“Inaction breeds doubt and fear. Action breeds confidence and courage. If you want to conquer fear, do not sit home and think about it. Go out and get busy.” -- Dale Carnegie

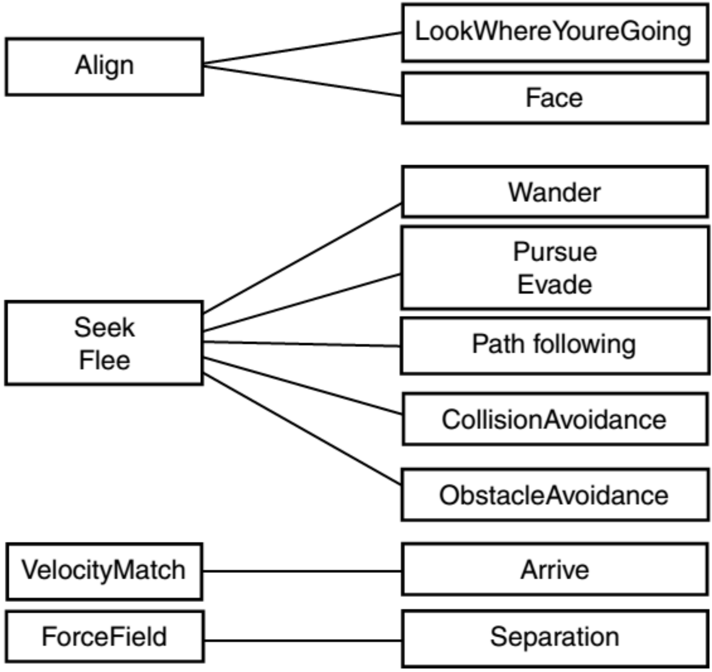
Hw 1.5

- Create pathnetwork as list of lines between all pathnodes traversable by the agent
  - For all pairs of pathnodes… (possible pathlines)
  - perform a ray trace against every line in worldlines, keeping those without intersections
  - For those pathlines remaining, verify no world point is within agent radius

Class N-2

1. When might you precompute paths?
2. This is a single-source, multi-target shortest path algorithm for arbitrary directed graphs with non-negative weights. Question?
3. This is a all-pairs shortest path algorithm.
4. How can a designer allow static paths in a dynamic environment?
5. When will we typically use heuristic search?
6. What is an admissible heuristic?
7. When/Why might we use hierarchical pathing?
8. Does path smoothing work with hierarchical?
9. How might we combat fog-of-war?

Class N-1

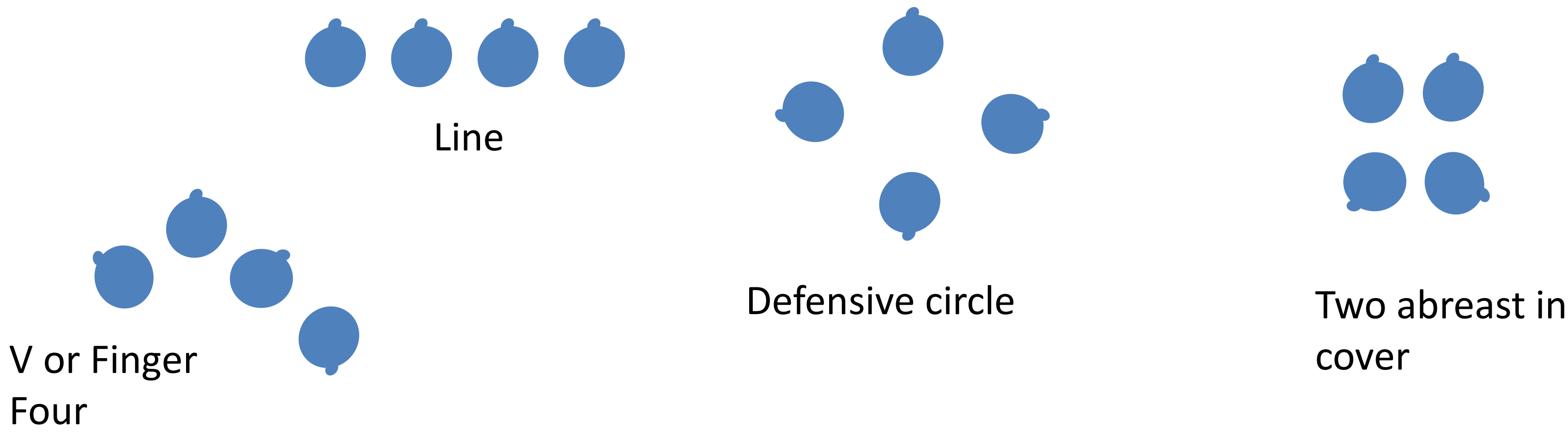


1. Steering vs flocking?
2. Steering Family Tree
3. How might we combine behaviors?
4. What three steering mechanisms enable flocking?

Formations

- Coordinated Movement: M Ch 3.7
- Path plan for leader (naive)
  - All others move toward leader
- Replace team with a virtual bot
  - All members controlled by a joint animation
- Path plan for leader (alt)
  - All team members path plan to an offset
  - Flow around obstacles and through choke points

Fixed Formations



Decision Making – FSMs

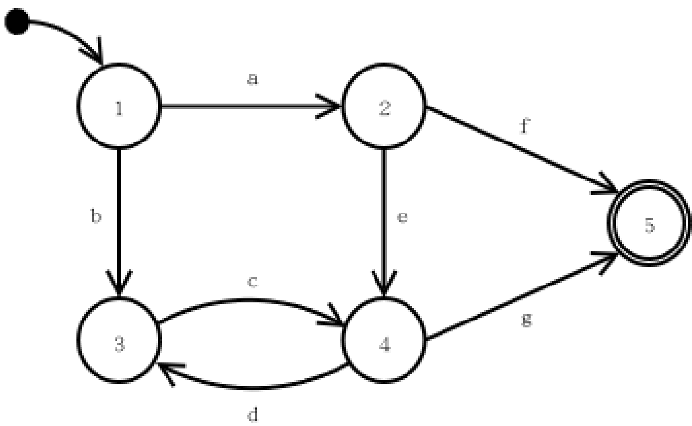
2016-06-02

Decision Making

- Classic AI:
  - making the optimal choice of action (given what is known or is knowable at the time) that maximizes the chance of achieving a goal or receiving a reward (or minimizes penalty/cost)
- Game AI:
  - choosing the right goal/behavior/animation to support the experience
- Decision-making must connect directly to animation so player can see the results of decision-making directly (explainable AI)
  - What animation do I play now?
  - Where should I move?

FSM theory

- A (model of a) device which has
  - a finite number of states (S)
  - an input vocabulary (I)
  - a transition function T(s,i) → s'
  - a start state ∈ I
  - zero or more final states ⊂ I



- Behavior
  - Can only be in one state at a given moment in time
  - Can make transitions from one state to another or to cause an output (action) to take place.

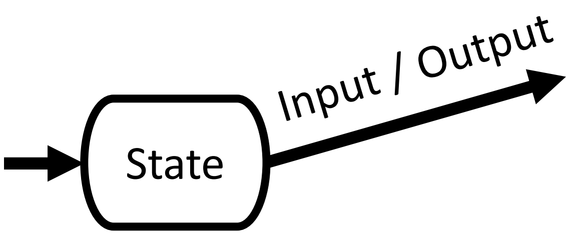
FSMs in Practice

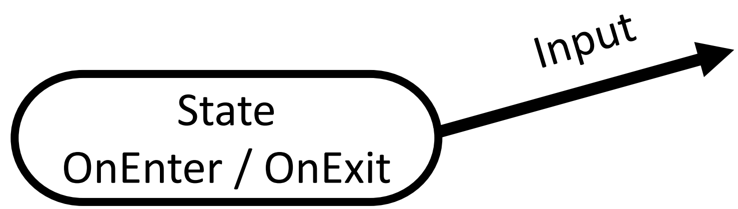
- Each state represents some desired behavior
- Transition function often resides across states
  - Each state determines subsequent states
- Can poll the world, or respond to events (more on this later)
- Support actions that depend on state & triggering event (Mealy) as well as entry & exit actions associated with states (Moore)

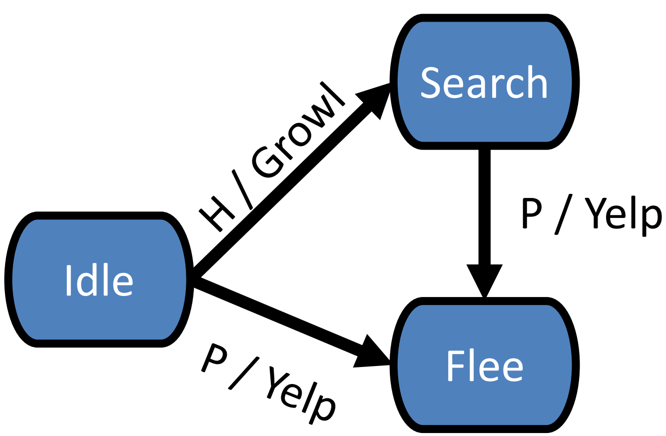
Mealy & Moore

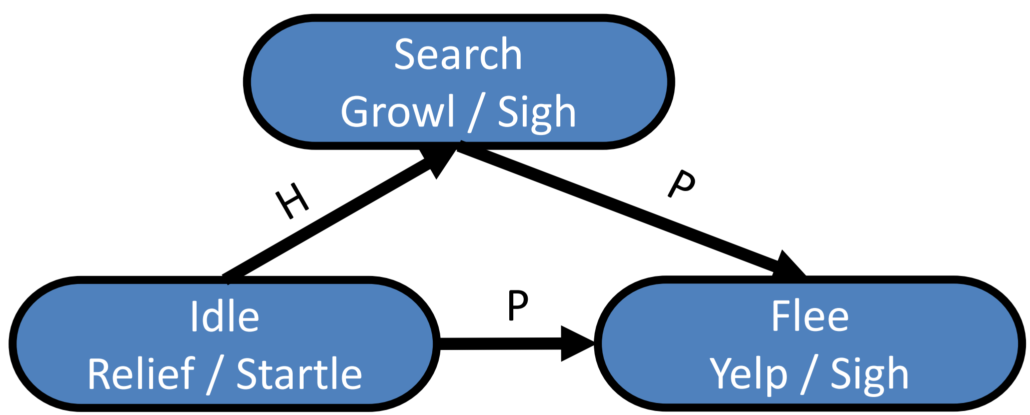
Mealy Output =
F(state, input)

Moore Output =
F(state)



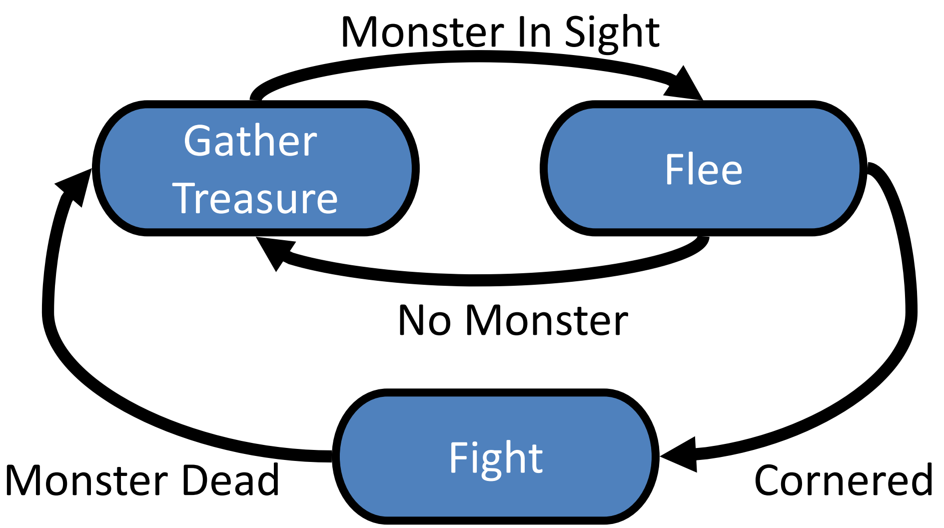






FSM as GAI

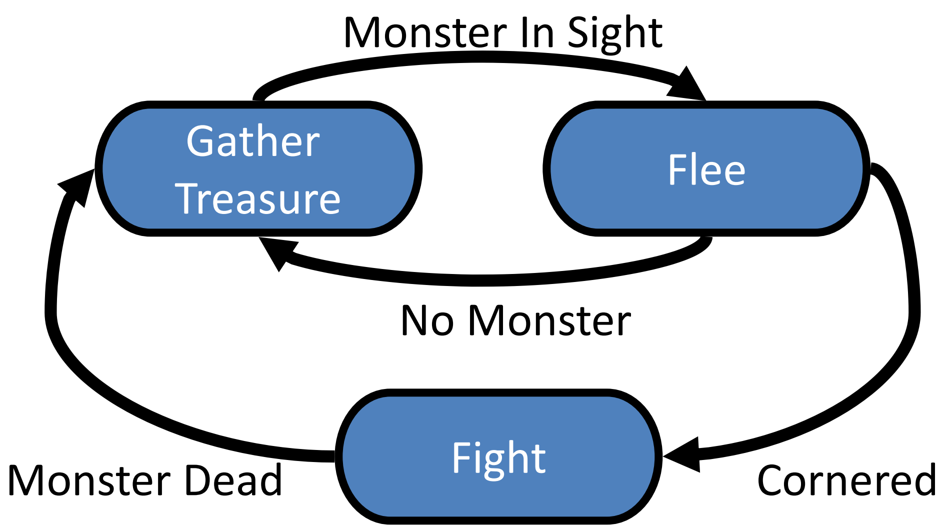
- Character AI modeled as sequence of mental states
- World events (can) force a change in state
- Mental model easy to grasp (for all)



Jarret Raim

State Transition Table

Current State	Condition	State Transition
Gather Treasure	Monster	Flee
Flee	Cornered	Fight
Flee	No Monster	Gather Treasure
Fight	Monster Dead	Gather Treasure

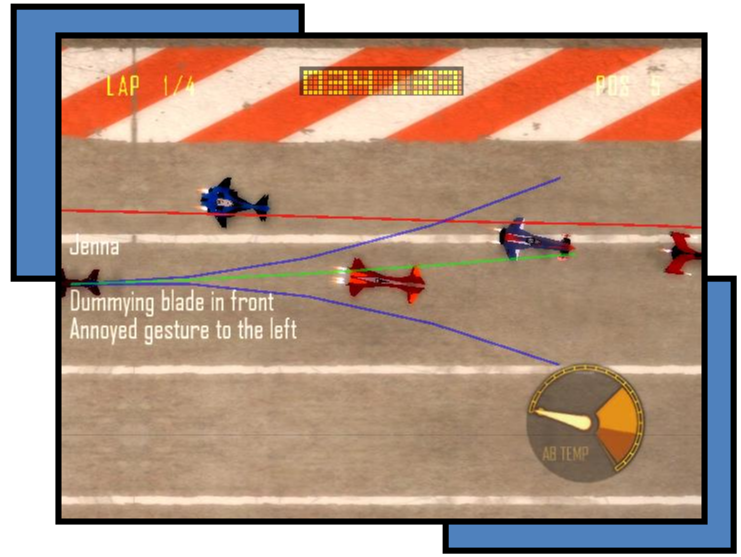


Advantages

- Ubiquitous (not only in digital games)
- Quick and simple to code
- (can be) Easy* to debug
- Fast: Small computational overhead
- Intuitive
- Flexible

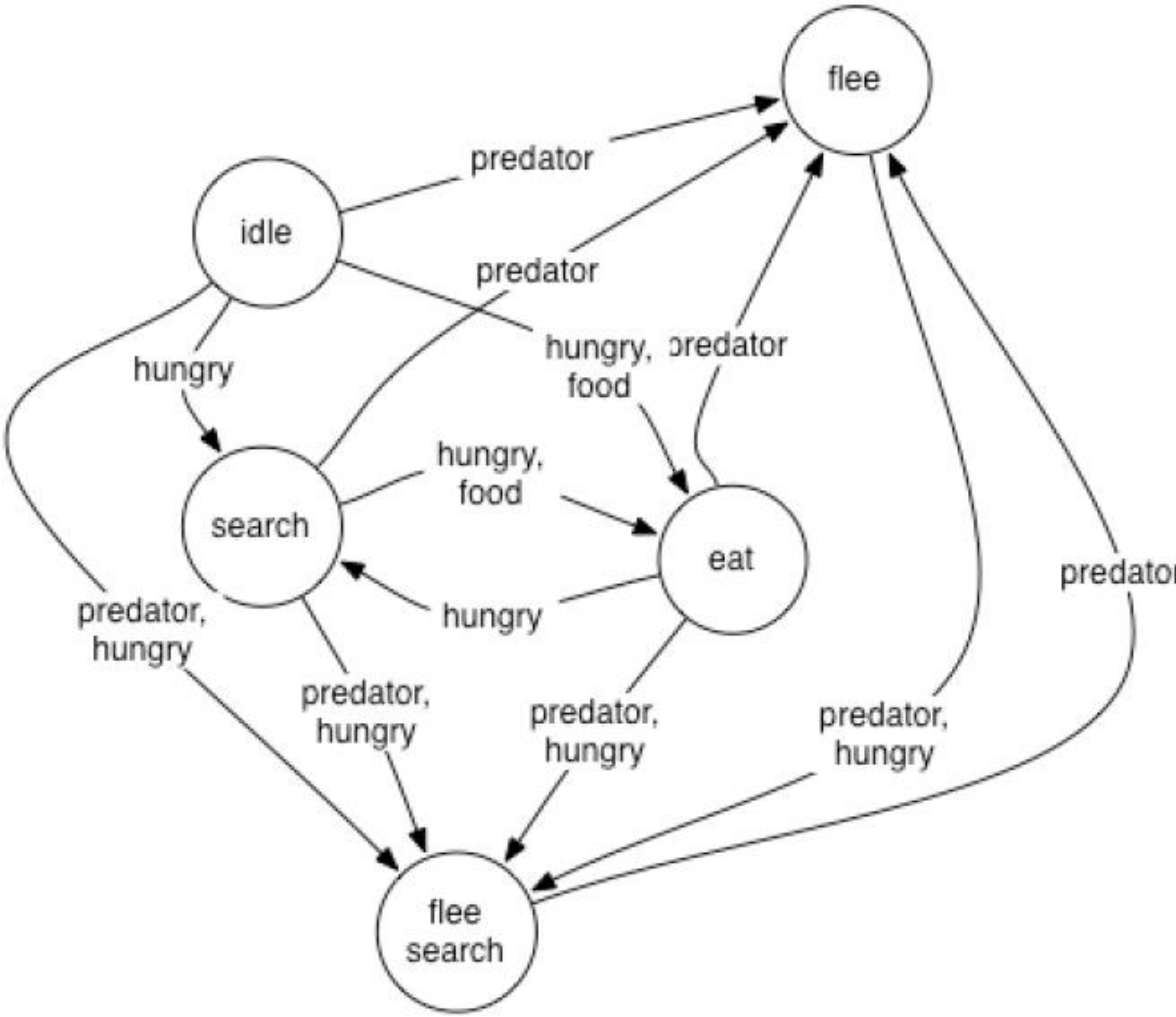
Debugging FSM's

- Offline Debugging
  - Logging
  - Verbosity Levels
- Online Debugging
  - Graphical representation is modified based on AI state
  - Command line to modify AI behavior on the fly.



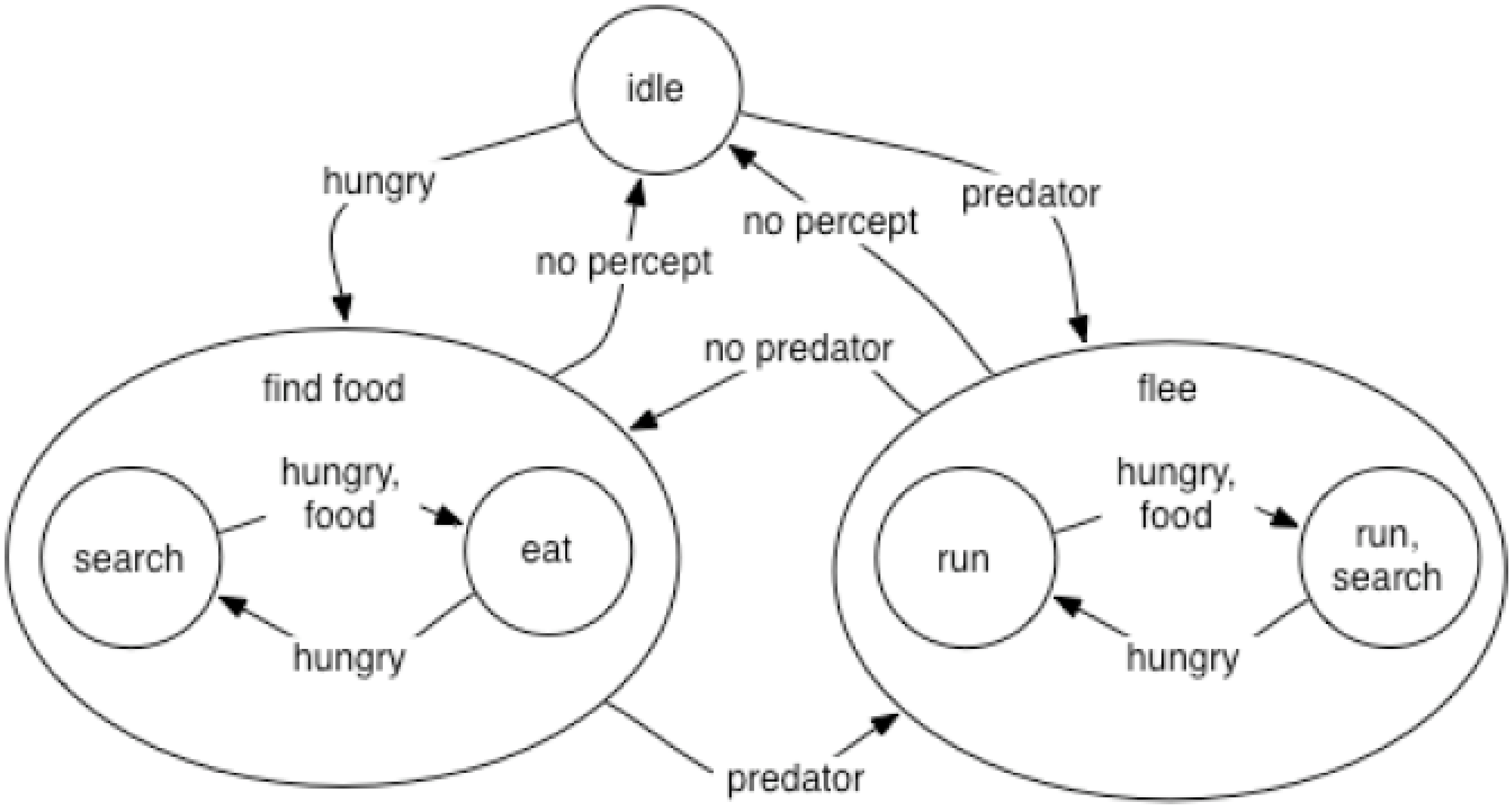
EXAMPLES

Example 1



* Usually animations are linked to states, transitions, or both.

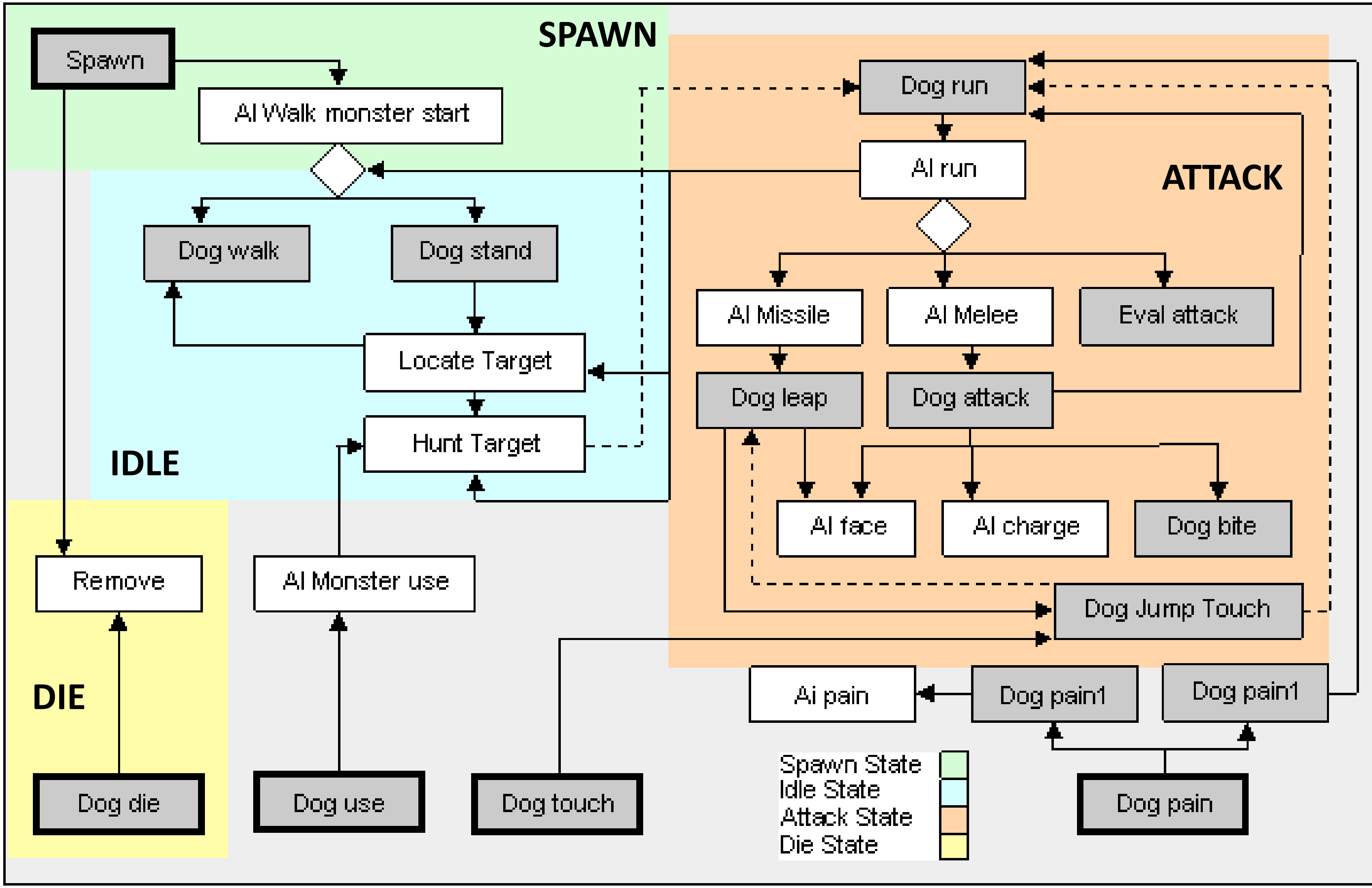
Hierarchical FSM Example



- Equivalent to regular FSMs
- Easier to think about encapsulation

FSM: Quake dog monster

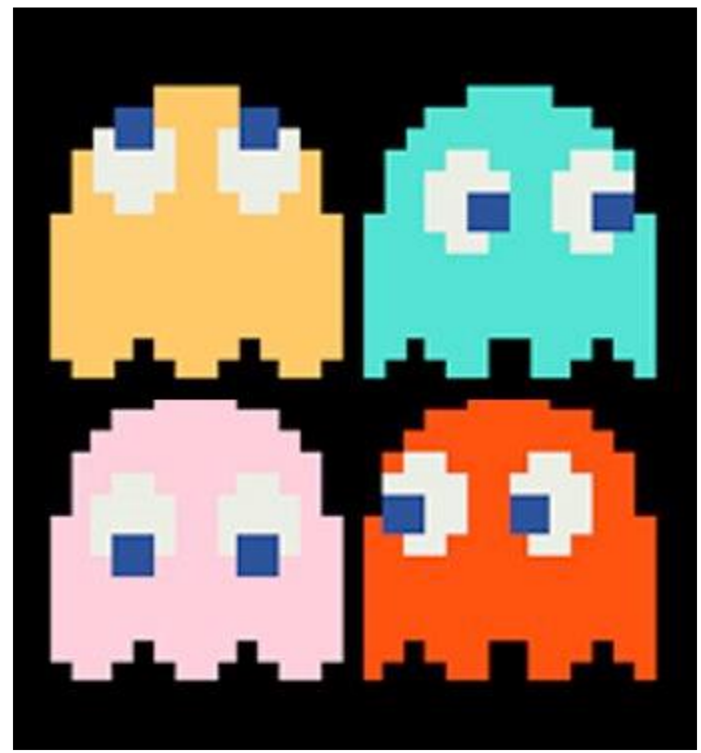
http://ai-depot.com/FiniteStateMachines/FSM-Framework.html



Main input event act. | Dog specific act. | (gen.) monster act.

FSM Examples

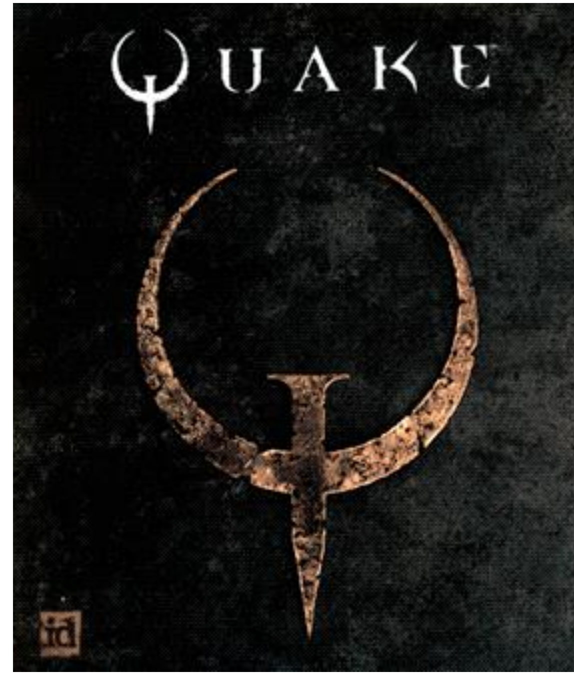
- Red: Shadow, blinky
  - "pursuer" or "chaser"
- Pink: Speedy, pinky
  - "ambusher"
- Blue: Bashful, inky
  - "whimsical"
- Orange: Pokey, Clyde
  - "feigning ignorance"



http://gameinternals.com/post/2072558330/understanding-pac-man-ghost-behavior

FSM Examples

- Pac-Man
- FPSs



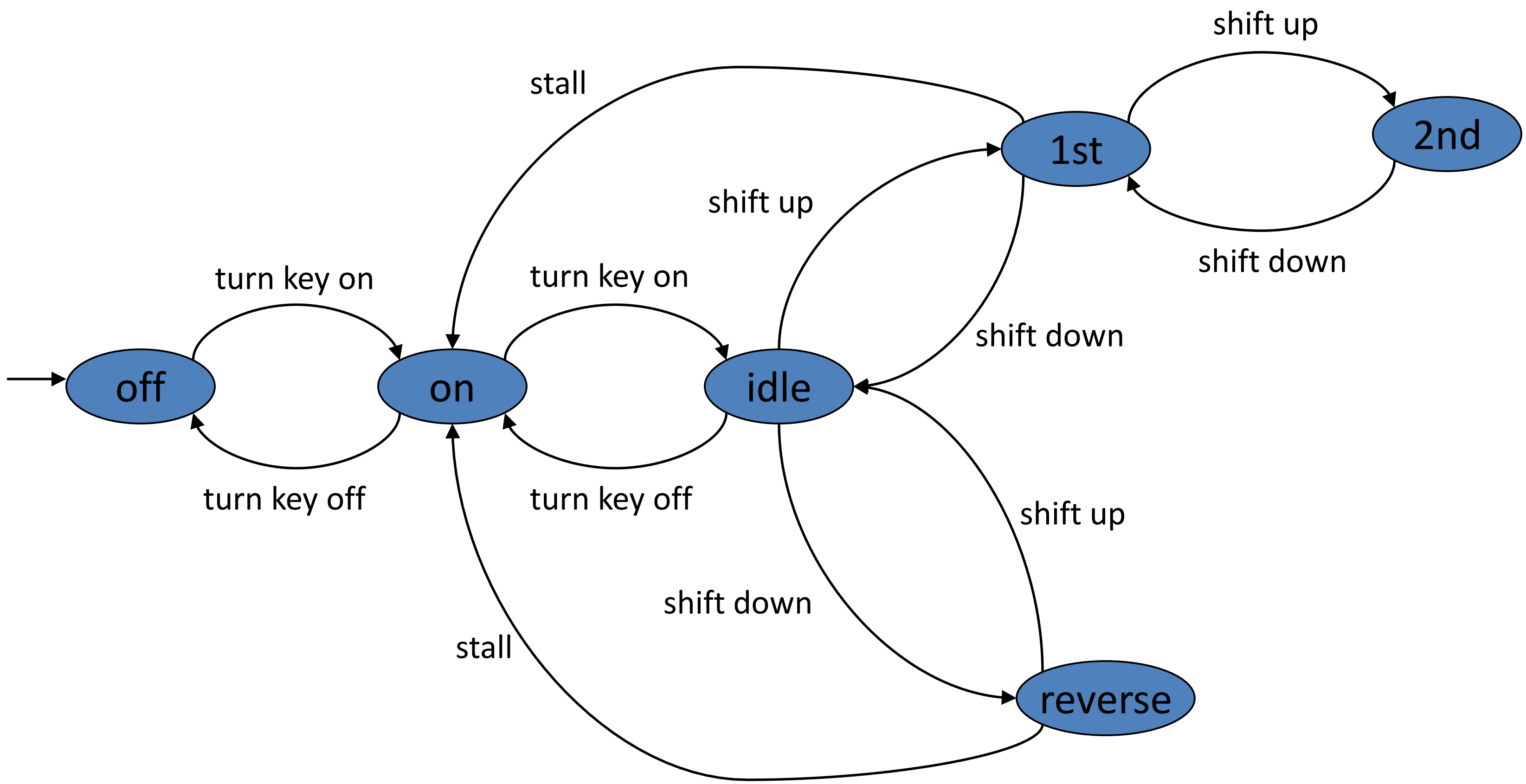
FSM Examples

- Pac-Man
- FPSs
- Sports Simulations

FSM Examples

- Pac-Man
- FPSs
- Sports Simulations
- RTSs

UnrealScript Example



```
public void runStateMachine (Event e)
{
    switch (state) {
        case 0:
            if (e.isTurnOn()) { power=true; state=1;}
            break;
        case 1:
            if (e.isTurnOn()) { startEngine(); state=2;}
            else if (e.isTurnOff()) { power=false; state=0;}
            break;
        case 2:
            makeEngineSound();
            if (e.isUpShift()) { gear=1; state=3;}
            else if (e.isDownShift()) { gear=-1; state=9;}
            else if (e.isTurnOff()) { stopEngine(); state=1;}
            break;
    …
    }
}
```


Sun. 8:58 PM
$5
4 h

FSM IMPLEMENTATIONS

Impl: Centralized Conditionals

- Simplest method
- After an action, the state might change.
- Requires a recompile for changes (hard-coded)
- No pluggable AI
- Not accessible to non-programmers
- No set structure
- Can be a bottleneck.

```
void RunLogic( int *state ) {
   switch( *state ) {
      case 0: //Wander
         Wander();
         if( SeeEnemy() )
            *state = 1;
         if( Dead() )
            *state = 2;
         break;
      case 1:  //Attack
         Attack();
         *state = 0;
         if( Dead() )
            *state = 2;
         break;
      case 3: //Dead
          SlowlyRot()
          break;
   }
```

… in Game Loop (w/ enum)

```
public enum State {STATE1, STATE2, STATE3};
State state = State.STATE1;
void tick ()
{
        switch (state) {
                case STATE1:
                        PlayAnimation(…);
                        if (…) state = newstate;
                        else if (…) state = newstate;
                        else if …
                        else …
                case STATE2:
                        PlayAnimation(…);
                        if (…) state = newstate;
                        else if…
                        else if…
                        else …
        }
}
```

Implementation: Macros

```
…
BeginStateMachine
        State(WANDER)
                Begin:
                        Wander();
                        if (SeeEnemy()) GotoState(ATTACK);
                        if (Incapacitated()) GotoState(INCAPACITATED);
        State(INCAPACITATED)
                Begin:
                        …
                Moan:
                        PlaySound(moan);
                        goto ‘Moan’;
EndStateMachine
```

Impl: State Transition Tables

Current State	Condition	State Transition
RunAway	Safe	Patrol
Attack	WeakerThanEnemy	RunAway
Patrol	Threatened && StrongerThanEnemy	Attack
Patrol	Threatened && WeakerThanEnemy	RunAway

If Kitty_Hungry AND NOT Kitty_Playful SWITCH_CARTRIDGE eat_fish

Impl: Tables Alt

Event → State ↓	E1	E2	E3
S1	----	A1/S2	A3/S1
S2	…	…	…
S3	…	…	…

S: state, E: event, A: action, ----: illegal transition

Implementation: Virtual FSM

State Name	Conditions	Actions
Current state name	Entry	Outputs...
	Exit	Outputs...
	Condition 1...	Outputs...
	Condition 2...	Outputs...
Next state name	Condition X	Outputs...
Next state name	Condition Y	Outputs...
...	...	...

https://en.wikipedia.org/wiki/Virtual_finite-state_machine

Implementation: Virtual FSM

State Name	Conditions	Actions
Patrol	Entry	SwingKeys()
	Exit	DropClipboard()
	Happy()	Whistle()
	NearDog()	PetDog()
Flee	Overwhelmed()	Scream()
Attack	!Overwhelmed()	TakeOutGun()
…	…	…

Impl: Distributed

- Rules for transition contained within state
- Good encapsulation
- Can swap in/out states easier
- AKA
  - "State Design Pattern" (Buckland italics)
  - "Embedded rules" (Buckland subheading)

Eat_fish cartridge knows when to switch to Use_litterbox

Impl: Distributed

```
interface Entity
{
    void update () ;
    
    //void changeState (State newstate);
}
```

Where “thinking” happens.

```
interface State
{
    void execute (Entity thing);
    
    void onEnter (Entity thing);
    
    void onExit (Entity thing);
}
```

Impl: Distributed

```
class Troll implements Entity
{   int liveTime=0;
    State currentstate, previousState;
    @Override
    void update () {
        liveTime++;
        currentstate.execute( this );
    }
    //@Override
    void changeState (State newstate) {
        previousState = currentState;
        currentstate.onExit( this );
        currentstate = newstate;
        currentState.onEnter( this );
    }
}
```

```
Class CoolState implements State
{  @Override
    void execute (Entity thing) {}
    void execute (Troll thing) {
        if ( thing.liveTime = 0 ) {
                thing.playAnimation(ani1);
                thing.changeState(new st);
        }
        else thing.doSomething();
    }

    @Override
    void onEnter (Entity thing) {…}
    @Override
    void onExit (Entity thing) {…}
}
```

Impl: Consolidated, Distributed

```
class StateMachine //implements Entity?
{   State currSt, prevSt, globalSt;
    Entity owner;

    StateMachine( Entity e ){ owner = e; }

    void update () {
        if( globalSt != null)
            globalSt.execute( owner);
        currentstate.execute( owner );
    }
    void changeState (State newstate) {
        previousState = currentState;
        currentstate.onExit( owner);
        currentstate = newstate;
        currentState.onEnter( owner );
    }
    void revertToPrev(){ changeState( prevSt ); }
    boolean isInState( State st ) { …}
}
```

```
class Troll implements Entity
{  StateMachine fsm;
    Troll(){
        fsm = new StateMachine( this );
        fsm.setGlobalState(
            TrollGlobalState.singleton() );
        fsm.setLocalState(
            TrollSleepInCave.singleton() );
    }

    void update(){
        liveTime++;
        fsm.update();
    }

   StateMachine getFSM()( return fsm; }
}
```

Impl: Python-like

```
class StateMachine:
  states #list of states
  initST
  curST = initST

  def update():
    triggeredT = None
    for t in curST.transitions():
      if t.isTriggered():
        triggeredT = t
        break

    if triggeredT:
      targetST = triggeredT.getTargetState()
      actions = curST.getExitAction()
      actions += triggeredT.getAction()
      actions += targetST.getEntryAction()
      curST = targetST
      return actions
    else: return curST.getAction()
```

```
class State:
  actions
  def getAction(): return actions
  entryActs
  def getEntryAction(): return entryActs
  exitActs
  def getExitAction(): return exitActs
  transitions
  def getTransitions(): return transitions

class Transition:
  condition
  def isTriggered(): return condition.test()
  targetState
  def getTargetState(): return targetState
  actions
  def getAction(): return actions
```

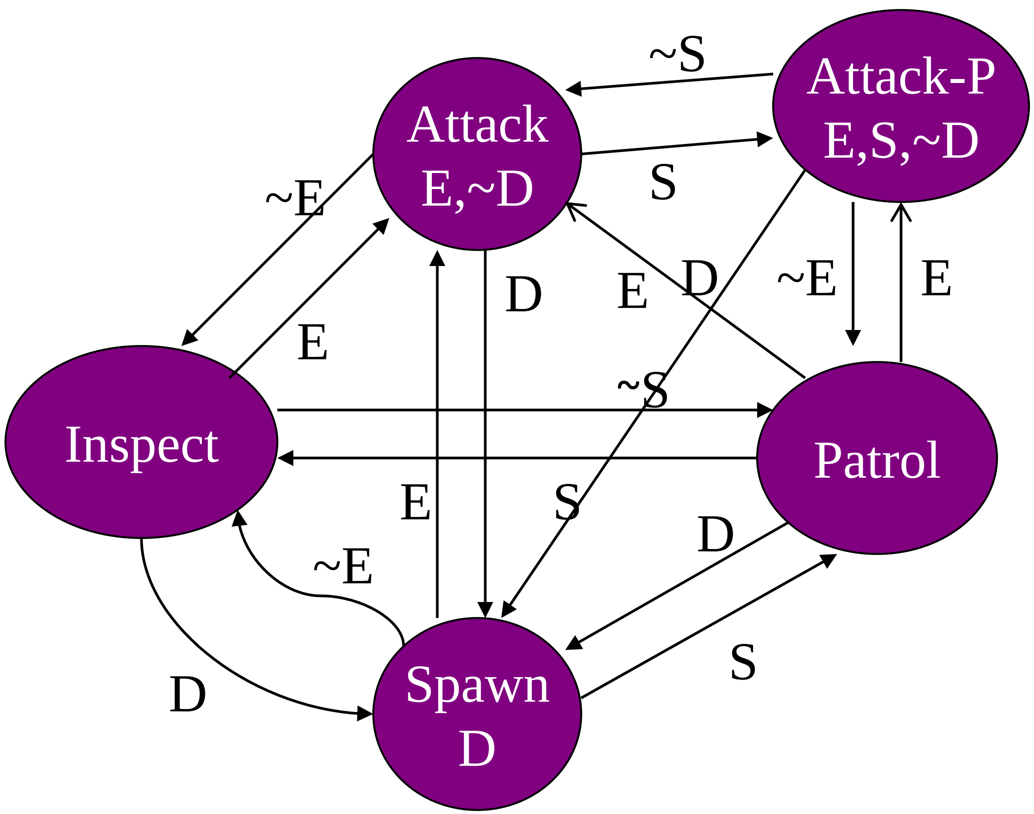
Global States

- May have multiple states that could happen at any time
- Want to avoid authoring many transitions from every other state to these
- Create a global state that is called every update cycle
- State “blips” (return to previous after global)

FSM Extensions

- Extending States
  - Adding onEnter() and onExit() states can help handle state changes gracefully.
- Stack Based FSM’s
  - Allows an AI to switch states, then return to a previous state.
  - Gives the AI ‘memory’
  - More realistic behavior
  - Subtype: Hierarchical FSM’s

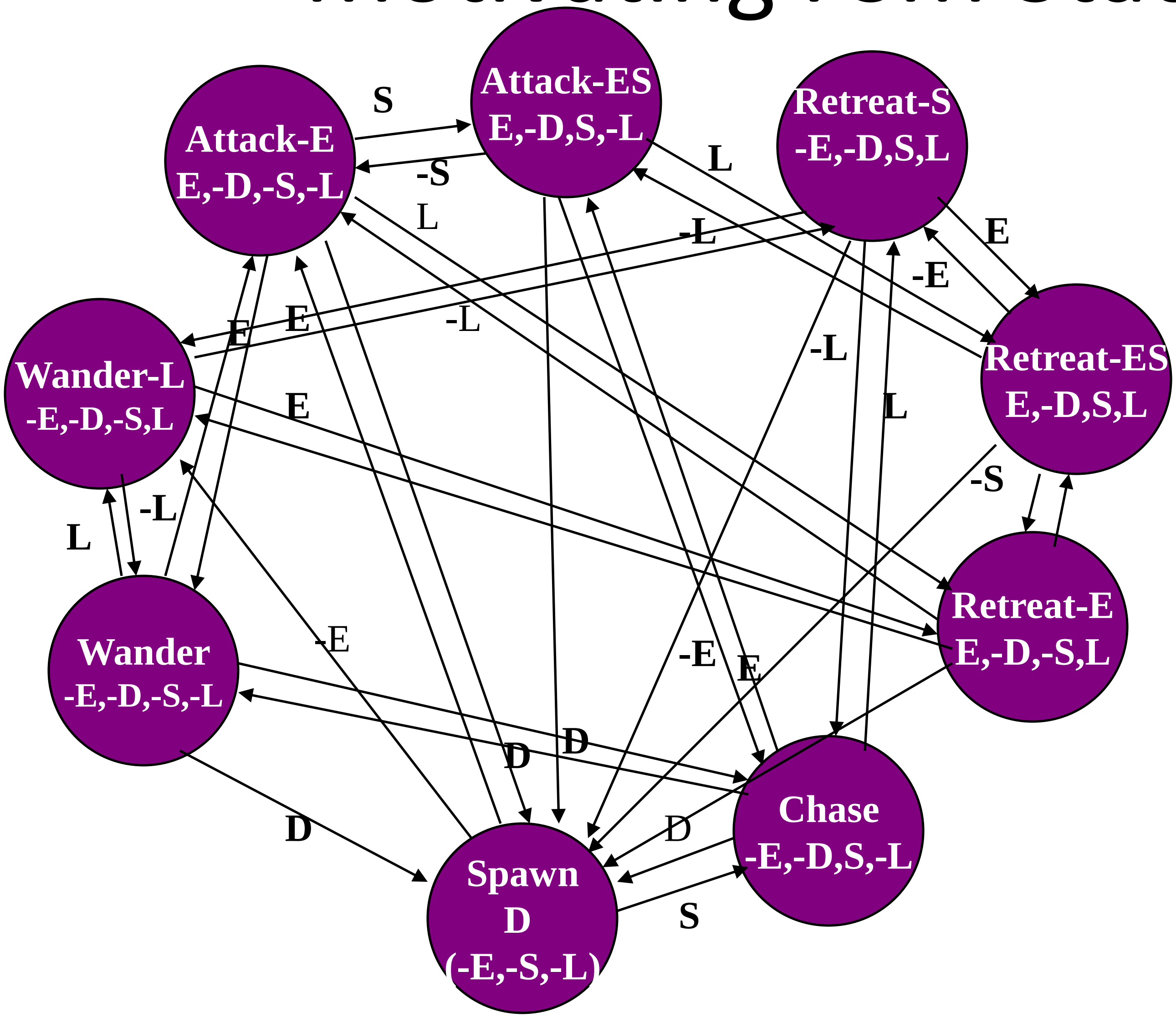
Motivating FSM Stacks



- Original version doesn't remember what the previous state was.
- One solution is to add another state to remember if you heard a sound before attacking.

E: Enemy in sight; S: hear a sound; D: dead

Motivating FSM Stacks (2)



Worst case:
Each extra state variable can add 2^n extra states
n = number of existing states

Using a stack would allow much of this behavior without the extra states.

E: Enemy in sight; S: hear a sound; D: dead

Stack FSM – Thief 3

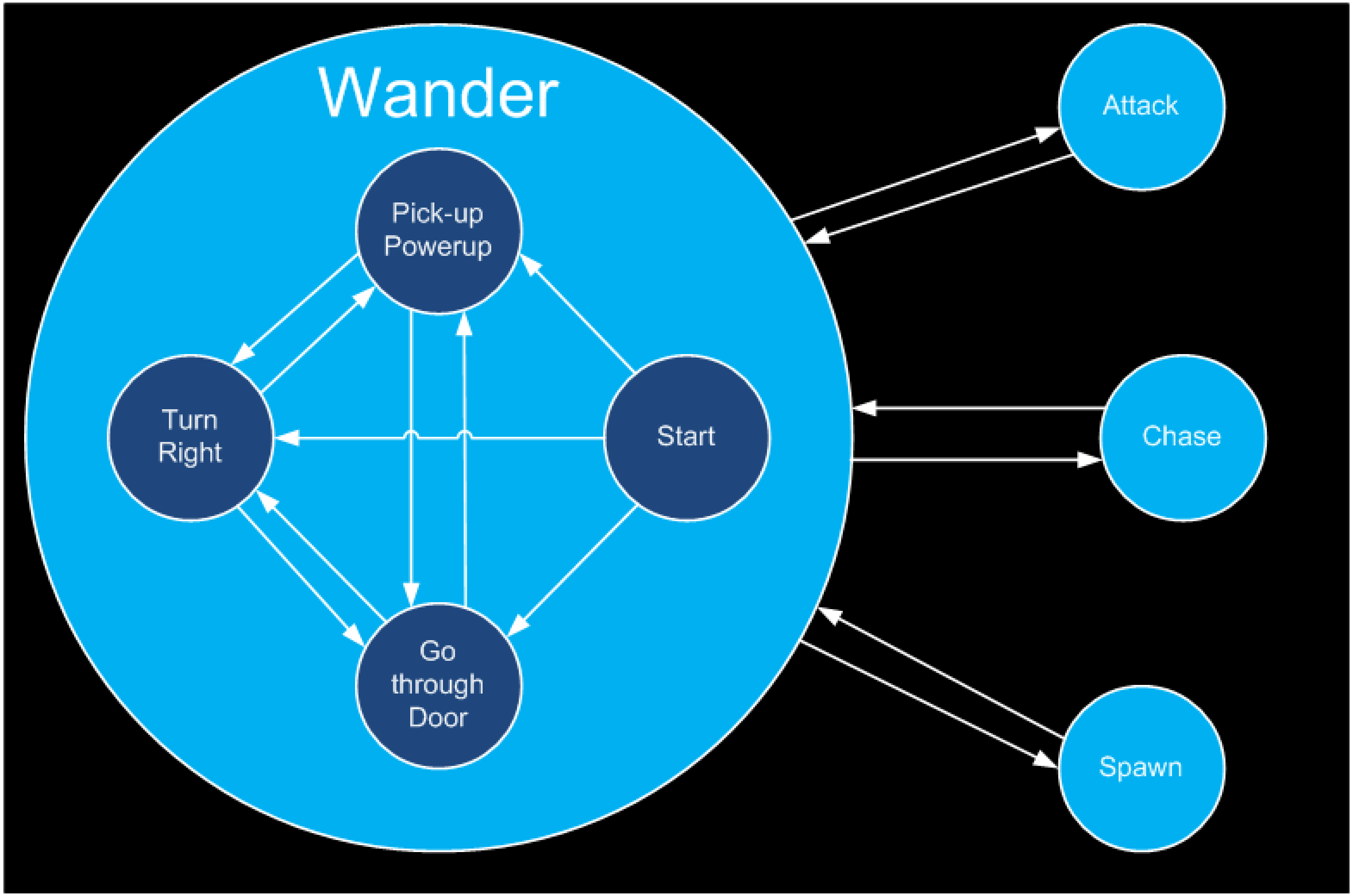
Stack allows AI to move back and forth between states.

Leads to more realistic behavior without increasing FSM complexity.

Hierarchical FSMs

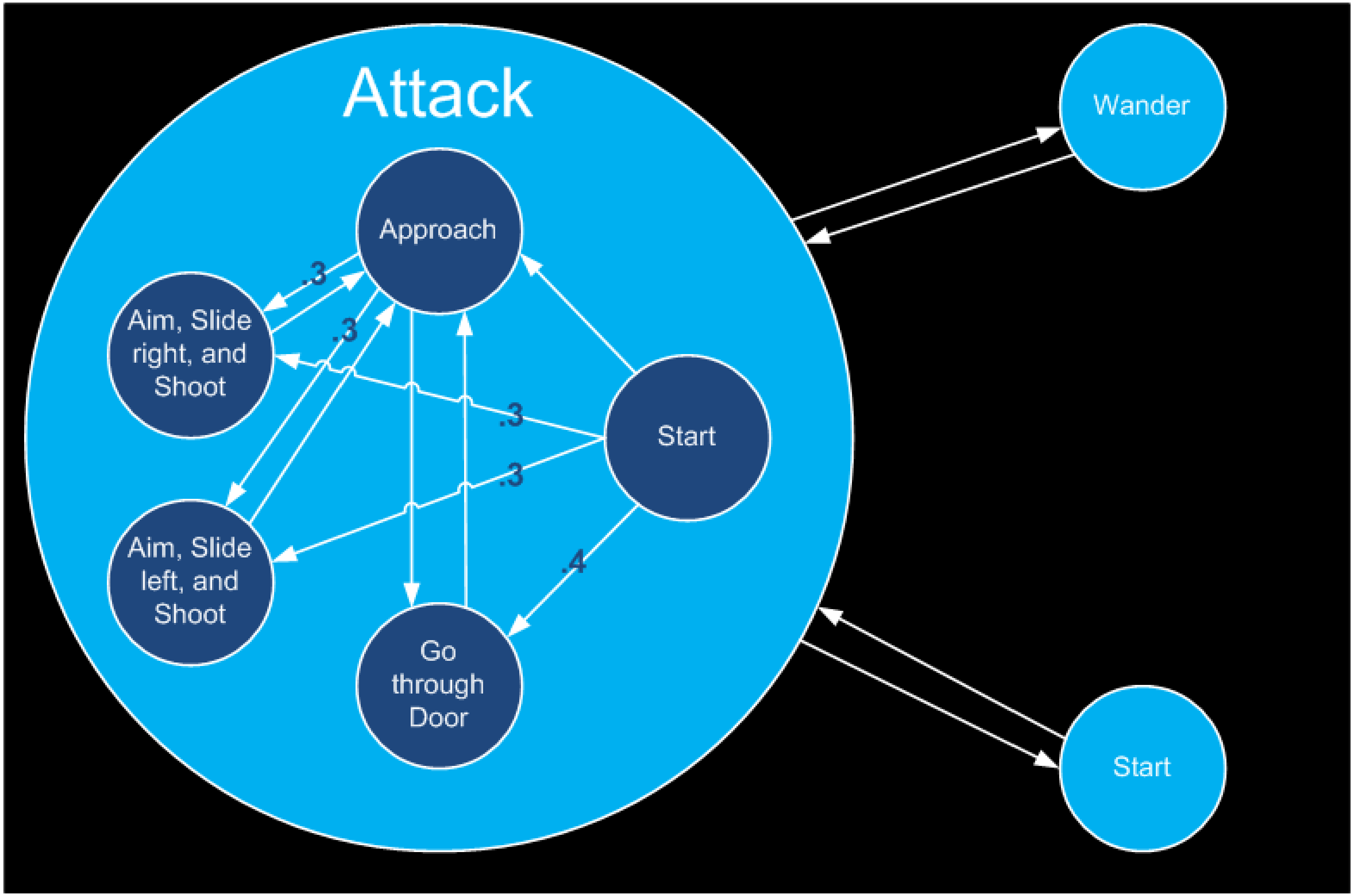
- Expand a state into its own sub-FSM
- Some events move you around the same level in the hierarchy, some move you up a level
- When entering a state, have to choose a state for it’s child in the hierarchy
  - Set a default, and always go to that
  - Random choice
  - Depends on the nature of the behavior

Hierarchical FSM Example



E: Enemy in sight; S: hear a sound; D: dead

Non-Deterministic Hierarchical FSM

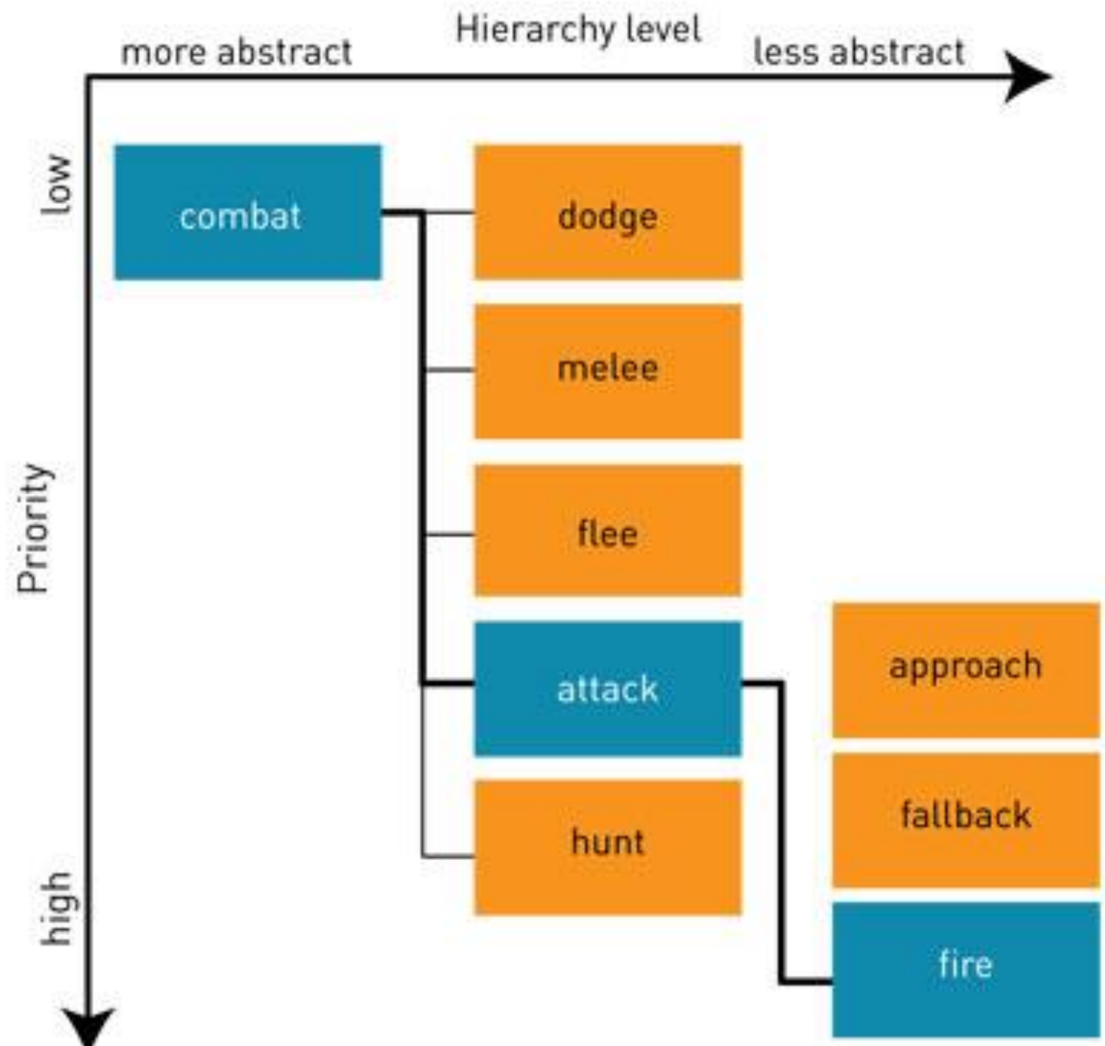


Hierarchical FSMs in *Destroy All Humans 2*

http://www.gamasutra.com/view/feature/130279/creating_all_humans_a_datadriven_.php

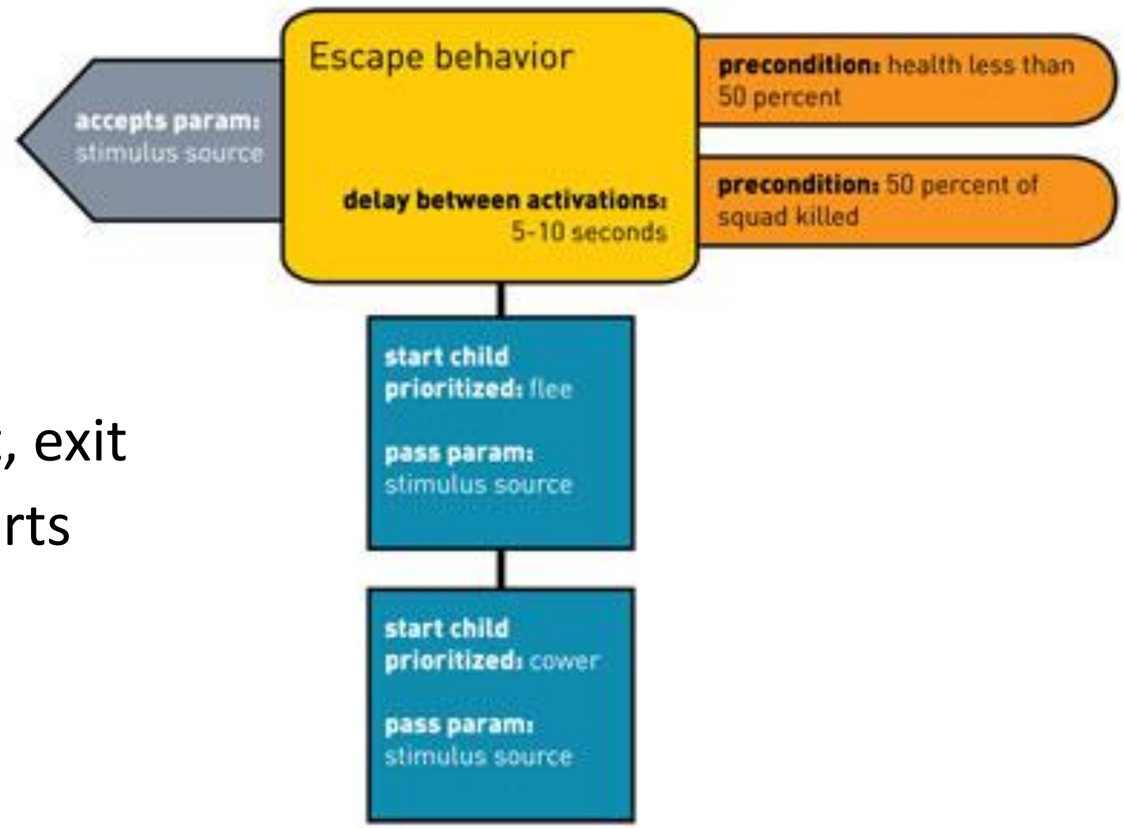
Hierarchical FSMs in *Destroy All Humans 2*

- Active (blue), pending (orange)
- Only active behaviors update
- Only active behaviors have children
- If * children startable, rank
- States can be marked as non-interruptable or non-blocking



Hierarchical FSMs in *Destroy All Humans 2*

- Self-contained behaviors
  - When to activate
  - What activates it, interrupts it
  - What to do on start, exit
  - What children it starts
- Code-supported behaviors exist for complex, non-generalizable cases



Hierarchical FSMs in *Destroy All Humans 2*

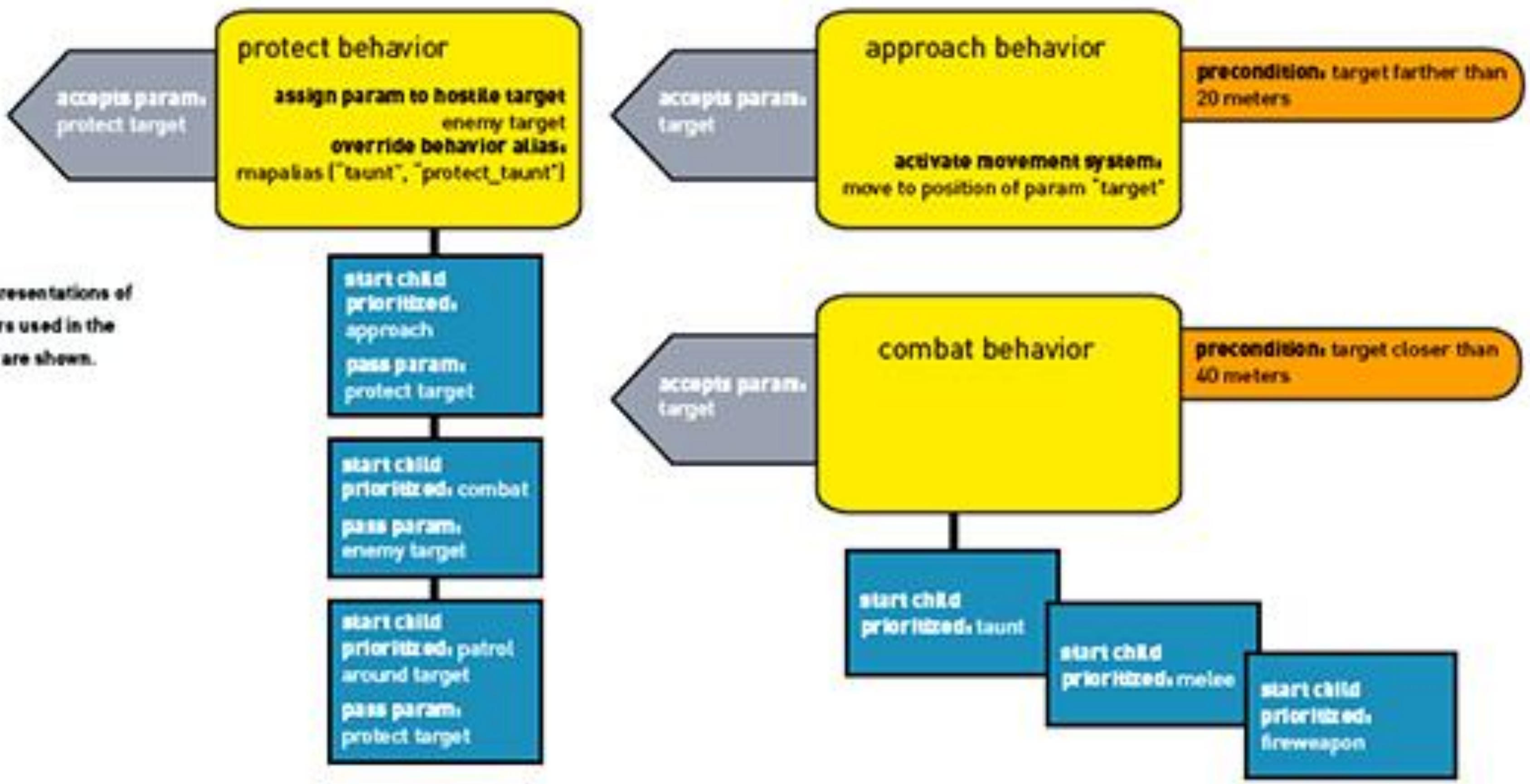


FIGURE 3 Representations of three behaviors used in the protect HFSM are shown.

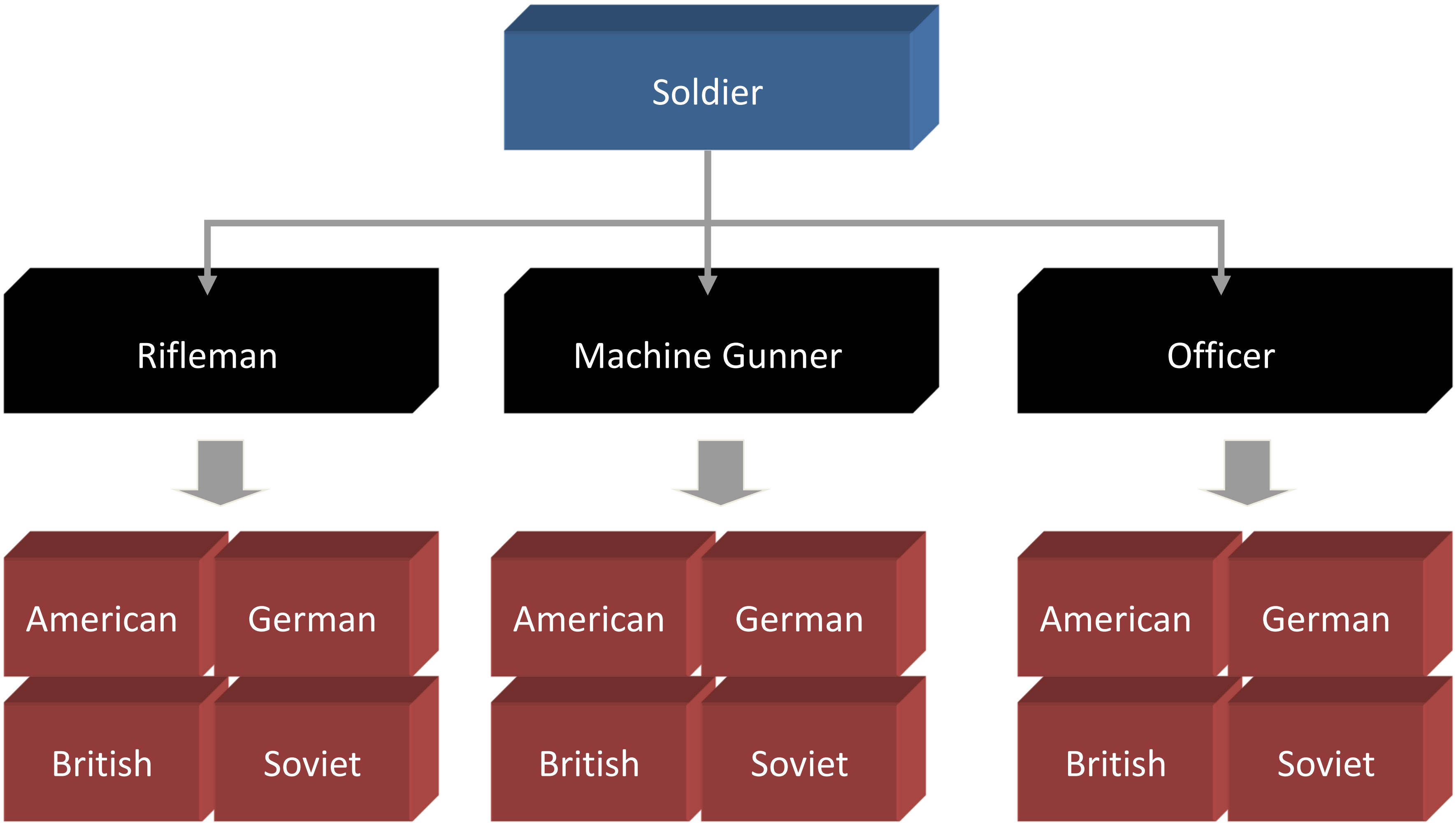
More FSM Extensions

- Fuzzy State Machines
  - Degrees of truth allow multiple FSM's to contribute to character actions.
- Multiple FSM's
  - High level FSM coordinates several smaller FSM's.
- Polymorphic FSM's
  - Allows common behavior to be shared.
  - Soldier -> German -> Machine Gunner

Polymorphic FSMs

- Small changes to low level behaviors may be needed for different types of entities
- Polymorphism allows multiple versions of a single FSM to be executed on NPC state

Polymorphic FSM Example



Impl: Data Driven

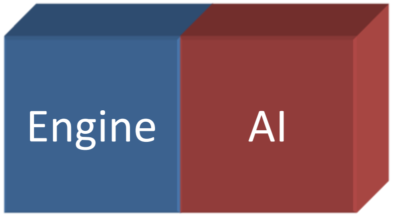
- Developer creates scripting language to control AI.
- Script is translated to C++ or bytecode.
- Requires a vocabulary for interacting with the game engine.
- A ‘glue layer’ must connect scripting vocabulary to game engine internals.
- Allows pluggable AI modules, even after the game has been released.

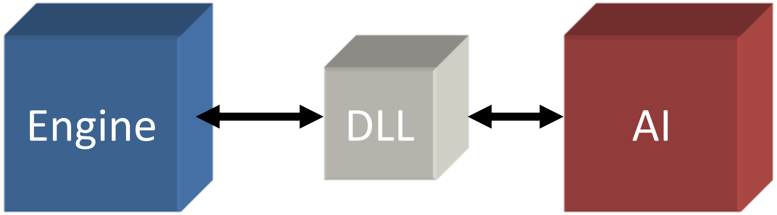
Scripted AI

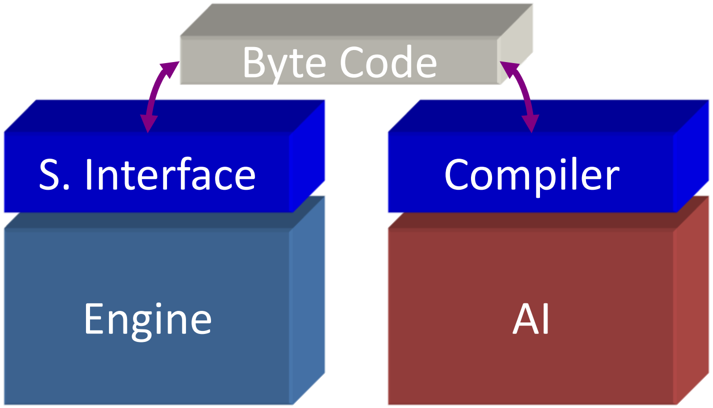
- Many game engines are virtual machines
- Script is a program written in a programming language that makes calls into the game engine
- AI is the script
- Examples: Lua, Ruby, UnrealScript
- Powerful when paired with trigger systems

Game Engine Interfacing

- Simple hard coded approach
  - Allows arbitrary parameterization
  - Requires full recompile
- Function pointers
  - Pointers are stored in a singleton or global
  - Implementation in DLL
    - Allows for pluggable AI.
- Data Driven
  - An interface must provide glue from engine to script engine.



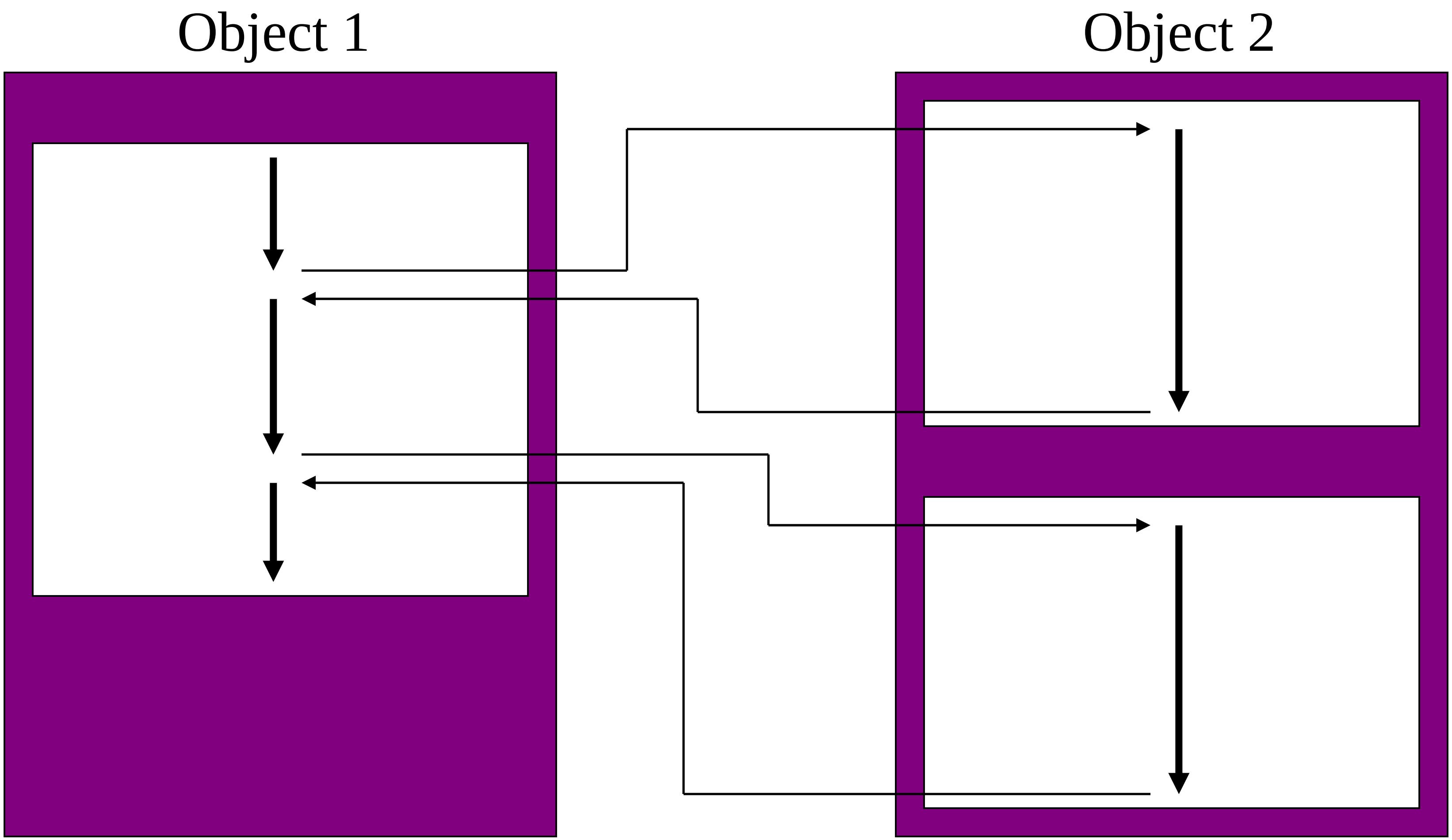




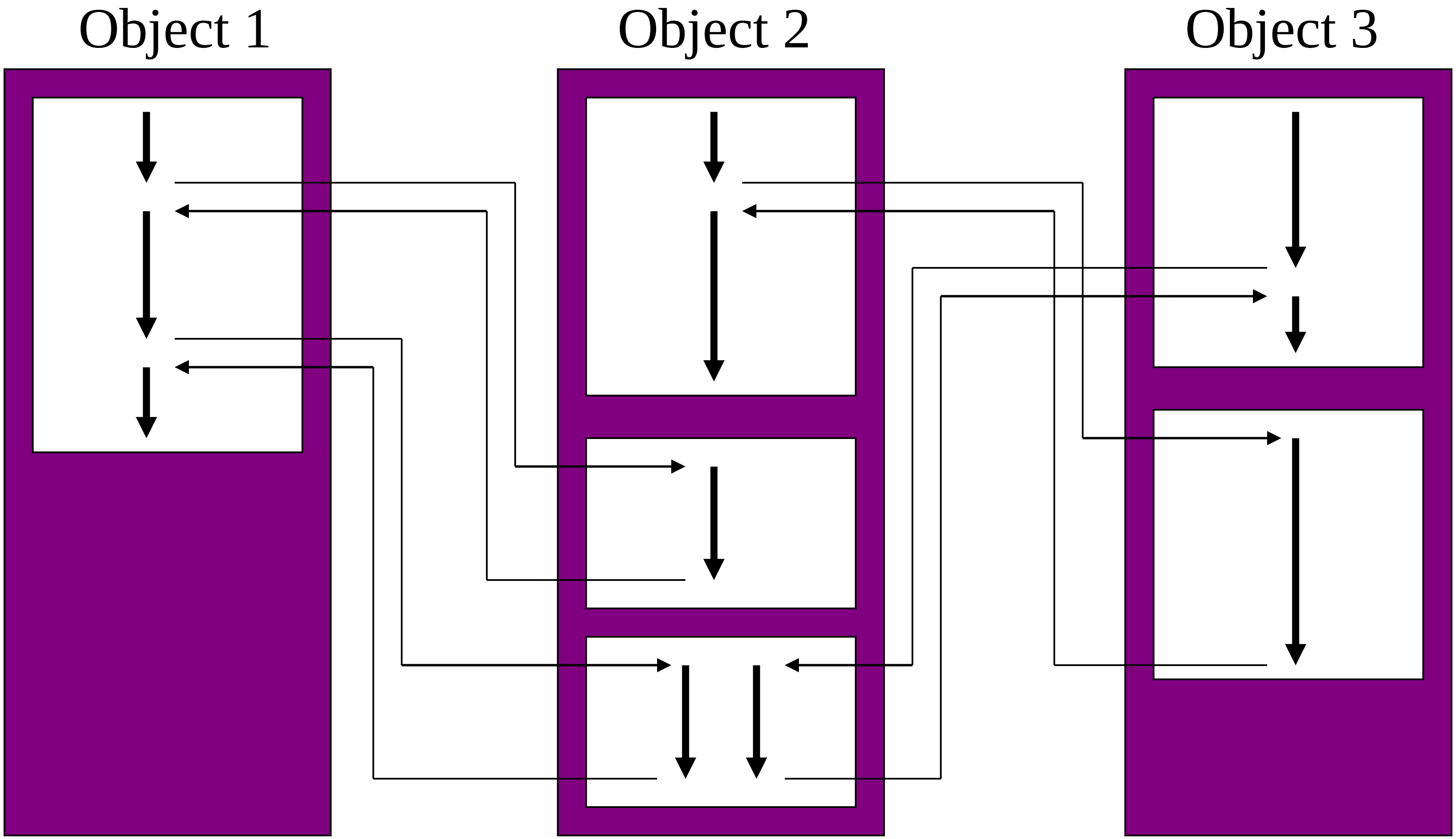
Processing Paradigms

- Polling
  - Simple and easy to debug.
  - Inefficient since FSM’s are always evaluated.
- Event Driven Model
  - FSM registers which events it is interested in.
  - Requires Observer model in engine.
  - Hard to balance granularity of event model.
- Multithreaded
  - Each FSM assigned its own thread.
  - Requires thread-safe communication.
  - Conceptually elegant.
  - Difficult to debug.
  - Can be made more efficient using microthreads.

Single-threaded execution



Multi-threaded execution



Messaging/Triggers vs Polling

- Well-designed games tend to be event driven
- Examples (broadcast to relevant objs)
  - Wizard throws fireball at orc
  - Football player passes to teammate
  - Character lights a match (delayed dispatch match)
- Events / callbacks, publish / subsribe, Observers (GoF)
  - See Buckland Ch 2: Adding Messaging (pp69)

Time Management

- Helps manage time spent in processing FSM's.
- Scheduled Processing
  - Assigns a priority that decides how often that particular FSM is evaluated.
  - Results in uneven (unpredictable) CPU usage by the AI subsystem.
    - Can be mitigated using a load balancing algorithm.
- Time Bounded
  - Places a hard time bound on CPU usage.
  - More complex: interruptible FSM's

FSM Pros and Cons

- Advantages:
  - Very fast – One array access
  - Can be compiled into compact data structure
    - Dynamic memory: Current state
    - Static memory: State diagram – Array implementation
  - Can create tools so non-programmer can build behavior
  - Non-deterministic FSM can make behavior unpredictable
- Disadvantages:
  - Number of states can grow very fast
    - Exponentially with number of events: $s=2^e$
  - Number of arcs can grow even faster: $a=s^2$
  - Hard to encode complex memories or sequences of action
  - Propositional representation
    - Difficult to put in “pick up the better weapon,” attack the closest enemy

References / See Also

- AI Game Programming Wisdom 2
- Web
  - http://ai-depot.com/FiniteStateMachines
  - http://www.gamasutra.com/view/feature/130279/creating_all_humans_a_datadriven_.php
  - https://en.wikipedia.org/wiki/Virtual_finite-state_machine
- Buckland Ch 2
  - http://www.ai-junkie.com/architecture/state_driven/tut_state1.html
- Millington Ch 5
- Jarret Raim's slides (Dr. Munoz-Avila's GAI class 2005)
  - http://www.cse.lehigh.edu/~munoz/CSE497/classes/FSM_In_Games.ppt
- Mark Riedl, Brian O'Neill, and Brian Magerko

Trajectory Update

- Start next homework, ASAP!
- To come: More decision making
  - Planning
  - Decision trees
  - Behavior trees
  - Rule based systems
  - Fuzzy Logic
  - Markov Systems