

Beyond Photorealism

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Abstract. For around 30 years the computer graphics research community has pursued photorealism as though it were the ultimate form of visual expression. Yet, as an art form, photorealism is one of many abstractions that an artist might use to convey ideas, shape, structure, emotion and mood. In this paper we describe how techniques and wisdom learned from photorealistic computer graphics can be adapted and applied to a diverse range of alternative styles for visual expression.

1 Introduction

From the first moments of the pioneering work in computer graphics some 30 years ago, the quest for realism has been an enduring goal. The term *photorealism* has been coined to denote techniques and art forms in which proponents strive to create synthetic images that are so lifelike they might be mistaken for photographs of real world scenes and objects. While advocates of photorealism have, over the years, conceived a wide range of methods and algorithms for synthetic image generation, the purest and dominant form of these has been *physically-based* techniques. These are inspired and driven by observations of the physical world, in which the interaction of light with the surfaces and objects in an environment, and the projection of an image on the film within a camera, are the key processes to be emulated.

The techniques of ray tracing and radiosity have become established as powerful complementary tools in the photorealistic rendering toolbox. In both cases, the physical behavior of light is *simulated* within a virtual world to yield, in the best cases, fine examples of the hallmarks of photorealism.

Pursuit of photorealism through simulation is the most demanding of tasks. Our world is incredibly rich and diverse; the processes of nature are complex and often hard to predict precisely. Today, researchers can define synthetic environments that contain just the right kind of objects made from the right kind of materials, illuminated by the right kind of lights, and from these create a convincing image. But we are still not quite ready to respond to the challenge of the general case. Many researchers have focused on the diverse elements of the physical world, such as materials simulation, light interaction, performance of optical systems and of the chemical process that transforms a momentary exposure of light on the surface of photographic film into a

permanent image. To solve the general photorealism problem there is still original research work left to do.

It is curious to note that often researchers set about a solution to these demanding physical simulations not because there is necessarily a clearly identified need for a solution, but because the technology can be applied to arrive at a solution. This is often the case of technologists with a solution in search of a problem. Certainly, there are plenty of viable applications of photorealism, including special effects in film and design visualization, however, the techniques applied are often empirical rather than physically-based – simulating reality is not so important as creating the *illusion* of reality in the mind of the observer.

2 Photorealism Defined

Before defining NPR, it is necessary to understand what is *really* meant by the term ‘photorealistic rendering’. **Photo** comes from the Greek *phos*, meaning light, or produced by light. **Realistic** means depicting or emphasizing what is real and actual, rather than abstract or ideal.

Rendering, in this context, is traditionally regarded to mean a perspective drawing showing, for example, an architect’s idea of a finished building. In the computer graphics community, rendering is taken to refer to the process by which the representation of a virtual scene is converted into an image for viewing.

The art of photorealistic rendering had many proponents long before the birth of computer graphics. The work of the artist Johannes Vermeer (1632-1675) exhibits properties that are photographic in their quality. The perspective within the subject matter is very closely observed, and brush



Figure 1: *The Music Lesson* by Vermeer.

strokes are short and subtle and cannot easily be discerned in the finished painting. It is widely believed that Vermeer used a *camera obscura* to compose his paintings – a lens system and a projection screen was placed in front of the subject (an indoor

scene) and the projected image was copied precisely. Despite whatever mechanical aids Vermeer may have used, his work stands as a most impressive example of photorealistic rendering at its best. However, some critics of his day were less appreciative of the work, accusing it of being cold, inartistic and prone to displaying ‘spiritual poverty’. Since the advent of photography, photorealism in art has become less fashionable, and has given way to more abstract and stylized forms of representation.

It is interesting that the criticisms of Vermeer’s work in the 17th century are equally true of some modern practitioners of photorealistic computer graphics. Certainly, the early attempts at photorealistic computer graphics, while technically impressive, were regarded as sterile and cold, being too perfect and lacking feeling. The efforts of numerous researchers over the last 30 years have placed a rich set of tools in the hands of the artist. Yet it is important to recognize that photorealistic rendering is not nor ever will be the panacea of the artist; it is simply one of many art forms at the artist’s disposal. An important skill of the artist is in choosing the right medium for each job, which will be guided by such considerations as aesthetic appeal and effectiveness of communicating the visual message.

Prior to the impressionist movement, the majority of fine art was intended to capture a view of nature – the talent of the artist was measured by how closely a painting resembled its subject. Impressionism introduced a popular art form in which the painting style was not necessarily an accurate reflection of reality. Impressionist artists were ridiculed by the critics of the time. A key differentiation of the art form was that the canvas itself was an active part of the picture – the shape of the brush strokes and the texture of the layers of paint were used to convey emotion and mood, with colors often being bold and exaggerated. Brush strokes can be used to direct the eye, and focus attention on the important elements of a composition. Long flowing strokes and short, sharp jabbing strokes convey stark contrasts of emotion, just as the choice of palette can evoke sensations of warmth or coldness.

3 Introducing NPR

A few years ago, a number of researchers began to pursue alternative forms of artistic expression in computer graphics. This research was often in marked contrast to that of the photorealistic rendering advocates, and became known as **non-photorealistic rendering** (NPR). It is rather absurd to describe a field of research and development after that which it is not, yet the term has endured and has become adopted by the computer graphics community to denote forms of rendering that are not inherently photorealistic. The terms *expressive*, *artistic*, *painterly* and *interpretative* rendering are often preferred by researchers of the field since they convey much more definitively what is being sought.

The term NPR is used in this paper in deference to current popular terminology, but that term is itself a hindrance to the NPR movement. By analogy, it would be like categorizing the whole of fine art into ‘Impressionist’ and ‘Non-Impressionist’, and using the latter term to categorize all art forms by the fact that they are not in keeping

with the Impressionist style. To do so has the effect of de-emphasizing and degrading other art forms. A richer vocabulary is needed to enable the art forms to develop through the written and spoken word as well as through the practice of the art itself.

So what is NPR? A definition along the lines of “a means of creating imagery that does not aspire to realism” is fundamentally flawed. For example, the images of Figure 2 fit this definition, but could they be regarded as examples of NPR? To strive for a definition of NPR is as pointless as defining “Non-Impressionist”. The field is in its infancy, and it is hard to be specific about what it is (and therefore more convenient to state what it is not). The richness and diversity of computer-assisted art forms is at least as wide as those of traditional art. Photorealism is but one form of representation; in time the term NPR will be replaced by others that are more specific to the branches of computer assisted art forms.

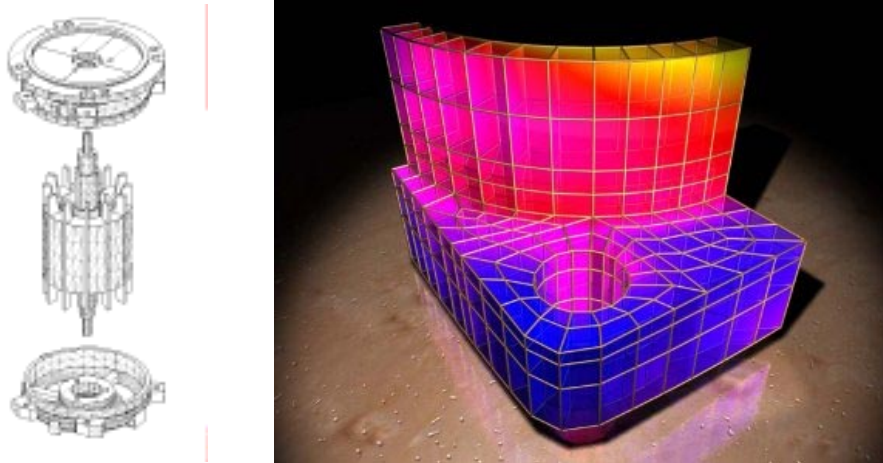


Figure 2: These images are not regarded as photorealistic. Are they NPR?

Not surprisingly, early proponents of NPR have focused their attention on *natural media emulation* – the reproduction of traditional art forms, such as styles based on the media of pen and ink, watercolor and oil on canvas. Natural media emulation can be regarded as one branch of NPR research. But NPR offers a much wider scope than this and the opportunity to experiment with new art forms that have not previously been popularized, either because they have not been ‘discovered’ or because those art forms would be impractical to create by hand.

In contrast to photorealism, in which the driving force is the modelling of physical processes and behavior of light, the processes of *human perception* can drive NPR techniques. This can be just as demanding as physical simulation but for different reasons – a technologist may find comfort in developing algorithms to reproduce a certain physical phenomenon that is objective and relatively predictable. The fact that the photorealistic rendering problem can be expressed as a single equation [Kajiya86] provides a comforting focal point of the quest – a notion that there is a single, correct

solution. Developing techniques to replace, augment or even assist the subjective processes of an artist requires a shared understanding of the use to which these techniques will be put, and the creative processes the artist undergoes. The finest examples of NPR work will be produced when artists and technologists work together to identify a problem and develop solutions that are sympathetic to the creative processes. For NPR there is no single correct solution – no rendering equation to solve.

The inclination of the technologist is often to pursue techniques that require minimal intervention by the user, and a goal might be to devise schemes that generate images fully automatically. This is certainly a guiding principle of photorealism, where involvement of the user to provide ‘hints’ for the software is generally regarded as a bad thing. A number of NPR researchers have demonstrated that generation of certain styles can be automated quite successfully, most notably the pen and ink emulation of Winkenbach [Winkenbach94], and the impressionist effects of Litwinowicz [Litwinowicz97] and Hertzmann [Hertzmann98]. However, it is important to differentiate between expressive *style* (such as impressionism, expressionism, photorealism) and the artistic *medium* (watercolor, pastel, charcoal). For the latter, it seems valid to express algorithmically how charcoal might appear on heavily textured paper, or a wet wash might cause bleeding in watercolor. However, simulating artistic expression is another matter – we should recognize that computers are not creative or inventive, but should be treated as tools that allow users to express themselves. When the task of generating a complete, stylized picture is delegated to the computer, this can give rise to results that are amateurish and simplistic.

Apodaca describes some of the techniques that are used for computer generated imagery in film making which he calls *photosurrealism* [Apodaca98]. Although based in realism, there are techniques that are distorted and shaped under the guidance of the director to arrive at the false reality that is deemed necessary to tell the story. Story telling is about creating illusion – convincing the audience that the unreal is real. Digital cinematographers require the most extreme flexibility in the tools that they use to create the required end result, usually resorting to effects that are inherently non-physical.

4 Comparing and Contrasting Photorealism and NPR

Table 1 provides a comparison of the trends of photorealism and NPR.

	Photorealism	NPR
<i>Approach</i>	Simulation	Stylization
<i>Characteristic</i>	Objective	Subjective
<i>Influences</i>	Simulation of physical processes	Sympathies with artistic processes; perceptual-based
<i>Accuracy</i>	Precise	Approximate
<i>Deceptiveness</i>	Can be deceptive or regarded as ‘dishonest’; viewers may be misled into believing that an image is ‘real’	Honest – the observer sees an image as a <i>depiction</i> of a scene
<i>Level of detail</i>	Hard to avoid extraneous detail; too much information; constant level of detail	Can adapt level of detail across an image to focus the viewer’s attention
<i>Completeness</i>	Complete	Incomplete
<i>Good for representing</i>	Rigid surfaces	Natural and organic phenomena

Table 1: Comparing and Contrasting Photorealism and NPR

5 An Overview of NPR Research

Here we provide a short overview of the trends in NPR research in recent years. This is not intended to be exhaustive, but simply to give an indication of approaches that have been popular.

Historically, NPR research can be regarded as having originated in early 2D interactive paint systems, such as Quantel Paintbox. These systems provided synthetic artist drawing objects, such as air brushes and pencil, and the user applied these to a canvas to create pixel-based effects. Researchers have developed these techniques further and two prominent areas emerged: 2D brush-oriented painting involving more sophisticated models for brush, canvas, strokes, etc., and 2D/2½D post-processing systems in which raw or augmented image data is used as the basis for image processing. A number of researchers have explored techniques that can be applied to photographic images to synthesize painterly renderings of those images.

One of the key approaches that separate branches of research in the field is the degree to which user intervention is required. Some researchers have favored automatic

techniques that require no or very limited user input, while others use the computer to place strokes at the guidance of the artist. 2½D paint systems have been developed in which augmented image data is used to automate paint actions initiated by the artist on pre-rendered scenes.

A more recent trend of NPR research has been the adoption of 3D techniques. The classic 3D computer graphics rendering pipeline exposes a number of opportunities within which NPR techniques can be applied to manipulate data in both 3D and 2D forms. A number of researchers have focused on providing real time algorithms for NPR which afford stylized visualizations of 3D data that can be manipulated interactively. The view-independence of some of these approaches provides obvious benefits for the generation of animation sequences.

Taxonomy for NPR is provided by [Teece98b], in which different approaches are classified primarily according to whether they are 2D or 3D, and whether user intervention is required. This provides four principle categories of NPR research as summarized in Table 2.

	2D or 2½D	3D
No User Intervention	Saito90 – Rendering 3D Shapes Bakergem91 – Free-hand Plotting Buchanan96 – Effects with Half-Toning Litwinowicz97 – Video Processing Treavett97 – Automated NPR Images Hertzmann98 – Using brushes of multiple sizes	Sasada87 – Drawing Natural Scenery Winkenbach94 – CG Pen & Ink Illustr. Strothotte94 – Rendering Frames Elber95 – Line Art Rendering Meier96 – Painterly Rendering Lebareadian96 – Rendered Cel Look Claes97 – Networked Rendering Markosian97 – Real-time NPR Gooch98 – Technical Illustration Gooch99 – Interactive Technical Illustration
User Intervention	Strassman86 – Hairy Brushes Haerberli90 – Paint by Numbers Litwinowicz91 – Inkwell Cockshott92 – Modelling Paint Texture Hsu94 – Skeletal Strokes Salisbury94 – Pen & Ink Illustration Schofield96 – Piranesi Curtis97 – CG Watercolor	Teece98a/b – 3D Expressive Painter

Table 2: A taxonomy of NPR systems, adapted from [Teece98b]

6 Kazoo and Non-Photorealistic Rendering

LightWork Design has developed LightWorks[®], a photorealistic rendering toolkit over the last ten years which is used primarily by 3D design products [LightWorks]. Over the past few years the company has observed a growing desire amongst users for forms of visualization other than photorealism. Photorealistic computer graphics has its place, but the visual messages conveyed can be too precise and sterile for certain applications. A designer often has the need to convey work in progress, which is incomplete and imprecise, or to express a design idea to inspire a client. Realistic rendering is not well suited to this.

To respond to this need, the company has developed the **Kazoo™** family of software for providing NPR styles to application programs [Kazoo]. The Kazoo Toolkit offers a configurable rendering pipeline that provides a software infrastructure within which a wide range of existing and new NPR styles can be developed. Some example styles are illustrated in Figure 3.



Figure 3. Example Kazoo Styles

The requirements of flexibility and configurability for NPR are much the same as those required in a photorealistic rendering system. Consequently, LightWorks served as an effective core technology on which to build Kazoo. Kazoo was designed to accommodate two configurable rendering pipelines. These are a *shading pipeline* and a *stroke pipeline*. The former accepts 3D surface geometry and yields raster image data. The latter also accepts 3D surface geometry and yields both 2½D resolution-independent stroke data (curves) or image data. A *Kazoo style* is implemented using

one or both of these pipelines configured to deliver the required result. When both pipelines are used, this may be in parallel (when usually the stroke output is superimposed on the shading output) or sequentially (when usually the output of the stroke pipeline drives the input of the shading pipeline). There is no limit to the number of passes through the pipelines that can be performed for the generation of a single image.

The Kazoo shading pipeline is an enhanced photorealistic renderer, with each stage being configurable such that it may be substituted with purpose-written software by the style writer. Input to the pipeline is 3D data represented as polygons, implicit surfaces and parametrically defined surfaces. A style may begin by optionally performing some deformation to the geometry, for example, to give a false perspective. This distorted geometry is then passed to the visibility-processing step to yield a collection of surfaces for shading. These surfaces are divided into multiple sample points within the visible region beneath each pixel. The sample points are shaded by a series of steps that treat orthogonal characteristics of the surfaces, including their illumination and reflectivity. Finally a post-processing step provides a framework within which image-based effects can be implemented. This step, as indeed are most others, is multi-pass in that repeated occurrences of the step can be applied as required.

The Kazoo stroke pipeline also begins with 3D surface data that may be optionally deformed. But it differs from the shading pipeline in that the visibility processing is designed to determine visible edges (boundaries and silhouettes) that are classified against surfaces. A stroke generation stage then evaluates these edges to yield continuous 2½D strokes. Intuitively, a stroke is a single line that would be placed on the canvas by an artist. The stroke generation combines the geometric properties of the edges and applies a series of heuristics to arrive at a candidate stroke drawing sequence. Note that at this point the strokes can be regarded as 2½D because their appearance is view-dependent.

Having evaluated a collection of strokes, the next stage in the pipeline is to optionally deform the strokes, for example, to provide randomness or to distort them. After deformation, the strokes can be either rasterized then post-processed as in the shading pipeline, or alternatively they can be used directly as resolution-independent strokes. Although the strokes are at this point recorded as a 2½D data set, sufficient geometric interaction is maintained with them so that 3D surfaces can be reconstructed through a back-projection stage. The resulting 3D data can be passed through one of the pipelines again for further processing.

These pipelines can be combined and programmed to enable a wide range of styles to be designed and developed. Further examples of Kazoo styles are given in the color plates.

7 Conclusion

It is remarkable that photorealism has endured for so long as the goal of the work of so many researchers in computer graphics. For a community that is so culturally diverse

and technologically advanced, the focus on so pure an art form to the exclusion of virtually all others is almost without precedent. But this begs the question: is computer graphics art or science? While the development of computer graphics systems is predominantly the domain of the scientist, it is artists who are responsible for the *application* of those systems. Computer-generated imagery is at its finest when technologists and users work together to define and solve common problems. Much of the work of researchers is done in environments that lack any art or user direction, or any strong sense of application or practical purpose. This can give rise to proliferation of solutions that lack tangible accompanying problems.

For the research community, NPR represents a gold mine of opportunity, with recent proponents having addressed a wide range of subject matter, including various artistic media such as pen and ink, watercolor and pencil sketch.

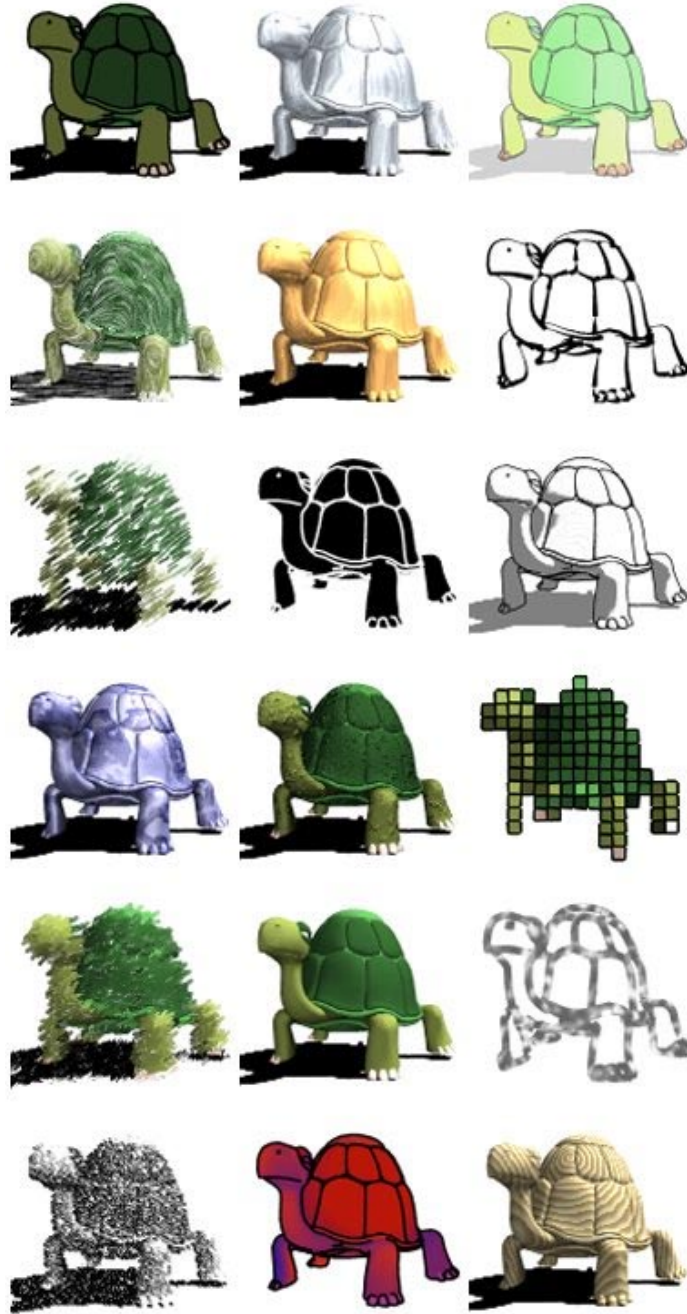
One of the refreshing aspects of NPR is that it brings closer together the disciplines of art and science; its value is far less on the technical brilliance of the techniques but on the aesthetics of the results, and the scope to convey shape, structure and artistic expression. It is an area that requires artists and engineers to work together to solve new and challenging problems in computer graphics.

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Single model rendered in a range of Kazoo Styles



Sample non-photorealistic image (courtesy of Scott Pritchard)