Scientific Foundations of Computer Graphics

Thomas Larsson
Department of Computer Engineering
Mälardalen University
Sweden

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Abstract

It is apparent that computer graphics has become a well-known technology that is used in a broad spectra of application areas. For example, in fields like computer aided design, animation, scientific visualization and medical science the importance of computer graphics is evident. But what are the scientific foundations upon which computer graphics relies? Is computer graphics merely a useful tool in various research areas and scientific projects or would it rather be regarded as a science in itself, with its own methodological framework and research methods? In this paper, the nature of computer graphics is discussed from a theory of science perspective. The research methods of computer graphics are discussed and reasons are given to support the conclusions that computer graphics is indeed worthy to be classified as both a science and an engineering discipline, as well as a special art form.

1 Introduction

Over the past 40 years, computer graphics has evolved from being an almost unknown subject into a well-known research topic in academia and industry. With applications from computer games and computer generated movies to virtual prototyping and data visualization, it has drawn people together from a diverse spectra of other research fields. Some examples besides other subfields of computer science are math, physics, biology and chemistry as well as some areas within the social sciences. Without doubt, computer graphics has its roots in many disciplines, both when it comes to applications and research.

Computer graphics is often said to be a technology for accomplishing image synthesis and interactive visualizations. A major goal is to improve the way computer generated pictures can simulate real world scenes and scenarios, which is accomplished by the development of powerful graphics hardware and software. But we argue that computer graphics also can be regarded as a science with its own scientific problems and solutions, although tightly interlinked with other areas. A simplified view of the broad nature of the scientific work

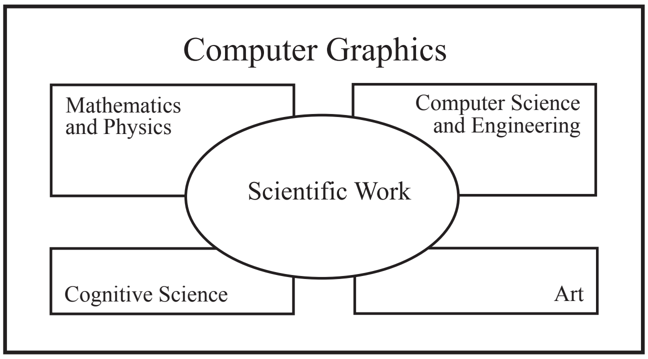

Figure 1: A view of the multidisciplinary science of computer graphics.

in computer graphics is given in Figure 1. As illustrated, the scientific work is heavily based on mathematics as well as on physics. There is also a clear and important overlap with other subfields in computer science and engineering. Cognitive science is also of great importance for the results and progress in many cases. Furthermore, art and artistic creation are not only important in computer graphics in general, but also when it comes to the science of the field, which might benefit from artistic methods and theory. We argue that a methodological framework that includes this broad perspective is needed. It is true that the scientific methodology of computer graphics can be formed partly by inheriting guidelines, methods and frameworks from other interrelated disciplines. To some extent, this has also been done, but this needs to be an ongoing process. The computer graphics community would benefit from discussing methodological issues more often to clarify the nature of the discipline and provide a powerful framework for the scientific work within all areas of the field.

In the rest of this paper, the nature of the computer graphics discipline is discussed and an overview of the research methods that are used in the field is given. We consider the scientific foundations upon which computer graphics stand and also how scientific the research methods are. Some criticism as well defense of these research methods will be presented and discussed. Finally, our conclusions about the nature of the computer graphics discipline are given.

2 Computer graphics

In 1960, William Fetter coined the term ”computer graphics” to describe new design methods at Boeing. Since then, computer graphics has grown into a huge field concerning a wide range of techniques for the creation, manipulation and visualization of models and images. Some of its sub-fields are graphics systems, rendering, modelling, animation and visual simulation. Other strongly interrelated fields are virtual reality, scientific visualization and computational geometry. Graphics have become and indispensable tool in a broad range of application areas. Interesting applications range from printing, design and manufacturing, interactive simulations and scientific visualization to education and entertainment. Accordingly, the Computing Curricula 2001 [Curr01] states that the importance of graphics and multimedia has increased due to the technical advances that have been made over the past decade. The same report divides the area of graphics and visual computing into four interrelated fields, which are computer graphics, visualization, virtual reality, and computer vision. The computer graphics field is defined in the following way:

> "Computer graphics is the art and science of communicating information using images that are generated and presented through computation. This requires (a) the design and construction of models that represent information in ways that support the creation and viewing of images, (b) the design of devices and techniques through which the person may interact with the model or the view, (c) the creation of techniques for rendering the model, and (d) the design of ways the images may be preserved. The goal of computer graphics is to engage the person's visual centers alongside other cognitive centers in understanding."

Note that computer graphics is said to be both the art and science of communication using computer generated images. Activities range from designing hardware devices to engaging a person's cognitive centers. Given such a broad nature of the subject one might ask what it is, if anything, that qualifies the graphics subject as a science? Is it not merely a tool, a technology, which have been found to be particularly useful in other sciences and engineering disciplines? In the following section, we will look at the scientific foundations of graphics and it's place in a modern philosophy of science.

3 Scientific foundations

Computer graphics can, like computer science in general, be regarded as a technology-oriented discipline, which supplies tools for other sciences and engineering disciplines. Before discussing wether it would be proper to classify computer graphics as a science in itself, we must decide what constitutes a science.

Science is often said to be the search for new knowledge or new truths, which are derived from the facts, not personal beliefs. By means of observations and systematic experimentation scientific laws and theories are formed from which reliable predictions can be made and new knowledge derived. The scientific work is often done using methods defined by an established framework. Scientific methods might, however, differ from one research field to another. In sciences like physics and chemistry the scientific methodology can be considered well-established, but this is not the case in some modern sciences, for example within the social sciences.

Engineering, on the other hand, is often said to be the application of science. Engineers solve practical problems by applying scientific laws and principles in order to produce usable machines or other products. In engineering things are built by professional practice, while scientist, in contrast, strive to increase the knowledge of the world around us and provide general truths.

To which one belongs the computer graphics discipline, given these short descriptions of science and engineering? In fact, there is an ongoing debate on the nature of the whole computer science area. Following the thread taken by Brooks, the whole computer science discipline is "not a science but a *synthetic*, an engineering, discipline". As he states it, computer scientists "are concerned with *making things*, be they computers, algorithms, or software systems" [Broo96]. Others, like for example Hartmanis, have taken the opposite direction, defending the "scienceness" of the discipline, arguing that computer science is in fact a new species among the sciences that by means of scientific methods explores the world of information [Hart95].

But what then, if anything, really constitutes a science? What is required for a field to qualify as a science? What characterize the scientific method? What is the difference between scientific knowledge and other forms of knowledge? How is scientific progress made? These are some examples of the questions debated in philosophy of science. Can we get the answers about the nature of computer graphics from the philosophers of science?

As discussed by Chalmers [Chal99], some major, but very different, efforts to explain the nature of science were made by for example Karl Popper and Thomas Kuhn. According to Popper, scientific work is performed by formulating testable hypotheses followed by numerous efforts to falsify them. Thus, scientific theories must be prohibitive, i.e. they have to rule out what cannot happen. Performing different kinds of experiments under different circumstances is a key activity in the falsification process. Hypotheses that can stand these tests are turned into theories from which new knowledge can be deduced. These theories are considered the best ones so far. Eventually, however, they might all be falsified or completely replaced by superior theories.

Kuhn, on the other hand, emphasizes the important role of an accepted scientific paradigm, in which all normal scientific activity is performed. The paradigm provides a framework for the scientific work and a theoretic base against which new results can be obtained. Minor problems or deficiencies that arise in the paradigm are called anomalies. These anomalies, however, are not enough to abandon the paradigm and this non-critical attitude is considered beneficial. Eventually, severe objectives against the paradigm will be presented at which a scientific revolution occurs. These revolutions are emphasized as the ground for huge scientific progress and some time after such a revolution has occurred a new improved paradigm will emerge.

Chalmers also presents some other noteworthy attempts to describe the nature of science that were made by Imre Lakatos, Paul Feyerabend, the Bayesians and the new experimentalists. All these schools of thought catched different and rivaling aspects of the nature of science. Although interesting, the presentation and discussion focuses on the philosophy of science as applied to physics. Modern disciplines, like computer science and its sub-fields, are hardly discussed at all. But the world around us is changing and so do the important fields of study. What once used to be a single discipline becomes many specialized fields. Are the requirements on modern sciences met in computer graphics research? If so, what is the philosophy of science in computer graphics? There are no simple answers to these questions.

The definition of science need to be extended to apply to more than traditional sciences. To be taken seriously, a modern philosophy of science has to incorporate recently developed disciplines, by realizing their value and proper place among the other sciences. However, it seems like philosophers of science cannot agree upon the nature of science even in physics, which have been

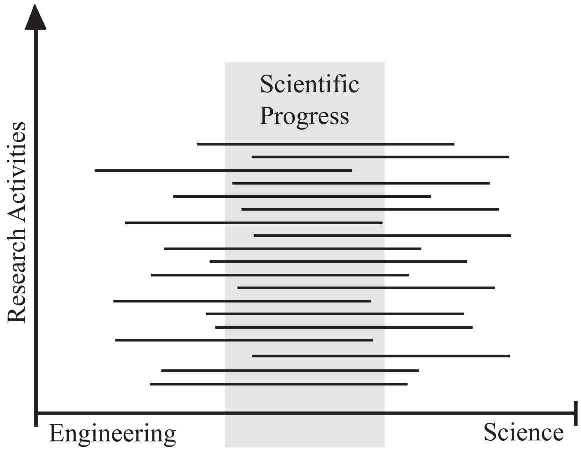

Figure 2: Progress of a modern science as a consequence of indistinguishable engineering and scientific research activities.

discussed since the days of Plato and Aristotle. It comes as no surprise that the situation is even worse when the nature of the so called modern sciences is debated. The traditional argumentation on how to separate science from engineering fails in many respects. Today, science and engineering are deeply overlapping and dependent on each other in many specialized fields. The nature of science has changed to include a much broader range of fields. For example, computer science, bioengineering and bioinformatics can serve as good examples of areas where the crucial activities, sometimes resembling engineering, science, or both of them at the same time, are interwoven tightly. In fact, we conjecture that it is neither beneficial, nor possible, to distinguish between the two in some disciplines. The engineering and scientific activities are so interlinked that the engineering is part of the science and vice versa, both when it comes to the research activities as well as their goals of discovery or inventions. This is illustrated in Figure 2. If there is something like pure sciences, i.e. unconstrained and unbiased long term search for fundamental laws of nature, then they will form a tiny subset of the many newer candidate disciplines claiming to be sciences. Modern philosophers of science must be able to grasp newer disciplines, which are not solely to be judged by comparison to traditional values and qualities found in traditional scientific communities. As we will see, the area of computer graphics constitutes an interesting example of such a modern discipline, where some of the scientific ingredients are very non-traditional.

Computer graphics research is strongly influenced by rigorous standards that have been used for a long time in mathematics and physics, but also by prominent engineering practices. Other areas contributing to computer graphics, for example art and psychology, can of course not be ignored. Clearly, computer graphics is a multi-disciplinary field. The relation to the classical sciences constitutes a solid ground for further developments, which has been thoroughly deployed. Many of the ingredients that for example Popper and Kuhn associated with sciences and scientific methods are present in computer graphics research.

But much in the same way as robotics and cognitive science, computer graphics has matured into a separate discipline with its own research problems and methodological issues. Just like any other modern science, computer graphics needs its own research principles and frameworks for scientific work.

This need has been identified. For example, a methodology or an abstraction scheme called the Universes Paradigm has been presented by Gomez and Velho [Gome95]. In their article, different levels of abstraction in the scientific work are referred to as the Physical Universe, the Mathematical Universe, the Representation Universe and the Implementation Universe. Examples of how to apply this paradigm to modelling, illumination, color theory, image processing as well as human-computer interface are discussed. In a closely related work [Gome96], the nature of graphical objects is discussed. A unified view of different object representations is presented by using the Universes Paradigm.

The challenge for such methodological frameworks is to successfully meet the broad perspective the subject require, ranging from pure mathematics into psychophysical experiments and art. Only by accepting the true nature of the discipline, a useful and complete methodology can evolve that cover the computer graphics subject in a broad sense. For example, related and important aspects in art and cognitive science are often ignored by researchers in the field. In the next section, we will look at some of the research methods that are used in computer graphics, which will give support to our claims about the nature of the graphics discipline.

4 Research methods

In 1998, ACM SIGGRAPH published a collection of 48 papers that were judged to be among the most important pioneering papers in the still very young computer graphics field [Wolf98]. The included papers were categorized under visibility, antialiasing, animation, architecture, shading, modeling, rendering from samples and foundations. This collection of papers can serve as a case study of how the field has been shaped.

The progress has been driven by theories and experiments in much the same way as in traditional and well-established sciences. In many cases, mathematical models and theorem proving are essentials parts of the scientific work. Methods from geometry, algebra, calculus, discrete mathematics, optimization, and statistics are used. The mathematical foundations used in computer graphics constitute a firm ground for further developments. Nevertheless, as pointed out by Goldman [Gold02], the extensive use of projective spaces and homogeneous coordinates are not enough in all areas of computer graphics. In some respects the mathematical foundation is inadequate. In fact, Goldman suggest a paradigm shift from projective geometry to Grassmann geometry, which would overcome anomalies between the traditional graphics pipeline and geometric design as well as provide new techniques and novel applications in the discipline.

Important areas in physics are also studied frequently, such as the spread of light, how light interact with surfaces, the motion of water and wind, and other atmospheric effects. Theories about such phenomena are then turned into corresponding computer graphics methods and algorithms. Another important area with significant implications in computer graphics is color theory, for example colorimetry, color appearance and color reproduction. There are also other fields that are interrelated contributors to computer graphics, for example computational geometry and high performance computing.

Sometimes, however, the motivation for an algorithm in computer graphics might seem to have little to do with science. Phrases like: "if it looks good, it is good" and "although it is not as accurate, it is significantly faster" are commonly used. So called graceful degradation of more rigorous theories is commonly studied and used to develop algorithms that simulate behaviors in the physical world. Just to mention some examples, polyhedra is often used to approximate bodies with curved surfaces and the ad hoc Phong lighting model, or some variation of it, is often used in interactive graphics applications. This is reasonable, though, as long as there are no better solutions available to reach the goals. One danger of this type of research is that too much efforts might be spent on optimizing special case solutions, with little or no general appeal. Sometimes you might get the impression that too many researchers are hacking on their own version of a special algorithm with a very limited horizon, instead of focusing on how to generalize theories and how to integrate different successful results with each other.

Today the goals of realism in image synthesis have increased as indicated for example by the name photo-realistic rendering. In order to simulate material appearance and how environments and objects are illuminated, theories and formulas developed in physics are studied and carefully adapted to the needs and constraints in computer graphics. But still, simplifications and approximations of corresponding discoveries in the natural sciences are used, and in fact, this will always be the case. Of course, we would not mind if we were able to simulate virtual models down to their proper molecule level as well as simulate the true physics of light, but this is simply not feasible. Instead, the goal is to search for methods and algorithms that produces realistic and usable results, with or without anchoring in for example physics. Ad hoc solutions have led to improved realism and performance, making new powerful applications and products possible.

As in the natural sciences in general, the role of empirical studies and experiments is essential to support or refute hypothesis. In the search for new methods and algorithms, questions of quality, performance and appearance must be determined by careful experimentation based on well-defined problems. The experimental setups are supposed to be thoroughly documented, so they can be repeated, which is a tradition borrowed from physics. However, too many times published papers fail in this respect. And far from all researchers provide the source code used in their experiments to make it easier for other researcher to re-run an experiment, perhaps under slightly different conditions. In any case, there seems to be no real tradition in repeating others experiments, partly because such work might not be considered as publishable results and researchers prefer working on what is considered to be more novel research.

Another very interesting aspect of computer graphics is that realities in the physical world around us, as well as other phenomena, can be visualized, experienced and explored in simulation applications, powered by real-time graphics and physically-based simulation engines. It seems to be no end of the calls for new methods and algorithms to improve and enhance these simulation systems. The design and implementation of these systems involves research that spans over applied mathematics, physics, hardware design, computational science, software engineering and cognitive science. An interesting example of how cognitive aspects have been considered can be found in the area of time-critical collision detection, with applications in interactive graphics simulations. The researchers conducted psychophysical experiments in order to evaluate the perceived effects of certain approximations and simplifications made to speed-up the algorithms [OSul01]. Visual simulation is a branch of the discipline with numerous important application areas. For example, the number of applications areas in virtual reality have increased dramatically during the 1990th and still continues to do so [Broo99].

In areas related to interface design and human computer interaction the employed methodology needs to be inspired by cognitive sciences and case studies are performed, for example, by using psychophysical experiments. In these fields, computer graphics continues to be important and it is clear that graphics researchers have to cooperate with cognitive scientists. In fact, any serious data visualization project need to take theories of perception into account, but surprisingly, issues related to perception seem to be ignored or not documented in many computer graphics research papers. However, the importance of perception and cognitive psychology in computer graphics research were addressed recently in a special issue of IEEE Computer Graphics and Applications. In this issue, the article Applied Perception [Tumb01] introduces seven other articles on different perception related topics in computer graphics.

With the tremendous growth of the game industry during recent years, where three-dimensional games have come to play a dominant role, a good opportunity for research collaboration between the computer graphics community and the game industry has emerged. Many results from computer graphics research have already been incorporated into game engines and solutions invented by game programmers might lead to progress within the graphics field as well as in other research areas [Lewi02]. This is another example of how research can be done in a very non-traditional way.

The role of arts in computer graphics is another interesting methodological issue. In many cases, computer graphics benefit from artistic thinking and artists have for a long time been using computer graphics as a new medium, which bring a new dimension into art. This seems to be a good and healthy example of mutual benefits between a science and an art from. Some people have concluded more far reaching consequences of this than necessary, although the interrelation between the two is apparent and for the better. In the book *Art@Science* [Somm98] it is stated:

> "Similarly, we suggest that art and science should no longer be considered separate and contrary disciplines, but instead complementary to each other, where patterns of mind (art) and patterns of matter (science) are reflections of one and other that are dynamically interrelated through the human consciousness, changing their states (just like electrons and neurons) from mind to matter and vice versa from matter to mind. We consider both of them part of a holistic, intrinsically dynamic and self consistent universe."

The vast heritage from the history of art can serve as rich inspirational source as well as a catalyst in the developing of new and better rendering methods in many application areas. Artistic techniques such as pencil, brush and paint effects have already been reproduced in new rendering methods. In visualization, there is a need for other rendering techniques than those striving for photorealism. Again, artistic traditions and methods might help in revealing the best ways to get pleasing pictures that expose the right kind of information. Recently, Herman and Duke have described a research goal, which they refer to as minimal graphics, with examples drawn from artistic paintings, and that also requires understanding of perceptual and cognitive theories [Herm01]. Besides rendering, art might influence the computer graphics research in for example modelling, animation and interaction design.

As we have discussed, there is a broad palette of research methods in the graphics discipline. Judging by the progress that has been made so far, there is a fruitful combination of science, engineering, and art in the discipline. These areas are overlapping. They are all givers and takers. In some cases, it seems easy to classify sub-activities in these branches into scientific and non-scientific parts, but in other cases the borders between for example science and engineering is extremely difficult to define. Instead of searching for contrived borders and trying to defend them, we believe that a more holistic view of the subject will serve the graphics discipline and its future development the most. For example, research about artistic processes and creation is important to enhance the borderland between science and art, which is of significant importance in many areas of computer graphics.

5 Conclusions

The graphics community has grown exponentially since the initial efforts were taken in the early 1960th. It exists well-established international journals, conferences, magazines and other periodicals for reporting and publishing and it has become a challenge to keep up with the progress. The nature of computer graphics and its scientific foundations can be judge by its early history as well as from the current lines of development and scientific publications. Just as in any other science, the published papers are of different quality. In order to make the distinctions between good and bad publications clearer, the methodology guiding the scientific work must mature in both conciseness and completeness and by taking the whole broad nature of computer graphics in account.

As the computer graphics discipline has matured, a healthy basis for cooperation between science, engineering, and arts has evolved. Fruitful cooperations among scientists, engineers, and artists in prominent research labs have already been established [Somm98]. A modern methodological framework has to cope with the situation and form a basis for scientific work with mutual benefits across real or imaginary discipline borders, in order to support progress in as efficient ways as possible.

The scientific activities and the engineering practices will continue to drive the whole computer graphics field forward, no matter what the scientific component within the field consist of. We can only dream of what progress the 21th century will bring in terms of new computer graphics discoveries. However, we can be sure that the computer graphics field will have an increasingly high impact on our society and on other sciences. The scientific part of computer graphics will continue to evolve in parallel with the methodological framework the researchers adhere to. Hopefully, this might lead us to a unified theory of computer graphics more capable of dealing with all aspects of the subject.

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