firestarter – A Real-Time Fire Simulator

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Abstract

Many obstacles exist in attempting to graphically render physical phenomena that are highly fluid and ostensibly chaotic in nature. Fire is a prime example of such phenomena. Given the unrealizable computational complexity of chemical-atomic modeling, this paper explores how to best apply our current understanding of the physical fire model to balance computational stresses for optimal realism. Special emphasis is given specifically to the constraints imposed by real-time rendering, as opposed to production pipeline rendering, introducing *firestarter* – a real-time fire simulator developed by the author using OpenGL – which features some unique implementations of previously discussed topics.

1 Introduction

Combustion is a complex process. The combustion of a candle flame has the following oxidation equation [8]:

$$C_{17}H_{35}COOH + 11O_2 \rightarrow 9H_2O + 5CO_2 + 5CO + 8C + 9H_2$$

This equation should give just about the right impression: we could never hope to compute a truly accurate fire simulation within any reasonable time frame, even if we did know all there was to know about fire (which we do not). Therefore, as the reader may be relieved to hear, this paper does not present complex analyses of physical and chemical equations. Rather, it discusses the rendering of these scientific phenomena from a purely computational perspective – how can we best represent them given the tools available to computer graphics developers? *firestarter* is a real-time fire simulator developed by the author using OpenGL that attempts to provide an answer to this question.

I will begin in section 2 by highlighting important aspects of some selected literature in 3D graphical fire rendering, with particular emphasis on those articles and papers influential in the creation of *firestarter*. Methods for both pipelined (e.g. film production) and real-time (e.g. interactive applications) visualization are explored. Section 3 discusses important physical properties of fire that need to be considered in designing a simulation, and section 4 expands by analyzing those properties and evaluating them in the context of real-time computation. In section 5, *firestarter* is presented and discussed at length, including a discussion of time complexity and other implementation specific issues and solutions. Finally, section 6 concludes with a discussion of some observations made during the design process, and recommends areas for future development.

2 Published Work in 3D Fire

2.1 The premiere ; the particle system

Consider a waterfall. It's a beautiful sunny spring day, and birds can be heard chirping merrily in the forks of the trees. You hear the rustling of leaves in the cool breeze, and water rushing over the waterfall's edge and pounding down onto the rocks below….

Now back up: once again envision that water running over the edge of the cliff. Imagine the water separating as it falls, parting into many individual, tiny droplets. Each of these droplets has its own position in space, its own velocity vector, its own size, its own mineral content, its own temperature, etc.. To view the water falling in this manner is to view the waterfall as if it were a particle system.

With the very first computerized graphical fire simulation, Reeves [10] introduced particle systems as a modeling, animating and rendering primitive back in 1983. In the film *Star Trek II: The Wrath of Khan*, his so-called "expanding wall-of-fire" was generated using a two-level hierarchy of particle systems. The top-level system was centered at the impact point of a genesis bomb, generating particles which were themselves particle systems. These second-level particle systems were modeled to resemble explosions where each such particle system acted like a volcano exploding upwardly, and then eventually falling back to the planet surface due to the pull of gravity. Due to the discrete nature of particles, an enormous amount of them were required to achieve good results, but since real-time speeds were not imperative, the results were certainly adequate for the time. As shall be seen, most fire simulations today are still done using particle systems of some form or another. A more in-depth discussion of particle systems and other modeling techniques is left to section 4.2.

Figure 2.1.1

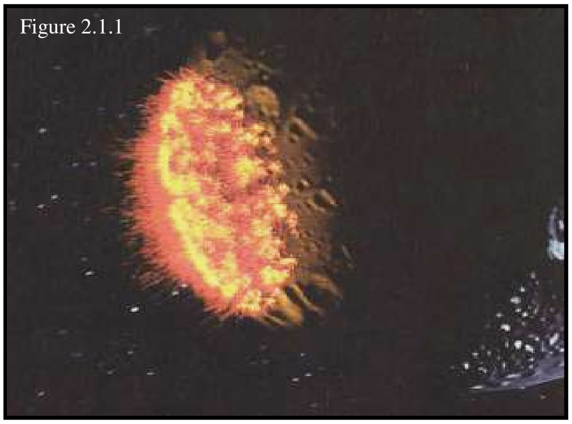
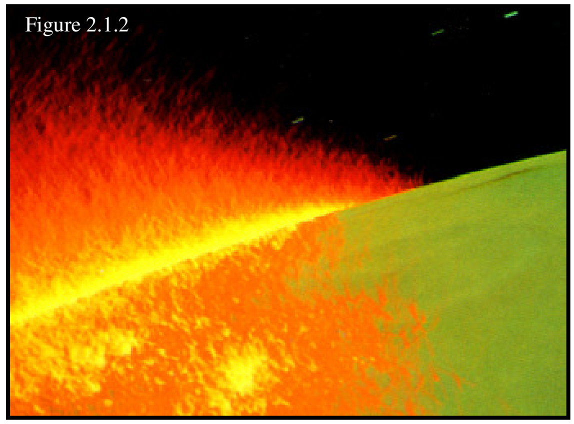


Figure 2.1.2



Figures 2.1.1 and 2.1.2: *The Genesis bomb from Star Trek II: The Wrath of Khan [10]. Both figures 1 and 2 show the wall of fire engulfing the planet, from different angles.*

2.2 Prerendered fire

To date, graphical fire appears to have had made its greatest leaps in the time insensitive area of prerendered production, where the computations are pipelined, or batched, to produce a sequence of frames (a movie). While real-time fire graphics is the focus of this paper, two pipeline simulators (in addition to Reeves' particle systems from section 2.1) are worth particular mention for two reasons. The first reason is that the philosophies behind the two simulations are curiously contrasted, and the second is that it is useful to know exactly what cutting-edge graphics-rendering today is capable of producing, what factors these studies have deemed to be the most important, and how those factors might otherwise be simulated under real-time time constraints.

In a paper published in 2002, Nguyen et al. [7] present a purely physics-based method for modeling fire. A snapshot is shown in figure 2.2.1. The simulation uses the incompressible Navier-Stokes equations to model the hot gases, thereby also modeling the expansion effects caused by vaporization, and the effect of buoyancy in supporting the elevation of smoke and soot. In the simulation, fire and smoke interact with objects in the environment, and the fire can spread to those objects that are flammable. As can be seen from the associated figure, the fire looks very realistic, particularly in the positioning and movement of the gaseous substances. Yet it is precisely the physical aspects of hot turbulent gases that are so hard to replicate in a real-time rendering;

modeling fire in this manner is very complex and requires a large series of complex equations to be solved on a large scale. We will expand on this in section 3.4

Shown in Figure 2.2.2 and 2.2.3, Lamorlette et al. [4], in a paper also published in 2002, introduce an entirely different sort of prerendered fire simulator. Sponsored by PDI/Dreamworks for the use in the animated motion picture movie, *Shrek*, this simulator has its focus on on aestheticism, control, and pliability rather than true realism. The philosophy being that, with the goals of artistic and behavioral control in mind, it would be difficult to achieve a desired behavior relying on strictly physics-based equations. Also, purely physics-based simulations such as that of Nguyen et al. scale very poorly, thus making animation of large fires extremely slow and inefficient. The simulation of Lamorlette et al. uses physics-based wind fields, but does not otherwise strive for physical accuracy. Stochastic models of flickering and buoyant diffusion reflect the appearance of the scene, and the simulation allows for noise to be composed over the wind fields for enhanced control over motion and scale. Other aspects of the simulation, such as combustion spread, flickering, separation and merging are all manually controlled through procedural mechanisms.

Figure 2.2.1: *A sample image from Nguyen et al. [7]. The cost of this simulation is approximately 3 minutes per frame using a Pentium IV.*

Figures 2.2.2 and 2.2.3: *Two images from the movie* Shrek*, the production of which used the described simulator [4]. The cost of this simulation is approximately 2.7 seconds per frame on a Pentium III.*

2.3 The real-time arena

3D real-time fire, almost by definition, finds its application in interactive applications. Among interactive applications, computer games, having had a need to somehow represent explosions and fire since their very inception, have been the prime candidates for utilizing graphical fire animations. Only in the past decade, however, has it become three-dimensionally feasible. Since that time, hardware rendering speeds have increased exponentially, allowing for more and more detailed special effects. Given the proprietary nature of games, however, literature on their fire visualization methods is rather lacking. Nonetheless, figures 2.3.1 through 2.3.5 demonstrate how fire graphics in computer games have evolved in recent years.


Figure 2.3.1


Figure 2.3.2

Figures 2.3.1 and 2.3.2: *Two examples of fire from the computer game Quake [8], released in 1996. In figure 2.3.1, the fire is drawn using a prerendered bitmap fire core, surrounded by real-time rendered glowing, animated particles. Figure 2.3.2 shows a volumetric rendering of fire using non-transparent polygons; although the polygon rendering is fast, it is not very realistic.*


Figure 2.3.3

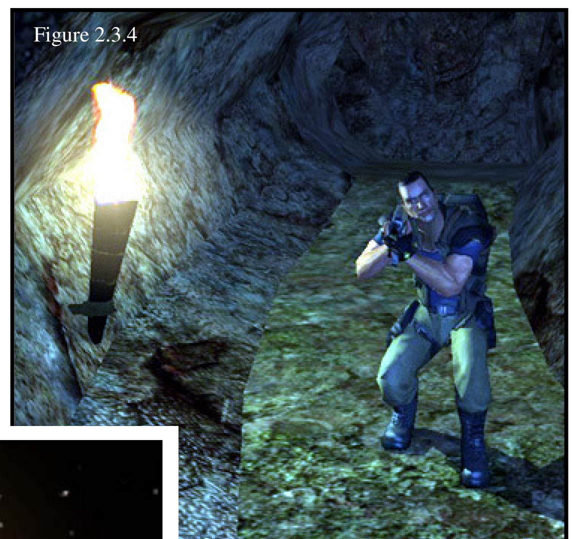


Figure 2.3.4


Figure 2.3.5

Figures 2.3.3, 2.3.4 and 2.3.5: *Figures 2.3.3 and 2.3.4 are screenshots from Far Cry, and figure 2.3.5 is from Unreal Tournament 2004. Both games were published concurrently with the writing of this paper, in the spring of 2004. The first two figures are two different renderings of fire. The third is of an explosion. Pictures are courtesy of Gamespot.com.*

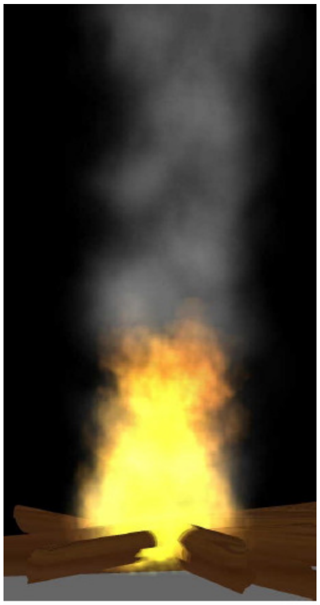
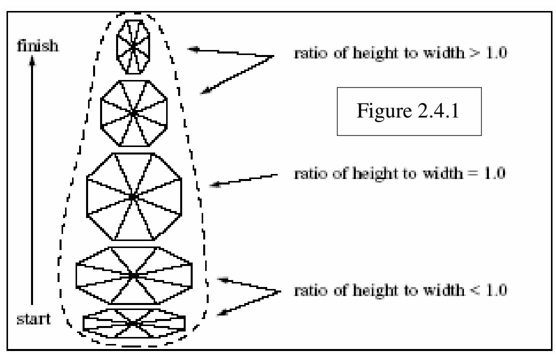


Figure 2.3.6: *A simple camp fire using texture splats and generating smoke [12].*

As an aside, combustion processes can loosely be classified into two separate types of phenomena: deflagrations (see figure 2.3.4) and detonations (see figure 2.3.5). In both of these processes, chemical reactions convert fuel into hot gaseous products. However, detonations are high speed events where shock waves and other compressible effects are important, whereas deflagrations are low speed events such as everyday hearth or torch fires. Detonations are distinct enough from regular fire that they are not explicitly considered in the rest of this paper. Nor has any attempt been made to simulate them in *firestarter*.

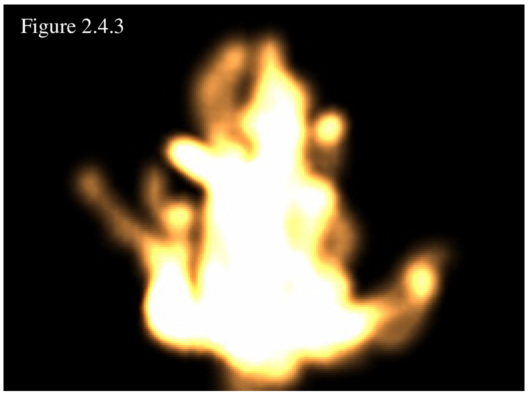
Independent of computer gaming, Wei et al. [12] proposed the use of texture splats (textures with a specified degree of transparency – discussed further in section 4.2) as their basic display primitive for the real-time fire simulation shown in figure 2.3.6 to the left. Not wishing to forfeit physics-based modeling of the behavior to achieve real-time performance, they utilized a model known as the Lattice Boltzmann Model to simulate physics-based equations describing fire evolution and its interaction with the environment (e.g. obstacles, wind and temperature). From the screenshots the simulation looks to be moderately successful. Unfortunately, the paper makes no mention of how fast the simulation actually runs.

2.4 Related works



Figures 2.4.1: an illustration showing *the modeling technique used by Perry et al. [2], applied in figures 2.4.2 and 2.4.3.*

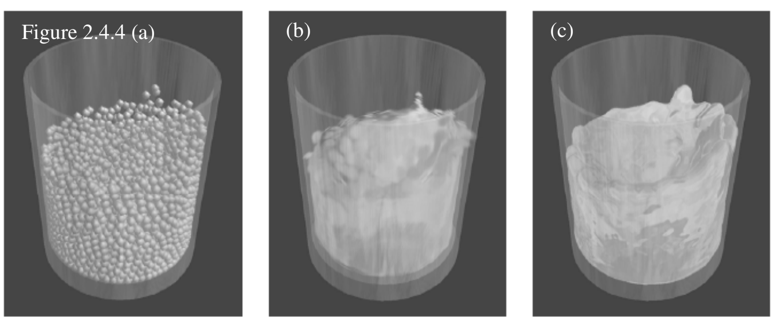
Perry et al. [9], and more recently Beaudoin et al. [2], both worked to simulate the spread of fire on polygonal meshes. While the spreading of fire is not a phenomenon that we aim to reproduce in *firestarter*, given the computational overhead, the model used for flame used by Perry et al. shown to the right is worth a closer examination. In their model, each flame is constructed out of a series of hexagon particles stacked and scaled above one another as shown in figure 2.4.1. The effect is very convincing on a small, candle-sized scale, as shown in figure 2.4.2, resembling something close to what a camera with low exposure film and a low shutter speed might produce. The results on any larger scale, however, are not quite so convincing, as shown in figure 2.4.3. This is of course an adequate rendering, however, given that the goal of the simulation was more in line with modeling the spread of fire than achieving a truly realistic visualization.

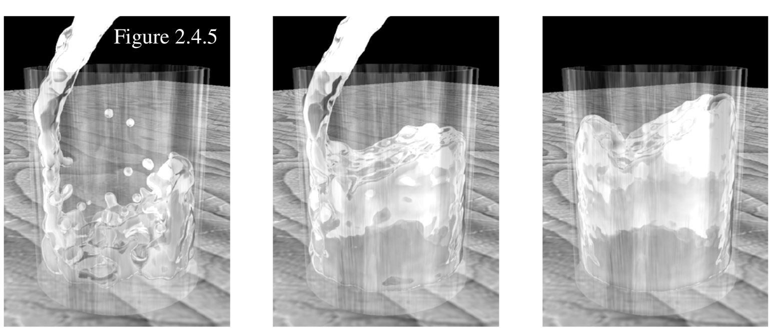


Figures 2.4.2 and 2.4.3: *Two figures showing the results of the flame modeling technique from figure 2.4.1, used by Perry et al. [2]. Figure 2.4.1 shows the results of a candle flame rendering model and figure 2.4.3 shows a larger scale fire rendering.*

In 2003, Müller et al. [6] investigated real-time particle-based water rendering, proposing a new method of handling surface tensions. The method was based on Smoothed Particle Hydrodynamics and utilized Computational Fluid Dynamics for physics-based modeling. While fire and water are clearly not the same, they share certain visual properties that make this work worthy of comparison. The visualization method used in rendering the water particle system was a method known as *point splatting* (explored in 4.2). Figures 2.4.4 show some results of the simulation. Using point splatting alone, they succeeding in rendering the pouring of water into a glass at 20 frames per second. Applying the marching cubes algorithm – a visualization technique which divides the scene up into small cubes, or voxels, and draws a plane inside each voxel intersecting the points of the surface data – results were more pleasing, but the frame rate dropped to 5 frames per second.

Using a volumetric approach such as the marching cubes algorithm is not effective when dealing with an intangible substance such as fire, which has no "surface," as such. Nevertheless the idea of point splatting is not an unrealistic one to apply to fire visualization, as we have seen it applied with textures in the fire simulator created by Wei at al. depicted in figure 2.3.6.





Figures 2.4.4 and 2.4.5: *Figure 2.4.4 shows a swirl in a glass induced by a rotational force field. The glass holds 2200 particles. Image* (a) *shows the particles,* (b) *the surface using point splatting, and* (c) *the iso-surface triangulated via the marching cubes algorithm. Figure 2.4.5 shows the pouring of water into a glass at 5 frames per second*. Images borrowed from Müller et al. [6].*

** On a 1.8 GHz Pentium IV with a GeForce 4 graphics card.*

3 Fire: the Physical Model

3.1 The house is burning! Or is it…?

Common perception of an object on fire is that the object itself is burning. It is, however, not the object that burns, but the fuel that the object emits into the surrounding environment that burns. This fuel rises to the surface of the object through heat, vaporizes, and then reacts with oxygen to ignite. Hence, fire requires the co-presence of three elements: fuel, heat and oxygen [11].

- *Fuel*. Fuel can be in the form of a solid, liquid or gaseous substance, although all fuels must be chemically decomposed into gases or vapors if they are to burn. This decomposition process takes place through the action of heat.

- *Heat*. Heat is a measure of the molecular activity occurring within an object, with higher the temperatures causing faster action in the molecules. If sufficient heat is applied to an object, the molecules may move so fast that they break away from the surface. This is how the fuel is transformed to gas.

- *Oxygen*. Oxygen is the oxidizing agent and is thus essential to combustion. At a certain stage, fire particles may change to smoke particles because of lack of oxygen in the air, which causes incomplete oxidization.

3.2 How to set a house on fire

The US Army Corps of Engineers [11] defines fire or combustion as "rapid oxidation with the action (evolution) of heat and light." Fire is subsequently described as being produced through the following stages:

1. Oxidation causes the combustible material to decompose, slowly giving off gases, including water vapor. It takes place continuously as long as it is exposed to an oxidizing agent, which may be air. At ambient temperatures, oxidation is usually so slow that the process is not noticeable to human senses. The combustible gases are not yet ignitable during this early stage.

2. The rate of oxidation increases as the temperature rises, with some of the gas eventually becoming ignitable. The point at which sufficient vapor is released to cause a flammable mixture in the air is known as the *flash point*.

3. At the aforementioned flash point, the evolved gases are too rich in carbon dioxide and water vapor to sustain flame very long. However, the heat of the flame will start a secondary decomposition reaction process, eventually allowing combustion to take place. This point is known as the *fire point* and is usually a few degrees above the flash point.

4. Oxidation may be so fast that it blankets the fuel surface and excludes air, preventing the char from burning and retarding the penetration of heat. This delays the ignition temperatures in penetrating deeper into the combustible material. However, as temperatures increase, the char begins to glow, air flows in to support combustion, and the fuel itself burns as well as its decomposition gases.

5. If more heat is generated than is lost through conduction, convection, or radiation, the flame will persist and fire will come into being. Combustion will be sustained until either heat, fuel, or the oxidizing agent are removed from the system.

3.3 Fire has genres

According to Nielsen [8], fire can loosely be divided into the following five visually characteristic groups:

- *Calm fire*. A typical calm fire is the one illuminating your typical candlelit dinner for two, and is thus the fiery analogue of the music industry's ambient genre. A calm fire is largely undisturbed by internal or external force alterations. Hence, the flame is perceived as calm, and appears to barely move, if at all.

- *Freely fed*. A freely fed fire is a fire that has no lack of fuel and receives plenty of oxygen, although both will fluctuate somewhat with time and position. This is in contrast to a calm fire, which has a more or less constant and regulated amount of both fuel and oxygen available for consumption at all times and in all regions of the fire.

- *Violent fire*. In a violent fire, external forces act strongly on the fire, resulting in an irregular fuel feed and the spread of fuel components in directions other than mostly vertically. Violent fires are temperamental and highly unpredictable due to the underlying complexity of the system and the number of contributing forces.

- *Pressure fed*. A pressure fed fire is a freely fed fire which has velocity vectors imposed on the fuel as it is released into the air.

- *Explosions.* In an explosion, the fuel is initially compressed. Ignition results in shockwaves, which induce new small explosions, resulting in further shock waves. Explosions were earlier referred to in this paper as detonations.

firestarter mostly resembles the freely fed fire, in that the fuel amount will be approximately constant, but not entirely so, and the amount of oxygen is somewhat stochastic, with a dearth of oxygen in the heart of the system where the flame is the hottest and the most oxygen is consumed. This type of fire is the most common type of fire, being the one that would most likely result from, to give a random example, lighting a house on fire.

3.4 Why fire looks the way it looks

Fire is a complex phenomenon, to say the least. For the purposes of this paper, it is necessary to provide an overview of only the most important physical traits affecting how we, as humans, visually perceive fire, without delving into mathematical specifics and introducing cumbersome equations. Some issues are the fire color spectrum, air friction causing drag, and the formation and appearance of soot and smoke.

Usually, in the natural sciences, fire is treated as a black body radiator for the purposes of color. To put it succinctly, a black body radiates photons in colors ranging from black to red, through orange and yellow, to white. This range of colors is referred to as the black body palette. This palette transposed onto a fixed spectrum as shown in figure 3.4.1 has limitations, however, since it does not consider the range of the chemical composition of the fuel, which affects the color of the flame. The model is further hindered by the fact that it is bounded by the color spectrum of computer monitor (or in this case, printer), which is only a subset of the full visible light spectrum (approx. 350nm to 780nm).

Figure 3.4.1: *The black body palette, a widely used approximation for the light perceived from carbon-based combustion. Figure borrowed from Nielsen [8].*

Where in the black body spectrum a flame's color falls depends on the type of fuel being burned and the flame's temperature. For those with a more advanced chemistry background, the color is caused by electrons jumping orbitals, thereby releasing photons of the appropriate frequencies. As is trivially self-evident, these frequencies happen to lie inside the visible light spectrum. While this is a very simplistic explanation, it is sufficient for the purposes of our simulation. The reader is referred to Nielsen [8] for a more detailed discussion.

The interaction of color and temperature can be observed by viewing a lit candle, not unlike the one shown in figure 3.4.2. The part of the flame closest to the wick is invisible, changing to a bluish color at the border of the base of the flame. At the hottest point, the flame is white. It then stays at a light yellow for some time, and eventually merges into orange and possibly red at the tip. A quick comparison of the candle flame colors and the black body palette highlights the shortcomings of the palette, because the palette is not specifically geared towards the rendering of a wax-fuelled flame. *firestarter* attempts to remedy this by allowing the user some limited customization control over the palette that is used during the simulation, as is elaborated in section 5.3.

Figure 3.4.2: *A candle flame.*

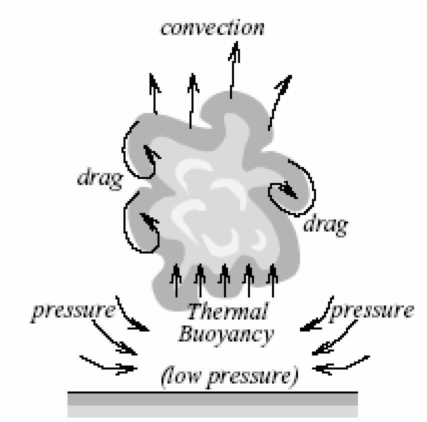


Figure 3.4.3: *The motion of a hot turbulent gas. Figure borrowed from Nielsen [8].*

Moving away from color, we will now go on to discuss factors that influence the motion of fire. The following example has been borrowed from Foster et al. [3] in illustrating the motion of a hot turbulent gas. Consider an old fashioned steam engine venting a jet of hot gas from its boiler. At the beginning, the governing factor in the motion of the gas is the velocity it has when rushing into the surrounding air. As it mixes with the slower moving air, the steam experiences *drag* (shearing forces), and starts to rotate in some places. This rotation causes more mixing with the air, and results in the characteristic turbulent swirling that we see when gases mix. According to Foster et al. [3], a second important factor that affects gas motion is temperature. As the steam is vented, it will rise, and hotter parts of the gas will rise more quickly than regions which have mixed with the cooler air. As the gas rises, it causes internal drag, and more turbulent rotation is produced. This effect is known as *thermal buoyancy*. The effects of drag and thermal buoyancy are shown in the accompanying figure 3.4.3. Another important factor, as suggested by Nguyen et al. [7], is the often-neglected aspect of the expansion of fuel as it reacts to form hot gaseous products. It is claimed that this expansion is the reason for the visual fullness observed in many flames, and in addition to those forces shown in figure 3.4.3, is also partially responsible for the visual turbulence. Unfortunately, for *firestarter*, all of these phenomena were evaluated as being far to complex to qualify for simulation in any real-time conformant fashion, and thus have been generalized to a rather nondescript "chaos factor," expounded on in section 5.2.

Finally, smoke and soot appear when there is insufficient oxygen to sustain combustion at the core of the fire. Rather, the combustion is incomplete, resulting in the creation of visible byproducts such as soot. Smoke results when the soot mixes with H_20, which it most commonly will do. Smoke from a fire will almost always be very dark, because of the high levels of carbon in the gas. However, other colors might appear from the fragments of the burning material or other byproducts, such as the gray color from steam (more H_20 than soot) [8]. Smoke and soot were implemented in *firestarter* as described in sections 5.2 and 5.3.

4 Issues in Real-Time Rendering

4.1 The core issue

According to Young [13], a real-time system is "any information processing activity or system which has to respond to externally generated input stimuli within a finite and specified period." Thus, a real-time graphical fire simulation is a simulation whose sequential behavior and environment must be computed within a period of time consistent with its real world behavior and environment. This is in contrast to production pipeline rendering, previously discussed in section 2.2, which involves the computation of each frame of simulation ahead of time, each individual frame taking as long as hours to be fully rendered. The frames are then sequences together to create a movie, of sorts.

In computer graphics generally, the tradeoff most commonly encountered is that between speed and realism. In real-time applications, though, rendering speed is given the highest priority; enhanced realism is almost always useless if the frame rate is not up to a certain standard. Therefore, the core problem in real-time rendering is balancing computational stresses to achieve optimal realism, given a minimum acceptable frame rate.

For each desired attribute, it is necessary to choose the algorithm that is optimal for our needs. Such optimality is often achieved by deploying hacks that have little relation to "real-world" observations but still accomplish the desired effect. Several examples will present themselves in this section. The idea is that, as long as the results are visually acceptable and the simulation runs fast enough, nobody is likely to notice much of a difference. There is historically no shame in this since these hacks have been a part of the graphics industry since its very inception. In fact, this *was* the industry at its very inception.

The simulation of fire can be broken up into three non-overlapping parts: modeling, animation, and visualization [8]. First, it is necessary to adopt an underlying structure, or model, for the simulation. Next, the method by which this model is chosen to interact with itself and is thereby given life is known as the animation technique. Finally, the modeling and animation need to be brought to the screen somehow through some visualization primitive (i.e polygons, textures, spheres, voxels, etc). The following sections will discuss each of these stages in sequence, and how they interact with one another.

4.2 Modeling and Visualizing fire

Stochastic fire modeling methods such as turbulence and noise fields are very effective at achieving realistic fire at the 2D level, but are too computationally expensive to work for 3D real-time animations, regardless of the visualization technique. Alternatively, a volumetric rendering model using voxels could run at real-time speeds if efficiently implemented, but would not seem to produce realistic results for a fire simulation given that fire does not have an explicit bounding surface (recall the use of the marching cubes algorithm to visualize water in section 2.4). At the other extreme of the speed spectrum we have volumetric modeling using polygons for visualization; polygons can be rendered very fast, although they are by nature not ideal for visualizing the licking nature fire, or swirling smoke and dust particles, and therefore generally yield crude and sub-par results. Somewhere in between, modeling using particle systems, however, can be as slow or as fast as desired because of their highly variable scale, further depending on the amount of detail incorporated into the system by the underlying animation and visualization techniques employed. As we have seen, most fire simulations are done using particle systems of some form or another. In the interest of brevity, from hereon this modeling method will be our main focus, since *firestarter* is no exception. Particle systems allow 3D behavior to be modeled in an intuitive and non-complex manner, although naturally they have their own share of problems as discussed below.

One problem with particle systems is that, by themselves, they assume the same environment for all particles in the system. A solution to this is to subdivide the environment into smaller pieces called *fields* [8]. A field contains information particular to a certain portion of the scene, which is typically bounded in the form of a cube, a rectangular prism, or other shape that can be patterned to form a mosaic with the environment. Fields, however, find their bane in memory usage. Ideally, the grid should surround the entire scene capable of being affected*, but the cubes should be small enough to make the fields have a meaningful impact on the simulation. This is a hard balance to strike, since placing as few as 10 field cubes across a single dimension in a cubic scene amounts to $10^3 = 1000$ fields, where individual calculations need to be made for each field at every frame. Yet even this number is a conservative estimate since the environment of a fire simulation is typically not cubic in shape, and thus the height is often significantly greater than the width/depth.

A second problem with particle systems is that, in their most primitive form, they require an enormous number of particles to fully simulate a physical system, since ideally we would be dealing with particle interactions at a molecular level. Clearly, we must generalize. *Texture mapping* is one such form of generalization, and some variation of it is the typically opted for solution when real-time rendering speeds are required. An example of texture mapped fire was seen in figure 2.3.6, and used the texture maps shown in figure 4.2.1†. In texture mapping of fire, a static animation of fire is mapped onto a polygon placed at the location of a particle in the particle system. Through this mapping, the idea is that this point now represents a cluster of fire particles arranged as depicted on the texture. The polygon will (typically) always face the viewer by rotating on the y-axis when the viewer moves around it. However, one will notice that the polygon can only really face the viewer along the *x* and *z* dimensions (rotating around *y*), and thus – as can be imagined – the fire can look strange when seen from above, particularly from a steep angle. There is also a problem with texture mapping in that the lighting of the scene will treat it as a solid face, and thus apply lighting effects to the fire, which is of course not realistic at all. If anything, the light intensity from the fire should be weakened rather than augmented by surrounding light sources due to the pupil dilation that occurs in human response to incoming light.

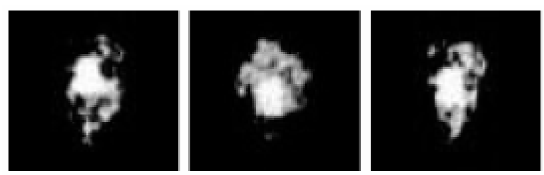


Figure 4.2.1: *Texture splats generated from real images, used by Wei et al. [12].*

One enhancement to texture mapping is *texture splatting*, which is a technique for simulating volume rendering. Texture splatting takes a texture bitmap and composes it with an opacity map, so that the bitmap is partially transparent. In other words, texture approximations at various depths are layered, or composited on top of one another by blending. *Point splatting*, as discussed in section 2.2, applies this technique to points (presumably spheres) rather than textures.

* the bounding of which can be no small problem if the fire is allowed to spread as well.

† in their implementation, the textures were *splatted* rather than *mapped*, the difference will be explained shortly.

Another enhancement to texture mapping is that, rather than consistently reusing the same texture map/splat on the same particle polygon, pictures of real fire can be sequenced onto polygons to lessen the static element, and make the fire look more mobile. This technique is claimed to yield very convincing results [8], although no visual examples could actually be found in the literature.

The observant reader will notice that the above method effectively incorporates prerendered aspects (textures and movie clips) into a real-time simulation*. Similarly, one could also argue that, by incorporating 2D textures, the simulation is not a truly 3D simulation anymore. These are example of the hacks discussed in the opening section of this chapter. Textures do not have any real world analogue, and are thus a hack, in the full sense of the word. Textures blur the 2D/3D distinction, although the use of 2D rendering in a 3D environment is most common given its comparatively much lower time complexity. As discussed in sections 5.1 and 5.3, *firestarter* is such a 2D/3D hybrid, although it also incorporates a volumetric aspect.

4.3 Animating fire

There are many ways in which fire can be animated. Among them, approaches using differential equations can produce accurate animations, but necessitate the tracking of a large number of variables. The simulations they produce are also difficult to control because their parameters are physical constants whose relationship to the desired visual effect is usually hard to ascertain. Additionally, the values of many parameters need to be guessed, since our understanding of fire is incomplete. Most importantly, however, this modeling technique is almost always computationally infeasible at the real-time level. The solution is typically some attempt at capturing the most important physical properties of the phenomenon, as highlighted in section 3.4, and then concocting an implementation for each of those properties that is both as efficient and realistic as possible. The goal is that the implementations are believable enough that they do not appear to be too *ad hoc*, and therefore just another hack. Inevitably, they will be just another hack, but we would naturally prefer elegant ones wherever possible.

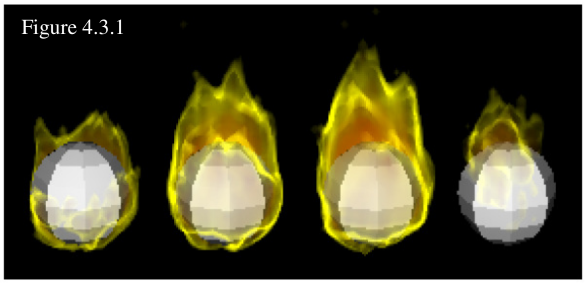
4.4 Motion blurring

An argument put forth by Beaudoin et al. [2] is that, although particle sets succeed in picturing the fuzzy, bumpy boundaries of clouds (for instance), they fail to show the characteristically crisp, sleek outlines of actual flame. This is true in that at any instant in time, flames do have a crisp, sleek outline. Yet when we see flame, we do not see it at an instant in time. Rather, we see it as it exists over some period of time, resulting in an important visual effect known as *motion blur*.

As the name implies, motion blur is a blurring of objects that move relatively to the viewer, and is demonstrated for the case of fire in figure 4.3.2. In all computer graphics systems that simulate moving objects, the shutter speed of the virtual camera plays an

* the simulation remains real-time because the prerendered aspects are reused

important role in the level of photo-realism. When frames in an animation are rendered without taking motion blur into consideration – as they are usually done – the result is a simulation of a camera with an infinite shutter speed. Yet if the animation runs at, for instance 25 frames per second, there is a 0.04 second interval between each frame during which the camera shutter is open. In a realistic visual simulation, this should be taken into account and the camera "exposure" simulated accordingly [8]. Note that textures used in a particle systems can serve a dual function in this respect by prerendering the blurring effect.



Figures 4.3.1 and 4.3.2: *Figure 4.3.1 shows the results from the (non-real-time) simulation produced by Beaudoin et al. [2]. Rather than using a particle system, the simulation uses a three polygon-layer volumetric modeling approach. While the results look to be successful, the simulation does not take motion blurring into account. Figure 4.3.2 shows a real fire. Note the motion blurring of the flame, particularly in the upper right-hand corner.*

5 *firestarter* – A Real-Time Fire Simulator

5.1 Modeling *firestarter*

- The fire itself is modeled using a particle system.
- The environment is modeled as a cylindrical grid of fields.
- The system outside of the cyclical grid is generalized to a space called the *globalCell*.
- Object interaction is not modeled in the simulation.

<u>*5.1.1 Variables*</u>

- The fire itself is modeled using a particle system. Each particle contains the following information regarding the modeling aspect of the fire system:

  - ***death*** – the time at which the particle dies. After this time expires, the death is reset to a new value and the particle is reborn at the base of the flame.
  - ***x, y, z*** – the 3D coordinate set of the particle at a given point in time.
  - ***currentCell*** – a pointer to the environment cell in which the particle is currently present.
  - ***xOrigin, zOrigin*** – the points at which the particle originated. The particle's position is reset to this coordinate pair at the base of the flame when the particle is reborn (see *death*).
  - ***cellOrigin*** – a pointer to the environment cell in which the particle originated.

- The environment is modeled as a cylindrical grid of fields. Each field in the environment is referred to as a cell in the code of the simulation. Each cell contains the following attributes relating to the modeling aspect of the environment:
  - ***x, height, z*** – the 3D coordinate set of the central point of the cell.
  - ***population*** – the number of particles presently located in the cell.
  - ***particleList*** – a pointer to a linked list data structure containing pointers to the particles located in the cell.
  - ***topCell*** – a pointer to the cell directly above this cell, if any.
  - ***leftCell, rightCell, frontCell, rearCell*** – pointers to the cells directly adjacent to the current cell, if any.
  - ***leftFrontCell, leftRearCell, rightFrontCell, rightRearCell*** – pointers to the cells diagonally adjacent to the current cell, if any.

- The system outside of the cyclical grid is generalized as a cell called the ***globalCell***. This "cell" renders all smoke particles, which become relegated from the above system (see *animation*), and contains all particles that have crossed the boundary of the environmental cylinder and are therefore no longer considered part of the system, and are subsequently not rendered until they die and are reborn.

5.1.2 User Preset Constants

- **PARTICLES** – the number of particles in the system.
- **GRID_HEIGHT** – the height of the cylindrical cell grid.
- **GRID_DIAMETER** – the diameter of the cylindrical cell grid.
- **CELL_HEIGHT** – the height of the grid cells (the *y* direction).
- **CELL_WIDTH** – the width of the grid cells (the *x* and *z* directions).

5.2 Animating *firestarter*

- Particles are born, or created, at the base of the cell grid system, within a certain radius of the grid system known as the "fuel radius." The ratio of the fuel radius to the cell grid radius is tunable by the user before the start of the simulation, but should be less than one for obvious reasons (see 5.2.3).

- Fire particle have a life specified by a user-controlled constant, after which time they are "reborn".
- Fire particles have a vertical velocity determined by a combination of the temperature of the cell in which the particle is located, and the aggregate speed modifier of the particle (each particle has a predisposed upward inclination). Both of these effects can be modified through two user-controlled constants.
- Fire particles have a horizontal velocity that is randomized and specific to the cell in which the particle is positioned. The randomization is context sensitive, and the degree is controlled by two user-controlled constants.
- Each frame, fire particles are checked against their position to determine if they have propagated into a new cell.
- Each frame, fire particles can potentially become smoke particles with a certain probability that is determined by a user-controlled constant. The probability increases as the particle rises higher.
- Smoke particles are advanced according to their momentum at the point at which the particles became smoke. Per frame, the upward velocity increases modeling the buoyancy effect, and the horizontal velocity decreases modeling the effect of air resistance. The degree of these velocity modifiers is controlled by a single user-controlled constant.
- One of the particularly redeeming qualities of the simulation is that it is frame rate sensitive. In other words, the simulation monitors the frame rate and calibrates its behavior accordingly, so that the fire's behavior is characterized along a *per second* basis, as opposed to a *per frame* basis. This is very effective at containing the simulation and having it appear as it was designed regardless of the frame rate (barring extremes).

5.2.1 Variables

- Each particle contains the following variables pertaining to the animation aspect of the simulation:
  - **Δx, Δy, Δz** – the 3D velocity vector of the particle at the last frame (used to store momentum information for smoke particles).
  - ***smoke*** – a Boolean indicating whether or not the particle is to be rendered as smoke if outside the environmental grid system.
  - ***speed*** – the predisposed upward velocity inclination of the particle. Generated using BUOYANCY_RANDOMNESS (see *5.2.2*)

- Each cell contains the following information pertaining to the animation aspect of the simulation:
  - ***xVector, zVector*** – the *x* and *z* velocity vectors of all particles in that cell at a particular frame in the simulation.
  - ***temperature*** – for all intents and purposes, this is the *y* velocity vector of all particles in the cell, although this vector is modified by the speed

attribute of the individual particles. This attribute also affects the color drawn at a particle.

5.2.2 User Runtime Adjustable Constants (aka. User-Controlled Constants)

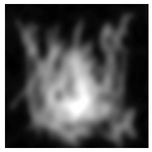
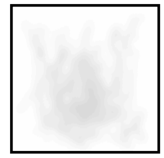
- **PARTICLE_LIFE** – the life of a particle in seconds before it is reborn.
- **FLAME_SPEED** – the average speed of a particle in units per second.
- **BUOYANCY_RANDOMNESS** – the degree of deviation in the upward velocity vector modifier (the *speed* attribute) of particles.
- **CHAOS FACTOR** – the degree of deviation in the sideways movement of both fire and smoke particles.
- **CENTRAL_DRAW** – the inverse of the rate at which the sideways movement remains consistent between frames (a higher value makes the simulation less context sensitive, and therefore more truly random).
- **SMOKE_RANDOMNESS** – the degree of deviation in the movement of smoke particles specifically. This modifier is cumulative with CHAOS_FACTOR.
- **SMOKE_AMOUNT** – the rate at which fire particles are converted into smoke.

5.2.3 User Preset Constants

- **FUEL_GRID_RATIO** – the ratio of the fuel radius to the grid radius. The circular area in which particles originate (set by the fuel radius) should be smaller than the actual radius of the grid (set by the grid radius). This is because fire expands from its fuel base, growing outwardly. It is important that the majority of particles remain in the grid system, or otherwise they will not be rendered.

5.3 Visualizing *firestarter*

- The cells in which particles originate have pointers to a circular chain of those particles. Of these particles, those which are fire particles are joined sequentially as a triangle strip with the fire texture mapped onto each successive quadrilateral. In other words, each cell at the base of the fire has a "wall" of fire rising out from it, where the wall is analogous to a very wrinkled, wavy banner rising up from the fuel.
- The color mapped over the top of the fire texture (which is itself purely monochrome) is based on the temperature value of the cells at the vertices of the quadrilateral, where the vertices are the particles of the system. The color palette is customizable according to temperature in the following manner:
    - The formula: color_base ± (temperature^2 * color_adjust)
    - Example (defaults):
        - Red: 0.75 + (temp^2 * 0.20) -- range: 0.75 - 0.95
        - Green: 0.40 + (temp^2 * 0.30) -- range: 0.40 - 0.70
        - Blue: 0.05 + (temp^2 * 0.10) -- range: 0.05 - 0.15

- The fire texture:  The smoke texture (enhanced[*]): 

- Smoke particles are rendered as 2D square textures oriented to face the viewer. The size of these squares is customizable by the user through the preset constant **SMOKE_SIZE**.
- Due to the nature of how blending is performed to achieve real-time speeds in graphics libraries such as OpenGL, for a surface to blend with the surface behind it (transparency) the surface behind must be rendered first. For the exact order and method in which this was done the reader is referred to section 5.4. For now, the OpenGL blending functions employed for fire and smoke are as follows:

  - **glBlendFunc(GL_SRC_COLOR, GL_ONE_MINUS_SRC_ALPHA)** for fire. This means that the color of a pixel is determined by the following formula:

    NewColor = SurfaceColor * TextureColor + (1 – SurfaceAlpha) * BackgroundColor

    More precisely, for each successive drawing over a pixel, the pixel's color is determined by the RGB color parameters of the surface determined by the temperature (see color palette discussion above) *times* the texture RGB color values (less than or equal to 1.0 – Higher in the middle and fading to 0.0 (black) at the borders). We add to this the background color by a factor of 1.0 minus the alpha channel. The alpha channel is 0.03 by default, and so 0.97 (97%) of the background RGB color is filtered through the image by default. In simpler, although slightly less accurate words, the textures are 97% transparent.

  - **glBlendFunc(GL_DST_COLOR, GL_NONE)** for smoke, which means that the color of a pixel is determined by the following formula:

    NewColor = BackgroundColor * TextureColor

    In more understandable terms, for each successive drawing over a pixel, the pixel's color is determined by its current RGB color values *times* the texture's RGB color values. Since the texture's RGB color values are less than 1.0 except on the very edges (where it is white), the new pixel color will always be darker than the old color because of the less-than-one coefficient. At the edges of the texture, however, the color will remain unchanged, giving a nice outward-fading, darkening blur effect.

5.3.1 User Preset Constants

[*] the texture is in actuality much lighter, but it has been darkened here for the viewer.

- **FIRE_BITMAP** – the bitmap to use for the fire. Recommended lighter in the center and darker towards the edges. A brighter bitmap will yield brighter results and may reduce the number of particles necessary to achieve a desired visual.
- **SMOKE_BITMAP** – the bitmap to use for the smoke. Recommended darker in the center fading to white at the edges. A darker bitmap will yield the appearance of denser smoke and soot.
- **FIRE_R_BASE / FIRE_G_BASE / FIRE_B_BASE** – the base RGB color components (see color palette discussion above).
- **FIRE_R_VARIABLE / FIRE_G_ VARIABLE / FIRE_B_ VARIABLE** – the variable RGB color component (see color palette discussion above).
- **FIRE_ALPHA_CHANNEL** – the degree of color contribution of the background elements for visualizing the fire. A higher value will yield brighter fire.

5.4 Algorithm Specifics

The simulation algorithm is as follows:

1. Initialization:
    a. Set up the OpenGL environment.
    b. Load the textures into memory.
    c. Initialize the cell data.
        i. Count the number of cells to be created given the specified grid bounds.
        ii. Establish cell position and orientation with respect to one another using the *breadth first search* algorithm.
    d. Initialize the particle data.

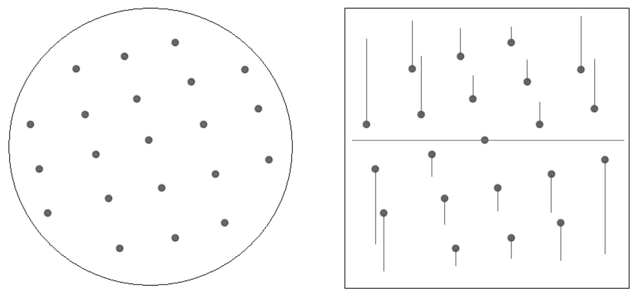
2. Rendering loop:
    a. Position the viewer.
    b. Draw the environment.*
    c. Determine the angle of view relative to the fire. If the fire is not in view, then do not perform the remainder of the loop and return to 2a. This prevents any unnecessary calculations being performed on the fire while it is not being rendered to the screen.
    d. Sort the cells by distance from the viewer for proper blending (see 5.4.1)
    e. Perform animation computations on the cells and the particles they contain
    f. Draw the cells in sorted order, rendering the particles that they contain to the screen.
    g. Loop to 2a.

* The torch is the default. If someone were to abstract the fire simulator into a class, then the simulator would be a component of the scene and this part of the algorithm would be removed.

5.4.1 Cell Distance Sorting Algorithm

It is necessary to sort the cells with respect to their distance from the viewer so that they are rendered in the correct order and blending is properly performed. A typical sorting algorithm would take O(n * log(n)) time complexity to complete. However, given that there are typically hundreds of cells in a horizontal slice of the grid, such a computation can be a very intense computation to have to perform at every frame. Fortunately, the knowledge that the distance from the viewer can be bounded within a certain range can be capitalized upon to produce a linear time algorithm.

Initially, the center points of the cells are located inside of a circular space in the grid. In order to create a bounded area that is constant in both its x and z dimensions, we must morph this circle into a square with edges, at an angle aligned with the viewer, and scale the points inside accordingly (see figures 5.4.1 and 5.4.2). Once this is done, we can assign rank numbers to the cells based on the distances of these points from the front edge of the square. Since the points are arranged in an ordered and distributed fashion in the circle, this algorithm is very effective at assigning unique rank numbers. The algorithm runs in linear time, with a multiplier that has been found to typically lie somewhere between 1.5 and 3.0, depending on the angle and layout of the cells within the circle. The multiplier exists because occasionally two points are assigned the same rank, at which point the latter point must then search for an open rank nearby. On the whole, however, this occurs rarely enough to make the benefits of the approximation algorithm worthwhile.



Figures 5.4.1 and 5.4.2: *Two diagrams showing the before and after of the scaling process. Note that the central points of the cells are scaled along with the circle.*

5.4.2 Time Complexity

The initialization code is O(c) + O(p), where c is the number of cells and p is the number of particles. In practice, however, code which traverses all the cells is run with much more frequency than code which traverses all the particles, being run only once, and thus the number of cells is by far the stronger determiner of the two.

Thanks to the blending algorithm, the drawing code is similarly O(max(c, p)). The complexity is linear to the maximum of either the number of cells or the number of particles. This is because all the particles are processed indirectly through the code that calls the cells. Hence, normally the number of particles will be the dominant factor. However, if for some reason there are more cells than particles[*], then there will be calls to cells where no particles are called, and the cell count will dominate.

[*] Not a recommended circumstance.

5.5 Results

The following pictures and data from the simulation were gathered from its execution on a 700Mhz Pentium III processor using an NVIDIA GeForce 256 graphics accelerator card.

Figure 5.5.1: firestarter *run with 5000 particles viewed from close by.*

Figure 5.5.2: firestarter *run using 500 particles at 230 fps.*

Figure 5.5.3: firestarter *run using 1500 particles at 100 fps.*

Figure 5.5.4: firestarter *run using 5000 particles at 50 fps.*

Figure 5.5.5: firestarter *run using 15000 particles at 25 fps.*

Shown in figures 5.5.1 through 5.5.5 are sample screenshots taken running *firestarter* given the default settings. It is naturally hard to gauge the effectiveness of the simulation from static images, but they give the reader some idea of how the simulation might look when run in real-time.

It was possible to achieve a realistic looking fire running at 50 frames per second using 5000 particles. Fewer particles were still capable of achieving realistic results, but only from a more remote distance.

The reader should note that the simulation defaults leave significant room for improvement, and are not optimized for efficiency at present. For instance, the texture used for fire is rather dull, and a brighter image would obviate the need for as many particles, since each texture mapping would lend more color to the rendering. The color palette defaults are also most likely sub-optimal, since they were chosen rather arbitrarily and not analyzed for the most effective distribution. Superior blending methods may also exist to the ones outlined in section 5.3.

As an interesting side note, Muller et al. [6] were able to speed up their simulation by a factor of 10 by storing copies of the particle objects in the grid cells rather than storing references to those particles. This doubled memory consumption, but greatly enhanced the proximity in memory of the information needed for interpolation, causing a subsequently large increase in the cache hit rate. *firestarter* does not exercise this degree of low level control, but a factor of 10 does seem rather appealing and so this is a promising area for future addition.[*]

6 Conclusions

It is difficult to predict how effective *firestarter* would be, incorporated into an interactive application such as a computer game. Computer games are the interactive realm to which it would most likely be destined given that it does not interact with other objects in the environment; *firestarter* would only be useful in a scene where the fire is acting as an ancillary entity – where the fire is not the focus of attention, but nonetheless adds aesthetic realism to the scene. [†]

It has been demonstrated that doubling the number of particles roughly halves the frame rate (this is consistent with the complexity analysis), and thus having multiple fires in the view of the user would place a severe strain on the application. Thus, it would appear that the strains are presently too great for the inclusion of *firestarter* into a complex environmental scene where it is not part of the focal point of a scene. On the other hand, the computer on which these test runs were executed is roughly five years behind modern-day state of the art computer systems. Most significantly, the GeForce 256 is several generations behind newer graphics cards available at the time of this writing, where 3D graphics acceleration is a field of computer graphics that has made considerable leaps in recent years.

Nonetheless, the simulation has been by and large successful in accomplishing the goals set at its inception. A new visualization technique has been introduced into the literature, which will potentially provide inspiration for other ideas heading into the future. *firestarter* is a worthy first attempt at modeling a highly complex system, and given that it is at present highly customizable, it may yet make a significant contribution, should people's curiosities be piqued.

[*] Note that if *firestarter* were integrated into a real-time interactive program where the fire was peripheral to the scene, then the performance increase might not be quite as realizable due to other components of the application also utilizing cache resources.
[†] This would not be the case in, for instance, a fire simulator for firemen, or an educational tool for a chemistry class.

7 References

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