Tune the Fire

New Mexico
Supercomputing Challenge
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THS 203
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Executive Summary

The purpose of this project was to determine the effect of soundwaves on a burning building. The soundwaves would cause a temporary vacuum and cause a rapid decrease in temperature which could aid firefighters escape a collapsing building. This project was influenced by a local fire which trapped two firefighters causing injuries that will affect the rest of their lives. This event allowed us to do a science fair project, which gave us the idea to code a model that depicts our findings. In a lab, we used tuning forks of certain frequencies that were directed at a burning stick and we observed which tone affected the flame the most. From those experiments, we developed a NetLogo model of a burning wall and the effect of these frequencies on the fire. In the lab, we also used different types of wood but we concluded that there were no major differences effects based on the type of wood. The hardest part of this project was coding the program, as we had to apply many changes to the program. In summary, a frequency of 100 kHz (kilohertz) affected the fire the most.

Project Introduction

In 2004, firefighters responded to a four-alarm two story warehouse fire in Taos, New Mexico. Upon entering the second story of the warehouse, two firefighters were quickly overcome by flames. One firefighter attempted to escape the flames by exiting through the stairwell but the stairwell then collapsed. The other firefighter then tried to escape the flames by climbing towards the roof. This firefighter was then faced with a decision to either jump off the building or burn to death. Both firemen did survive but will have health issues for the rest of their life. New technologies can be integrated into firefighting to avoid events like this from happening. Signal generators emit signals at a select frequency. These signals can assist in extinguishing flames in wooden materials. The focus of this project is twofold: first, to determine what ultrasonic frequencies will assist the extinguishing process the most. Second, to model an ultrasonic frequency array that is capable of attaching to a transportation device. This device could be implemented into firefighting techniques to assist the firefighter escape entrapment.

To further investigate this issue on a larger scale requires a computer model that visually expresses the impact of ultrasonic frequency signals on wood-based materials. The model will use the best performing array as a base for the computer model. The model will have a 2 electrode, or a parabolic array that emits a signal with a 100 kHz frequency. Amplitude of the wave will vary. The wood source in the model will have a series of graphs which display the pressure of the fire, the mass of the fuel source, and the temperature of the fire. The sound waves' impact will be expressed by the variations in the graphs of the fuel source. A visual decrease in flame height and a change in flame color will also represent the effectiveness of the fire suppression array. Overall, the computer model will express the effects of the suppression array on a larger scale than what was tested in the experiment.

Fire

The actual definition of fire is "the rapid oxidation of a material in the exothermic chemical process of combustion, releasing heat, light, and various reaction products" (Glossary of Wildland Fire Terminology, 2012). The flame is the visible portion of the fire. Depending on the substances burning and any impurities, the color of the flame and the fire's intensity will be different. Fire in its most common form can result in conflagration, which has the potential to cause physical damage through burning. Fire qualifies as an amorphous solid, holding the properties of a solid, liquids and in particular, a gas. Fire is an important process that affects ecological systems across the globe. The positive effects of fire include stimulating growth and maintaining various ecological systems. Fire has been used by humans for cooking, generating heat, signaling, and propulsion purposes. The negative effects of fire include water contamination, soil erosion, atmospheric pollution and hazard to human and animal life (Glossary of Wildland Fire Terminology, 2012).

Fires start when a flammable and/or a combustible material, in combination with an oxidizer such as oxygen is exposed to a source of heat or ambient temperature above the flash point for the fuel/oxidizer mix, and is able to sustain a rate of rapid oxidation that produces a chain reaction. This is called the fire tetrahedron. Fire cannot exist without all of these elements in place, and it can be extinguished by removing any element of the fire tetrahedron (Glossary of Wildland Fire Terminology, 2012).

A traditional Bunsen burner flame burns between 1,300 to 1,600 °c. Fire behavior is a description of how a fire will progress through a structure, or how flames are impacted by outside sources. Fire will follow its tetrahedron sources, and can go away from areas where it is lacking in the combustion sources (Fire.gov, 2012).

Every year there are approximately three thousand people killed in structure fires, and almost 17,000 injuries from structure fires in the United States (USFA, 2012). An average of 118 firefighters is killed every year in structure fires. Fire has killed more Americans than all natural disasters combined (NIST, 2009). There are an estimated 1.5 million fires per year, and these fires have cost $15.5 billion in property loss. These fires result from accidents, arson, forest fires, and other "acts of God" (USFA, 2012).

Fire is the rapid oxidation of a material in the exothermic chemical process of combustion, releasing heat, light, and various reaction products. Originally, it was thought that a fire needs three things to exist: oxygen, heat temperature and fuel, commonly known as "the Fire Triangle". This has since been upgraded to "the fire tetrahedron" where a rate of rapid oxidation produces a chain reaction has been added to the previous triad of fire sustainability. Take any one of the ends of the tetrahedron away, and the fire can be extinguished, or will not even start. Small fires are relatively easy to extinguish because they have a smaller area to cover, and can be completely covered. On larger fires that take up more space, it is difficult to take away any of the three legs of the triangle, because of the sheer amount of space. The two most difficult fires to extinguish are structure fires and forest fires (USFA, 2012).

The flame is the visible portion of the fire. If hot enough, the gases within the flame may become ionized to produce plasma. Depending on the substances involved in the fire, and any impurities, the color of the flame and the fire's intensity will be different. Fire in its most common form can result in conflagration, which has the potential to cause physical damage through burning. Fire is an important process that affects ecological systems. The positive effects of fire include stimulating growth and maintaining affected ecological systems. Fire has been used by humans for cooking, generating heat, signaling, and propulsion purposes throughout history. The negative effects of fire include air and water contamination, soil erosion, and hazard to human and animal life (NIST, 2009).

A structure fire is a fire that involves the structural components of residential or commercial buildings, such as homes, townhouses, apartments, high-rises, and shopping malls. This is full on involvement of the entire structure, rather than room specific fires, such as chimney fires or auto fires. Structure fires are amongst the deadliest, because of the building materials involved in the conflagration. Many of the building materials that burn within the home emit highly toxic gases, including foam, which can produce cyanide gas. This, in addition to the close proximity of the fire to the victims, as well as the massive amounts of smoke produced by the many different items that can burn within the home can result in massive fatality and injury; far more than most other fires (USFA, 2012).

Many building safety codes have added methods of preventing or putting out fires immediately. Some buildings have sprinkler systems; others are built with materials that have a higher kindling point (the point at which a substance ignites). There really are no such things as completely resistant materials, but many do not ignite as fast or burn as hot as others. The safety codes are not retroactive towards older buildings, therefore producing a hazard in older buildings that are 'grandfathered' in and exempt from newer safety codes (J. Fambro, 2016).

A forest fire is one that takes place in the forest and mostly involves trees. However, as more and more dwellings move further into forest land, forest fires are increasingly becoming more dangerous, and cause more property damage than in previous years. As the population continues to increase and spread out, what used to be considered 'nature's housekeeping' is now a major problem, and has to be put out before it puts life and property in danger. Numerous forest fires and wildfires (those that are completely out of control) involve structure fires once the fires reach areas of habitation (Hering, 2001).

A Bunsen burner can produce a focused flame in relatively high temperatures. It is a common piece of laboratory equipment that can run off of either Propane or Natural Gas. The flame can be adjusted to be either extremely hot (1500^{0}C) or standard (1 100^{0}C). It safely burns a continuous stream of gas, and allows oxygen to be integrated with the gas flow producing different temperatures of flame. The flame can be consistent and controllable. Natural gas is the safer Bunsen burner, because it is not as explosive in the presence of oxygen and heat as Propane is. The flames from a Bunsen burner can reach temperatures that exceed traditional structural fires, or can simulate the temperatures and flames that are experienced over a longer standing fire (MST, 2009).

Flame

A flame is a mixture of reacting gases and solids emitting visible, infrared, and sometimes ultraviolet light. The frequency spectrum of flames depends on the chemical composition of the burning material and reaction products. In the burning of organic matter, for example wood, or the incomplete combustion of gas, incandescent solid particles called soot produce the familiar red-orange glow of 'fire'. This light has a continuous spectrum. Complete combustion of gas has a dim blue color due to the emission of single-wavelength radiation. The dominant color in a flame changes with temperature. The distribution of a flame in normal gravity depends on convection. The lighter color of a flame is based on impurities, and should be traditionally blue (Glossary of Wildland Fire Terminology, 2012).

Sound

Sound travels in waves, which are variations of pressure in a medium (solid, liquid, plasma or gas). The energy from vibrating objects, such as speaker membranes, moves from particle to particle in the air in a repeating pattern of high- and low-pressure zones that human beings perceive as sound (Snyder, 2008). Sound perceptible by humans has frequencies from approx. 20 Hz to 20,000 1-IZ (Ensminger and Bond, 2012).

I-IZ (Hertz) = unit of frequency defined as one cycle per second. Expressed as Kilohertz (10^{3} Hz, symbol kHz), megahertz (10^{6} Hz, MHz), gigahertz (10^{9} Hz, GHz), and terahertz (10^{12} Hz, THz) (Snyder, 2008).

In air at standard temperature/pressure, the corresponding wavelengths of sound waves range from 17 m to 17 mm. Sound moves air, and air propagates sound. Sound waves resonate (vibrational travel) through air media (Ensminger and Bond, 2012). The perception of sound in any organism is limited to a certain range of frequencies. Other species have a different range of hearing. Dogs can perceive vibrations higher than 20 kHz, but are deaf to anything below 40 Hz. As a signal perceived by one of the major senses, sound is used by many species for detecting danger, navigation, predation, and communication (Soundry, 2012).

During propagation, waves can be reflected, refracted, or attenuated by the medium. The behavior of sound propagation is generally affected by three things: 1) relationship between density and pressure, which determines the speed of sound within the medium. 2) The motion of the medium itself, if the medium is moving, the sound is transported further. 3) Viscosity of the medium; determines the rate at which sound is attenuated. When sound is moving through a medium that does not have constant physical properties, it may be refracted (dispersed or focused). Sound is transmitted as longitudinal or compression waves, and in solids, can be transmitted through longitudinal and transverse waves. Longitudinal sound waves are waves of alternating pressure deviations from the equilibrium pressure, causing local regions of compression and rarefaction, while transverse waves (in solids) are waves of alternating shear stress at right angles to the direction of propagation. The sound oscillates through the waves, producing kinetic energy (Soundry, 2012)

Sound waves have distinct properties and characteristics including; sinus waves of various frequencies (the bottom waves have higher frequencies than those above.) Sinus waves are characterized by: Frequency, the period, wavelength, wavenumber, amplitude, sound pressure, sound intensity, speed of sound and direction. Sound pressure is the difference, in a given medium, between average local pressure and the pressure in the sound wave. Sound pressure is measured in decibels (Soundry, 2012).

Pitch is a perception that allows the ordering of sounds on a frequency-related scale. Pitches are compared as "higher" and "lower" as associated with musical melodies. Pitch is a major auditory attribute of musical tones, along with duration, loudness, and timbre. Pitch may be quantified as a frequency. Pitch is an auditory sensation in which a listener assigns musical tones to relative positions on a musical scale based primarily on the frequency of vibration. Frequency is the measurement of the oscillation of the sound waves (Hartmann, 1997).

Sound and Fire

In 2007, Mythbusters tackled a common urban legend about sound extinguishing fire. They confirmed that this was possible using a speaker near a candle. This, along with many of their experiments was questioned due to the fact that the speaker produced air currents that could have extinguished the flame due to its proximity in addition to the sound waves. In their case, they extinguished a candle flame with vocal sounds, and a propane flame with a tone generator, both produced via speaker sound (Mythbusters Results, 2007).

The concept of sound extinguishing fire has been around since the 1800s, and it is known that sound can extinguish fire, but the exact mechanism of how is not known. John Tyndall experimented with vocal practices in extinguishing flame in 1857. According to the ideal gas law, temperature, pressure and volume are related; therefore, a decrease in pressure can lead to a corresponding decrease in temperature. In 2004, students from the University of West Georgia tested if sound waves could extinguish fires in hopes of using sound to extinguish flames in a spacecraft. This group placed a candle in a large topless chamber with three bass speakers attached to the walls. A rock song was pumped through the speakers, and once a low note was hit, the flame was extinguished. It has been determined that there is most likely a special frequency that can extinguish a flame, generally between 40 and 50 hertz. Theoretically the pressure drop produced by the sound wave can extinguish flame (Snyder, 2008).

In 2011-2012, DARPA (Defense Advanced Research Projects Agency) presented their new system that can extinguish flames using only sound. DARPA has been working for a long time in their Instant Fire Suppression program. DARPA arranged two speakers on either side of liquid fuel flame and then amped up the acoustic field. This increases air velocity through the sound, which thins the area of the flame where combustion occurs (at the 'flame boundary'). When the flame boundary is thinned, the flame will extinguish. The acoustics also disturb the pool of fuel and accelerates fuel vaporization. It was determined that the sound did not have to be cranked up to achieve the flame extinguishing. DARPA has also worked in the field of 'flame bending' by disrupting the ironic field using cold plasma disruption techniques (Clark, 2012).

Ultrasonic

Ultrasonics is an investigational study into the effects of propagation and application of sound wave energy as it interacts with matter, in frequency levels above human perception levels (Ensminger and Bond, 2012). It is a branch of acoustics that deals with liquids, solids and gases at frequencies above 16 covers the range from below 15 1-IZ to above 1 THz (10^{3} GHz). Ultrasound is a form of mechanical energy and is traditionally compared to electromagnetic waves. Sonar operates at or around 20 kHz, while high resolution spectroscopy in solids occurs at 100 GHz. There are numerous areas of study within ultrasonics, including specialty application areas like underwater acoustics, medical imaging, destructive and nondestructive product testing, surface acoustic wave (SAW) devices for electronics, and microscopy. The forces acting across an area at a given point on the wave are compared to electrical voltage with the velocity potential equivalent to current. Ultrasonics also include the science of energy-matter interaction and technologies for generation and interaction (Ensminger and Bond, 2012). Some younger people and people with a higher level of hearing can hear up to 16 kHz, so some areas of the frequency can be heard by humans, and can definitely be heard by other animals. Ultrasonics have been used for testing and applications since the 1970s in the aerospace, nuclear, defense, and petroleum industries, particularly for non-destructive testing purposes. Actual ultrasonic testing has been truly conducted since WWI in 1918 (Ensminger and Bond, 2012). The history of ultrasonics is synonymous with the history of acoustics but is also very underdeveloped, and only recently have the science of ultrasonics been explored for more in-depth applications such as communications and materials testing at the biomedical level. Ultrasonics truly got its birth in materials sciences in the development of SONAR (Sound Navigation and Ranging), through the propagation of sound underwater. (Ensminger and Bond, 2012)

Ultrasonic waves are stress waves, and can only exist in traditional media. Sound and ultrasound do not transmit through a vacuum. The energy in ultrasonic waves is transmitted from one mass/element/material through direct contact between the masses (this includes gas to gas, gas to solid, gas to liquid, etc.). These waves propagate through and interact with solids, liquids and gases. The properties of the wave travel are interlinked with fundamental mechanical and thermal properties of the propagation medium. Ultrasonic waves are both acoustic and elastic waves. Acoustic waves are compression waves that commonly move through gases and many liquids. Elastic waves are waves in solids whose movement properties are dependent upon the medium they are moving in, in response to vibrations, complying to Young's Modulus (Ensminger and Bond, 2012).

Young's Modulus the measure of stiffness of an elastic material, by defining the limitations of stress and strain on the material (The Physics Classroom, 2016).

These waves occur in various forms that include compression, shear, surface and interface vibrations. Interactions with structure, scattering and underlying theory depend on the ratio between feature size and wavelength of the radiation. Each wave type in a given homologous medium travels at a velocity dependent on the properties of the medium. Similar to light, ultrasound is reflected from surfaces, refracted from one medium to another, which effects change in the velocity of sound, and diffracted at the edges of surfaces or around obstacles, and energy is scattered from particles or rough surfaces (Ensminger and Bond, 2012).

Rayleigh scattering is used for small features, where dimensions are a small fraction of wavelength. Long wavelength scattering and ray theory apply to larger features where dimensions are cast over several wavelengths. Mid-frequency scattering features are the order of a wavelength and numerical methods. The attenuation of energy of propagation is due to multiple mechanisms including absorption (energy is converted into heat because of elastic motion), scattering due to a non-homogeneous material, diffraction, reflection and refraction. There is also the concept of inverse scattering, the determination of scatter characteristics based on the measurements of the scattered waves (Ensminger and Bond, 2012).

Ultrasonics can be categorized in many different ways. Applications in terms of low intensity and high intensity is natural. Low-intensity applications are those where the primary purpose is transmitting energy through a medium to learn about some aspect of the medium, or to pass information through it without causing a change in the state of the medium in which there is no movement. These applications are traditionally the characterization of minerals, electronic devices using surface waves, sensing in industrial processes, medical diagnoses, and tissue grading. This category encompasses marine applications as well, but these applications require higher energy usage. High-intensity applications produce an effect on a medium or its contents that the wave moves through. Sometimes the interactions are non-linear and can involve thermal, mechanical, shear force and cavitation. Typical applications include medical therapy and surgery, sonochemistry, sonoluminescence, particle motion in fluids, atomization of liquids, machining of brittle materials, cleaning, disruption of biological cells, the production of nanomaterials, medical diagnoses, machining of brittle materials, marine applications such as sonar and communications, fish and submarine detection, cleaning, disruption of biological cells, and other domestic-type uses. Loomis and Wood determined that vegetable and animal tissues were disrupted by high-power ultrasonic energy, and through vibrational friction could cause the excitement of molecules as indicated by an elevation of temperature. (Ensminger and Bond, 2012).

Cavitation is the generation and then rapid collapse of a bubble in fluid can cause erosion in solid objects. It is the formation of bubbles in a liquid medium, but can also form bubbles in gas state. During the rarefaction portion of the cycle, when the pressure in the wave is below ambient, gas pockets form and expand. There are two types of cavitation; gaseous cavitation where gases trapped within the media are released, and is caused at low magnitude, and vaporous cavitation, where vapors of the liquid are set off, and is generally found at high intensity. The acoustic bubble is a phenomenon where energy can be concentrated in as much as 13 orders of magnitude which physically manipulates solids, liquids and gases. High localized stresses are developing during the formation and collapse of cavitation bubbles. Free chemical ions are produced within the vicinity of the bubble walls. Liquids can include lipids and cellulose particles. The collapsing bubble generates short duration high pressures and temperatures. Cavitational collapse can generate light in sonoluminescence, and also produces localized high pressures and temperatures which have the potential for fusion. Cavitation can produce increased chemical activity, erosion of surfaces, rupture or fragmentation of suspended particles, emulsification of mixtures and dispersion of small particles in the liquid. Onset of cavitation occurs at intensities/cavitation thresholds that rely on factors such as nuclei sizes, ambient pressure, amount of dissolved gases, vapor pressure, viscosity, surface tension and the frequency and duration of the ultrasonic energy. Cavitation dissipates the energy and impedes transmission of the wave beyond the object. To be effective, the bubble must be capable of expanding with the rarefaction part of the cycle, and collapsing before total pressure reaches its minimum value. The bubble must collapse catastrophically in less than one quarter cycle of the impressed wave, and relies on the surface tension of the bubble. (Ensminger and Bond, 2012).

An ultrasonic transducer can send and receive ultrasonic signals, as can a frequency generator, which can only send ultrasonic signals. Transmitters and receivers couple energy into material or receive energy that has been propagating in a medium. Ultrasonic transduction can be achieved at frequencies ranging 16kHz to above 100 GHz. General ultrasonic applications use an operating frequency near 20 kHz. Ultrasonics work at temperatures below cryogenic freezing levels to above 1500°C. Traditional ultrasound for imaging works by transmission and reflection of the sonic wave energy, scattering from smaller structures and selective absorption employing the Doppler effect. (Ensminger and Bond, 2012).

Doppler Effect - the change in frequency or wavelength of a wave (or other periodic event) for an observer moving relative to its source, will produce larger waves with less power unless otherwise amplified. (The Physics Classroom, 2016). Is the change in frequency due to the effect of the motion? The period of the wave may be compressed or expanded, depending on the nature of the motion (Ensminger and Bond, 2012).

An ultrasonic transducer is also known as a horn, which is a transmission line of various configuration. The amplitude of vibration at the radiating surface depends on the geometry of the transmission like, energy losses and the amplitude of vibration at the driven end. An array is a group of horns/transducers, or transmission lines that are put together to try to enhance or destroy the transmission waves of ultrasonics. These are traditionally organized in a parabolic or circular arrangement for maximum cupping of the energy. The horns are traditionally attached to other configurations of other items to enhance and focus the ultrasonic emission. The more horns that are configured, the less quality of the final amplitude particularly at higher frequencies, and the higher amplitudes will produce frequency shift. Lower frequencies in configuration can produce a broad tuning curve. Larger configurations need a node, and an antinode, (cathode and anode) for properly tuning and frequency preservation. (Ensminger and Bond, 2012)..

The ultrasonic waves work in two methods: pitch-catch, where the energy is emitted then detected; or pulse-echo where the energy is emitted, then bounced back with slightly less amplitude to be processed by the receiver/sensor (ear) There is also the passive SONAR system that has two antennae that pulse-echo-amplify, where the energy is sent forth, received, processed then bounced back with less signal loss than with the pulse-echo method. Piezoelectric materials assist in making ultrasonic transducers capable of operation at elevated temperatures and in harsh environments. Increased matching layers with intermediate acoustic impedance properties can be used particularly to increase the efficiency of energy transmission and reception with particularly fluids and gases. The majority of high powered applications run at 20120 kHz. All ultrasonic transducers have band-pass characteristics which limit the frequency spectrum generated and filter received energy. An elastic medium may be considered as consisting of a series of homogenous incremental elements or masses based on density, thickness and cross-sectional area. When a net longitudinal force is applied to the element, the element accelerates, reaching a new velocity. When the element moves from its initial position, it applies a force to succeeding elements, which then undergo acceleration. For equilibrium to exist, the elastic forces on the element must equal the inertial forces imposed on the element, which is known through plane-wave. (Ensminger and Bond, 2012).

The ratio of force to velocity is considered acoustical impedance, which is used to calculate reflections and transmissions to match components for effective energy transfer from one element to another. When the stationary impedance in a transmission line produced a reflection that is in phase with an incident, the two waves reinforce each other to produce a standing wave, or resonance. At a given frequency, the particle motion at any point in an ultrasonic wave is sinusoidal if the stresses developed in the waves remain in the linear, elastic range of the medium (Ensminger and Bond, 2012). If two of these waves of different frequencies are superimposed, their amplitudes are alternately added/subtracted so that the overall effect is a wave with an amplitude equal to the difference in the frequencies of the same two waves, known as a beat frequency. These are produced between the initial outgoing wave and the received wave in which the frequency has been shifted by the Doppler effect. (Ensminger and Bond, 2012). As a wave propagates through a medium, its amplitude decreases (attenuates) caused by the spreading of the wave front, conversion of the acoustical energy to heat (absorption) and scattering from irregular surfaces. At higher intensities of ultrasound, the waves become increasingly nonlinear, and the absorbed energy can produce considerable heat, and cavitation which is associated with the stresses generated in the ultrasonic waves and their rate of change. Free chemical radicals are produced with cavitation which results in chemical reaction. Real world situations such as oxygen and other impedance items exist, which can drive the amplitude of vibration down exponentially as an energy loss. Energy losses decrease with decreasing amplitude of vibration. (Ensminger and Bond, 2012).

An ultrasonic wave can consist of an infinite number of oscillating elements connected by elastic springs so that each element is influenced by the motion of its nearest neighbor. Oscillation is induced in each mass by introduction of energy at a given rate. These elements do not move in unison, because mass has inertia and accelerates at a rate corresponding to the applied force and because it is elastic and deforms under stress. The disturbance will propagate through the medium at the velocity of sound. The type of oscillatory motion that the disturbance produces is a factor in the speed at which the disturbance travels through the medium. Rate of propagation depends on the type of wave, elastic properties of the medium, density of the medium, mode of vibration, frequency and amplitude. Gases transmit only compressional (longitudinal) waves, liquids transmit longitudinal and surface waves, while solids can transmit nearly all wave modes. Some common ultrasonic particle trajectories are as follows: longitudinal and extensional will move back and forth parallel to the direction of propagation. Transverse shear will move orthogonal to direction of propagation. Rayleigh waves move in a parallel ellipse perpendicular to the surface. Torsion waves move in a circular path perpendicular to the axis. Love waves move parallel to the surface perpendicular in layered media, covering velocity more than the substrate. Shear waves pass energy from element to element through stresses. Surface waves follow the contour of the surface of a medium, and only penetrate shallowly, depth is approximately 1 wavelength per mm. Ultrasonic waves are also polarized, and the reaction of these waves is dependent upon the type of wave in accordance to the target. When an ultrasonic wave encounters an interface between two media, the energy of the wave is partitioned in a manner that depends on the type of wave, how the wave approaches the interface, and on the acoustic properties of the media. Snell's law is used to determine the angle of reflection and refraction. (Ensminger and Bond, 2012). Snell's Law is the relationship between the angles of incidence and refraction and the indices of refraction of the two media. (The Physics Classroom, 2016).

Four separate boundary conditions exist for general cases, in which both sides of the interface must have equal quantities of; normal. tangential displacements, and normal, tangential stresses. In simple reflection and transmission at normal incidence, the total displacement is the same in either medium at the boundary. Stresses on one side of the interface are equal to those on the other side. Intensity is related to the amplitude of the particle vibrations, the acoustic pressure is used to denote the amplitude of the alternating stress, and intensity is proportional to the square of the acoustic pressure. Direction of the propagation is important, but the waves can circulate and impact with each other to produce slightly stronger refractions, temporarily. The direction of the stresses can also indicate the direction in which the wave will impact the media. (Ensminger and Bond, 2012).

Diffraction is the modification of wave fronts when they pass by edges of opaque bodies, through narrow slits or being reflected or transmitted from surfaces. This causes the curvature of waves around objects in their paths. Diffraction reduces utilization in full of a wave front and focusing of the wave. Diffraction is described using Huygens' principle, which indicates that every vibrating point on a wave front is regarded as the center of a new disturbance (Ensminger and Bond, 2012). New disturbances act as point sources, each emitting a spherical wave, which is presumed to affect areas only along its wave front, in a forward moving wave pattern. The wavelength in this cases should be smaller than the dimensions of the surfaces or obstacles encountered. When waves are out of phase, it produces destructive interference, when they are in phase, they reinforce each other. Directivity or beam pattern refers to the relative response of a receiver or pressure/intensity of the radiated wave plotted as a function of position with respect to the transmitter in polar or rectangular coordinates. These are functions of the wavelength in a medium into which the wave is radiated and of the radiation surface. Ultrasonic energy can also be focused. Longer wavelengths produce sound in a region rather than a point, and the smallest practical focal region is a sphere one wavelength in diameter. The sharpness of the focus is proportional to the ratio of the aperture of the device to the wavelength. Standing waves are periodic waves having a fixed distribution in space, which is the result of interference of progressive waves of the same frequency and kind (Ensminger and Bond, 2012).

Waves can be superpositioned with each other, when two simple-harmonic sound waves of nearly the same intensity but of slightly different frequencies are combined. The superposition of the amplitudes of vibration indicate max and min at periodic intervals, producing a third wave. This third wave will be at a simple harmonic at a frequency equal to the difference between the frequencies of the initial waves (Ensminger and Bond, 2012). This will produce a non-constant vibration rate. Attenuation is the diminishing of intensity of wave front as it progresses through the medium. The factors that contribute to this are spreading of the beam, scattering, absorption and mode conversion which partitions the energy. Ultrasonic waves commonly encounter scattering, because anything that can reflect or refract can produce scattering, such as metals, porosity in any media, bubbles and other reflective surfaces. Attenuation can vary over many orders of magnitude. Relaxation is when the material responds with lag in the ultrasonic signal production. This phenomenon can cause a lag between an applied strain and the resulting stress in the material. This causes absorption, primarily noted at the higher ultrasonic (MHz) range. AS frequency increases, absorption also increases, going up to a certain peak and then decreasing, and the energy transfer is interrupted, or ceased, such as vibrational motion of molecules that can be stopped with higher frequencies causing velocity dispersion. This is also called a relaxation frequency, where the ultrasonic waves will not impact as much as others, and also produces a threshold (Ensminger and Bond, 2012).

Smaller power waves remain consistent in their power and focus, with minimal scattering. Higher power phenomena are less reliable, and are susceptible to a higher amount of scattering, phenomena, and less control. There are further side-effects with higher level amplitudes, such as shock waves and harmonic generation. Higher power phenomena are also more susceptible to relaxation and diffraction (Ensminger and Bond, 2012).

Ultrasound's heat transfers and vibrational echo properties made it ideal for medical diagnosis and for the treatment of tumors and some medical diseases. Commonly known uses are such things as the ultrasound used to image babies in the womb, and search beneath the epidermal and upper epithelial layer for abnormalities. MRI and other diagnostic machines also employ ultrasound technology. Ultrasonic measurements can be made through temperature extremes ranging from the cryogenic to above 1500°C. High power ultrasonics can be used for cleaning, emulsification, atomization and welding (Ensminger and Bond, 2012). The interaction of ultrasonics with living tissue is very different from engineering materials. While living, tissue has more resiliency to exposure to ultrasonics, exposure limits are a function of irradiation time and intensity. High doses of ultrasonics can damage tissue, lyse cells and modify DNA and the cell cycle. As power is increased, ultrasound-tissue interactions become complex, involving thermal, cavitational, mechanical, and sonochemical interactions (Ensminger and Bond, 2012). There is the potential for medical applications, including transdermal drug delivery, hyperthermal cancer treatment, controlled and targeted drug release and disruption of protein carrier systems. Ultrasonics also interact with cellulose, and while it does not destroy cellulite because the molecular structure is too loose, it can disrupt fibers within cellulose structures at lower frequencies and has been used to separate cellulose fibers and to impregnate cellulose fibers with anionic dyes (Morehead, 1950, Mohod & Gogate, 2011).

Frequency Harmonics

The lowest resonant frequency of a vibrating object is called its fundamental frequency or natural resonance frequency. Most vibrating objects have more than one resonant frequency and those used in musical instruments typically vibrate at harmonics of the fundamental. A harmonic is defined as an integer (whole number) multiple of the fundamental frequency. Vibrating strings, open cylindrical air columns, and conical air columns will vibrate at all harmonics of the fundamental. Cylinders with one end closed will vibrate with only odd harmonics of the fundamental. Vibrating membranes typically produce vibrations at harmonics, but also have some resonant frequencies which are not harmonics. It is for this class of vibrators that the term overtone becomes useful - they are said to have some non-harmonic overtones (Ensminger and Bond, 2012).

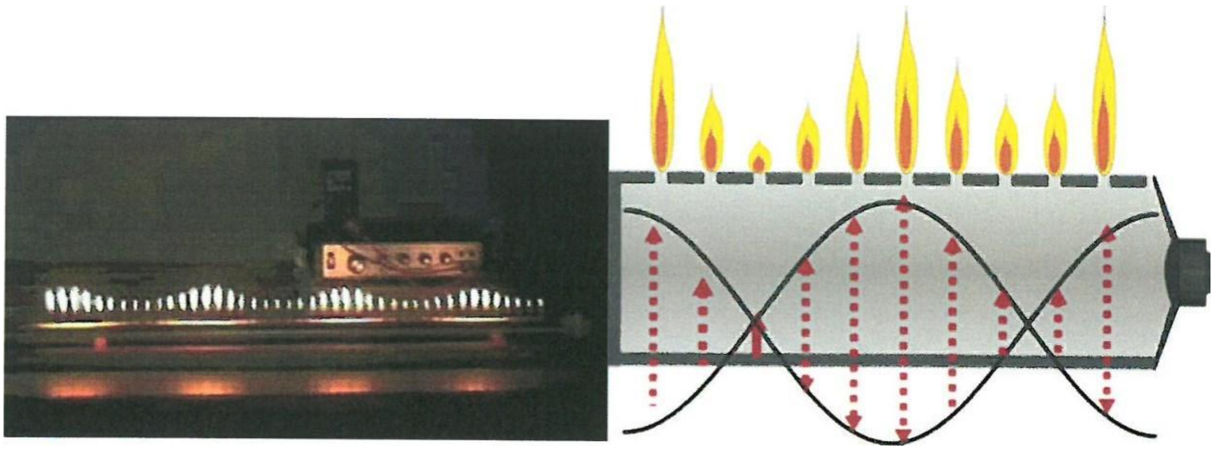
The term harmonic in its strictest sense describes any member of the harmonic series. The term is employed in various disciplines, including music and acoustics, electronic power transmission, radio technology, etc. It is typically applied to repeating signals, such as sinusoidal waves. A harmonic of such a wave is a wave with a frequency that is a positive integer multiple of the frequency of the original wave, known as the fundamental frequency. The original wave is also called 1st harmonic, the following harmonics are known as higher harmonics. As all harmonics are periodic at the fundamental frequency, the sum of harmonics is also periodic at that frequency. For example, if the fundamental frequency is 50 Hz, a common AC power supply frequency, the frequencies of the first three higher harmonics are 100 1-IZ (2nd harmonic), 150 Hz (3rd harmonic), 200 Hz (4th harmonic) and any addition of waves with these frequencies is periodic at 50 1-IZ (Ensminger and Bond, 2012).

In sound applications, a resonant frequency is a natural frequency of vibration determined by the physical parameters of the vibrating object. This same basic idea of physically determined natural frequencies applies throughout physics in mechanics, electricity and magnetism, and even throughout the realm of modern physics. Some of the implications of resonant frequencies are: 1. It is easy to get an object to vibrate at its resonant frequencies, hard to vibrate at other frequencies. 2. A vibrating object will pick out resonant frequencies from complex excitation and vibrate at those frequencies, essentially "filtering out" other frequencies present in the excitation. 3. Most vibrating objects have multiple resonant frequencies (Kim, Macosko, 2008).

Resonance is a phenomenon that occurs when a vibrating system or external force drives another system to oscillate with greater amplitude at a specific preferential frequency. Increase of amplitude as damping decreases and frequency approaches resonant frequency of a driven damped simple harmonic oscillator. Frequencies at which the response amplitude is a relative maximum are known as the system's resonant frequencies, or resonance frequencies. At resonant frequencies, small periodic driving forces have the ability to produce large amplitude oscillations. This is because the system stores vibrational energy. Resonance occurs when a system is able to store and easily transfer energy between two or more different storage modes (such as kinetic energy and potential energy). However, there are some losses from cycle to cycle, called damping. When damping is small, the resonant frequency is approximately equal to the natural frequency of the system, which is a frequency of unforced vibrations. Some systems have multiple, distinct, resonant frequencies. Resonance phenomena occur with all types of vibrations or waves: there is mechanical resonance, acoustic resonance, electromagnetic resonance, nuclear magnetic resonance (NMR), electron spin resonance (ESR) and resonance of quantum wave functions. Resonant systems can be used to generate vibrations of a specific frequency, or pick out specific frequencies from a complex vibration containing many frequencies (Kim, Macosko, 2008).

The Ruben's Tube

The Ruben's tube is a pipe that has evenly spaced holes along the top, sealed at both ends. One side of the seal is attached to a speaker or some other sound frequency generator, and the other side of the seal is attached to a propane tank. The tube is filled with gas, and the gas that is released through the holes in the tube is ignited. The sound waves are then demonstrated as the sound vibrations are produced through the tube, by the flames. This tube was invented by German physicist Heinrich Rubens in 1905. (Muse, 2012)


(Pictures: Muse, 2012)

Using a constant frequency will produce a standing wave inside the tube, producing points with changing pressure with peaks and troughs. Flames at the lower points of the pressure wave will be less because there will be less gas moving through the holes, and where the pressure is more constant, the flames will be higher (Muse, 2012).

Copper

Chemical element with symbol Cu, atomic number 29. It is a soft, malleable and ductile metal with very high thermal and electrical conductivity. A freshly exposed surface of pure copper has a reddish-orange color. It is most commonly used as a conductor of heat and electricity, a building material, and as a constituent of various metal alloys. Copper is found as a pure metal in nature, and was the source of the first metal to be used by humans, around 8,000 BC. Its compounds are commonly encountered as copper(II) salts, which often produce blue or green colors to minerals such as azurite, malachite and turquoise and have been widely used historically as pigments. The corrosion state is also used in architecture and art. The corrosion also protects the metal rather than completely deteriorating it. Copper not only corrodes in oxygen, but also will undergo galvanic corrosion when exposed to other metals. Copper tarnishes when exposed to sulfides, which react with it to form various copper sulfides. Copper is recyclable (Hammond, 2004).

Copper is essential to all living organisms as a trace dietary mineral because it is a key constituent of the mitochondrial respiratory enzyme complex cytochrome c oxidase. In mollusks and crustaceans copper is a constituent of the blood pigment hemocyanin, which is replaced by the iron-complexed hemoglobin in fish and other vertebrates. The main areas where copper is found in humans are the liver, muscle and bone. Copper compounds are used as bacteriostatic/antimicrobial substances, fungicides, and wood preservatives. Certain isotopes of copper are used in radiation based emission topography. Compounds that contain a carbon-copper bond are known as organocopper compounds. They are very reactive towards oxygen to form copper(l) oxide. The human body contains copper at a level of about 1.4 to 2.1 mg per kg of body mass. Required Daily Amount for copper in normal healthy adults is estimated to be 0.97 mg/day and as high as 3.0 mg/day. Copper is absorbed in the gut, then transported to the liver bound to albumin. After processing in the liver, copper is distributed to other tissues in a second phase. Copper transport in the tissues involves the protein ceruloplasmin, which carries the majority of copper in blood. Ceruloplasmin also carries copper that is excreted in milk, and is particularly well-absorbed as a copper source. A lack of copper can cause anemia-type symptoms and cellular dysfunction. An overdose of copper can cause liver failure, DNA damage, and the potential enhancement of neurological diseases such as Alzheimer's (Hammond, 2004).

Natural Gas

Natural gas is a naturally occurring hydrocarbon gas mixture consisting primarily of methane, (and other hydrocarbons) carbon dioxide, nitrogen and hydrogen sulfide. Natural gas is an energy source that provides heating and electricity. It can also be used as fuel for vehicles and in the manufacture of plastics and other commercially important organic chemicals. Natural gas is found in deep underground natural rock formations or with other hydrocarbon reservoirs in coal beds. Petroleum is also another resource found with natural gas. Most natural gas was created over time through biogenic and thermogenic mechanisms. Biogenic gas is created by methanogenic organisms in marshes, bogs, landfills, and shallow sediments. Thermogenic gas is produced deeper in the earth, at greater temperature and pressure, from buried organic material (Naturalgas.org, 2012).

Natural gas must undergo processing to clean the gas and remove impurities such as water before it can be used as a fuel. The by-products of processing include ethane, propane, butane, pentane, and higher molecular weight hydrocarbons, hydrogen carbon dioxide, water vapor, and sometimes helium and nitrogen. This gas is generally called methane. It is colorless, shapeless, and odorless in its pure form. Natural gas is combustible, abundant in the United States and when burned it gives off a great deal of energy and few emissions. Unlike other fossil fuels, natural gas is clean burning and emits lower levels of potentially harmful byproducts into the air (Naturalgas.org, 2012).

Pine

Pine is a type of coniferous tree in the genus Pinus, in the family Pinaceae. There are over 115 species of pine, that grow all over the world, but primarily in areas of lower temperatures, and for the most part in the Northern Hemisphere. These are abundant trees that are commonly used for building materials. Pines are evergreen trees with a high amount of resin inside, and can grow up to 80 meters tall. Pines are a long living species that can live between 100- 1,000 years.They are fast growing softwood that is very popular and easy to use for planning and producing lumber. Pine wood is widely used in high-value carpentry items such as furniture, window frames, paneling, floors and roofing, and the resin of some species is an important source of turpentine. Because pines have no insect or decay resistant qualities after logging, they are generally recommended for construction purposes as indoor use only. When this wood is left outside it cannot be expected to last more than 12-18 months depending on the type of climate it is exposed to (woodmagazine.com, 2016).

Plywood

Plywood is multiple layers (plys) of different types of wood adhered together with an adhesive. It is an engineered wood from the family of manufactured boards which includes medium-density fiberboard (MDF) and particle board (chipboard). All plywood bind resin and wood fiber sheets to form a composite material. The grain of the wood is alternated by 90 degrees. This alternation of the grain is called cross-graining and has several important benefits:

it reduces the tendency of wood to split when nailed at the edges; it reduces expansion and shrinkage, providing improved dimensional stability; and it makes the strength of the panel consistent across all directions. There is usually an odd number of plies, so that the sheet is balanced—this reduces warping. Because plywood is bonded with grains running against one another and with an odd number of composite parts, it is very hard to bend it perpendicular to the grain direction of the surface ply. Plywood is made with virtually any type of wood.

Project Description

The experimenters conducted experiments to identify the most effective frequency for suppressing a plywood fire. The experimenters conducted these experiments by lighting a sample piece of plywood on fire and projecting a certain frequency at the flame. During experimentation, it was determined that the fire suppression was most effective on plywood samples. In the model, we decided to use only one type of wood and a set frequency of 100 kHz. Below is the procedure used to identify the most effective frequency.

Tuning Fork and Bunsen Burner Test

7. Light Bunsen Burner, turn off lights.
8. Place Bunsen Burner within enclosure with denoted lines and mounted ruler to prevent air from manipulation the flame and to be able to record flame movement.
9. Tap tuning forks of various increasing frequencies against the desk with the same amount of force to produce consistent sound waves.
10. Move tuning fork within 3 cm of the top and bottom of the flame, observe any potential movement during duration of sound emission from the fork, or for 1 minute.
11. Repeat steps with all tuning forks
12. Extinguish flame, analyze data

Other Fuels and Tuning Forks

8. Place other fuel items within clamp.
9. Ignite using Bunsen Burner.
10. Place clamp apparatus within enclosure to prevent air from manipulating the flame.
11. Tap tuning forks of various increasing frequencies against the desk with the same amount of force to produce consistent sounds waves.
12. Move tuning fork within 3 cm of the top and bottom of the flame, observe any potential movement during duration of sound emission from the fork, or for 1 minute.
13. Repeat steps with all tuning forks.
14. Extinguish flame (if necessary), analyze data.

Frequency Trials

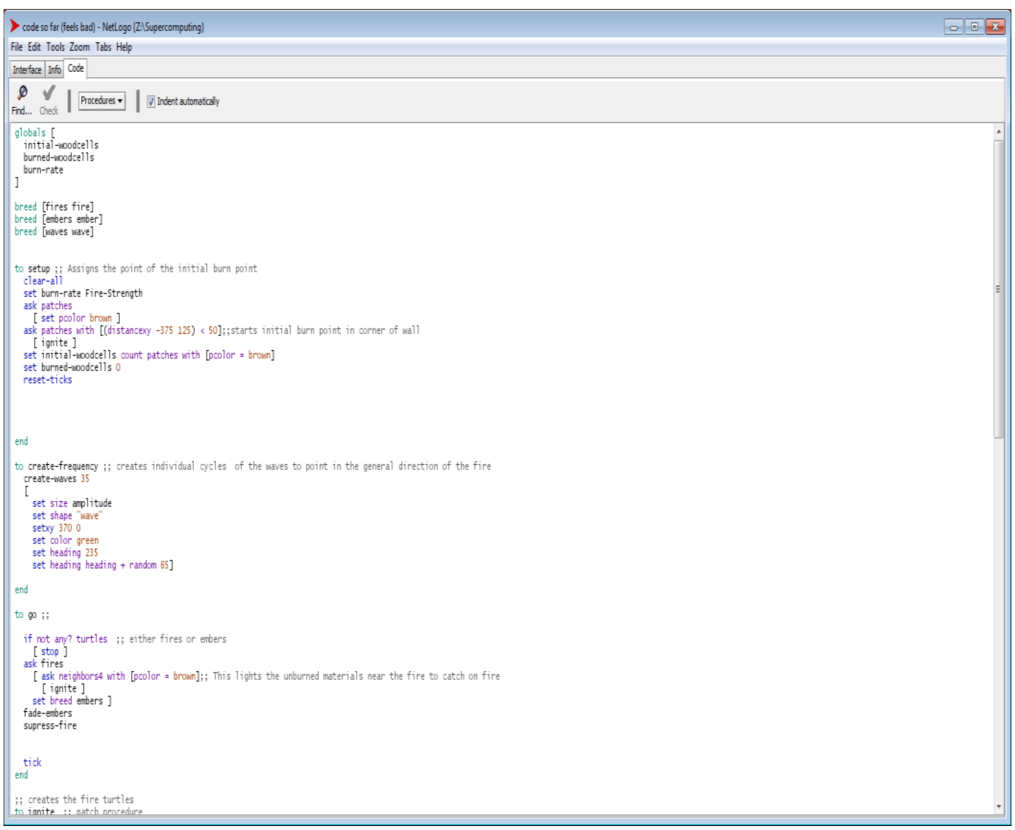
6. Place electrode within conductance bridge measuring apparatus.
7. Calculate Frequency using inductance (micro Henry) and capacitance (farads).
8. Tune Frequency generators to calculated frequency
9. Place leads on either side of flame within 3 cm of flame of each object within clam apparatus, observe flame behavior for nearly matched electrodes in 2 and 4 electrode arrays.
10. Observe flame behavior at differing increasing frequency levels. Measure flame movement and behavior during trials, measure weight and size of fuel source before and after trials.

To further investigate this issue on a larger scale requires a computer model that visually expresses the impact of ultrasonic frequency signals on wood-based materials. The model will use the best performing array as a base for the computer model. The model will have a 2 electrode, or a parabolic array that emits a signal with a 100 kHz frequency. Amplitude of the wave will vary. The sound waves' impact will be expressed by the variations in the graphs of the fuel source. A visual decrease in flame speed and flame growth will depict the effectiveness of the fire suppression system. Overall, the computer model will demonstrate the effects that an ultrasonic sound fire suppression system will have on burning plywood.

In the model, the fire starts in the corner of the plywood wall and spreads to all other areas of the wall. The fire sprouts other fires near the edge of the fire at random. The frequency starts on the opposite edge of the wall from the fire. The individual cycles of the frequency impact the edge of the burning and slow the burn rate. This process continues until the burning process is complete. The initial burn rate of the fire determines the strength of the fire, therefore the larger the burn rate, the more difficult it is for the frequency to extinguish the flames.

Results

The data from the lab determined that 100 kHz is the most effective signal frequency. Through research it has also been determined that higher amplitude of the wave will prove more effective. Our research also suggests that a parabolic copper array will direct the waves more efficiently than the two electrode system (tuning fork). The model has been constructed. The NetLogo model features only one type of wood (a wall). There is also only one frequency. To expand and further complicate our model, we could introduce every variable of temperature, pressure and fuel turtles so that every variable is represented.




```
globals [
  initial-woodcells
  burned-woodcells
  burn-rate
]

breed [fires fire]
breed [embers ember]
breed [waves wave]


to setup ;; Assigns the point of the initial burn point
  clear-all
  set burn-rate Fire-Strength
  ask patches
    [ set pcolor brown ]
  ask patches with [(distancexy -375 125) < 50];;starts initial burn point in corner of wall
    [ ignite ]
  set initial-woodcells count patches with [pcolor = brown]
  set burned-woodcells 0
  reset-ticks




end

to create-frequency ;; creates individual cycles  of the waves to point in the general direction of the fire
  create-waves 35
  [
    set size amplitude
    set shape "wave"
    setxy 370 0
    set color green
    set heading 235
    set heading heading + random 65]

end

to go ;;

  if not any? turtles  ;; either fires or embers
    [ stop ]
  ask fires
    [ ask neighbors4 with [pcolor = brown];; This lights the unburned materials near the fire to catch on fire
      [ ignite ]
    set breed embers ]
  fade-embers
  supress-fire


  tick
end

;; creates the fire turtles
to ignite  ;; patch procedure
```

code so far (feels bad) - NetLogo {Z:\Supercomputing}

File Edit Tools Zoom Tabs Help

Interface Info Code

Find... Check Procedures ▾ Indent automatically

```
    ]
    ask fires   ;; Ignites fire and turns brown patches to red
      [
        set color red
      ]
  ]
  set pcolor black
  set burned-woodcells burned-woodcells + 1  ;;for percent burn monitor
end

;; achieve fading color effect for the fire as it burns
to fade-embers
  ask embers
    [ set color color - 0.3  ;; make red darker
      if color < red - 3.5     ;; makes the older burned materials look black
        [ set pcolor color
          die ] ]
end

to emit-frequency
  ask waves
  [
    if xcor < -350 [die]
    if ycor > 120 [die]    ;; this optomized the code by killing the waves that already acted on the fire
    if ycor < -120 [die]

    fd 10 ;; this makes the frequency of the waves.
  ]
  create-frequency

end

to supress-fire

  ask patches
  [
    if pcolor = black
    [
    if any? waves-on neighbors   ;; If waves are on neighboring patches of fire, it decreases the burn rate

    [
      repeat 100
      [set burn-rate burn-rate - .00000025]
    ]
  ]
    ]

end
```

code so far (feels bad) - NetLogo {Z:\Supercomputing}

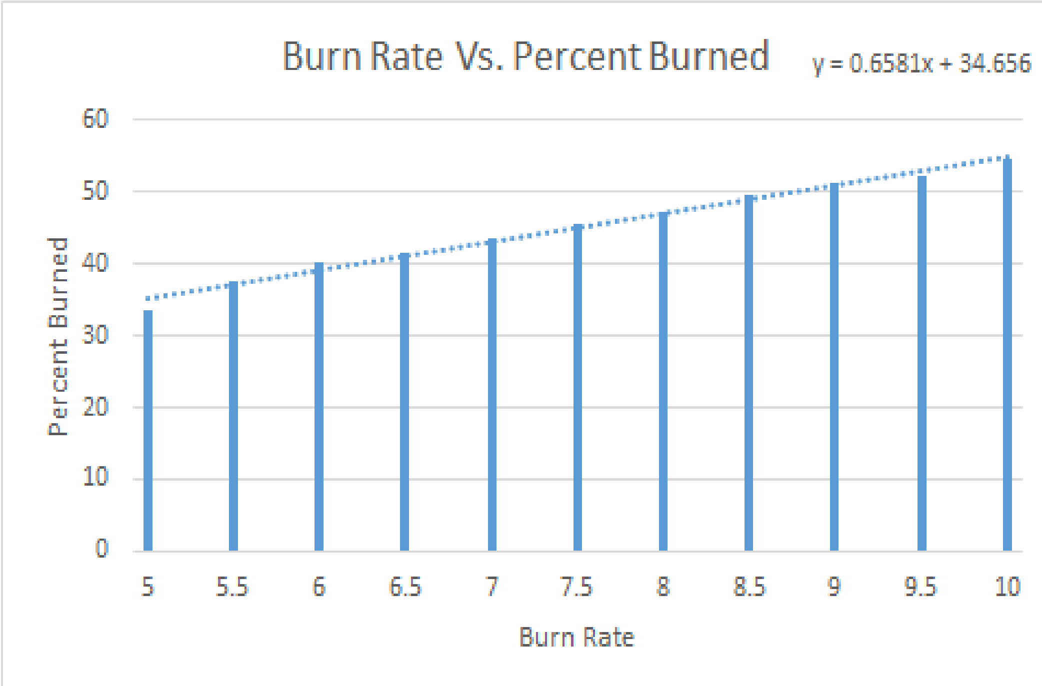
File Edit Tools Zoom Tabs Help

Interface Info Code

Find... Check Procedures ▾ Indent automatically

```

  tick
end

;; creates the fire turtles
to ignite  ;; patch procedure
  if  not any? waves-on neighbors
  [
    if not any? waves-on self
      [
        sprout-fires random burn-rate
      ]
    if any? waves-on neighbors
      [
        ask fires [die] ;; kills fire if a wave is on a neighboring patch

      ]
    ask fires   ;; Ignites fire and turns brown patches to red
      [
        set color red
      ]
  ]
  set pcolor black
  set burned-woodcells burned-woodcells + 1  ;;for percent burn monitor
end

;; achieve fading color effect for the fire as it burns
to fade-embers
  ask embers
    [ set color color - 0.3  ;; make red darker
      if color < red - 3.5     ;; makes the older burned materials look black
        [ set pcolor color
          die ] ]
end

to emit-frequency
  ask waves
  [
    if xcor < -350 [die]
    if ycor > 120 [die]    ;; this optomized the code by killing the waves that already acted on the fire
    if ycor < -120 [die]

    fd 10 ;; this makes the frequency of the waves.
  ]
  create-frequency

end

to supress-fire

  ask patches
  [
    if pcolor = black
    [
    if any? waves-on neighbors   ;; If waves are on neighboring patches of fire, it decreases the burn rate
```

This chart details trials run through our model. We conducted three trials for each burn rate, which altered the intensity of the fire. We then averaged the values for each burn rate and produced the chart above. The more intense the fire was, the more it burned the wall. The frequency applied did eventually extinguish the flames.



Recommendations

The experimenters derived this project from a previous experimental project, where the theory was tested on small samples of plywood. The previous experimentation provided a small scale data set which the experimenters applied to the modeling of the fire suppression system.

Acknowledgements

Our mentor and sponsor Tracy Galligan was very helpful with our project. Jenay Barela, Zak Willis, and Rowan Kinney assisted with our code to troubleshoot the issues. Uri Wilensky for inspiration regarding the burning section of the model. Jim Fambro for being the inspiration for the original idea to assist firefighters.

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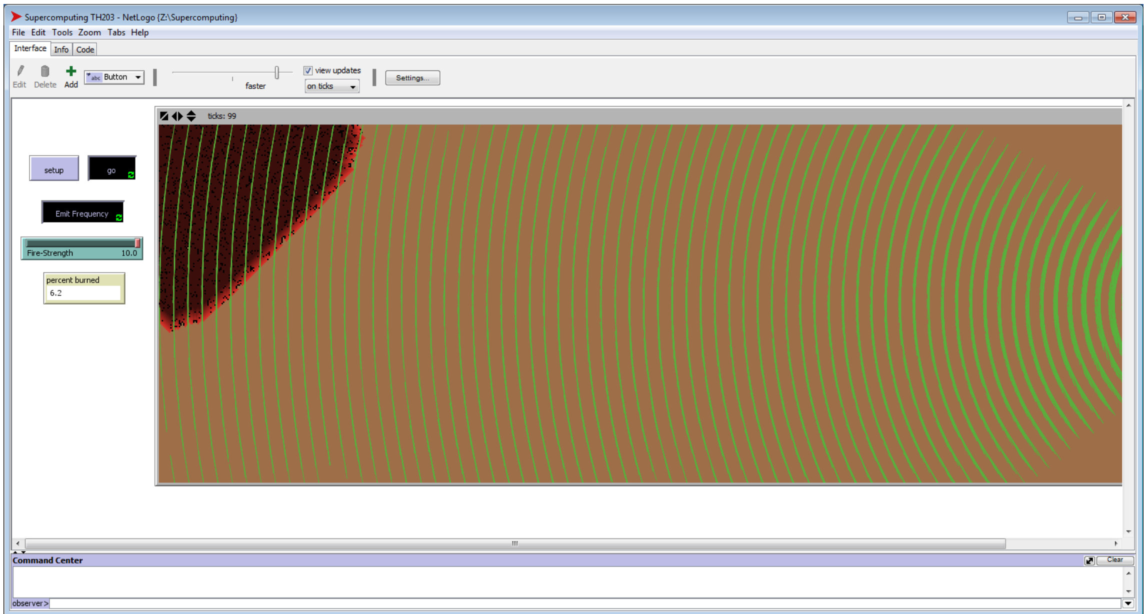
Appendixes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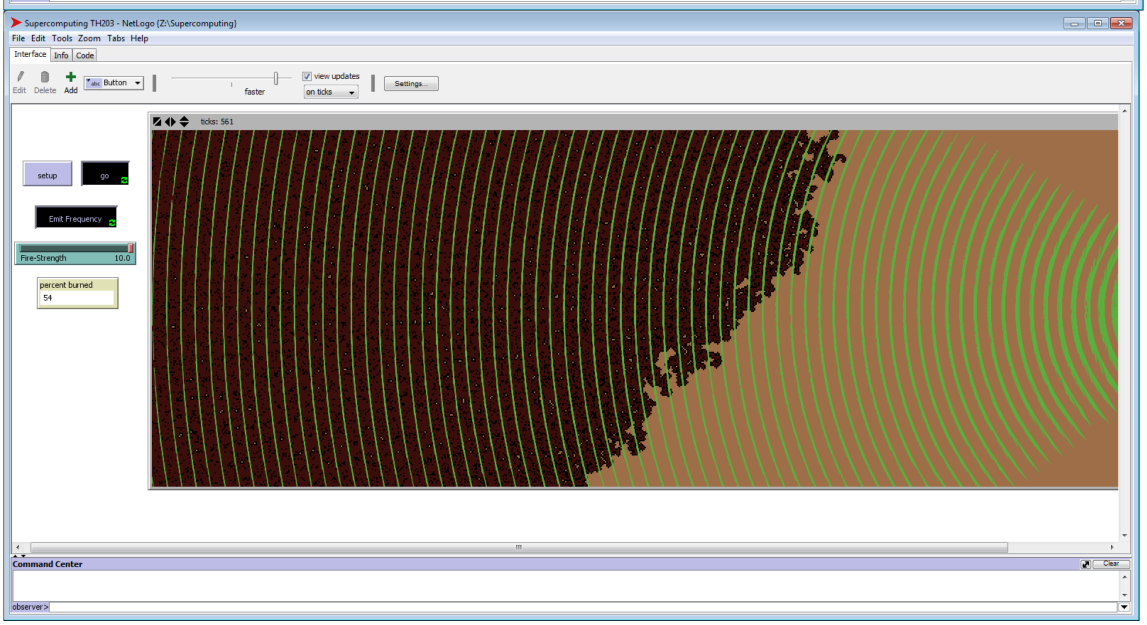
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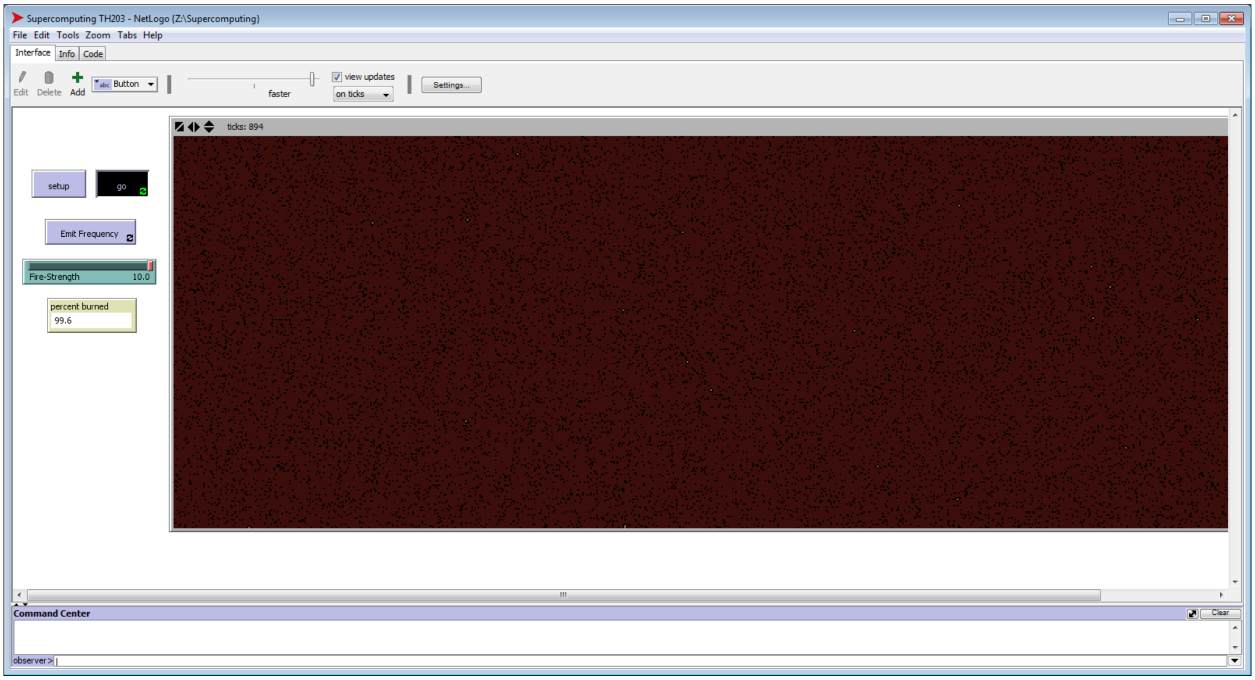
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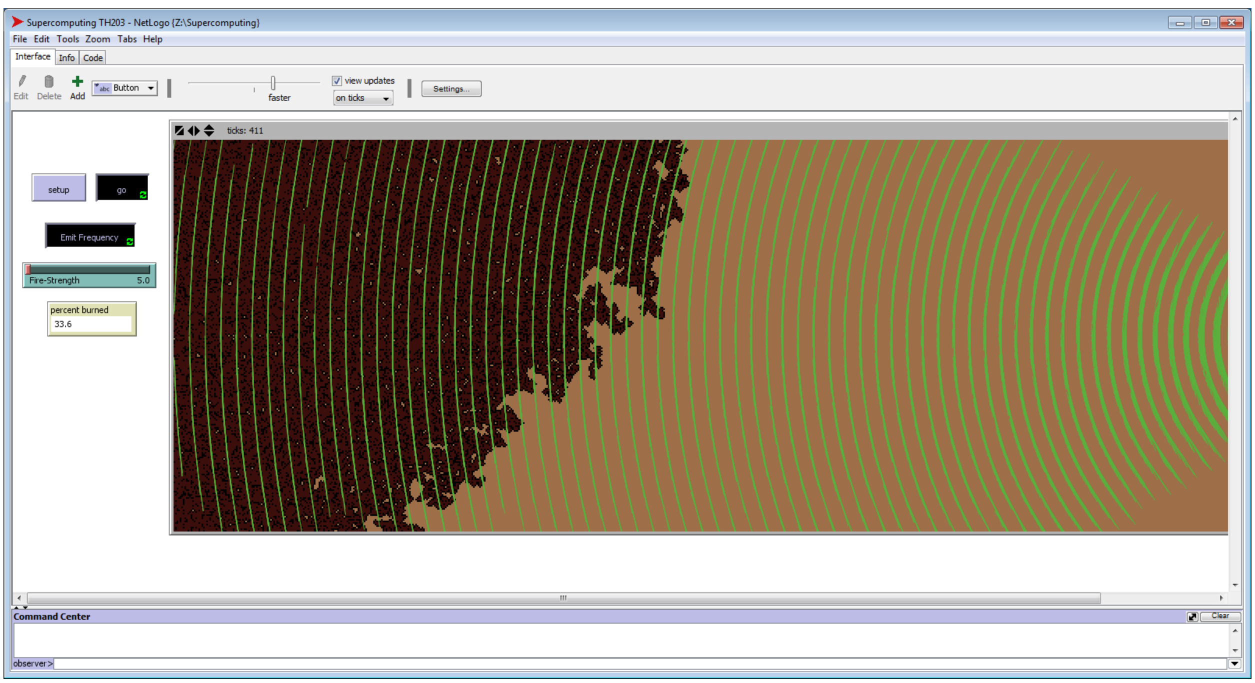
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percent burned
33.6
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observer>