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Building a Hierarchical Finite-State Automaton: A Primer

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Abstract

This primer introduces concepts in hierarchical finite-state automata (HFA) and their use, gives a rough formalism, and then builds an entire HFA library, with all the trimmings, in Lua. The primer is intended to educate the reader on how HFA can be used, how they are programmed, and how HFA libraries are built.

1 Introduction

A **Hierarchical Finite-State Automaton** (or HFA) is a finite-state automaton which contains *other* finite-state automata within it. It's a relatively common technique for making automata for agents or robots.

Nesting or composition of automata should hardly be alien to software programmers: it's essentially how we write code. We first write basic functions, then higher-level functions which call the basic functions, and so on until our program is complete. The only difference in the HFA case is that our coding model is automata and not general-purpose programming languages.

A plain finite-state automaton isn't hard to build: it's often little more than a loop, a global variable, and a case statement. But HFA can be complicated. In this primer we will build a complete HFA library from scratch, with some additional useful gizmos. Before we get all that, let's start with what kind of machines we're going to build. In short, we're going to assume that our HFA are:

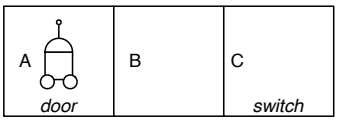
- Hierarchies of Deterministic Finite-State Automata (DFA)
- In the form of Moore machines
- With behaviors (which may themselves be other DFA) assigned to each state
- Which are designed to be pulsed repeatedly, each time progressing the automaton just a little bit.

Such automata are very useful for programming robots or simple agents in fields such as video games, simulation, robotics, and multiagent problems.

If you are unfamiliar with basic notions of finite-state automata (for example, what a DFA is), we won't be covering that. Furthermore, the description of things here will be breezy and informal, sufficient for purposes of this report but admittedly inexact. Formalists have been dutifully warned.

As mentioned, our HFA are DFA, and thus only one state is active in a given automaton at a given time. Perhaps the most common use of these kinds of automata is determining if strings belong to certain **regular languages**. Such automata have a distinguished **start state** and (among other states) one or more **accepting states**. We are not interested in these kinds of automata: we will not be tokenizing strings, and thus our automata will have no accepting states. Rather our automata will *do things* while active in a given state. That is, they will have **behaviors** associated with those states. These behaviors may be either other DFA, or they may be hard-coded **basic behaviors** we have given the DFA to perform.

2 Policies, Mealy Machines, and Moore Machines



Consider a very simple robot scenario, with three rooms, A, B, and C, as shown at right. The robot is located in room A. When in A, the robot can either go *right* to room B, or it can *go out a door* to exit the scenario, but only if the door is *open*. When in room B, the robot can go *left* to room A or *right* to room C. Finally, when in room C, the robot can go to *left* to room B, or it can *flick a switch* which opens the door. The robot would like to go out the door.

The robot can sense a few things. First, it knows at all times what room it is in. Second, if it is in room A, it can

sense if the door is open or not. Third, if it is in room C, it can sense if the switch is flicked or not. How might we make a simple program to solve this?

Policies Imagine if our program consisted of a table of items of the form *When sensing ...* $\longrightarrow$ *Do this...* We might construct a program which looks like this:

When Sensing ...	*Do this ...*
In A, Door closed	Right
In B	Right
In C, Switch unflicked	Flick
In C, Switch flicked	Left
In B	Left
In A, Door open	Out

In essence, we have written a *function* $\pi(\vec{f}) \rightarrow a$ which takes the current *sensor features* $\vec{f}$ and returns a *behavior* to perform. This is known as a **policy**.[1] This program looks like it'd do the job, but if you look closely, there's a bug. This table isn't describing a *sequence* of rules to do, but it's rather supposed to be describing a *set* of rules for various situations. And we need to have two different rules for the same situation: "*In B*". This is called having two situations which are **perceptually aliased**: we can't distinguish between them, yet we need to do a different action in each of them. And that's not permitted.[2]

The problem here is that this scenario requires some degree of memory, otherwise known as **internal state**,[3] to do its task. When in room B, the robot needs to remember whether it had flicked the switch or not. But policies, in this basic form, don't provide for memory. We need a finite-state automaton.

Mealy Machines If we assumed that our internal state started at state 0, we could instead write a program like this:

When in State ...	*and Sensing...*	*Do this...*	*and set State to ...*
0	In A	Right	0
0	In B	Right	0
0	In C	Flick	1
1	In C	Left	1
1	In B	Left	1
1	In A	Out	1

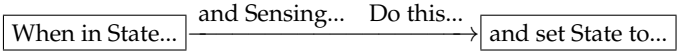
Notice that our "In B" confusion is cleared up because each "In B" row has a different internal state value (0 and 1). This is a two-state DFA called a **Mealy machine**.

[1] Yes, π is the standard symbol for policies. Don't ask.

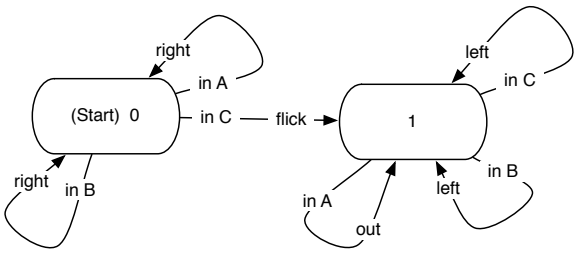
[2] One way around this is to do actions with a certain degree of randomness: that is, we might have one rule of the form "*In B* $\rightarrow$ *Go Right 50% of the time, Left 50% of the time*". This would eventually work! But it might not be a great idea, particularly in robotics, where such randomness might land you in the ditch, breaking your fancy $10,000 robot. We'd like a somewhat more principled approach.

[3] As opposed to **external state**, which is the term sometimes used to describe the current situation of the agent, or its current sensor features. When someone just says **state**, unfortunately they might refer to internal or external state: it's not consistent.

We can draw this table as a graph. Each edge in the Mealy machine graph connects a state to another state and is labeled with *two* labels: the current sensor information and the behavior to perform. Each edge corresponds to one rule (a line) in our table. That is, an edge may be described as:



Thus we can write our Mealy machine in graphical form like this:



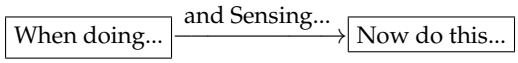
Note that now that we have internal memory we don't need to rely on as much sensor information. This isn't always the case.[4]

Moore Machines Mealy machines are straightforward implementations of standard DFA. But we're going to focus on a somewhat different formulation which is often more intuitive for programming purposes. In this different formulation, each state will be associated with a **behavior**, though multiple states could be associated with the same behavior. When in a state, we are doing its associated behavior. Transition edges will only be labeled with the sensor situation. If no edges match the current sensor situation, we continue in the current state, and continue doing its behavior. In this model, we might write our program as:

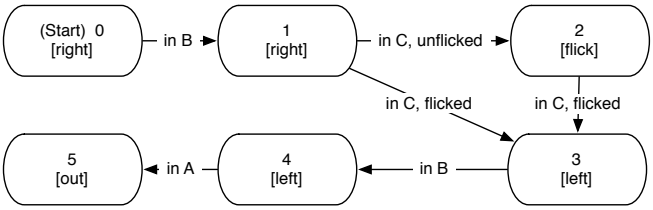
When doing...	*and Sensing...*	*Now do this...*
0 [Right]	In B	1 [Right]
1 [Right]	In C, unflicked	2 [Flick]
1 [Right]	In C, flicked	3 [Left]
2 [Flick]	In C, unflicked	3 [Left]
3 [Left]	In B	4 [Left]
4 [Left]	In A	5 [Out]

We now have six states, each of which is associated with a behavior (in [square brackets]). In two cases, the same behavior is associated with two different states. It looks more complex, but it's really not: in fact, we have exactly the same number of edges still. Our simplified edges are still lines in the table, but they take this form:

[4] This program only works right if we start in state 0 and there's no noise in our state transitions. As an exercise, ask yourself: what program would we need to write if our internal state could start randomly either as 0 or 1? Would it need the additional sensor information we had omitted? How about if the robot started randomly in any room? How about both random initial states and random rooms?

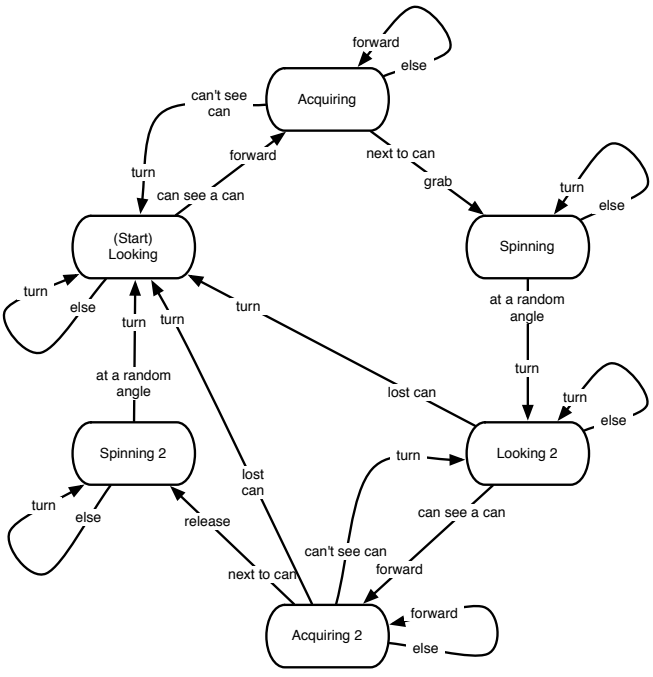


The resultant DFA program is:

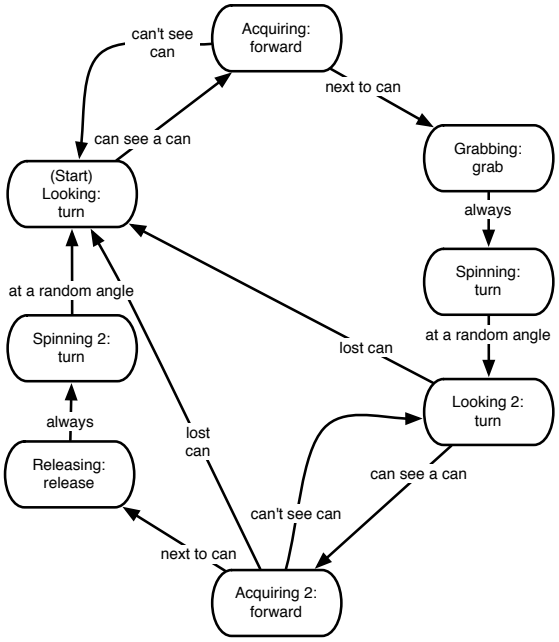


This is known as a **Moore machine**. Some items to note. First, a Moore machine, as we're defining it here, has no self-loops in its edges: they're unnecessary since we have the rule that if no transition edge is matched by the current situation, we just continue in the current state and continue doing its behavior. Second, note that the Moore machine we constructed feels much more like a sequence of operations than a set of rules. This isn't really a feature of Moore machines: it's more a result of our example, which requires a sequence of operations to perform the task, and this feature of our example is just made more clear in the Moore machine configuration.

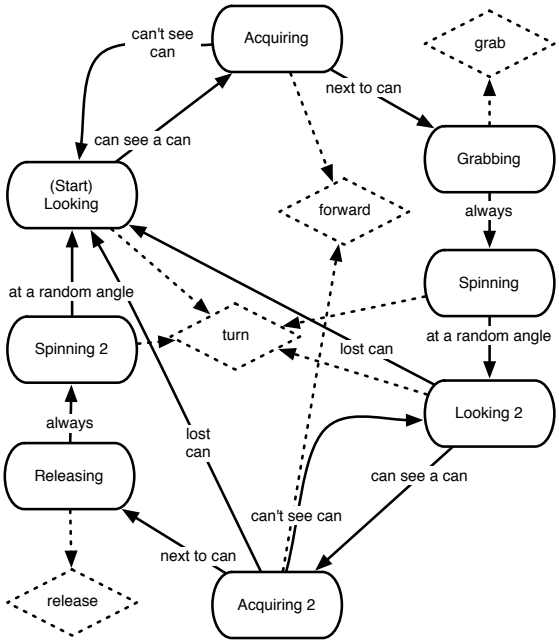
Consider the following more interesting example. A can-collecting robot repeatedly spins around until it finds a can, acquires the can, looks for another can, moves to the second can, and releases the first can. It then turns to some random angle to prevent it from constantly grabbing the same can over and over again. Then it repeats. Additionally, if the can slips out of its gripper, or if it loses sight of a can, it must recover from this. Here's a Mealy machine program which performs this task. The machine has six states. We have given them names here rather than mere numbers:



The Moore machine version isn't much different. In the Mealy Machine, the edges entering the Spinning and Spinning 2 states have different behaviors (*grab*, *pick random angle* vs. *turn*, for example), and to compensate for this, the Moore machine has two additional states. But other than that you can see the obvious similarity (and lack of self-loops).

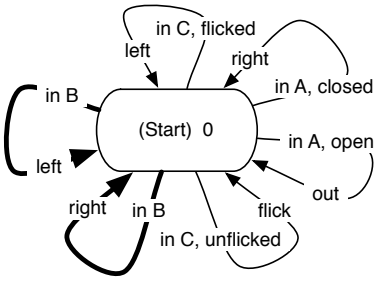


Another way to view this is to separate the behaviors from the states. This makes clear the many-to-one relationship between states and behaviors.

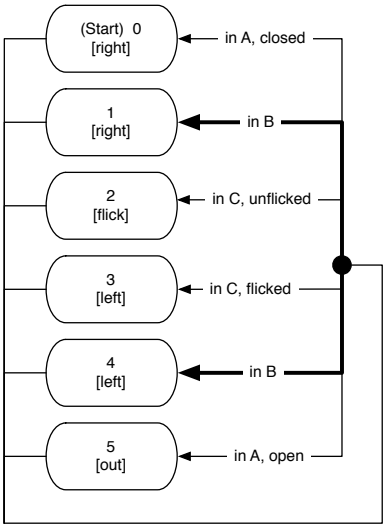


Relationships Between Policies and Automata Though it may not look like it at first, Mealy and Moore machines are equivalent: anything you implement in one model can be implemented in the other.

Additionally, policies may be viewed simply as degenerate versions of either Mealy and Moore machines. For example, a **a policy is a Mealy machine with a single state**. To see this, here's the previous (broken) policy we developed, shown as a Mealy machine. The invalid rules are shown in bold lines:



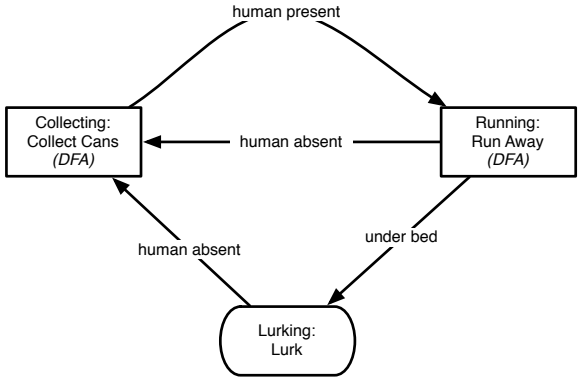
Similarly, a **policy is a Moore machine where each state has the exact same outgoing transition edges.** Here's the same policy shown as a Moore machine, again with the invalid rules shown in bold lines:



3 Hierarchies of Moore Machines

So far the **behaviors** we've attached to states are **basic behaviors**, that is, hard-coded behaviors such as *grab* or *go forward* or *go left*. But in a Hierarchical Finite-State Automaton, behaviors can also be something else: they can be other automata.

Consider extending our can collecting robot. The can collecting behavior works great. We've created a second automaton called *Run Away* which runs and hides under the bed. Last, we have a basic (hard-coded) behavior called *Lurk* which stays quiet, in some low-power mode. We have decided to tie these three behaviors in a higher-level finite-state automaton which collects cans in a student's bedroom when the student is away. But when the student comes in the room, the robot runs away to hide under the bed, then lurks there until the student leaves again, at which time it resumes collecting cans. We could do this with the following automaton:



Notice that we have three states, each associated with a different behavior. But two of these behaviors are unusual: they are *other automata*. This hierarchy could continue as far as you liked: you could use this new automaton as a behavior in an even higher-level one, and so on.

How would all this work? When we transition into a state which has an automaton as its behavior, the automaton is reset. As long as we stay in that state, we continually pulse the automaton. When we leave the state, the automaton is suspended.

It's important to note that an HFA could use the same behaviors multiple times in its hierarchy: that is, the hierarchy isn't a tree so much as a **directed acyclic graph** (or DAG). For example, consider a robot soccer automaton. At the top level, the *Play Soccer* automaton iterates between *Do Defense* and *Do Offense*, depending on the ball location on the field. Each of these sub-automata might include, somewhere in them, automata behaviors such as *Acquire Ball* or *Get Open*. And certainly various basic behaviors will be reused numerous times in many different places in the hierarchy, such as *Run* or *Kick* or *Turn*.

This is the basic advantage of using an HFA: modular reuse. Once you have defined a behavior such as *Get Open*, you can reuse it multiple times simply by referring to it, rather than reimplementing it over and over again. Of course, you *could* flatten a hierarchical finite-state automaton into a giant morass of states and basic behaviors, but this could really be a mess. In the same vein, assuming you had no need for recursion, you *could* flatten a computer program into a single function, a-la BASIC, but it'd be a mess.

Speaking of recursion, it should be clear at this point that you are not permitted to have recursion in your HFA hierarchy. That is, an automaton may not contain itself. Automata are simpler than Turing-complete programming languages. A finite-state automaton has *finite state*. Recursion requires a stack, thus infinite state.

4 A Basic Model

We're going to build HFA in the form of Moore machines. Before we do so, let's get down to brass tacks.

The Start State Rather than having some state designated as a start state, we'll have a **distinguished start state**, meaning an initial state literally called Start which is associated with an empty behavior. Our automaton will immediately transition out of this dummy Start state to some other state as appropriate, and begin with that one. This allows us to choose an effective "start state" based on the initial conditions, using a transition function we provided, rather than having an initial state fixed in stone. Generally we won't ever transition *into* Start.

Transition Functions So far we've described DFA as having transitions in the form of edges. But that's not really how we're going to represent things. Instead, each state is associated with a **state transition function** which, when passed the current world situation, returns a new state to transition to (or perhaps just returns the current state, meaning that the DFA should not transition at all). Essentially a state's transition function is the collection of all of the state's outgoing transition edges.

We can abstract this even further, defining the **automaton transition function** as a function which, when passed the current state in the automaton and the current world situation, returns a new state to transition to. This function can be implemented simply by looking up the state transition function for the passed-in state, then calling it and returning what it returns.

Formal Model A more or less formal model is as follows. A hierarchical finite state automaton (HFA) $H = \{S, B, M, F, T\} \in \mathcal{H}$ where:

- $S = \{S_0, S_1, ..., S_n\}$ is the set of *states*. Exactly one state is *active* at any particular time: we will refer to this as S_*, and call it the *current state*. Initially (at timestep $t = 0$), a distinguished *start state* $S_0 \in S$ is the current state.
- $B = \{B_0, B_1, B_2, ..., B_p\}$ is a set of *behaviors*. A behavior may be a *basic behavior*, or it may another hierarchical finite-state automaton $H' \in \mathcal{H}$, with the constraint that recursion is not permitted: automata may not contain themselves (either directly or by transitivity). Multiple different HFA may serve as behaviors in H. The behavior B_0 is an empty basic behavior and does nothing.
- $M : S \to B$ is the *mapping function* which associates states with behaviors. A behavior may be associated with several states. The start state S_0 is associated with B_0.
- $F = \{F_1, F_2, ...\}$ is a set of *situations* in the environment, where each F_t describes the current situation at time t.
- $T : F \times S \to S - \{S_0\}$ is the automaton's *transition function* which, given a state $S_i \in S$ and the current situation F_t, returns a state $S_j \in S, j \neq 0$ to transition to. It's perfectly plausible that $S_i = S_j$ unless $i = 0$. We may view T as a set of *state transition functions* $\{T_0, T_1, ..., T_n\}$, one per state, where each $T_i : F \to S$.

Generally we will have one **top-level automaton** $\boldsymbol{H} \in \mathcal{H}$ which directly or through transitivity contains all other automata or behaviors of interest, and serves as the entry point to our system. Each timestep t, $\boldsymbol{H}$ will be **pulsed**, which causes it to do the following:

1. It first determines a new state S_{new} to transition to, as $S_{new} \leftarrow T(F_t, S_*)$.
2. It then sets $S_{old} = S_*$ and $S_* \leftarrow S_{new}$.
3. It then determines the behavior B_* associated with the new current state S_* as $B_* \leftarrow M(S_*)$.
4. If $S_{new} \neq S_{old}$, then it *resets* B_*. In particular, if B_* is itself an HFA H_*, then this will cause H_* to set its own internal state $S_* \leftarrow S_0$.
5. Finally, it pulses B_* (both behaviors and automata may be pulsed).

Note that because the transition is performed *before* the pulsing, S_0 can never be pulsed, which is just fine since S_0 has no associated behavior.

Mapping States to Behaviors In the formal model above, we can map multiple states to the same behavior. But to make coding more straightforward, we won't actually do that. Instead, we'll assume that, within a given HFA, each state must be mapped to a **unique behavior**. This allows us to just treat the behaviors as the states themselves, which is very convenient when writing an HFA library. Plus, in *most cases* each state will have a unique behavior anyway.

But doesn't this restrict our FSA's capabilities? After all, one would think that the three-room robot example earlier would be impossible, since the robot has to go "right" in two different states (0 and 1). Surely this brings up the spectre of perceptually aliased states again.

One would think this, but actually no! Because our HFA is *hierarchical*, we can get around it with a trick.

Let's say we need to make two states S_1 and S_2 which each map to the same behavior B_4. We do it as follows:

- Map S_1 to B_4.
- Map S_2 to a new HFA H_7.
- HFA H_7 has a simple transition function: its start state S_0 immediately and always transitions to a state S_1', whose behavior is B_4. H_7 then never transitions out of S_1'.

I call this trick creating a **wrapper HFA**: essentially H_7 is a behavior which does the exact same thing as B_4 (because it calls B_4 itself), but is a *different behavior* than B_4.

5 Implementing an HFA Library

We'll implement the HFA library in Lua. It's a language similar to Python in many respects, and JavaScript in other ways. Some notes to make it easier to follow if you're not familiar with the language. Comments start with two hyphens (`--`). A function of the form *foo(x,y)* is defined using the pattern `foo = function(x, y)`. Local variables must be explicitly declared as `local`, else they are considered global. A dictionary (hash table) with string keys `"a"`, `"b"`, and `"c"`, pointing to the values stored in the variables `x`, `y`, and `z` respectively, could be defined with the literal:

```
mydict = { ["a"] = x, ["b"] = y, ["c"] = z }
```

Thereafter, we can access the value stored with `"a"` either as `mydict["a"]` or as `mydict.a` I defined a few closures (functions defined inside other functions or scopes which use their local variables) here and there; dynamic programming languages like Lisp or Javascript use these in spades. `nil` is the empty value, equivalent to `NULL` in C or `null` in Java. The rest you can probably figure out.

One more note: for succinctness, the code shown will have no error checking at all.

Defining a Behavior To build an HFA, we must define the concept of a *behavior*. A behavior is some kind of object which contains, among other things, three functions: **start**, **stop**, and **go**. We'll do this in Lua using a dictionary keyed with the names `start`, `stop`, and `go`. Later we'll use a slot in the dictionary keyed `parent`, which will refer to the behavior which is pulsing this one (if any). Last, we'd like to know if the behavior has been pulsed yet, and also we'll give the behavior a name. Here's a simple utility function that builds such a behavior.

```
makeBehavior = function(name, start, stop, go)
  return { ["start"] = start, ["stop"] = stop, ["go"] = go,
           ["name"] = name, ["parent"] = nil,
           ["pulsed"] = false }
end
```

When we first pulse a behavior, we call its `start` function, followed by calling its `go` function once. When we next pulse the behavior, we just call its `go` function. Finally, when we are finished with a behavior, we call its `stop` function. Thereafter if we wish to pulse it again, we start from the beginning (calling `start`, then `go`, etc.).

It's up to you to define the `start`, `stop`, and `go` functions for your behavior. Typically you get things set up in the `start` function, iterate the behavior once or more in the `go` function, and close up shop in the `stop` function. You don't have to implement all (or even any!) of these functions: instead, you could just pass in `nil`.

Let's do an example. Suppose you were writing a behavior which moves a game agent `forward` by one step. Here you don't care about starting up or shutting down. You might write:

```
forward = makeBehavior("forward", nil, nil,
  -- write the go function
  function(behavior) goForwardOneStep() end)
```

Another example. Let's say you want to write a robot behavior which starts walking, and when the behavior is exited he needs to clean up and get in a decent pose before he does something else, or otherwise he'll fall over. Once the robot is walking, there's no reason to tell the robot to continue to walk, so the `go` function isn't relevant. You might write:

```
walk = makeBehavior("walk",
  -- write the start function
  function(behavior) startWalking() end,
  -- write the stop function
  function(behavior) stopWalking() end,
  nil)
```

A final example. You want to write a game behavior which causes the agent to fire his laser. This is a one-shot behavior, so you only need to bother writing the `start` function:

```
fire = makeBehavior("fire",
  -- write the start function
  function(behavior) fireLaser() end,
  nil, nil)
```

Pulsing Let's assume that we're going to only pulse a single behavior —- likely an HFA, and as part of that pulsing it'll recursively pulse sub-behaviors as necessary. We could define this with as the functions:

```
-- Pulse a behavior
pulse = function(behavior)
  if (not (behavior.pulsed)) then
    behavior.pulsed = true
    if (not (behavior.start == nil)) then
      behavior.parent = nil
      behavior.start(behavior)
    end
  end
  if (not (behavior.go == nil)) then
    behavior.go(behavior)
  end
end
```

```
-- Reset the behavior
reset = function(behavior)
  if (behavior.pulsed) then
    if (not (behavior.stop == nil)) then
      behavior.stop(behavior)
    end
    behavior.pulsed = false
  end
end
```

We'll discuss the `behavior.parent` stuff later.

Defining an HFA An HFA is a special version of a behavior. It has the same slots as a behavior, plus extra slots. Additionally, the start, stop, and go slots of the HFA are filled in with special hard-coded functions which we'll define in a moment (called `startHFA`, `stopHFA`, and `goHFA`). We also have a few additional slots of interest. First, `transition` will hold our HFA's transition function. Second, `current` will hold the current (active) state. Because we have defined states to have unique behaviors, in this code **states *will literally be* behaviors**. The object which `current` will hold will be a behavior or HFA object.

Every HFA will have a special start state,[5] which is a hard-coded behavior which does nothing at all. We'll define it as the following constant:

```
start = makeBehavior("start", nil, nil, nil)
```

Now as before, we can make a small utility function which sets these slots for us. We'll also include some additional slots, to be discussed and used later on:

```
makeHFA = function(name, transition)
  return { ["start"] = startHFA, ["stop"] = stopHFA,
           ["go"] = goHFA, ["name"] = name,
           ["parent"] = nil, ["pulsed"] = false,
           ["transition"] = transition,
           ["current"] = start,

           -- These is for other gizmos we'll add
           -- later, so you can ignore them for now
           ["counter"] = 0, ["timer"] = 0,
           ["done"] = false, ["failed"] = false,
           ["targets"] = nil, ["behaviorTargets"] = nil,
           ["goReturned"] = nil, ["propagateFlags"] = false,
           ["events"] = { }, ["returnEvent"] = nil }
end
```

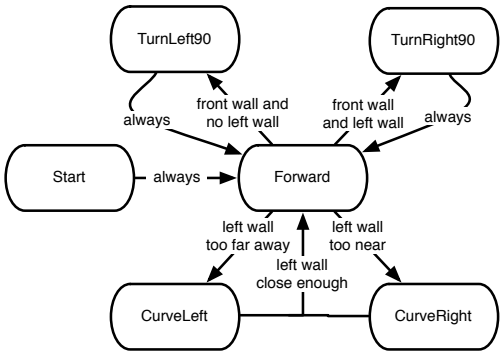
When you make an HFA, you provide a `name` (as before) and a `transition`: a function which, when passed the HFA in question, returns the next state the HFA should transition to. The transition function usually does this by querying the current state of the HFA (via its slot `current`), plus extracting the world situation as it sees fit, and then determining where to transition to.

This function could be very simple to write. But it in most cases general, though, it'd be more convenient to write a bunch of per-state transition functions rather than one monolithic HFA-wide transition function. Here we'll make a simple utility function to do this:

[5]Though this state is called `start`, this is not the same thing as the function stored in the `start` slot of a behavior. Sorry for the confusion.

```
makeTransition = function(transitions)
  return function(hfa)
    local transition = transitions[hfa.current]
    if (type(transition) == "function") then
      return transition(hfa)
    else
      return transition
    end
  end
end
```

This function will take a dictionary of **per-state transition functions** and return an HFA-wide transition function suitable to hand to the `makeHFA` function. Each per-state transition function is keyed by the state (behavior) it is associated with. Instead of a transition function , we may simply store a state keyed by another, which indicates that the transition is made *unilaterally* from the one state to the other. For example, let's build an HFA for the following wall-following behavior:



Notice the three edges labeled "always": these are unilateral transitions. Suppose we had built five behaviors stored as the global variables `turnLeft90`, `turnRight90`, `forward`, `curveLeft`, and `curveRight`. We also have a few sensor functions such as `frontWallAhead()` or `leftWallTooNear()`. We might implement the HFA, and its HFA-wide transition function, as:

```
myTransition = makeTransition(
  {
  [start] = forward,
  [forward] = function(hfa)
      if (frontWallAhead() and noLeftWall()) then
        return turnRight90
      elseif (frontWallAhead()) then return turnLeft90
      elseif (leftWallTooFar()) then return curveLeft
      elseif (leftWallTooNear()) then return curveRight
      else return forward end
    end,
  [turnRight90] = forward,
  [turnLeft90] = forward,
  [curveRight] = function(hfa)
      if (leftWallCloseEnough()) then return forward
      else return curveRight end
    end,
  [curveLeft] = function(hfa)
      if (leftWallCloseEnough()) then return forward
      else return curveRight end
    end
  })

wallFollow = makeHFA("WallFollow", myTransition)
```

Notice that the keys are *actual behaviors*, rather than "strings", like we've seen before.

Making a Wrapper HFA A wrapper HFA has just a single sub-behavior of interest, and a unilateral transition function from `start` to that behavior. Thus we can define a utility function for wrapper HFAs very simply:

```
makeWrapper = function(name, wrappedBehavior)
  return makeHFA(name,
                 function(hfa)
                   return wrappedBehavior
                 end)
end
```

Making a Policy Recall that a policy is just a Moore machine where all of the states have the same transition function. If that's the case, we don't need to do call `makeTransition` at all. We can just directly provide a single transition function and it'll be used regardless of what state we're in. For example, take the transition function we defined for `[forward]` above. Imagine if we wanted to use that transition function for *all* the states: that is, we would make a policy out of this transition function. We could do it simply as:

```
myTransition = function(hfa)
  if (frontWallAhead() and noLeftWall()) then
    return turnRight90
  elseif (frontWallAhead()) then return turnLeft90
  elseif (leftWallTooFar()) then return curveLeft
  elseif (leftWallTooNear()) then return curveRight
  else return forward end
end

wallFollow = makeHFA("WallFollow", myTransition)
```

Policy implemented. Or even simpler: what if regardless of what state we are in, we always transition to `forward`? That's a brutally simple policy. Essentially we start in `start`, then immediately transition to `forward` and stay there. To do this, we could just say:

```
myTransition = function(hfa) return forward end
wallFollow = makeHFA("WallFollow", myTransition)
```

Hmmm, wait a minute. That's exactly the same procedure as our `makeWrapper` function. Ah, right. A wrapper is just a trivial policy which immediately goes to a certain state and stays there.

HFA Functions Armed with this knowledge, now we're ready to define the `startHFA`, `stopHFA`, and `goHFA` functions which form the heart of our HFA.

Let's start with `startHFA`. This function simply resets the current state to `start`.[6]

```
startHFA = function(hfa)
  hfa.current = start
end
```

Equally simple is `stopHFA`. All we have to do is stop our subsidiary behavior. To do this, the function just calls `stop` on the current state, assuming the `stop` function was implemented for the state.

```
stopHFA = function(hfa)
  if (not (hfa.current.stop == nil)) then
    hfa.current.stop(hfa.current)
  end
end
```

Done and done. Now the only actually interesting function: `goHFA`. This function has three parts. First, it must determine what state to transition to. Second, it must perform the transition. If the transition involves changing to a new state, this is done by calling `stop` on the old state, then calling `start` on the new state (first setting the new state's `parent` backpointer to the HFA so the state knows who its current parent is). The current state is then updated. Third, it must call `go` on whatever the current state is. The code looks like this:

```
goHFA = function(hfa)
  -- DETERMINE TRANSITION
  local newBehavior = hfa.transition(hfa)

  -- PERFORM TRANSITION
  if (not (newBehavior == nil)) then
    if (not (newBehavior == hfa.current)) then
      if (not (hfa.current.stop == nil)) then
        hfa.current.stop(hfa.current)
      end
      newBehavior.parent = hfa
      if (not (newBehavior.start == nil)) then
        newBehavior.start(newBehavior)
      end
      hfa.current = newBehavior
    end
  end

  -- EXECUTE
  if (not (hfa.current.go == nil)) then
    hfa.current.go(hfa.current)
end
```

And that's pretty much all there is to it![7] Perhaps the most surprising part of this implementation is that although an HFA consists of a collection of states (or, in our case, behaviors), in this implementation there is no set or array of states at all: all that exists is a transition function. That's really all you need for an HFA.

6 Targets

One item I've found to be useful to add to an HFA is the ability to add parameters to behaviors or transition

[6] At this point we could bring up an extra gizmo not being implemented in this document: the notion of an *interruptable automaton*. If you were doing this kind of automaton, and transitioned away, then transitioned back again, it'd start right where it left off. In essence it treated your transition-away-then-back as an interrupt to handle some exceptional condition. The straightforward way to implement this would be to not reset the current state to `start` in `startHFA`. This is all a nice notion but it has a lot of buggy interactions with other mechanisms, like the `parent` backpointer, and later utility function such as flags, counters, and timers. So I'd advise against it.

[7] Does the `behavior.parent=nil` line in the `pulse` function make sense now?

functions. For historical reasons I have called these **targets**. The idea is simple. Let's say you're writing the HFA for a soccer-playing robot. You might need to write a basic behavior called *GoToGoal*, and another one called *GoToBall*, and another one called *GoToMidfield*, and another one called *GoToNearestOpponent*. Or you could just write a single behavior called *GoTo(X)*, where *X* can be specified later. *X* is a **target**.

Similarly, you might need to write a transition function for the *GoTo(X)* state (behavior) which says that if the distance to *X* is less than 3 meters, transition to *Stop*, else continue doing *GoTo(X)*. Thus it'd be helpful if your transition function likewise had access to targets.

To keep things simple, targets will be untyped. That is, you cannot create a target designed for (say) positions like "the goal" or "the ball location", and a different kind of target designed for (say) lengths of time such as "time ball has been in possession " or "time until halftime". There can only be one kind of target, and the user will have to be careful what he passes in as a target in different situations. This is analogous to languages such as Lua, or Lisp, or Python, which have untyped parameters and variables, as opposed to Java or C, which are typed.

We will add targets to our HFA by changing the `start`, `stop`, and `go` functions of all behaviors and HFA to accept, in addition to the behavior itself, a set of zero or more targets (such as *X*), each bound to a value (such as an object representing "the ball"). These will take the form of a dictionary where the keys are the target names and the values are the values bound to those targets. For example, if we had a target value object representing the goal stored in `goal`, and a target value object representing the ball stored in `ball`, and we were intending to pass them into some behavior called *getBetween(X, Y)*, where *X* and *Y* were two targets the robot was supposed to position itself between, we might store them bundled like this:

```
targetBindings = { ["X"] = goal, ["Y"] = ball }
```

We pass these into the `getBetween`'s `start`, `stop`, and `go` functions. It's up to `getBetween`'s functions to use these bindings as it sees fit (and keep in mind, that since you're binding these things, the objects you bind to the targets can be whatever you deem appropriate). For example, here's a possible *getBetween(X, Y)* behavior:

```
getBetween = makeBehavior("getBetween", nil, nil,
  -- write the go function.  NOTICE IT NOW TAKES TARGETS
  function(behavior, targets)
    -- we assume X and Y are actually objects that
    -- our made-up function halfWayBetween understands
    local pos = halfWayBetween(targets.X, targets.Y)
    moveTowards(pos)
    end)
```

Now let's modify the `pulse` and `reset` functions to pass in the right bindings:

```
-- Pulse a behavior
pulse = function(behavior, targets)
  if (not (behavior.pulsed)) then
    behavior.pulsed = true
    if (not (behavior.start == nil)) then
      behavior.start(behavior, targets)
    end
  end
  if (not (behavior.go == nil)) then
    behavior.go(behavior, targets)
  end
end

-- Reset the behavior
reset = function(behavior, targets)
  if (behavior.pulsed) then
    if (not (behavior.stop == nil)) then
      behavior.stop(behavior, targets)
    end
    behavior.pulsed = false
  end
end
```

Now we need to modify our `startHFA`, `stopHFA`, and `goHFA` functions to accept bindings. Targets pose a special difficulty for HFA. An HFA is a behavior, so it has bindings. But it also uses behaviors as its states, and they might have their own bindings. The HFA may pass some of its targets to its current behavior. Thus we need a way for the HFA to **map** its targets to the behaviors' targets. For example, if the HFA's job is to go to *X* while constantly starting at *Y*, then wall follow around *X*, and to do this it is using a behavior called `goTo(Obj, LookingAt)` and another behavior called `wallFollow(Thing)`, then it needs to stipulate that $X = Obj = Thing$, and $Y = LookingAt$.

We'll define a mapping as a dictionary whose keys are a sub-behavior's targets, and whose values are the HFA's targets meant to be mapped to them. Thus we for `goTo` we have:

```
gotoMap = { ["Obj"] = "X", ["LookingAt"] = "Y" }
```

... and for `wallFollow` we have:

```
wallFollowMap = { ["Thing"] = "X" }
```

For reasons which will become clear in a moment, we also need to indicate the behavior for which these mappings will be used. Let's store that with a key of 0 (zero):[8]

```
gotoMap = { [0] = goTo,
            ["Obj"] = "X", ["LookingAt"] = "Y" }
wallFollowMap = { [0] = wallFollow, ["Thing"] = "X" }
```

In addition to binding targets to each other, we can explicitly provide a value for a target. We call this a **ground target value**. For example, we could say that we should be going to *X* but looking only at `theGoal`, a

[8] Why zero? Answer: we need something other than a string. Zero seemed reasonable.

target value object I just made up. To do this we provide the value directly rather than a string:

```
gotoMap = { [0] = goTo,
            ["Obj"] = "X", ["LookingAt"] = theGoal }
wallFollowMap = { [0] = wallFollow, ["Thing"] = "X" }
```

We'll use these mappings in our transition function. The way it works will be as follows: our transition function can either return a new state to transition to (if the state takes no targets), or it can return a mapping. This mapping contains the state to transition to (as the item keyed by "0"),[9] plus all the mappings necessary to convert the HFA's targets into the behavior's targets. Besides `start` we have only `goto` and `wallFollow`, which both take targets, so everything in the following example will return a mapping:

```
myTransition2 = makeTransition(
  {
  [start] = gotoMap,
  [goto] = function(hfa)
     if (closeEnough() then
       return wallFollowMap
     else
       return goToMap
     end,
   [wallFollow] = wallFollowMap,
   })

myHFA = makeHFA("MyHFA", myTransition2)
```

Now we need a way of taking the "transition" (a state or a mapping object) returned by the transition function and translating it into a set of targets the underlying behavior will be able to use. The particular translation will depend on the current targets provided by the parent HFA. To do this, we use the following utility function:

```
translateTargets = function(targets, mapping)
  mapped = { }
  for mapname, original in pairs(mapping) do
    if (not (mapname == 0)) then
      -- we are mapping a target to another target
      if (type(original) == "string") then
        mapped[mapname] = targets[original]
      else
        -- we assume it's a ground target value
        mapped[mapname] = original
      end
    end
  end
  return mapped
end
```

The Lua function `pairs` returns key/value pairs from a dictionary (in this case `mapping`). We're setting `mapname` to each key and `original` to each pair in turn.

The `translateTargets` function takes a set of targets mapped to values from the HFA, plus a set of mappings from the transition function, and returns a new, properly mapped set of targets and their values to give to an underlying behavior. Armed with this, we can now perform the translation in our `goHFA` function.

[9] Now do you see why we included the behavior in the mappings?

Recall that HFA have a mysterious slot called `behaviorTargets`. We'll now use this slot during `goHFA`: it holds the mapped targets for the current behavior, so we can reuse them on each call to `go` without rebuilding them. While we're at it, let's store the HFA's own targets (as opposed to the sub-behavior's mapped targets) in a slot called `targets`. This probably isn't that useful in general except for debugging.

```
goHFA = function(hfa, targets)
  hfa.targets = targets

  -- DETERMINE TRANSITION
  local newBehavior = hfa.transition(hfa)

  -- EXTRACT TARGETS
  -- the old targets for the behavior we're stopping
  local oldBehaviorTargets = hfa.behaviorTargets

  -- figure the new targets.  Both behaviors and mappings
  -- are dictionaries, but we can tell them apart because
  -- a mapping has a 0 (zero) key in it.
  if (not (newBehavior == nil) and
      not (newBehavior[0] == nil)) then
    -- extract the new targets
    hfa.behaviorTargets = translateTargets(targets,
                                           newBehavior)
    -- update the underlying behavior
    newBehavior = newBehavior[0]
  else
    hfa.behaviorTargets = nil
  end

  -- PERFORM TRANSITION
  if (not (newBehavior == nil)) then
    if (not (newBehavior == hfa.current)) then
       if (not (hfa.current.stop == nil)) then
         hfa.current.stop(hfa.current, oldBehaviorTargets)
       end
      newBehavior.parent = hfa
      if (not (newBehavior.start == nil)) then
        newBehavior.start(newBehavior, hfa.behaviorTargets)
      end
      hfa.current = newBehavior
    end
  end

  -- EXECUTE
  if (not (hfa.current.go == nil)) then
    hfa.current.go(hfa.current, hfa.behaviorTargets)
  end
end
```

Once `hfa.behaviorTargets` is set, we can also use it in our `stopHFA` function. So we define:

```
startHFA = function(hfa, targets)
  hfa.current = start
end

stopHFA = function(hfa, targets)
  hfa.targets =  nil
  if (not (hfa.current.stop == nil)) then
    hfa.current.stop(hfa.current, hfa.behaviorTargets)
  end
end
```

... and we're done! Now so far we've been using targets just for behaviors, and have been concentrating on mapping them from HFA to HFA to behavior. But targets can also be used in transitions too. Instead of

passing targets to a transition, we'll just directly access the HFA's current targets in our transition functions. For example, if we want to perform goTo only until we're close enough to whatever the HFA had called *X*, we could say:

```
myTransition2 = makeTransition(
  {
  [start] = goToMap,
  [goto] = function(hfa)
     if (closeEnough(hfa.behaviorTargets.X) then
       return wallFollowMap
     else
       return goToMap
     end,
   [wallFollow] = wallFollowMap,
   })

myHFA = makeHFA("MyHFA", myTransition2)
```

Going way back to our wall-follower provides additional opportunities. Instead of saying `frontWallAhead()`, we could say `ahead(...)`, passing in a target which specifies the object of interest to us (perhaps a wall, perhaps not). Recall that the WallFollow behavior took a target called `Thing`:

```
myTransition = makeTransition(
  {
  [start] = forward,
  [forward] = function(hfa)
      if (ahead(hfa.behaviorTargets.Thing)
          and noLeftWall()) then
        return turnRight90
      elseif (ahead(hfa.behaviorTargets.Thing)) then
        return turnLeft90
      elseif (leftWallTooFar()) then return curveLeft
      elseif (leftWallTooNear()) then return curveRight
      else return forward end
    end,
  [turnRight90] = forward,
  [turnLeft90] = forward,
  [curveRight] = function(hfa)
      if (leftWallCloseEnough()) then return forward
      else return curveRight end
    end,
  [curveLeft] = function(hfa)
      if (leftWallCloseEnough()) then return forward
      else return curveRight end
    end
  })

wallFollow = makeHFA("WallFollow", myTransition)
```

Obviously we could have used this target in other functions as well.

7 An Alternative Transition Method

In the HFA we've developed so far, we have separate behaviors (states) and transition functions for them. Another approach that's often done (in plain DFA anyway) is to have **events** posted to the HFA which may trigger transitions. Events are just strings, such as `"finished"`, or `"failedToKick"`, or what have you. The current state's go function itself may post such an event to suggest a transition. This is sometimes a more convenient model than the more general transition model we've described here.

Recall that our HFA had three special slots, `events`, `returnEvent`, and `goReturned`. The `events` slot holds a list of strings called *events*. These events have been posted by various sources. You can post an event yourself using the function:

```
-- post an event to the end of the HFA's event list
postEvent = function(hfa, event)
        table.insert(hfa.events, event)
end
```

In this case, the event will be added to the end of the list. Events are cleared every iteration, immediately after determining the transition but before performing it. You can clear all the events manually if you like:

```
-- clear all events on the HFA's event list
clearEvents = function(hfa)
        hfa.events = { }
end
```

You can have a state's go function return an event (a string) rather than `nil`. This is usually done to indicate that your state wants the HFA to transition to somewhere else. If a go function returns an event, it is posted at the very end of the events list.

HFAs are obviously themselves states: but you don't have any control over what they return, unlike hand-coded states you've created. How might you get an HFA to return an event? This is done by setting `hfa.returnEvent` to the event string. Then the HFA will return this event at the end of its go function. There's a utility function to do this for you:

```
-- set the event the HFA returns after goHFA is done
setReturnEvent = function(hfa, event)
        hfa.returnEvent = event
end
```

We need to modify the `stopHFA(...)` function to clean up the HFA's events when it is called.

```
stopHFA = function(hfa, targets)
  hfa.targets =  nil
  if (not (hfa.current.stop == nil)) then
    hfa.current.stop(hfa.current, hfa.behaviorTargets)
  end
  clearEvents(hfa)
end
```

Obviously we'll need to make some modifications to the `goHFA` function too. Here's how it'll work. When the HFA is calling the `go(...)` function of the underlying state, the return value of that function will get

stored away in the slot `hfa.goReturned`. The next iteration, the first thing that `goHFA` will do is check to see if `hfa.goReturned` has any event in it. If it does, it will post that event, then clear it.

After `goHFA` has determined what transition to use, it will clear all the existing events. Then it extracts the targets and performs the transition as usual. It executes the underlying `go(...)` method, possibly yielding an event to put in `hfa.goReturned`, and then it finally returns an event of its own if that event had been set in `hfa.returnEvent`. All in all it looks like this:

```
goHFA = function(hfa, targets)
  hfa.targets = targets

  if (not (hfa.goReturned == nil)) then
    postEvent(hfa, hfa.goReturned)
    hfa.goReturned = nil
  end

  -- DETERMINE TRANSITION
  local newBehavior = hfa.transition(hfa)

  clearEvents(hfa)

  -- EXTRACT TARGETS
  -- the old targets for the behavior we're stopping
  local oldBehaviorTargets = hfa.behaviorTargets

  -- figure the new targets.  Both behaviors and mappings
  -- are dictionaries, but we can tell them apart because
  -- a mapping has a 0 (zero) key in it.
  if (not (newBehavior == nil) and
      not (newBehavior[0] == nil)) then
    -- extract the new targets
    hfa.behaviorTargets = translateTargets(targets,
                                           newBehavior)
    -- update the underlying behavior
    newBehavior = newBehavior[0]
  else
    hfa.behaviorTargets = nil
  end

  -- PERFORM TRANSITION
  if (not (newBehavior == nil)) then
    if (not (newBehavior == hfa.current)) then
       if (not (hfa.current.stop == nil)) then
         hfa.current.stop(hfa.current, oldBehaviorTargets)
       end
      newBehavior.parent = hfa
      if (not (newBehavior.start == nil)) then
        newBehavior.start(newBehavior, hfa.behaviorTargets)
      end
      hfa.current = newBehavior
    end
  end

  -- EXECUTE
  if (not (hfa.current.go == nil)) then
    hfa.goReturned = hfa.current.go(hfa.current,
                                    hfa.behaviorTargets)
  end

  -- RETURN THE RETURNEVENT IF ANY
  if (not (hfa.returnEvent == nil)) then
    return hfa.returnEvent(hfa, targets)
  else
    return nil
  end
end
```

We'll also need to tweak `startHFA` to clear out `hfa.goReturned` in the first place:

```
startHFA = function(hfa, targets)
  hfa.current = start
  hfa.goReturned = nil
end
```

Transitioning on Events We now have a facility for posting and clearing events. How do we transition on them? By creating a new kind of transition function. We'll make a function called `event(...)` which builds a transition function which transitions based on events as indicated in its arguments.

`event(...)` takes a table of states or transition function, keyed by events. If an event has been posted, it will return the appropriate state, or call the appropriate transition function and return whatever it had returned. For example, imagine if we had a system which posted the events `"leftWallCloseEnough"`, and `"bumpedIntoWall"`. We might revise the `curveRight` and `curveLeft` transition functions like this:

```
myTransition = makeTransition(
  {
  [start] = forward,
  [forward] = function(hfa)
      if (ahead(hfa.behaviorTargets.Thing)
          and noLeftWall()) then
        return turnRight90
      elseif (ahead(hfa.behaviorTargets.Thing)) then
        return turnLeft90
      elseif (leftWallTooFar()) then return curveLeft
      elseif (leftWallTooNear()) then return curveRight
      else return forward end
    end,
  [turnRight90] = forward,
  [turnLeft90] = forward,
  [curveRight] = event({
      ["leftWallCloseEnough"] = forward,
      ["bumpedIntoWall"] = turnRight90 })
    end,
  [curveLeft] = event({
      ["leftWallCloseEnough"] = forward,
      ["bumpedIntoWall"] = turnLeft90 })
    end
  })

wallFollow = makeHFA("WallFollow", myTransition)
```

This says that when curving right, if the `leftWallCloseEnough` event was posted, transition to `forward`. If the `bumpedIntoWall` event was posted, transition to `turnRight90`. Otherwise continue curving right. What if both were posted? Then whichever event was posted *first* wins. The `curveLeft` state is similar.

Note that you could have whole transition functions rather than states. That is, instead of `["leftWallCloseEnough"] = forward`, you might do `["leftWallCloseEnough"] = function(hfa) ...` The `event(...)` method is pretty straightforward to write:

```
-- build a transition function based on events
event = function(transitions)
  return function(hfa)
    for event in ipairs(hfa.events) do
      local transition = transitions[event]
        if (not (transition == nil)) then
          if (type(transition) == "function") then
            return transition(hfa)
          else
            return transition
          end
        end
      end
    return nil
  end
end
```

8 Utility Behaviors

I've found it useful to have certain utility behaviors built into the library:

- Behaviors which increment or reset **counters** so HFAs can conveniently do things for a set number of times.
- Behaviors which update or reset **timestamps** so HFAs can conveniently do things for a set amount of wall-clock time (useful for HFAs involved in robotics).
- Behaviors which raise **flags** to signal parent HFAs that it might be a good time for the parent HFA to transition to something else now.

Each of these behaviors will need to update some special slots stored in the HFA. Let's discuss these in turn.

Counters We'll include one **counter** in each HFA. The counter is just an integer which starts at zero and increments or is reset to zero as requested. At any time, our transition functions can query the current counter value and make transition decisions based on it. This would allow us, for example, to try kicking a ball six times, and if we still have failed, go do something else.

If our HFA were called `hfa`, the counter in the HFA will be called `hfa.counter`. We'll create two behaviors which modify it:

```
-- increments the parent HFA's counter
bumpCounter = makeBehavior("bumpCounter",
  function(behavior, targets)
    if (not (behavior.parent == nil)) then
      behavior.parent.counter = behavior.parent.counter + 1
    end
  end, nil, nil)

-- zeros the parent HFA's counter
resetCounter = makeBehavior("resetCounter",
  function(behavior, targets)
    if (not (behavior.parent == nil)) then
      behavior.parent.counter = 0
    end
  end, nil, nil)
```

Notice that we're also *finally* making use of the `parent` slot in behaviors. This slot was set in our `goHFA` function before the behavior was called.

If you're too spooked about accessing the slot directly, your transition functions can get the current counter value using the following convenience function:

```
currentCounter = function(hfa) return hfa.counter end
```

Timers Timers are just like counters, only they store intervals of time. Whereas counters are useful for simulations, timers are particularly useful for real-time stuff like robotics or game agents. We'll include one single timer, in the HFA slot `timer`.

Unfortunately, Lua doesn't have a good measure of system time (Google for "lua time milliseconds"): its finest resolution is one second. But it's better than nothing. Here we'll make a behavior which sets `timer` to the current time, and provide a utility function which measures the difference between the current time and the last time the timer had been set.

```
-- updates the timer to the current time
resetTimer = makeBehavior("resetTimer",
  function(behavior, targets)
    if (not (behavior.parent == nil)) then
      behavior.parent.timer = os.time()
    end
  end, nil, nil)

-- returns the number of seconds
-- since the timer was last updated
currentTimer = function(hfa)
  return os.time() - hfa.timer
end
```

Flags A flag is a slot in an HFA which is either true or false. Flags are most often used by HFA to inform their parent HFA that they think they have finished their task (or failed at it) and perhaps the parent should now transition to something else.

We'll define two flags: `done` and `failed`. The actual flag slot is stored in the parent HFA, and the parent HFA's transition functions can test these flags (to determine if they should transition somewhere else) using the following convenience functions:

```
-- isDone(hfa) returns the current done flag in the HFA
isDone = function(hfa) return hfa.done end

-- isFailed(hfa) returns the current failed flag in the HFA
isFailed = function(hfa) return hfa.failed end
```

A child HFA sets a flag in its parent HFA by transitioning its current state to a **flag-setting behavior**. There are four such behaviors provided, which differ based on what happens *after* the flag is set. In some cases you just want to set the flag. In other cases, you set the flag because you're out of stuff to do: where you should you transition to then? In these other cases, we just automatically transition to the start of the automaton. So we have:

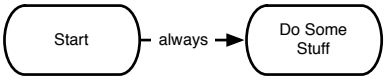
- **sayDone** raises the `done` flag.
- **sayFailed** raises the `failed` flag.
- **done** raises the `done` flag and immediately resets to the `start` state, so the next transition will be out of the `start` state. This is often more convenient than `sayDone` because you don't have to specify a transition function for this state. More often then not, when your HFA thinks it is "done", you don't care about specifying further behaviors: you might as well just start it over again if its parent foolishly decides to continue on.
- **failed** raises the `failed` flag and immediately resets to the `start` state, so the next transition will be out of the `start` state. This is often more useful than `sayFailed` for the same reason that `done` (above) is more useful than `sayDone`.

These behaviors set flags using an internal function called `setFlag`. We'll include one last gizmo in `setFlag` called **flag propagation**. Often we see HFA which look like this:

Note the transition to `done` when the flag is `done`. Ick. In fact often we see whole cascades of HFA and parent HFA with this pattern. Rather than explicitly add all these "done" behaviors into these HFA, we can simply tell the HFA to propagate their `done` and `failed` flags to their parents: that is, when their `done` flag is set, they automatically set their parent's `done` flag (similarly `failed`):

```
myHFA.propagateFlags = true
```

Then the HFA would look like:



... because flag propagation is being handled automatically. Thus `setFlag` will look like this:

```
-- Internal utility function.
-- Sets a flag in the *parent* of the given HFA
setFlag = function(hfa, flag)
    if (not (hfa.parent == nil)) then
        hfa.parent[flag] = true
        if (hfa.parent.propagateFlags == true) then
            setFlag(hfa.parent, flag)
        end
    end
end
```

Armed with this function, we can create our four behaviors:

```
-- done: sets the "done" flag in the HFA's parent,
-- and transitions to "start"
done = makeBehavior("done", nil, nil,
    function(behavior, targets)
      if (not (behavior.parent == nil)) then
          behavior.parent.current = start
          setFlag(behavior.parent, "done")
        end
    end)


-- sayDone: sets the "done" flag in the HFA's parent
sayDone = makeBehavior("sayDone",
    function(behavior, targets)
      if (not (behavior.parent == nil)) then
          setFlag(behavior.parent, "done")
      end
    end, nil, nil)


-- failed: sets the "failed" flag in the HFA's parent,
-- and transitions to "start"
failed = makeBehavior("failed", nil, nil,
    function(behavior, targets)
      if (not (behavior.parent == nil)) then
          behavior.parent.current = start
          setFlag(behavior.parent, "failed")
        end
    end)


-- sayFailed: sets the "failed" flag in the HFA's parent
sayFailed = makeBehavior("sayFailed",
    function(behavior, targets)
      if (not (behavior.parent == nil)) then
          setFlag(behavior.parent, "failed")
      end
    end, nil, nil)
```

It's convenient, or sometimes critical, to reset these flags, counters, and timers whenever we start an HFA, or in some cases whenever we iterate the HFA. We'll do this in `startHFA`. Specifically, we'll reset the `hfa.done`, `hfa.failed`, `hfa.counter`, and `hfa.timer` variables, yielding:

```
startHFA = function(hfa)
    hfa.done = false;
    hfa.failed = false;
    hfa.counter = 0;
    -- maybe this is too costly and we should
    -- restrict it to the resetTimer function?
    hfa.timer = os.time()
    hfa.goReturned = nil;
    hfa.current = start;
end
```

Last but not least, we want to clear the `hfa.done` and `hfa.failed` flags every iteration, so we modify `goHFA` as follows:

```
goHFA = function(hfa, targets)
  hfa.targets = targets

  if (not (hfa.goReturned == nil)) then
    postEvent(hfa, hfa.goReturned)
    hfa.goReturned = nil
  end

  -- DETERMINE TRANSITION
  local newBehavior = hfa.transition(hfa)

  clearEvents(hfa)

  -- EXTRACT TARGETS
  -- the old targets for the behavior we're stopping
  local oldBehaviorTargets = hfa.behaviorTargets

  -- figure the new targets.  Both behaviors and mappings
  -- are dictionaries, but we can tell them apart because
  -- a mapping has a 0 (zero) key in it.
  if (not (newBehavior == nil) and
      not (newBehavior[0] == nil)) then
    -- extract the new targets
    hfa.behaviorTargets = translateTargets(targets,
                                           newBehavior)
    -- update the underlying behavior
    newBehavior = newBehavior[0]
  else
    hfa.behaviorTargets = nil
  end

  -- PERFORM TRANSITION
  if (not (newBehavior == nil)) then
    if (not (newBehavior == hfa.current)) then
       if (not (hfa.current.stop == nil)) then
         hfa.current.stop(hfa.current, oldBehaviorTargets)
       end
      newBehavior.parent = hfa
      if (not (newBehavior.start == nil)) then
        newBehavior.start(newBehavior, hfa.behaviorTargets)
      end
      hfa.current = newBehavior
      hfa.done = false
      hfa.failed = false
    end
  end

  -- EXECUTE
  if (not (hfa.current.go == nil)) then
    hfa.goReturned = hfa.current.go(hfa.current,
                                    hfa.behaviorTargets)
  end

  -- RETURN THE RETURNEVENT IF ANY
  if (not (hfa.returnEvent == nil)) then
    return hfa.returnEvent(hfa, targets)
  else
    return nil
  end
end
```