succeed
- Composites and Wrappers dictate the traversal of the tree on an update

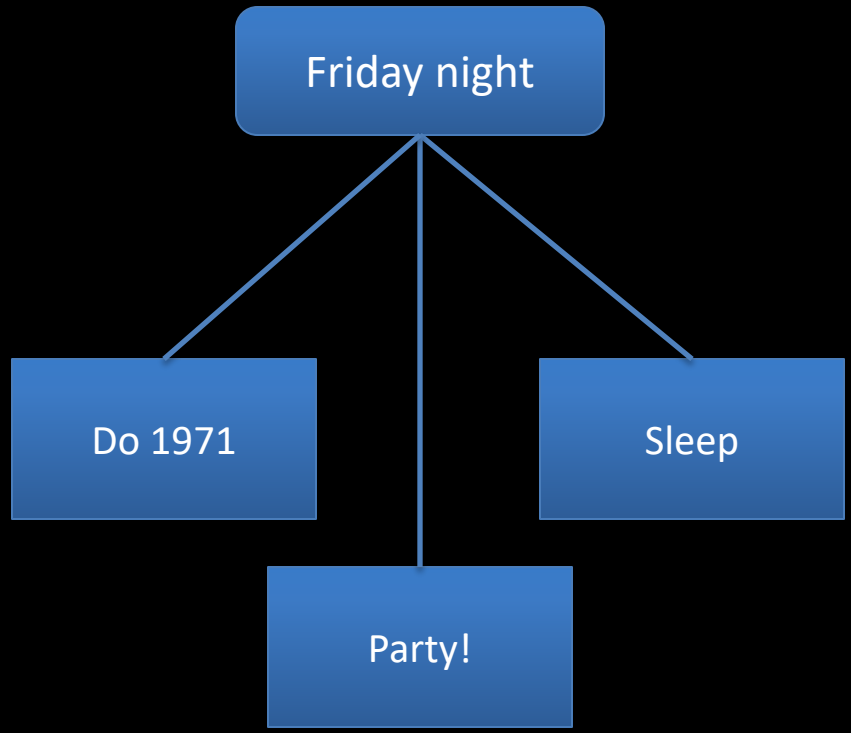


The Composites

- Maintain a list of children nodes
- Update by updating the children nodes (usually in a particular order)
- Return RUNNING if a child returns RUNNING
- Return SUCCESS/FAIL under other circumstances depending on the type of composite

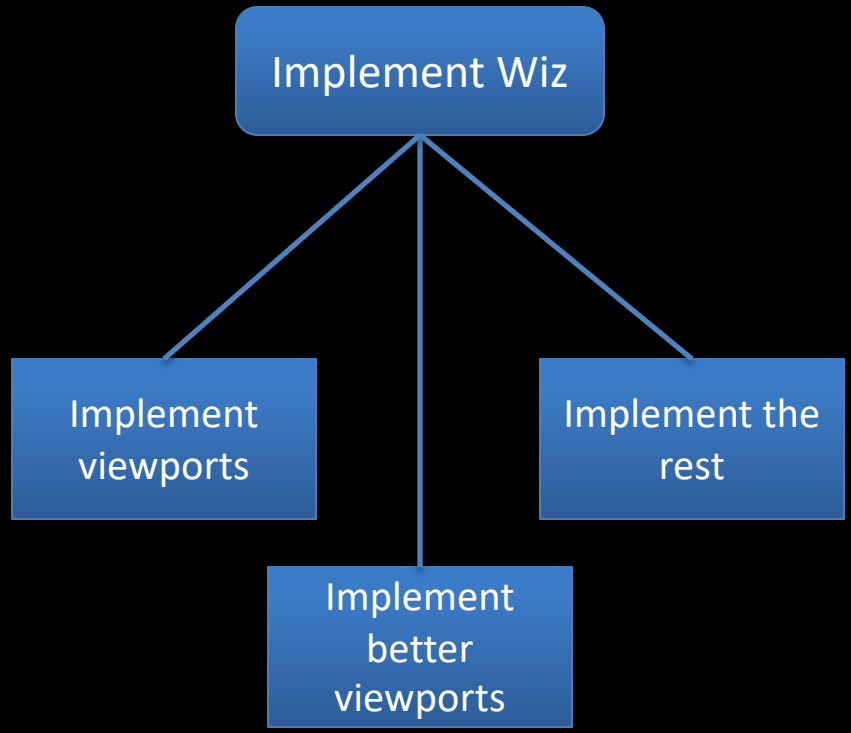
The Selector

- On update, updates each of its children in order until one of them *doesn't* fail
  - Hence "select", as this child has been "selected"
- Returns FAIL only if all children fail
- Kind of like an if else statement or block of or's
  - If child 1 succeeds, else if child 2 succeeds, etc…



The Sequence

- On update, updates each of its children in order until one *does* fail
- Returns SUCCESS if the entire sequence completes, else FAIL
- If one behavior fails then the whole sequence fails, hence “sequence”
- Similar to a bunch of and’s



Other Nodes

- Wrappers contain a single child and modify its behavior. Examples include:
  - Invert child
  - Repeatedly update child X times until FAIL or SUCCESS
- Random Selectors update its children in random order
  - For unpredictable behavior
  - Harder to debug though
- Some engines define composites that allow for multiple tasks to be executed simultaneously

Behavior Tree Node

- Just needs to be updated and reset
- Sample contract:

```
enum Status { SUCCESS, FAIL, RUNNING };
class BTNode {
public:
	virtual Status update(float seconds) = 0;
	virtual void reset() = 0;
}
```

Composites

- Needs a list of children
- Also should keep track of what child was running
- Sample contract:

```
class Composite: public BTNode {
    std::vector<BTNode *> m_children;
    BTNode *m_lastRunning;
}
```

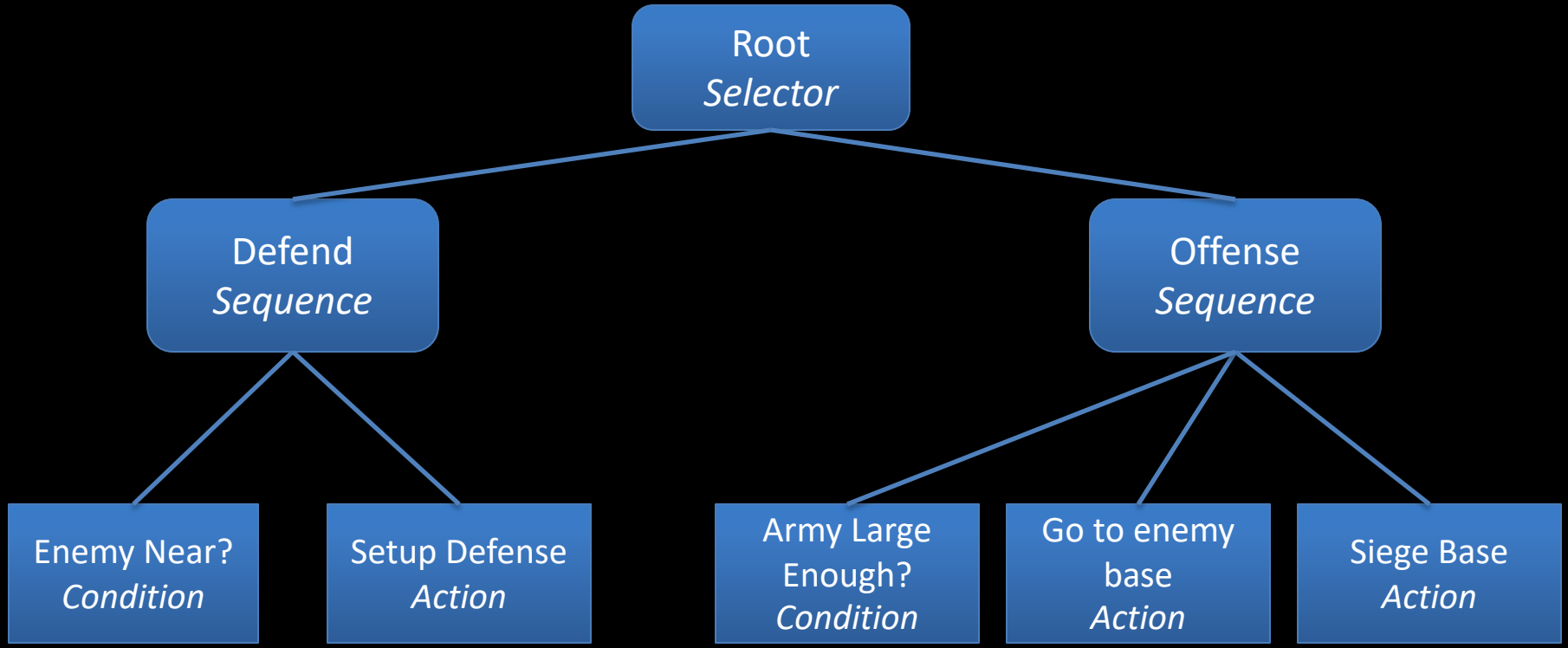
Note about Composites

- Sequences start updating from the previously RUNNING child
  - Previously running child should be left intact after returning, unless the entire sequence was completed
  - Goal is to complete the entire sequence – “I was in the middle of something and should continue where I left off”
- Selectors should always update from the first child
  - Should reset the previously running child if a child before it starts RUNNING
  - Children have priority – “I should always go back to defend my base, even if I’m in the middle of an offensive sequence”

Behavior Trees

QUESTIONS?

Example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Defend
Sequence
Offense
Sequence
Enemy Near?
Condition
Setup Defense
Action
Army Large Enough?
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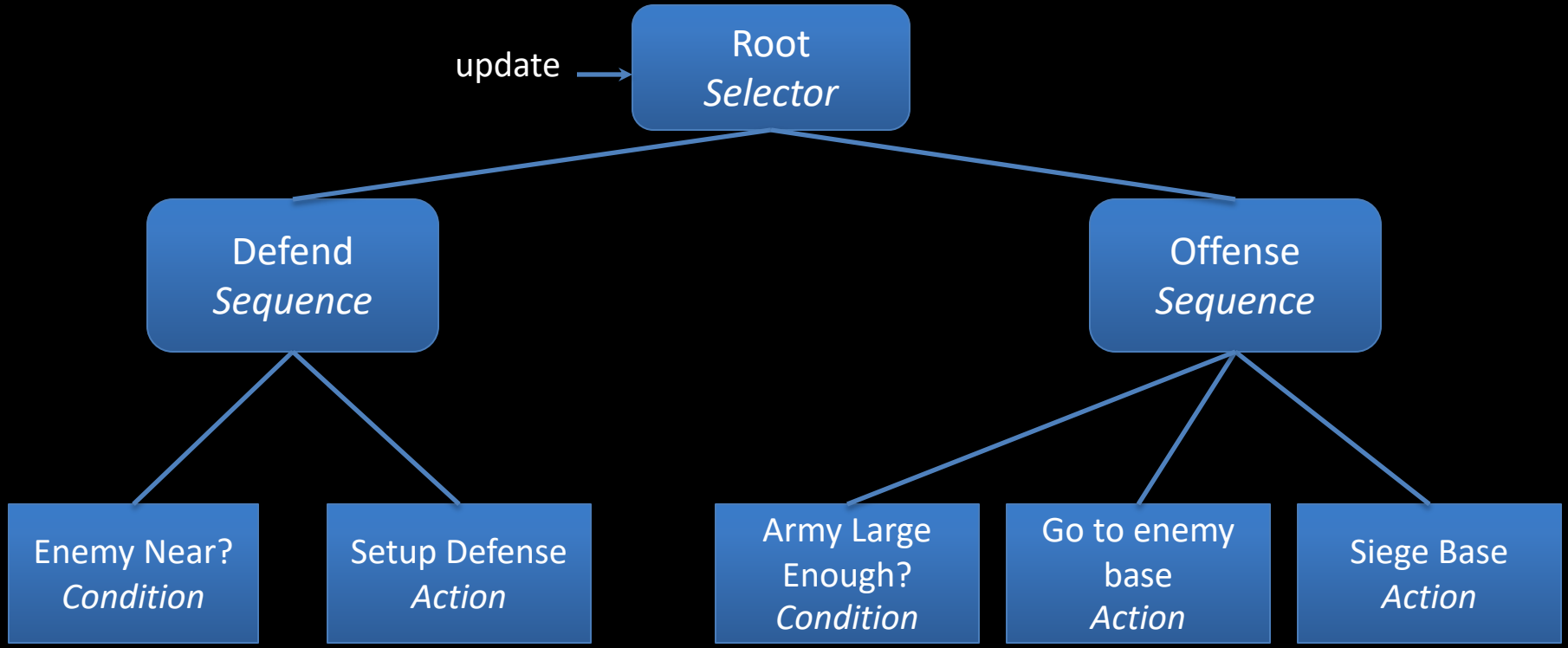
Go to enemy base
Action
Siege Base
Action

Example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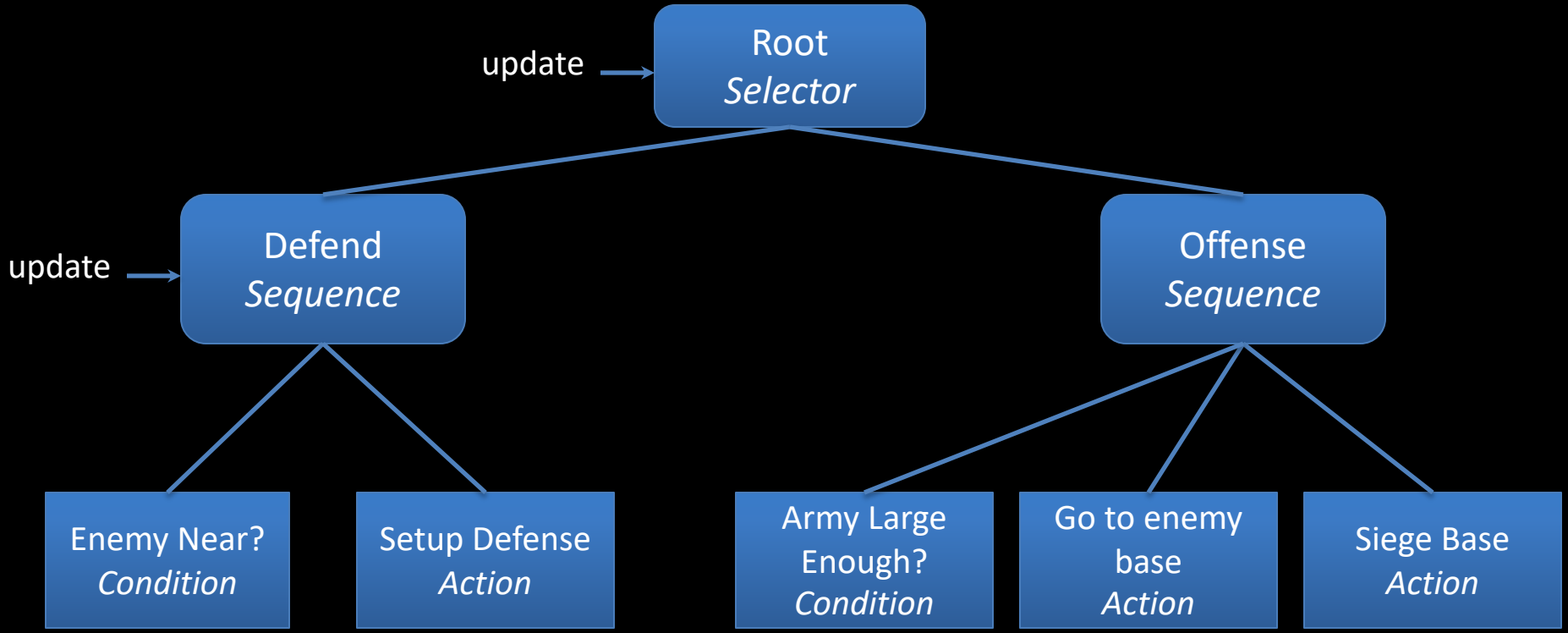
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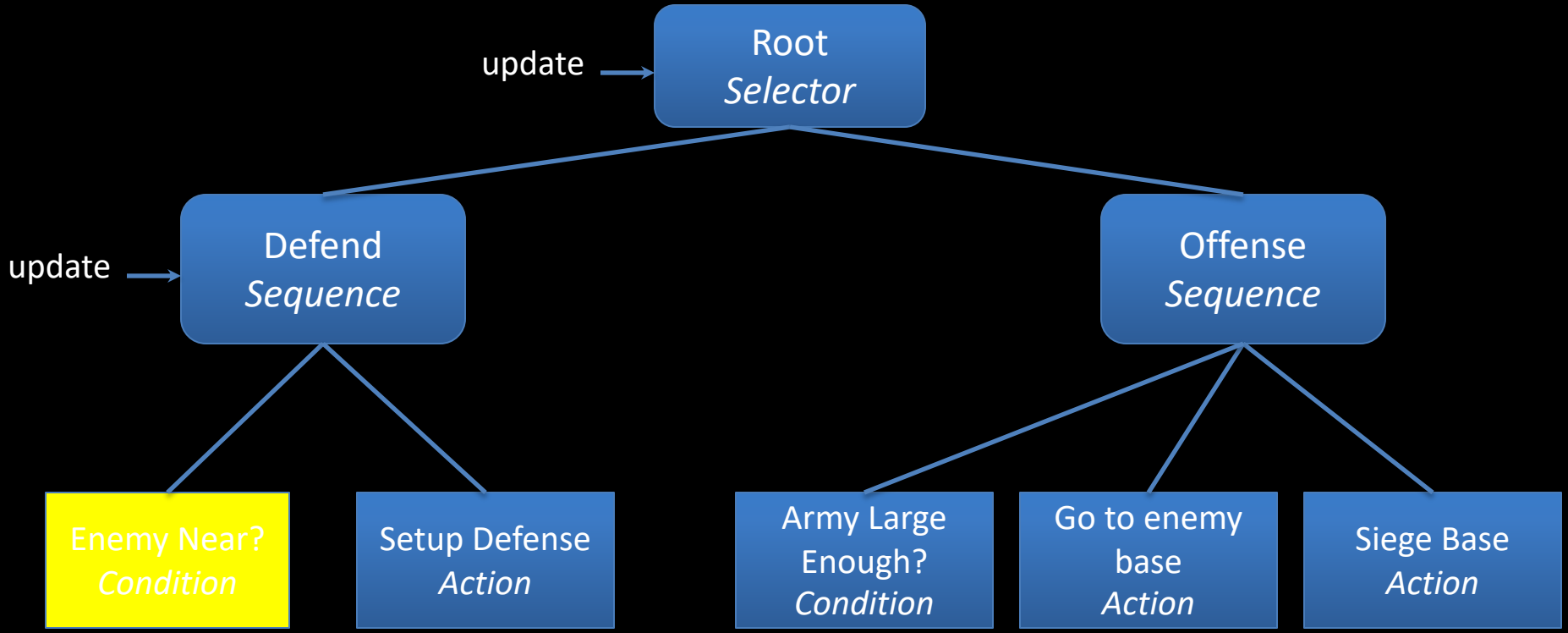
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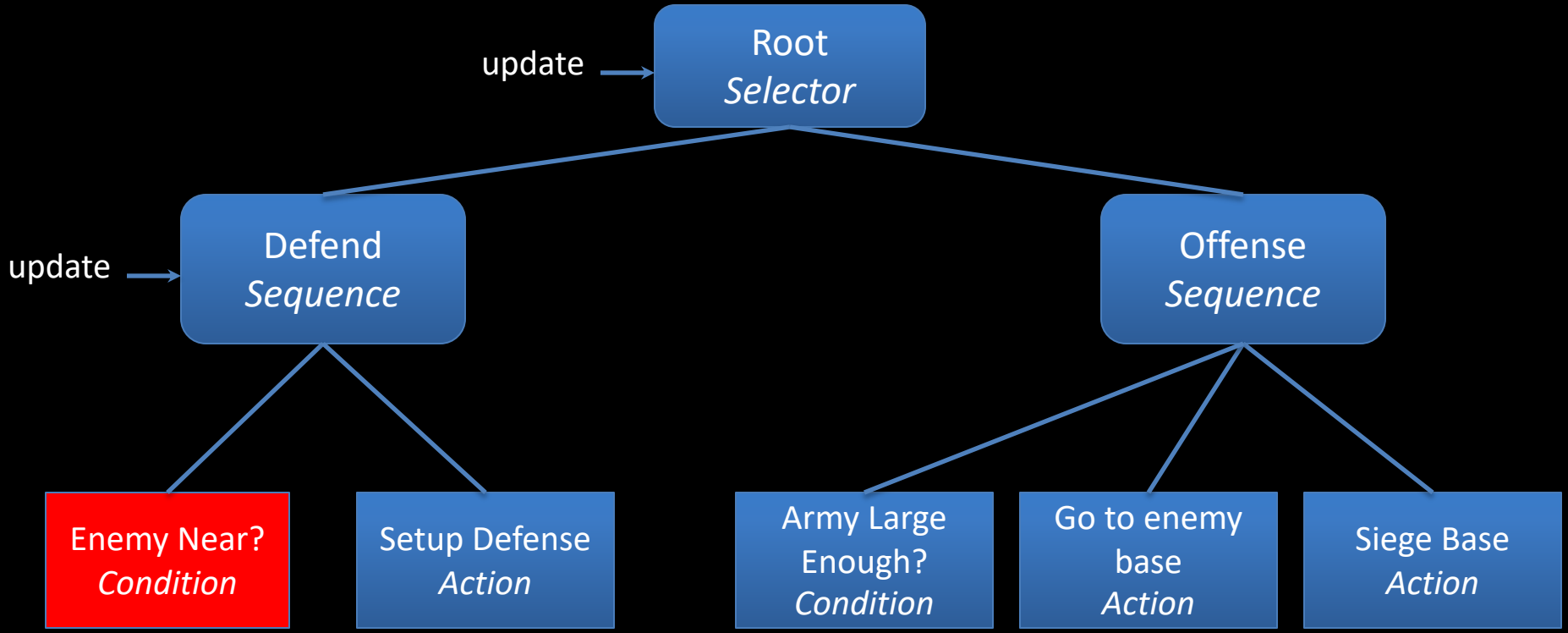
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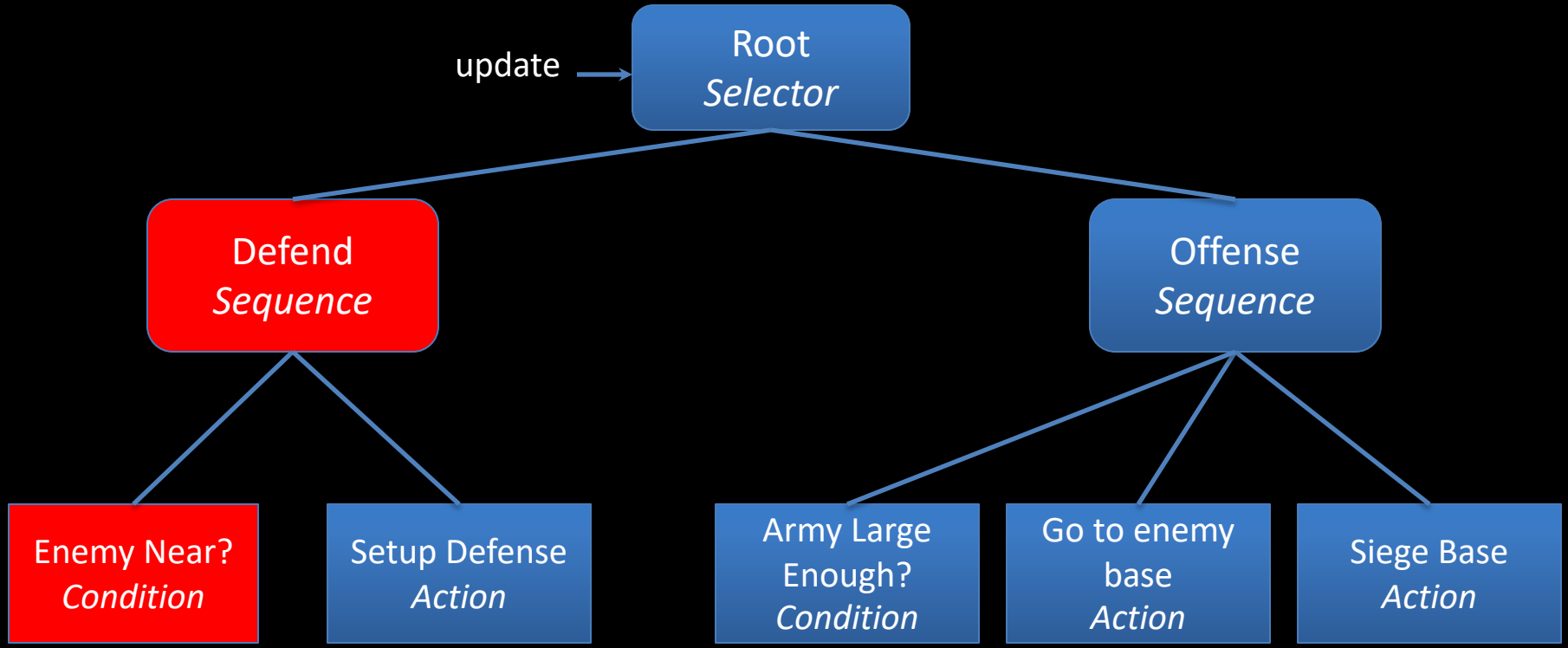
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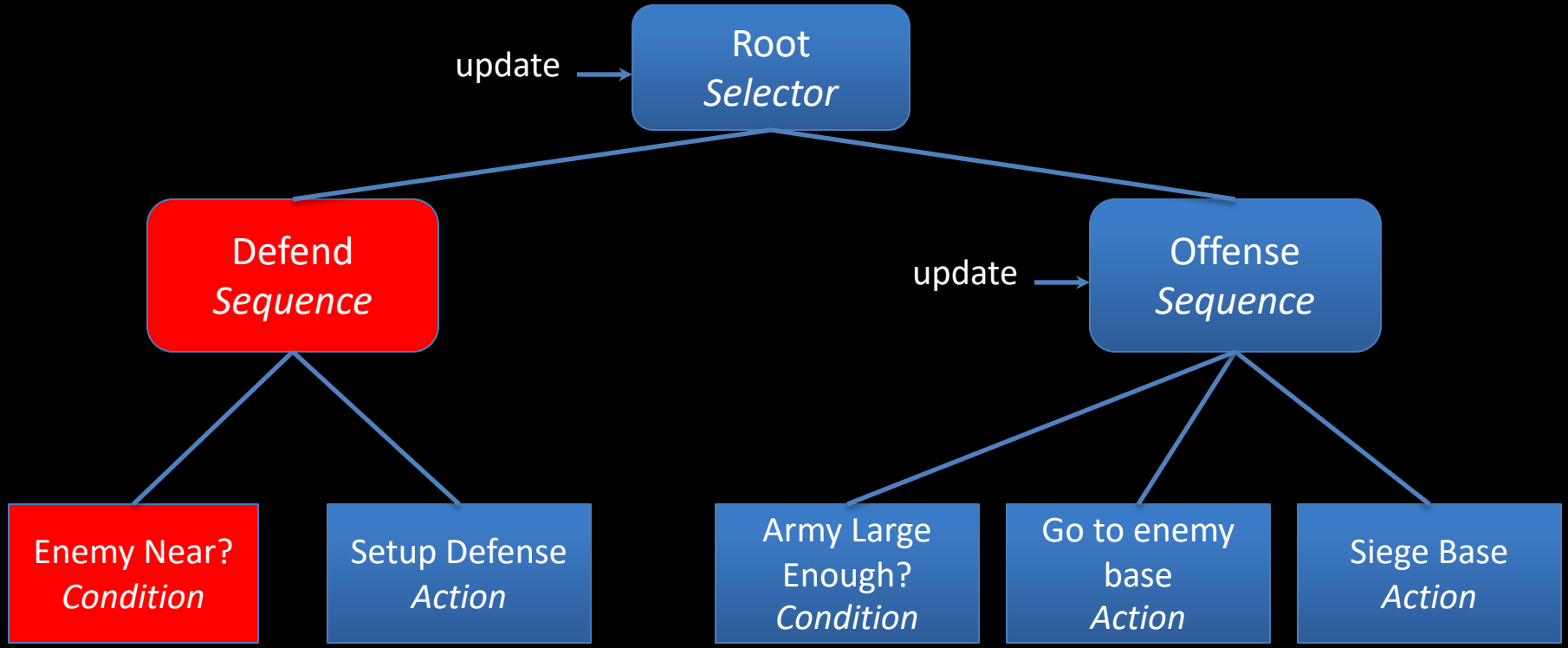
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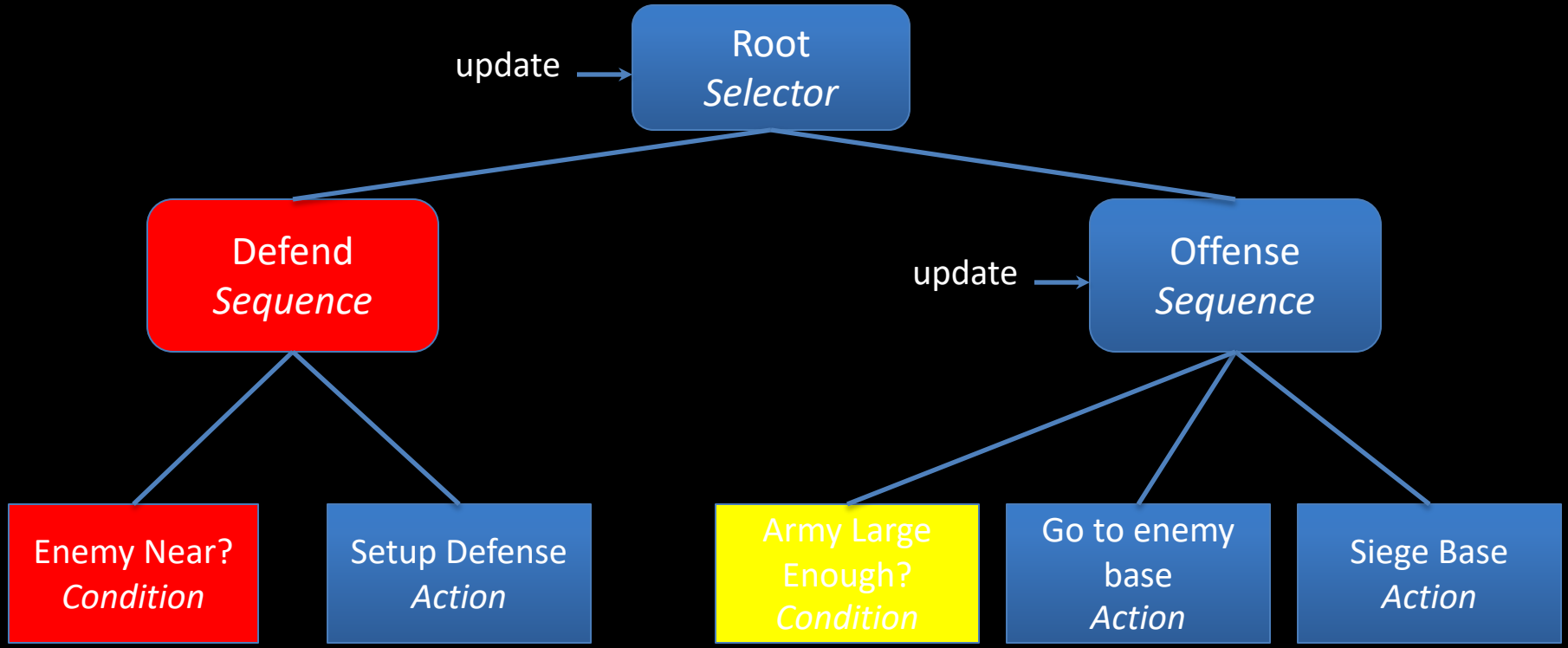
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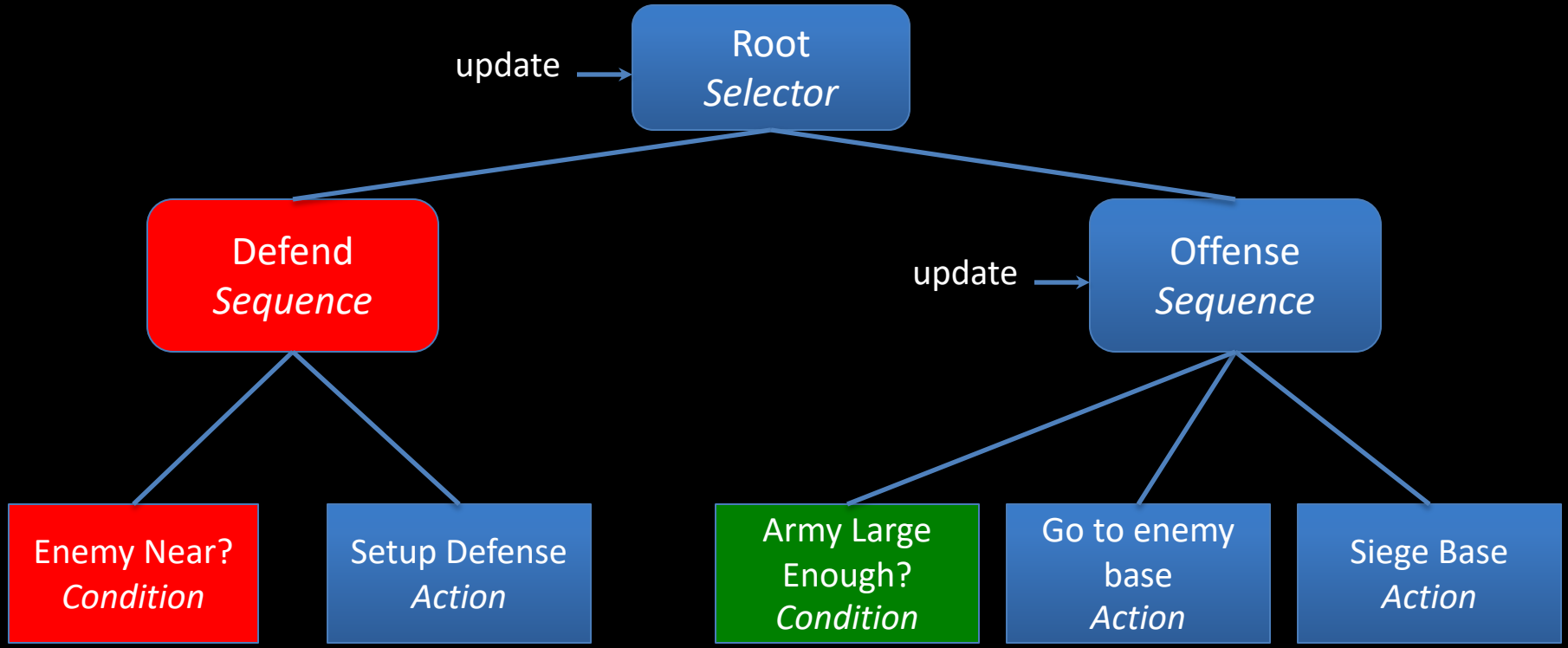
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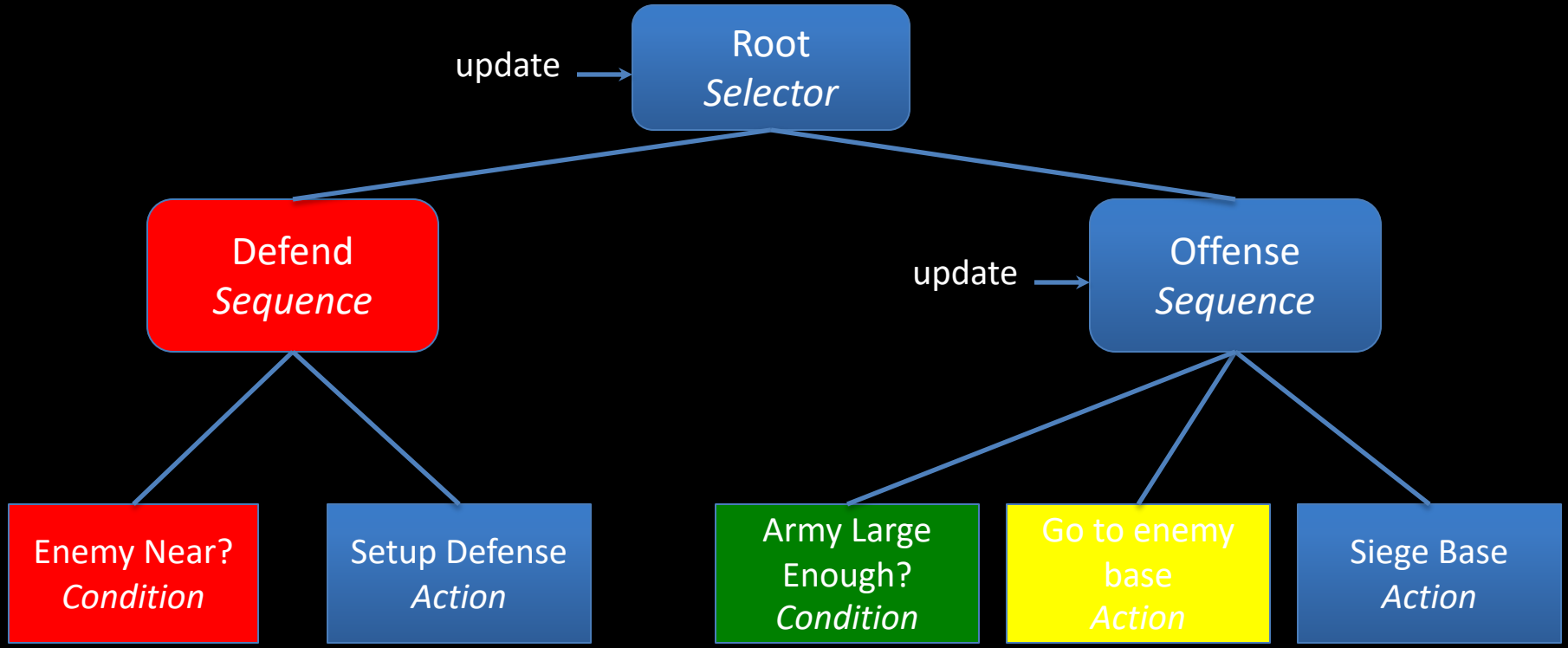
Example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Army Large
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Go to enemy
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Action
Siege Base
Action

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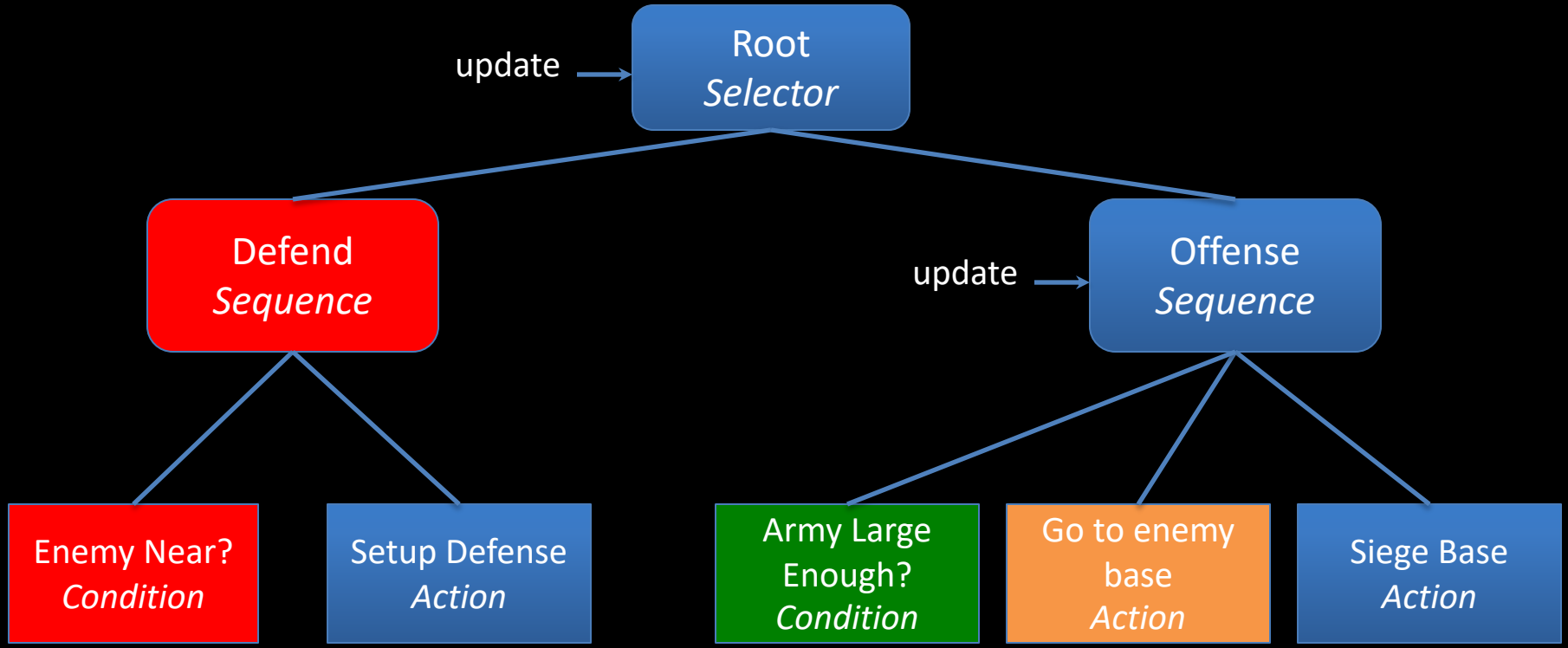
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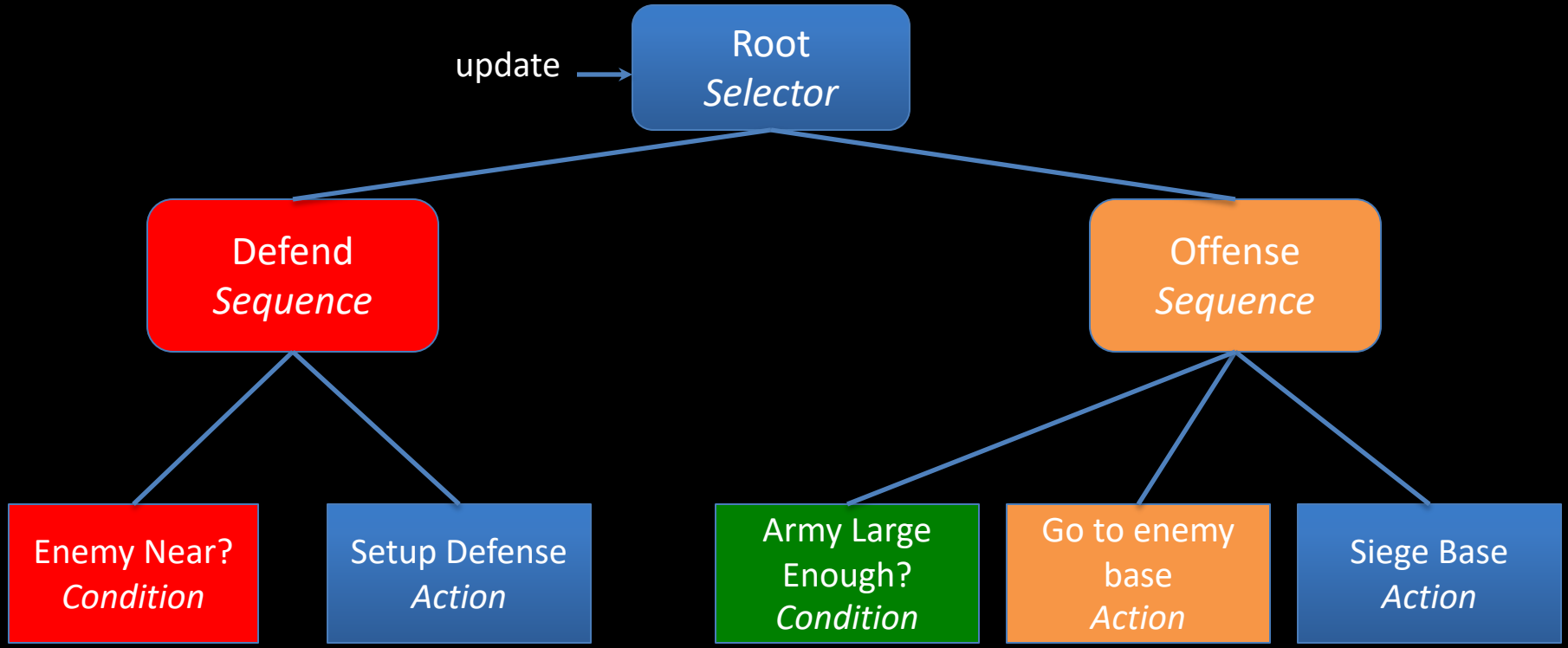
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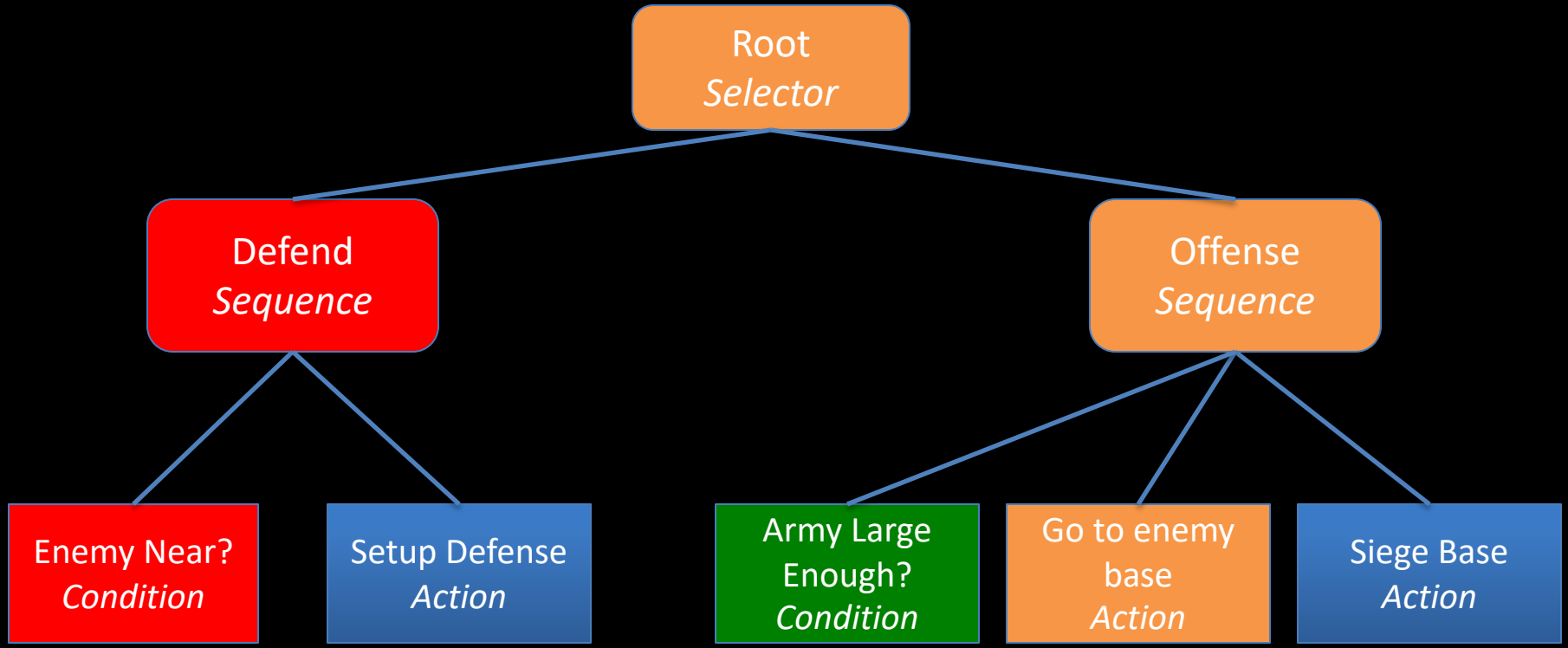
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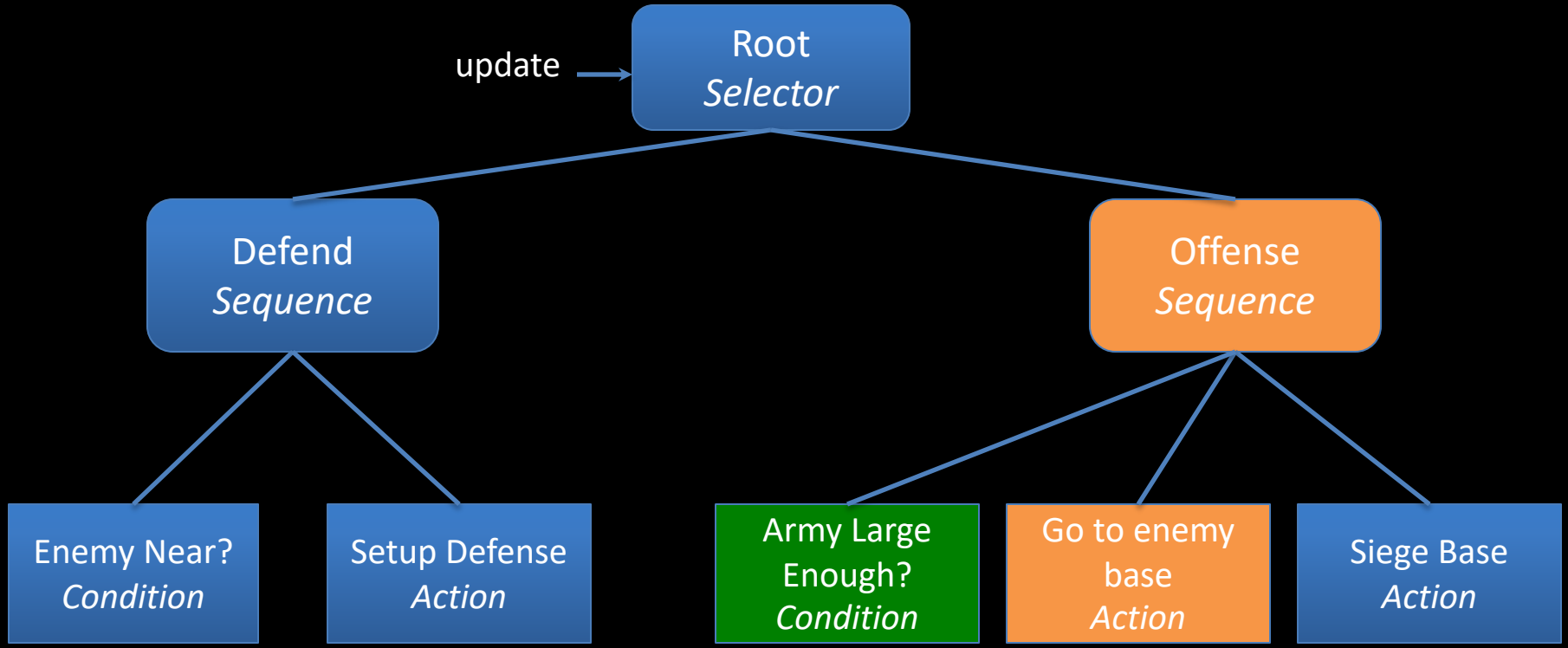
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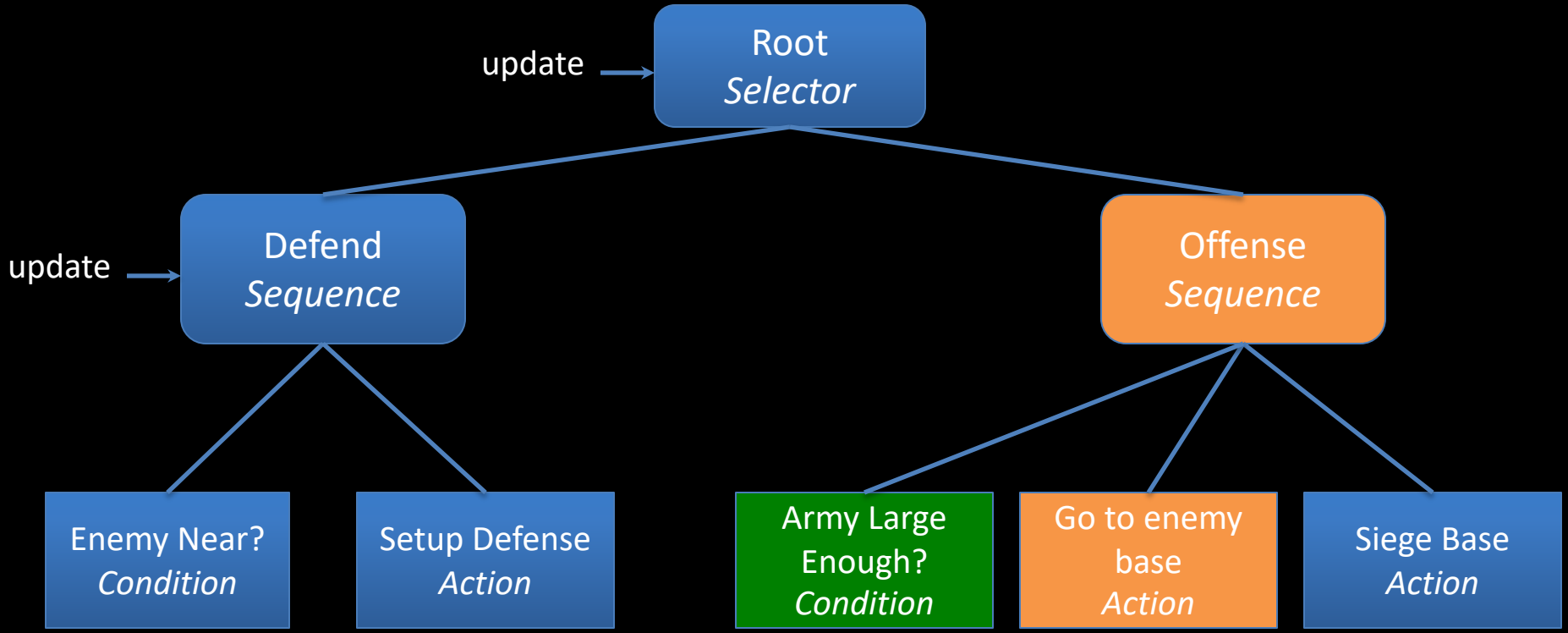
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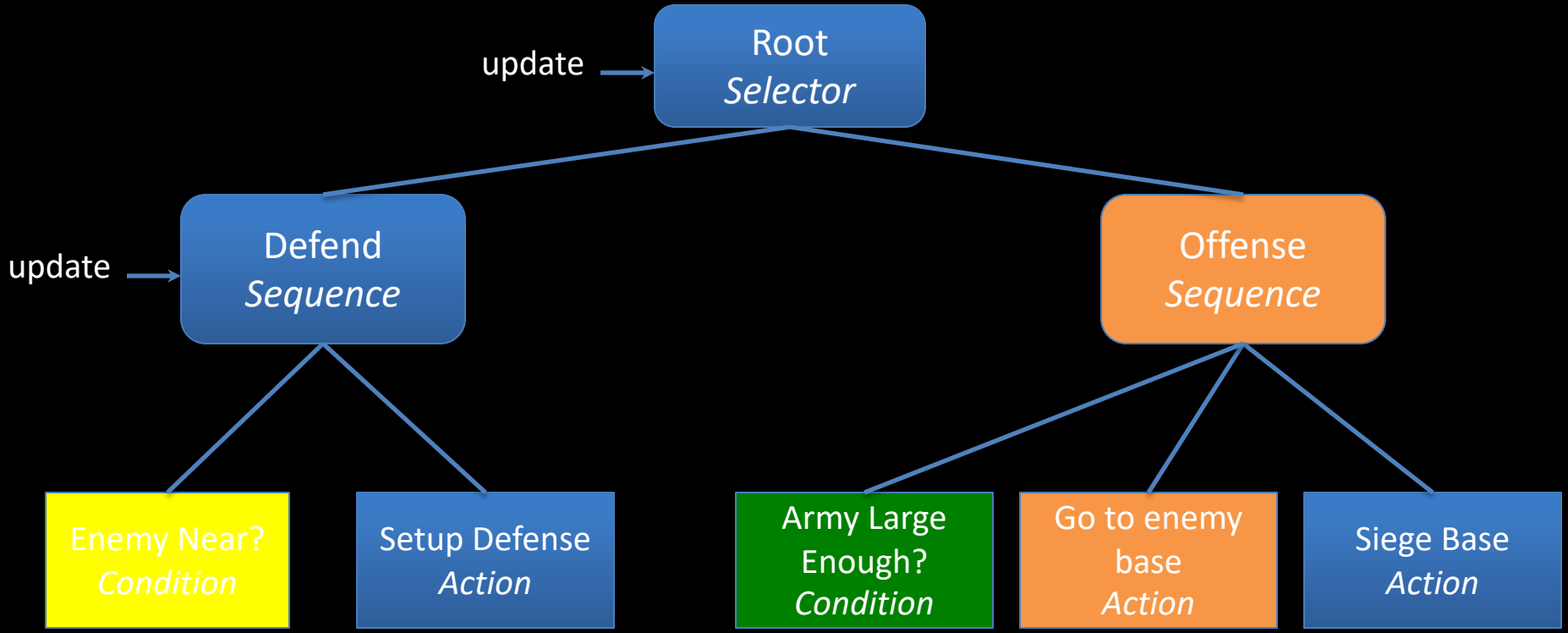
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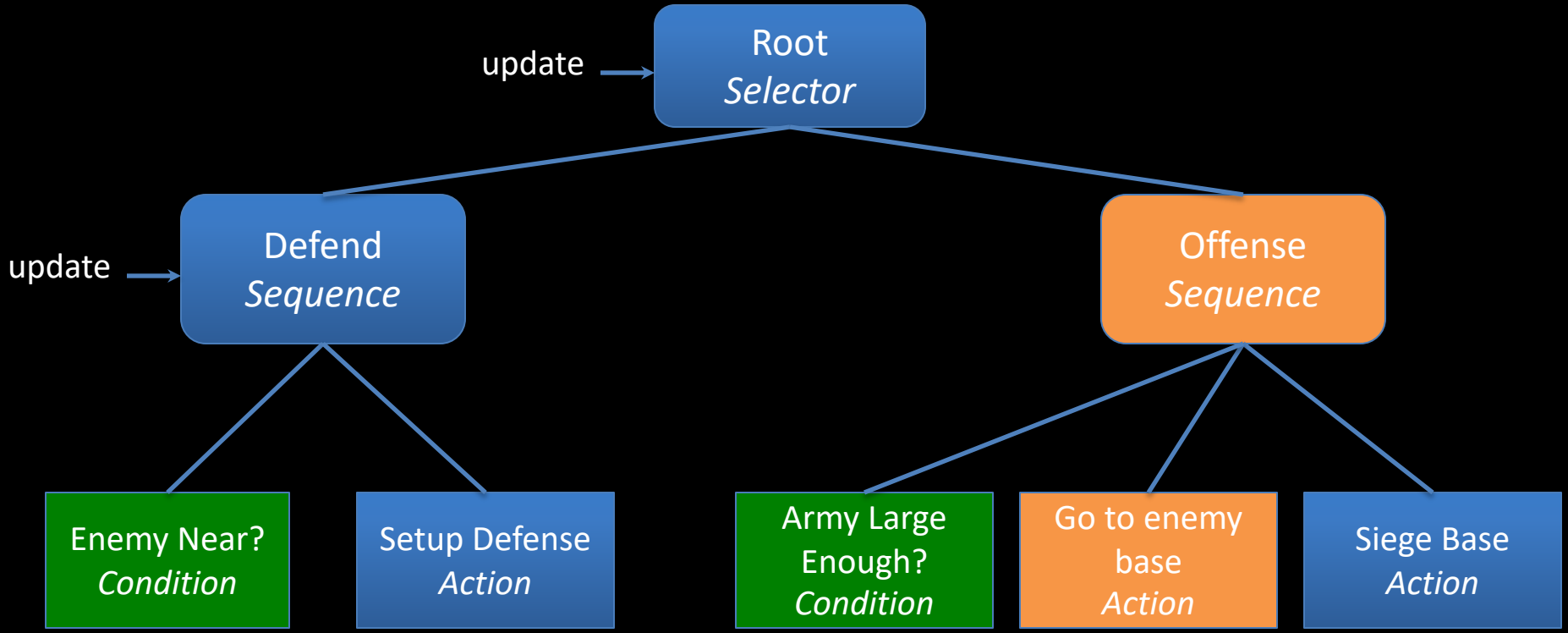
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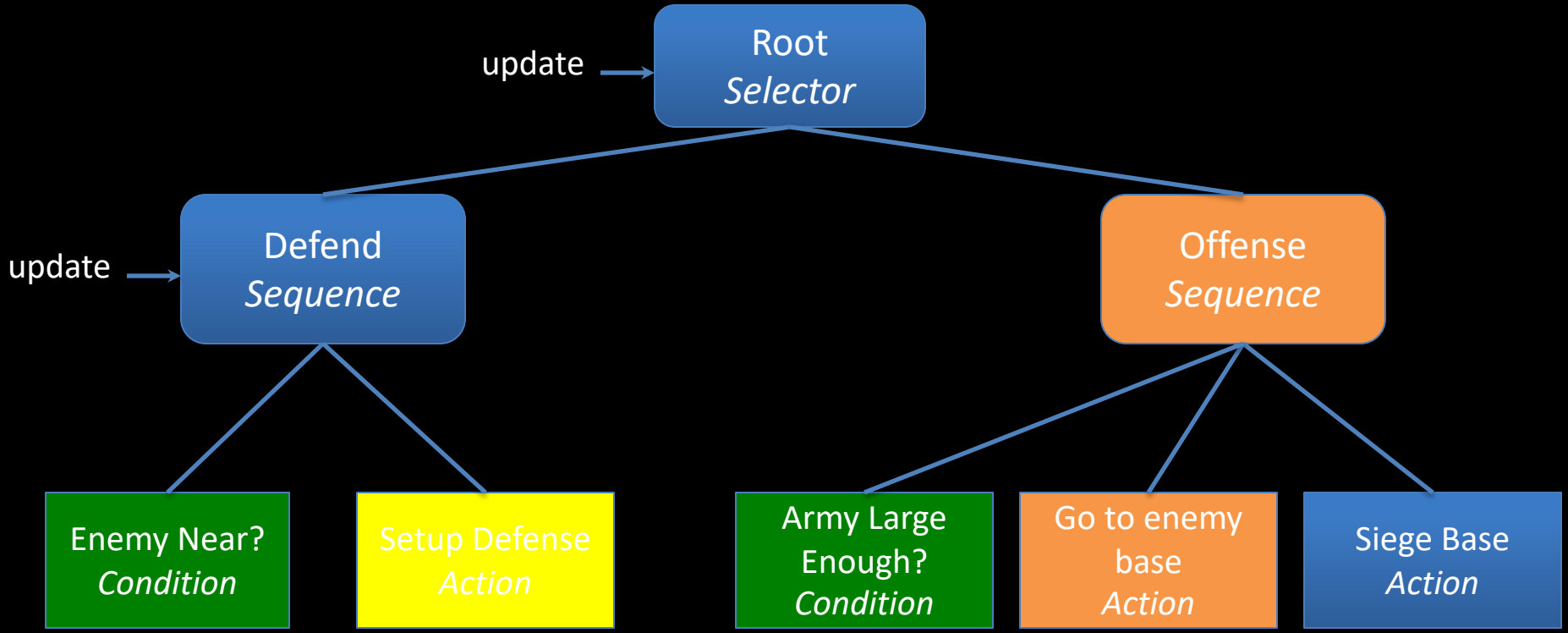
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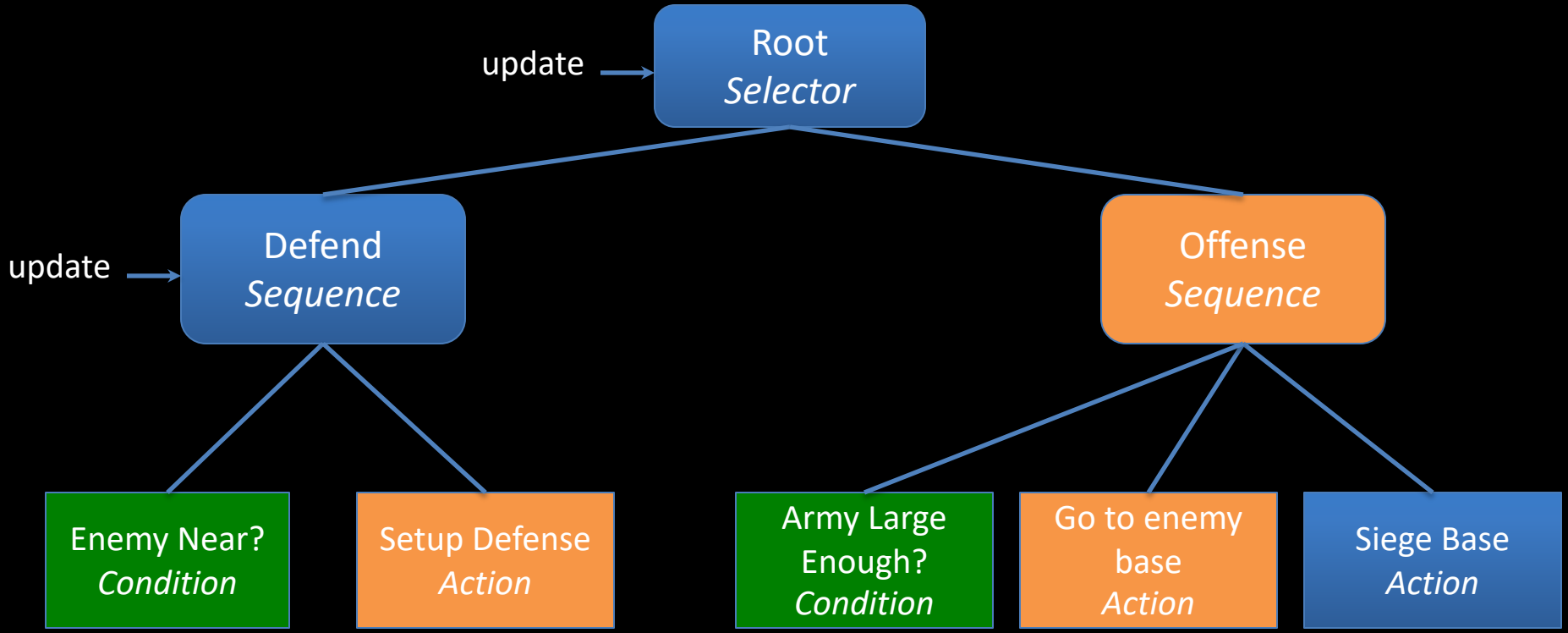
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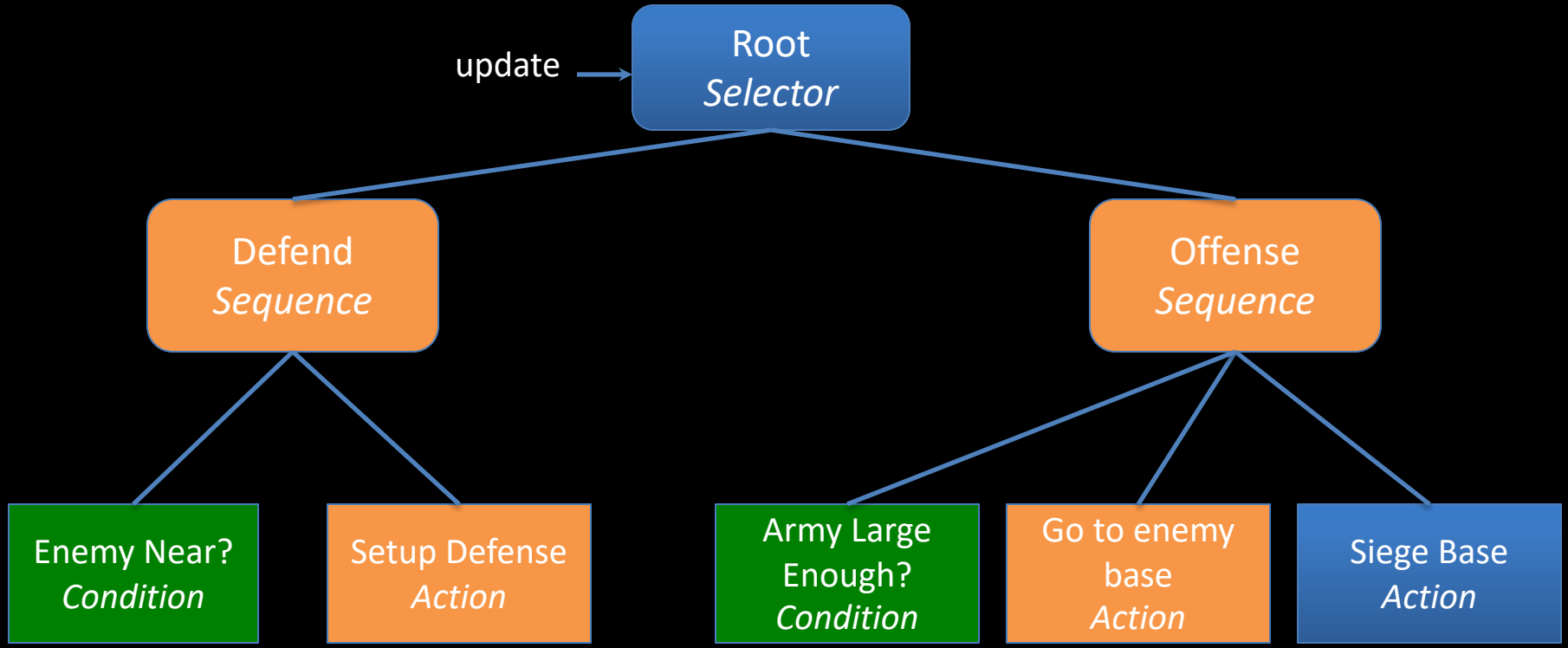
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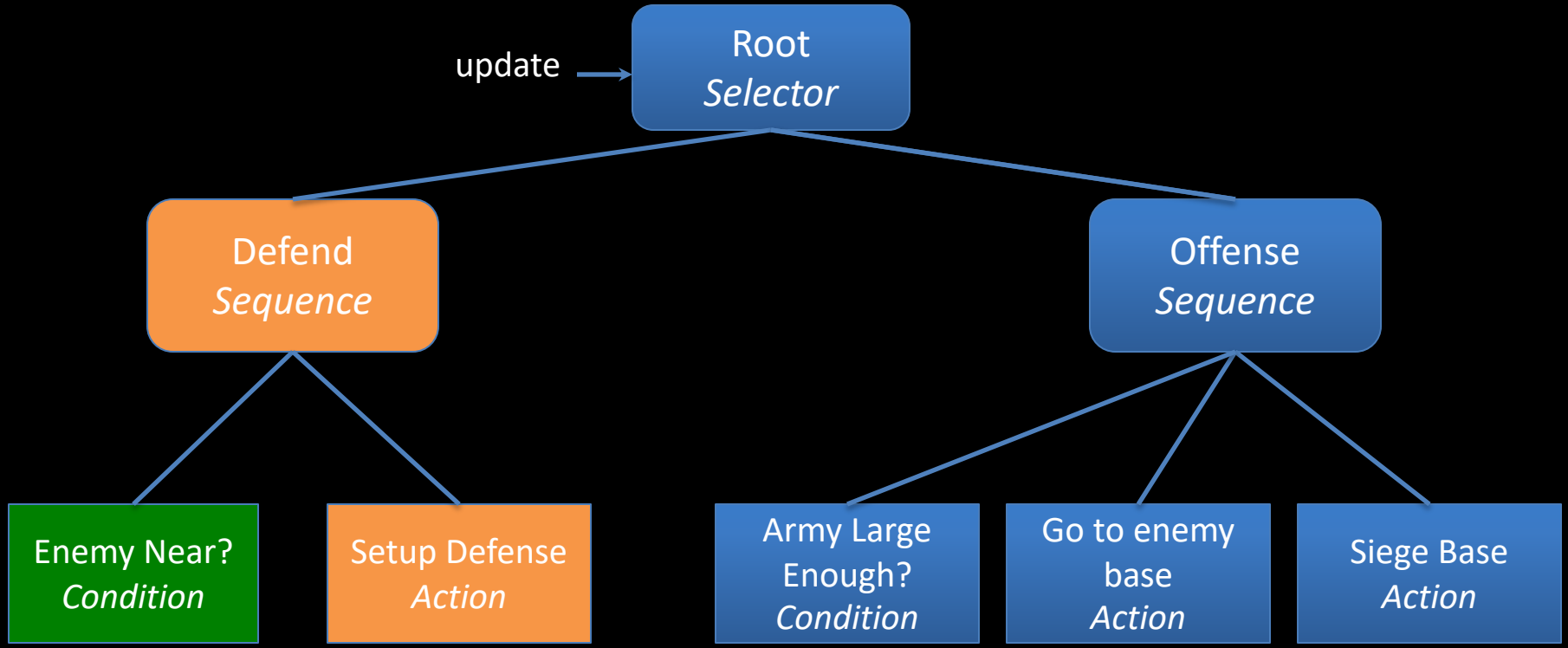
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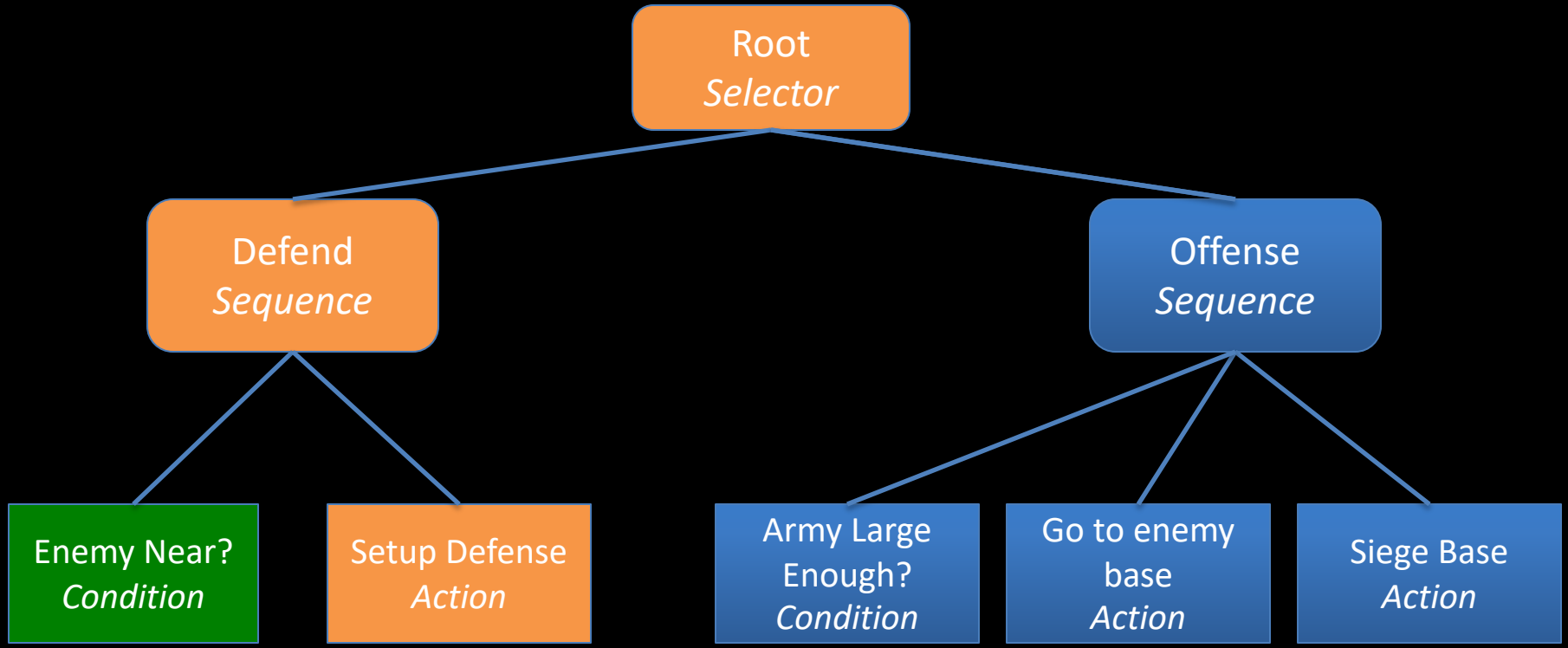
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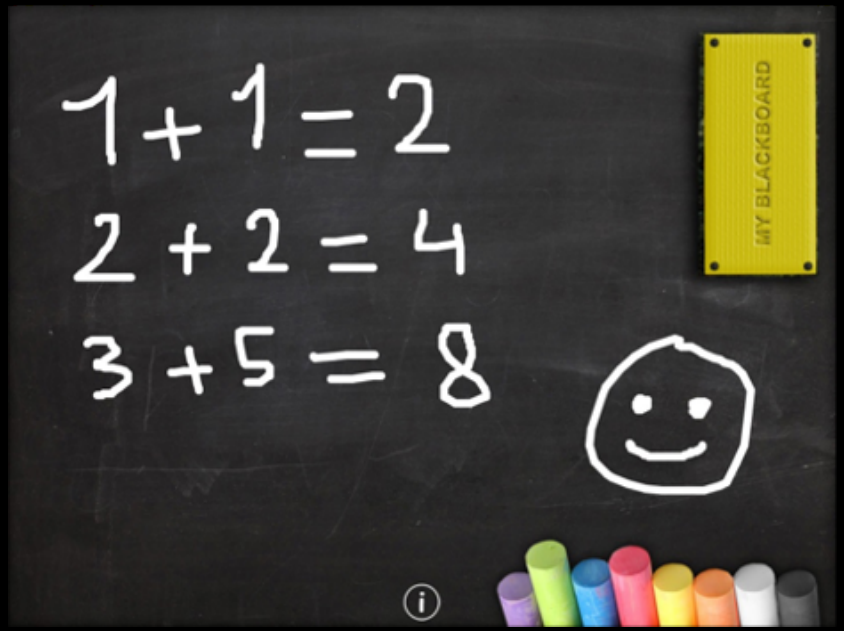
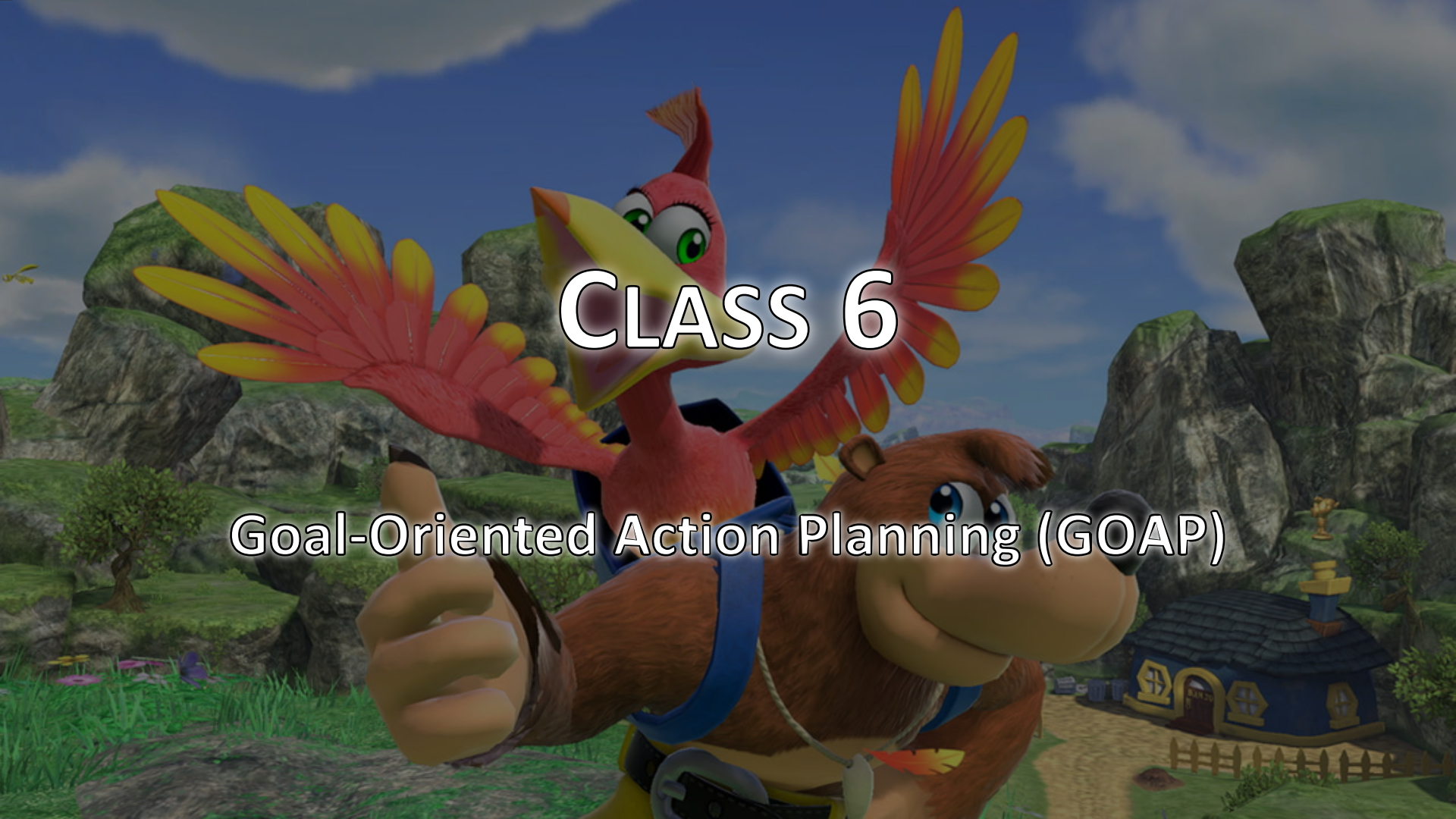
Data Persistence

- Your behavior tree nodes might need to communicate somehow
  - Finding a target, going to the target are separate nodes
- How to share data?
- Blackboard: shared object that holds information, that nodes can write and read from
  - Minimally, a `map<string, ???>`
- Certain groups of nodes can share different blackboards



In Summary

- Interfaces/abstract classes for:
  - BTNode
  - Composite
  - Condition/Action
- Full classes for:
  - Sequence
  - Selector
  - Other wrappers
- Game-specific classes extending Condition/Action

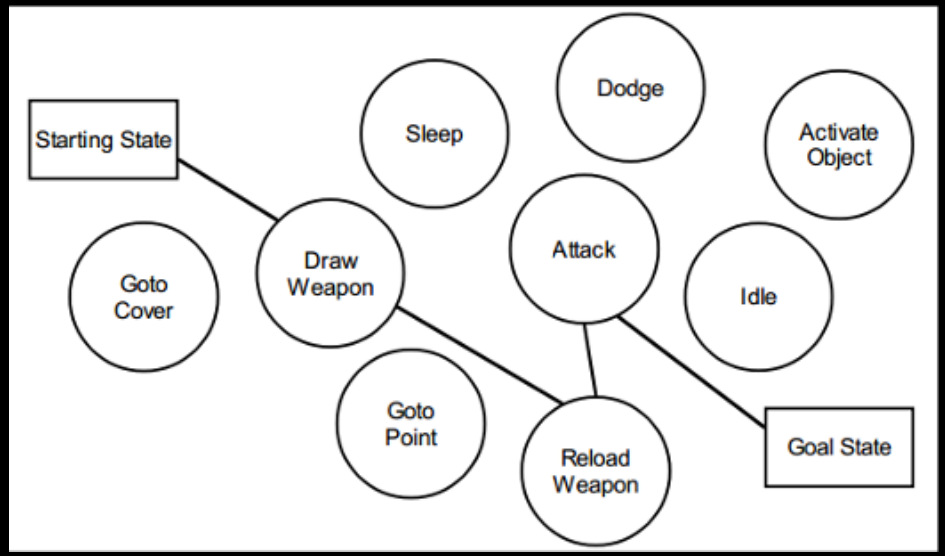

Class 6
Goal-Oriented Action Planning (GOAP)

Issues with BTs

- Behavior trees aren’t perfect
- Lots of enemies
  - Too much work to code each
  - Minor tweaks change a lot of code
- Procedurally generated enemies
  - Behavior trees usually aren’t expressive enough

What is GOAP?

- GOAP is a graph of game states
- We can search over it
  - A*



The Nodes

- Each node is a GameState
- GameStates are probably a map of string tags to booleans or integers
- The tags and their meaning are determined game-side

```
class GameState {
    std::map<std::string, int> m_props;
}
```

The Edges

- Each edge is an Action the AI can take
- Each Action has a cost and a Condition
- Actions also change the GameState

```
class Action {
public:
    virtual void changeState(GameState &s) = 0;

private:
    std::vector<Condition *> m_conditions;
    float m_cost;
}
```

Planning

- Goal
  - Generate a plan or “path” of actions
  - This plan should take you from start state to end state
- Just use A* !

Planning contd.

- Start at a state
- Add neighboring states to priority queue
  - Go through all actions
  - All actions whose conditions are true from the current state are allowed
  - Generate a neighbor for each by applying the corresponding action to a copy of the game state
- Pop lowest cost state from priority queue
- Continue
- Return “path” or list of actions that took you from start to end state

Actions

- Just like behavior trees, GOAP has actions
- Actions are much simpler in GOAP
  - Change one or more of the tags in the game state

Conditions

- Just like behavior trees, GOAP has conditions
- Conditions are also much simpler
  - Return true or false
  - Determined entirely by GameState

Conditions

```
class Condition {
public:
	virtual bool is_met(GameState &s) = 0;
}
```

GOAP

- The game defines a start state based on the current game world
- The game also defines a goal (Condition)
- Once the search is done, you need to map the list of actions to some real game effect
- Usually only the first action is executed before GOAP is run again
  - The action might not be completed before a new plan is generated
  - E.g., following the player

Goal Oriented Action Planning

QUESTIONS?

Problems

- Depending on the Actions available, GOAP can generate an infinite graph without any goal states
- This can be handled by any of the following:
  - Allow each action to be used once/max # of times
  - Specify a maximum cost

Problems

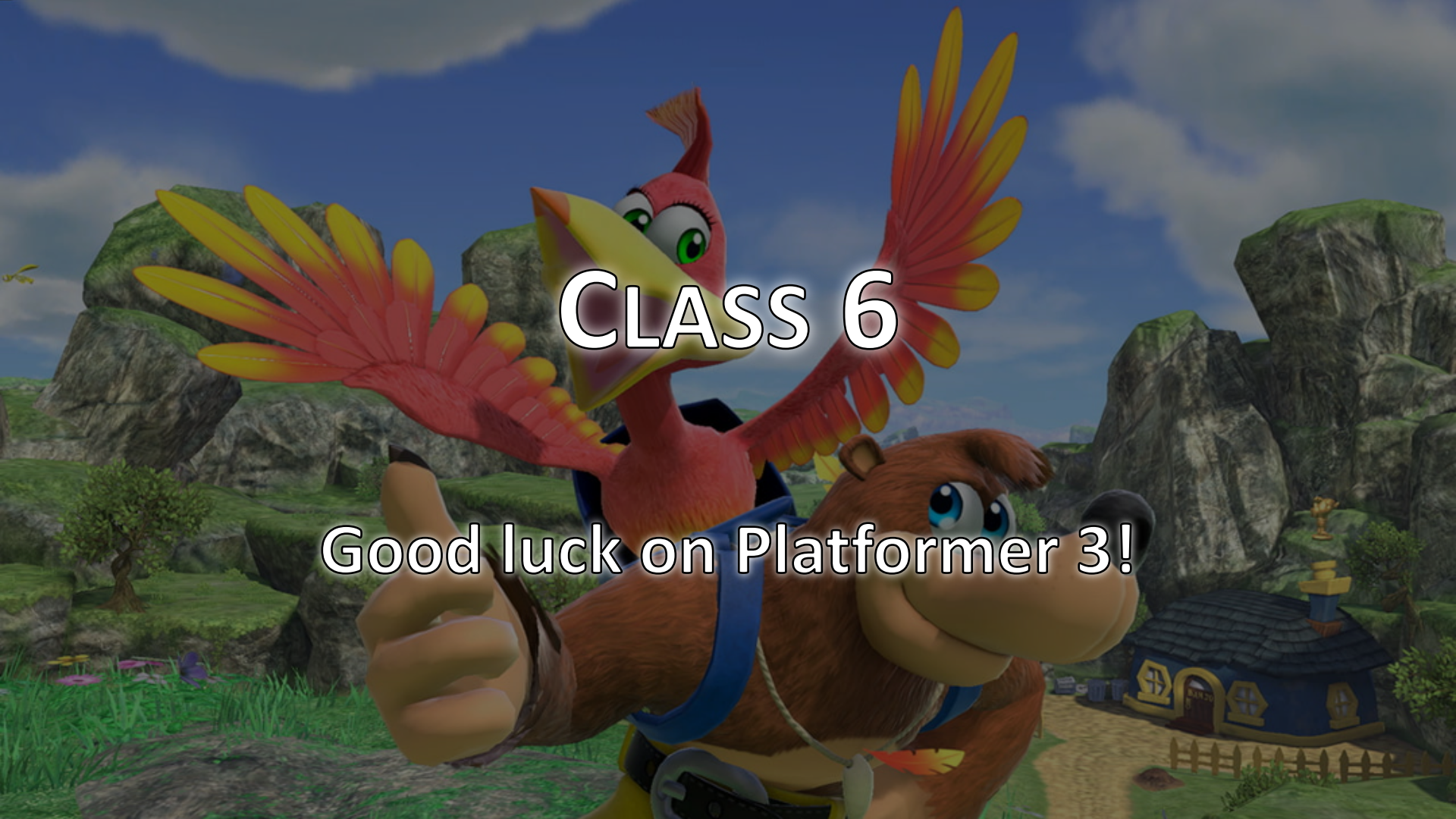
- With lots of actions and a distant goal, GOAP can be really slow
- GOAP is best used to solve small problems

Problems

- GOAP optimizes over a single parameter (time, cost, etc.)
- GOAP is good for short, discrete problems:
  - Which combo should I use?
  - Which route should I take?
- GOAP is bad for long-term, strategic problems:
  - How do I optimize my economy?
  - Which item will maximize my options next level?

Mix and Match

- Behavior trees and GOAP don't have to be mutually exclusive
- Behavior tree can determine the strategy (setting up which actions are available, how much each is weighted, what the goal is, etc.)
- GOAP can determine the plan to execute that strategy
- Behavior tree turns that plan into concrete actions
  - e.g., sequence


Class 6
Good luck on Platformer 3!