The Control and Spread of Wildfires

New Mexico
Supercomputing Challenge
Final Report
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Team Number 71

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Problem Explanation

This year our project is over the spread of wildfires, especially grass fires in Eastern New Mexico. Fire has been an important tool for humans through the ages, however, uncontrolled it can cause large amounts of damage. Annually in the US over 4000 people die from fires, and 25,000 are injured. Uncontrolled fires also cause an estimated annual damage of over 8 billion dollars. We believe that by modeling fire behavior we will be able to help homeowners and authorities to better prepare and prevent wildfires, there by reducing costs, both human and economic. To do this we will try to model the spread of a grass fire as accurately as possible. Using this information we would then determine how to place firebreaks to retard the fire's progression and protect valuable property such as homes and even towns.

We want to be able to model a fire under varying conditions. To do this we must identify the major variables that effect a fires progression. We also need know what a fire is, if we are to control it.

Research

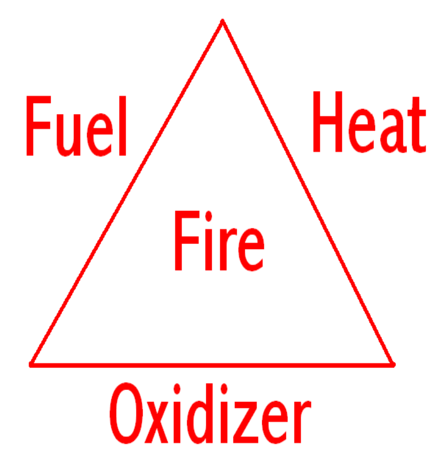
What is Fire

Fire is a chemical reaction between a fuel and an oxidizer. The chemical reaction requires an ignition source or an input of heat to start this reaction. This is commonly referred to as the fire tetrahedron, because fire can't exist with out any of its components:

Fuel—Anything that can be oxidized, such as organic matter, fossil fuels, natural gas, hydrogen, or reactive metals such as magnesium or sodium.

Oxidizer—Primarily oxygen (the same elemental gas that we need to live), which is required for the combustion reaction we are interested in, however other oxidizers such as fluorine and chlorine will sustain a fire as well.

Heat—Any heat source that will reach the fuels ignition



Fire Tetrahedron

point (the temperature at which the fire can begin to burn). The heat can come from electricity, friction, radiant heat, or another chemical reaction. Heat is the one component of the tetrahedron that is not present under normal circumstances. Fuel and oxidizers can be found together virtually everywhere, but they do not combust (burn) because there is no heat source. Once a fire is started, the heat produced is sufficient to sustain and grow the chain reaction as long as the tetrahedron is kept intact.

The Chemical Reaction

Since fire is a chemical reaction, materials are changing and energy is released. When heat is applied to a fuel, it vaporizes. Then the resulting volatile compounds combine with the oxidizer, thus burning or oxidizing. The oxidizing vapor is the flame we see. This process releases lots of heat and light very quickly enabling the reaction to continue. The chemical formula for the combustion of propane is:

$$C_3H_8 + 5O_2 \longrightarrow 3CO_2 + 4H_2O \; \triangle$$

The propane combines with oxygen when it burns producing carbon dioxide, water and releasing energy. This is representative of what happens when most things burn, but with more complex organic materials there is another process as well.

In wood for example, after the volatile compounds evaporate, there are two main components left, char, almost pure carbon, and ash, the unburnable materials left. The char then oxidizes as well releasing a lot of heat, but not as much light.

Putting a Fire Out

To put a fire out, you must remove any part of the fire tetrahedron, fuel, oxidizer, or heat. Doing this can be done several ways. Some are by using water, foam, back burning, explosives, carbon dioxide (CO_2), fire blankets, and dirt.

Water—(removes heat) Because water has a high specific heat, it can absorb a fire’s heat faster that the fire can produce it, if the supply of water is high enough. Water is what most people think of when putting out a fire, but it is not always the best choice such as in electrical fires, reactive metal fires, and petroleum and petroleum product fires.

Foam—(removes heat and oxidizer) Foam is a solution that is very frothy, it puts a fire out by both smothering it, removing the oxidizer, absorbing the heat, and by reflecting radiant heat back. Water and air are ingredients in foam, but with foam you would use much less water, letting you put out a greater amount of fire with less water.

Back Burning—(removes fuel) Back Burning is the use of a small controlled fire to burn fuel in front of the fire that is out of control. This method is mainly used when there is a large grass or forest fire.

Explosives—(removes oxidizer) The use of explosives to put out fires is mainly used in oil well fires. An explosive is set off in the fire and it displaces the fires oxygen source for just enough time that the fire goes out.

Carbon Dioxide—(removes oxidizer) CO_2 is mainly used in fire extinguishers. The CO_2 smothers the fire.

Fire Blankets—(removes oxidizer) These are made of a fire resistant material, and are usually placed over a small fire to smother it.

Dirt—(removes oxidizer and fuel) Dirt is a nonflammable material of which there is usually great abundance. Dirt can smother a fire, but is usually part of a firebreak. A firebreak is a predetermined area that is removed of vegetation and flammable materials to prevent a fire from crossing it or to slow a fire down enough for firefighters to be able to control it.

<u>The uses of Fire</u>

It is believed that people have had control of fire for about 1 to 1.8 million years. Mankind has found many uses for it. Fire has been used to clear land of brush to help make farming possible and make an area for housing. Fire was and is used to harden bricks and pots and to cook with. It has saved many lives when surgeons learned to sterilize their instruments. Fire has also been used to fight wars ever since people could control it. From burning ancient crops to the flamethrowers in the World Wars and the use of napalm in Vietnam, people have used fire's destructive and frightening power to fight each other. People have also used fire to work ore into metal and metal into useful products. Most power plants use some sort of fire as their energy source, whether they're burning coal, oil, or natural gas.

Solving the Problem

We will use StarLogo TNG as our programming language. We used this language because it is easy for amateur programmers to use, and it is appropriate considering the variables that we plan to include. We plan to solve our problem by introducing an agent in “SpaceLand” that will consume fuel and multiply and progress in accordance to the following variables:

Fuel Load—The amount of fuel available per square area of land. This will be determined in our model by a scale of 1-10 in shades of green, the darker the green, the greater the fuel load. The fuel load in an area can change greatly, on one side of the fence there can be a green wheat field which has an extremely low fuel load, and on the other side of the fence, there can be land enrolled in CRP (Conservation Reserve Program) which can have a very high fuel load. The fuel load in a single pasture can change too depending on what kind of grass grows from place to place. The fuel loads that we will use for our model will be:

1) Very, very low—less than 200 pounds of grass per acre
2) Very low—from 200-500 pounds of grass per acre
3) Moderately low—from 500-800 pounds of grass per acre
4) Moderate—from 800-1100 pounds of grass per acre
5) Moderately high—from 1100-1500 pounds of grass per acre
6) Very high—over 1500 pounds of grass per acre

Dryness—The amount of moisture in the area. Often the land will be very dry before a thunder storm and lightning can easily start a fire, but as the storm progresses it may rain, decreasing the dryness retarding the fire’s progress and maybe even putting the fire out.

Wind Direction—Wind direction plays a vital role in fire control. If the wind direction changes significantly while a fire is burning, fire fighters may have had a chance to control its progress or set up a firebreak, but if the fire suddenly changes direction, it may become uncontrolled once again.

Wind Speed—Wind speed is also very important in fires. A fire under a light wind might not ordinarily cross a firebreak such as a road, but if the wind was blowing enough, the road might not even slow down a raging fire. We will use these numbers to represent the different wind speeds:

0—0-3 mph
3—15-25 mph

1—3-10 mph
2—10-15 mph
4—over 25 mph

With control of these variables in our model, we will "start a fire" on the map and let it burn until the entire map is consumed or the fire burns itself out. We can then alter the map by adding a firebreak and running the model again.

Our model runs on these basic principles:

1) Burn

a) Test to see if patch color is some shade of green

b) If so, then add one shade of white to the patch.

c) If not, then test to see if patch is already burned

i) If so, then "die"

ii) If not, then have a 66% chance of dieing (This gives a fire a chance at crossing a firebreak with sparks and tumbleweeds).

2) Spread

a) Test to see if a random number between 0-100 is less than or equal to dryness.

b) If so, then choose a random number between 0-360 for a direction

i) Then create a new fire and send him 1 step in the chosen direction.

3) Wind

a) Select a random number between 0-45 and add it to the wind direction

b) Then divide wind speed by 2 and add 0.5 and take that many steps in the chosen direction.

Mathematical Model

The mathematical formulas that our model follows are stated below.

Setup

F_1 = first fire agent generated

F_1 is randomly placed on an x y grid according to …

$x \sim U[-50.5, 50.5)$

$y \sim U[-50.5, 50.5)$

Where *U* is uniform distribution.
F_1 is randomly placed on a "patch".
A "patch" is an area that is centered on an x y grid where $x_0, y_0 \varepsilon \mathbb{Z}$
A "patch" includes…

$x \varepsilon [x_0 -0.5, x_0\ 0.5)$

$y \varepsilon [y_0 -0.5, y_0\ 0.5)$

Spread

f_i = fire agent i
t = time
P = probability

The probability that a fire sparks another fire is …

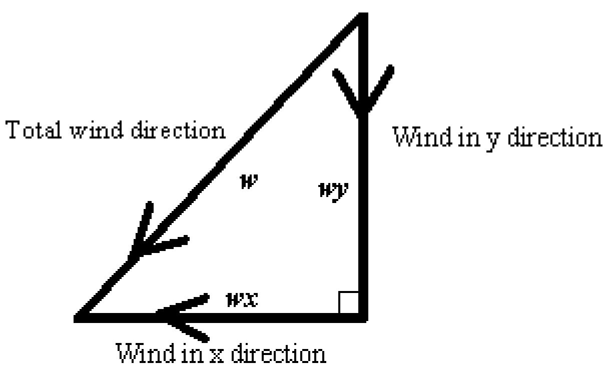
$P(f_i \text{ produces } f_j), [t,t+1)$

The location of f_j is…

$x_j = x_i+\cos\theta r+\mathbf{wx}$

$y_j = y_i+\sin\theta r+\mathbf{wy}$

Where "θr" is a random angle uniformly distributed on $[0,2\pi)$
Where "$\mathbf{w}$" is a wind vector composed of x and y directions



Burn

L_k = fuel level in "patch" K

The fuel level decreases by the number of "fires" on that "patch"

$L_{kt+1} = max(L_{kt} – n, 0)$

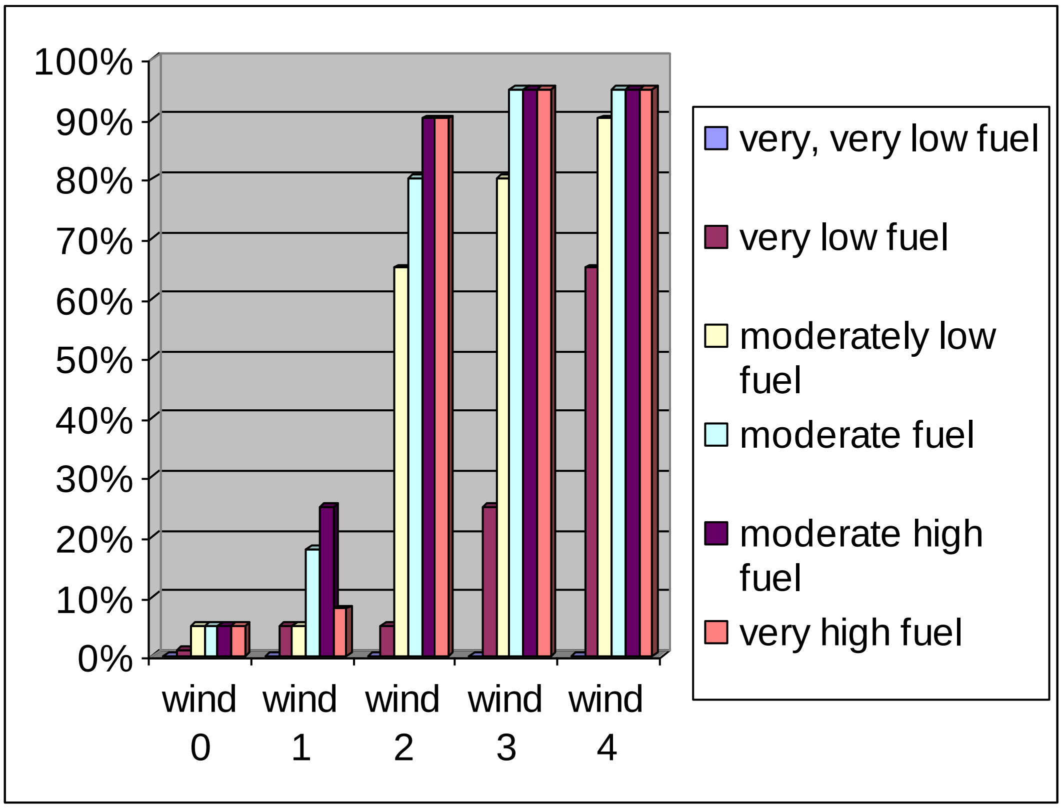
Where "n" is the number of fire on "patch K"

If $L_{kt} = 0$, all agents on "patch K" "die", in the time interval, $(t, t+1]$

Results

Crossing a Road

We ran our model several times under different scenarios. First we set up a single road, dryness was left constant for most trials as was wind direction. Dryness was left at 100% so the fire would not be retarded, and the wind direction was set at NNE to better test effectiveness of the firebreaks and to get a better visual effect. The road ran from east to west. Then we ran our code with the varying fuel load levels from very very low to very high and with varying wind speeds from 0 to 4 levels. The results from this experiment are placed in the graph below. The model was run 5 to 15 times per set of conditions. Conditions in which outcomes were obvious such as very very low fuel and low wind were run 5 times, average conditions were run 10, and wind speed 1 with very high fuel was run 15 times. Logic does not support this particular piece of information, but these were the results of our model.

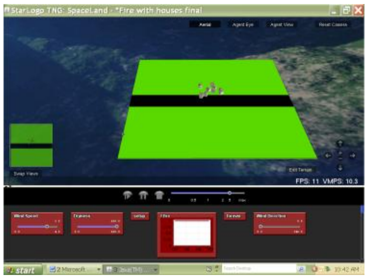
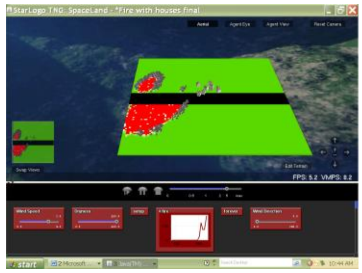
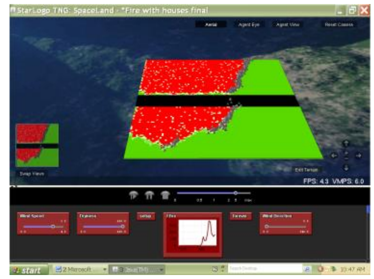


The percent chance that a fire has of crossing a road.

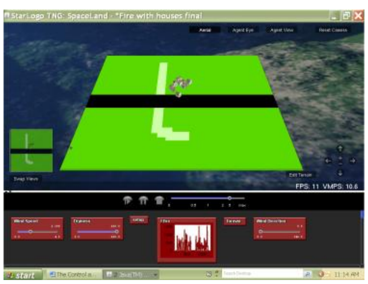
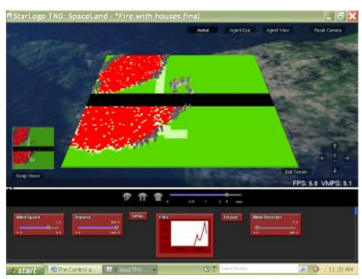
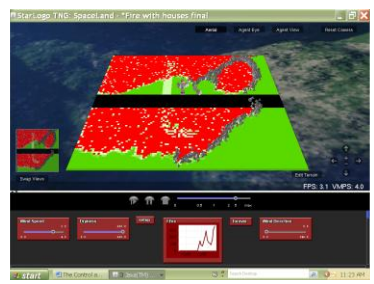
Firebreaks

Next we ran models concerning the use of hastily constructed firebreaks for the protection of a small village. This particular scenario includes a road across the middle of the screen, a village on the north side of the road, and a fire starting on the southwest side of the road. The wind is at a level 3, it is 100% dry, there is a moderate fuel level on both sides of the road, and the wind is blowing NNE.

First we ran the scenario without a firebreak; the fire quickly jumped the road and engulfed the village. However, the road did slow the fire down substantially.

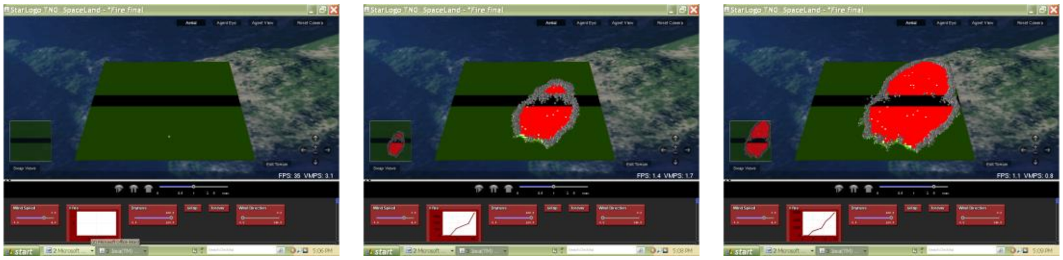
Next we ran a model with everything staying the same, except a small firebreak is placed around the village. The fire break is not an earthen barrier; it is only a small area with a very low fuel level placed around the village. We are trying to simulate a concerned citizen who used a shredder hooked up behind a tractor to mow some of the grass down. The firebreak slowed the fire down enough that the village was almost the last thing that burned in the screen.

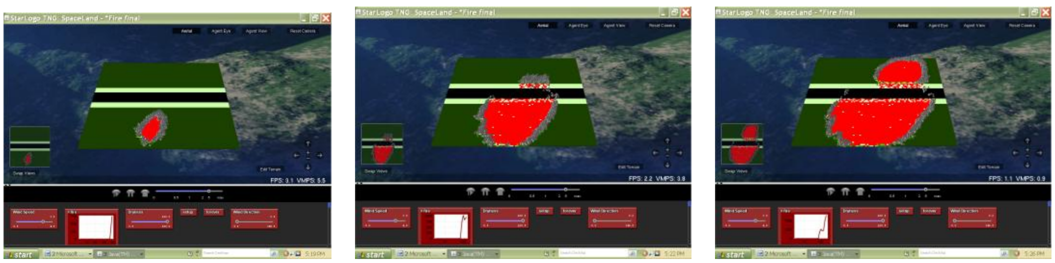
Roadside Maintenance

One part of a fire crossing a road that we had almost overlooked (but not quite) was the ditches beside the road. We tested that the surrounding grass could be very heavy, the roadside could be mowed off very short and we wondered how this varying condition from the rest of the grass would affect a fire crossing a road.

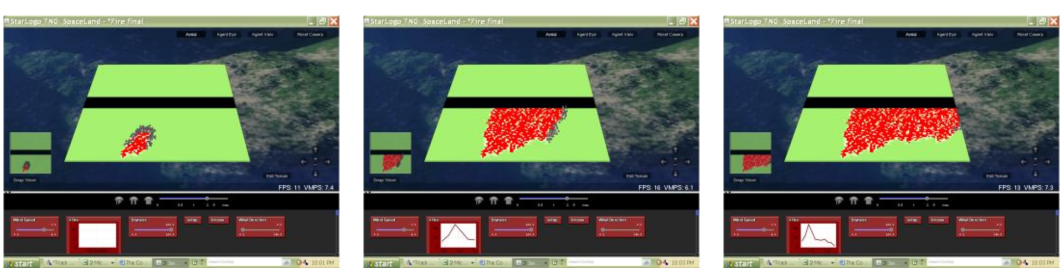
We started this model with very heavy grass all around the road with a very low fuel loads in the ditch. It was 100% dry, with a wind speed level of 3, with a wind direction of NNE. First we ran a control with no ditch. The fire slowed down a little, but the fire crossed the road quickly, and the fire was virtually unstopped.



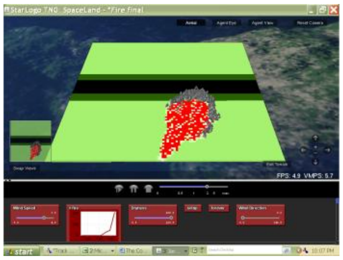
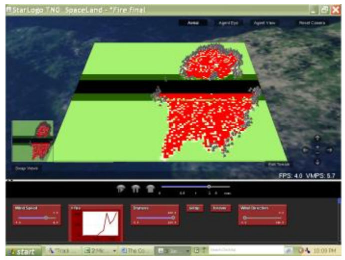
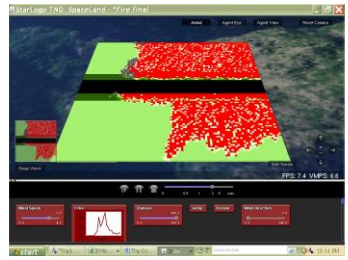
Then we placed a ditch in the scenario. The ditch was made by placing the low fuel grass half the width of the road on each side of the road. This did not stop the fire, but it slowed the progression of the fire significantly**.** The ditch's low fuel level greatly reduced the amount of fire and the fire's ability to cross the road.



Next we tested the opposite scenario, which includes a moderately low fuel loads in the pasture but a very high fuel load in the ditch. This is a common situation in Eastern New Mexico during moderate rainfall years. The rangelands are in average condition, but runoff from the road into the ditches gives the roadside extra moisture. The ditches then get overgrown with weeds and tall grass due to the runoff from the road watering the ditches more than other places. To model this we set up a moderately low fuel levels on each side of the road all the way up to the road with a NNE wind, 100% dry, with a wind speed of 3. We started the fire on the south side of the road and let it burn. The fire, as shown by the above graph had about an 80% chance of crossing the road, in our control model though the fire did not cross the road that time, and a road that was already in place served as an adequate firebreak.



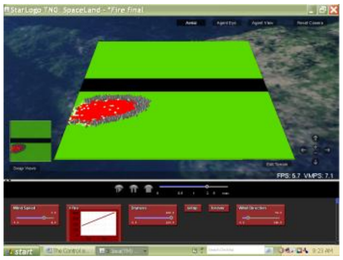
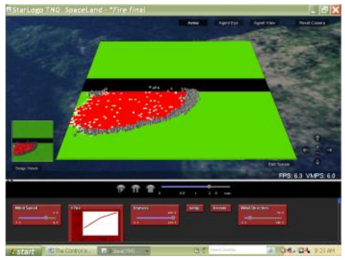
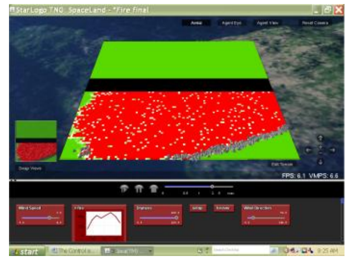
After that we filled the ditch with weeds and grass so that we had a high fuel level half the width of the road on both sides of the road. All the other variables remained the same. In running this model we found that the brief area of high fuel was enough to enable the fire to cross the road. It also acted as an area to spread the fire to other places that would not have ordinarily been burned.

Wind Angle to the Road

While we were running our model we noticed an interesting effect that we did not expect to see. The fire has a greater chance of crossing a road or firebreak if it intercepts the road at a right angle. To model this we set up a road with out a ditch with moderate fuel levels on each side of the road, 100% dry, with a wind speed of 3, and as a control a wind direction of NNE, which is very close to intercepting the road at a 90^{o}. According to our previous graph the fire should be able to cross the road just about every time, and this was true in our control. Then we shifted the wind just about 12 degrees to the east, this time the fire only had about an 80% chance of crossing the road. Then we moved the wind to about 45 degrees to the road. Surprisingly the fire had only about a 15% chance of crossing the road. Then we moved the wind to about 80 degrees to the east and the fire had virtually no chance of crossing the road.

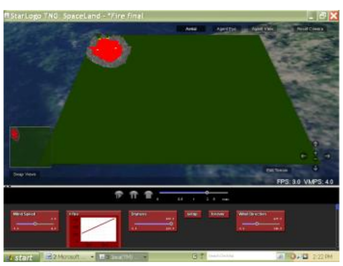
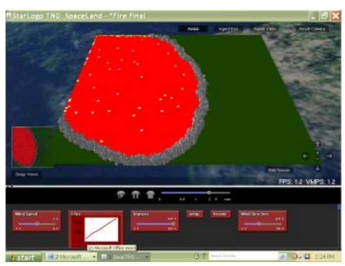
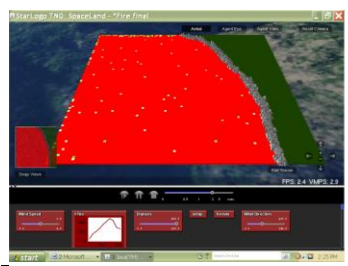
Angle to the Road	Percent Chance of Crossing Road
90 degrees	100%
78 degrees	80%
45 degrees	15%
10 degrees	0%

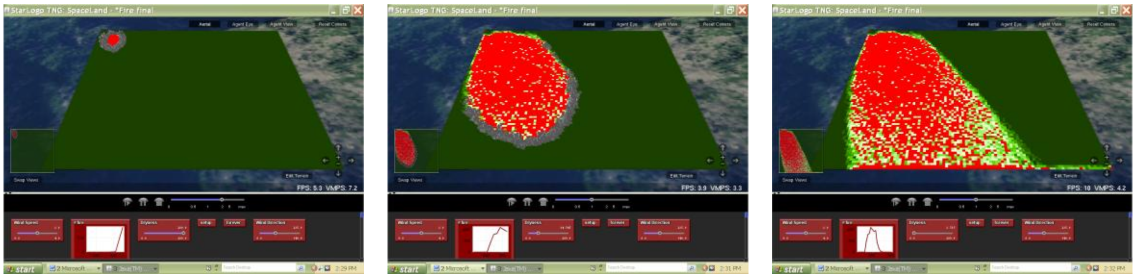
This is what we believe was happening, when the fire was traveling at a right angle to the road, the distance across the road perpendicular to the road is the shortest distance. Then as you move away from your right angle the distance across the road in that direction will get farther and farther until you are no longer moving across the road, but with the road. There fore the fire has a less and less chance of crossing the road.

Rain

Often a lightning strike from a thunderstorm will start a fire, but it will start raining and dampen the fire or put it out. We have the capability to model this as well. To do so we took the road out and started a fire in the north west corner with a level 2 wind, the wind direction is south east, and with a very high fuel level. We started the fire with the dryness level at 100% for the control. The fire rapidly grew, soon engulfing the entire area leaving very few patches completely unburned.

Next to test the effect of rainfall we set up the same scenario, with a beginning dryness level of 100%, and then as the fire progressed we steadily increased the moisture level of the fuel. This time the fire did not spread out over the entire area, but moved strictly with the wind. As the moisture level grew the fire also had a less and less complete burn, leaving more fuel before spreading out. The rain very effectively controlled the fire. This was shown as a test to the programs capabilities, and would probably not enter a real scenario because rainfall can not be controlled by the firefighters or any one else for that matter.



Conclusion

We learned a lot about the properties of fire from our model and from our research. We learned that a common road is an effective firebreak. A road helps stop a fire and it is a good place for firefighters to travel. But we also learned how easily a fire can spread in dense grass and that with a heavy wind behind it, a fire in this condition is nearly impossible to stop until the wind dies down or there is a lighter fuel load. We also learned how important roadside maintenance can be in reducing fire hazards, as a mowed ditch can prevent a fire from crossing a road, but an overgrown ditch can allow a fire to cross a road.

With our model we should be able to model nearly any small grassfire in Eastern New Mexico. We hope that we can use this model to aid the local fire departments in preparing for and fighting a fire under their circumstances.

Later

Later we would like to implement terrain into our model. Terrain, such as hills and draws would greatly affect our fire, because heat rises, fire would prefer to move uphill rather than downhill. This would enable us to model a more mountainous area. In our model we were representing a fire on the Llano Estacado, some of the flattest land in the world, so this did not affect our model.

Our model was a good representation of a fire in a small area. Our program and computer resources, however, are too limited to handle a large scale event; there fore the use of a supercomputer would be necessary to model a large fire accurately. A supercomputer with its advanced capabilities would allow the fire service to forecast the progress of a fire. The possibility of using widespread topographical mapping, real time weather conditions and forecasting, and surface condition maps would allow better use and safer use of limited firefighter resources. Taken to the next level this could become a statewide resource, streamlining rural and urban interface firefighting, making it more effective and safer saving lives and preventing excess property damage.

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David Rush, Forrest Volunteer Fire Department, Training Coordinator

Addison-Wesley, Chemistry of Firefighting, copyright 1990

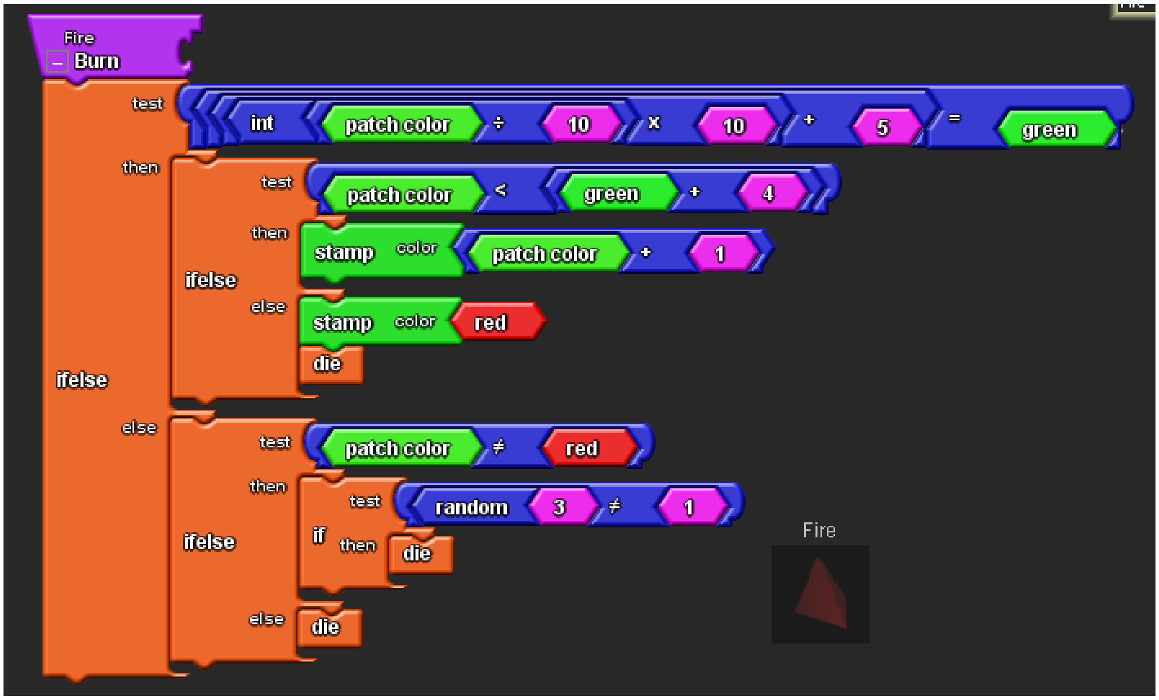
Acknowledgements

We would like to thank Nick Bennett for coming all the way to Melrose from Albuquerque to help us with our programming and developing our mathematical model.

We would also like to thank David Rush of the Forrest Fire Department for helping us determine how to most accurately set up our model.

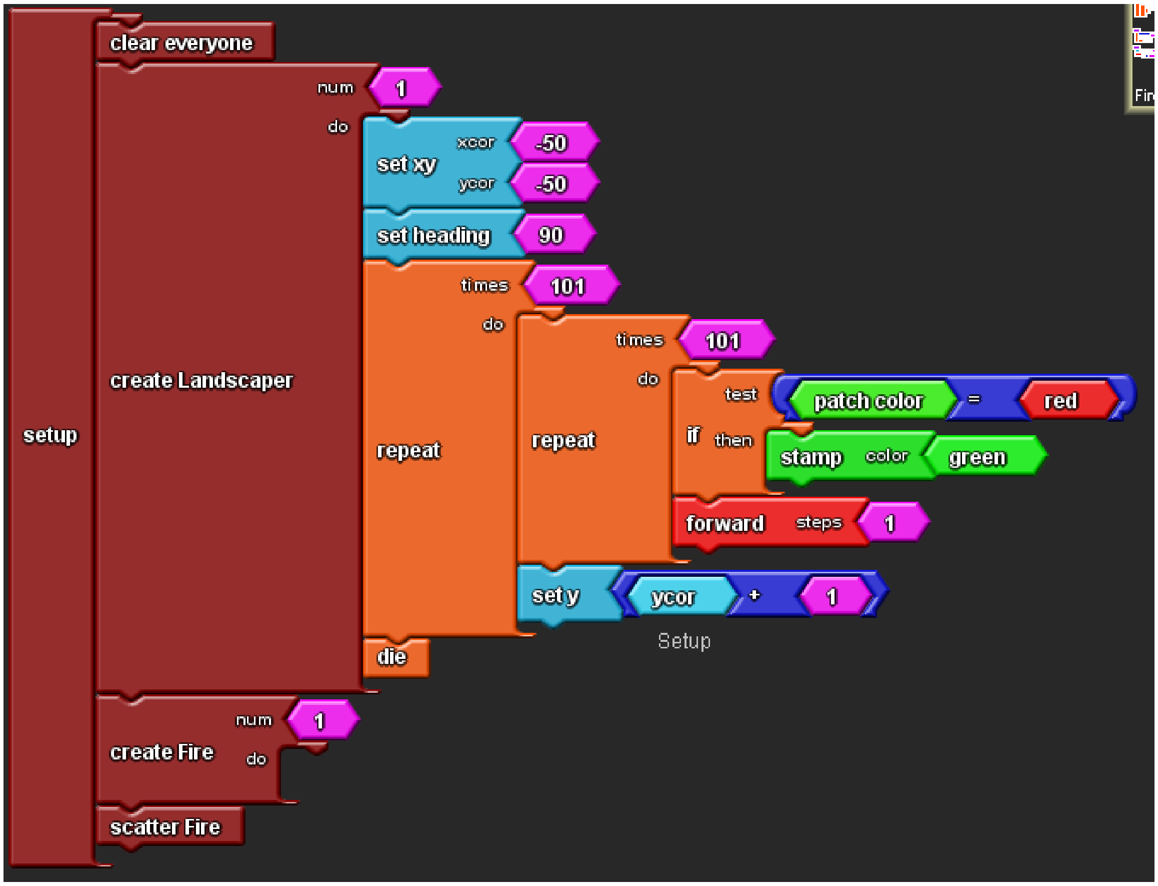
Appendix

The following are screenshots of our StarLogo TNG code.



Burn Procedure

Spread and Wind procedures.



Setup Procedure

Burn forever procedure with Dryness, Wind Speed, and Wind Direction sliders, and a graph counting the number of fire agents.