Temporal Coherence with Digital Color

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ABSTRACT

To structure time with abstract visual materials requires a visual grammar of line, shape and color. Color is especially problematic, difficult to measure in all but the simplest applications; the literature of color theory and harmony is often confusing. To devise a syntax for structuring time with color, one can turn to the concepts of tension-release, of neutral, balanced and weighted color domains and of discrete computer raster images; they help to create and measure time-based color compositions. In parametrically defined color palettes, *Color Study #7* (a computer-generated animated film) demonstrates the application of these ideas to a simple and effective compositional approach. Codifying this now common filmmaking practice, the author hopes to encourage others interested in aesthetically strengthened visual presentation to explore and develop time-based visual grammars.

Music composition usually structures materials in time-based relationships, through historically established grammars or, over the last century, often through grammars invented by the composer. These grammars allow control of the materials so that a composed piece will make formal sense in time. They offer a meaningful framework upon which a composer's particular musical vision can be built.

As in music, the fundamental dimension of animation is time. The problems for the animator are the same ones a music composer faces—temporal coherence. But in using abstract visual materials, there is no centuries-old tradition the artist can turn to for guidance. Abstract visual composition ('composition' used here with respect to time rather than space) has two aspects that need to be considered, the graphic forms or shapes, and color.

A large body of theoretical work exists for static imagery. Extracting basic principles from the time-based art forms (theatre, poetry, music, dance, etc.) and applying them, along with fundamental ideas of color theory and graphic design, provides a starting point for a grammar and eventually a language of abstract visual composition.

Even in static imagery, use of color has proven to be an especially thorny issue and hence artists often make decisions based on personal whim. Some are so intimidated that they avoid the issue altogether, using only grayscale or restricting their output to black pen plotters. The literature on color theory is often contradictory or confusing, caught up in heady geometric descriptions and vague terminology. With the addition of the time dimension, aesthetic control of color appears to be futile. However, some basic principles about color relationships and interactions, combined with a common thread found in the temporal arts, suggest a possible direction.

Music theory and analysis are based on measurement of the sonic dimensions, such as pitch, rhythm and timbre. Our Western musical practice deals with organized collections of these dimensions as discrete events. This has simplified the invention or codification of musical syntax. In measurements of color relationships, such codification has been problematic. To allow easy measurement of color relationships, works on color theory and harmony have been forced to use simple geometric shapes [1].

With computer graphics, this situation has changed. We now have the capability of measuring color relationships with great precision because of the discrete nature of raster images. This simplification of color measurement allows us to apply theories of color harmony with precision and to explore their use in time. The computer then affords the animator powerful tools for composing pieces with structural integrity in temporal color relationships.

TENSION-RELEASE

Most time-based art forms (Western art forms in particular) have in common the idea of *tension-release*. A sense of motion in time occurs through the creation of tension and its resolution. Narrative forms such as theatre or literature ordinarily create conflict that builds to a climax and resolves itself in the denouement. Simple poetry accomplishes this motion through establishment of a rhyme scheme, repetition or a patterning of imagery that sets up expectations and moves tension to resolution as the expectations are met. In music a common approach is to move from dissonant to consonant pitch relationships.

There are myriad subtle ways in which this dynamic manifests itself in all the temporal arts, but the underlying principle of tension-release is what actually moves us through time. Can we establish this same relationship when using color in time?

The Neutral Color Domain

We must first find a color domain that can be defined as relaxed or resolved. The most obvious solution here is the grayscale, or the absence of color—a *neutral* domain. There is no percept of tension with color if there is no color. Starting with this premise we can build a hierarchy of color relationships and construct a simple, but effective, color grammar.

The Balanced Color Domain

In the nineteenth century Chevreul defined the phenomena of successive contrast and simultaneous contrast for subtractive color [2]. These phenomena allow us a perceptual basis for the idea of a neutral or gray color domain as being relaxed. In the case of successive contrast, staring at one of a pair of complementary colors will cause its complement to appear when one's attention is moved to a neutral ground. For example, staring at red and then focusing on a

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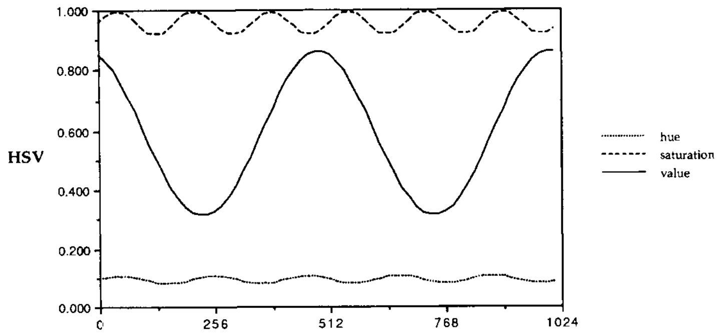

Fig. 1. Frame 1800 from the color palette of *hsv* space shows color map entries 0–1,023.

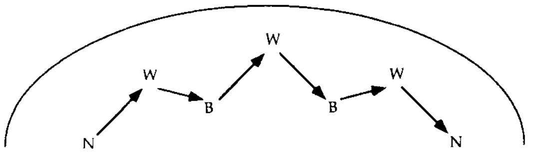

Fig. 2. Color domain arch form shows neutral (N), balanced (B) and weighted (W) functions.

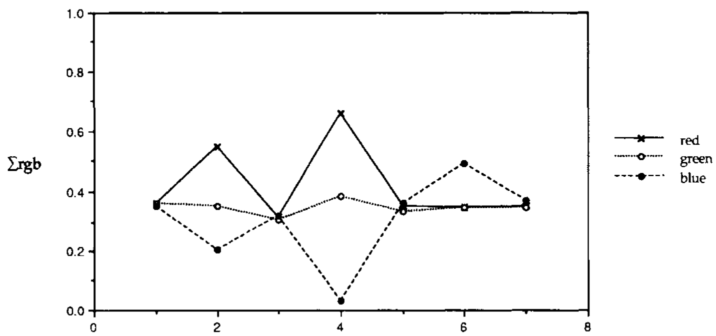

Fig. 3. *rgb* summations for keyframe color maps of *Color Study* #7.

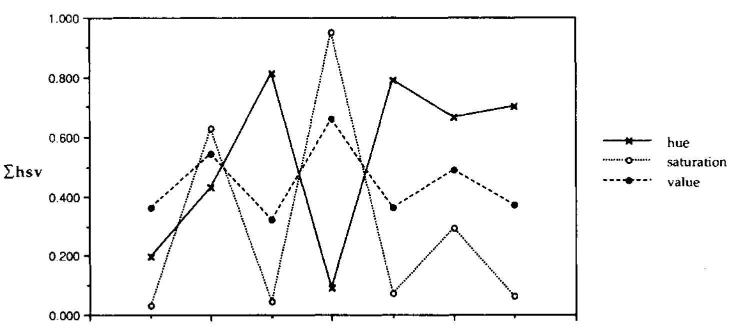

Fig. 4. *hsv* summations for keyframe color maps of *Color Study* #7.

neutral gray background will cause green to appear. Fatigue in the cones of the eye, caused by the imbalanced color domain of red alone, has caused a tension in the color percept.

In the case of simultaneous contrast, also based on the principle of color complements, prolonged observation of a color will cause its complement to appear in neighboring regions. For example, a light gray square surrounded by red will appear green. Here a lateral inhibition in the retina causes the complementary impression. Again we have a tension in the color percept.

These ideas indicate that the eye is always striving to balance the color environment, to create the relaxed state that exists when it is viewing an unperturbed gray. Expressing a similar premise nearly two centuries ago, Goethe stated in his treatise on color,

> The whole ingredients of the chromatic scale, seen in juxtaposition, produce an harmonious impression on the eye. . . . When the eye sees a colour, it is immediately excited, and it is its nature, spontaneously and of necessity, at once to produce another, which with the original colour comprehends the whole chromatic scale. A single colour excites, by a specific sensation, the tendency to universality.
>
> To experience this completeness, to satisfy itself, the eye seeks for a colourless space next [to] every hue in order to produce the complemental hue upon it.
>
> If again, the entire scale is presented to the eye externally, the impression is gladdening, since the result of its own operation is presented to it in reality. We turn our attention therefore, in the first place to this harmonious juxtaposition [3].

More recently Rudolf Arnheim sums up what many color theorists discuss in their attempts to define and codify color harmony.

> These three fundamental primaries [he is speaking of the subtractive primaries—red, yellow and blue] behave like the three legs of a stool. All three are needed to create complete support and balance. When only two are given they demand the third. The tension aroused by incompleteness of the triplet subsides as soon as the gap is filled.
>
> This particular structural combination of mutual exclusion and attraction is the basis for all color organization—much as the particular structure of the diatonic scale is the basis of traditional Western music [4].

From all this we can define the second level in our hierarchy as a *balanced* color domain. A color domain is in balance if the sum of the colors in an image will neutralize each other so as to equal gray.

The Weighted Color Domain

The remaining color juxtaposition is the domain where one hue is dominant. This *weighted* color domain will be the most dynamic, the most unsettled and, in an abstract sense, the most dissonant. To say a color domain is dissonant or inharmonious is not to say it is bad. As a matter of fact, in music the most beautiful and interesting sounds may be those with kinetic energy, those that create tension. The same is true for visual imagery. (In music, harmony deals with all pitch relationships, not just those that are consonant; unfortunately, when color harmony is discussed a qualitative aspect usually is attached to the label. This paper considers color harmony to include the set of all color relationships, in the hope of finding some guiding principles for structuring those relationships as they unfold in time.)

Similar to the consonance-dissonance

structure in music is the three-level hierarchy of color relationships that we have now defined. We can apply these to abstract visual composition: tension moves to resolution from weighted to balanced to neutral color domains.

Color Measure

What is of importance in applying these ideas of color theory is not the specific colors used but rather the relationships of the colors. A simple way to measure color relationships of a raster image to determine the quality and syntactic function of its color domain is to make separate summations of all red, green and blue (r, g and b) intensities in the image and to normalize them between 0.0 and 1.0 [5]. The simple formulae are

$$r_{sum} = \left(\sum_{i=0}^{n-1} r_i \right) / \text{MAX}$$

$$g_{sum} = \left(\sum_{i=0}^{n-1} g_i \right) / \text{MAX}$$

$$b_{sum} = \left(\sum_{i=0}^{n-1} b_i \right) / \text{MAX}$$

with n being the total number of pixels in the image and MAX being the maximum possible summation intensity for each color. Assuming 8 bits for each color, MAX $= 2^8 n$. The summation triplet for red, green and blue values is denoted Σrgb. A totally white image, for example, would have a summation of

$$\Sigma rgb = (r_{sum}, g_{sum}, b_{sum}) = (1.0, 1.0, 1.0)$$

The quality or syntactic function of the color domain described by Σrgb is easily determined. If the components are equal, the image is either neutral or balanced. If the image is seen to be all in the grayscale it is neutral; otherwise it is a balanced color domain. If the components are not equal, the image is weighted.

Using simple transformations we can also create an *hsv* summation triplet for the image [6]. The hue (h) will tell the favored hue in a weighted color domain (0–1 in circular fashion, with red = 0, green = 0.333, blue = 0.666 and red = 1.0). The value (v) tells the maximum intensity of the image (0–1), and the saturation (s) tells us how balanced (s = 0) or weighted (s = 1) the color domain is. If for example

$$\Sigma hsv = (0.666, 0.295, 0.492)$$

the summation triplet indicates a color domain with a weighting in blue. The saturation level is low, which would indicate a gray-blue weighting, a low-saturate blue. With an intensity value near 0.492, we can also expect the image to be relatively bright.

It is important to reiterate that the summation triplets Σrgb and Σhsv tell us little about the actual color values in the image but give more general information about the color domain of the image. To understand this clearly, we can pick for analysis two color keyframes from the animation *Color Study #7* (see Color Plates 1a and 2a).

Color Plate 1a is frame 2400 from the study. It is an example of a balanced color domain. The *rgb* and *hsv* summations for the images are

$$\Sigma rgb = (0.355, 0.335, 0.362)$$

$$\Sigma hsv = (0.790, 0.0746, 0.362)$$

We can tell from both triplets that the image is balanced. The *rgb* components are nearly equal, and the saturation level is near zero. If there is a weighting at all, it is in the violet range, but the overall effect should be minimal as the *rgb* summation intensities balance one another.

To further illustrate this balance, we can redistribute the pixels from frame 2400 in random order within the raster. If the image is truly balanced, the overall impression when seen from a slight distance should now be gray. The pixels should mix together like the dots of a Seurat painting. This image can be seen in Color Plate 1b. It has a neutral quality with perhaps a slight tinge of violet as indicated in Σhsv.

Color Plate 2a, frame 3000 from the study, has the following summation triplets:

$$\Sigma rgb = (0.347, 0.348, 0.492)$$

$$\Sigma hsv = (0.665, 0.295, 0.492)$$

Here we have a domain weighted in blue with low saturation. Redistributing the pixels gives us an image with a definite blue weighting, but not highly saturate, as seen in Color Plate 2b.

Parametrically Defined Color Palettes

Now that we have defined a basic color syntax, how can it be compositionally applied? An early problem encountered is how to move from one color domain to another. One solution is to use color maps for key images and to interpolate from one keyframe map to the other.

In its simplest form this solution is not satisfactory, as interpolating through the *rgb* values from one map to the next can often wash out all detail in an image. For example, in Table 1, linear interpolation from a start color to an end color has a pure gray as the midpoint color. Setting up keyframe color palettes to avoid these relationships would require heavy constraints and make the task overly difficult and needlessly limiting.

A simple and effective method is to define the keyframe color maps parametrically and then to interpolate through the parameters rather than through the actual color values. The ICARE color map editor designed by graphic artist Donna Cox will allow this parametric definition [7]. With ICARE, the *rgb* entries in a color map are derived from periodic functions. Parameters of amplitude, frequency, phase and offset are plugged into a sine function that calculates the *rgb* array elements for the color map. In *Color Study #7* this approach was applied to an *hsv* rather that an *rgb* color space and then transformed into the *rgb* map entries.

Table 2 shows the parameters defining the color palette for frame 1800 (Color Plate 3) of the study.

Figure 1 shows graphically the *hsv* components for each entry of the 1,024-

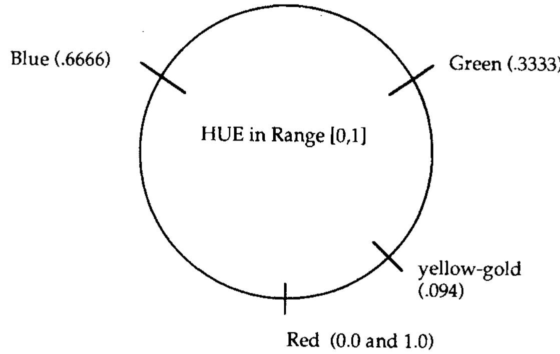

Fig. 5. Hue values normalized to the range of 0–1 as used in Σhsv color domain components.

element color map used with the image. The hue component is of very low amplitude centered around yellow-gold. The color is highly saturate, with little visible gradation as defined by a high offset for the saturation value with a low amplitude. The value component shows a high amplitude, which should manifest as apparent gradations of lightness and darkness that give the appearance of pseudo-3-dimensionality to the raster image.

By selecting keyframe color maps, defined parametrically, we can interpolate through the parameters to create in-between palettes, with a separate color palette for each image in the animation. Since we have the ability to measure the color domain with respect to neutral, balanced or weighted function, it is now possible to create a weighted color domain and interpolate to a balanced or neutral domain. The reverse is of course also true. We can now structure time with color!

A Compositional Approach

Color Study #7 illustrates one method of applying these ideas to temporal color composition. An analysis of the compositional approach used with respect to the evolving color relationships in the study reveals an underlying arch form (Fig. 2). The arch form is a common musical architecture in which the focus or perhaps climax of the piece occurs in the middle. The closing half works its way to the end as a loosely mirrored unraveling of the first half.

We accomplish this analysis of the study by dividing its 3,600 frames into six equal sections of 600 frames each, using seven keyframe color palettes. A storyboard of the entire composition can be seen in Color Plate 4 with the animation progressing from upper left to lower right. The study begins and ends in a neutral color domain. The peak of the study is at frame 1800 (see Plate 3) which has the maximum hue weighting of any image in the composition.

Figure 3 illustrates the movement of the color by examining Σrgb components for each keyframe palette. Balanced or neutral domains will have equal Σrgb values. Looking at the components for keyframes 1 and 7, along with the corresponding images (first and last images in the storyboard, Color Plate 4), we can see that they are neutral. Keyframe 2 is a weighted color domain with an orange tendency. Σrgb for keyframe 3 returns us to a balanced domain (corresponding approximately with row 2, image 2 of Plate 4) and then the study progresses to the climax point at keyframe 4 with a yellow-gold weighting (Plate 3). Again we return to the balanced domain we analyzed earlier (Plates 1a and 1b), and then on to another weighted relationship, also analyzed earlier (Plates 2a and 2b). The blue weighting resolves itself to the neutral keyframe 7 palette, ending the composition (corresponding with the image in the lower right of Color Plate 4).

In Fig. 4 we can also follow the arch form, using Σhsv components. The actual image intensity, or value (v), peaks at the midpoint, keyframe 4. The saturation summations agree with the Σrgb components: low saturation values indicate neutral or balanced domains. The hue component indicates overall hue weighting for saturated domains; keyframe 4 shows a hue value of 0.094 or yellow-gold (see Fig. 5). Actual Σrgb and Σhsv components for the keyframe palettes can be seen in Tables 3 and 4.

Unresolved Issues

Color is only one aspect of a visual composition, and color domains are one small part of a complete color grammar. Although we have established a syntax for moving through color relationships we have not dealt with the connotative aspects of particular hues—what might be considered the semantic side of a color grammar.

Other issues remain: questions of shape and form; the distribution of different hues and values over the image; questions of temporal design; and the evolution of abstract shapes in time. A complete time-based visual grammar has many facets, all of which must eventually be considered in abstract visual composition. These questions are, of course, more than can be covered in a short paper, but they suggest many directions for further study.

The imagery for *Color Study* #7 is a visualization of a simple mathematical process. Each frame is a two-dimensional grid of 10-bit numbers, which are assigned color from a 1,024-element color map. Although the procedure for creating the animation frames is beyond the scope of this paper, it uses a simple design principle that is worth noting. The piece is set up with a start frame and an end frame defined. All frames in between are calculated as interpolations revealing a single gestural phrase. A simple motion of relaxation-tension-release is created by moving from and to points of dynamic symmetry [8], from one point of visual balance in spatial composition to another.

As temporal color relationships are of primary importance in the study, elements of motion and shape were minimized, using either simple shapes or a single gesture. Theories of tension-release in pure design already exist and provide a good point of departure for further work in the non-color design aspects of a time-based visual grammar [9]. Combined with this color research, they begin to establish a language for abstract visual composition.

Final Remarks

Color Study #7 illustrates rigorous control of color relationships over time. It shows that it is possible to create coherent compositions with a formal foundation similar to that found in traditional Western music practice.

The idea of a neutral-weighted dynamic with respect to color is not a new one. Hence this work serves not so much as theoretical invention but rather as codification of a practice in filmmaking that dates back at least 50 years. In 1939, MGM's *The Wizard of Oz* was divided into three sections. The opening and closing, set in the stability of 'home', were in neutral black and white. The action of the story in the land of Oz was in color.

Today's music videos make extensive use of the interplay of neutral (black and white) and weighted domains. An hour's worth of viewing demonstrates that, though filmmakers may not follow a rigorous theory, they instinctively understand the kinetic potential of structuring time with color.

The work discussed here is but a start toward a design language for abstract visual composition. Over the last century experimental animation has made only a small mark on the artistic landscape [10]. Many of the problems these filmmakers faced have been alleviated with the advent of computer technology. Obstacles of expense, equipment access and time expenditure all have

Table 1. Start, midpoint and endpoint of the color map, which defines color as 1 byte (0–255) each of red, green and blue.

	start	mid	end
red	160	120	80
green	200	120	40
blue	20	120	220

Table 2. Sine function parameters of frame 1800, color map (*hsv* space).

		hue	saturation	value
amplitude	[0–1]	0.012	0.039	0.273
frequency		5.0	6.0	2.0
offset	[0–1]	0.094	0.953	0.586
phase	(radians)	0.0	0.0	1.885

Table 3. Σ*rgb* components for keyframe palette color domains.

keyframes	red	green	blue
1	0.361	0.363	0.352
2	0.547	0.352	0.204
3	0.318	0.306	0.320
4	0.659	0.386	0.034
5	0.355	0.335	0.362
6	0.347	0.348	0.492
7	0.354	0.349	0.373

Table 4. Σ*hsv* components for keyframe palette color domains.

keyframes	hue	saturation	value
1	0.197	0.030	0.363
2	0.072	0.627	0.547
3	0.810	0.044	0.320
4	0.094	0.948	0.659
5	0.790	0.075	0.362
6	0.665	0.295	0.492
7	0.704	0.064	0.373

been minimized. As interest in technology for technology's sake wanes (as the technology becomes more readily available), the focus will return to its creative use. The body of work and theory will grow.

In abstract animation, the need for a working vocabulary and grammar is paramount. There is of course no one solution for each aesthetic problem to be encountered. It is doubtful that artists will even agree on what the problems are. This research offers one approach to the problem of color.

Although this paper has focused on the technical elements of a process, it must be remembered that the details of craft are important to the artist but should be invisible and seamless to the audience. As in analyzing a music composition, we can graph, chart and quantify the elements of a piece and lose sight of the work as a piece of music. We are, after all, dealing with art. While we accept the discipline and responsibility of the craft, we must be cautious of overintellectualizing what we do, and of leaving the work cold and sterile.

Finding that balance is a challenge all artists face. John Whitney says, "Art, unlike science, is proven by art alone" [11]. As we each find our own way, and as we discover and share new techniques, the work eventually will speak for itself, with time as the final arbiter.

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10. Russett and Starr [9].

11. Whitney [9].

Acknowledgments

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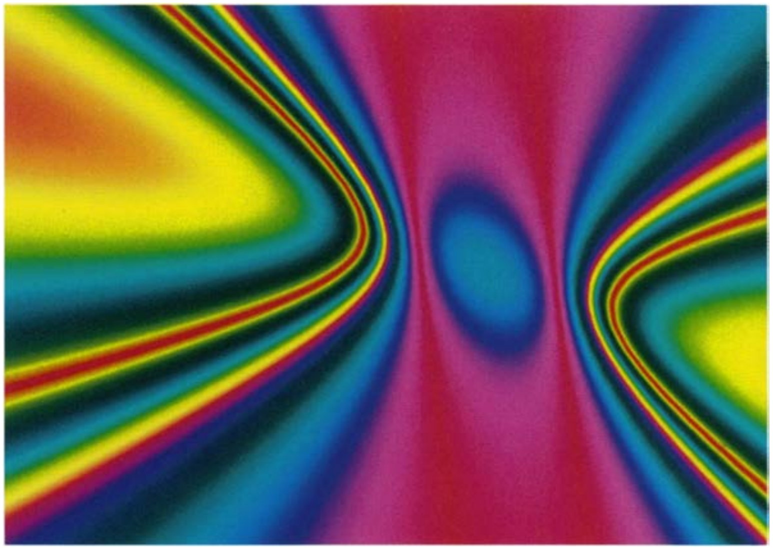
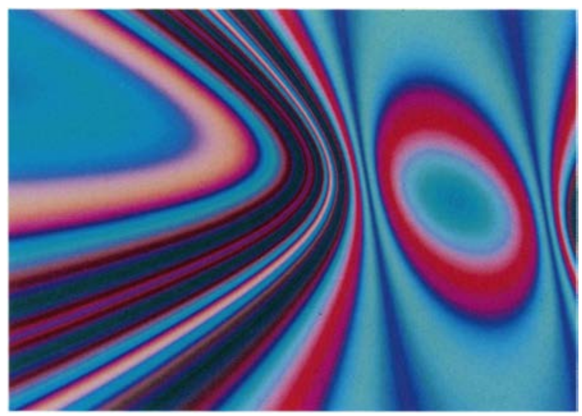


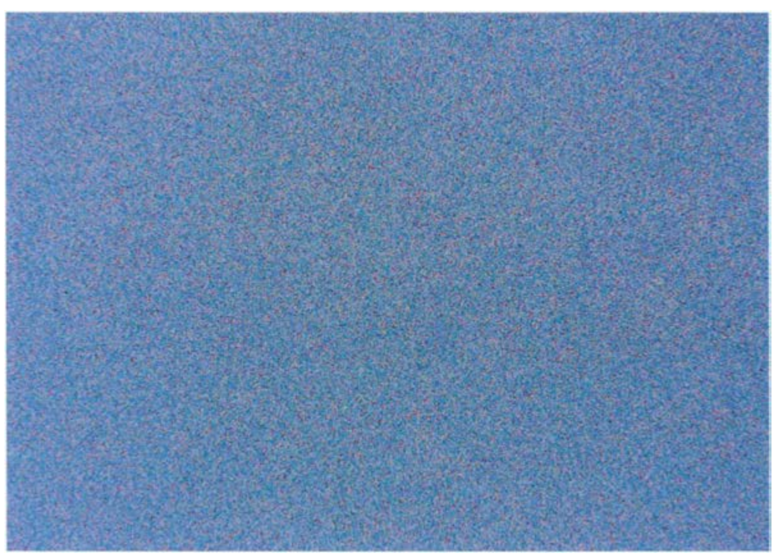
Color Plate 1a. (left) Frame 2400 of *Color Study #7* (keyframe color palette 5), an example of a balanced color domain in which *rgb* summation intensities balance one another.

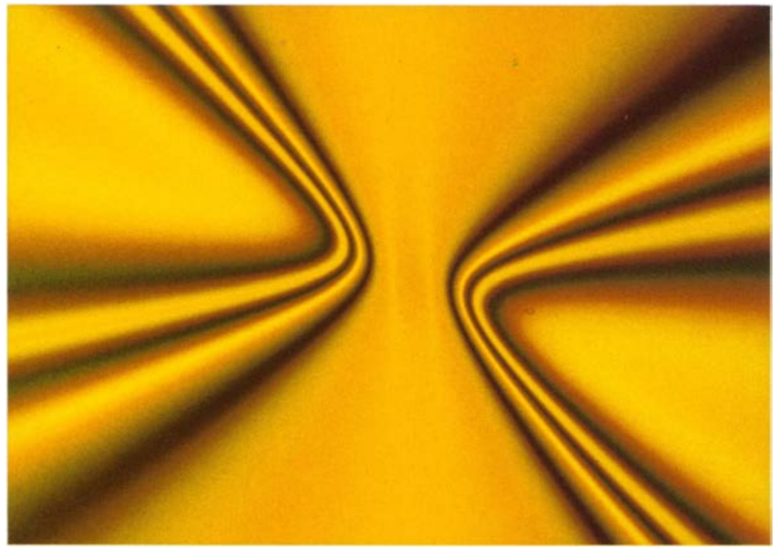
Color Plate 1b. (left) Random redistribution of pixels in frame 2400 (see Color Plate 1a), demonstrating a neutral quality due to the balanced color components.

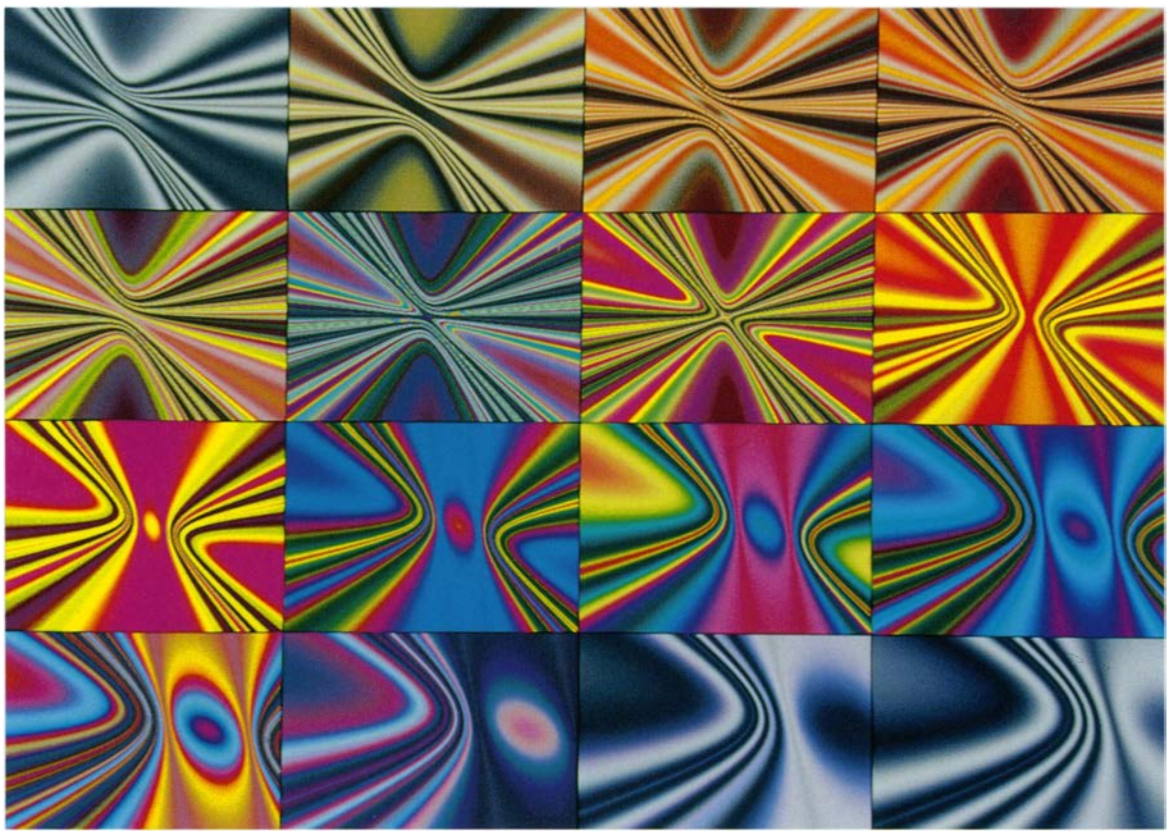


Color Plate 2b. (right) Random redistribution of pixels in frame 3000 (see Color Plate 2a), demonstrating a weighting in low-saturate blue.

Color Plate 2a. (right) Frame 3000 of *Color Study #7* (keyframe color palette 6), a domain weighted in blue with low saturation.







Color Plate 3. (top) Frame 1800 of *Color Study #7* (keyframe color palette 4), climax of the composition, with a high-saturate yellow-gold weighting.

Color Plate 4. (bottom) Representative frames from the entire composition of *Color Study #7*, beginning, at the upper left, in the neutral color domain, passing through a colored domain (orange), then a balanced domain (row 2, image 2) and to the peak with maximum weighting (yellow-gold); the study resolves at the lower right in the neutral domain after passing through another weighted domain (blue).