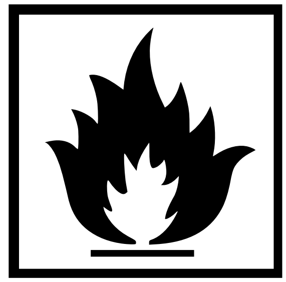
CHAPTER 34
Practical 11
Fire



Aims

In this practical we will study a common and useful natural sound effect, fire. We will analyse the physical and acoustic properties of fire and combine several contributory signals to create a composite effect.

Analysis

What is fire?

Fire is a complex phenomenon. It is an example of a composite sound effect, having many contributory parts and it is an example of a volumetric extent, coming from more than one location. Fire is an oxidisation reaction that has gone out of control. It starts when fuel gets hot and starts to oxidise. This generates heat in an exothermic reaction. The hotter something gets the better it oxidises and the more it oxidises the hotter it gets, ever more rapidly in a runaway process. This positive feedback causes a reaction that is self sustaining and will increase in size and rate so long as fuel and oxygen are supplied. The following things usually happen.

Liquefaction and Boiling

As they heat, some solids melt and then boil. In wood, resins and oils are forced to the surface under pressure. In other materials, wax or plastics may melt and flow from the initial fuel. Some of these change to a vapour state causing bubbles.

Outgassing

Recall Boyle's law, one of the many gas laws from kinetic theory, which says the product of pressure P and volume V is a constant for a fixed temperature T (written $PV = kT$). So if temperature increases, either the volume increases or pressure builds up. In the first case gas must escape from the fuel and comes out making a hissing sound. Where the escape path is impeded by trapped liquids we may hear periodic buildup and relaxations of pressure which sound strongly pitched.

Explosion

Where there is an immovable constriction and gases cannot escape to the surface because they build up in a sealed cavity, pressure will increase until it causes an explosion. The gas does not ignite or burn inside the fuel, it simply forces the solid fuel apart.

Stress

Explosive pressure isn't the only cause of disintegrating solid state materials. Thermal expansion of solid materials causes them to creak and groan.

Disintegration

Eventually the stress may build up until the fuel starts to disintegrate making loud cracking sounds. This can cause large scale structural shifts as pieces of fuel fall away or collapse on top of one another. If constrained they may fracture suddenly, as glass does when heated.

Flames

Gases released are often flammable themselves, they are a fuel too. With a high enough temperature flammable gas released by the reaction ignites into flames. Flames do not burn throughout their entire volume but on a combustion front, a skin covering the outside of the flame where it mixes with oxygen. Even where oxygen is pre-mixed in a forced flame we can see the same effect in a clean Bunsen burner, with combustion happening on an exterior front.

Convection

In the free atmosphere, hot gaseous by-products of the reaction, perhaps water vapour and carbon dioxide, expand. The density of hot gas is lower than the surrounding air and so because it is lighter, it rises leading to a low pressure around the flame. This is called convection. The temporary low pressure sucks surrounding air and fresh oxygen into the fray.

Flame acoustics

The tendency of the combustion front to propagate is determined by the cross sectional area and the pressure of the gaseous state fuel [Razus2003]. Flames tend to pass into areas if they are a larger adjacent free volume at lower pressure. Lower pressure above the flame draws it upwards. The flame itself acts as a resonant cavity, a tube of low pressure gas that oscillates chaotically from side to side as cool air rushes in to replace convected air. You can see this happening in a candle flame that flickers even when there is no wind. Expanding and rising gas changes the shape of the flame, elongating it into a thinner, taller volume. But to talk about a gas being lighter or heavier we must consider weight, which is a product of mass and gravity. A flame in zero gravity forms a perfect sphere. In Earth gravity however the cooling gas is heavier, so it falls back down causing instabilities around the flame and making it oscillate.

The energy exchange model in this case can be thought of as kinetic energy of a light, hot, rising gas and potential energy of a heavy, cold gas. The inflow of air around the base of the flame leads to vortices, turbulent patterns that shift the flame sideways or in spiral formations. All of these movements lead to low frequency sounds. They are usually manifest as roaring, fluttering sounds in the $3 - 80$Hz range. Popping, or gaseous state explosions happen where the flammable gas and air mixture is suddenly at an ideal pressure and temperature. This happens when the heat production from burning happens exactly in phase with an increase in pressure as a flame collapses. Placing a candle in a tube of the correct diameter to create a flame resonance causes a regular popping sound. The reverse principle is used in rocket engine design to minimise stress on the combustion chamber by modulating the fuel flow.

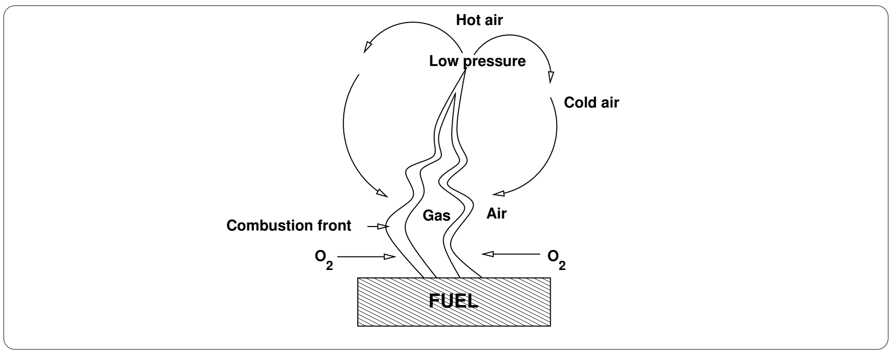


fig 34.1: Flame gas dynamics

Smouldering

Smouldering is combustion without flames where the oxidation reaction happens over the fuel surface. A fine, low level sound that lies between hissing and crackling can be heard in some rare cases such as yellow or white hot glowing charcoal. Here the source can be considered intense Brownian motion amplified by the acoustic properties of the surface.

Radiation

Fire can spread without direct contact. Nearby objects absorb electromagnetic radiation of infra-red wavelengths and heat up. The black body interpretation of radiation and absorption means darker materials will tend to absorb more energy than shiny objects like metals which reflect the radiation away. Nearby objects with a low flash point, like paper and wood, will begin to produce vapour and may burst into flame. We should therefore consider the larger environment. Near to a fire we may hear creaks and groans from stresses in structures that are rapidly heating up or cooling down, but aren't burning.

Model

All these processes in our model lead to a diverse bunch of sounds. Listed below are 10 common sonic features of fire and their causes. I've ranked the list in order of importance to the sound of fire. We are going to pick only the most significant three components and combine them to create a realistic fire sound, but for truly great fire effects you might like to work your way down the remaining items on the list as a future exercise.

- lapping - combustion of gases in the air, on the combustion front (flames)
- crackling - small scale explosions caused by stresses in the fuel
- hissing - regular outgassing, release of trapped vapour
- bubbling - boiling of liquids
- creaking - internal stress of fuel expansion or nearby structures
- fizzing - aerial conflagration of small particles
- whining - periodic relaxations during outgassing
- roaring - low frequency turbulent cycles of flames
- popping - gaseous phase explosion where heat and pressure are in phase
- clattering - settling of fuel under gravity

Method

In terms of acoustic intensity, lapping, crackling and hissing form the dominant part of the sound of fire. We will compose each separately using subtractive synthesis based on filtered white noise, then combine these additively into the correct texture. Each sonic component will be created in its own subpatch. Several instances of each component are then blended together according to a single control for the *intensity* of the fire.

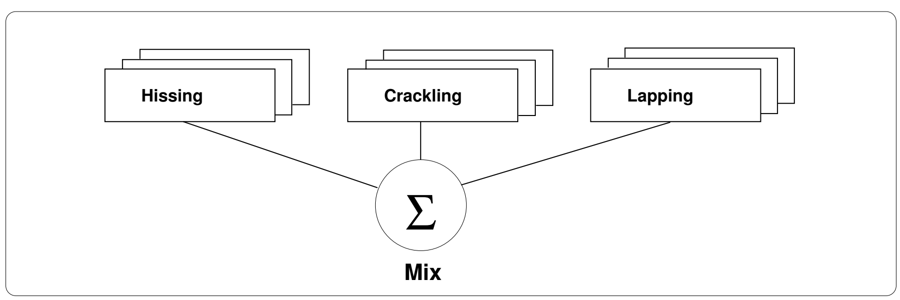


fig 34.2: Fire components

DSP Implementation

Hissing

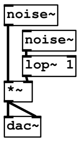


fig 34.3: hissing1

With only a white noise generator we already have a fair starting point for a hissing sound. But it's a constant noise. Hissing in a fire comes and goes, usually in short bursts with silence in between. What we need to do is modulate the hissing with a random low frequency signal, but where do we get one of those? An easy way is to use another noise generator through a low pass filter. Remember that white noise contains every frequency, so it must contain some low ones as well as high ones. The low pass filter selects the ones we want. Build and listen to the patch in Fig. 34.3. What is wrong with this sound?

Changing the hissing dynamics

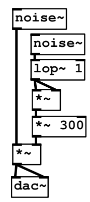


fig 34.4: hissing2

What's lacking in this first attempt is correct loudness and distribution. It's still an almost constant noise, occasionally getting louder or quieter. The hissing from a real fire seems much more volatile and violent. Hisses come though in loud bursts, appearing much more suddenly and much more loudly than the gentle modulation above. We need to modify the dynamics of the low frequency modulator and we do this by taking the square of the modulating signal. Taking the square of a normalised signal makes values close to 1.0 pass through unaltered but lower values much quieter. It expands the dynamic range of the modulator signal. Because the average level is now lower we must amplify the result to get back to a sensible level. Listen to the patch of Fig. 34.4 and compare it with the previous patch. What differences do you hear? There should be bits where the hissing almost completely disappears leaving silence, with occasional loud bursts of noise.

> **Keypoint**
> Raising a normalised signal to a fixed power expands its dynamics. Conversely, taking the root of a normalised signal compresses its dynamics.

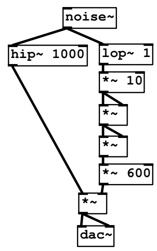


fig 34.5: hissing3

That's almost what we want, but the sound is still a little too regular. Let us continue applying the squaring technique to increase dynamic range. We increase the expansion to the 4th power by squaring again. This time the signal almost vanishes, so we need to boost it again, by ten times. This value needs to be carefully selected. A 4th power is a large expansion and we can easily end up with a signal that is far too quiet one moment and much too loud the next. The trick is to balance the makeup gain block with the preamplification, I started with 2.0 and 2000 then adjusted both values until it sounded right. You will frequently need to use this technique of adjusting the input and output ranges of a function. Sometimes the best values must be found by trial and error. The best way is to attach some sliders to the multiplication blocks then play with them until it works. Once you have the correct values you may hard-code them back in as fixed values and remove any variables like sliders.

> Keypoint
> Instead of calculating scaling values sometimes you must find the sweet-spot of a function by hand. Use sliders to fine tune the domain and range before fixing these values in code.

Changing the hissing tone

Listen carefully to your work at this point and compare it to some examples of recorded fire. There are a few too many low frequencies in the hissing sound that make it sound a bit "wide". Adding a `hip~` filter fixes this. Roughly, the sound of escaping gas is related to the volume moving relative to the aperture size. Gas escaping from a burning solid forces its way through tiny cracks and channels just a few millimeters wide creating a high pitched sound.

Optimisations

Remember that we intend to run our procedural sounds in real time. One of our goals in designing practical procedural sound effects is to use the minimum processing power required to achieve the desired effect. Often we need to work through our code making small improvements on the first attempt. Notice the optimisation which incrementally improves our hissing sound generator. We have reused the same noise source to derive both the low frequency modulator and the high frequency signal source. This is okay to do here, but for a number of reasons we will discuss shortly it isn't always acceptable to reuse signal generators in this way.

Crackling

Fire crackles are short, sharp explosions, often in wood, coal or other solids where a piece of material disintegrates under pressure. Because our effect is for a hypothetical, generalised fire, we don't know the exact size and material of the fragments.

We will construct a crackle generator that can approximate a range of tones that might be found in burning coal, wood and cardboard. Again we start with a noise source. To get a short snap begin by modulating it with a tight envelope of 20ms. The envelope is produced using a line segment generator which jumps immediately to 1.0, then quickly decays back to zero. Again we obtain a square law decay, closer to a natural envelope found in real sounds.

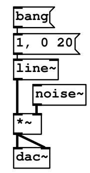


fig 34.6: crackling1

Crackle density and control

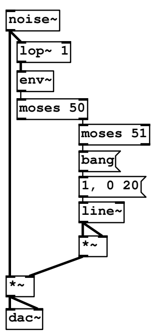


fig 34.7: crackling2

As it stands we must manually fire the envelope generator in Fig. 34.6 by pressing the bang message. That's no good. We need it to automatically produce intermittent crackles at random times. In Fig. 34.7 we obtain a random trigger. Again a [lop~] provides a slowly moving random source. Instead of using it directly as a modulator we convert it to a control signal using the [env~] unit which gives the RMS value of the input signal as a control rate float between 0.0 and 100, representing the decibel amplitude. A pair of stream splitters using [moses] create a window right in the middle of this range. Each time the input signal crosses into this range it passes through and triggers the line envelope. Remember that the values here are floats, not integers, so a [select] object would be inappropriate. Changing the low pass filter frequency alters the signal volatility and hence the number of times per second it crosses its midpoint. This gives us a simple way to control crackle density.

Crackle tone

Right now, every crackle sounds the same. We would like a bit of variety in the sounds. To get some colour and variation we can do two things. First we can make the decay time of each crackle a little different. Recall the Gabor period and that short sounds have a somewhat different property than longer ones. By varying their duration we create clicks that seem to change in tone. We substitute a random number into the decay time of the envelope. Since we started with a fixed decay of 20ms let's make it a random range up to 30ms. Furthermore, we can explicitly make the tone of each crackle unique using a resonant filter. That's achieved by adding a random number to the frequency input of our filter. Of course we need to choose an appropriate range of random numbers here too. Those between 100 and 1000 give good frequencies for burning

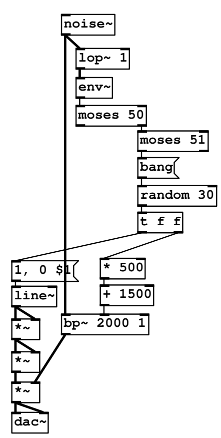


fig 34.8: crackling3

wood, but in the patch of Fig. 34.8 we allow crackles over most of the audio spectrum, between 1.5kHz and 16.5kHz. Now we have crackles which vary in tone and duration. This combination gives a realistic result.

Flames

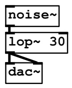


fig 34.9: lapping1

So far so good. But our fire is still missing one essential element, the roaring, lapping sound made by burning gas. The sound of flames burning is a low "woofing" noise. To focus the frequencies into the right range a lop~ unit is used. On its own a single lop~ unit is too mild, we still have a lot of mid and high frequencies getting through. Also the tone of a real flame has a resonance to it.

Resonance comes about because the pressure created by the burning gas effectively creates a tube of air in which the sound resonates. So how do we achieve this? By using a resonant band pass filter we get a little closer to the sound we want. A couple of small problems remain. There's a bit too much low frequency in the sound. Components below 20Hz are inaudible but they still have an effect on the digital sound signal.

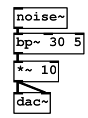


fig 34.10: lapping2

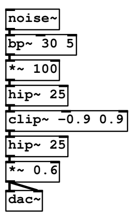


fig 34.11: lapping3

Frequencies close to zero waste the available dynamic range. We remove them here using a hip~ unit at 25Hz. Also the flame generator and the hiss generator suffer from being a bit too lively in dynamics. Sometimes they go over level when played loudly, but when we attenuate them they are too quiet. We can fix this problem by using a clip~ unit to cap the level. This limiting, even though it introduces distortion, is acceptable here because the signal goes over level infrequently and the distortions introduced actually improve the sound somewhat. For rare cases where the modulation drifts too high and causes the clip~ to briefly lock at a constant DC signal, an extra hip~ fixes things.

Putting it all together

To create the composite effect the parts are now mixed. We create a single unit consisting of three separate parts. Before wrapping up this exercise let's make an optimisation. Each of the units that generate lapping, crackling and hissing are based on a noise generator, so can't we just factor it out and use the same the generator for all of them? This is an interesting question, one we have already considered when building the hiss generator. The answer is "It depends". For some applications this would be a bad idea, it would reduce the degree of variation in the sound because all the units would react in unison to a common signal. But for fire the answer is surprisingly **yes**. It's not only an optimisation, it's an improvement and a great

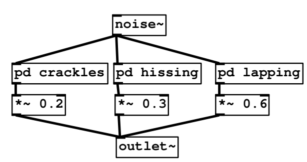


fig 34.12: fire-generator

idea. Why? Because the noises we hear have a common causal linkage. Fire tends to rise up and wane in such a way that crackles, hiss and lapping all move together, so making the noise source a common unit improves the overall sound in a subtle way by adding some coherency.

> Keypoint
> DSP optimisation by reuse depends on causal correlation. Some sounds are features of the same underlying process and signals can be combined, while others are independent and must be kept separate.

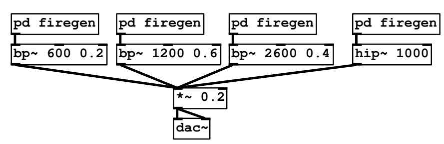


fig 34.13: fire-all

Finally we want a big roaring fire, not the small sound our single fire generator gives. Let's arrange a bunch of them, each with slightly different settings, into the mix to create a big fire sound. A collection of four fire generators that gives an impressive sound is shown in Fig. 34.13. Should we factor out the noise generator one more time? This time the answer is no, we want some degree of chaos and incoherency in the mix so let's allow each fire generator to have its own random basis.

Results

Source .... **http://aspress.co.uk/sd/fire.html**

Conclusions

Physics based component analysis can be a powerful tool. Reducing a sound to separate phenomena and synthesising each separately provides a great deal of control. For extents like fire and water a subtractive approach starting from white noise is appropriate. Optimisations can be made by factoring out generators or resonators if all components share a causal link that includes them.

Exercises

Exercise 1

To simulate an absolutely top whack fire we would build unit generators for each of the model components. But simply having them all running together would be naive. There is a proper causal linkage between events in a fire. To get the fire to build up properly we would start with a little smouldering, then crackling and lapping, building up to grand ensemble of boiling and fizzing when the fire is most active. Certain occurrences like hissing and bubbling may go together in groups. A wood fire is often said to "spit" as oils inside the wood evaporate, which is immediately followed by an upsurge in the amount of flames as flammable fuels vapourise. Have a go at creating some of the other texture generators. Perhaps you can create a common control to set the intensity of your fire with distinct levels of combustion in which different generators become more active.

Exercise 2

A spectrogram analysis of fire would be too confusing to print in this textbook and of limited use, so I have avoided it and relied on the physical analysis. See if you can obtain a high resolution spectrogram of a real fire recording and try to match features we have discussed to components heard in the recording. Print out the spectrograph on a large sheet or use a graphics package to notate the spectrogram to show where you think crackles, hisses, pops or other features appear.

Exercise 3

Try to reverse the process in exercise 1 and produce the sound of a fire being extinguished with water. Listen to some recordings of this first. Explain why you might hear a big increase in shrieking and whining components. What is happening to the water?

References

Razus D., Oancea D., Chirila F., Ionescu N.I. (2003) "Transmission of an explosion between linked vessels". Fire Safety Journal, Volume 38, Number 2, March 2003 , pp. 147-163(17)