Disclaimer: I use these notes as a guide rather than a comprehensive coverage of the topic. They are neither a substitute for attending the lectures nor for reading the assigned material.

"A good decision is based on knowledge and not on numbers." – Plato

"Once you make a decision, the universe conspires to make it happen." – Ralph Waldo Emerson

"The quality of decision is like the well-timed swoop of a falcon which enables it to strike and destroy its victim." – Sun Tzu

Announcements

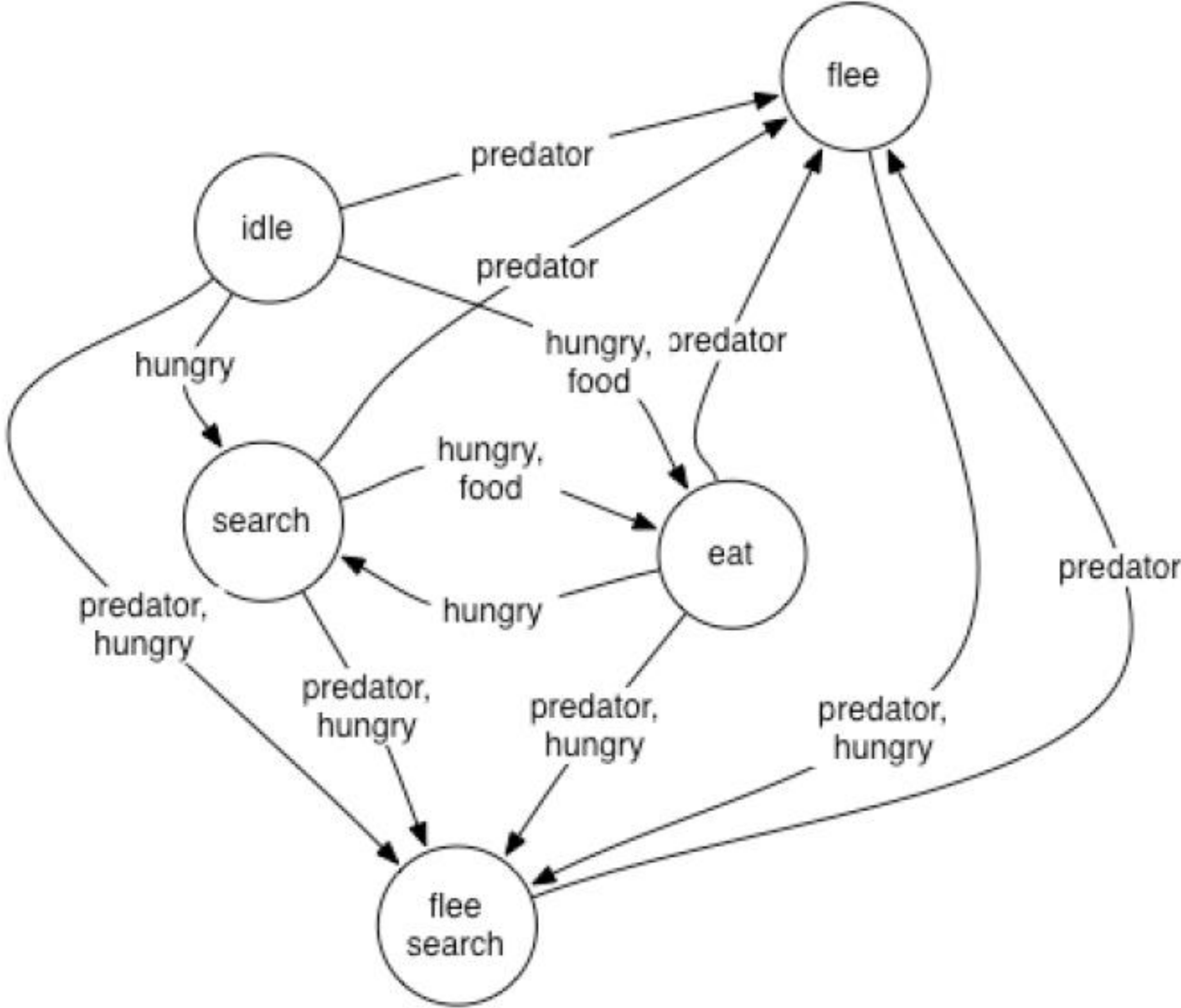
- HW4 is posted, due this Sunday

N-1&2: Decision Making, FSMs

1. How can we describe decision making, (function of what to what?)?
2. What makes FSMs so attractive? What is difficult to do with them?
3. Two drawbacks of FSMs and how to fix?
4. What are the performance dimensions we tend to assess?
5. What are two methods we discussed to learn about changes in the world state?
6. FSMs/Btrees: R___ :: Planning : D____
7. When is R__ good? When is D__?
8. H______ have helped in most approaches.
9. What are two methods we discussed to learn about changes in the world state?

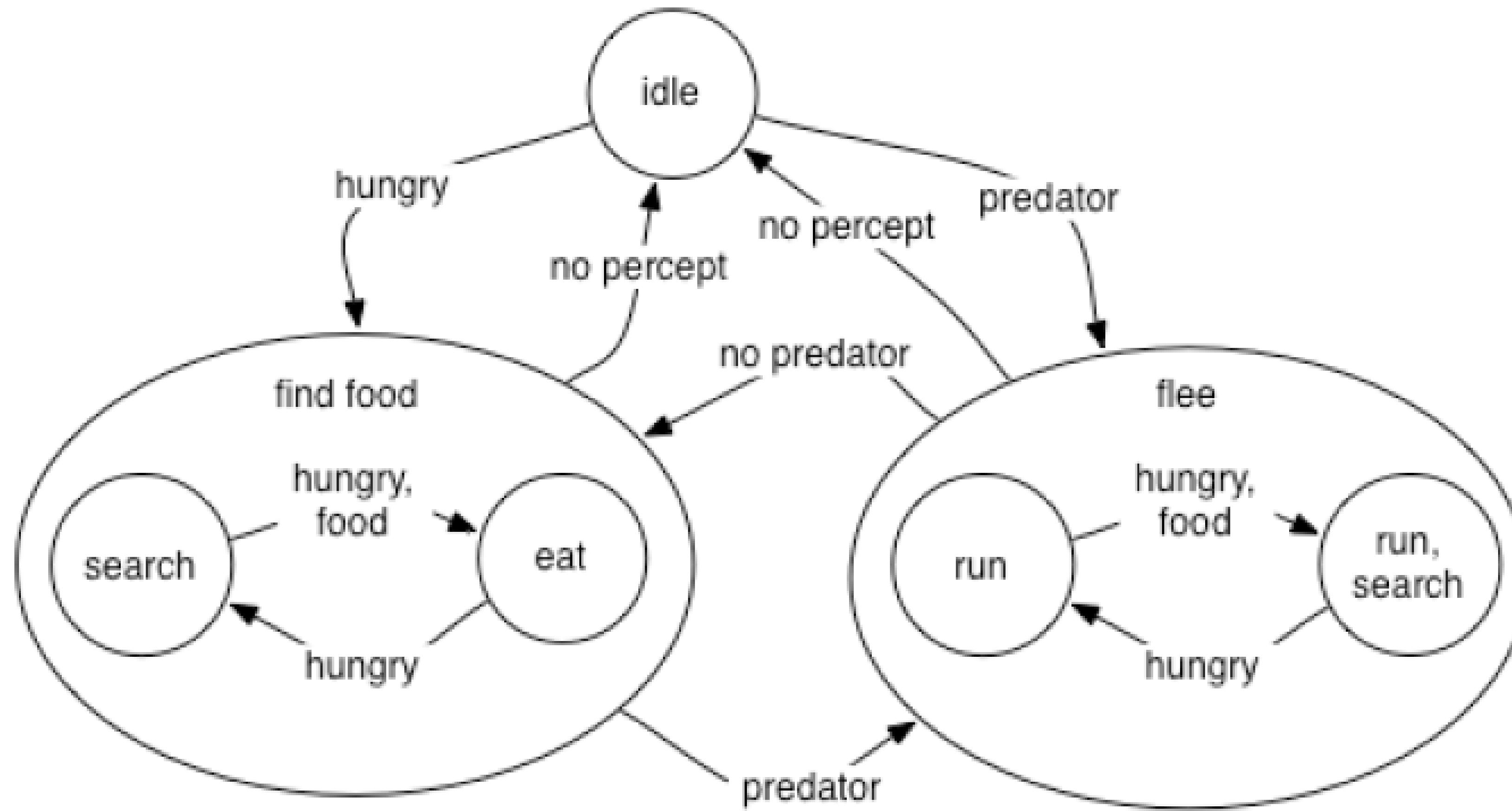
FSMS CONTINUED. EXAMPLES…

Prey Example



* 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

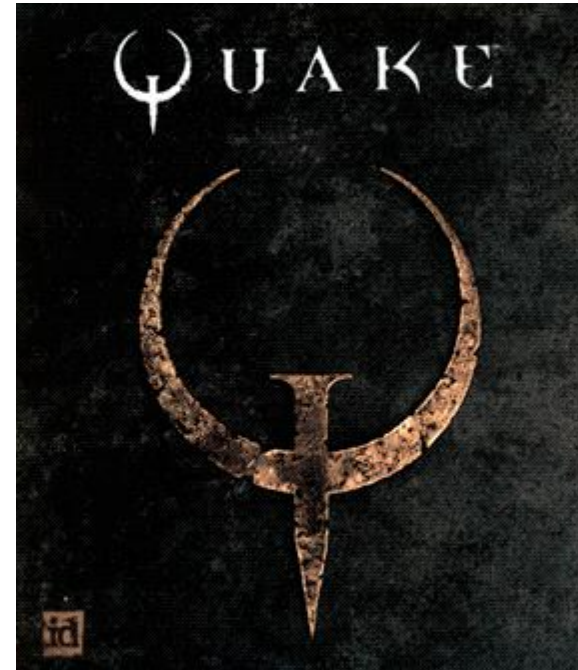
SPAWN
Spawn
AI Walk monster start
IDLE
Dog walk
Dog stand
Locate Target
Hunt Target
ATTACK
Dog run
AI run
AI Missile
AI Melee
Eval attack
Dog leap
Dog attack
AI face
AI charge
Dog bite
Dog Jump Touch
DIE
Remove
Dog die
AI Monster use
Dog use
Dog touch
Ai pain
Dog pain1
Dog pain1
Dog pain

Spawn State
Idle State
Attack State
Die State

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

FSM Examples

- Pac-Man
- FPSs
  - What might be states?
  - NPCs only?



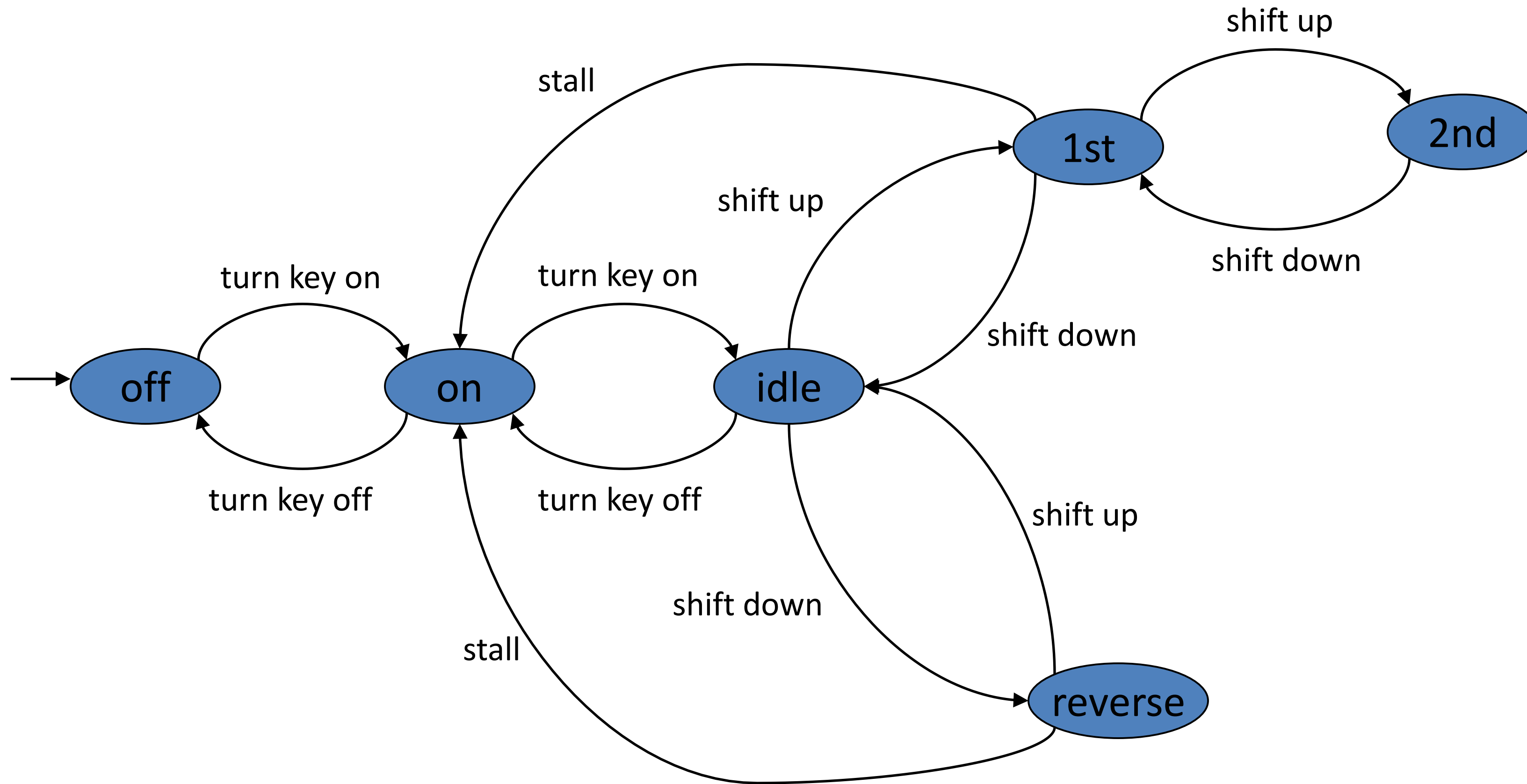
FSM Examples

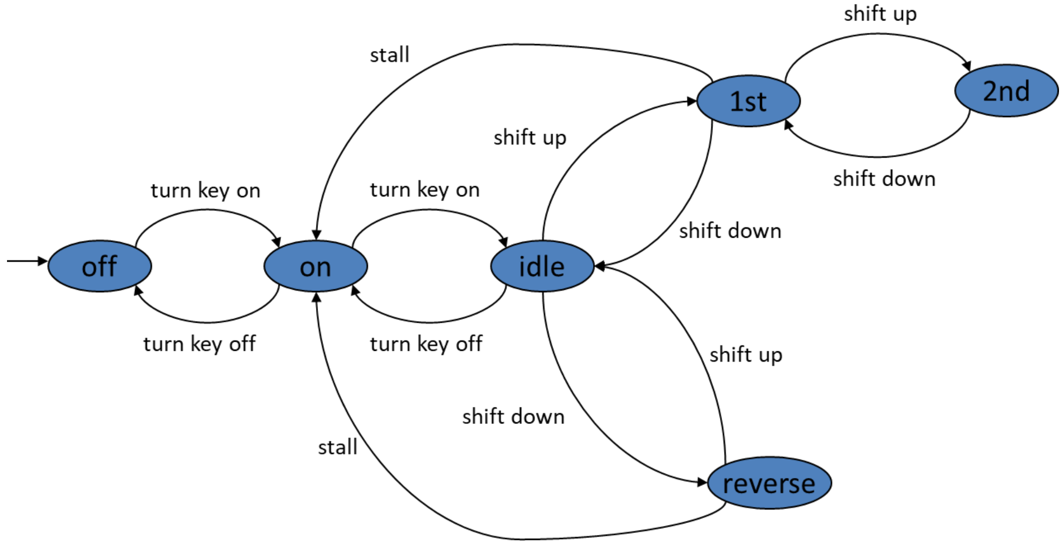
- Pac-Man
- FPSs
- Sports Simulations
  - What might be states?

FSM Examples

- Pac-Man
- FPSs
- Sports Simulations
- RTSs
  - What might be states?

UnrealScript Example






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

    ...
    }
}
```

Choices have consequences

FSM IMPLEMENTATIONS

Implementations

- Centralized conditionals
  - If / then statements
  - Throw it all in a switch statement
    - Simple, but not extendable
  - Macros
- Distributed / Object oriented
  - State as class; transition rules within
    - Agent carries reference to current state. Extendable
- State as table (central or distrib)
  - Can be stored separately, easier for designers

```
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 2: //Dead
                        SlowlyRot()
                         break;
}
```

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
```

See Buckland Ch2 for Kitty example

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

Impl: State Transition Tables Alt Alt

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

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	EnemyNear()	TakeOutGun()
…	…	…

Impl: Distributed State Design Pattern

- Rules for transition contained within the states themselves
- Good encapsulation – OOP
- 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 / Object Oriented

```
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);
}
```

http://www.ai-junkie.com/architecture/state_driven/tut_state1.html

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; }
}
```

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)

Impl: Python-like

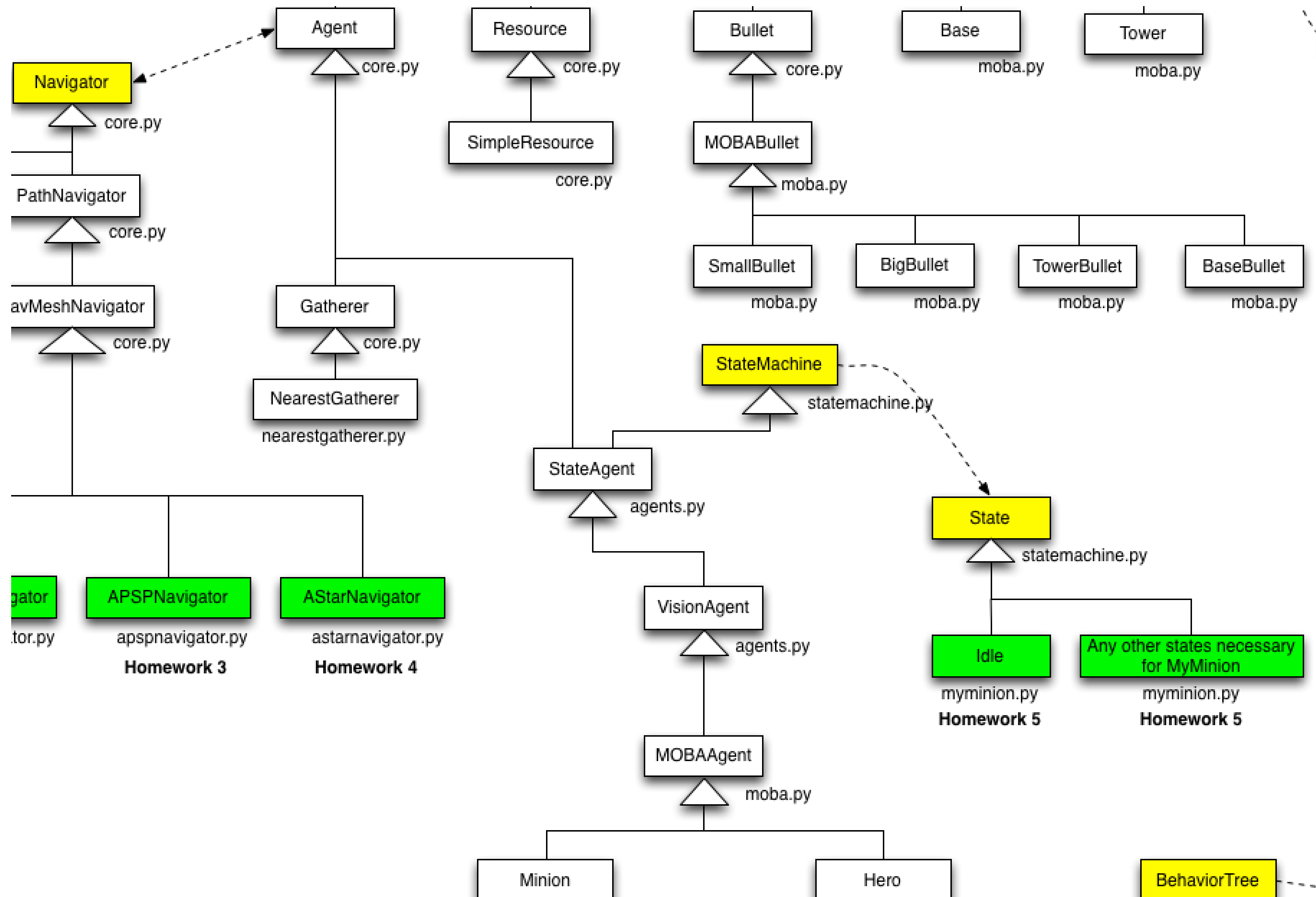
```
class StateMachine:
  states #list of states
  initST
  curST = initST

  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
```

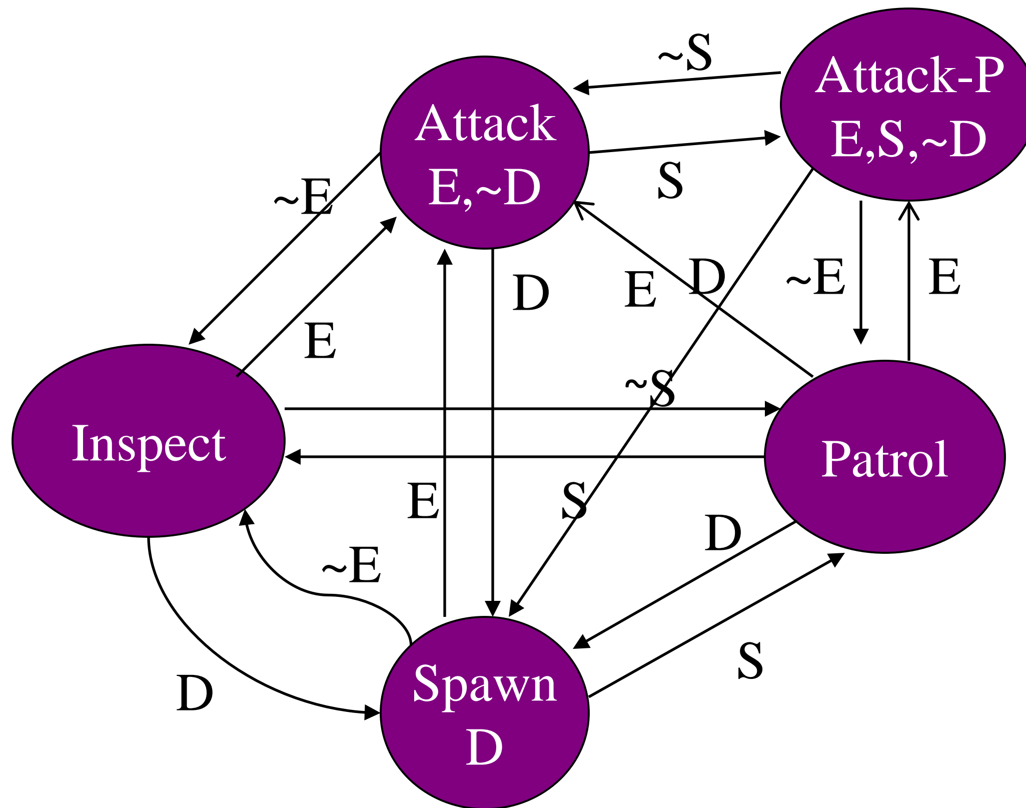


Agent
core.py
Resource
core.py
Bullet
core.py
Base
moba.py
Tower
moba.py
Navigator
core.py
SimpleResource
core.py
MOBABullet
moba.py
PathNavigator
core.py
SmallBullet
moba.py
BigBullet
moba.py
TowerBullet
moba.py
BaseBullet
moba.py
avMeshNavigator
core.py
Gatherer
core.py
NearestGatherer
nearestgatherer.py
StateMachine
statemachine.py
StateAgent
agents.py
State
statemachine.py
gator
tor.py
APSPNavigator
apspnavigator.py
Homework 3
AStarNavigator
astarnavigator.py
Homework 4
VisionAgent
agents.py
Idle
myminion.py
Homework 5
Any other states necessary for MyMinion
myminion.py
Homework 5
MOBAAgent
moba.py
Minion
Hero
BehaviorTree

FSM Extensions

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

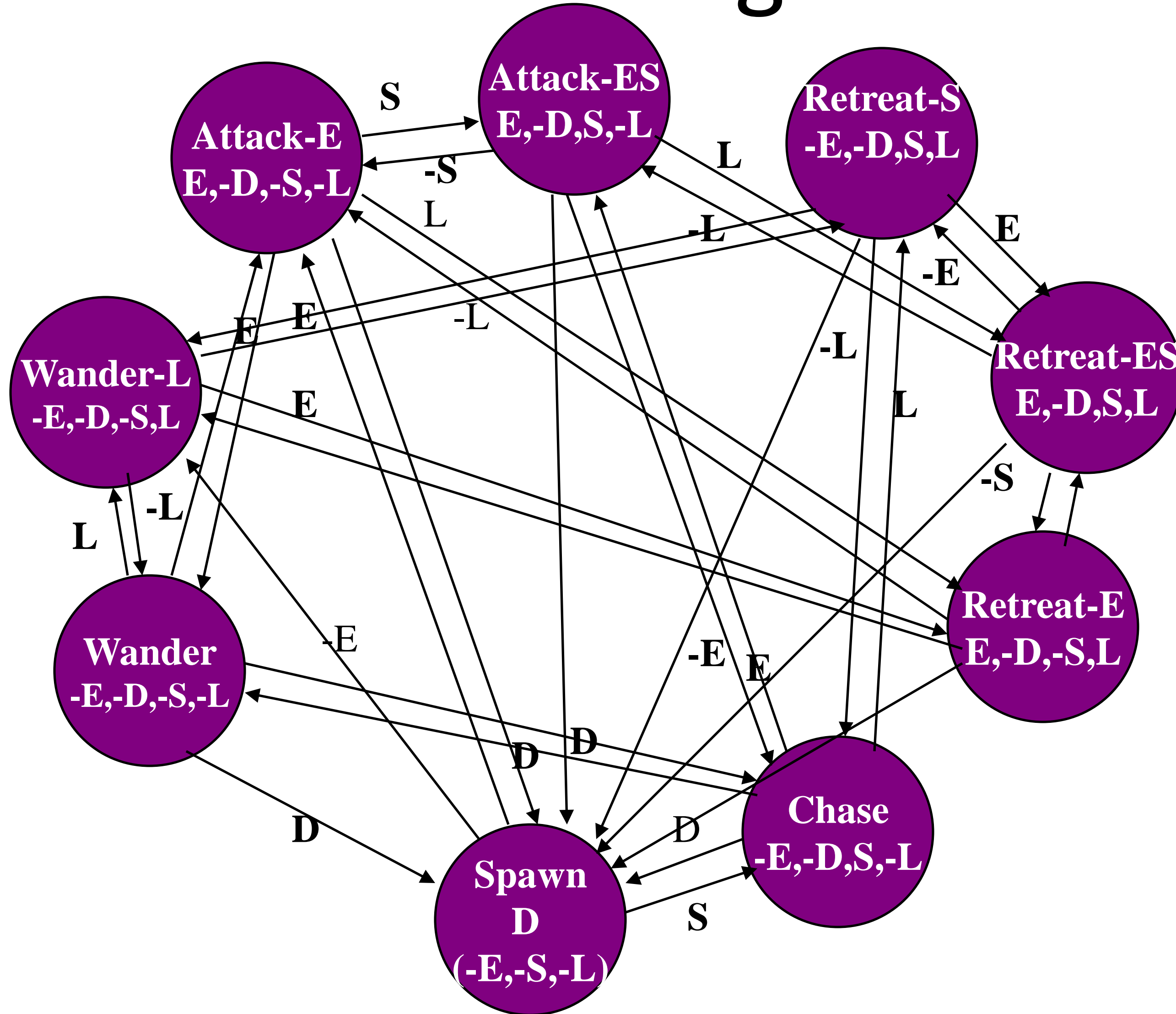
Motivating FSM Stacks



- 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.

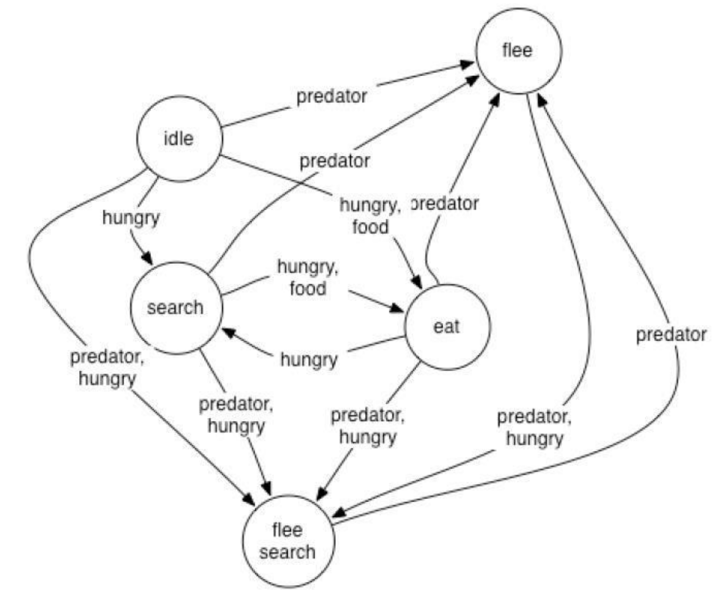
Leads to more realistic behavior without increasing FSM complexity.

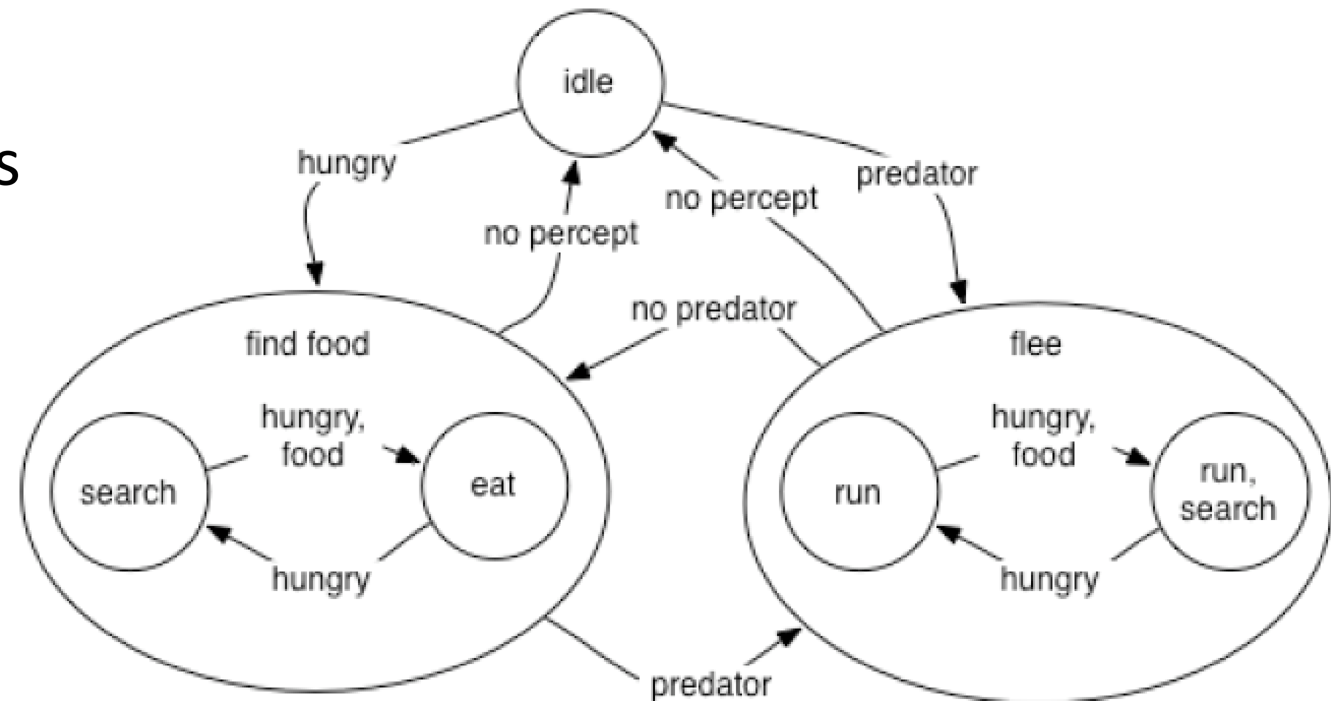
Hierarchical FSMs

- 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

- Equivalent to regular FSMs, adding recursive multi-level evaluation
- Easier to think about encapsulation
- Hierarchical approach addresses *entry, update, exit* and *any* (wildcard) at multiple levels
- But how to deal with transition from lower level state?



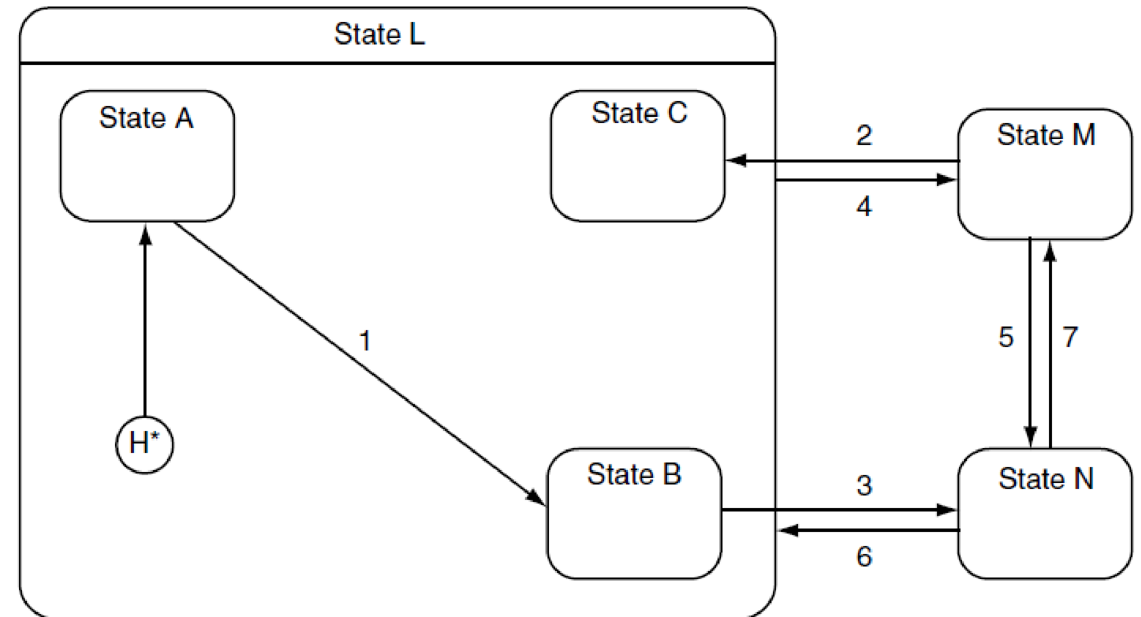


Hierarchical FSM

- Changes in world state event (input vocabulary) can be used for transitions at any level in hierarchy
- If a low-level state does not handle a potential transition event, the unhandled event is dealt with at a higher level
- Allows designer to avoid duplicating transitions
- …but you need a way for low-level state to transition out once high level transition has been identified…

Hierarchical FSM

- Recursive algorithm
  - Highest level transitions are always honored, bypassing lower level updates
  - Hierarchical states remember what child state they are in
  - All actions, whether associated with entry, update, or exit are deferred. These are collated in order of recursive evaluation and only executed once the entire HFSM is evaluated
  - Furthermore, transitions that change levels in the hierarchy are deferred when transitioning up (recursively chained when going down)



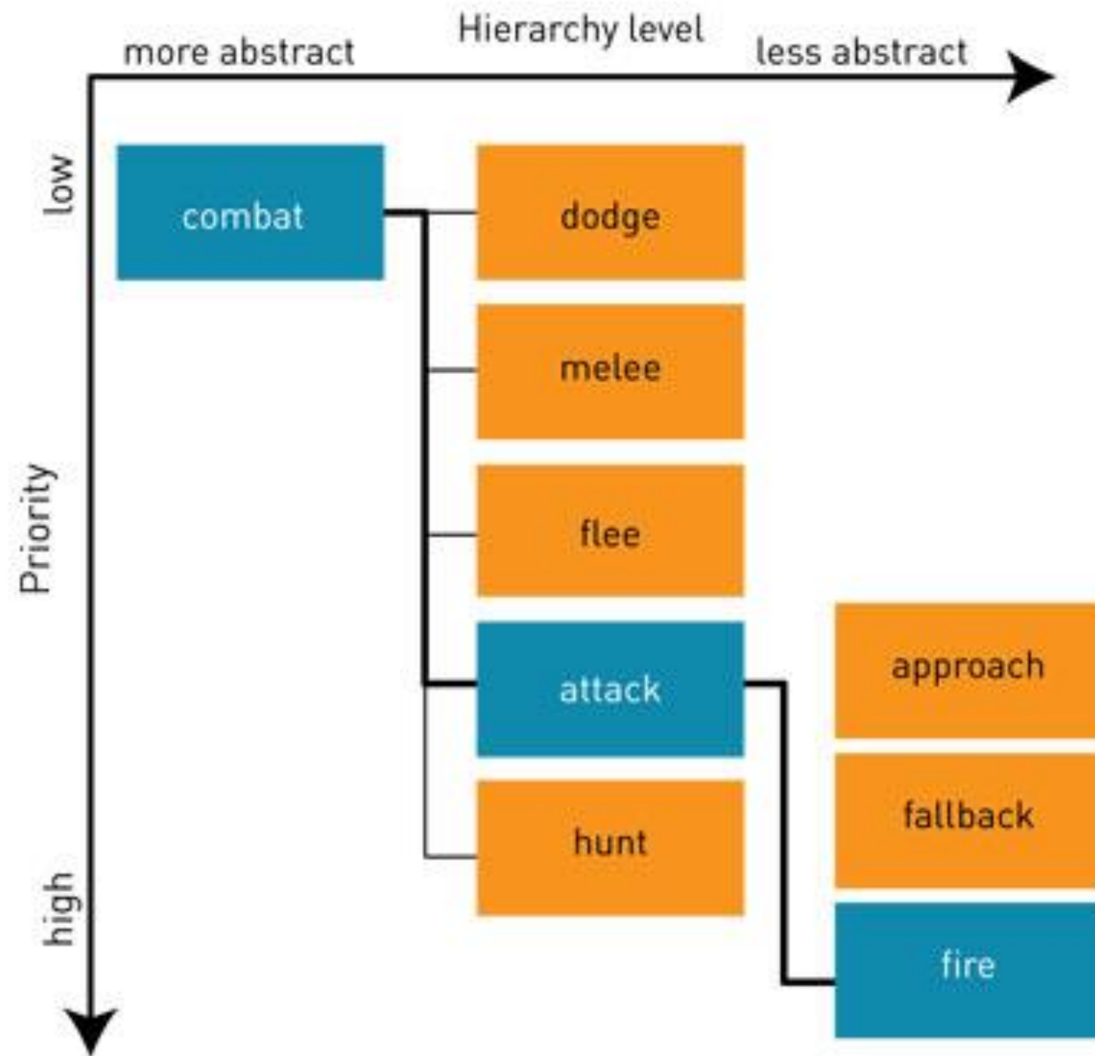
M&F 5.19

Hierarchical FSMs in *Destroy All Humans 2*

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

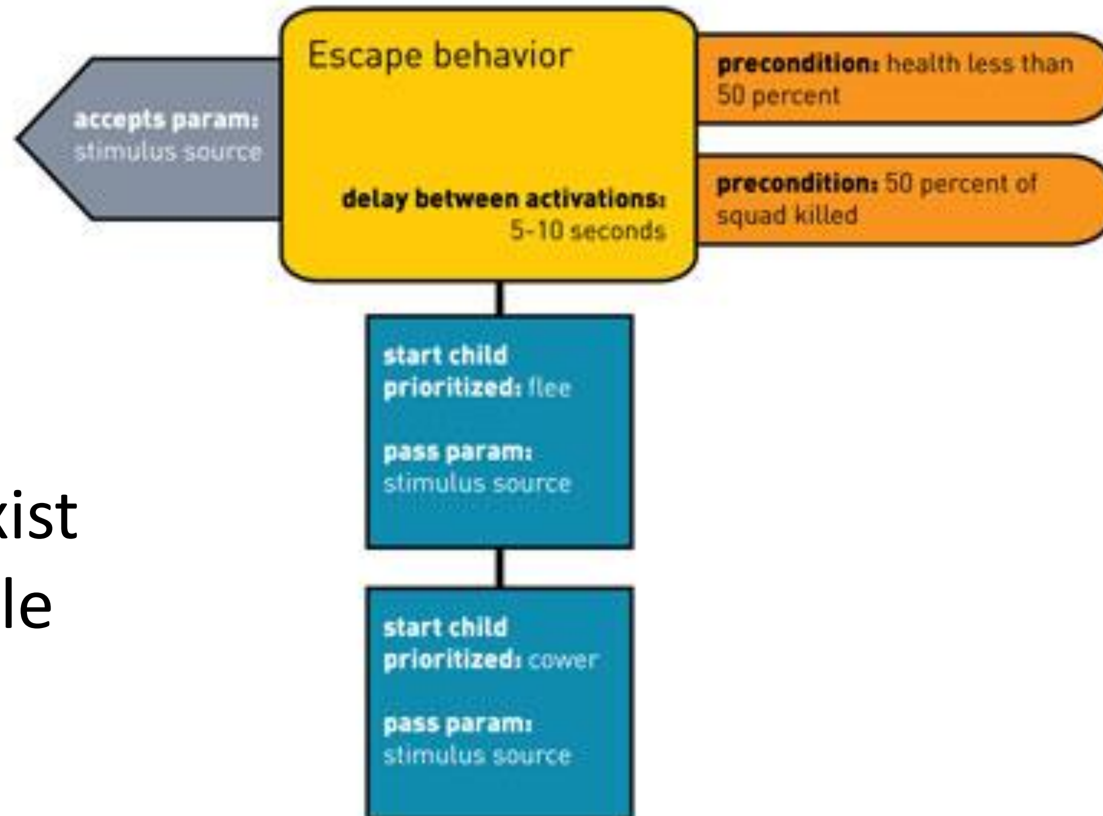
Hierarchical FSMs in *Destroy All Humans 2*

- 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*

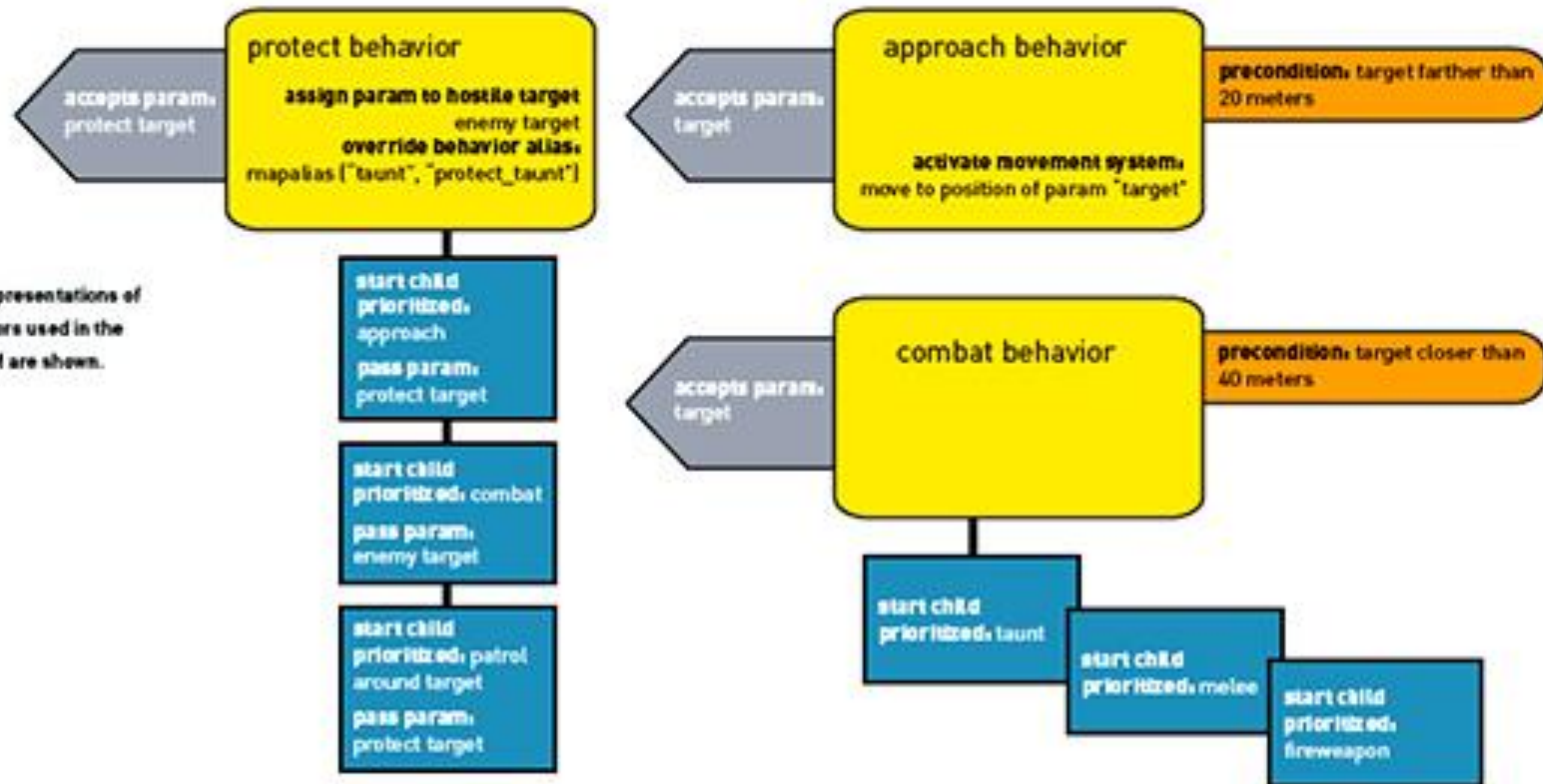


FIGURE 3 Representations of three behaviors used in the protect HFSM are shown.

More FSM Extensions

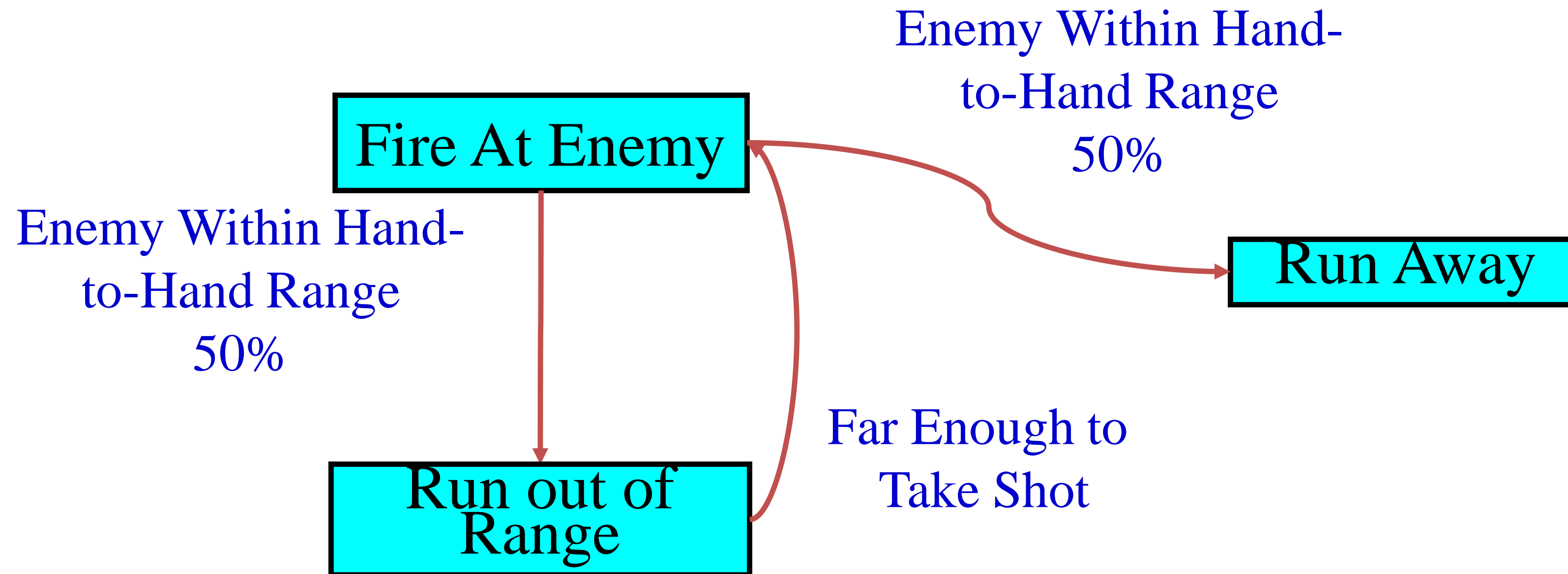
- Fuzzy State Machines
  - Degrees of truth allow multiple FSM's to contribute to character actions.
- Multiple FSM's
  - High level FSM coordinates several smaller FSM's.
- Polymorphic FSM's
  - Allows common behavior to be shared.
  - Soldier -> German -> Machine Gunner

Probabilistic State Machines

- Personalities
  - Change probability that character will perform a given action under certain conditions

	Aggressive	Passive
Attack	50%	5%
Evade	5%	60%
Random	10%	10%
Flock	20%	20%
Pattern	15%	5%

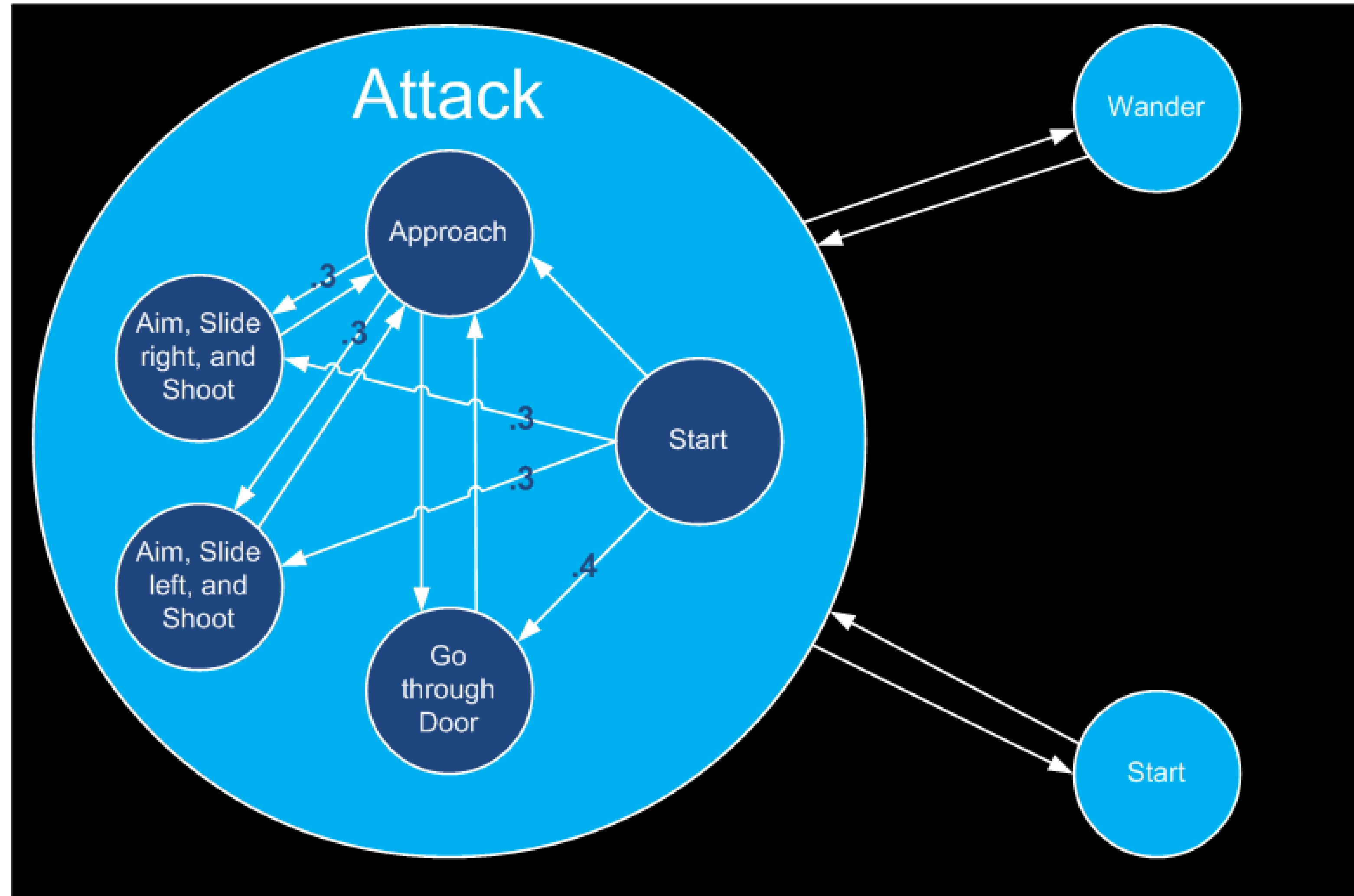
Probabilistic Example



Probabilistic State Machines

- Other aspects:
  - Sight
  - Memory
  - Curiosity
  - Fear
  - Anger
  - Sadness
  - Sociability
- Modify probabilities on the fly?

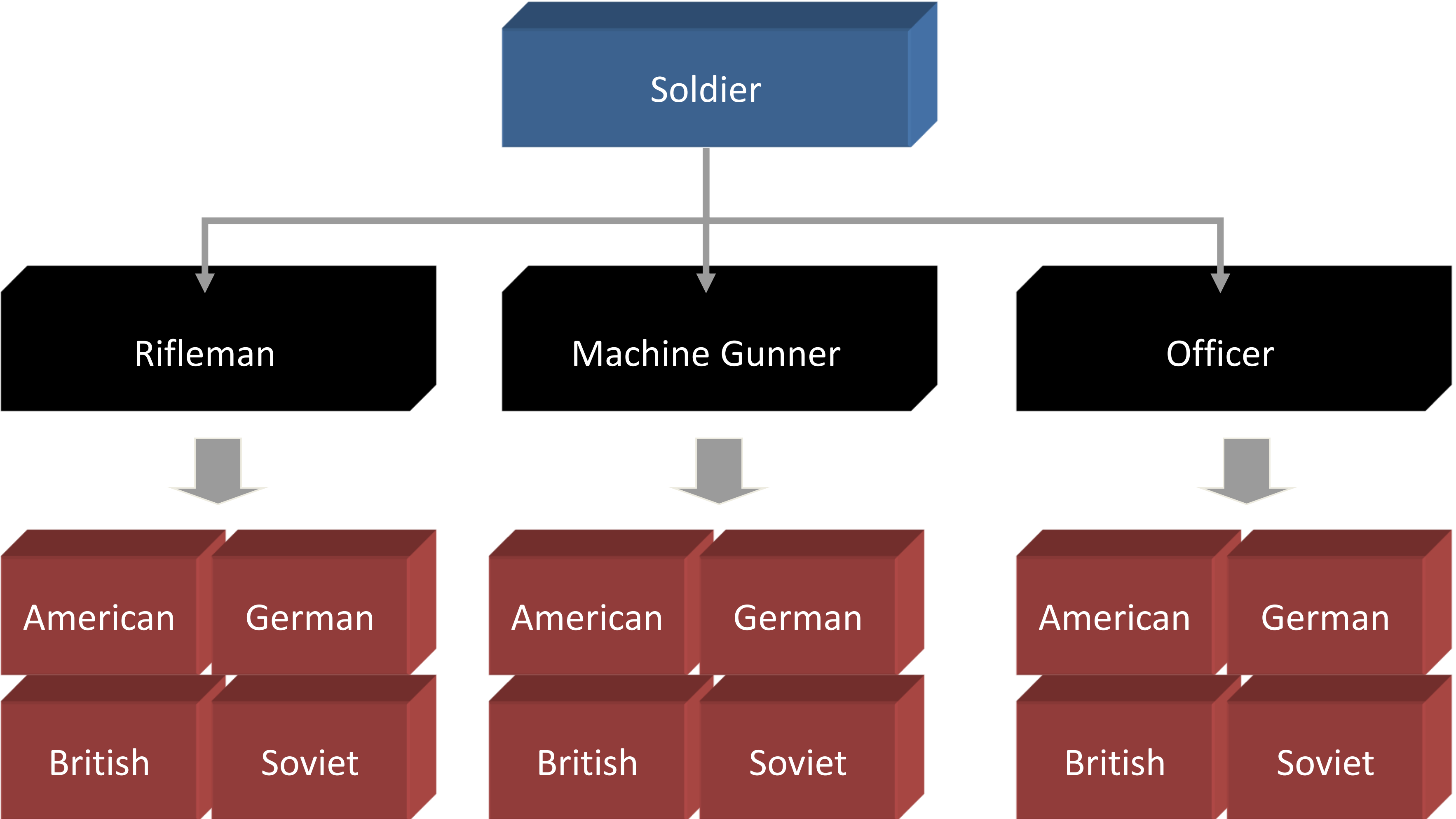
Non-Deterministic Hierarchical FSM



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



Other FSM extensions

- Inter-character concurrent FSM
  - Coordination of multiple characters
- Intra-character concurrent FSM
  - Coordination of multiple behaviors within one NPC
- Levels of detail (LODs)
  - Analogous to LOD in graphs
  - E.g. crowd simulation
    - Close NPCs use fully elaborated FSM
    - Faraway NPCs use simpler FSMs or worse

Impl: Data Driven

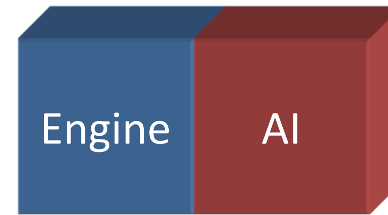
- Developer creates scripting language to control AI.
- Script is translated to C++ or bytecode.
- Requires a vocabulary for interacting with the game engine.
- A ‘glue layer’ must connect scripting vocabulary to game engine internals.
- Allows pluggable AI modules, even after the game has been released.

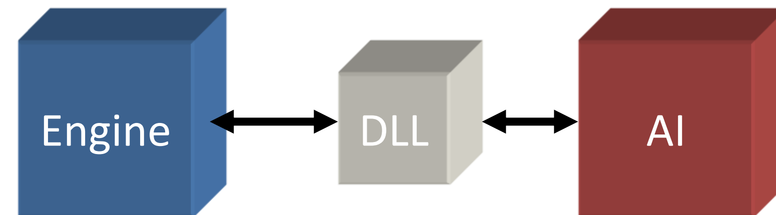
Scripted AI

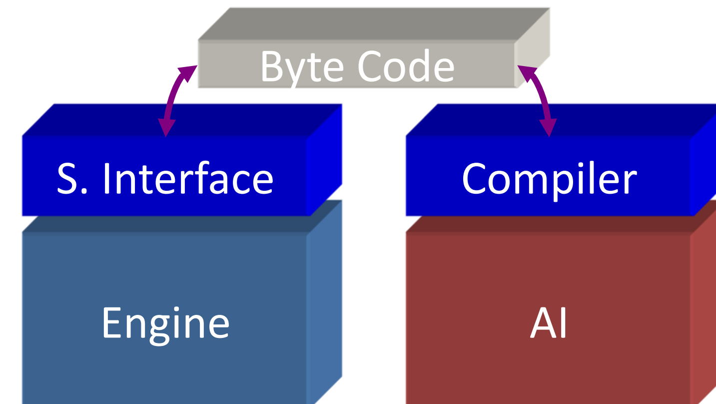
- Many game engines are virtual machines
- Script is a program written in a programming language that makes calls into the game engine
- AI is the script
- Examples: Lua, Ruby, UnrealScript
- Powerful when paired with trigger systems

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.



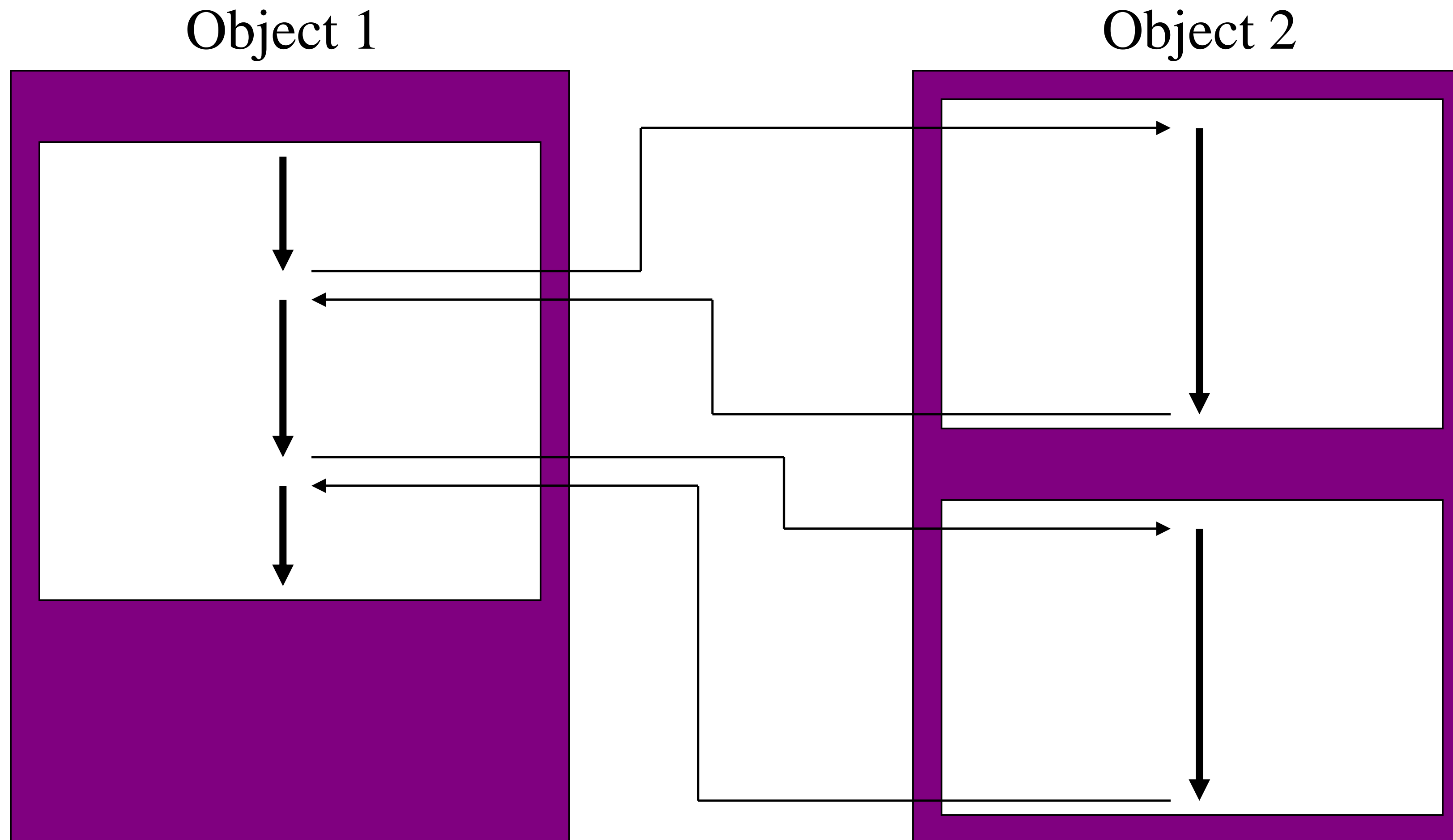




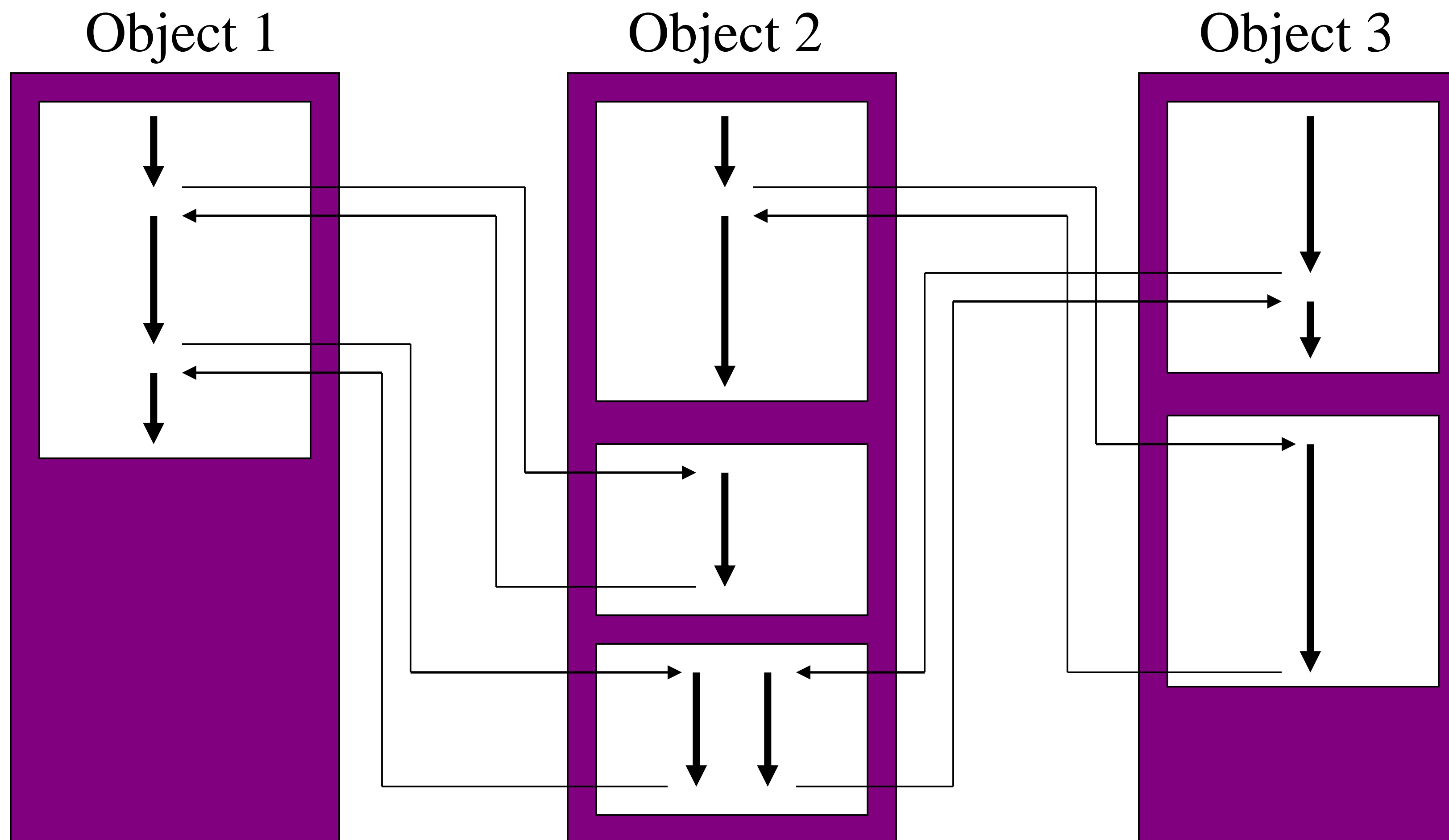
Processing Paradigms

- 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 & Cons

Pro

- Ubiquitous (not only in digital games)
- Quick and simple to code
- (can be) Easy* to debug
- Very fast: Small computational overhead
- Intuitive
- Flexible
- Easy for designers without coding knowledge
- Non-deterministic FSM can make behavior unpredictable

Con

- When it fails, fails hard:
  - A transition from one state to another requires forethought (get stuck in a state or can't do the "correct" next action)
- Number of states can grow fast
  - Exponentially with number of events in world (multiple ways to react to same event given other variables): $s=2^e$
- Number of transitions/arcs can grow even faster: $a=s^2$
- Doesn't work with sequences of actions/memory

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

- HW4: A*
- To come: More decision making
  - Planning
  - Decision trees
  - Behavior trees
  - Rule based systems
  - Fuzzy Logic
  - Markov Systems