Fractal Expressionism—Where Art Meets Science

Richard Taylor

1 INTRODUCTION

If the Jackson Pollock story (1912–1956) hadn't happened, Hollywood would have invented it any way! In a drunken, suicidal state on a stormy night in March 1952, the notorious Abstract Expressionist painter laid down the foundations of his masterpiece *Blue Poles: Number 11, 1952* by rolling a large canvas across the floor of his windswept barn and dripping household paint from an old can with a wooden stick. The event represented the climax of a remarkable decade for Pollock, during which he generated a vast body of distinct art work commonly referred to as the "drip and splash" technique. In contrast to the broken lines painted by conventional brush contact with the canvas surface, Pollock poured a constant stream of paint onto his horizontal canvases to produce uniquely continuous trajectories. These deceptively simple acts fuelled unprecedented controversy and polarized public opinion around the world. Was this primitive painting style driven by raw genius or was he simply a drunk who mocked artistic traditions? Twenty years later, the Australian government rekindled the controversy by purchasing the painting for a spectacular two million (U.S.) dollars. In the history of Western art, only works by Rembrandt, Velázquez, and da Vinci had commanded more "respect" in the art market. Today, Pollock's brash and energetic works continue to grab attention, as witnessed by the success of the recent retrospectives during 1998–1999 (at New York's Museum of Modern Art and London's Tate Gallery) where prices of forty million dollars were discussed for *Blue Poles: Number 11, 1952*.

Aside from the commercialism and mythology, what meaning do Pollock's swirling patterns of paint really have? Art theorists now recognize his patterns as a revolutionary approach to aesthetics [11, 31]. In a century characterized by radical advances in art, his work is seen as a crucial development. However, despite the millions of words written on Pollock, the precise quality which defines his unique patterns has never been identified. More generally, although abstract art is hailed as a modern way of portraying life, the general public remains unclear about how a painting such as *Blue Poles: Number 11, 1952* (color plate 9) shows anything obvious about the world they live in. The one thing which is agreed upon is that Pollock's motivations and achievements were vastly different from those associated with traditional artistic composition. Described as the "all-over" style, his drip paintings eliminated anything that previously might have been recognized as composition; the idea of having a top and bottom, of having a left and right, and of having a center of focus. Pollock's defense was that he had adopted a "direct" approach to the expression of the world around him, concluding that "the modern painter cannot express this age, the airplane, the atom bomb, the radio, in the old form of the Renaissance. . .each age finds its own technique" [14].

Appreciation of art is, of course, a highly subjective and personal judgement. Standing in front of one of Pollock's vast canvases, looking at the dense web of interweaving swirls of paint, no one can be told whether such imagery should be liked or not—least of all by a computer. A computer calculates the parameters of an object in a fundamentally different fashion to the human observer. People observe the many different parameters of the painting (for example, the size, shape, texture and color) at the same time, capturing the "full impact" of the painting. In contrast, the computer's approach is reductionist—it separates information, calculating each parameter in isolation. As a consequence, although a computer analysis can never tell you whether an art work should be "liked," it can tell you what the painted patterns "are" with remarkable precision and objectivity. Its reductionist ability to scrutinize individual parameters allows it to quantify information which might have been lost in the "full impact" witnessed by a human observer. The computer can employ its superior computing power (it calculates over six million patterns lying within the canvas) and precision (it examines patterns down to sizes of less than one millimeter) to quantify the painted patterns on Pollock's canvas. This deconstruction of Pollock's paintings into mathematical parameters might, at first, appear to be of little use in the world of art, where human assessments such as beauty, expression and emotion seem more appropriate. However, in this Chapter I will demonstrate that a computer analysis is crucial in order to identify what art theoreticians call the "hand" of Pollock—the trademarks that distinguish him from other artists.

What then is the identifying "hand" of Pollock? The surface of *Blue Poles: Number 11, 1952* has been likened to a battlefield. The vast canvas, stretching across five meters from end to end, contains shards of broken glass embedded in the paint encrusted surface, blood stains soaked into the canvas fabric and eight splattered "poles" violently imprinted by a plank of wood. With each clue shrouded in Pollock mythology, it is clear that an understanding of the essence of Pollock's work requires a rigorous distillation of fact from fiction. During his peak years of 1947–1952, the drip paintings frequently were described as "organic." suggesting the imagery in his paintings alluded to Nature. Lacking the cleanliness of artificial order, his dripped paint clearly stands in sharp contrast to the straight lines, the triangles, the squares and the wide range of other artificial shapes known within mathematics as Euclidean geometry. But if Pollock's swirls of paint are indeed a celebration of Nature's organic shapes, what shapes would these be? What geometry do organic shapes belong to? Do objects of Nature, such as trees and clouds, even have an underlying pattern, or are they "patternless"—a disordered mess of randomness? During Pollock's era, Nature's scenery was assumed to be disordered and his paintings were likewise thought to be random splatters devoid of any order. However, since Pollock's time, two vast areas of study have evolved to accommodate a greater understanding of Nature's rules. During the 1960s, scientists began to examine the dynamics of Nature's processes—how natural systems, such as the weather, evolve with time. They found that these systems weren't haphazard. Although natural systems masqueraded as being disordered, lurking underneath was a remarkably subtle form of order. This behavior was labelled as chaotic and an area of study called chaos theory was born to understand Nature's dynamics [7, 15]. Whereas chaos describes the motions of a natural system, during the 1970s a new form of geometry, called the fractal, was proposed to describe the patterns that these chaotic processes left behind [4, 12]. Since the 1970s many of Nature's patterns have been shown to be fractal, earning fractals the dramatic title of "the fingerprint of God." Examples include coastlines, clouds, flames, lightning, trees and mountain profiles. Fractals are referred to as a new geometry because the patterns look nothing like the traditional Euclidean shapes which humanity has clung to with such familiarity and affection. In contrast to the smoothness of artificial lines, fractals consist of patterns which recur on finer and finer magnifications, building up shapes of immense complexity.

Given that Pollock's paintings often are described as "organic," an obvious step towards identifying the "hand" of Pollock is to adopt the pattern analysis techniques used to identify fractals in Nature's scenery and apply the same process to Pollock's canvases. Following ten years of researching Jackson Pollock, in 1999 I published the results of a computer analysis which revealed that his drip paintings used the same building blocks as Nature's scenery—the fractal [26]. Previous theories attempting to address the artistic significance of Pollock's patterns can be categorized loosely into two related schools of thought—those which consider "form" (i.e., the pattern's significance as a new approach to visual composition) and "content" (i.e., the subject or message the patterns convey). Clearly, the identification of Pollock's patterns as fractal is a vital step for understanding their artistic significance, both in terms of "form" and "content." Rather than using the traditional terminology of Abstract Expressionism, his works are now being re-interpreted as a direct expression of Nature, and the discovery has since been labeled as "Fractal Expressionism" [25, 27].

In this chapter I will discuss the analysis techniques used to identify the fractal fingerprint of Pollock's work. In addition, I will present two recent developments of the research—one which focuses on the "content" and the other on the "form" of his drip paintings. The first concerns the multidisciplinary debate triggered by my results over the precise process that Pollock used to generate his fractal patterns. Exploration of Pollock's painting process raises intriguing questions for many researchers. For art theorists, identification of the method Pollock used to paint the fractals may provide clues as to why he painted them and thus to the artistic meaning—the "content"—of his fractals. His process also offers an intriguing comparison for scientists studying fractal generation in Nature's systems. For psychologists, the process represents an investigation of the fundamental capabilities and limits of human behavior. How did a human create such intricate patterns with such precision, twenty-five years ahead of their scientific discovery? Most examples of "fractal art" are not painted by the artist but instead are generated indirectly using computer graphics [17, 18].[1] How did Pollock construct and refine his fractal patterns? Pollock received significant media attention at his creative peak in 1950 and the resulting visual documentation of his painting technique offers a unique opportunity to study how fractals can be created directly by a human. I will present an analysis of film sequences which recorded the evolution of his patterns during the painting process and I will discuss the results within the context of recent visual perception studies of fractal patterns. Whereas these results explore the generation process in the hope of learning more about the "content" of Pollock's fractals, the second recent development concentrates on the precision with which the "form" of Pollock's fractals can be identified. In response to my results, a number of art museums and private art collectors inquired about the potential of the fractal analysis to authenticate and date Pollock's paintings. As the commercial worth of Pollock's paintings continue to soar, judgements of authenticity have become increasingly crucial. If a new drip painting is found, how do we decide if it is a long-lost masterpiece or a fake? When dealing with such staggering commercial considerations, subjective judgements attempting to identify the "hand" of the artist may no longer be adequate. I therefore will demonstrate the considerable potential that the fractal analysis technique has for detecting the "hand" of Pollock by examining a drip painting which was sent to me to establish its authenticity.

2 THE "DRIP AND SPLASH" TECHNIQUE—A COMPARISON WITH NATURE

Pollock's first exploration of the drip and splash technique took place during the winter of 1942–1943. Described as his "preliminary" phase, he completed the initial stages of the painting using the brushwork style of his previous paintings, but then dripped a final layer of paint over the surface. In late 1945 he moved from Manhattan to the Long Island countryside where he renovated an old barn for his studio and by the end of 1946 his first major drip paintings were under way. The procedure appeared basic. Purchasing yachting canvas from his local hardware store, he often abandoned the European ritual of stretching the canvas. The large canvases simply were rolled out on the floor of the barn, sometimes tacked, sometimes just held down by their own weight. Then he would size the canvas with one or two coats of industrial quality Rivit glue. Even the traditional painting tool—the brush—was not used in its expected capacity: abandoning physical contact

[1] Note that early Chinese landscape paintings also have recently been analyzed for fractal content. See R.F. Voss.[32] Although the individual brushstrokes were found to be fractal, the images constructed from the brushstrokes were non-fractal illustrations. In contrast, for Pollock's paintings the image itself was a fractal pattern.

with the canvas, he dipped a stubby, paint-encrusted brush in and out of a can and dripped the fluid paint from the brush onto the canvas below. The brushes were so stiff that, during a visit to see Pollock at work, fellow artist Hans Hofmann exclaimed, "With this you could kill a man."[2] Sometimes he even wouldn't use a brush, preferring trowels, sticks, or basting syringes. "I continue to get further away from the usual painter's tools," stated Pollock [20]. He used these tools in a strange yet rich variety of ways. A film by Hans Namuth and Paul Falkenberg of Pollock painting shows him sometimes crouched down near the canvas, almost drawing with the drips. Other actions show him flinging the paint across large distances. William Rubin (a previous director of The Museum of Modern Art, New York) described another variation on the dripping process, where Pollock would "place a stick in the can of paint, and by tilting the can, let the pigment run down the stick onto the canvas" [23]. Sometimes he even poured the paint directly from an open can. All of these techniques—which abandoned contact with the canvas—are grouped loosely under the descriptive label "drip and splash" technique.

In terms of the paint, an industrial quality enamel called Duco (technically, pyroxylin lacquer), was found to be the most pliable. Pollock had first used Duco in the 1930s during art workshops, and he now returned to using it because of its ease of application, good covering power and quick drying qualities. In addition, aluminum, silver, gouache and oil paints all contributed to his growing battery of effects. The stream of paint produced a continuous trajectory and its character was determined by physical and material variables refined and mastered by Pollock, including the viscosity of the paint, and the height, the angle and the speed of pouring. Most crucially, the paint trajectory directly mapped the artist's gestures and movements. Pollock's wife, Lee Krasner, later remarked that the secret to Pollock's success was his ability to work in air and know exactly where the paint would land—the paint trajectories captured two-dimensional fingerprints of his three-dimensional motion through the air. One of Pollock's friends, Bob Friedman, wrote, "Once Pollock painted in the barn his work began to open up, to shout, to sing" [5]. The barn offered freedom of motion, allowing him to approach his vast canvases from all four sides. Only afterward did he decide which way was up and which was down. As Pollock explained, "On the floor I am more at ease. I feel nearer, more a part of the painting, since this way I can walk around it, work from the four sides and literally be *in* the painting" [20]. Color plate 9 shows a photograph of Pollock above one of his paintings.

Contrary to mythology, a Pollock painting was not born easily. Pollock revisited his canvases frequently over weeks or even months, building up intricate layers woven into the increasingly dense web of paint. A typical canvas would be worked and reworked many times. Although he preferred not to think of his approach in terms of stages, the tortuous history of many of his paintings followed a common route. On his own admission, he would start the process by picking the paint can which was nearest at hand. Working feverishly, he would apply paint quickly in short, decisive bursts and the canvas would be covered with a basic pattern within half an hour. Namuth recalls photographing this first stage: "His movements, slow at first, gradually became faster and more dance-like as he flung black, white and

[2] Hoffmann's remark is quoted in O'Connor [14, p.203].

FIGURE 1 A photograph of Pollock with *Number 32, 1950* taken in 1950 by Rudolph Burckhardt. *Number 32, 1950* (enamel on canvas, 269 by 457.5cm) was painted by Pollock earlier in 1950 (Kunstsammlung Nordrhein-Westfalen, Dusseldorf, Germany).

rust-colored paint onto the canvas. My photography session lasted as long as he kept painting, perhaps half an hour. In all that time, Pollock did not stop" [13]. After this initial session, Pollock then would break off and step back for a period of contemplation and study. The first stage was over and at this point Pollock would have little idea when he would be sufficiently inspired to resume the painting. Instead, his thoughts would turn to other paintings. In this way, Pollock kept three or four paintings open at all times. However, no painting was safe—a canvas which had laid dormant for several months suddenly would regain his attention. Subsequently, a getting acquainted period would ensue, in which he decided how to add strength to the pattern. The next burst of activity might range from a small adjustment to a complete re-working. Glancing up from a newspaper he might spy some "imperfection" in the pattern and reach awkwardly around the back of his chair, "correct it" with whatever brush was closest at hand and then return to the paper. Alternatively, the painting might be deemed to be lost and he would start from scratch. In this way, the periods between different assaults could vary vastly from work to work. Some of Pollock's layers were laid down quickly, "wet on wet." In other works, a layer would be scrubbed into the surface with a rag before the next layer was deposited. Sometimes, Pollock would wait for a layer to dry and the following day the painting would be nailed to the studio wall for further contemplation (although the extent to which this happened remains controversial). Some paintings were even stretched before being reworked. To the casual observer the whole approach appeared very random. But, in this unique way, Pollock would revisit a painting at irregular periods until he decided the pattern was complete—"concrete" in his language—and the painting would be a record of his released experience.

There are a number of striking similarities between the above description of Pollock's painting style and the processes used by Nature to build it's scenery. His cumulative painting process is remarkably similar to the way patterns in Nature arise—for example, the way leaves fall day after day to build a pattern on the ground, or the way waves crash repeatedly on the shore to create the erosion patterns in the cliff face. The variation in intensity of his painting process also mirrors Nature: just as, say, the rain might change from a short, light drizzle on one day to an extensive storm on the next, Pollock's sessions would vary from small corrections on one day to major re-workings on the next. His method of leaving a painting dormant for a while before his return for a new onslaught is also similar to the cyclic routine of Nature—for example, the tides and the seasons. More generally, this idea of the painting as an ongoing process, occurring indefinitely, clearly reflects Nature's process of pattern generation. Out of all the Abstract Expressionists, Pollock was one of the main pursuers of this so-called "continuous dynamic" process. Another was Arshile Gorky, whose explanation is very similar to Pollock's: "When something is finished that means it is dead, doesn't it? I believe in everlasting. I never finish a painting—I just stop working on it for a while. I like painting because it is something I never come to the end of."[3] "He hated signing. There's something so final about the signature," recalled Krasner about Pollock.[4] Clearly, Nature has an advantage over the artist—its process really can go on forever while Pollock had practically-induced time frames. This notwithstanding, the "continuous dynamic" painting process suggests a closeness with natural evolution. Pollock's unease with the signing process—the artificial act which recognizes the canvas as an "art work" rather than as a piece of Nature—suggests an empathy that Pollock may have felt for natural processes. Furthermore, Pollock's spontaneous and unpremeditated painting process also bears a striking similarity to Nature: Nature doesn't prepare and think about its patterns—they are determined by the interaction with the environment at the specific moment in time that the patterns are being created. Interestingly, because of his unpremeditated style, Pollock often was regarded as an Action Artist and during Pollock's era the art critic Harold Rosenberg said that Action Art had "broken down every distinction between art and life," and that "the painting is not Art; it's an Is. It's not a picture of a thing: it's the thing itself...it doesn't reproduce Nature; it is Nature" [22]. Other parallels between Pollock's method of painting and natural processes are apparent. Gravity plays a central role for both Pollock and Nature. Pollock's whole approach of abandoning the easel and instead laying the canvas

[3] Gorky's statement was originally quoted by Talcott Clap, *Arshile Gorky: Paintings, Drawings, Studies* 43, catalogue. The Museum of Modern Art, New York, 1962.

[4] Krasner is quoted in Friedman [5, p.185].

on the ground triggers comparisons with Nature's processes. Many of Nature's patterns are built in the horizontal plane and controlled to an extent by gravity (for example, the falling rain or falling leaves). Unlike traditional brushstroke techniques, Pollock's dripping technique similarly exploited gravity. Furthermore, in adopting the horizontal plane, the canvas became a physical space, a terrain to be traversed.

Just as there are similarities between the processes used by Nature and Pollock, there are also similarities between the patterns generated by these processes. Pollock abandoned the heavy frames that in previous art movements had been used to isolate the work from its surroundings. His whole philosophy of what he called an "unframed space" was, indeed, compatible with Nature—no natural scenery has its patterns artificially bound and restricted. Some of Pollock's paint trajectories ignore the artificial boundaries of the canvas edge and travel beyond it—a characteristic which is alien to traditional artistic compositional values and clearly closer to Nature's expansive and unconfined patterns. Pollock's choice of a large canvas—one which dominates a viewer's environment—is also similar to Nature's scenes. As fellow Abstract Expressionist Mark Rothko described in 1951, "To paint a small picture is to place yourself outside the experience. . .However, you paint the larger picture, you are in it."[5] Similarly, Pollock regarded his own vast paintings as environments. Furthermore, his approach from all four sides of the canvas replicated the isotropy and homogeneity of many natural patterns. The resulting uniformity of his "all-over" composition lacks any center of focus. This characteristic stands in contrast to traditional art compositions and instead shows similarities with Nature's patterns. Like natural patterns, Pollock's paintings are also astonishing feats of pictorial invention: Nature's processes and the painting process chosen by Pollock both generate a rich variety of complex structure. No two natural patterns are exactly the same and this is also true of Pollock's paintings. Color plates 10 and 11 compare some typical natural patterns with those of Pollock's drip trajectories. Although there are specific differences, an underlying, shared quality can be identified. Could it therefore be that the basic trademark of Nature's pattern construction also appears in Pollock's drip work? The superficial similarities between both the processes and patterns used by Pollock and Nature clearly offer clues to a common approach. However, in order to establish this connection rigorously, it is first necessary to go beyond vague descriptions such as "organic" and, instead, identify the precise generic qualities of Nature's dynamics and the patterns produced.

3 CHAOS

In 1960, Edward Lorenz used a computer to plot the irregularities in weather patterns. His findings, which could be applied to many of Nature's processes, showed the weather to be fundamentally unpredictable. He found a new regime of behavior—one which would be later labeled as chaos [7, 15]. When he looked

[5] Mark Rothko's statement originally appeared in *Interiors*, May 1951 and is quoted by Charles Harrison, 'Abstract Expressionism', *Concepts Of Modern Art*, edited by Nikos Stangos, 196. London: Thames and Hudson, London, 1974.

carefully at how the weather varied with time he found that, despite apparent randomness, the behavior was really an intermediate state between highly ordered behavior and fully random behavior. He noticed that the behavior had a pattern, but with disturbances—a kind of orderly disorder. Unlike truly ordered systems, the disturbances made the behavior unpredictable. But it wasn't fully random behavior either. There was an underlying quality—an order which was masquerading as randomness. He found that the defining characteristic of chaotic systems lay in the equations which mapped out their behavior. The equations are not like those of well-ordered systems, where the outcomes are relatively insensitive to small changes in the parameters fed into the equations. Well-ordered systems are predictable because a small error in the knowledge of the initial conditions will not alter greatly the way the system evolves with time. In contrast, the outcomes of chaotic equations are exponentially sensitive to initial conditions. Tiny differences in the starting conditions become magnified as the system evolves, resulting in exponentially diverging outcomes and hence a long term behavior which cannot be predicted. This signature of chaos (extreme sensitivity to initial conditions) often is referred to as the Butterfly Effect—where even a small variation, such as a butterfly flapping its wings in the Amazon, could have dramatic consequences for the wind patterns across the North American skies. The sensitivity of Nature's chaos arises in part due to a principle called "holism"—where everything in the system is connected intimately to, and hence sensitive to, everything else.

Since its discovery, chaos theory has experienced spectacular success in explaining many of Nature's processes. Given the similarities with Nature, could Pollock's painting process therefore also have been chaotic? There are two revolutionary aspects to Pollock's application of paint and, remarkably, both have potential to introduce chaos. The first is his motion around the canvas. In contrast to traditional brush-canvas contact techniques, where the artist's motions are limited to hand and arm movements, Pollock used his whole body to introduce a wide range of length scales into his painting motion. In doing so, Pollock's dashes around the canvas possibly followed Lévy flights: a special distribution of movements, first investigated by the mathematician Paul Lévy in 1936, which has recently been used to describe the statistics of many natural chaotic systems.[6] The second revolutionary aspect concerns his application of paint by letting it drip on to the canvas. In 1984, a scientific study of dripping fluid by Robert Shaw at the University of California showed that small adjustments to the "launch conditions" (in particular, the initial flow rate of the fluid) could change the falling fluid from a non-chaotic to chaotic flow [24]. Although Shaw considered the case of a flow which occurs in drips, the result is true also for a continuous flow of liquid. For example, water flowing along a river or a pipe can be made to descend into the turbulence of chaos by simply adjusting the way the liquid is "launched." Whether working with a dripping or continuos flow, it is possible to tune the flow

[6]Whereas random motion is described by Brownian statistics, chaotic motion can be described by Lévy statistics. In Brownian motion a particle makes random jumps (or 'flights') and each jump is usually small: the resulting diffusion can be described by a Gaussian distribution with a finite variance. In Lévy diffusion, on the other hand, long jumps are interspersed with shorter jumps, and the variance of the distribution diverges. For more details on Lévy flights see C. Tsallis [30, 9].

from chaotic to non-chaotic and vice versa. Therefore, Pollock likewise could have mastered a chaotic flow of dripping paint. Whether he was dripping fluid from a stick or directly from a can, he could have mastered a particular "launch" condition, for example a particular flick of the wrist, which generated chaos in the falling fluid.

Perhaps, then, this potential for chaotic activity could be confirmed by an analysis of the dynamics of these two sets of Pollock's motions? In 1950, Hans Namuth took a series of black and white photographs and together with Paul Falkenberg shot a 16mm color film of Pollock painting. However, although suggestive, the film footage lacks the statistics required to confirm conclusively that the motions in his two processes were exclusively chaotic. To obtain reliable statistics, it would be necessary to undertake a detailed examination (including simultaneous zoom shots from above and the side) of the motions of Pollock and his dripping paint during production of at least one hundred trajectories. Even if Pollock were alive today to participate in such an exhaustive experiment, the filming conditions would be sufficiently intrusive to make the approach impractical. Therefore, an analysis of his painting motions is destined to be a limited method for deducing if he was chaotic. Instead, it is more informative to look for the signature of his chaotic activity in the patterns which record the process—the paint trajectories themselves. The logical way forward in this investigation is to make a visual comparison of the drip trajectories painted by Pollock and drip trajectories generated by processes which are known to be chaotic. If Pollock's trajectories are likewise generated by chaotic motion, then the resulting trajectory patterns should have similar visual characteristics to those of the known chaotic system.

The two chaotic processes proposed for generating Pollock's paint trajectories occur over distinctly different size ranges. These sizes can be estimated from the film and still photography of Pollock's painting process. Based on the physical range of his body motions and the canvas size (which, for example, is 4.8m for *Blue Poles: Number 11, 1952*), the Lévy flights in his motion across the canvas are expected to have had lengths with values lying approximately between 1cm and 4.8m. Thus, his Lévy flights would have generated features in the resulting paint trajectories with sizes lying between the same values. In contrast, the drip process is expected to have shaped the paint trajectories over much finer sizes—between the approximate sizes of 1mm and 5cm. This range is calculated from variables which affect the drip process (such as paint velocity and drop height) and those which affect paint absorption into the canvas surface (such as paint fluidity and canvas porosity). As a result, Pollock's motion around the canvas predominantly influenced the directions of the paint trajectories—what I will call the "bones" of the trajectories. In contrast, the dripping process predominantly determined what I will call the "flesh"—the variations in the thickness of the trajectories. Figure 2 shows a schematic representation of this concept. The top pattern shows the trajectory "bones" shaped by Pollock's motion around the canvas. The bottom pattern shows both the "skin" and the "bones," generated by contributions from both Pollock's motion and the drip motion.

First I will investigate the trajectory bones produced by the motion of Pollock across the canvas. A simple system which generates drip trajectories can be designed where the degree of chaos in this motion can be tuned. A series of patterns

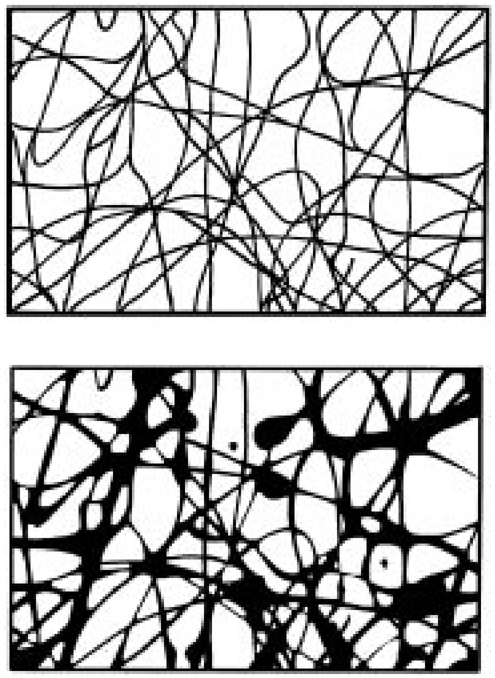

FIGURE 2 A schematic demonstration of the "flesh" and "bones" of Pollock's trajectories. The bottom picture shows the "skin" and "bones" of the trajectories. The top picture shows only the "bones." The "flesh" produced by the dripping process while the "bones" are produced by Pollock's motion around the canvas. These trajectories are taken from a 13cm by 20cm section of *Number 14, 1948*. *Number 14, 1948* (enamel on gesso on paper, 57.8cm by 78.8cm) was painted by Pollock in 1948 (Yale University Art Gallery, New Haven).

then can be produced which vary from non-chaotic through to totally chaotic. In fact, the ideal system to do this was introduced to the art world in its crudest form by Ernst in 1942 as he dripped paint from a bucket. Ernst, who was continually on the lookout for new artistic techniques, described his procedure as follows: "Tie a piece of string, one or two meters long, to an empty tin can, drill a small hole in the bottom and fill the tin with fluid paint. Then lay the canvas flat on the floor and swing the tin backward and forward over it, guiding it with movements of your hands, arms, shoulder and your whole body. In this way surprising lines drip onto the canvas."[7] What Ernst did not realize, and nor did the scientists of that era, was that the unguided pendulum was an even more interesting system than the guided one. When left to swing on its own, the container follows an ellipse which spirals into the center, and this motion is captured by an identical trajectory pattern on the canvas. This is a well-defined motion (called damped

[7]Max Ernst is quoted by Werner Schmalenbach, *Masterpieces Of 20th Century Art*, 254. Munich, Prestel-Verlag, 1990.

simple harmonic motion) and the pattern generated is non-chaotic. It is due to this very stable, predictable motion that pendula are found in the clocks of many households around the world. This periodicity in the pendulum's motion is one of science's legendary discoveries: Galileo Galilei made his discovery by swinging a church lamp back and forth. And this is how the story stayed for more than three hundred years until the 1980s, when chaologists surprised the scientific community by discovering that the very same pendulum, this great symbol of regularity, also could be made to descend into the unpredictability of chaos [29]. By knocking the pendulum at a frequency slightly lower than the one at which it naturally swings, the system changes from a freely swinging pendulum to what is called a "forced pendulum" or "kicked rotator." The motion of this system now has become a standard system in science for demonstrating chaotic trajectories: by tuning the frequency and size of the kick applied to the pendulum, the motion can evolve from the non-chaotic motion of the free pendulum through to increasingly chaotic motion.

Using a refinement of this pendulum concept, I have generated the two distinct categories of drip trajectory paintings [28]. Figure 3 shows a drip painting in progress. Example sections of non-chaotic (top) and chaotic (middle) drip paintings are shown in figure 7. Since Pollock's paintings were built from many crisscrossing trajectories, these pendulum paintings likewise feature a number of trajectories generated by varying the pendulum's launch conditions. For comparison, the bottom picture is a section of Pollock's *Number 14, 1948* painting. Introduction of chaos into the pendulum's motion induces a clear evolution in the "bones" of the drip trajectories and, in a visual comparison, Pollock's trajectories bear a closer resemblance to the pattern generated by the chaotic motion (middle) than to the non-chaotic motion (top). Figure 4, therefore, offers a clue that Pollock's motion around the canvas was chaotic. In fact, the introduction of chaos into the motion of the pendulum induces a change in both the "flesh" and the "bones." The sharper changes in trajectory direction within the "bone" pattern of the chaotic system also induces variations in the dynamics of the dripping fluid. This generates the large variations in the "flesh" thickness across the painting observed in figure 4 (middle). This result, therefore, emphasizes an inter-dependence of the two processes determining the "flesh" and the "bones": the dynamics of the container's motion can affect the dynamics of the falling fluid. This is expected also for Pollock's painting technique—his motions around the canvas will have contributed to the way he launched the paint from his painting implement. Nevertheless, the motion of the launch implement (whether it was a stick or a can) is just one of the factors which dictates the launch conditions and hence the dynamics of the falling liquid. For example, it is possible to hold the launch implement stationary, so removing the issue of its motion, and adjust other launch parameters to tune the falling fluid from a chaotic to non-chaotic flow. In particular, the falling liquid's flow rate and viscosity can be adjusted. In Shaw's original experimental investigation of the chaotic dynamics of dripping fluid, he used a stationary tap and adjusted its aperture to change the flow rate of the fluid. A laser beam was shone through the falling fluid and used to detect the emergence of chaos as the dynamics of the fluid flow was altered. Figure 5 shows the pattern created by a similar experimental set-up where I used a chaotic flow of paint to create a pattern

FIGURE 3 A photograph of the guided pendulum apparatus (referred to as the "Pollockiser") used to generate drip paintings. The photograph was taken during filming for the Australian Broadcasting Corporation's television program *Quantum* in March 1998.

on a horizontal canvas placed below the tap. In figure 5 this drip pattern generated by the chaotic flow of paint is compared to the "flesh" of Pollock's paint trajectories. Again, there is a visual similarity. This offers a clue that Pollock mastered a method of launching paint from his painting implement which induced chaos in the motion of the falling fluid.

The preliminary investigations shown in figures 4 and 5, therefore, raise the possibility that the two components of Pollock's painting process—his motion around the canvas and his dripping process—both produced similar visual qualities to patterns generated by chaos. If Pollock's drip patterns were generated by chaos, what common quality would be expected in the patterns left behind? Many chaotic systems form fractals in the patterns that record the process [4, 7, 12, 15]. Is the shared visual quality revealed in figures 4 and 5, therefore, the fractal? It should be stressed that the above comparisons serve only as initial indications. Both Pollock's patterns and those generated by chaos are characterized by endless variety, and thus a comparison of two individual patterns is of limited use. Furthermore, any similarities detected by using only two pictures might be a result of coincidence rather than a sign of a common physical origin. Thus, although important as initial clues to fractal content, a systematic analysis involving an assessment of many patterns must be undertaken. Furthermore, the analysis should be divorced from subjective visual comparisons and instead should involve the calculation of a parameter which identifies and quantifies the fractal content objectively. An analysis which does this will be presented in the next section.

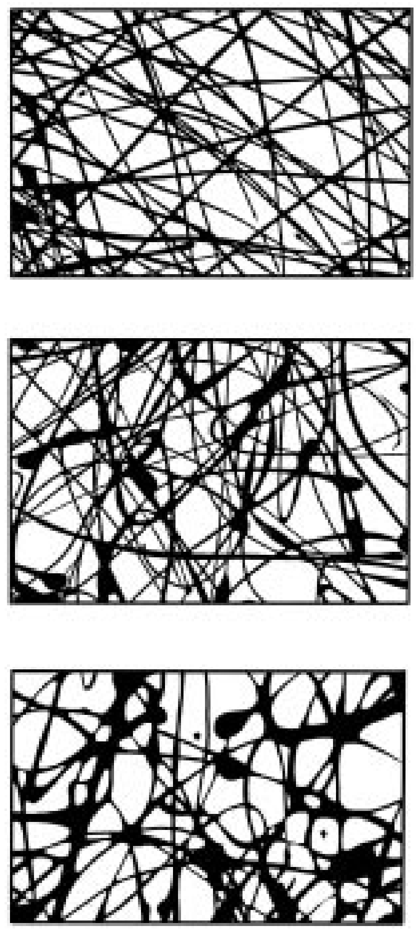

FIGURE 4 The detailed patterns of non-chaotic (top) and chaotic (middle) drip trajectories generated by the "Pollockiser," compared to a section of Pollock's *Number 14, 1948* painting (bottom). All three sections are approximately 13cm by 20cm.

4 FRACTALS

In 1975 Benoit Mandelbrot coined the term "fractal" from the Latin adjective to mean "fractured" or "irregular" [4, 12]. Although appearing fractured and irregular during a superficial inspection, a more detailed examination of Nature's fractals reveals a subtle form of repeating order. Mandelbrot showed that Nature's fractal patterns obey a scaling relationship called statistical self-similarity: the patterns observed at different magnifications, although not identical, are described by the same statistics. The results are visually more subtle than the instantly identifiable, artificial fractal patterns generated using exact self-similarity, where the patterns repeat exactly at different magnifications. However, there are visual clues which

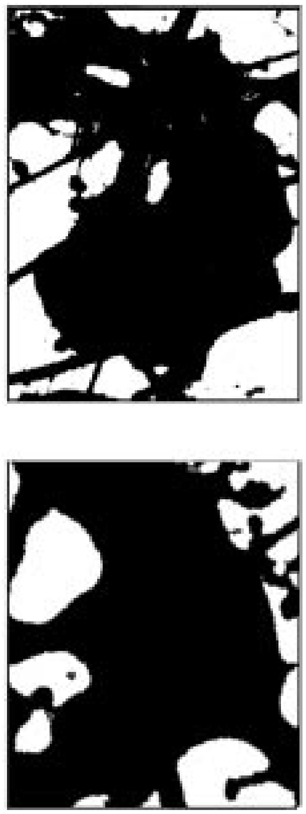

FIGURE 5 A comparison of the paint marks (the "flesh" pattern) made by Pollock's drip process (top) and those produced by a known chaotic flow (bottom). The top image is taken from a section of Pollock's *Number 32, 1950*. Both sections are approximately 13.5cm by 18cm.

help to identify statistical self-similarity. The first relates to "fractal scaling." The visual consequence of obeying the same statistics at different magnifications is that it becomes difficult to judge the magnification and hence the length scale of the pattern being viewed. This is demonstrated in color plate 12(top) and plate 12(middle) for Nature's fractal scenery and in plate 12(bottom) for Pollock's painting. A second visual clue relates to "fractal displacement," which refers to the pattern's property of being described by the same statistics at different spatial locations. As a visual consequence, the patterns gain a uniform character and this is confirmed for Pollock's work in figure 6, where the pattern density P is plotted as a function of position across the canvas.

Pollock's patterns therefore display both "fractal displacement" and "fractal scaling"—the two visual clues to fractal content. When Mandelbrot first introduced the concept of fractals, he stressed that perhaps the most significant associated advance was that there was now a way of identifying and describing

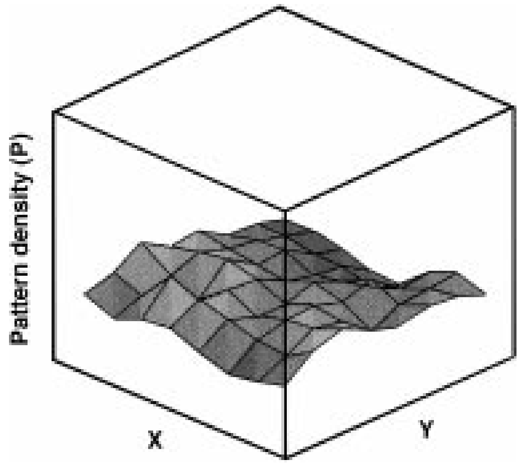

FIGURE 6 A plot showing that the pattern's spatial density P remains approximately constant at different locations across the canvas. To produce this plot, the scanned photograph of a Pollock painting is covered with a computer-generated mesh of identical squares. Within each square, the percentage of the canvas surface area covered by the painted pattern (P) is then calculated. The X and Y labels indicate the locations in the length and height directions respectively. The square size used to calculate P is $L = 0.05$m. The plot is for the painting *Number 14, 1948*. The plotted ranges are as follows: P spans the range between 0 and 100%, X and Y span the range from 0 to 0.43m.

patterns which were previously beyond scientific quantification. He noted, "Scientists will. . .be surprised and delighted to find that now a few shapes they had to call grainy, hydra-like, in between, pimply, pocky, ramified, seaweady, strange, tangled, tortuous, wiggly, whispy, and the like, can henceforth be approached in rigorous and vigorous fashion" [4, 12]. I will now apply this "rigorous" approach to Pollock's trademark patterns to confirm the visual clues to fractal content. A traditional method for detecting statistical self-similarity is shown in figure 7 for a schematic representation of a Pollock painting. A digitized image (for example a scanned photograph) of the painting is covered with a computer-generated mesh of identical squares. By analyzing which squares are occupied by the painted pattern (shaded gray in figure 7) and which are empty, the statistical qualities of the pattern can be calculated. Reducing the square size is equivalent to looking at the pattern at a finer magnification. Thus, in this way, the pattern's statistical qualities can be compared at different magnifications. A crucial parameter in characterizing a fractal pattern is the fractal dimension, D, and this quantifies the scaling relationship between the patterns observed at different magnifications [4, 8, 12]. For Euclidean shapes, dimension is a simple concept and is described by the familiar integer values. For a smooth line (containing no fractal structure) D has a value of 1, while for a completely filled area its value is 2. However, for a fractal pattern, the repeating structure at different magnifications causes the line to begin to occupy

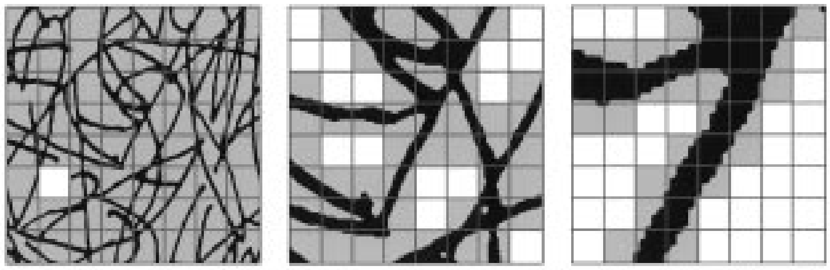

FIGURE 7 A schematic representation of the technique used to detect the fractal quality of Pollock's patterns. A computer generated mesh of identical squares covers the surface of the painting. Then the size of the squares in this mesh is decreased gradually. From left to right the square size is decreased and in each case the number of "occupied" boxes (indicated by the gray shading) is counted.

area. D then lies in the range between one and two and, as the complexity and richness of the repeating structure increases, its value moves closer to 2. D can be used therefore to identify and quantify the fractal character of a pattern. Using the computer-generated mesh shown in figure 7, D can be obtained by comparing the number of occupied squares in the mesh, $N(L)$, as a function of the size, L, of the squares. For fractal behavior, $N(L)$ scales according to the power law relationship $N(L) \sim L^{-D}$, where D has a fractional value lying between 1 and 2 [4, 8, 12]. Therefore, by constructing a "scaling plot" of $\log N(L)$ against $\log L$ the fractal behavior manifests itself as the data lying on a straight line and the value of D can be extracted from the gradient of this line.

The two chaotic processes proposed for generating Pollock's paint trajectories operated across distinctly different length scales. His chaotic Lévy flights across the canvas are expected to have occurred over relatively large distances—between 1cm and 4.87m (where 4.87m corresponds to the canvas size). In contrast, the chaotic drip process is expected to have shaped the trajectories over significantly smaller sizes—between 1mm and 5cm. Due to the presence of these two chaotic processes, it is expected that the fractal analysis of Pollock's paintings will reveal the presence of two sets of fractals patterns—one set occurring across small L values and one set across large L values. Furthermore, because the two chaotic processes have distinctly different physical origins (one generated by drips and the other by Pollock's motions) the two sets of fractal patterns are expected to be described by different D values. Note that systems described by two or more D values are not unusual: trees and bronchial vessels are common examples in Nature. I will label the value of L at which the transition between the two sets of fractal patterns occurs as L_T. Based on the size ranges specified above, L_T is expected to occur at approximately 1cm.

The analysis of Pollock's paintings confirm these expectations. For example, figure 8 shows the "scaling plot" for the aluminum paint trajectories within *Blue Poles: Number 11, 1952* which has a canvas size of 2.10m high by 4.87m wide. Data plotted on the extreme left hand side of the graph corresponds to patterns with a size $L = 0.8$mm while data on the extreme right hand side corresponds to $L = 10$cm (note, although not shown, the analysis continues beyond the range shown, right up to $L = 1$m). The data, represented by the black line, follows one gradient for small L values (i.e., on the left) and another gradient for large L values (on the right). The different gradients indicate that the two fractal patterns have different D values. These two D values are labeled as the drip fractal dimension, D_D, (produced by the chaotic motion of the dripping paint) and the Lévy flight fractal dimension, D_L, (produced by the chaotic motion of Pollock's Lévy flights across the canvas). For the aluminum paint trajectories analyzed in figure 8, the fractal dimensions have values of $D_D = 1.63$ and $D_L = 1.96$. The value of L_T (the size at which the transition between the D_D and D_L ranges occurs) is 1.8cm, consistent with the value predicted above. The patterns were analyzed for L values ranging from 1mm up to 1m and fractal behavior was observed over this complete range—the largest observed fractal pattern in the painting is over one thousand times larger than the smallest. This immense size range is significantly larger than for observations of fractals in other typical physical systems.[8] One of the consequences of observing the fractal patterns over such a large size range is that the fractal dimension can be determined with great accuracy.

Having established their fractality, how do these fractal patterns evolve in character through the years? Art historians categorize Pollock's development of the drip technique into his "preliminary" phase (circa 1943), his "transitional" phase (circa 1947) and his "classic" phase (circa 1950). The sparse drip patterns of his "preliminary" drip paintings were deposited over a foundation of brushed paint (see, for example, *Water Birds*, shown in color plate 13). To determine the fractal quality of the drip trajectories of these paintings, the underlying layers of brushed paint were removed electronically from the scanned images of the paintings prior to the analysis. For these "preliminary" paintings the dripped layer was found to have a very low fractal dimension and that the foundation patterns of brushed paint were not fractal. For Pollock's "transitional" paintings, the dripped layers of paint assumed a more dominant role over the underlying brushed layers in regard to their contribution to the visual impact of the painting (see, for example, *Full Fathom Five*, shown in color plate 10). For these "transitional" paintings the dripped layers were found to have a higher fractal dimension than for the dripped layer of his "preliminary" paintings. Furthermore, the patterns established by the underlying brushed layer (with the dripped layers removed) was also fractal. For Pollock's "classic" drip paintings, there were few, if any, underlying brush marks—the paintings were constructed almost entirely from layers of dripped paint (see, for example, *Blue Poles: Number 11, 1952* shown in color plate 9). For these paintings, the dripped layers were found to have even higher fractal dimensions than the dripped layers of the "transitional" paintings.

Consider the evolution of the D_D and D_L values in more detail. The analysis shows that D_D gradually increased over the years. The drip patterns of *Untitled:*

[8]Unlike fractal patterns generated by mathematical equations, fractals in physical systems do not range from the infinitely large through to the infinitesimally small. Instead physical fractals are observed across only a limited range of sizes. A recent survey of observations of fractals in physical systems suggests that the largest pattern is typically only 30 times larger then the smallest pattern. See Avnir et al. [3].

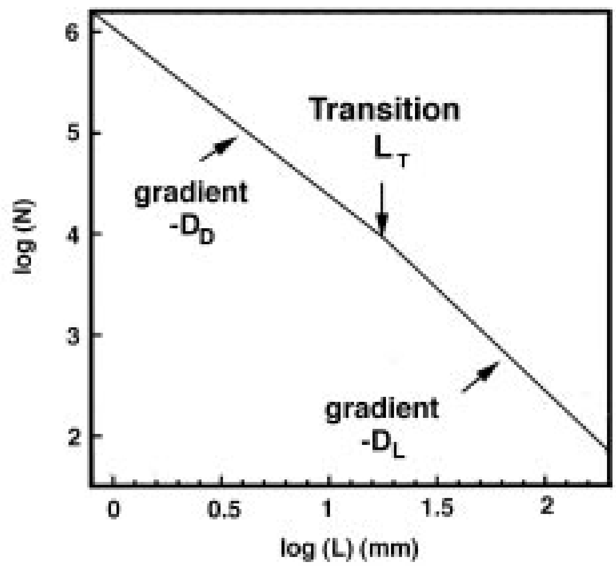

FIGURE 8 A plot of $\log(N)$ versus $\log(L)$ for the pattern created by the aluminum paint trajectories within *Blue Poles: Number 11, 1952*. The horizontal axis spans the range between 0.8mm and 10cm. The data points lie on the black line—for clarity, due to the large number of points (over 2000), the individual points are not shown.

Composition With Pouring II and *Water Birds*, both painted in 1943, have low D_D values. Similarly, *Untitled*, painted in 1945 has a D_D value of 1.12. This indicates that the drip trajectories within these "preliminary" paintings have low fractality for the small sizes of L characterized by D_D. However, by 1946, when Pollock painted *Free Form*, he had succeeded in refining his drip technique to produce well-defined fractal patterns. *Number 14, 1948* painted in 1948, has a D_D value of 1.45 and *Autumn Rhythm: Number 30, 1950* painted in 1950, has a D_D value of 1.67. In 1951 Pollock mostly used the drip technique to draw figurative representations and these paintings are not fractal. However, he still occasionally painted non-figurative "all-over" compositions with the drip technique, such as *Untitled* with a D_D value of 1.57. In 1952, *Blue Poles: Number 11, 1952* represented a final and brief return to his "classic" style and has the highest D_D value of any completed Pollock painting with a value of 1.72.

The fractal quality of his patterns at large L sizes—as characterized by D_L—also evolved through the years. Analysis of the patterns of *Untitled: Composition With Pouring II, Water Birds* (1943), and *Untitled* (1945) do not yield straight lines in the region of the graph where D_L should be extracted, indicating that these early paintings are non-fractal in the large L size regime (just as they are not fractal in the small L size regime). However, by the time he painted *Free Form* in 1946 Pollock had evolved his drip paintings such that they had become fractal for the large L sizes. Indeed, throughout the period 1947–1952 (excluding 1951;

TABLE 1 The results of the fractal analysis, revealing an increase in fractal dimension through the years 1945–1952.

Year	**Painting Title**	$\mathbf{D_D}$	$\mathbf{D_L}$	**Canvas Area** (m^2)	**A** (%)
1945	*Untitled*	1.12	–	0.24	4
1947	*Lucifer*	1.64	>1.9	2.79	92
1948	*Number 14, 1948*	1.45	>1.9	0.46	28
1949	*Number 8, 1949*	1.51	>1.9	1.56	86
1950	*Number 32, 1950*	1.66	>1.9	12.30	46
1950	*Autumn Rhythm*	1.67	>1.9	14.02	47
1951	*Untitled*	1.57	>1.9	0.53	38
1952	*Blue Poles*	1.72	>1.9	10.22	95

see above), the D_L values are significantly higher than the D_D values. In other words, as Pollock perfected his technique, the fractal patterns at the large L sizes became significantly more dense with fractal structure than the fractal patterns at small L sizes. In fact, during his "classic" period of 1950 the D_L values became remarkably high, approaching a value of 2. This trend culminated in 1952, when *Blue Poles: Number 11, 1952* was painted with a D_L value of 1.98. Typical results mapping out this evolution of D values with the years are summarized in Table 1. Also summarized in the table are the canvas surface area and the percentage of this area covered by the painted pattern (A).

In figure 9(a) the D_D values of typical paintings are plotted against the year in which they were painted. The dashed lines are included as guides to the eye and reveal the basic trend in the evolution of D_D. The graph displays a rapid increase in D_D during the evolution from Pollock's "preliminary" to "transitional" phase as he established his drip technique, followed by a more gradual increase as he refined his technique towards the "classic" style. His drip technique evolved considerably during the period 1943–1952. His initial drip paintings of 1943 consisted of a few dripped trajectories which, although distributed across the whole canvas, occupied less than 10% of the $0.36\mathrm{m}^2$ canvas area. By 1952 he was spending six months laying down extremely dense patterns of trajectories which covered over 90% of his vast $10.22\mathrm{m}^2$ canvas. Figure 9(b) and (c) shows a correlation between the high D_D values of his "classic" patterns and his use of a large canvas and high pattern density.

5 THE FRACTAL CONSTRUCTION PROCESS

How did Pollock construct and refine his fractal patterns? In many paintings, though not all, Pollock introduced the different colors more or less sequentially: the majority of trajectories with the same color were deposited during the same period in the painting's evolution. To investigate how Pollock built his fractal patterns, I have electronically de-constructed the paintings into their constituent colored layers and examined the fractal content of each layer. The analysis shows

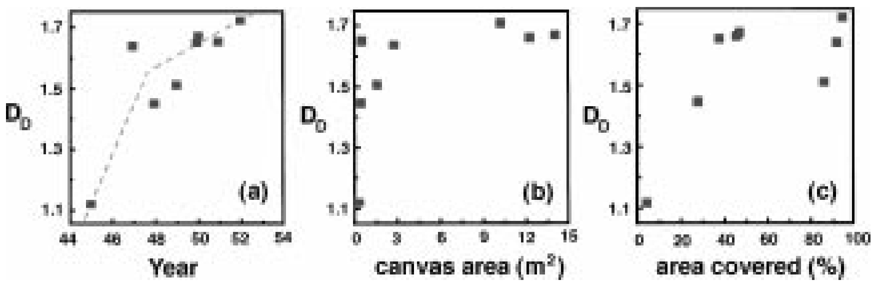

FIGURE 9 The Evolution of Pollock's paintings through the years. The painting's fractal dimension D_D is plotted against (a) the year in which it was painted, (b) the canvas area and (c) the percentage of this area covered by paint. In (a) the dashed line is a guide to the eye.

that each individual layer consists of a uniform fractal pattern. The initial layer in a Pollock painting plays a pivotal role within the multilayer construction—it has a significantly higher fractal dimension than subsequent layers. This layer essentially determines the fractal nature of the overall painting, forming the foundation of the painting and acting as an "anchor layer" for the subsequent layers. The black anchor layer of the painting *Autumn Rhythm: Number 30, 1950* is shown in color plate 14. As subsequent layers are added to this painting, the D_D value rises only slightly—from 1.66 (with just the black anchor layer) to 1.67 (the complete painting with all the layers). In this sense, the subsequent layers merely fine tune the D_D value established by the anchor layer. The anchor layer also visually dominates the painting. Pollock often chose the anchor layer to be black, which contrasts against the light canvas background. Furthermore, the anchor layer occupies a larger surface area than any of the other layers. For *Autumn Rhythm: Number 30, 1950* the anchor layer occupies 32% of the canvas space while the combination of the other layers—brown, gray, and white—occupies only 13% (the remaining 55% corresponds to exposed canvas).

Since the fractal content and visual character of a Pollock painting is determined predominantly by the anchor layer, I will examine the evolution of this layer in detail. In the anchor layer's initial stage, the trajectories are grouped into small, unconnected "islands," each of which is localized around a specific region of the canvas. Pollock then went on to paint longer trajectories which extended across the length of the canvas. These extended trajectories joined the islands, gradually submerging them in a dense pattern of trajectories which became increasingly fractal in character. The visual evolution of this process is documented in figure 10 which shows a processed image of a painting filmed during Pollock's "classic" period of 1950.[9] Pollock painted the image on a glass surface with the camera recording from below. Using a video recording of the original film, the image was processed to remove background color variations. The image also was reflected around the

[9]This section of a painting was filmed by P. Falkenberg and H. Namuth. The completed painting, which covered 121.9cm by 182.9cm, no longer exists [11].

FIGURE 10 A 69cm by 69cm section of a painting filmed (a) 5, (b) 20, (c) 27, and (d) 47 seconds into Pollock's painting process. The film was shot by Hans Namuth in 1950.

TABLE 2 A summary of the anchor layer's parameters as they evolve during the first 47 seconds of the painting process.

T(s)	$\mathbf{D_D}$	**A (%)**
5	–	3.3
20	1.52	16.5
27	1.72	42.5
47	1.89	70.2

vertical axis so that the final image appears from Pollock's point of view. The resulting black and white representation shown in figure 16(a) was then converted into a bitmap format for fractal analysis. The film records a 69cm by 69cm region lying within one of the islands. To analyze the fractal content the computer covers this region with a mesh of identical squares as described earlier. The first image, shown in figure 10(a), is recorded at 5 seconds into the painting process. At this initial stage of the painting, the scaling plot fails to condense onto a straight line—indicating that painting is not fractal at this early stage. As Pollock starts to paint more extended trajectories, the pattern density of the painting starts to rise rapidly with time. This rise in pattern density with time T is quantified in Table 2, where the percentage of the canvas area occupied by the painted pattern, A, is shown to rise rapidly over the first minute—by $T = 47$s, more than two thirds of the surface is covered with paint. Figure 10(a)–(d) show that the rapid rise in A with time is accompanied by an increase in spatial uniformity—a signature of fractal patterning. The scaling plots confirm this introduction of fractal content. By $T = 27$s, the scaling plot condenses onto a straight line and a value of $D = 1.72$ is obtained from the gradient. By $T = 47$s, D has risen to 1.89, reflecting the rich complexity of fractal structure in the pattern shown in figure 10(d). At this stage, after less than one minute, the crucial stage of Pollock's fractal generation process is over: the anchor layer has been defined.

Labeling the formation of the anchor layer as phase one, and the subsequent multilayer fine-tuning process as phase two, for some of Pollock's works there was also a phase three, which took place after the painting process was completed. The uniformity and fractal character of the completed patterns sometimes deteriorated towards the canvas edge. To compensate for this Pollock cropped some of his canvases after he had finished painting, removing the outer regions of the canvas and retaining the highly fractal central regions. The complete paintings, generated by this highly systematic three-phase process, follow the fractal scaling relationship (the straight line within the scaling plots) with remarkable accuracy and consistency. How did Pollock arrive at this remarkable fractal generation process? Some insight can be obtained by considering investigations of human aesthetic judgements of fractal images. A recent survey revealed that over ninety percent of subjects found fractal imagery to be more visually appealing than non-fractal imagery and it was suggested that this choice was based on a fundamental appreciation arising from humanity's exposure to Nature's fractal patterns [28]. The survey highlighted the possibility that the enduring popularity of Pollock's Fractal Expressionism is based on an instinctive appreciation for Nature's fractals shared by Pollock and his audience.

It is clear from the analysis that Pollock's painting process was geared to more than simply generating a fractal painting—if this were the case he could have stopped after twenty seconds (for example the image in figure 10(b) is already fractal). Instead he continued beyond this stage and used the three-phase process over a period lasting up to six months. The result was to fine tune the patterns and produce a fractal painting described by a highly specific D_D value. The investigations shown in figure 9(a) show that Pollock refined his technique through the years, with the D_D value of his completed paintings rising from 1.12 in his early attempts in 1945 to 1.72 at his peak in 1952. In 1950 Pollock generated a fractal painting characterized by $D_D = 1.89$ (see fig. 10(d)). However, he immediately rubbed out this pattern and started again, suggesting that a pattern with such a high fractal dimension wasn't visually appealing to him. The highest D_D of any completed painting is for *Blue Poles: Number 11, 1952* with a value of 1.72. This was painted towards the end of his career in 1952. Therefore, it can be speculated that Pollock's quest was to paint drip patterns characterized by approximately $D_D = 1.7$. Why would Pollock refine his process to generate fractals with high D_D values? It is interesting to note that, in a recent survey designed to investigate the relationship between a fractal pattern's D value and its aesthetic appeal, subjects expressed a preference for patterns with D values of 1.8 [16], similar to Pollock's "classic" paintings of 1950–1952. Although a subsequent survey reported much lower preferred values of 1.26, this second survey indicated that self-reported creative individuals have a preference for higher D values [2], perhaps compatible with Pollock's quest to paint patterns with high D values. Table 3 lists the D values for examples of Nature's scenery. It is interesting to note that Pollock's "preferred" D value corresponds to the fractal dimension of a scenery familiar to us all in our every day lives—trees in a forest. It is possible to speculate therefore that Pollock's paintings were an expression of a fundamental appreciation of the natural scenery which surrounded him—an appreciation acquired either through evolution or learnt implicitly through his life. Within this context it is significant to note that Pollock's development of the drip and splash technique occurred as he moved from downtown Manhattan (artificial scenery) to the countryside (natural scenery). Perception studies are planned to examine these possibilities further.

In addition to exploring the aesthetic appeal of Pollock's patterns, perception studies also may provide an answer to one of the more controversial issues sur-

TABLE 3 Common natural scenery and their measured fractal dimensions.

Scenery	D
Cauliflower	1.1 − 1.2
Mountain Profile	1.2
Stars	1.2
Coastlines	1.2 − 1.3
River	1.2 − 1.3
Waves	1.3
Lightning	1.3
Volcanic Cloud	1.3
Clouds	1.3
Mud Cracks	1.7
Ferns	1.8
Forests	1.9

rounding Pollock's drip work. Over the last fifty years there has been a persistent theory which speculates that Pollock painted illustrations of objects (for example, figures) during early stages of the painting's evolution and then obscured them with subsequent layers of dripped paint [11, 31]. Since fractal patterns do not incorporate any form of figurative imagery, my analysis excludes the possibility that the initial stages of his paintings featured painted figures. Why, then, is the "figurative" theory so persistent? A possible answer can be found by considering my analysis in the context of the perception studies of Rogowitz and Voss [21]. These studies indicate that people perceive imaginary objects (such as human figures, faces, animals etc.) in fractal patterns with low D values. For fractal patterns with increasingly high D values this perception falls off markedly. Rogowitz and Voss speculate that their findings explain why people perceive images in the ink blot psychology tests first used by Rorschach in 1921. Their analysis shows that ink blots are fractal with a D value close to 1.25 and thus will trigger perceptions of objects within the patterns. Although not discussed by the authors, their results may explain the Surrealist method of Free Association where the artist stares at painted patterns until an image appears [1]. It could be that the patterns produced by the Surrealists (e.g., the Ernst's "frottage," Dominguez's "decalcomania," and Miró's washes) were fractal patterns of low dimension. Their findings also explain why figures are perceived in the initial layers of Pollock's paintings. The fractal analysis of the evolution of Pollock's patterns shows that his paintings started with a low D value which then gradually rose in value as the painting evolved towards completion (see table 2). Thus it is consistent with the findings of Voss and Rogowitz that an observer would perceive objects in the initial patterns of a Pollock painting (even though they are not there) and that these objects would "disappear" as D rose to the high value which characterized the complete pattern.

6 FRACTAL ANALYSIS AND JUDGEMENTS OF AUTHENTICITY

Finally, I briefly will consider the use of the fractal analysis technique to authenticate a Pollock drip painting. The results presented so far emphasize that fractal patterns are not an inevitable consequence of dripping paint—it is possible to generate drip paintings which have a non-fractal composition (see, for example, figure 4 (top)). Indeed, to emphasize this fact I have analyzed the paint marks found on the floor of Pollock's studio. Although dripped, these patterns are not fractal. In contrast, the patterns on Pollock's canvases are the product of a specific drip technique engineered to produce fractals and all of the drip paintings I have analyzed (over 20 in number) have this fractal composition. Therefore, fractality can be identified as the "hand" of Pollock and a fractal analysis can be used to authenticate a Pollock drip painting. Developing this argument one step further, the analysis also may be used to date an authentic Pollock painting. The D_D value of Pollock's work rose through the years, following a predictable trend (see for example figure 9(a)). Charting this progress, it should be possible to determine the D_D value of the painting and from this to suggest an approximate date. Recently, these proposals were put to the test. Color plate 15 shows a drip painting of unknown origin which lacks a signature but is thought to have been painted during Pollock's era. The painting was sent to me by a private collector in the USA to determine if the painted patterns were consistent with Pollock's. Painted using a drip technique, the painting has a uniform quality lacking any center of focus. These characteristics are shared with Pollock's "all-over" style. However, unlike a typical Pollock painting, my analysis shows that patterns at different magnifications are not described by the same statistics—the scaling plot fails to condense onto a straight line. It is not possible to characterize this painting with a D_D or D_L value and to plot it along side Pollock's drip paintings in figure 9. Despite any superficial similarities with Pollock's work, this painting does not contain fractal patterns—the characteristic "hand" of Pollock is absent. Clearly this use of a computer to detect the fundamental characteristics of painted patterns is a powerful one and will become part of a growing collection of scientific tools (which already includes techniques such as X-ray analysis to detect patterns hidden underneath subsequent layers of paint) employed by art theoreticians to investigate works of art. Such developments are a signal of the growing interplay between art and science.

7 CONCLUSIONS

The profound nature of Pollock's contribution to modern art lies, not only in the fact that he could paint fractals on a canvas, but in how and why he did so. In this chapter I have used a fractal analysis technique to examine the painting process Pollock used to construct his drip paintings. This analysis reveals a remarkably systematic method capable of generating intricate patterns which obey the fractal scaling behavior with precision and consistency. These results have been presented within the context of recent perception studies of the aesthetic appeal of fractal patterns. Nature builds its patterns using fractals as its basic building block. Having evolved surrounded by this fractal scenery, it perhaps therefore is not surprising that humanity possesses an affinity with these fractals and an implicit recognition of their qualities. Indeed, it is possible to speculate that people possess some sort of "fractal encoding" within the perception systems of their minds. The study of human responses to fractal images and the characterization of their aesthetic appeal is a novel field of research for perceptual psychologists, one which offers huge potential [2, 4, 6, 12, 16, 19, 21, 28]. Pollock's enduring popularity may be a consequence of a shared appreciation of Nature's fractal patterns operating within the psyche of both the painter and the observer. This chapter therefore raises a fundamental question: could Pollock have distilled Nature's very essence—fractal patterning—from within his mind and recorded this imagery directly on canvas? As Pollock himself noted, "Painting is self-discovery. Every good painter paints what he is,"[10] concluding that "I am nature" [33]. Clearly, a discussion of Pollock's fractals would be incomplete without considering the art historical context of his work. It is hoped, therefore, that the results presented here will stimulate a debate between scientists, psychologists and art theoreticians regarding the artistic significance of Pollock's fractal drip paintings.

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