Chapter 4: Experiments and Results

The algorithm has been implemented in Scheme [Abelson et al, 1985], a LISP-like language, and has been tested in a 3D graphical interactive story system based on *The Three Little Pigs*. In this story system an autonomous wolf inhabits a cartoon world similar to the Warner Brothers' *Coyote/Road-Runner* cartoons. The wolf tries to catch little pigs through a variety of methods, including climbing down chimneys, blowing down houses, or simply planting bombs in front of the pigs' houses. A human controller can “play God” to the wolf, controlling when bombs go off, whether houses blow down, and whether character actions succeed or fail. The controller can also move objects around or remove them completely from the world. In the test scenarios only the wolf is an autonomous character, and a single pig is controlled by hand. The physics of the world, although still controllable by a human player, does not yet have an easy-to-use interface. Future versions will have three autonomous pigs in addition to the wolf, and will provide a GUI interface for real-time control of the virtual world.

Locations in the 3D world are continuous (x,y,z) coordinates. Objects in the world consist of the wolf, a pig, a house that can be built or destroyed and through which the wolf cannot pass, a pogo-stick that can be used to jump to the roof of the house, and a chimney that can give the wolf access to the house. There is also a bundle of dynamite (TNT) and a detonator plunger to make it explode. In addition to the four behavior modules specified earlier the wolf has *Blow-down-object*, *Pogo-to-location*, *Plant-tnt-at-location*, and *Explode-object* behaviors. The specification for the behaviors of the more advanced wolf is shown in Appendix A.

The house can be made of three different materials, straw, twig, or brick. The straw house can be destroyed either by huffing-and-puffing-and-blowing-it-down, or by exploding it with the TNT. Blowing on the twig house will fail, but the TNT will still work. Both methods will fail to destroy the brick house. The wolf does not know what material the house is, and must find out by trial and error what methods work. The house is a large structure, and (location-of <house>) returns four values: the locations of the front door, the back wall, and the two side walls[1]. It is possible to walk inside the house from one location to another, and from anywhere inside the house to the outside, but the wolf cannot walk from a location outside the house to a location inside except by climbing down the chimney to the fireplace. The wolf can walk to any location on the ground so long as there is a path to it[2], but he cannot walk to locations above ground-level. He can, however, pogo-stick to locations above the ground as long as he has the pogo-stick.

Each experiment described below is designed to test a different aspect or design goal of the algorithm. Specifically, the experiments test the proper handling of multiple goals, multiple ways of performing an action, multiple conflicting goals, opportunistic behavior, and graceful handling of the failure of an action.

4.1 Experiment 1: single goal and single method

4.1.1 Setup

Goal: *Hunger-satisfied* = 22

Actions available to the wolf: All

Objects in world:

1. As explained in Section 3.2.1, transformations are one-to-many, and thus can produce multiple outputs for a single input. All four locations are passed as separate suggestions to the modules that use the location of the house.
2. i.e., so long as the location is not inside the house when he is outside

House is straw

Pig starts in the house

Wolf starts a short distance away from the house, nearest the front door.

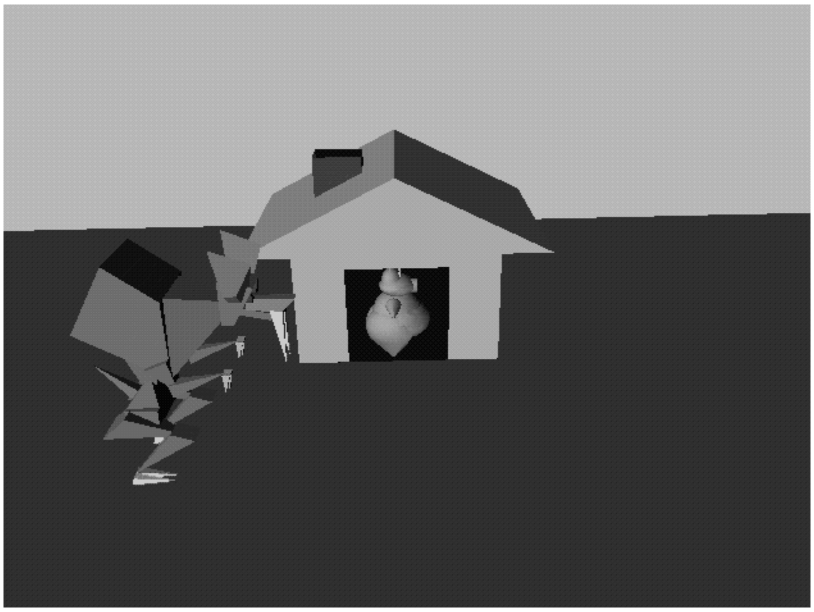

Figure 11: Initial conditions for Experiment 1

4.1.2 Result

The wolf walked to the front door of the house, huffed-and-puffed-and-blew-it down, walked over to the pig, picked it up, and ate it.

4.1.3 Variations

Variation 18. If the wolf instead starts nearest to the left-hand wall of the house, he will walk to that wall to do his huffing and puffing.

Variation 19. If, while the wolf is walking towards the front-door, the pig suddenly runs out the back, the wolf will walk around the house rather than blow it down (i.e., adapting to the changing situation).

4.1.4 Discussion

The main experiment shows the standard handling of a plan-like sequence of actions to satisfy a goal. Variation (1) shows how the wolf prefers closer locations when given otherwise equal choices. Variation (2) shows how he can smoothly handle changes in the environment.

4.2 Experiment 2: Multiple methods / complimentary goals

4.2.1 Setup

Goal: *Hunger-satisfied* = 22, *Desire-to-destroy-things* = 10

Actions available to the wolf: All

Objects in world:

House is straw
Pig starts in the house
Wolf starts a short distance away from the house
TNT lies a short distance away from the house in a unique location
detonator lies a short distance away from the house in a unique location
pogo-stick lies a short distance away from the house in a unique location

4.2.2 Result

The wolf walked to the house, huffed-and-puffed-and-blew-it down, walked over to the pig, picked it up, and ate it.

4.2.3 Variations

Variation 1. When the wolf's goals were changed to *Hunger-satisfied* = 22, *Desire-to-be-in-high-places* = 10, instead of blowing down the house the wolf went to the pogo-stick, picked it up, bounced to the chimney of the house, climbed down the chimney, dropped the pogo-stick, picked up the pig, ate the pig, picked up the pogo-stick, and bounced back up to the roof of the house.

4.2.4 Discussion

This experiment shows how multiple goals can contribute to determining the next action. In environments where there are several methods for accomplishing the same action, often it is possible to satisfy lower priority goals at the same time a primary goal is being satisfied. Note that *Hunger-satisfied* was deliberately made higher than the secondary goal to avoid introducing conflicting goals into the experiment. Conflicting goals are addressed in the next experiment.

4.3 Experiment 3: Multiple Inhibitory Goals

4.3.1 Setup

Goals: *Hunger-satisfied* = 30, *Destruction-urge* = 20, *Carrying-pogo* = 10

Actions available to the wolf: All except *Blow-down-object*

Objects in world:

House is straw
Pig starts in the house
Wolf starts a short distance away from the house
TNT lies a short distance away from the house in a unique location
detonator lies a short distance away from the house in a unique location
pogo-stick lies a short distance away from the house in a unique location

4.3.2 Result

The wolf walks to the pogo-stick, picks it up, and bounces to the TNT. He then drops the pogo-stick to pick up the TNT, brings the TNT to the house and places it there. He walks to the detonator and explodes the house. He then walks to the pogo-stick, bounces to the pig, drops the pogo-stick, eats the pig, and then picks up the pogo-stick again. The same result occurs regardless of the distance between the pogo-stick and the wolf.

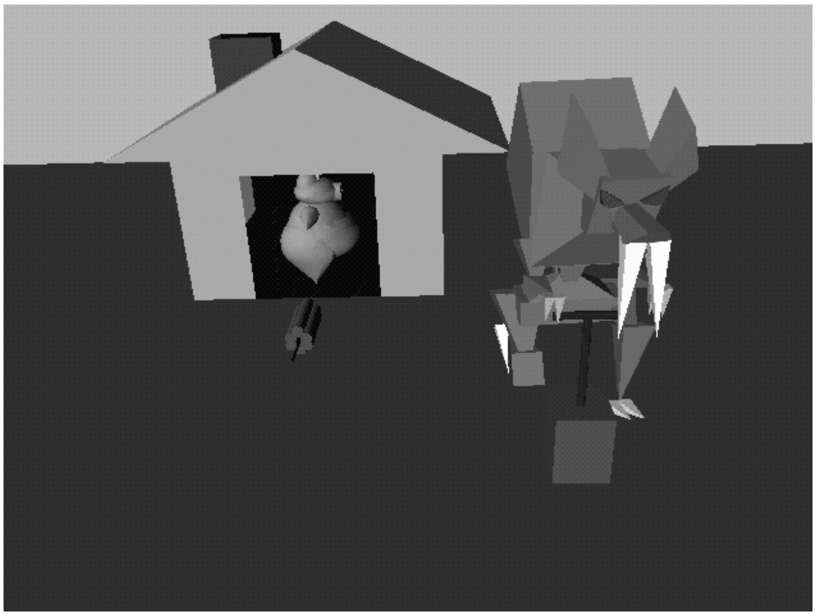

Figure 12: The wolf about to destroy the house

4.3.3 Variations

Variation 1. With the goals set to *Destruction-urge = 30, Carrying-pogo = 20, Hunger-satisfied = 10*, everything happens the same as before until the wolf gets to the pig. At this point he simply stands on top of the pig and refuses to release the pogo-stick, because it is a more important goal than satisfying his hunger.

Variation 2. With the goals *Carrying-pogo = 30, Hunger = 20, Destruction-urge = 10*, the wolf gets the pogo-stick and bounces to the TNT. At this point he refuses to drop the pogo-stick, and gives up on exploding the house. He bounces to the chimney of the house and climbs down. Again he refuses to drop the pogo-stick, and gives up on eating the pig. At this point no recommended action is executable, so all the giveup blacklists are cleared and he bounces to the TNT. The cycle repeats ad infinitum, with the wolf going between TNT, chimney, and pig.

Variation 3. With all three goals set equal to 30 and the *conflictor-multiplier* parameter set to 1.0, the wolf gets the pogo-stick, bounces to the TNT, drops the pogo-stick, picks up the TNT, walks to the house and plants the TNT, and explodes the house. He then walks back to the pogo-stick and bounces to the pig. At this point he refuses to drop the pogo-stick, because this action would undo his goal of carrying the pogo-stick. Having no other actions to take, the wolf does nothing from this point on.

Variation 4. With all three goals set equal to 30 and the *conflictor-multiplier* parameter set to its default of 0.9, the story begins the same as in variation 3, above, but once the wolf gets to the pig he instead gets into a loop: he first drops the pogo-stick, then picks it back up, then drops it again, ad infinitum.

4.3.4 Discussion

The results of this experiment and variations 1 and 2 happened as should be expected: the wolf always tried to satisfy lower priority goals but would sacrifice them to satisfy a higher priority goal. The last two variations show what happens when two goals of the same priority conflict. Recall that the *conflictor-multiplier* parameter is a kind of gauge on how much dithering should be allowed. A value of 1.0 means conflictor-links carry their full energy, so an even slightly higher-energy suggestion will always win out. In variation 3, *Carrying-pogo* has slightly more inhibitory power than *Drop-object <pogo-stick>* has energy, because *Drop-object* is one hop further removed from its energy source, *Hunger-satisfied*. In variation 4, the energy from the conflictor link is reduced just enough to allow *Drop-object <pogo-stick>* to act, but then the wolf is in a situation where he must choose between picking up the pig and picking up the pogo-stick again. As in variation 3, the pogo-stick wins because of the slight bias towards shorter action-paths. The specific failures in variations three and four are due to general problems the PHISH-Nets algorithm has with situations where the ordering of actions is especially important. This point will be discussed further in Section 5.5.1.

4.4 Experiment 4: Undoing one goal to accomplish another

4.4.1 Setup

Goals: *Destruction-Urge = 30*, *Hands-are-free* = 30

Actions available to the wolf: All except *Blow-down-object*

Objects in world:

House is straw

Pig starts in the house

Wolf starts a short distance away from the house

TNT lies directly in front of the house

detonator lies a short distance away from the house

pogo-stick lies a short distance away from the house in a unique location

Special: *Explode-object* is modified such that the wolf must not only be standing next to the detonator to explode an object but must actually be holding the detonator. The *conflictor-multiplier* is set to its default of 0.9.

4.4.2 Results

At the start of this scenario the wolf has already satisfied the goal of having nothing in its hands. It goes to the detonator and undoes this goal by picking up the detonator. It explodes the house, then drops the detonator.

4.4.3 Variations

Variation 1. Changing the *conflictor-multiplier* from its default to 1.0 causes the wolf to walk towards the detonator but he takes no action once he gets to it.

4.4.4 Discussion

In this experiment, *Hands-are-free* is satisfied at the start, but needs to be undone to achieve the wolf's other goal. *Hands-are-free* inhibits *Pickup-object*, but because the *conflictor-multiplier* parameter is less than 1.0 the inhibition is slightly less than its total energy and the wolf picks up the detonator. At this point there are two unsatisfied goals, one that would be satisfied by dropping the detonator and one that would be satisfied by exploding the house. *Explode-object <house>* inhibits *Drop-object <detonator>*, but there is no inhibition in the reverse direction. This condition gives *Explode-object <house>* the clear advantage. After the detonation is complete, the wolf drops the detonator, thereby achieving both goals. Note that this experiment is different from the situation in Section 4.3, variations 3 and 4, where there was mutual inhibition instead of inhibition on only one side.

It should be noted that the environment in this experiment is equivalent to the A-on-B, B-on-C blocks-world problem described in [Sussman, 1975]. In this classical problem, a robot must satisfy the two goals of having block A stacked on top of block B and having block B stacked on block C. At the start of the experiment, A is already stacked on B and must be taken off if B is to be moved.

4.5 Experiment 5: Mutual inhibition

4.5.1 Setup

Goals: *Carrying-pig* = 22, *Carrying-detonator* = 22, *Destruction-urge* = 10

Actions available to the wolf: All

Objects in world:

House is straw

Pig starts away from the house in the same location as the detonator

Wolf starts a short distance away from the house

detonator lies in the same location as the pig

4.5.2 Results

The wolf approaches the location where both the detonator and pig are. When he gets there, for a single time-step he starts to move towards the house to blow it down, but on the next timestep he picks up one of the two objects at random. He then walks to the house and blows it down.

4.5.3 Discussion

Both *Carrying-pig* and *Carrying-detonator* need use of the wolf's hands and therefore inhibit each other. In such a situation it is important to insure that the two behaviors do not eliminate each other, thereby allowing a third, lower priority behavior to take effect. In the example above, as soon as the wolf gets within reach of both objects the behaviors *Pickup-object <pig>* and *Pickup-object <detonator>* inhibit each other. Due to the conflictor-multiplier parameter, each brings the other's energy value to slightly above zero, and the uninhibited *Destruction-urge* can take over. However, if the inhibition is not taken into account then both *Pickup-object <detonator>* and *Pickup-object <pig>* have energies higher than the action that was finally chosen, so at the end of the timestep the action with the largest amount of inhibition is placed on the inhibited blacklist, as described in Section 3.4. In this case, both have equal amounts of inhibition, so one of them is placed on the list. In the next timestep, the action that was placed on the inhibition blacklist cannot pass inhibition, so the other action remains uninhibited and becomes active. Thus, after one timestep of performing a less relevant action, the wolf will either pick up the pig or pick up the detonator, and then go to satisfy his lesser goal.

4.6 Experiment 6: Opportunism

4.6.1 Setup

Goals: *Destruction-urge* = 22

Actions available to the wolf: All

Objects in world:

House is straw
Wolf starts a large distance away from the house
TNT lies between the wolf and the house, but slightly to one side
detonator lies a short distance away from the house in a unique location
pogo-stick lies a short distance away from the house in a unique location

4.6.2 Results

The wolf begins by walking towards the house. As he nears the TNT, he modifies his course, picks up the TNT, and then continues towards the house. Once at the house, he huff-and-puffs and blows the house down.

4.6.3 Variations

Variation 1. Same as above except the TNT is placed some distance further away from the wolf's path to the house. In this case, the wolf is not diverted and proceeded to blow down the house, ignoring the TNT.

4.6.4 Discussion

In an unpredictable world it is often wise to be opportunistic, favoring actions that are immediately available even if they satisfy less important goals. The extra boost of energy given to modules especially close to completion give characters a degree of opportunism. In this experiment, grabbing the TNT was less important than going to the house, because exploding the house takes more steps than blowing it down, but the wolf still picked up the TNT "just in case" if it was close.

4.7 Experiment 7: Failure of actions

4.7.1 Setup

Goals: *Hunger-satisfied* = 22, *Destruction-urge* = 22

Actions available to the wolf: All

Objects in world:

- House is brick
- Pig starts in the house
- Wolf starts a short distance away from the house
- TNT lies a short distance away from the house in a unique location
- detonator starts a short distance away from the house in a unique location
- pogo-stick lies a short distance away from the house in a unique location

4.7.2 Results

The wolf goes to the house and huffs-and-puffs to try and blow it down. Because the house is made of brick the action fails, so he goes to the TNT, picks it up, places it by the house, goes to the detonator and tries to explode the house. This also fails. He then goes to the pogo-stick, bounces to the roof of the house, climbs down chimney, drops the pogo-stick, picks up the pig, and eats it.

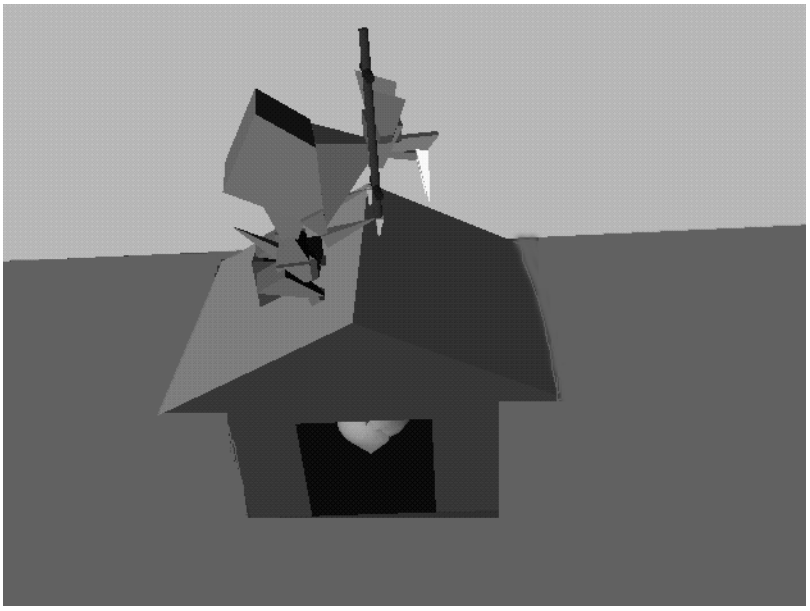

Figure 13: The wolf climbing down the brick house chimney

4.7.3 Discussion

This experiment shows how PHISH-Nets handle failure of actions robustly by using multiple methods to achieve a goal. When blowing the house down failed, the binding *<house>* was added to the failure blacklist for *Blow-down-object* and not tried again. The wolf then tried to explode the house, but this action also failed and the binding *<house>* was added to the failure blacklist for *Explode-object*. With no other methods available to destroy the house, the wolf used the pogo-stick to catch the pig, thereby satisfying his remaining goal. Note that not only did the wolf not pathologically continue to try blowing the house down, but he also went on to try other methods of simultaneously satisfying both goals before finally giving up and satisfying only his hunger.

4.8 Experiment 8: Giving up on the impossible

4.8.1 Setup

Goals: *Destruction-urge* = 30, *Carrying-pig* = 10

Actions available to the wolf: All except *Blow-down-object*

Objects in world:

House is straw

Pig starts a short distance away from the house

Wolf starts a short distance away from the house in a unique location

TNT lies a short distance away from the house in a unique location

Special: After the wolf places the TNT by the house, but before he grabs the pig, the TNT is moved away from the house.

4.8.2 Results

The wolf starts by going to get the TNT and placing it next to the house. He then decides that there is no way to explode the house because there is no detonator, and proceeds to satisfy his secondary goal of carrying the pig. While he is walking to the pig the TNT is moved away from the house, but the wolf has already given up on that action so he does not pathologically move the TNT back to its starting location. Instead, he goes and picks up the pig.[3]

4.8.3 Variations

Variation 1. Add the detonator to the world, but place it in the house. This time the wolf drops the TNT, but does not add exploding the house to his giveup blacklist. However, because there is no pogo-stick in this variation, he cannot get to

3. At this point, there are no actions selected so the wolf actually clears his giveup-buffer, carries the pig over to the TNT, drops the pig, and takes the TNT to the house, continuing in this loop ad infinitum.

the roof to climb down the chimney to get to the detonator. He therefore goes satisfy his secondary goal to pick up the pig. Because exploding the house was not added to the wolf's giveup-blacklist, when the TNT is moved away from the house, he goes to replace it before going to pick up the pig. If a pogo-stick is added to the world, the wolf then uses the pogo-stick to get to get to the chimney, climbs down, and explodes the house before going back to the pig.

Variation 2.This variation is radically different from the standard version of the experiment. In this variation, the wolf has three goals: *Carrying-pig* = 30, *Carrying-detonator* = 20, and *Destruction-urge* = 10. The pig, wolf, and detonator all start some distance away from the straw house in unique locations. The wolf has all abilities, including *Blow-down-object*. The wolf first walks to the pig and picks it up. He then walks to the detonator, but when he gets there he ca not drop the pig because *Carrying-pig* inhibits *Drop-object* *<pig>*. The wolf then gives up on picking up the detonator, and walks to the house to blow it down. Even if the detonator is moved away from the wolf, he will not pathologically walk to the detonator, but will instead service his lesser achievable goals. After blowing down the house, no action is selected, so all the giveup blacklists are cleared. The wolf then goes back to the detonator and stands over it, but still refuses to drop the pig.

4.8.4 Discussion

This experiment shows how PHISH-Nets give up on behaviors with preconditions that cannot be satisfied. In the first example, the wolf gives up on going to the location of the detonator, and in turn gives up on exploding the house. Variation number two is a similar case, except that the wolf gives up on holding the detonator not because the action is unavailable, but because the action is being inhibited such that it cannot be executed.

Variation number one shows a case where the wolf does not realize that getting the detonator is impossible. Since the wolf could satisfy the preconditions for *Explode-object <house>* by walking to the detonator, he does not add the binding to his giveup blacklist. With only local knowledge there is no good way to detect that to get to the detonator he must explode the house, and to explode the house he has to get to the detonator. This problem is discussed further in Section 5.5.1.