Viewing Progress in Non-photorealistic Rendering through Heinlein's Lens

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Abstract

The field of non-photorealistic rendering is reaching a mature state. In its infancy, researchers explored the mimicry of methods and tools used by traditional artists to generate works of art, through techniques like watercolor or oil painting simulations. As the field has moved past mimicry, ideas from artists and artistic techniques have been adapted and altered for performance in the media of computer graphics, creating algorithmic aesthetics such as generative art or the automatic composition of objects in a scene, as well as abstraction in rendering and geometry. With these two initial stages of non-photorealistic rendering well established, the field must find new territory to cover. In this paper, we provide a high level overview of the past and current state of non-photorealistic rendering and call to arms the community to create the areas of research that make computation of non-photorealistic rendering generate never before realized results.

CR Categories: I.3.m [Computer Graphics]: Miscellaneous—Non-Photorealistic Rendering

Keywords: non-photorealistic rendering, grand challenges, meta-paper

1 Introduction

There has been much discussion revolving around the current and future state of the non-photorealistic rendering (NPR) field. We survey the recent research that has been conducted in the NPR domain and discuss implications for the future. In particular, we postulate on where we see NPR research in terms of the technological maturation model put forward by Robert A. Heinlein [1985]. Heinlein is credited with having anticipated many technological advances, and some say that his writing, while sometimes controversial, has been influential in provoking thought and discussion about the role and evolution of technology [Dinerman 2007]. Heinlein's model suggests that new technologies evolve over time through three stages of maturation:

1. Imitation: the new technology emulates previous work.
2. Optimization: the performance of the technology is improved.
3. Acceptance: the technology is no longer perceived as "new".

While we do not agree with all of Heinlein's opinions, we find that his maturation model is an interesting lens through which to examine the state of NPR, and can serve as a useful starting point to provoke discussion on what directions should be taken into the future. We believe that NPR is currently at the second stage of the maturation model, and we outline the path we believe should be taken in order to advance the field into the third stage of maturation.

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Rapid advances in computer graphics technology allow computer screens to be filled with complex visual information at near real time rates [HPG 2009]. Simulations and visualizations that once required supercomputers are now commonly run on desktop workstations or PC clusters. While Moore's law has correctly anticipated faster processors, larger disk drives and higher memory capacity, these advances have done little to help people understand the meaning of their data. The lack of understanding stems from the fact that machines process data in numerical form, while humans more easily comprehend visual data. We rely on graphs and charts that visually emphasize key features and relationships in the data to attain insight.

In the computer graphics and visualization communities, *rendering* is the process by which data is converted into an image. Photorealistic rendering denotes images based on physical simulations. The goal of photorealistic rendering is to create images indistinguishable from photographs of equivalent real world scenes. In contrast, the area of NPR is concerned with images that are guided by artistic processes. An underlying assumption in NPR is that artistic techniques developed by human artists have intrinsic merit based on the evolutionary nature of art. NPR techniques, such as illustration, are driven by aesthetic and communication constraints rather than physical simulations. *Visualization* is the process of using computer graphics to transform numerical data into meaningful imagery, enabling users to observe information [Yagel et al. 1991; Upson et al. 1989; Drebin et al. 1988; Senay and Ignatius 1994]. The art of non-photorealistic visualization lies in choosing visual representations of the data that maximize human understanding [Grinstein and Thuraisingham 1996]. The resulting display allows a viewer to detect, analyze and discover features in numerical data which may not have been recognized otherwise.

NPR images convey information more effectively by omitting extraneous detail, focusing attention on relevant features, and clarifying, simplifying, and disambiguating shape. In fact, a distinguishing feature of NPR is the concept of controlling detail in an image to enhance communication. The control of image detail is often combined with stylization to evoke the perception of complexity in an image without explicit representation, as shown in the drawings in the right two images of Figure 1. NPR images also provide a more natural vehicle for conveying information at a range of detail levels. Additional advantages of artistic imagery include:

- Communication of uncertainty – Photorealistic computer graphics imply an exactness and perfection that may overstate the fidelity of a simulation or scan.
- Communication of abstract ideas – Simple line drawings, like the force diagrams used in physics textbooks, can communicate abstract ideas in ways that a photograph cannot.
- Evoking the imagination – A simple animation can express ideas beyond the physical and logical norm. For example, a biologist may want to reveal an exciting new discovery to colleagues, but needs a way to illustrate a chemical process that cannot be seen with the naked eye.

In many applications a non-photorealistic image has advantages over a photorealistic image. NPR images are often easier to un-

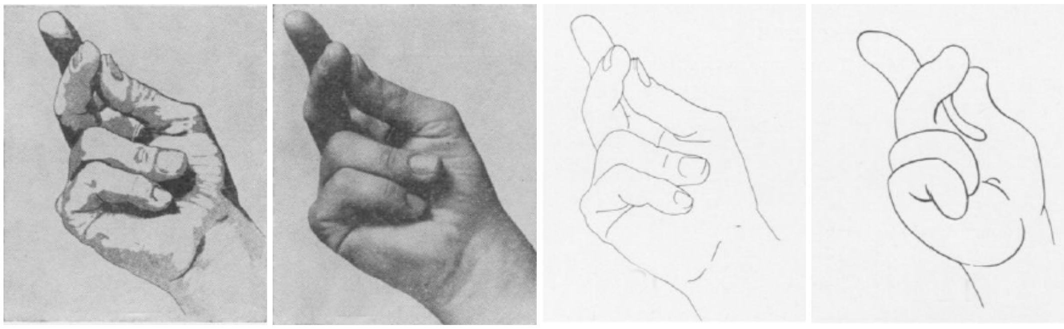

Figure 1: Ryan and Schwartz [1956] demonstrated that line drawings with exaggerated features, such as the last image depicted above, evoke more rapid and accurate responses than photographs.

derstand than photographs [Gooch et al. 2004; Sukel et al. 2003]. In their classic 1956 experiment, Ryan and Schwartz demonstrated that line drawings with exaggerated features of interest evoked a more rapid and accurate response than photographs or plain line drawings [Ryan and Schwartz 1956]. Examples of the stimulus images used by Ryan and Schwartz are shown in Figure 1. Although there is a wealth of computer graphics research dealing with the display of three dimensional images, there has been little exploration into evaluating the effectiveness of artistic techniques in an interactive setting. Sukel et al. found that trained dancers learned more rapidly from NPR animations than from video [Sukel et al. 2003]. Barfield et al. [1988] as well as Gooch and Willemsen [2002] found that increasing the realism in a simulation meets with only limited performance increases in terms of model recognition and distance estimation. Gooch et, al. found increased learning speed using facial illustrations [Gooch et al. 2004].

In the following sections, we overview recent work done in the NPR domain, and provide some insight on how we feel the field can further progress through the technological maturation model. The first stage of technological maturation is focused on imitation - using the new technology to accomplish what had previously been done with the old technology. This is analogous to the early NPR work that was mostly devoted to simulating traditional artistic media, such as painterly rendering, line drawings, and pen and ink rendering, to name only a few [Haeberli 1990; Lansdown and Schofield 1995; Winkenbach and Salesin 1996]. The second stage of maturation involves progressively improving and optimizing the performance of the technology, often at the cost of complexity. At NPAR 2002, David Salesin gave a keynote talk on the "Seven Grand Challenges" facing NPR researchers [Salesin 2002]. These challenges, by and large, fall into this second stage of the maturation model. And while there is still much work that can be done in addressing them, we feel that the path forward for the discipline is to graduate towards the third stage of maturation. In the third stage, the technology becomes seamless and almost transparent. It is no longer seen as new technology, but rather as a natural medium that is part of everyday life. The technology is not just used to imitate previous technology, but instead to do new things that were never possible with more primitive technology. Instead of using a computer to represent paint strokes, for example, we can view computation as its own medium, and use it to produce new artistic effects and visualizations that can incorporate elements such as interaction, collaboration, human perception and cognition like never before.

2 Review of NPR Challenges

The challenges that follow are based on those put forth by David Salesin, but have been updated to reflect the current trends in non-photorealistics rendering and visualization research. In each case, we summarize the challenge as described by Salesin, and then we discuss the relevant research. We show that in many cases, the work that remains to be done involves optimizing already existing algorithms and methods, echoing the second stage of technology maturation. In Section 3, we propose future directions for NPR research that we believe will lead the discipline towards the third stage of technological maturation.

2.1 Challenge 1: Algorithmic Aesthetics

David Salesin originally posed this challenge in terms of considering how to encode what makes something beautiful. He believed that some aspects of aesthetic appeal could be defined algorithmically. Salesin discussed this notion further in the context of abstract art, calligraphy, relighting, and cropping.

Salesin is not the only one to consider what makes art work. Ramachandran and Hirstein [1999] developed a neurological theory of aesthetic experience based on eight heuristics that artists have deployed over the centuries to stimulate the visual areas of the brain. Their work implies that these 'rules of aesthetics' are embedded in some form in successful art, and that they can potentially be extracted in some manner to gain a greater insight into human perception.

Researchers in the NPR community have long been motivated by the artistic masterpieces of the past. In fact, the initial focus of NPR was on simulating traditional artistic media, and this was no doubt spurred to some extent by the manner in which artists throughout history have been successful in creating works that appeal to human sensibilities. We would divide work in this area into two categories. The first category involves simulating the physical process of producing a piece of artwork. Published research in this category has reached a considerable stage of sophistication. Examples include Sousa and Buchanan's system for generating pencil drawings based on simulating the interaction between graphite particles on paper [Sousa and Buchanan 2000], or AlMeraj et al.'s system that uses a model of the muscles in the human hand to produce line drawings that look like those created by real humans [AlMeraj et al. 2009]. The second category is to derive algorithmic theory that approximates the artwork itself. This area is most in keeping with the challenge of algorithmic aesthetics as proposed by Salesin. Examples from the rendering community include Celtic knotwork [Kaplan and Cohen 2003], virtual cinematography[He et al. 1996], aesthetic portraits [Ostromoukhov 1999], decorative mosaics [Hausner 2001], floral ornamentation [Wong et al. 1998], automatic cropping methods [Santella et al. 2006], creating color palettes for synthetic images [Cohen-Or et al. 2006], and scene composition [Kowalski et al. 2001; Gooch et al. 2001].

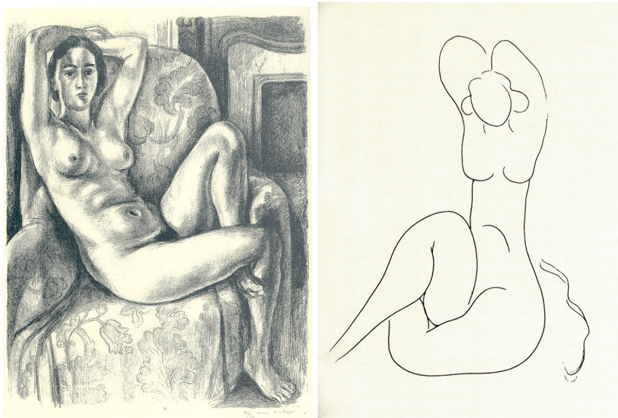

Figure 2: *Capturing the essence of an image. Matisse first created a complex sketch, complete with shading. The next image illustrates a mirror drawing of the same figure with less than 20 lines. Drawings by Henri Matisse. Left: "Nude with a blue cushion near a fireplace." Lithograph. 63.3 x 47.8 cm. Bibliotheque Nationale, Paris 1925. Right: "...La torsem et native nue..." Etching. From Mallarme 1932. Permission pending.*

There has been considerable progress in simulating artistic media, but we are still far from producing images that are indistinguishable from those created by artists. The field of computational aesthetics has formed to explicitly look at these and other related issues. We see this as a step in the right direction, and we suggest that the community should continue to devote attention to the second category of work, inviting researchers and artists to collaborate in order to develop deeper insight into the algorithmic structure of artwork. This area of future work will have to strike a balance between allowing or requiring an artist to be in the loop and the automation of aesthetics.

At the end of the day, we would argue that our notions of algorithmic aesthetics should not be limited to studying what has worked in the past for traditional artistic media, and should also concentrate on identifying the underlying principles of aesthetics that can be used in the future to create new forms of art, as described in Section 3.

2.2 Challenge 2: Abstraction to capture the essence of an image

> "You know you've achieved perfection in design,
> Not when you have nothing more to add,
> But when you have nothing more to take away."
> Antoine Saint-Exupéry.

Consider the drawing and sketch by Henri Matisse in Figure 2. Although both works of art depict the same women with high cheek bones and a slender face, the first image contains complex strokes to indicate shading and modeling of the subject, and the second communicates the essence of subject through a few simple strokes. As elucidated by the quote above by Antoine de Saint Exupery, much of NPR research is not about what we add, but we what we can take away.

We believe image and data abstraction to be one of the most fruitful areas of current research. The large number of commercial image processing programs have made imagery a method through which anyone can express their ideas. For example, consider the world wide web. Nearly anyone can create a web page, but how many of them can be considered works of art? How long do you have to look over a page before you find what you are looking for? Abstraction requires a separation of image content from rendering style, and the removal of superfluous distractors so that the most salient information can more easily be recognized and retained. Current examples of abstraction include caricatures [Gooch et al. 2004], painterly rendering [DeCarlo and Santella 2002], and the LineDrive map renderer [Agrawala and Stolte 2001]. Lum and Ma investigated tone-shading, silhouettes, gradient-based enhancement, and color depth cues [Lum and Ma 2002]. Work has also been done on abstracting 2D shapes [mi:] and 3D models in order to capture the essence of their shape [Mehra et al. 2009]. Salesin listed future areas of exploration including sketching down to the essence as shown in Figure 2, conventionalization (applying a specific style to regularize form), and automatic font generation from a single example.

Abstraction will continue to be an important area of work as information grows ever more pervasive in our society. Nevertheless, we feel that the approaches that have been proposed provide guiding principles for achieving meaningful and effective abstractions. In the future, we hope that these principles will be further refined, and applied to a wider variety of domains, such as improving visualizations in cases where a physical analog of the data does not exist.

2.3 Challenge 3: Visualization including cognitive principles.

Visualization must effectively communicate and enable analysis of the supplied information, while easing the cognitive burden of a user. The new area of Visual Analytics, or the science of analytical reasoning facilitated by interactive visual interfaces, combines knowledge representations, information visualization, and human-centered computing. Ebert [2005] adapted the following four steps for processing data from Bertin[1983] to create a formalized approach:

- define the problem or question,
- determine the data through abstraction to process or extract the relevant data,
- determine the characteristics of the relevant data including types, quality, sizes, dimensionality, etc., and
- map the characteristics of the data to a suitable visual representation, appropriate for the given task.

In scientific visualization, important features and relationships in the data are usually specified by a domain expert or software detection prior to rendering. In information visualization rendering is often used to expose previously unknown relationships in the data that are then discovered by the viewer. In either case, the effectiveness of the resulting visualization relies on the integration of data feature importance and expressive rendering.

Once the data has been processed and distilled, one of the most difficult tasks is to choose the most effective visual representation such that the external and internal representations given by the visual representation and a viewer's cognition correspond. Norman [2002] and Tversky [2002] define a few guiding cognitive principles for effective visual representations.

- appropriateness principle: a visual representation should provide just enough (not too little nor too much) information as is required for the given task;
- naturalness principle: representation should match the information being represented for the most effective representation and new visual metaphors must match a viewer's cognitive model of the information;

- matching principle: representation should match the task being performed and present affordances that suggest appropriate actions and interactions

- principle of apprehension: content of the representation should be easily and accurately perceived

For the non-photorealistic rendering community, Salesin mentioned adding dimensions to 2D visualizations, creating design assembly instructions (such as for Origami), creating appealing informative maps, methods for layering information, as well as enabling the comparison and evaluation of visualization methods.

There has been some movement in the community to address the issues that Salesin put forth. Tateosian et al. [2007] describe visualization approaches that use non-photorealistic rendering techniques to engage viewers and promote prolonged inspection. Agrawla et al. [2003] used abstraction principles to generate step by step assembly instructions. Several researchers have sought to quantify the effectiveness of different visualization techniques by comparing them to one another using user studies [Chen and Czerwinski 2000; Feng et al. 2009].

It will be of continuing importance to build visualization tools based on the sorts of cognitive principles described by Normal [2002] and Tversky [2002], but the work described here shows that this process is already well underway.

2.4 Challenge 4: Interaction enabling "right-brained" thinking

Interaction is still one of the most difficult research paradigms, enabling humans to "tell" the computer what to do, and get exactly what was requested as a result. A good interactive system should balance the division of labor between the artist/user and the computer. Interactions should be simple, flexible and support the full design cycle. In particular, Salesin was looking for interaction that favored the right side of brain. Tools designed for artists need to provide them with the flexiblity to express themselves, without letting the controls or the parameters of the system get in the way. There are several NPR-related interaction systems such as Harold [Cohen et al. 2000], SnakeToonz [Agarwala 2002], Video Tooning [Wang et al. 2004], and real-time video abstraction [Winnemöller et al. 2006], which enable users to build scenes and animations by letting the computer take care of the tedious details, but allow the artists to control the content.

We posit that it is important to design interaction tools for both sides of the brain. While it is undeniably important to design tools that will allow artists to express themselves, it is also worthwhile to design interactive approaches that favor left-brained interaction, so that users without any artistic skill of their own can leverage the knowledge built into the tools to create compelling visuals. Many semi-procedural approaches have been developed that favor this sort of interaction by allowing the user to adjust a small set of parameters or perform some minimal interaction in order to achieve the desired results.

Future areas of research that continue to be addressed include output sensitive algorithms, power-tools for expressive content creation, and more tools for creating animations from video. The needs of users and artists will continue to change, so there will always be some evolution with regard to the tooling that best suits their current requirements. While a worthwhile pursuit, we do not feel that this is the basis on which the future of the field will rest.

2.5 Challenge 5: A "Turing Test" for CG Imagery

Salesin mentioned a non-photorealistic rendering Turing Test in which computer-generated imagery should be indistinguishable from the artist's images created by hand. The implicit assumption here is that human-generated artwork has intrinsic value, but because this value is difficult to quantify in its own right, we can instead evaluate CG imagery by determining if it is indistinguishable from imagery produced by humans.

The sort of Turing Test proposed by Salesin seems reasonable for evaluating some notion of aesthetics, but there are other aspects of NPR that benefit from a different sort of evaluation. When we view NPR in the context of modifying the information content of an image, we find that the nature of the Turing Test changes significantly. In essence, this form of NPR is about representing information visually, and so the test of its effectiveness should be more related to the evaluations used in the information visualization community. In the area of visualization, computer imagery is used to aid the viewer in performing a task or making a decision. Therefore, we propose cognitive evaluation as a method to determine the effectiveness of a given visualization technique.

Not all user evaluation of imagery assesses effectiveness. For example, forced choice experiments are often used to detect differences or preferences. Schumann et al. [1996] polled architects for their impressions of sketchy and traditional CAD renderings, and based on the results, argued for the suitability of sketchy renderings for conveying the impression of tentative or preliminary plans. Similarly, most perception results have little power as effectiveness measures because most theories of perception were developed for simpler environments than those being depicted in computer graphics and visualization. The perception research we draw on was conducted by studying one dimension at a time: color, shape, texture, and motion are all studied in separate experiments. In application, interactions between these dimensions are likely to be of great perceptual significance and therefore merit further study.

The effectiveness of a visualization method can be evaluated by measuring its ability to communicate. Measuring the communication content of a visualization method can best be performed in an indirect manner: a behavioral study is conducted in which participants perform specific tasks on sets of visual stimuli. Relative task performance is then related to the effectiveness of the visualization. If participants are statistically better at performing a task given a certain type of visualization, then that method of visualization can be said to be more effective for the given task.

An early study [Ryan and Schwartz 1956] examined the amount of time needed to judge the position of features in photos and hand drawn illustrations. Faster responses suggested more effective illustrations. Similarly Agrawala and Stolte [2001] demonstrated the effectiveness of their map design system using feedback from real users. Interrante [1996] assessed renderings of transparent surfaces using medical imaging tasks. Performance provided a measure of how clearly the rendering method conveyed shape information. Gooch and Willemsen [2002] tested users' ability to walk blindly to a target location in order to understand spatial perception in a non-photorealistic virtual environment. Gooch et al. [2004] compared performance on learning and recognition tasks using photographs and facial illustrations. Cole et al. [2008] compared line drawings produced by artists with the results of common line drawing algorithms. Investigations like this draw on established research methodologies in psychology and psychophysics to produce meaningful results.

There remain many approaches yet to be tested. Many methods have been proposed for conveying information through visual representations without evaluation of their effectiveness. In addition to evaluating this large backlog of untested techniques, these ideas should be carried forward and applied as a litmus test to new approaches in order to ensure that they truly are a step in the right direction from their predecessors.

2.6 Challenge 6: New Artistic Media

The creation of new artistic media and styles is one of the toughest challenges for the non-photorealistic rendering community. We see this as perhaps the most important challenge facing NPR as it matures beyond the second level of technology adoption. Section 3 provides a more detailed description of this challenge and why it is so critical to the maturation of the field.

2.7 Challenge 7: Naming the field

There has been considerable discussion on the proper naming of the field. The term NPR (especially in its abbreviated state) seems overly general, including all rendering which does not have a photorealistic purpose. Some other names have been put forward, such as "Stylized Rendering" or "Expressive Rendering", but we feel that those terms are not inclusive enough to cover all of the material that currently fits under the purview of NPR.

For better or for worse, the field in which we work is now known widely as non-photorealistic rendering, and while self-examination can indeed be a worthy pursuit, the amount of energy devoted towards the semantics of a new name for an already established field could perhaps be better spent pushing the discipline in directions that will lead to exciting new discoveries.

3 Future Direction of NPR

> "A major new medium changes the structure of discourse; it does so by encouraging certain uses of the intellect, by favoring certain definitions of intelligence and wisdom, and by demanding a certain kind of content – in a phrase, by creating new forms of truth-telling."
> – Neil Postman, "Amusing Ourselves to Death".

Since its inception, NPR has mostly been focused on looking backwards, attempting to emulate and imitate styles from ages past. Even now, the majority of the work in the field is devoted to refining and optimizing algorithms that are intended only to simulate traditional artistic techniques. If we are to move beyond the second stage of technology maturation, we need to discover and demonstrate NPR algorithms that are capable of producing results beyond the scope of traditional artistic techniques. We need to show that the computation of NPR techniques can be an artistic medium in its own right, not just to imitate the great works of the past, but also to create the art of the future. Creating new artistic media is a difficult task, but there have been several noteworthy attempts that are described in the following section.

We see two clear ways in which computation can be leveraged in order to enable the creation of new artistic media, although there are doubtless others. The first is by automating time-consuming tasks, thus allowing art to be created on a scale that would have been prohibitive in the past. The second manner in which computation can lead to new artistic media is by enabling communication, collaboration, and interaction within the artistic process at rates which would not have been possible without computation.

Computer imaging has made it easy to create image and video mosaics [Klein et al. 2002; Kim and Pellacini 2002; Zelnik-Manor and Perona 2007]. The aesthetic or artistic value of such images

Figure 3: *"Pearblossom Hwy." by David Hockney, 11th-18th April, 1986, #2, 1986. Photographic collage of chromogenic prints, 78 x 111 in. J. Paul Getty Museum, Los Angeles. Permission pending.*

may be debatable in comparison to "Pearblossom Hwy" by David Hockney, shown in Figure 3. However, Hockney's work took him more than a week to photograph, and five studio days to compose, whereas computational approaches can achieve results in a matter of minutes. Computation has made this artform accessible even to those who cannot afford to devote a prohibitive amount of time to the creation of such mosaics.

Fractal art [Mandelbrot 1982] is another medium that has greatly benefitted from the use of computation. While fractal formulations exitsted long before they were used in computer graphics, the scale and speed at which fractals can now be generated allows us to observe their recursive structures in a manner that was never possible before the use of computation. Daniel White's 3D Mandelbulb is an example of a structure that could not be created physically, but can now be appreciated thanks the use of non-photorealistic rendering techniques [Aron 2009].

The Wooden Mirror (1999) by Daniel Rozin is another example of computer imaging and technology used to create a form of interactive art. The mirror is made of 830 square pieces of wood, 830 servo motors, as well as control electronics, a video camera, a computer, and a wooden frame. In near real-time, the camera captures a person standing in front of the mirror, and uses the servo motors to alter the orientation of the wood pieces, producing a "pixelized" wooden image of the object in front of the camera, as shown in Figure 4. Creating such a device without the benefit of automation would be extremely difficult, both in terms of producing the mirror and in terms of manipulating it interactively to match the image in front of the camera. Given these factors, it seems fair to conclude that this work of art would not be feasible without the extensive use of computation.

Computation enables communication and collaboration within the artistic process at a rate that was never possible in the past. Users can be both artists and observers, and can work with one another to produce collaborative art that evolves over the course of the exchange. The Electric Sheep program [Draves 2006] is an example of this form of artistic medium that could not exist without computation. Electric sheep generates patterns based on the fractal flame algorithm, and allows users to vote on the results. The fractals evolve based on their popularity, creating a form of generative and collaborative art that changes at a pace beyond anything that could have been achieved without using computation as part of the medium.

In addition to the potential artistic merit, we believe that the de-

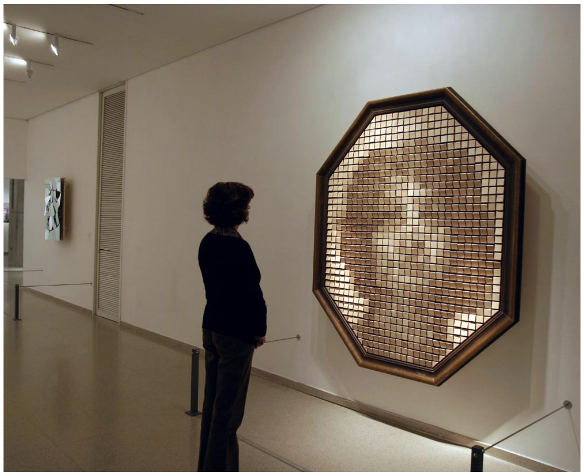

Figure 4: *Wooden Mirror, new artistic medium combining computer imagery and hardware. Copyright 1999 Daniel Rozin. Permission pending.*

velopment of new media can be beneficial when applied to illustrative visualization tasks. Researchers have had considerable success using traditional artistic media such as painterly rendering as a metaphor for information visualization. We contend that new media has the potential to provide a new set of rich metaphors that can extend the vocabulary of visualization. Ultimately, this could lead to a better understanding of how computation can be used to make the visual display of information more comprehensible.

4 Conclusion

The application of computer technology into interdisciplinary fields like visual art has introduced several new forms of popular media, including online games and computer animated films. Consequently, there is a greater need than ever before for computer graphics to serve as a form of expression, both for creating artistic content, and for visually representing information. In order to meet this demand, it is important for NPR to progress towards the third stage of technological maturation, so that it can not only be used to mimick the methods of the past, but also to invent the methods of the future. We believe that the path towards the third stage involves developing NPR algorithms that can create media that would not have been feasible to produce without the use of computation.

Once this third stage is achieved, NPR will truly become a standalone medium, no longer solely dependent on mimicking the artistic methods of the past. It will encompass both old approaches and new, using computation to take into account cognitive, psychophysical, collaborative, and interactive principles that cannot necessarily be translated onto a canvas. Computation will not just be the tool used to simulate some other medium, but will itself be a powerful medium for expressing artistic and visual content.

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