PHYSICAL PIXELS

by

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Abstract

The picture element, or *pixel*, is a conceptual unit of representation for digital information. Like all data structures of the computer, pixels are invisible and therefore require an output device to be seen. The physical unit of display, or *physical pixel*, can be any form that makes the pixel visible. Pixels are often represented as the electronically addressable phosphors of a video monitor, but the potential for different visualizations inspires the development of novel phenotypes. Four new systems of physical pixels are presented: *Nami*, *Peano*, the *Digital Palette* and *20/20 Refurbished*. In each case, the combination of material, hardware and software design results in a unique visualization of computation. The chief contribution of this research is the articulation of a mode of artistic practice in which custom units of representation integrate physical and digital media to engender a new art.

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Introduction

The effort to make computation visible will always be affected by the material interpretation of what is essentially immaterial. Yet, like all forms of art, it is through the revelatory process that we come to understand that which cannot be revealed. This thesis examines the *picture element*, or *pixel*, as one method for visualizing the numeric and electronic abstraction of computation.

The deconstruction of images into a quantifiable unit of representation is at least as old as the tile mosaics of ancient Greece. In contrast to a mosaic tile, which has an appearance intrinsic to its physicality, a picture element begins as a non-visible quantum of information. It serves to represent, but has no appearance *per se*.

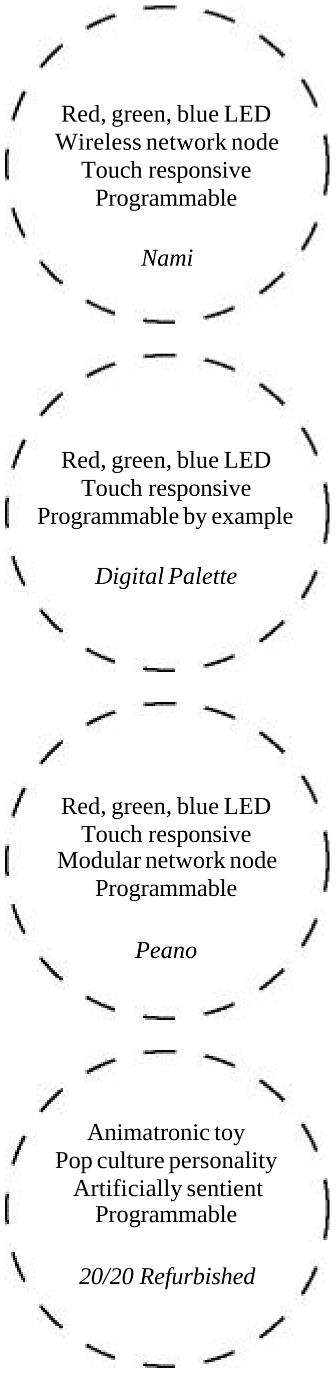
To be seen, the pixel needs a physical form hereafter termed the *physical pixel*. To date, video has been the predominant medium for making pixels visible, along with tapestry, punch cards and print. All of these forms are different visualizations of the same fundamental data structure. Due to variation in physical media, different output devices will provide a unique experience of the same digital information. The physical appearance of a pixel is a matter of interpretation, a specific material manifestation of an invisible medium.

I present four research projects with four physical pixels, each of which offers a different perspective on the computer as a medium for artistic expression. The basic organization of visible data is consistent throughout, but each project defines the pixel as a different computational and material unit. In the *Nami* example, our pixel is a wireless network node with full-spectrum colored light. The *Digital Palette* treats the pixel a source of electronic "paint" for coloring other physical pixels. In the *Peano* project, I demonstrate how the pixel can be used as a building block for computer animated sculpture. Finally, *20/20 Refurbished* presents the observer with a reactive surface made of Furbies™ that are modified to behave as pixels with personality. This body of work is defined by a mode of artistic practice in which custom units of representation unite physical and digital media. Like the painter's brushstroke or sculptor's touch, the physical pixel is the mark of a new art.

This research is presented as part of a tradition of optical deconstruction in the visual arts, including the history of computer graphics. I include several prior examples in which physical pixels have revealed a novel insight into the nature of computation. Finally, I endeavor to understand what is consistent about the pixel throughout any material manifestation, and therefore any art made with a pixel-based organization of digital information.

The principle contributions of this thesis are:

1. The articulation of a new media termed the *physical pixel*
2. Four examples of physical pixels, each of which encapsulates a unique combination of physical and digital into a synthetic form
3. A conceptual framework for the design of physical pixel media



What is a pixel? A pixel is a unit of representation with a data structure and a physical form.

Each of these circles encapsulates a unit of representation with different properties, as described in this thesis. *Italics indicate the display system.*

The Slow Birth of New Media

Among Marshall McLuhan's most important contributions to twentieth century thought is "The medium is the message." His statement is not meant to proclaim the disappearance of content, but "merely to say that the personal and social consequences of any medium -that is, of any extension of ourselves- result from the new scale that is introduced into our affairs by each extension of ourselves, or by any new technology."[1] In other words, stories, mythologies and characters do not change significantly with time, but media change radically; and the way in which we perceive content is equally if not more influenced by the message of a medium than the narrative itself. The skillful use of a medium is critical to the success of an artist. Instinctively, we know when there is a lack of true ownership over the material from which an artwork was made. A message inappropriately delivered in paint will look as wrong as a eulogy written in icing on cake.[2] This is an extreme example, but the more subtle situations are those which regularly inflict our communication with unwitting friction and misunderstanding. In the best case, a medium will enhance a message by contributing implicit meaning to an artist's explicit intention; but weak content in a strong vehicle, or strong content in the wrong vehicle, will not be delivered effectively. Content aside, the misguided media-vehicle will drive our attention elsewhere.

Bush Model TV56 405 Line TV

The computer monitor. From the Conrac Corporation's *Raster Graphics Handbook* (Second Edition). Van Nostrand Reinhold Company, Inc., New York, NY. 1985. Note the similarities in the television and desktop computer interfaces.

Unpacking the message of a medium is essential to creative work, enabling the artist to see the material for what it *is* and not what it *seems to be*. In his essay "The Question Concerning Technology", Heidegger describes this essential pursuit in terms of *technç*, the Greek root for the word *technology*, originally associated with "knowing in the widest sense … to be entirely at home in something, to understand and to be an expert in it."[3] Technç embodies the wisdom that precedes *poiçsis*, or the "poetical bringing into appearance and concrete imagery".[4] In the absence of technç, an artist will be hindered from this poetic process of revealing truth, for "Only the true brings us into a free relationship with that which concerns us from out of its essence."[5]

At this early stage in development, art made with the computer[6] is still undergoing differentiation from previous modes of expression. Work in new media typically involves a

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[1] McLuhan, Marshall. Understanding Media: the extensions of man. The MIT Press, Cambridge, MA, 1994. Page 7.

[2] Note that a failure of this type is due to both societal perception and the impracticality of cake icing for permanent record. The inappropriateness of the medium is partly cultural, and partly essential to the material.

[3] Heidegger, Martin. The Question Concerning Technology and Other Essays. Harper and Row Publishers, Inc., New York, NY, 1977 (Hereafter referred to as TQCT). Page 14.

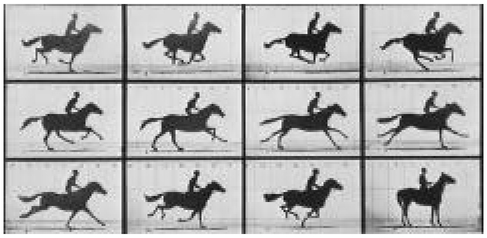
[4] TQCT, page 10.

[5] TQCT, page 6.

[6] As Charlotte Burgess astutely observes, "art made with a computer" has no strict definition at this time. Use of the phrase "computer art" is avoided in this document because it merits careful definition, an exercise that extends beyond the scope of this thesis.

transposition of previous experience, regardless of whether or not the content is appropriate or interesting in the new medium. In his 1932 article, *A New Instrument of Vision*, Mohology-Nagy summarizes the influence of "the aesthetic-philosophic concepts that circumscribed painting" on the early years of photography:

> Up to now, photography has remained in rather rigid dependence on the traditional forms of painting; and like painting it has passed through the successive stages of all the various 'isms'; though ill no sense to its advantage. Fundamentally new discoveries cannot for long be confined to the mentality and practice of bygone periods with impunity. When that happens all productive activity is arrested.[7]



Eadweard Muybridge's *The Horse in Motion* (1878). Developed as part of an "atlas for the use of artists."

Art made with a computer is no exception to this tendency. In 1975, Anne Murray stated "The first decade of experimentation has shown that the computer can be programmed to simulate the styles of previously existing art,"[8] as though emulating pre-existing art is somehow a prerequisite to work in a new medium. Murray continues, "graphic designers, printmakers, sculptors, film makers, architects and choreographers… prefer to work in conjunction with a programmer who can translate their ideas into the mathematical language of the machine."[9] Her description of the programmer as translator for the artist is reminiscent of Muybridge's "specific intention" in photography "to create an atlas for the use of artists, a visual dictionary of human and animal forms in action."[10] In both cases, the technologist – programmer or photographer- was not considered the artist, but servant to an artist and his/her preconceived notions about art in an unfamiliar medium.

The computer is often treated as a means for representing traditional forms of art. This perception can be dangerous insofar as it can mistake art represented on a computer with the original form, not unlike the confusion of printed reproduction with an authentic painting.[11] The visual narrative may be the same, but the media of one art is not necessarily interchangeable with another. In *Being Digital*, Nicholas Negroponte writes,

This is not a painting. Adapted from René Magritte, *The Betrayal of Images* (1929).

> Computers and art can bring out the worst in each other when they first meet. One reason is that the signature of the machine can be too strong. It can overpower the intended expression … The flavor of

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[7] Moholy-Nagy, Laszlo. *A New Instrument of Vision*, 1932.

[8] Anne H. Murray quoted from: Leavitt, Ruth. Artist and Computer. Crown Publishers, Inc., New York, NY, 1976 (Hereafter abbreviated A&C). Page 3.

[9] Anne H. Murray quoted from A&C, page 1.

[10] Newhall, Beaumont, The history of photography : from 1839 to the present. Museum of Modern Art, New York, NY, 1982.

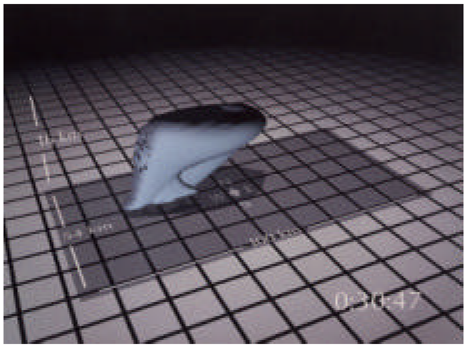
[11] Walter Benjamin discusses the profound implications of printed media for painting in his famous essay, "The Work of Art in the Age of Mechanical Reproduction."

> the computer can drown the subtler signals of the art.[12]

That art made in other media does not jibe with the computer is no fault of the machine. To view a painting on a monitor is to alter the identity of the work entirely, although certainly not to transform the work into "computer art." In his 1965-66 *Brushstrokes* series, Roy Lichenstein made brilliant commentary on the transposition of painting into the print medium by returning the brushstroke to the canvas as a subject, rendered in paint as it *appears* in print. Lichenstein reminds us that the substance of one medium is simulacrum in another. Although his brushstroke subjects are compositionally predominant, the paintings are *about* a relationship to print. The "flavor of the computer" that drowns "the subtler signals of the art" is the essence of media that Lichenstein harnesses to make his art.

Roy Lichenstein's *Big Painting VI* (1965). Oil and Magna on canvas, 92.5 x 129 inches. Kunstsammlung Nordrhein-Westfalen, Dusseldorf.

Numerous artists have emerged with no distinction between computer scientist and creator, producing artworks that have no comparable identity in any other medium. Nevertheless, *computer graphics* is nearly synonymous with *screen-based*, and the pixel is commonly perceived as a phosphor of a desktop monitor.[13] To be sure, the popularity of the video monitor has much to do with its availability and high-quality image, but a normative concept of image representation is also involved. The rectangular monitor, the flat screen, the uniform surface texture, high realism and the Cartesian image plane, characterize the majority of computer graphics. It is no coincidence that these are descriptors that could be equally applied to a high Renaissance painting, also heavily influenced by the philosophy of René Descartes. Perhaps it is the very same fear of infinite reality that inspired Descartes to seek proof of the existence of everything, including God, which motivates the contemporary thinker to seek Cartesian order in the approximate infinity of digital information.[14]



The Cartesian grid of computer graphics illustrated in full glory. Image from the videotape "Study of a Numerically Modeled Severe Storm," National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign. Caption and illustration adapted from Edward Tufte's *Visual Explanations: Images and Quantities, Evidence and Narrative*. Graphics Press, Inc., Cheshire, CT, 1997.

Although innovative art has been made with the computer, metaphor impedes a deeper understanding. In part, metaphor is our only access to an invisible medium; most concrete representations of computation look *like* something else. The monitor is *like* the frame, the screen is *like* the canvas, the software tools simulate brushes, and many peripheral devices seek comparison to instruments of the draftsman. This is a challenge for every art form, made all the more treacherous as simulation by one medium of another becomes increasingly facile. In 1961, Clement Greenberg commented, "What had to

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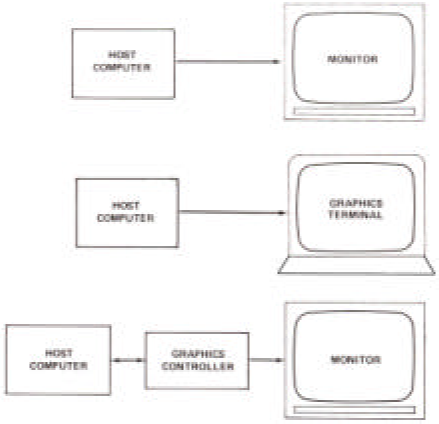
[12] Negroponte, Nicholas. Being Digital. Random House, Inc., New York, NY, 1996. Page 223.

[13] Many people mistake the RGB phosphor for *the* pixel as opposed to a material instance of *a* pixel.

[14] Sean Cubitt traces the history of the grid through Descartes to the foundations of Christianity itself: "The grid derives its onscreen presentations from modernist design practice, which itself can be traced back to Descartes's invention of neutral space defined only by coordinates rather than contents, and to Mercator's redefinition of the map as a blank field of longitude and latitude into which the marks of coordinate space can be drawn. But behind this insipid, unmarked space can be glimpsed an older grid deployed in the mediaeval scriptoria, a grid made up not of modular, transferable boxes, but of points and cruxes, in each of which the divine and the sublunary met. From: Cubitt, Sean. Digital Aesthetics. Sage Publications Ltd, London, 1998 (Hereafter referred to as DA). Page 89.

be exhibited and made explicit was that which was unique and irreducible not only in art in general *but also in each particular art…*”[15] (Italics mine). To the extent that new media inspires a *reinvention* of traditional expression, a connection to the past can be deeply meaningful; but the *reproduction* of old ideas is tiresome. Art made with the computer must consciously parry comparison to reveal a fresh perspective on historic art forms instead of mimicking tradition. The danger of metaphor derives from its purchase of a mind frame from pre-existing media, as observed by Charles Csuri, “Most people are inclined to think of computer art as static graphics or animated film.” The connection to painting, film and video is further affirmed in the terminology of programming itself.[16] Metaphor may be a useful device for user interface, but adherence to the familiar can seduce an artist to “shut [their] eyes to the constellation of truth after which we are *questioning*.”[17] As stated by Steven Holtzman, “If virtual worlds are mere reflections of the natural, built on borrowed metaphors from the real world, then indeed we may create little more than the antithesis of the natural.”[18] When questioning the computer as a creative medium, care should be taken that preconceptions do not preempt a revelation.



Three (rather limited) options for visualizing computation, adapted from the Conrac Corporation’s *Raster Graphics Handbook* (Second Edition). Van Nostrand Reinhold Company, Inc., New York, NY. 1985.

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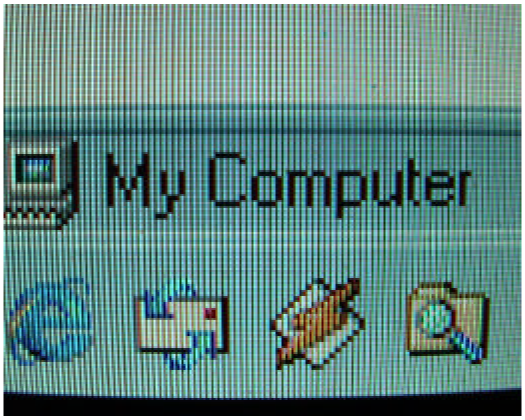
[15] O’Brian, John (Editor). *Clement Greenburg: The Collected Essays and Criticism Vol. 4 - Modernism With a Vengeance, 1957-1969*.

[16] Metaphor permeates the semantics of programming languages. The examples are too numerous to recount, but suffice a few: Java contains methods for creating a *canvas* on which to *draw*, *paint* and *repaint*; Lingo conducts animation of *cast members* on the *stage*.

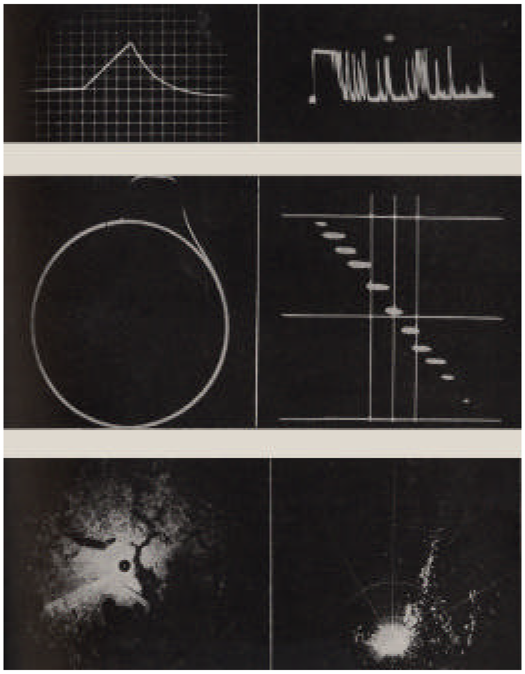
[17] TQCT, page 35.

[18] Holtzman, Steven. Digital Mosaics: the aesthetics of cyberspace. Simon and Schuster, Inc., New York, NY, 1998. Page 61.

The origins of the picture element derive from the cathode-ray tube (CRT), a display technology popularized by television and later co-opted by computer graphics. *Pixel*, short for *picture element*, emerged in the late 1960s as a way to describe video.[1] Despite the comparatively large storage requirements of the raster display, computer scientists recognized that specifically addressing the entire grid of a CRT would lead to a dynamic and flicker-free, color image.[2] With the development of low-cost memory in the 1970s, bitmap raster graphics replaced vector systems as the predominant paradigm of computer graphics and the concept of a digital pixel was born. As described by Nicholas Negroponte, "The real power of the pixel comes from its molecular nature, in that a pixel can be part of anything, from text to lines to photographs. *Pixels are pixels* is as true as *bits are bits*. (…) The same bits can be looked at by the viewer from many perspectives."[3] Like any data, the digital pixel has no absolute appearance; it is a mathematical description that needs to be interpreted by a physical output device in order to be visible. Nevertheless, our contemporary concept of the pixel is concretely rooted in material origins, for reasons examined in this chapter.



The pixel as we know it.



Cathode-ray tube images, circa 1948. From *Cathode Ray Tube Displays* (Theodore Soller, Editor). McGraw-Hill Book Company, Inc., New York, NY, 1948.

The history of video has played a dominant role in the definition of *picture element* and thus bitmapped raster graphics on the whole. To understand this influence requires a look at the development of video in the context of film animation, print, painting and other forms of image creation, which have influenced our traditional perception of the image. In 1948, at the dawn of television, Theodore Soller describes the cathode-ray tube like a form of electric painting,

> The cathode-ray tube is a form of visual indicator that permits an interpretation of electrical phenomena in terms of a *picture painted* on a phosphorescent screen which is controlled in position and intensity by electrical signals. Under the proper conditions, it *paints this picture* in an extremely facile way, being capable of utilizing many millions of separate data per second.[4] (Italics mine)

This notion of a painting made by "electrical signals" is altogether different from film animation, which at the time

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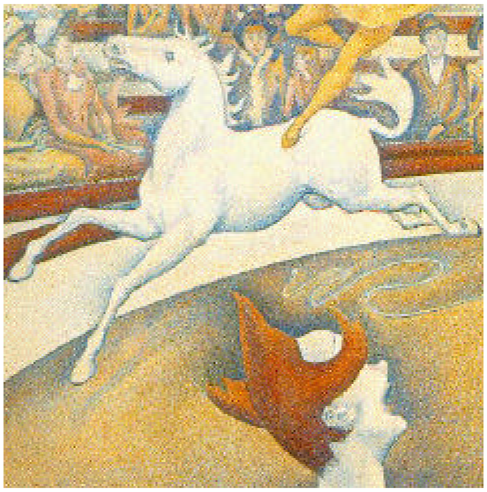
[1] Oxford English Dictionary. The specific reference is to a 1969 article in *Science*, vol. 15 (August). Further research into the origins of *pixel* reveal a reference to the concept, if not the name, as early as 1940, in which M. W. Baldwin attributes image sharpness to "the number of elemental areas in the image." He quantifies resolution of these elements in terms of "liminal units." (From: M. W. Baldwin's "The Subjective Sharpness of Simulated Television Images." Proceedings of the I.R.E., 1940. Page 460.) Thanks to Steve Gass for his generous assistance with the search for pixel etymology.

[2] A. Michael Noll of Bell Telephone Laboratories published the seminal paper on this topic in 1971, "Scanned-Display Computer Graphics." He uses the term "dot" or "point" instead of "pixel," presumably an indication that the language of computer graphics had yet to merge with video terminology.

[3] Negroponte, Nicholas. Being Digital. Random House, Inc., New York, NY, 1996. Page 107.

[4] Soller, Theodore (Editor). Cathode Ray Tube Displays. McGraw-Hill Book Company, Inc., New York, NY, 1948. Page 1.

Soller made his observation, was the best-known medium for dynamic imagery (and is still popularly considered to be the nearest cousin of the video image). Despite the superficial similarities of film and video, Soller alludes to a critical divide between the two media. Whereas cinema creates the illusion of motion using the mechanical sequencing of high-resolution frames, video is the result of "many millions of separate data per second" changing in unison to present a coordinated image on an immobile output device. In this respect, video participates in a trend of pictorial deconstruction that began with the daguerreotype and Impressionism, was "echoed later in Seurat's *pointillisme*, and is still continued in the newspaper mesh of dots that is called "wirephoto."[5] Through a reduction of the image "into a fabric of tiny, uniform, color-bearing dots … repeated over the surface of the canvas with machine-like regularity,[6]" video unites the temporal image with the spatial plasticity of painting.



Detail from George Seurat's *The Circus* (1891). Oil on canvas, 73 x 59 1/8 inches. Musee d'Orsay, Paris.

While the cathode-ray tube was still undergoing development in the hands of engineers, the notion of a video-like medium occupied the minds of many artists. Abstract animators such as Hans Richter and Oskar Fischinger handmade precious frame after frame of film to create the moving painting. Notably, Alexander Alexeieff and Claire Parker painstakingly crafted a physical screen of 1,000,000 pins that they sculpted to achieve a movable surface for their film animation. Kinetic artists, including Alexander Calder and Yakov Agaam, incorporated motion into art through the use of natural phenomena and viewer interaction with sculpture. In particular, Agaam experimented with a wide variety of moving parts, modular compositional elements and sculptural surfaces in which an observer could participate to experience a dynamic artwork. Beginning in the 1950s, Mary Ellen Bute and later, Nam Jun Paik, were among the first to directly manipulate the analog signal to a cathode-ray tube, using electronics for abstract effects *within* the video medium, as opposed to *recorded by* the film medium. Through the use of magnets and circuitry, Bute, Paik and other early video artists were able to paint with time-varying electrical phenomena directly onto the video medium itself.

Mary Ellen Bute (1954). Photograph by Ted Nemeth, from Robert Russett and Cecile Starr's *Experimental Animation* (Revised Edition). Da Capo Press, Inc., New York, NY, 1976.

Whereas early work with the cathode-ray tube depended on an analog source for the visible signal, computer science elevated the electronic painting to a new level of mathematical abstraction and discrete control. It became unnecessary to know the nuts and bolts of video electronics; programming afforded linguistic access to the "black box" terminal. Digital processing was an attractive alternative to the time-consuming process of film animation and the analog-dependency of television. In the late 1950s, artists began a gradual shift towards the computer as a medium, as explained by John Whitney regarding his animation machine of 1958,

Yakov Agaam's *Lumiere de minuit (Midnight Light)* showing the visible changes as the same piece is viewed from four different perspectives. From Frank Popper's *Agaam* (Third Revised Edition). Harry N. Abrams, Inc., New York, NY, 1990.

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[5] McLuhan, Marshall. Understanding Media: the extensions of man. The MIT Press, Cambridge, MA, 1994. Page 190.
[6] Anne H. Murray from: Leavitt, Ruth. Artist and Computer. Crown Publishers, Inc., New York, NY, 1976. Page 1.

> [My animation machine] is actually is doing mechanically what an oscilloscope would do; and that's when I began to realize that what I was doing mechanically could be done on the cathode ray tube computer terminal.[7]

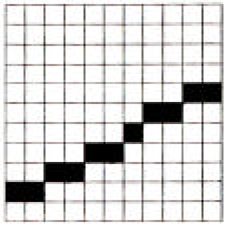
Through the computer, mathematics provided a new means for animating an electronic image, achieving effects that were previously restricted to direct manipulation of the display device. Mathematics reduced the image to *information* from which an illusion could be modeled numerically, as opposed to media that captured or physically built a picture. As described by Richard Norman in his text *Electronic Color*,

> Unlike the image on a television screen, the computer picture is the invented image of its designer, a plastic image that can be shaped and changed, an image that is alive and capable of responding to further *information*.[8] (Italics mine)

A critical shift occurred when the means by which information was used to manipulate an image transitioned from analog to digital. Although film, photography, print and television are all technological, the image-making capabilities of these media are accessible through *manual* control, even if such physical craft necessitates electronic components. In contrast, the programmer's art is abstract logic organized into computer instructions, like a form of machine age poetry. The computer program is an intangible set of commands by which a machine executes logic; and according to this logic, a system of physical pixels (or other display device) illustrates the state of the machine. With bitmap raster graphics, the video pixel evolved from an analog locale on a cathode-ray tube into a point with mathematically specific syntax.

Logical access to every pixel of the video monitor, combined with sufficient data storage, rapidly broadened the pictorial applications of the medium. Video games are an obvious example, but nearly every other form of graphical user interface of the past thirty years has followed in the video tradition as well. Bitmapped raster graphics on the video monitor rapidly became the popular perception of computation. Although "jaggies" were a nuisance to early raster graphics, Frank Crow and other graphics pioneers of the early 1970s made it a priority to "perfect" the computer-controlled video image through the elimination of pixel evidence[9]. Thanks to their emphasis on higher level content and virtual realism, pixels have become practically invisible in screen-based computer graphics.

Nam Jun Paik's direct manipulation of the video signal in *Magnet TV* (1965). Photograph taken from the Guggenheim Museum web site.



Jaggies: the inevitable consequence of continuous geometry on a finite grid. Conrac Corporation. *Raster Graphics Handbook* (Second Edition). Van Nostrand Reinhold Company, Inc., New York, NY. 1985.

Realism in computer graphics. Illustration from Newman and Sproull's *Principles of Interactive Computer Graphics* (Second Edition). McGraw-Hill Book Company, Inc., New York, NY, 1979.

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[7] Russett, Robert and Starr, Cecile. Experimental Animation (Revised Edition). Da Capo Press, Inc., New York, NY, 1976. Page 184.

[8] Norman, Richard B. Electronic Color: the art of color applied to computer graphic computing. Van Nostrand Reinhold, New York, NY, 1990. Page 72.

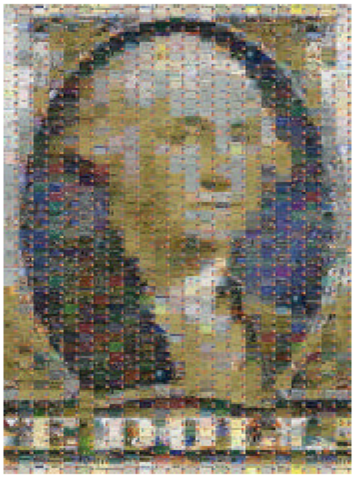
[9] Franklin C. Crow's seminal paper on antialiasing was presented to the SIGGRAPH community in 1977, "The Aliasing Problem in Computer-Generated Shaded Images."

Nevertheless, the pixel remains integral to our perception of the computer, just like the brushstroke, the tooth of paper, the brand of film or the grit of clay. Certain artworks specifically bring our attention to the tiny physical pixels of the screen, as exemplified by John Maeda's *Single Pixel* (1995). Other screen-based work creates graphic representations of the pixel, such as the down-sampled portraits made by Ed Manning's BLOCPIX™. Similarly, anyone who has "zoomed down to the level of the pixel" in Adobe Photoshop™ is familiar with their illustration of the image pixel as an evenly colored square. Leon Harmon and Kenneth Knowlton (*Studies in Perception*, 1966-67), later followed by Robert Silvers (*Photomosaics*™, 1997), substituted the uniformly colored square with digital pictures, treating the graphical pixel as though it were a collage element.

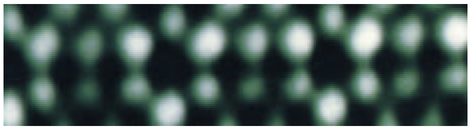

Ed Manning's portrait of Ralph Nader using BLOCPIX™ (1973). From Ruth Leavitt's *Artist and Computer*. Crown Publishers, Inc., New York, NY, 1976.

As the center of attention, or the unit that constitutes an image, the pixel will always represent digital fragmentation. Part of the broader trend in scientific deconstruction, the pixel is considered by many to be the ultimate form of visual representation, as stated by Carl Sagan,

> Any work of art is ultimately pointillist. There are a large but finite number of atoms or molecules in a painting or sculpture. Color and brightness have no meaning on any finer scale. If you knew the position, reflectivity, and "color" of every small molecule in a work of art, you could, in principle, reconstruct as many identical copies as you wished, each of them equally original.[10]


The digital image as pixel. Robert Silvers, "Portrait of George Washington from the one dollar bill -- for Mastercard "The Future of Money" promotion." (c. 1997). From: http://www.photomosaic.com/gallery.htm

This mentality goes hand in hand with the Cartesian philosophy that reality is reducible to a mathematical equation, and it is only a matter of time before we analyze the world into tiny bits and reconstitute it according to our own control algorithms. Of course, there are ways to visualize computation that do not involve the reduction of everything into dots. Digital information can be used to generate a continuous representation such as the vector display, or the computer-generated drawings of Harold Cohen and Charles Csuri. The use of pixels to visualize computation is a choice that affects the meaning of the art.


Silicon atoms: the ultimate pixel. Photo from P.W. Atkins' *Molecules*. W. H. Freeman and Company, New York, NY, 1987.

The physical qualities of the pixel also affect our perception. The flatness and luminescence of a monitor contribute to a unique experience of pixel graphics, no matter how imperceptible the individual units of representation may be. The structure and physical properties of the video display device are fundamental to any screen-based pixel, be it an actual physical pixel or a representation of the pixel. In some situations, the qualities of the screen are problematic. For example, visualizations that are three-dimensional, modular or tangible are hard to represent with a single monitor. The need

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[10] Prueitt, Melvin L. Art and the Computer. McGraw-Hill Book Company, Inc. New York , NY 1984., Page viii.

for alternate visualizations has motivated a variety of new output devices for computation. In the next section, I discuss the history of physical pixels beyond the monitor.

An image that was not made from pixels. Charles Csuri's *Sine-Curve Man* (1966). Silkscreen on plastic, 36 x 40".

Beyond the Monitor

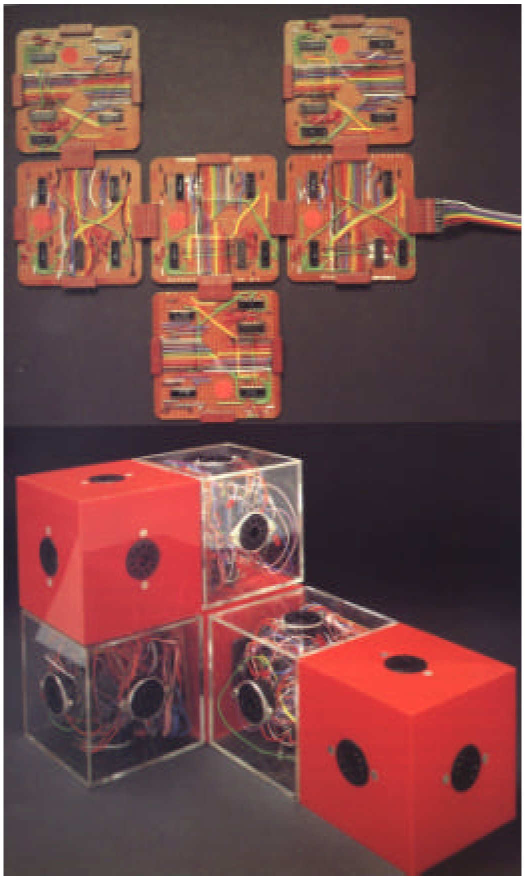
The digital pixel, often made physical as a phosphor element, can just as well be visualized through light bulbs or actuated tiles or swarming ants or any other discrete unit that can be made to change visibly in response to digital information. For example, Eric Staller's *Lightmobile* (1985) uses 1,700 computer-controlled light bulbs to animate a car. The choice of form is a matter of aesthetic preference. There are an endless variety of visualizations made possible by various materials and organizations of pixels, just as there are visualizations made possible by data structures other than pixels.

Eric Staller's *Lightmobile* (1985). A computer controls the 1,700 bulbs to flicker in twenty-three different patterns of light. From Goodman, Cynthia. *Digital Visions: Computers and Art.* Harry N. Abrams, Inc., New York, NY. 1987.

Pixels beyond the monitor are often static. For example, the printed image is intended to create a permanent artifact of computation that does not respond to further digital information. By contrast, the research presented in this thesis is specifically concerned with physical pixels that change visibly with the time-varying state of a computer.

John Frazer and his colleagues at the London Architectural Association have been innovating alternate representations of computation since the late 1960s. For thirty years, Frazer's research has been motivated by an "evolutionary architecture", or one in which the computer contributes generative rules, responsive behavior and other life-like qualities to building structures. Not surprisingly, he finds the two-dimensionality of monitors and plotters restrictive for his exploration of a three-dimensional material space, and his background in architecture naturally leads him to physical modeling systems. The 1978 *Generator Project* was among the first of many "intelligent physical modelling" systems that Frazer would construct in his quest to "get away from conventional, drawing board dependent design approaches." He writes,

> Important new ideas emerged from the Generator project. These included embedded intelligence and learning from experience during use, the isomorphism of processor configuration and model structure, and the question of consciousness.[1]



Frazer's *Intelligent Beermats* (1980) and *Three-dimensional Modelling System* (1980). Photo from Frazer, J. *An Evolutionary Architecture*. Architectural Association: London, 1994.

In 1989, Anagnostou (et al.) developed a similar system for engineering problems wherein the use of a two-dimensional model "remains both tedious and complex."[2] In their paper entitled "Geometry-defining processors for engineering design and analysis," Anagnostou reinforces Frazer's frustrations with the flat interface, stating "Unfortunately, the intrinsically two-dimensional graphics tablet is no longer an ideal interface in the context of three-dimensional geometries."[3]

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[1] Frazer, J. An Evolutionary Architecture. Architectural Association: London, 1994 (Hereafter abbreviated AEA). Page 41.

[2] Anagnostou, G., Dewey, D., and Patera, A, "Geometry-defining processors for engineering design and analysis," in: *The Visual Computer*, 5:304-315.

[3] Ibid.

Nevertheless, the early building systems of both Frazer and Anagnostou persist with a video display to visualize the computation.

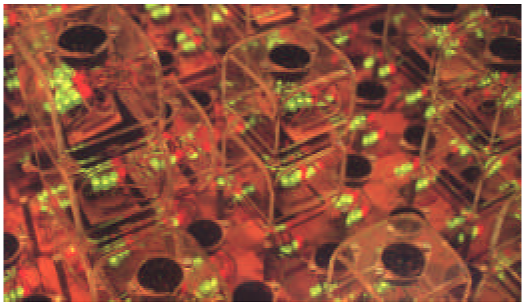
In 1990, in his “most ambitious of these models,” Frazer incorporated colored light into the building blocks of the *Universal Constructor* making the virtual relationships and behaviors of a three-dimensional structure visible without the aid of a monitor. Frazer describes the revolutionary advantages of display intrinsic to the objects themselves,

> Each cube could have any one of 256 states which were displayed by means of eight light-emitting diodes (LEDs). Thus the eight-bit code could be used to map the state of the cell to any form or structure; to environmental conditions such as wind; to sound, or even to dance. (…) The range of different applications was diverse and included three-dimensional cellular automata responding to a site problem, a curve-fitting program controlled by a Fibonacci series, and an encoding of the Laban dance notation.[4]

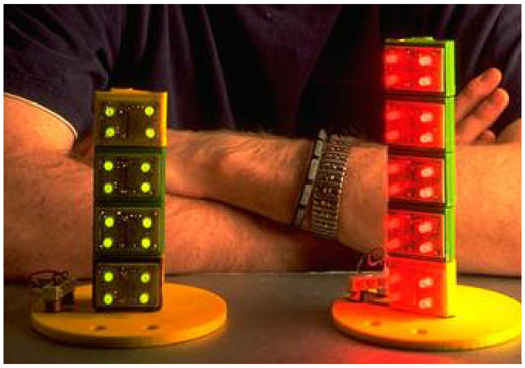
Frazer’s Universal Constructor uses visual feedback to encourage the interactor to modify the quantity, spatial location and orientation of the physical pixels that he calls “cells”. Frazer explains,

> In a typical experimental application the system will request an interactor to configure an environment consisting of cells in different states. Using lights, the model then indicates its proposed response by asking the interactor’s assistance in adding or removing units. The participator can in turn modify the environment.[5]

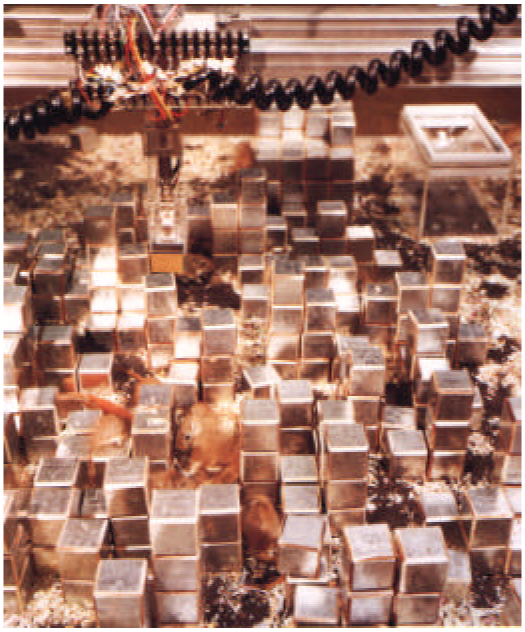
The computer and the display become an integral unit. This notion of the graphics embedded in a system of networked computers has also been implemented in *Programmable Beads* [Borovoy, Kramer 1997] and *Stackables* [Kramer, Minar 1997]. In all of the cases described, patterns of colored LED light are used to reflect the state of a network that operates rule-based programs of behavior, such as cellular automata. As the building units are rearranged, the behavior of the system responds to the new network geometry in the way that flocking birds assume flight patterns, traffic jams take form or ant colonies self-organize. Whereas these modular systems are intended for physical interaction by the user, other artists have made the pixel a three dimensional unit in stand-alone sculpture. Artist Nam Jun Paik has used the entire television as a unit of construction and graphical representation in his sculpture. In Nicholas Negroponte’s *Seek* (1969-70), a machine arm rearranges paper blocks to build a dynamic architecture for gerbils, also creating an interesting display system wherein the blocks are movable pixels.



Frazer’s *Universal Constructor* (1990), showing the vertically stacking units of construction, each approximately eight inches on a side. Photo from Photo from Frazer, J. *An Evolutionary Architecture*. Architectural Association: London, 1994.



Rick Borovoy and Kwindla Kramer’s *Stackables* (1997). Photo from: www.media.mit.edu/projects/beads/index.html.



Nicholas Negroponte's *Seek* (1969-70). Photo from Cynthia Goodman’s *Digital Visions: Computers and Art*. Harry N. Abrams, Inc., New York, NY. 1987.

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[4] AEA, pages 45.
[5] AEA, page 49.

Computation made visible by a modular building system is equally significant to sculpture as the computer has been for video, albeit less explored at this time.

Artists and engineers seek new forms of physical pixels to solve a problem or create a personal aesthetic. Joseph Jacobson and the Micromedia Group at the MIT Media Laboratory have tailored the *shape* of electrophoretic ink pixels to suit the geometry of a particular display application. Jacobson's physical pixels are also flexible, suggesting a future for electronic display that compares with the look and feel of paper. Danny Rozen's *Wooden Mirror* (1999) uses a computer to convert video input into a real-time video image made of 840 wooden chips and the noise of their respective motors. The result is a unique reflection of the viewer in wood and sound. In her wall installation *Chorus* (1999), Soda member Lucy Kimbell created a grid of "sonic greeting cards opening and closing in choreographed teams for a raucous and unruly … choir."[6] In each of these cases, the inventor desires a visualization of computation that cannot be achieved with pre-existing display technologies. The physical pixel presents a valuable opportunity for specializing, personalizing or reinventing our perception of computation.

Danny Rozen's Wooden Mirror (1999). Photo by Marianne K. Yeung.

Detail of an early E Ink™ demonstration, revealing the variable pixel geometry specialized for an animated display of text, below.

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[6] http://www.soda.co.uk/soda/chorus.htm

In the following sections, four systems of physical pixels are described: Nami, the Digital Palette, Peano and 20/20 Refurbished. The projects are presented in the order in which they were built to reveal the processes that led from one to the next, although the flow of research was not strictly linear. The idea for Peano was conceived shortly after Nami, but long before a mechanical design could make it a reality. In the interim, the Digital Palette was developed to enhance the interface to Nami. 20/20 Refurbished was motivated by a desire to incorporate the observer into a "living" composition made by pixels with personality.

Nami

Nami is a display system comprised of untethered pixels that wirelessly link to form an amorphous network[1]. The name *Nami* derives from the Japanese word for wave, describing the radial propagation of a message within the nodes of the network, like ripples made by raindrops in a pond. The original impetus for Nami was Robert Poor's *Hyphos* research concerning the self-organization of wireless nodes into a network of amorphous structure.[2] Nami was the first, physical platform for demonstrating the Hyphos concept to a broader audience.

The Nami Orb.

The design challenge for Nami centered on the most direct and intuitive way to illustrate decentralized networking. An advanced topic normally communicated through technical diagrams and graphical simulation, decentralized networking can be difficult to comprehend. With Nami, we endeavored to communicate the usefulness of a decentralized network to wirelessly linking toys, appliances and other physical objects in the home. This demonstration is best served in situ, where the viewer can directly experience the wireless objects communicating and watch how the system changes as the nodes are rearranged. Further, decentralized networking is *specifically* liberated from central control, and simulation by a single computer makes this point difficult to appreciate. Instead of building the physical network and illustrating it through screen-based simulation, it was decided that the sensible approach would be a decentralized network that was its own display device. In this case, the physical pixels are the network nodes themselves.

The Nami network. Photograph by Robert Poor.

System Overview

Nami is comprised of an unspecified number of nodes that are designed to self-organize in a decentralized network. The Nami network node, or *orb*, is approximately the size, shape and heft of a large bagel. The physical form of an orb was purposefully chosen to make the object non-threatening and comfortable to touch. The most prominent feature is a frosted hemispherical dome, lit from within by a glowing colored light that changes hue based on the state of the node. When the dome is touched, an orb picks a new color and emits an infrared pulse to signal nearby orbs to change their color and relay the message. In this way, colored light spreads like a wave throughout the entire network, creating a visible pattern of the communication pathways in a decentralized system.

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[1] Nami was developed by Robert Poor, Kelly Heaton, Andrew Wheeler and Anita Stout (1999). The concept of an amorphous network used in this discussion was describedby: Coore, Daniel and Nagpal, Radhika, "Implementing Reaction Diffusion on an Amorphous Computer," in: 1998 MIT Student Workshop on High Performance Computing in Science and Engineering, MIT/LCS/TR-737.

[2] Poor, R. Hyphos: A Self-Organizing, Wireless Network. MS thesis, MIT Media Laboratory, 1997.

Anatomy of the Nami Orb

Each orb contains five major subsystems: light generation, a controlling processor, touch sensing, wireless communications and a power supply, as described in the following sections.

Light Generation

Beneath the plastic dome are eight high-intensity LEDs: three red, two green and three blue. Arranged in a ring, light from the LEDs is diffused by two layers of frosted mylar. A PIC12C673 microcontroller generates three channels of Pulse Width Modulation (PWM) signals to control the brightness of the red, green and blue LEDs. Each channel is refreshed at a rate of 112.5 Hz with eight bits of brightness resulting in 24 bits of low-flicker color. Color commands are sent from the controlling processor to the PWM-dedicated processor over a 4800 baud serial line, specifying the brightness for the RGB channels and a rate to ramp from the current values to the final values. Ramp rates can be as short as one PWM cycle (8.9 mSec) or as long as 17 seconds. At each PWM cycle, the RGB brightness values are gamma corrected and converted to corresponding PWM periods.

Controlling Processor

A PIC16C76 microcontroller is the central processor for an orb. It monitors touch sensing, sends commands to the light generation PIC, receives and transmits infrared data to its neighbors and controls battery recharging. The behavior of each orb is encoded in the controlling processor's program. This program directs touch response, message relay, message execution and color expression. Except for a unique ID, every orb has identical software. Consequently, the emergent behavior in a Nami network is the visible product of multiple instances of the same program.

Touch Sensing

An orb has a capacitive touch sensing system that is triggered when direct contact is made with the dome. A disk of mylar coated with conductive Indium Tin Oxide (ITO) acts as one plate of a capacitor while the ground plane of the orb's circuit board serves as the other. By measuring the time to charge the capacitor, the controlling processor can detect a change in capacitance.

Wireless Communication

A Nami network node is equipped with a bi-directional infrared (IR) communication link. A conical mirror at the center of each circuit board disperses IR light from three emitters in a circular plane, parallel to the surface on which the orb is placed. Similarly, the conical mirror collects light

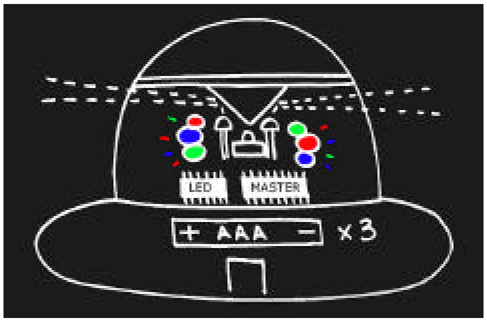


Diagram of the Nami Orb that shows the red, green and blue LEDs; touch sensitive dome (capacitive); two microprocessors (one master and one LED-dedicated); rechargeable batteries; and infrared transmitter and receiver.

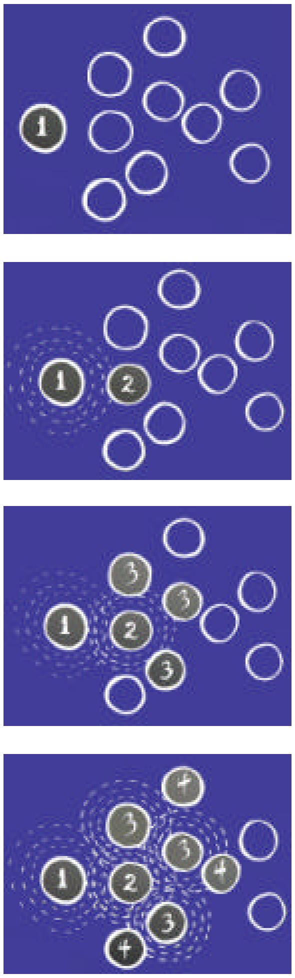


Illustration of the spread of a message within the Nami network.

and directs it to an IR receiver on the circuit board. Using this infrastructure, an orb can communicate with its immediate neighbors without regard to the rotation of sender or receiver. Communication is 25 KBaud and intentionally limited to approximately eight inches.

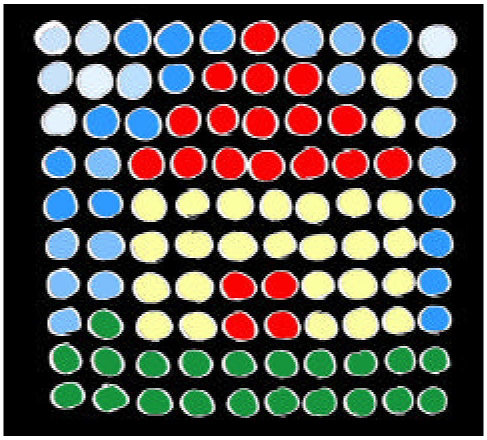
Power Supply

At full brightness, the LEDs for a single orb consume over a watt of power. An orb uses three AAA NiMH rechargeable batteries and a DC power jack for recharging. A fully charged orb will run for about five hours and can be recharged in twelve hours.

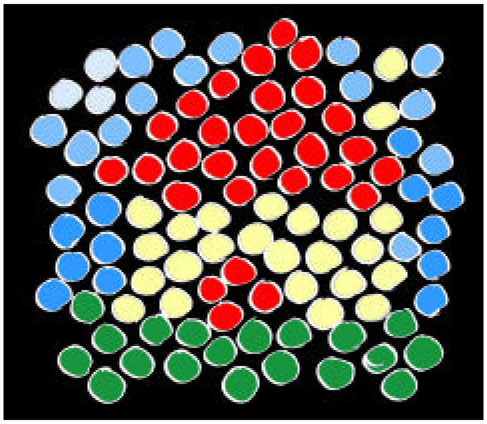
Visualizing the Nami Network

The amorphous, community-like structure of Nami is fundamental to the aesthetic of computer graphics in the system. Nami can reveal many insights that a Cartesian system cannot, and vice versa. Applications that require absolute spatial coordinates are not well suited to a decentralized network, making Nami inappropriate for the pixelated image to which we are accustomed on the CRT. The determination of absolute network geometry requires many more processors than are realistic for a physical pixel network at the present time.[3] It is only possible to know the *relative* location of a picture element in a decentralized network, using the following method. The main processor for an orb carries a unique ID that must be announced for the node to be known by the other elements in the network. This announcement is relayed through the standard channels of communication enabling all network nodes to record the number of other nodes traversed by the message prior to reaching them. Thus, the coordinate system for a decentralized network is a relational map; a node will not know spatial coordinates, but it will know the messaging distance between itself and other members of the network. Given the known radius of communication for the Nami infrared system, it is possible to generalize messaging distances into physical distances. Nevertheless, only directional systems of communication will provide directional information and the Nami communication infrastructure is not designed for this purpose.

There are two general categories of visualization made possible by the Nami network. On the one hand, Nami *is* a decentralized network made visible. Quite literally, Nami embodies the spirit of computer graphics: computation made visible in a direct and effective manner. This is particularly critical to the educational value of Nami because the actual structure of the network is radically different from a simulation run by one central processor such as the desktop PC. Although we were not able to conduct a user survey, it seems intuitive that a concrete learning experience would be



A house illustrated with a Cartesian system.



The same house illustrated with an amorphous coordinate system. Note that the recognizable image of both illustrations can be created using Nami, but only with an interface device such as the *Digital Palette* (described in the next section). Such images cannot be achieved using the infrared communications network due to the absence of absolute spatial coordinates for the orbs.

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[3] Coore, Daniel, “Establishing a Coordinate System on an Amorphous Computer,” in: 1998 MIT Student Workshop on High Performance Computing in Science and Engineering, MIT/LCS/TR-737

more immediately meaningful to a majority of people than a symbolic one. Once you have experienced Nami, it is much easier to make sense of the complex details of decentralized networking. At the very least, Nami provides an invaluable access to computation for young children or other people who cannot comprehend the computer through "input devices" or symbolic abstraction. Nami is, in concrete terms, a decentralized system; that it happens to be visible is an added bonus which requires no conceptual "leap of faith" to associate with the network. All the more, missed messages and ignored touch signals are a humbling reality of hardware that contributes a uniquely "real-world" flavor to the viewer's experience of an electronic system.

Children playing with Nami at the Tokyo Toy Fair (1999). Photograph by Robert Poor.

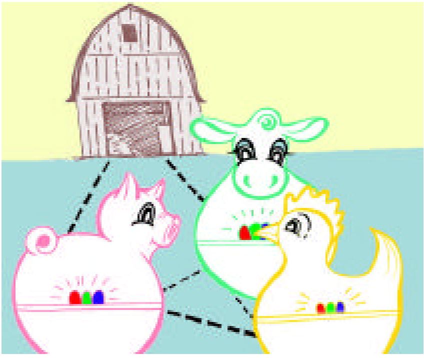
From a more abstract approach, Nami provides a platform on which content may be visualized. The content suitable for Nami may be any behavior that occurs within a decentralized system, such as the spread of gossip through a crowd, the flow of a chemical gradient, a gas lattice structure, or the oscillations of particles in a springy mesh. These are examples in which the entire network is necessary to witness the emergent behavior. Individual nodes carry identical software, but behave differently according to user input and their location within the larger system. The result of numerous nodes executing the same instructions in an amorphous organization is beautiful: patterns of behavior that are unique to the system and impossible to predict with certainty. Through minor modification of the software, an entirely new experience will emerge out of the new rule set. For example, if the orbs are programmed to change color immediately upon receipt of an incoming message, the network will behave much differently than if the orbs change color very slowly. In the case of a gradual color change, the viewer can rearrange the orbs or initiate a new message as the old one propagates, thereby creating a flood of color in multiple directions. Robert Poor's *Tri-state touch* program gives every orb three possible states: random color, opposite color, or blue-to-black. Each time an orb is touched, it will change state based on the cycle index and relay a message that carries this index, a value between 0 - 2. When another orb receives the message containing the index, it will update its state and relay the message, but it does not increment its internal cycle index. An orb must be touched sequentially to cycle through all of the Tri-touch states. As a result, all of the orbs in the network maintain some state in the cycle, but not necessarily the same state at the same time. It is up to the user to determine the current state of an orb and to use this knowledge to initiate the desired effect in the network.

One orb will relay a color message until the entire network shares the same hue.

Tri-state touch is one example of a program is adaptable to a puzzle or game, such as Othello™. Another application of a smart network node is character modeling with graphic output as an indication of emotional state. A Nami orb can be programmed with preferences, such that it "wants" to communicate with some orbs, but not others. This effect is achieved by maintaining an internal counter that is

The Nami version of Othello.

incremented by messages that have “good” IDs and decrement by “bad” ones. If an orb receives more good messages than bad ones, it will remain lit with color; but if it does not receive messages from the desired source, or receives messages from bad sources, it will eventually cease to glow with colored light. A simple set of rules such as these take advantage of Nami as a living community, wherein members of the community react differently to each other. Suddenly, the meaning of Nami changes from a visualization of decentralized networking to an illustration of society with social individuals. By designing a physical form to reflect the identity of unique characters, such as the form of a cow to enclose a bovine personality, a Nami orb could be transformed into a doll with colorful emotional state, as suggested by the conceptual illustration for *The Color Farm*.



The Color Farm. Concept for a network in which farm animals use colored light to represent variable character and emotional state. Each character contains the same basic hardware, but their software is designed with unique preferences. The different software personalities are reflected in the different designs of the physical casings (a pig, chicken and cow are example characters). A children’s story would come with the play environment to help children relate to color mapping and preferences of the networked characters, including friends and enemies, hunger, sleep and other desires.

Digital Palette

The Digital Palette (1999) is a device for mixing colors of light and recording temporal sequences of colored light. Following the completion of Nami, Kelly Heaton and Steven Gray collaborated to develop an instrument for easily and intuitively controlling the color of an LED physical pixel without necessarily writing code or mapping color from a monitor. As described by William Finzer and Laura Gould, this method of “programming by demonstration” is motivated by a belief that,

> [I]t should be possible to place the control of interactive computer graphics in the hands of … designers, those with an understanding of the power of such systems but not necessarily with the ability or willingness to write the complex programs that are necessary to control the systems.[1]

Anatomy of the Digital Palette

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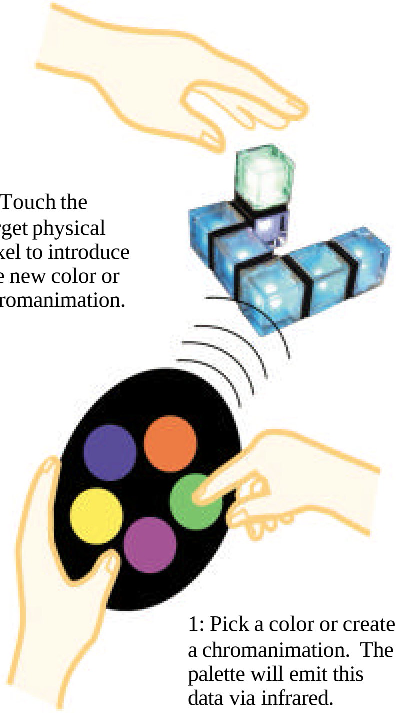
[1] Finzer, William F. and Gould, Laura, “Rehersal World: Programming by Rehersal.” From: Cypher, Allen (Editor); co-edited by Daniel C. Halbert … [et al.]. Watch What I Do: programming by demonstration. The MIT Press, Cambridge, MA, 1994.

Our answer to this problem is a hand-held, infrared remote control device that contains five physical pixels, made of mixing red, green and blue light-emitting diodes, which can be used to program the color or color animation for other physical pixels. The color of the palette pixels can be adjusted using a knob that maps to a value on a wheel of 256 discrete hues. An artist selects between the five palette pixels using direct touch, just like a Nami orb. The quantity five was chosen to give the artist the ability to select and store multiple colors, analogous to a paint palette.

To create color animation (hereafter referred to as *chromanimation*), the Digital Palette requires two modes of operation, "mix" and "paint", which may be accessed using a flip switch. In the paint mode, the color or chromanimation seen in the touch-selected palette pixel is the data that will be transmitted to by the Digital Palette via infrared. The color commands encoded in this transmission can be received and executed by another infrared enabled physical pixel, such as a Nami orb. It is possible to change the hue of a palette pixel in the paint mode by using the knob, and the hue of temporal color sequences may also be shifted. A palette pixel may only be programmed with new chromanimation when the Digital Palette is in the mix mode.

In the mix mode, all of the palette pixels at first appear as solid colors. These colors may be changed with the knob, just like paint mode, but no data is transmitted to the outside world while in mix mode. The purpose of the palette pixels in mix mode is to provide a source of color for synthesizing a new chromanimation. To create a chromanimation, the artist first sets the colors of all the palette pixels to the colors they wish to use in their sequence. Next, the artist touches the palette pixel they wish to program. Once ready to create the chromanimation, the artist holds down the "learning button," located on the handle of the palette, and proceeds to touch up to five colors in a temporal sequence that the palette records. When the learning button is released, the recording process is complete and the palette pixel will begin to animate with the looping chromanimation, the duration of which is determined by the total length of time the learning button was activated. For example, if the learning button is held while red, green and yellow are touched for one, three and one seconds respectively, the palette pixel will display: one second red, three seconds green and one second yellow with a loop duration of five seconds. Similarly, the delay between changing colors in the chromanimation is determined by the rate at which the colors were touch selected during the recording process. The Digital Palette is programmed to fade between selected colors according to the length of the delay, such that long delays give a gentle transition and short delays produce a blinking effect.

If the chromanimation is successful, the artist can switch back to the paint mode and the recently programmed palette pixel will animate with the new sequence. All of the other palette



2: Touch the target physical pixel to introduce the new color or chromanimation.

1: Pick a color or create a chromanimation. The palette will emit this data via infrared.

How to use the Digital Palette. Note that the introduction of color into another physical pixel requires direct selection of the object.

pixels will return to their previous paint-mode color or chromanimation. If the artist is unsatisfied with a chromanimation, they can remain in mix mode and reprogram a new sequence, or else chose a static color and return it to the selected palette pixel in paint mode. Whatever information is contained in the touch selected palette pixel in mix mode will be returned with the pixel when the artist switches back to paint mode.

The Digital Palette aspires to be a simple device for assigning color or creating color animation for a physical pixel. In its current form, the Palette cannot be used to design animation that changes across multiple pixels or responds to rules, such as an interactive graphics algorithm. Instead, it acts like a source of electronic paint that is applicable one physical pixel at a time. For example, if an artist chooses the color red with the Palette, they must then touch a physical pixel to apply that color to the object. The artist may continue to touch other physical pixels and color them red as well, or they may select a different color. The important link between the Digital Palette and a physical pixel is touch; although the data is transmitted from the Palette continuously, a physical pixel will only respond to the information if it is touched. This preserves the direct physical relationship that Hiroshi Ishii (et al.) calls a "tangible user interface."[2] There are no command lines or text menus associated with the Digital Palette, only the direct response to color that is familiar to an artist from prior media.

The Digital Palette with Nami

Our use of the painterly metaphor was intended to ease the artist into use of an unfamiliar device, although the additional function of animation may or may not be intelligible from our current design, particularly in the context of a painter's palette.[3] The Digital Palette's association with painting also threatens to impede a novel interpretation of the physical pixel as a tool or display, given that a computer and painting are completely different media. On one hand, the mixing and direct application of colors to a physical pixel seems analogous to painting with real pigment; but unlike physical paint, colored light is not permanent and not necessarily static. The five physical pixels of the Digital Palette can become any color or chromanimation. Anecdotal experience indicated that these properties could be confusing in the context of a painter's palette, especially without text labels or other instructions on the tool itself. Nevertheless, there is something fundamental about the artistic experience of mixing and applying color to objects. Continued work with physical pixels will hopefully reveal what aspects of the painterly experience are relevant and which are mere metaphors.

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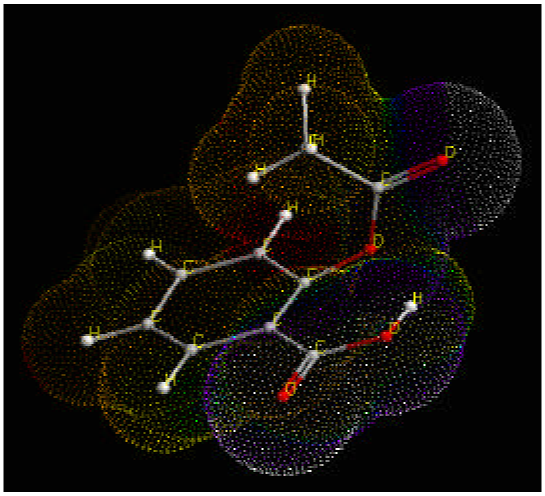
[2] Ishii, H. and Ullmer, B, "Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms," in: *Proc. of CHI97*, pp. 234-241.

[3] This observation is based on conversation with numerous visitors to the MIT Media Laboratory, notably Rachael Strickland and Bill Verplank.

Peano

Peano is a building set comprised of one-inch cubes that connect to form a modular, full-color display in three-dimensions. The original inspiration for Peano was a smart molecule kit: a set of elements common to organic chemistry that could be used to model and explore molecular structure. With colored light as a visual indicator, the modeling system was intended to provide feedback regarding formal charge or other properties of interest to the student of chemistry. A chemistry set designed as a system of physical pixels could represent the electron distribution across the molecular model as a continuous, time-varying effect that responds to the addition or subtraction of atoms in real-time. Simulations exist for display on a computer monitor, but not as an animated physical model.

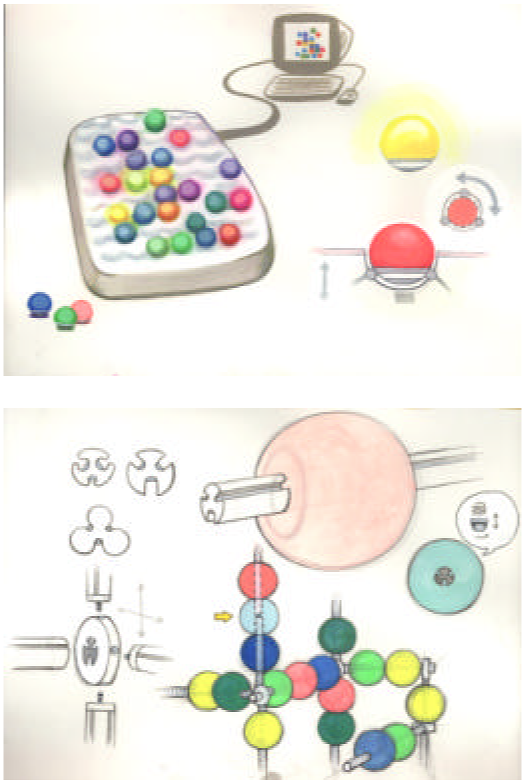


“Electrostatic Surface of Aspirin,” by Roger Sayle with RasMol (Glaxo Welcome, 1995).
From: http://www.umass.edu/microbio/rasmol/sayle3.htm.

Although technically feasible, the search for appropriate connectors proved discouraging. A fruitless quest for small, reasonably priced, yet durable connectors with four or more electrical conductors *and* radial symmetry motivated an effort to build the simplest possible geometry with a modular, three-dimensional structure.[1] Further, the use of many connectors per physical pixel threatened to obscure the desired visual effect. Thus, the decision to restrict the number of connections eliminated the molecule concept, wherein numerous bonds per element would be required for accurate modeling.

Several others [Frazer 1978, 1990], [Anagnostou et al 1989], [Borovoy, Kramer 1997], [Kramer, Minar 1997], [Gorbet et al 1998], [Anderson 1999], [McNerney, 1999] have developed computational building kits, some of which reveal simple and clever solutions to the problem of network connectivity. Frazer’s *Universal Constructor* (1990) and Kramer and Minar’s *Stackables* (1997) are the closest precedents, each with only two connectors per element and full knowledge of network status and structure. However, neither provides full-spectrum color animation and both systems are limited to stacking objects in one direction only. Frustrated by the “mathy” feel of most computational building systems, not to mention the flat interface of graphics on a monitor, I endeavored to create an organic, sculptural material for interactive computer animation.[2]

I soon discovered that organic forms are not easily translated into the inflexible structure of computer electronics. Basic requirements, such as power and data communications, continually precipitated engineering solutions that were too



Early stages in the Peano design process.

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[1] For the molecule application, I considered the use of potentiometers at each connection. A variable change in resistance could be used to calculate basic information about molecular structure, such as “cis” and “trans” conformations. For more information on connectors, please refer to the “The Design of a Modular Display System” in the Appendix.

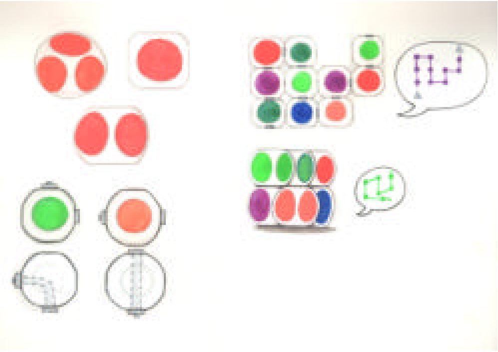
[2] At first, I struggled to design an actuated sculptural system. After investigating pneumatics, hydraulics, heat-actuated gels and shape memory alloys, I decided that such a system is best accomplished with a biological model – an avenue for future research.

big, too rigid, too impractical or otherwise impossible.[3] The physical design challenge persisted through several iterations until a satisfactory solution was finally achieved. The successful geometry was inspired by a string of beads, coiled in a stack to create a three-dimensional form with one-dimensional network structure. This realization led to the notion of a close-packing curve, or Peano Curve, named after the Italian Mathematician Giuseppe Peano (1858-1932). In honor of Giuseppe, "Peano" was chosen as the name for our system. A Peano Curve, sometimes referred to as a Hilbert Curve, is a linear structure that turns at 90-degree angles to define a three-dimensional space with Cartesian coordinates. The usefulness of the Peano geometry derives from the simplicity it affords a modular network. Because the Peano topology is linear, a one, two or three-dimensional geometry may be built from a set of elements that have only two connectors each. Due to the strict rules of the Peano shape grammar, a central processor can easily infer the structure of the display. Like Frazer's *Universal Constructor*, Peano's network is one dimensional, but the building elements can rotate in space to define a complex geometry.

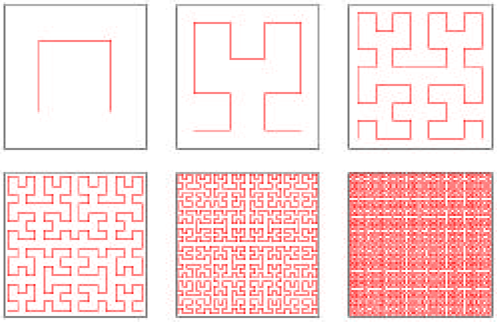
Despite the numerous advantages of the Peano design, it is undeniably "mathy." To compensate for this character, I focused on development of smooth color animation for the rigid structure. Where the physical form of Peano is cubic and strictly rule-based, the computer animation of colored light can be programmed to give an organic illusion. The gentle animation of color in Nami, as well as Golan Levin's drawing program *Aurora* (1999), provided valuable inspiration for the interactive animation I sought to achieve in Peano. In particular, Levin's screen-based *Aurora* invites the interactor to draw with a haze of multiple colors that blend with a soft and mutable quality. Peano is similarly designed to permit direct and programmatic control over the animation of colored light in sculpture, albeit formally rigid in the present design.

System Overview

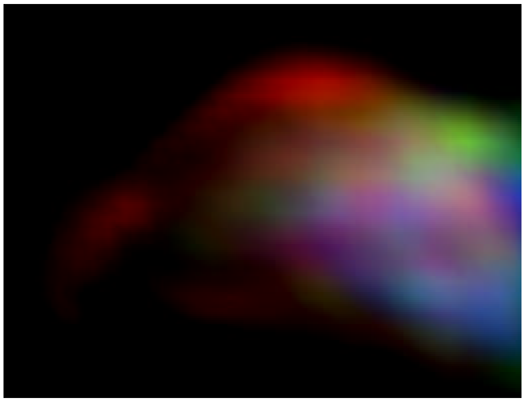
In the fall of 1999, Kelly Heaton, Steven Grey, Paul Pham and Alex Jacobs began work on Peano as described above. Peano is a three-dimensional, modular display system comprised of 128 or fewer one-inch cubes made from a colorless, diffusive plastic material. In the center of every Peano cube (abbreviated hereafter as "cube") there is a single, multicolored LED that illuminates the entire volume to produce a full-spectrum of colored light. Each cube contains six major subsystems: connectors, light generation, control processor, touch sensing, data communications and power regulation. These systems are described in the following sections.



The successful Peano design (1999).



The Peano Curve. Image source: http://www.math.ohio-state.edu/~fiedorow/math655/Peano.html



Golan Levin's *Aurora* (1999), an organic compliment to the rigid structure of the Peano Curve.

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[3] These design constraints are discussed in greater detail in "The Design of a Modular Display System" in the Appendix.

Connectivity

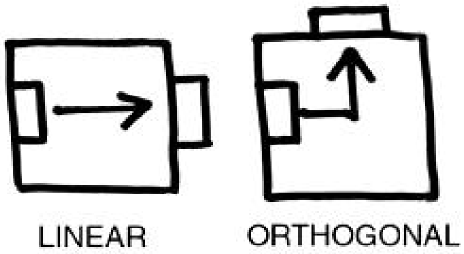
Every Peano cube has two connectors, one male and one female, that occupy two of the six faces. The male and female connectors are positioned on the cube in one of two ways, forming two different shape grammars: linear and orthogonal. A linear configuration has connectors that are positioned on opposite sides of the cube; and an orthogonal configuration has connectors that are positioned on adjacent sides of the cube. The connectors are designed such that the cubes can join together in one of four orientations, enabling the construction of a linear geometry with three-dimensional topology. The male connector has a total of eight pins: six of the eight pins form the electrical continuity for the network, including two each for power, ground and data; and the remaining two pins are used for peer-to-peer communications, rotation and bus-ready. The rotation pin is keyed to pull one female pad of the downstream cube to ground, insuring that every cube knows the rotation of its upstream neighbor. The bus-ready pin is a flag used by a cube to signal an upstream neighbor to place data on the bus. This way, data returns to the CPU in linear sequence and the network topology can be inferred.

Light Generation

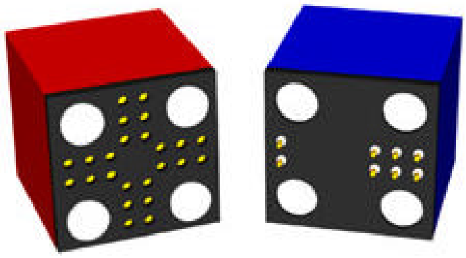
In the center of a Peano cube is a single multicolored LED that illuminates the entire volume. The inside cavity of the clear acrylic cube is frosted to evenly diffuse the light across the surface.[4] Since light is not visible through the two sides with connectors, these interior surfaces are coated with a flat white paint to reflect light out of the cube. The LED of the orthogonal cube is purposefully bent at a right angle to face into the painted circuit boards, such that the light will be reflected evenly.[5] Like Nami, the red, green and blue channels are controlled by Pulse Width Modulation (PWM). The controlling processor uses the same look-up table used by a Nami orb for gamma correction.

Control Processor

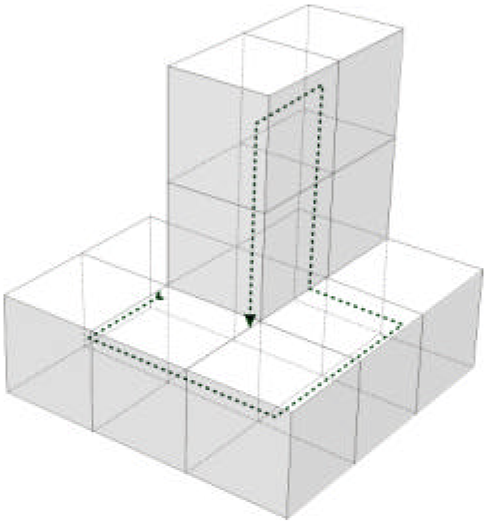
Each Peano cube contains a PIC16F876 flash memory microcontroller that handles all of the internal processing. The function of the microprocessor is to perform all of the local operations that could not be accomplished by the master CPU for a modular network of physical pixels. It monitors touch sensing, receives and transmits data on the bus, handles light generation, detects rotation and initiates upstream data transfer. The microprocessor is a slave to the CPU, controlling the bus only when queried. If the bus is idle for more than 100 ms, control will revert to the CPU to prevent deadlock in the event that a user disconnects a cube that was controlling the bus. Since the controlling processor is



The two member shape grammar of Peano.



The male and female connectors of a Peano cube. The smaller pins / pads in the middle are electric conductors. The larger circles in the outer corners represent the mechanical connectors (the female connector has magnets and the male has ferrous slats). Note that the male pins will connect to the female pads in four orientations, and power and ground are given two pins each to support a higher current rating for the system. Illustration by Alex Jacobs.



Peano builds a three-dimensional structure with linear network geometry.

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[4] Light diffusion is a tricky art. For more on this topic, please refer to “The Design of a Modular Display” in the Appendix.

[5] This happens naturally in the linear cubes; but were the LED of the orthogonal cubes not bent, the majority of light would travel out of one of the translucent faces.

electronically erasable, a Peano cube may be easily reprogrammed (in-circuit) with different firmware to prototype new behaviors for the cube.

Touch Sensing

Touch events are detected using the same RC circuit as Nami. A thin wire surrounding the edge of the male and female connectors of each block forms the capacitor for the circuit. The wire is slightly recessed to avoid erroneous touch-selection, but easily accessible from every side of the cube.[6]

Data Communications

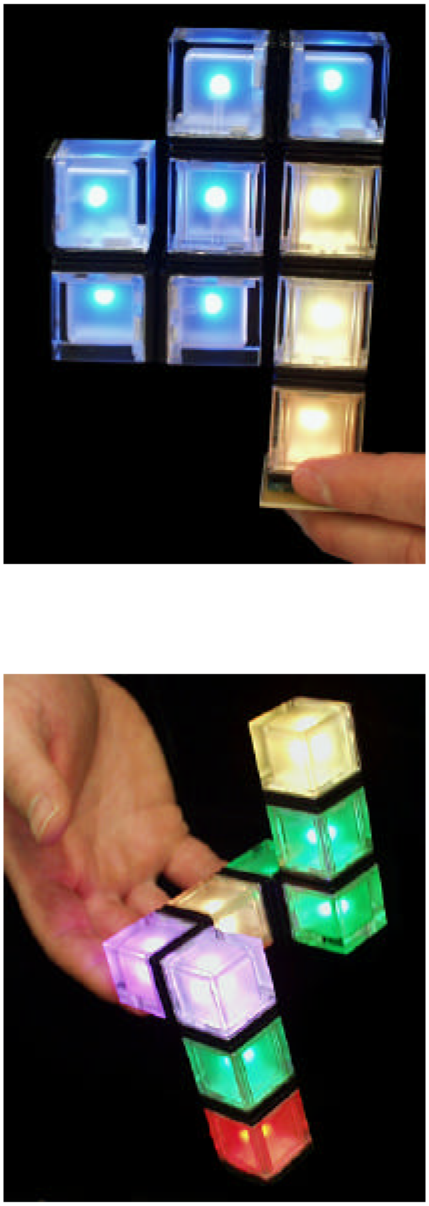
Communication between the host CPU and up to 128 Peano cubes occurs over an RS485 bus operating at 57,600bps. There are 3 commands recognized by a cube: *get*, *set* and *sync*. The *get* command is used to retrieve a cube's unique ID, type (linear or orthogonal), touch status and neighbor rotation. The *set* command designates the new color value for a cube, but is not executed until the *sync* command is received. The *sync* command avoids the ripple effect of asynchronous color change in the display network. The networked cubes can be addressed in three different ways: individually, in a specified range, or all cubes following a specified node in the network. As mentioned previously, a cube will put data onto the bus only when commanded by the CPU *and* flagged by its downstream neighbor. This protocol insures that the topological information for the network is correct.

Power Regulation

Power and ground lines for the Peano network are rated for 12 Volts and 6 Amps, or the maximum power required by a 128 physical pixel network at full brightness (white). For safety reasons, the system is designed so that only an exposed female connector can be "live." Internal to each block is a regulator that supplies 5 Volts to the circuit. The circuit is also protected against grounding due to wrong connections.

Control of the Peano Network

The central processor for our Peano network is a Pentium III 600 MHz processor that is connected to the first cube of the display by an RS232 serial cable. A custom Java application was developed by Paul Pham to manage two major tasks: operate the Peano display and provide a software interface to the system.



Nine Peano cubes arranged in two of many possible combinations of geometry and color.

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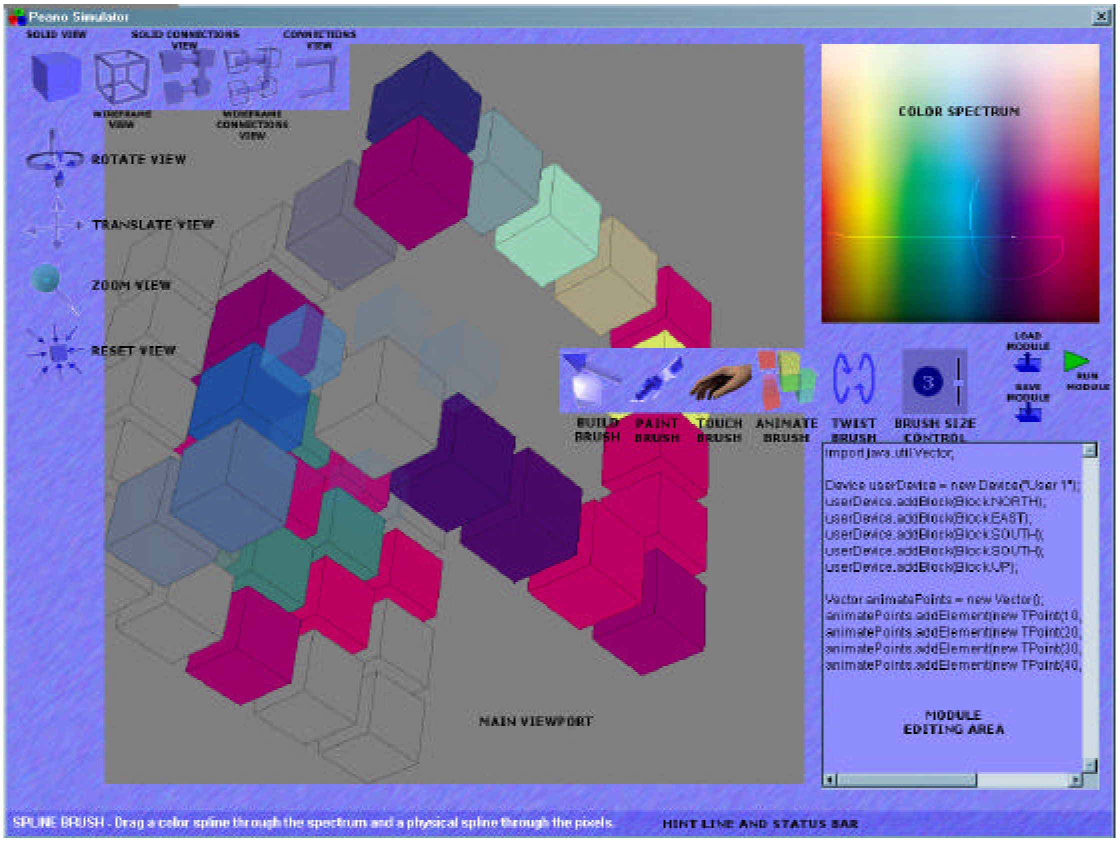
[6] I intended to coat the exterior of the Peano cubes with Indium Tin Oxide (ITO), but the expense proved prohibitive for a prototype. For the record, I am told by manufacturers that it is possible to use ion-assisted deposition to apply a thin (several micron) film of this conductive material to a volume of plastic. Such material exists in flat sheets, as used for Nami and some touch sensitive screens. I am not aware of a commercial product with ITO on the surface of a *volume*, despite the usefulness of touch detection in many consumer applications.



```
import java.util.Vector;

Device userDevice = new Device("User 1");
userDevice.addBlock(Block.NORTH);
userDevice.addBlock(Block.EAST);
userDevice.addBlock(Block.SOUTH);
userDevice.addBlock(Block.SOUTH);
userDevice.addBlock(Block.UP);

Vector animatePoints = new Vector();
animatePoints.addElement(new TPoint(10,
animatePoints.addElement(new TPoint(20,
animatePoints.addElement(new TPoint(30,
animatePoints.addElement(new TPoint(40,
```

SPLINE BRUSH - Drag a color spline through the spectrum and a physical spline through the pixels.

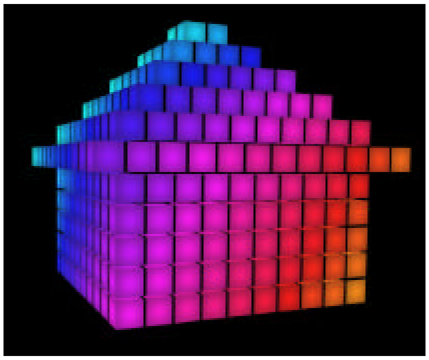
Annotated illustration of the Peano software interface. Design by Paul Pham and Kelly Heaton (1999 – 2000).

Display Operation

While the display is operational, the CPU must update the color information for every cube at a rate of 15 Hz and query the network status at a rate of 3 Hz. A network query returns the following information for each cube: unique ID, linear order, type, rotation and touch status. The Cartesian coordinates of the display are calculated from the linear order, type and rotational information for all of the cubes in a network. If necessary, the CPU will calculate and transmit new color values to the display followed by a *sync* command.

Software Interface[7]

Information about the physical system is accessible to the user through a custom software application that is viewable on a computer monitor. The program has two options for controlling the display network: a graphical user interface and an interpreted language environment. Both of these programs take input from the Peano cubes, such as touch and reconfiguration, as well as traditional desktop input devices, such as the mouse and keyboard. The graphical user interface consists of a 3D simulation of the Peano geometry, and several controls: render and view options for the simulation, a color



Concept for a Peano sculpture.
Illustration Alex Jacobs.

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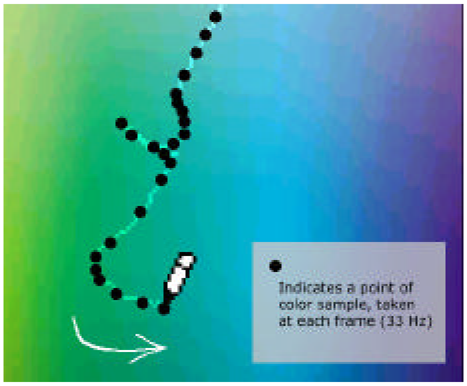
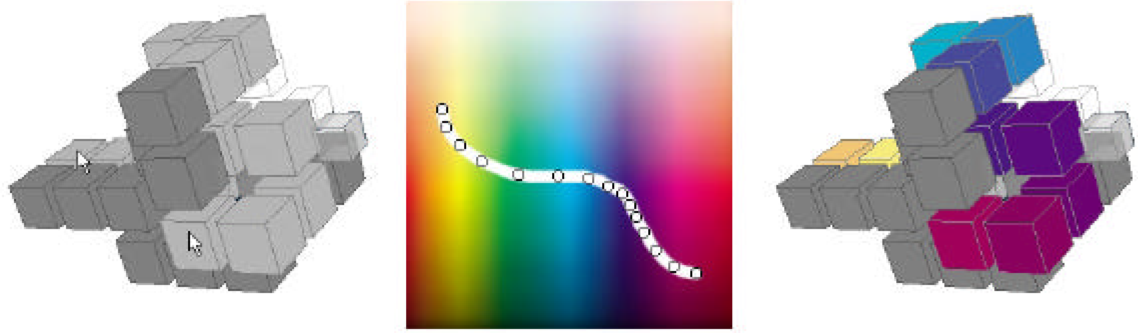
[7] For more information on the Peano Software Interface, including the Peano API, please refer to: http://www.media.mit.edu/~kelly/physPix/peano.htm

manipulation program, and information access to the cubes. The simulation was created to illustrate the display geometry and state, thereby aiding in the development of control algorithms for software applications, as well as providing a screen interface to coloring the cubes. ColorAnime is a gesture-based drawing tool that was developed as part of the software interface to facilitate color animation of the cubes.[8]

ColorAnime consists of a color palette, which can be any digital image represented on the screen, and an internal record of gesture sequences made within the digital image palette. The duration of a gesture, made by mouse movement or other drawing instrument for the PC, defines a temporal sequence of color that is looped to form a chromatic animation, or *chromanimation*. The chromanimation is applicable to a single cube, which will then loop through the color sequence indefinitely, or it can be used like a brush across multiple cubes. When "painting" more than one cube, the user designates a pathway across blocks in the display and then applies the color sequence to this pathway. The pathway for the brush may be indicated using the screen interface, or by touching a sequence of cubes in the physical system. In both cases, the width of the brush must be selected using the screen interface. The color animation is then antialiased along the pathway to provide a smooth aesthetic, analogous to antialiased graphics for the video monitor[9].



The ColorAnime method of sampling gesture across an image to form a temporal sequence of color, or *chromanimation*.



Using ColorAnime, a gesture drawn through any digital image (example HSB space shown in center) translates to color across the Peano cubes. The colors will animate sequentially at a rate determined by the speed of the gesture. Illustration by Paul Pham.

The Peano interpreted language environment, a specialized subset of Java developed by Paul Pham, was inspired by John Maeda's *Design By Numbers*. The language is intended to provide a familiar access to a unique display of computation, such that software applications could be developed with relative ease as compared to Nami, which requires reprogramming every node. Our objectives were twofold: visualize Cartesian mathematics in a three-dimensional, modular display; and prototype software behaviors that could later become embedded in the cubes themselves. The eventual

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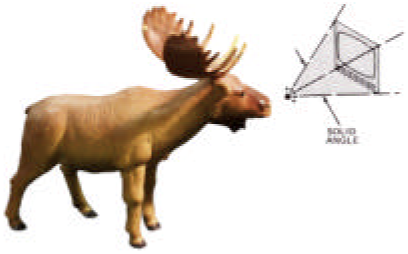
[8] ColorAnime was developed by Kelly Heaton, Scott Snibbe and Paul Pham (1999-2000).

[9] The antialiasing algorithm was adapted by Paul Pham from the Gupta-Sproull method, described in: Foley, James D. [et al.] Computer Graphics: principles and practice (Second Edition in C). Addision-Wesley Publishing Company, Inc., Reading, MA, 1997.

goal for Peano is a free-standing system without the use of a screen interface, which although familiar, distracts from the insights of a new display format.

Visualizing the Peano Network

Like the computer monitor, Peano is a Cartesian system controlled by one processor to make a colored-light display of computation. The similarities stop here. Whereas the video display is a fixed image plane, Peano is a flexible quantity of modular pixels that connect to form a network with an exponential variety of spatial configurations. The individual elements participate in a common network controlled by a central processor, but each physical pixel is programmable to function semi-autonomously. We take advantage of the microprocessor in each cube to generate full-spectrum light, detect touch, respond to a unique ID, and return information regarding the display geometry. Although the overall behavior for the network is centralized, our control algorithms are subject to feedback from the physical structure, including quantity of pixels, linear sequence and orientation.



The monitor limits the observer to a single viewing angle.

Many of these parameters are normally associated with puzzles, such as a Rubik's Cube™. Peano shares certain characteristics with spatial toys, but it can be augmented with software behavior to unite physical and virtual play into a single device. Imagine, for example, if Tetris™ were modified to function in a modular, three-dimensional space, or Simon™ could be rearranged into shapes other than a colorful pie. Computer animation in Peano can be designed to react to modifications in the physical structure. Peano may be used to teach spatial geometry, color relationships, quantity, sequencing and other properties learned through visual mathematics. Whereas painted blocks have been used to teach construction for centuries, Peano introduces concrete relationships combined with the logic and ephemeral abstraction of computation.

Peano can be enjoyed from any point of view.

Whether perceived as a toy or an art form, Peano is a sculptural medium designed for creative exploration. Physical structures can be built by hand and then "painted" with colored light using a tool such as ColorAnime or the Digital Palette. Colored light may remain static and specific to each cube, or the artist can write software for dynamic graphics. For example, an antialiased sphere of light can be programmed to move slowly about the structure in response to touch. Skillful animation suggests an organic form internal to, or passing through, the rigid physical geometry of Peano. Visual effects, made by possible by software control of the LEDs, are analogous to the illusion of computer animation on a monitor (the graphics are rich and deep, whereas the screen is rigid and flat). Peano adds several degrees of freedom to the physical interface, including modularity, direct touch response and three spatial dimensions. Like Nami, the tactile engagement and direct feedback from a physical object draw the artist into an intimate relationship with the display system.

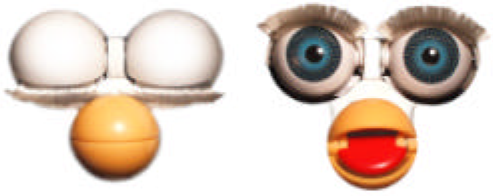
This relationship is further enhanced by the absence of a strict point of view onto the visual experience. A sculptural system for computer animation, Peano can be rotated in real space, placed in context of other objects and generally appreciated as part of our physical environment.

20/20 Refurbished

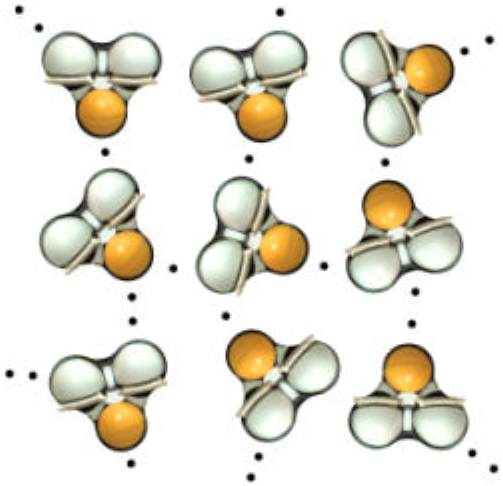
20/20 Refurbished is a proposed art installation, designed to incorporate the observer into a narcissistic relationship with a reactive composition. The piece is not intended to reflect the viewer according to straightforward expectations, like a literal mirror or real-time video image. More than a simple digital mirror, the pixels of 20/20 Refurbished will look and talk back to create a circular dialogue between the observer and the observed. The resolution of pixels is sufficient that a viewer who approaches the piece will witness the impact of their presence and become drawn into a mutable composition of sight and sound. If the artwork is left undisturbed, the pixels will close their eyes and say nothing, save for the occasional trigger by *doppelgänger*.

The physical pixels of 20/20 Refurbished are made from the 1999 Limited Edition Christmas Furby™, modified to reveal only the eyes and mouth in a softened triangular shape. Through the phenomenon R. L. Rutksy describes as “the birth or coming to life of the machine,” a pixel made of Furby™ is “infused with a living spirit, with a soul; it is a “dead” technological object reanimated, given the status of an autonomous subject.”[1] Usually perceived as a “fuzzy, computerized, mechanized doll that talks, blinks, sleeps and asks to be fed,” Furby™ is part of a new generation of consumer products that blur the distinction between real and artificial life.[2] Unlike the dolls of yesteryear, enlivened only by a child’s imagination, Furby™ is animated by a programmatic personality, inviting a curious dialogue between a real and simulated being. These toys, designed to substitute biological Fido with a battery-operated pet, are a fascinating but disturbing step towards the widespread acceptance of artificial life.[3] As part of 20/20 Refurbished, the cultural implications of a disembodied Furby™ contribute a complex psychology to the pixels that spans the superficially playful to the profoundly perverse.

Each pixel will be actuated by a motor to achieve two visible states, open or closed. The pixels will be augmented with a PIC16F876 microcontroller that prompts the Furby™ to speak in response to viewer proximity, as determined by an infrared detection system. Although the Furby™ pixels retain their original logic, the added microcontroller will be programmed to control their behavior in an unorthodox manner. Whereas Furby™ normally has sensors that respond to “real” interaction by a human or another Furby™, such as tummy tickling, back rubbing and infrared communication, the added microprocessor will cause the Furby™ pixel “think” these



The two visible states of the Furby™ pixel



When no observer is detected, a Furby™ pixel will close its eyes and remain quietly watching with an infrared detector (shown here as black dots).

When an observer is detected, a Furby™ pixel will open its eyes and begin speaking.

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[1] Rutsky , R. L. High Techn : art and technology from the machine aesthetic to the posthuman. University of Minnesota Press, Minneapolis, MN, 1999. Page 24.
[2] Boston Globe (February 24, 1999)
[3] Sherry Turkle’s research with children and Furby™ substantiates this claim. From: Turkle, Sherry. The Second Self: computers and the human spirit. Simon and Schuster, New York NY, 1984.

inputs are occurring even though the inputs to the pixel are fully simulated, or “virtual.” All of the normal sensors of the Furby™ will be disconnected and replaced by our custom software.

When the infrared emitted by each pixel is bounced off the presence of a viewer, an invisible relationship will be made manifest through the response of the artwork. Four hundred of these identical pixels will be arranged in a loose interpretation of the Cartesian grid, suggesting an organic departure from the pixelated rationalism that is characteristic of most computer graphics. An observer located within sensing range of 20/20 Refurbished will experience hundreds of disembodied creatures looking and talking back at them in the form of their silhouette. The observer is thereby reproduced in Furby™, itself a unit of reproducible identity.

Like a mirror, 20/20 Refurbished requires an observer to make the surface come to life. Like a work of art, the ownership of the reflected identity will be ambiguous. The disembodied creatures need the presence of a body to come to life. The observer needs the disembodied creatures to visualize their digital semblance. The observer’s act of observing the art is narcissistic by default of their reflection in the composition, yet the art needs the viewer to be complete. Does the audience make the art; is the art making the audience; or is the art the audience?

The observer will be invited to participate in these multiple layers of meaning made by pixels that are artificially sentient and full of personality.

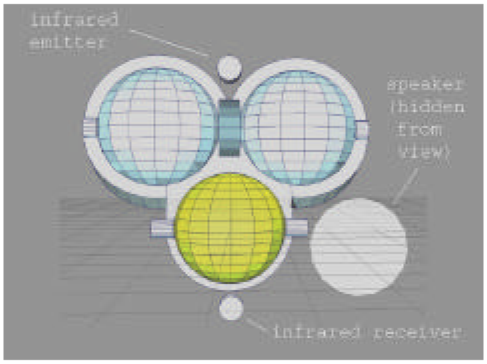
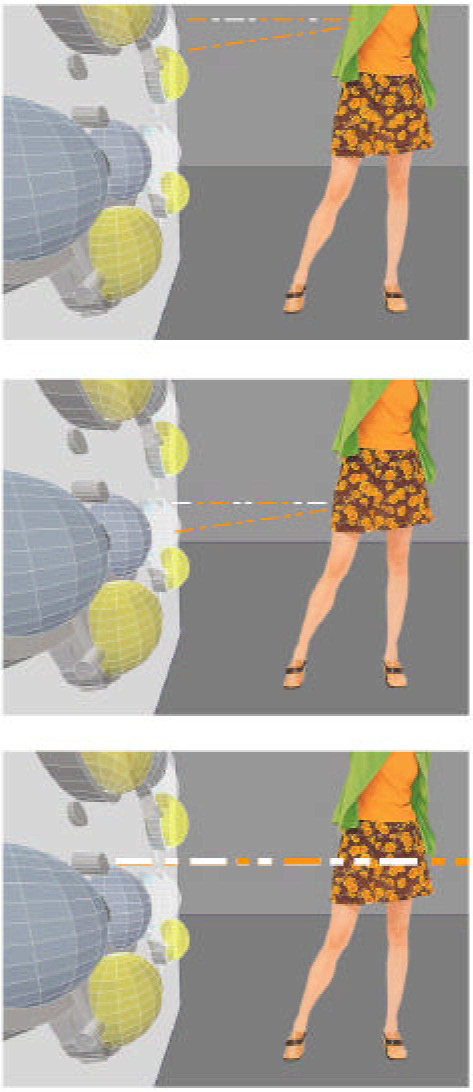


Diagram of the Furby™ pixel showing the infrared emitter, receiver and the speaker (hidden from view behind the front panel of the display).

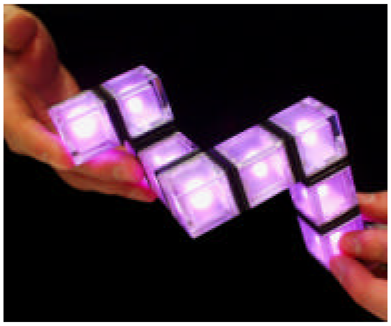


Each pixel uses an infrared detection circuit to probe for an observer in front on the display.

The 1999 Limited Edition Christmas Furby™ prior to refurbishing. Already, the toy is a unit of mechanical reproduction and pop culture iconography, qualities that we encapsulate in the form of a pixel for viewer reflection.

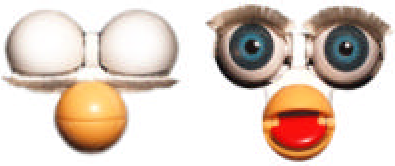
The physical pixel is a synthesis of old and new forms of art. Once limited to an artifact of material manipulation, the mark of an artist is now defined by a relationship between atoms *and* bits. Like the signature stroke of a painter, the physicality of a pixel can still express a unique style; only now, that style is augmented by information design. This is a property of the physical pixel that I came to understand gradually, learning along the route to a body of work for which the design decisions were not always well defined.

The physical design of Nami (above, orbs shown on a prototype recharging station) and Peano (below). Both forms were purposefully designed to be abstract.



One of our objectives for Nami was to create a playful interface to a decentralized network. Since no additional meaning was assigned to the orbs at the onset of the project, the physical form was made to be general and abstract. The style was guided more according to the efficacy of user interface than an artistic vision for a new sculptural media.[1] The Peano cube is similarly abstract because we wanted a medium from which other art could be made, like a sculptural version of the pixels of a video monitor. Had we developed the molecule kit, the meaning of the physical pixels would have been specific to chemistry; and consequently, much different than the general Peano cube.

The decision to create abstract physical forms for these pixels enabled us to think of them in many different ways, and also to focus on a variety of graphical behaviors. But I discovered that general platforms are not especially useful for art unless the platform is useable as a creative medium. To be useable, a medium needs to be malleable. If everything made from the medium looks like a rearranged version of the medium, then it is not particularly useable. This may be the greatest failure of Nami and Peano: neither system can be made to look like anything other than itself, and yet they are both designed for general use.[2] There is no clear meaning behind these systems of physical pixels, yet software content cannot "reinvent" them with the level of sophistication which video pixels can be graphically reinvented.



Contrast the abstract form of Nami and Peano with the highly content-driven design of the Furby™ pixel.

In contrast, a Furby™ pixel has a character with unalienable content. Although people will perceive the meaning of a Furby™ pixel in different ways, it is definitely a unit of content as much or more than it is a unit of pictorial representation. The meaning of a Furby™, both as a toy and

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[1] Only in hindsight did I come to perceive Nami as a physical pixel; and now, I would approach the system with a much clearer view of the relationship between physical form and software behaviors.

[2] I am speaking specifically about their usefulness as an artistic medium. I do think both systems have clear value for education and toys, independent of their artistic value. Nami has been an excellent tool for demonstrating decentralized networking, but we have not developed any particularly successful games or sculptural applications to date. This is partly a consequence of time, partly the difficulty of reprogramming the nodes, and partly my own uncertainty about the expressive potential of Nami as a sculptural and graphical medium. Peano was completed so close to the deadline of this thesis document that I have not had sufficient time to develop applications; and cannot, therefore, assess with certainty the usefulness of the display.

as a pixel, has been specifically designed and is in no way intended as a general platform.

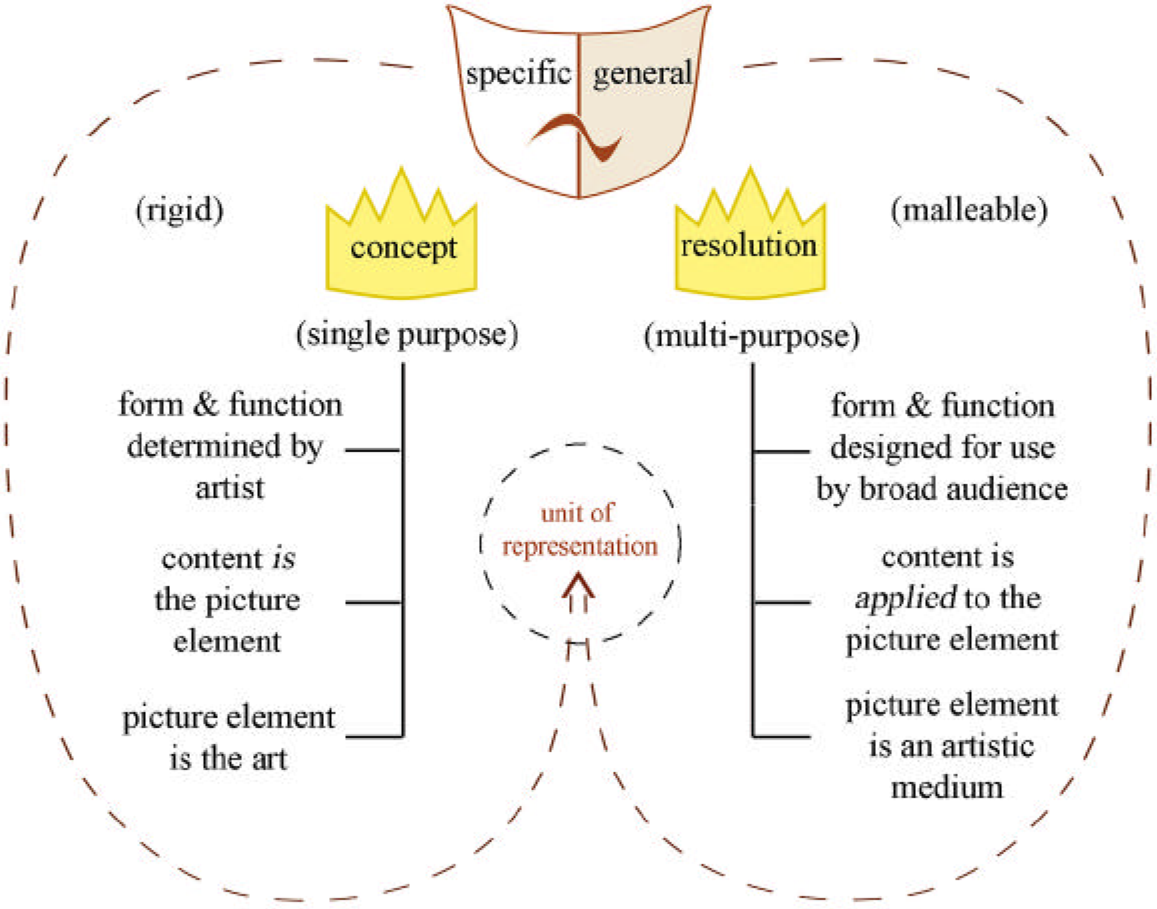
I believe that both approaches to the physical pixel are useful and necessary in the quest for new art. 20/20 Refurbished is likely to have a more immediate impact; but it will not offer insight into computational media that would be useable by a general audience. 20/20 Refurbished is intended as commentary on the contemporary reflection, made by a combination of software, sculpture and pop culture. As such, the physical and software design of the Furby™ pixels is specific to the installation, much in the same way that compositional elements of a painting are essential to *that* context, but nowhere else. A kit for the construction of smart molecules would be similarly limited to a specific application, albeit scientific visualization instead of artistic commentary.

Unlike 20/20 Refurbished, Nami and Peano are systems of physical pixels that strive to be more generally useful for creating sculptural computer graphics. Due to the significant challenges to engineering a new display technology, a truly universal platform for sculptural computation will require more time and effort. Keeping the big picture in mind, any incremental steps are valuable as a learning experience.

A Conceptual Framework for the Design of Physical Pixel Media

There are two primary classes of physical pixel: *specific* (Furby™ pixel, Digital Palette) and *general* (Peano, Nami). *Specific* pixels have a clear and singular purpose, in this case described as the content of a work of art. The *general* pixel is a medium with which art can be made. The *general* pixel has no intrinsic content because it serves to represent a diversity of content. The video pixel is currently the most widely appreciated form of *general* physical pixel. The *specific* pixel is a contemporary form of the artistic mark, encapsulating a unique style of physical and digital expression.

The two sides of the diagram reveal the principle differences in the design process (hierarchy reads from top to bottom, ending with the unit of representation).

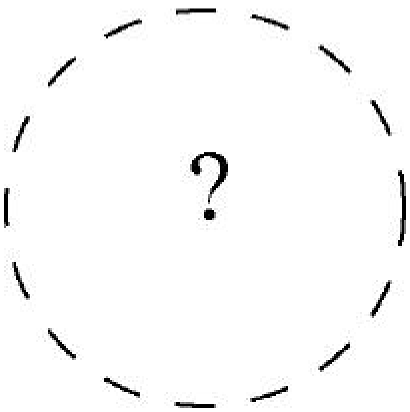


The lessons of Nami and Peano are several. Most importantly, a general-purpose creative medium needs to be either high resolution or highly malleable. For example, LEGO™ bricks are not malleable whatsoever, but if you have enough of them you can build something interesting. By contrast, a single piece of rope is only one object, but it can be twisted and looped to form many interesting knots. A pixel is much more like a LEGO™ brick than a rope, given that it participates in a system of discrete units (whereas the rope might describe a vector display). This comparison seems to indicate that many physical pixel elements are the key to the success of a sculptural system for computer graphics. It is not to suggest that a physical pixel couldn't deform shape; but suffice it to say that a high resolution of elements appears to be the magic ingredient of pixelated media.

In our prototyping mode of operation, we were never able to build more than fifty objects for either network. The effort to construct many pixels is a deterrent to high-resolution systems, absent a clever technique for mechanizing the manufacturing process. And not only mechanization of the physical construction, but also the electrical infrastructure and power distribution for all of the discrete elements.

The Digital Palette differs from the other three projects in that it is an instrument for working with other types of physical pixels. In a sense, the Palette is a tool that needs a medium. It can be used at the present time to change the color or chromanimation of a Peano cube or Nami orb; yet it seems that the Palette can and will be more interesting as future systems of physical pixels are developed. Likewise, the extent to which it remains a “palette” may become less emphasized, as the relevance of our painterly metaphor is replaced by a better understanding of a new medium.

There are two major reasons why future work with physical pixels is important. First, alternate visualizations of computation, particularly those that explore other spatial dimensions, are critical to learning about the computer as a medium. Whether it is science or art that drives the innovation, the end result benefits the community at large. The second reason concerns the importance of individuality in artistic expression. There is nothing inherently wrong about working with a prefabricated display device to make art; but to the extent that an artist avoids the development of new media in favor of pre-existing ones, opportunities for novel visions of computation are compromised. Despite low-resolution results, difficult engineering and the high risk of failure, the *effort* to achieve new insights into computation is deeply meaningful in its own right. Often, it is through the toughest struggle that a truly unique art will emerge.



Conclusion

The physical pixels presented in this thesis are but a few examples of computation made visible. Both the material form and the computer infrastructure determine our perception of a pixel, suggesting that there exists at least as many variations on the physical pixel as there are materials and computers combined. It is not useful to speculate on every possible appearance, but instead to open our minds to the possibility of different manifestations insofar as these new forms will change the way we perceive the computer as an expressive medium. Variations on the physical pixel may enhance the modularity of the display, make social commentary, provide tangibility, or lend a signature aesthetic to a work of art. Imagination and ingenuity can conceive of many instances of the pixel beyond this body of research.

To be sure, there are plenty of cases wherein the video monitor is the ideal medium for illustrating pixel graphics. Likewise, there are visualizations that cannot be revealed with the pixel data structure whatsoever. Just as the decisions regarding a physical pixel deserve careful consideration, other choices should be thoughtfully addressed by any artist who uses the computer as their medium. Constraint is often the mother of invention, but perceived limitations must not be taken for granted. Both the pixel (data structure) and the physical pixel (visible form) are critical factors in our understanding of art made with the computer. Our choices make the art.

When choosing to work with any form of physical pixel, the *meaning* associated with the invisible pixel is inextricable from our perception. There are various cultural and historical factors that contribute to the meaning of the pixel, including Cartesian rationalism, scientific deconstruction and a history of optical analysis in the visual arts. Any work with physical pixels, of any material form, engages in a dialogue with this conceptual and perceptual foundation. For example, the gentle flow of colored light within Nami or Peano is an effort to counterbalance the physical fragmentation inherent to a pixelated display system. Such fragmentation is fundamental to the pixel and therefore any art made visible by physical pixels. Discrete representation is not only aesthetically distinctive, but suggests a philosophy of perception.

The look of computation is open for artistic interpretation. Like poetic thought, pixels and other data structures have no concrete appearance. The computer provides a unique opportunity to reveal invisible layers of meaning in multiple dimensions and with a rich variety of physical media.

Poetry made visible by William Blake in *Fiery Pegasus*, 1809. Pen, ink and watercolor, approximately 9 x 6.5 inches.

The British Museum, London.

Appendix: The Design of a Modular Display System

The design of a modular display is an exercise in constraint. As with any system, a change in one design parameter affects all others, such that a resultant system is the product of compromise. Nami, Peano and 20/20 Refurbished are all characterized by design decisions that contribute to certain capabilities, but eliminate others. The purpose of this appendix is to generalize, insofar as possible, the recurring challenges to our development process.

Design Concept

A clear design vision is central to the development of a successful display device. Although this statement seems self-evident, there are numerous occasions in which engineering will present an alternate path; and often these detours will veer away from the original objective. Strong goals demand the cleverest solutions. The following questions should be continually revisited throughout the development process:

- What will be visualized?
- What are the quantitative and qualitative properties required by the display to achieve the desired visualization?
- What is the power budget?
- Will the device be safe for an audience?
- Is the system innovative?

Power

At the present time, electronic devices require the distribution of power and ground. If the pixels of a display are to be wireless, power and ground must somehow reach every picture element in the system. Batteries internal to each object are the easiest solution to this problem, although not ideal for display devices that have many pixels, or picture elements that are very small.

Direct contact between display elements and a power source is one alternative. The obvious disadvantage to direct contact is the spatial freedom lost by tethered picture elements. In cases where the physical pixels connect to form an electrical bus, care must be taken to insure that each individual element can handle the maximum voltage and current draw of the entire system. A hybrid of rechargeable battery power and external supply benefits from both approaches, but significantly increases the complexity (and expense) of the system.

Network Architecture

Data communication within a system of physical pixels shares some common problems with power distribution; namely, all elements in the system must be able to receive, and in some cases, send, data. Generally speaking, there are three approaches to network architecture of a display: centralized, partially distributed and decentralized. A *centralized network* involves the standard, I/O display device paradigm wherein a CPU performs all computation and controls the pixel actuation. Here, the pixels do not have any processing power. An example physical pixel device of this kind is an LED matrix display. *Partially distributed* processing describes a system in which one central processor coordinates the behavior for a network of smart devices. Pixels that act as "slaves" in a larger network structure, but contain an embedded microprocessor for local sensor or display control, fall into this category. Peano and 20/20 Refurbished are networks with partially distributed processing. *Fully distributed* processing involves no central coordination for a network of smart devices. In this case, each physical pixel contains a processor that controls all behavior and communications for that device. Displays with fully distributed processing cannot be treated as a Cartesian system, but a decentralized network in which emergent behaviors are visible. Nami is an example of a physical pixel network with fully distributed processing.

Mechanical

Mechanical connectivity is immaterial for wireless physical pixels and straightforward for displays that are fully tethered. However, reconfigurable display systems that require direct contact for electrical connectivity *require* good mechanical design. The "flakiness" of mechanical connectors is often the downfall of a modular display.[1] The connectors for a modular system should discourage wrong electrical connections, restrict movement to minimize a noisy signal, and protect the user from electrical shock. Care should also be taken to avoid the use of magnetic connectors where the magnetic field might interfere with an analog circuit (although we did not experience this problem due to an almost exclusively digital circuit).

Display Materials

This section suggests a few ideas for creating color and graphics, but I encourage the reader to consider more creative solutions to these reasonably traditional materials. For example, I have often entertained the idea of using a matrix of addressable scents to control the swarming of insects as though they were a slow-motion digital video display. Be creative; the physical pixel can be anything you make it to be.

Generally speaking, display materials fall into three categories: emissive, reflective and mechanical. A reflective material or mechanical device should be used wherever possible due to a significantly lower power budget. Emissive materials need a constant supply of power to maintain their state, whereas reflective or mechanical substances are usually actuated only during a change of state. Unfortunately, the only commercial materials that display a continuous range of color with a refresh rate of at least 30 Hz are emissive. E Ink™ is a new, thin film reflective material that will update at 30 Hz or higher, but only two discrete colors are attainable at the present time. Light Emitting Didodes (LEDs) are currently the best option for color graphics due to their relative power efficiency, ease of use and wide frequency range. Commercially available LEDs are brightest when purchased as a discrete color with a narrow viewing angle, although difficult to diffuse completely without a milky or "pastel" effect. A multicolored LED combines an R, G and B filament in one diffuse package that delivers uniform color and a wider viewing angle, but light intensity is sacrificed.[2] LEDs are not ideal for volumetric displays that are transparent due to the need for a diffusive material to achieve color blending. Also, diffusive layers must be offset at least 0.75" from the light source to be effective, thereby contributing a minimal thickness to the display. Incidentally, this offset was the only factor determining the depth of the "pots of paint" in the Digital Palette.[3] Organic Light Emitting Diodes (OLEDs) are an emerging technology that is much smaller than traditional LEDs, enabling color diffusion without a diffusive layer; and they may also be printed on a flexible, clear plastic that will appear semi-transparent in layers. Phosphor-based materials, such as electroluminescent (EL) film, are a voltage-controlled alternative to LEDs that provide a monochromatic and opaque source of light. With any display material, the life span should be taken into consideration. Finally, every display material will have a unique dynamic range. Where color is the desired effect, gamma correction should be implemented, as described in detail by Foley [et al].[4]

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[1] We were fortunate to have fairly reliable connectors for Peano, despite the fact that they were custom-made. Based on prior experience with other modular systems, we worked really hard to maintain precise tolerances in the custom manufacture and we strongly encourage this approach, albeit tedious and expensive. The female pads of a Peano cube are gold-plated for longevity and the male connectors are spring probes available through Interconnect Devices, Inc. The spring probes of the male connector were chosen for their high current rating, low contact resistance, durability and long mating cycle. Had there been a suitable connector available off the shelf, we would have used it without question; but the rarity of modular, digital systems meant that we were on our own. Radial symmetry is especially hard to achieve with multiple data lines, and rotating connectors (such as a multi-conductor slip ring) are totally out of the price range of a toy (starting at $60 and up).

[2] A Peano cube contains a single full spectrum, sunlight visible RGB LED available through LEDtronics, Inc. A Nami orb uses a cluster of discrete red, green and blue LEDs available from Nichia Corporation, but I am not aware of a domestic vendor and the components are difficult to purchase direct.

[3] I considered making a make-up compact with digital eye shadow, etc., but this cannot be done with standard RGB LEDs due to the depth required for adequate diffusion. Perhaps OLEDs will make this project possible.

[4] Foley, James D. [et al.] Computer Graphics: principles and practice (Second Edition in C). Addision-Wesley Publishing Company, Inc., Reading, MA, 1997. Pages 564-5.

Physical Design

Of all the engineering requirements for a display, aesthetic design is often be the hardest to achieve and the easiest to ignore. Appearance is not critical to the success of engineering, so often a prototype will work but look terrible due to multiple sacrifices in aesthetics. This is the greatest failure since, after all, it is a *display*. As discussed for Nami and Peano, decisions in the physical design have major implications for the perception and applications of the system. Circuitry, batteries, sensors and connectors are all likely components of a physical pixel and they must be accommodated without obscuring the visual effect. Similarly, a tangible display element should not be impossible to touch due to heat, electricity, fragility or other consequences of poor design.

Alloway, Lawrence. Roy Lichenstein. Abbeville Press, New York NY, 1983.

Anagnostou, G., Dewey, D., and Patera, A, “Geometry-defining processors for engineering design and analysis,” in: *The Visual Computer*, 5:304-315, 1989.

Anderson, D., Frankel, J., Marks, J., et al., “Building Virtual Structures With Physical Blocks (Demo Description), in: *Proc. of UIST’99*.

Atkins, P. W. Molecules. W. H. Freeman and Company, New York, NY, 1987.

Baudrillard, Jean. Simulacra and Simulation. The University of Michigan Press, Ann Arbor, MI, 1994.

Bohm, David. Wholeness and the Implicate Order (Second Edition). Routledge, New York, NY, 1995.

Borovoy, Rick and Kramer, Kwindla, Programmable Beads
http://el.www.media.mit.edu/projects/beads/index.html. 1997

Brotchie, Alastair. *Surrealist Games.* Redstone Press. London, England. 1991.

Chip, Herschel B. Theories of Modern Art: a source book by artists and critics. University of California Press, Inc., Berkeley, CA, 1968.

Comiskey, J. D. Albert, Hidekazu Yosihizawa & Joseph Jacobson, “An electrophoretic ink for all-printed reflective and electronic displays.” Nature, Vol. 394, 16 July 1998.

Conrac Corporation. Raster Graphics Handbook (Second Edition). Van Nostrand Reinhold Company, Inc., New York, NY. 1985.

Coore, Daniel, “Establishing a Coordinate System on an Amorphous Computer,” in: 1998 MIT Student Workshop on High Performance Computing in Science and Engineering, MIT/LCS/TR-737

Coore, Daniel and Nagpal, Radhika, “Implementing Reaction Diffusion on an Amorphous Computer,” in: 1998 MIT Student Workshop on High Performance Computing in Science and Engineering, MIT/LCS/TR-737

Coyne, Richard. Technoromanticism: digital narrative, holism, and the romance of the real. MIT Press, Cambridge, MA, 1999.

Cubitt, Sean. Digital Aesthetics. Sage Publications Ltd, London, 1998.

Cypher, Allen (Editor); co-edited by Daniel C. Halbert … [et al.]. Watch What I Do: programming by demonstration. The MIT Press, Cambridge, MA, 1994.

David S. Ebert, Edward Bedwell, Stephen Maher, Laura Smoliar, Elizabeth Downing: Realizing 3D Visualization Using Grossed-beam Volumetric Displays. CACM 42(8): 100-107 (1999)

Downing, Elizabeth, Hesselink, Lambertus, Ralston, John and Macfarlane, Roger, “A Three-Color, Solid-State, Three-Dimensional Display,” *Science* 1996 August 30; 273: 1185-1189.

Elkins, James. The Object Stares Back: on the nature of seeing. Harcourt, Inc., Orlando, FL, 1996.

Fielding, Raymond (Editor). A Technological History of Motion Pictures and Television: an anthology from the pages of the Journal of the Society of Motion Pictures and Television Engineers. University of California Press, Berkeley, CA, 1967.

Fink, Donald G. Computers and the Human Mind. Doubleday and Company, Inc., Garden City, NY, 1966.

Foley, James D. [et al.] Computer Graphics: principles and practice (Second Edition in C). Addision-Wesley Publishing Company, Inc., Reading, MA, 1997.

Frazer, J. An Evolutionary Architecture. Architectural Association: London, 1994.

Goodman, Cynthia. Digital Visions: Computers and Art. Harry N. Abrams, Inc., New York, NY. 1987.

Gorbet, M., Orth, M., and Ishii, H., "Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography," in: *Proc. of CHI98*, pp. 49-56.

H. Abelson, D. Allen, D. Coore, C. Hanson, G. Homsy, T. Knight, R. Nagpal, E. Rauch, G. Sussman and R. Weiss, "Amorphous Computing," AI Memo 1665, August 1999.

Hearst, Marti A., "TileBars: Visualization of Term Distribution Information in Full Text Information Access," in: *Proc. of CHI99*.

Heaton, K., Poor, R., Wheeler, A., "Nami," in: Conference Abstracts and Applications of SIGGRAPH99, Emerging Technologies, p. 214.

Heidegger, Martin. The Question Concerning Technology and Other Essays. Harper and Row Publishers, Inc., New York, NY, 1977.

Holtzman, Steven. Digital Mosaics: the aesthetics of cyberspace. Simon and Schuster, Inc., New York, NY, 1998.

Ishii, H. and Ullmer, B, "Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms," in: *Proc. of CHI97*, pp. 234-241.

Kirsch, Russell A. *IEEE Annals of the History of Computing*, Institute of Electrical and Electronics Engineers, Inc., 1998, pp. 7 – 13.

Kramer, K. and Minar, N., Stackables: Manipulated Distributed Displays. http://el.www.media.mit.edu/projects/stackables/. 1997

Leavitt, Ruth. Artist and Computer. Crown Publishers, Inc., New York, NY, 1976.

Leigh, J., Johnson, A., DeFanti, T., "CAVERN: A distributed architecture for Supporting Scalable Persistence and Interoperability in Collaborative Virtual Environments." Virtual Reality: Research, Development and Applications, Vol 2.2, December 1997, pp. 217-237.

Maeda, John. Design By Numbers. The MIT Press, Cambridge, MA, 1999.

McLuhan, Marshall. Understanding Media: the extensions of man. The MIT Press, Cambridge, MA, 1994.

Mitchell, William J. The Art of Computer Graphics Programming. Van Nostrand Reinhold Company, Inc., New York, NY, 1987.

Negroponte, Nicholas. Being Digital. Random House, Inc., New York, NY, 1996.

Newhall, Beaumont, The history of photography : from 1839 to the present. Museum of Modern Art, New York, NY, 1982.

Newman, William and Sproull, Robert. Principles of Interactive Computer Graphics (Second Edition). McGraw-Hill Book Company, Inc., New York, NY, 1979.

Norman, Richard B. Electronic Color: the art of color applied to computer graphic computing. Van Nostrand Reinhold, New York, NY, 1990.

O'Brian, John. *Clement Greenburg: The Collected Essays and Criticism Vol. 4 - Modernism With a Vengeance, 1957-1969*. University of Chicago Press, Chicago, IL, 1995.

Poor, R. Hyphos: A Self-Organizing, Wireless Network. MS thesis, MIT Media Laboratory, 1997.

Popper, Frank. Agam (Third Revised Edition). Harry N. Abrams, Inc., New York, NY, 1990.

Popper, Frank. Origins and Development of Kinetic Art. Studio Vista Limited, London, 1968.

Prueitt, Melvin L. Art and the Computer. McGraw-Hill Book Company, Inc. New York , NY 1984.

Rodis-Lewis, Genevieve. Descartes: his life and thought. Cornell University Press, Ithaca, NY, 1998.

Russett, Robert and Starr, Cecile. Experimental Animation (Revised Edition). Da Capo Press, Inc., New York, NY, 1976.

Rutsky, R. L. High Techn : art and technology from the machine aesthetic to the posthuman. University of Minnesota Press, Minneapolis, MN, 1999.

Silvers, Robert. Photomosaics. Henry Holt and Company, Inc., New York, NY, 1997.

Soller, Theodore (Editor). Cathode Ray Tube Displays. McGraw-Hill Book Company, Inc., New York, NY, 1948.

Sontag, Susan. On Photography. Bantam Doubleday Dell Publishing Group, Inc., New York, NY, 1977.

St.-Hilaire, P., Benton, S. A., Lucente, M., and Hubel, P.M., "Color images with the MIT holographic video display," in: S.A. Benton, ed., SPIE Vol. 1667, Practical Holography VI (Feb., 1992), paper 1667-73, pp. 73-84.

Sutherland, I. E. Sketchpad: A Man-Machine Graphical Communication System. Technical Report No. 296, 30 January 1963. Massachusetts Institute of Technology Lincoln Laboratory.

Thompson, D'Arcy Wentworth. On Growth and Form (abridged edition). Cambridge University Press, Cambridge, 1961.

Tufte, Edward R. Visual Explanations: Images and Quantities, Evidence and Narrative. Graphics Press, Inc., Cheshire, CT, 1997.

Turkle, Sherry. The Second Self : computers and the human spirit. Simon and Schuster, New York NY, 1984.

Underkoffler, J. The I/O Bulb and the Luminous Room. MIT Media Laboratory Ph.D. thesis, 1999.

Wolfe, Rosalee (Editor). Seminal Graphics: Pioneering Efforts That Shaped the Field. A Publication of ACM SIGGRAPH, 1998.

Wolfreys, Julian (Editor). The Derrida Reader: writing performances. University of Nebraska Press, Lincoln, Nebraska, 1998.

Yarin, P. Towards the Distributed Visualization of Usage History. MS thesis, MIT Media Laboratory, 1999.