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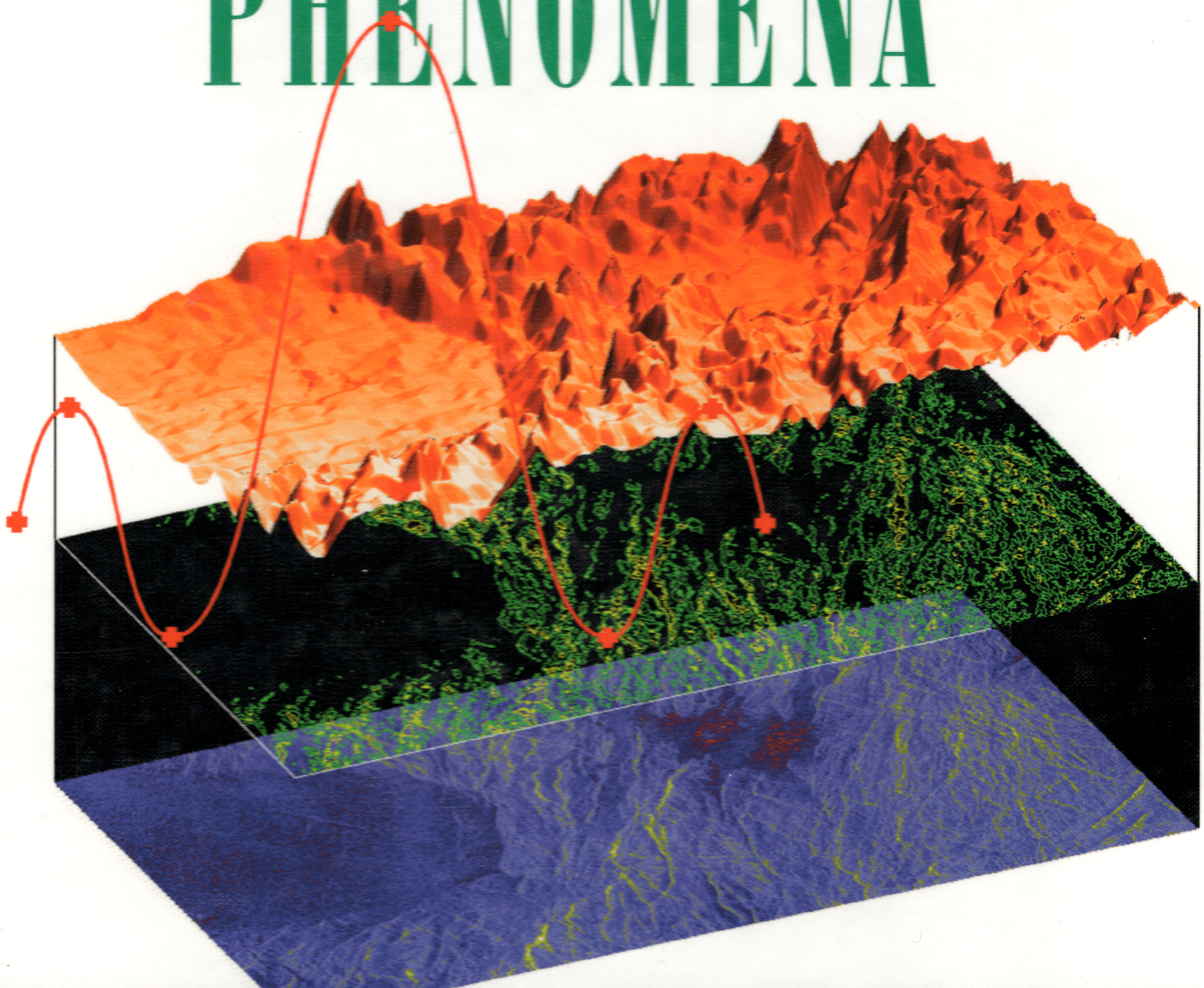
VISUALIZATION OF NATURAL PHENOMENA



ROBERT S. WOLFF ▪ LARRY YAEGER

VISUALIZATION OF NATURAL PHENOMENA

Larry + Bob —
Loved the book!
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— Davis

Robert S. Wolff
Larry Yaeger

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Of the numerous definitions of the Greek word "telos," the one most representative of our publishing philosophy is "to turn," or "turning point." We perceive the establishment of the TELOS publishing program to be a significant step towards attaining a new plateau of high quality information packaging and dissemination in the interactive learning environment of the future. TELOS welcomes you to join us in the exploration and development of this frontier as a reader and user, an author, editor, consultant, strategic partner, or in whatever other capacity might be appropriate.

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To our families

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Foreword

by David C. Nagel

In the last five years visualization has gone from the lab to become a desktop technology for many scientists. Images and 3-D renderings of data sets and mathematical models have evolved from the high-priced hardware and customized software of graphics professionals to low-cost, off-the-shelf commercial software running on personal computers. As such, scientific visualization has taken its place beside mathematical modeling as an everyday means of interacting with one's data. This has significantly changed both the amount and the quality of information that scientists are able to extract from raw data, and has effectively established a new paradigm for scientific computing. In addition, new, low-cost hardware and software technologies such as CD-ROMs, digital video, and Apple's QuickTime time-based media and compression technologies have enabled large amounts of image and animation data to be easily accessible to the average researcher or teacher through the personal computer.

However, little has been done in the way of providing a context within which the researcher or teacher could learn which approaches might be best suited for a given problem. Furthermore, most scientists are unfamiliar with the terminology and concepts in modern computer graphics, which simply steepens the learning curve for them to apply the new technologies to their work. As a result, researchers and teachers are not yet taking full advantage of the new paradigm.

In *Visualization of Natural Phenomena* (VNP) the authors have bridged the gap between the computer graphics professional and the working scientist or educated layperson and, as such, have provided an important tool to those teachers and researchers who are strongly interested in scientific visualization, but have not yet incorporated it into their daily work. By using examples of real data sets from a variety of fields and researchers to illustrate basic concepts in image processing, computer graphics, and multimedia technology, VNP brings this complex world to the users' desktop in a form that they can readily understand.

If VNP were just a textbook alone it would be extremely useful. However, by incorporating a CD-ROM with animations, videos, and software, VNP has achieved a level of technology and information integration that no other product for this market ever has. This is exciting for both users and developers, and it sets a new standard for integrated text/software products in the future. I congratulate the authors and the publisher for their efforts in this landmark product, and I encourage scientists, educators, and students of all levels to enjoy the text, images, animations, and software in *Visualization of Natural Phenomena*.

David C. Nagel, Senior Vice-President and General Manager,
Apple Computer Advanced Technologies Group and
Macintosh Software Architecture Division
Apple Computer, Inc.
Cupertino, California

August, 1993

Foreword

by Larry L. Smarr

Human beings have evolved over millions of years interacting with a physical reality. We have developed a powerful eye-brain system, complemented by the other senses, with which to probe this physical world. As we walk through a forest or drive madly down a freeway, our visual "wetware" automatically sorts out the incoming photon field and connects it to a rich stored base of images, ideas, and interpretations. Just as transparently, this visual thinking is quickly coupled to our reasoning, decision-making, and motion capabilities.

Today these same humans are becoming exponentially immersed in a new information-based reality, pouring out of supercomputers, digital instruments, and stored databases. Instead of the hundreds of thousands of generations that our bodies had to adapt to the physical world, we have had to make this transition in less than one. In contrast to the physical reality in which nature automatically transforms the underlying numerical values of density, velocity, and material properties into light, color, and shape, all that comes out of the computer is an endless stream of numbers.

Scientific visualization was invented as the process whereby humans use software to do the work of converting number to image that nature does by physical processes. We have to invent ideas for how to represent the numbers as visual paradigms and then turn those ideas into software algorithms and computer programs. The fact that we have such a wide choice in how to transform numbers into various visual modalities is both the power and the pain of scientific visualization.

For computational scientists, this field has seemed like a set of black arts for many years. One marveled at the beautiful masterpieces that were produced by graphics professionals, but had little idea of how to do it oneself. This new book, *Visualization of Natural Phenomena*, gives us one of the first opportunities to explore systematically the subfields of scientific visualization. By demystifying the subject and giving us a sense of how to do it ourselves, the authors provide the community with a great service.

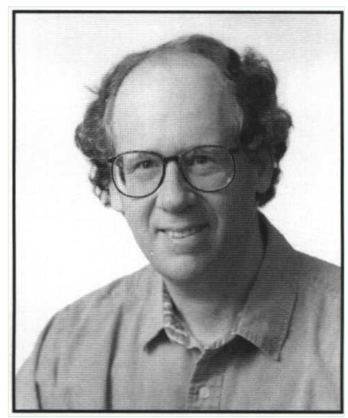
As supercomputers move toward being able to compute at over one trillion operations per second, visual output is the only sensible way for scientists to couple to this numerical reality. But the broader use of scientific visualization for communicating the results of scientific research to our colleagues in other fields and to the public at large is just as important as the discovery process itself. The power of visualization for this purpose lies in the fact that the image is a much more universal language than the underlying mathematics in which the science is couched.

Given that, the authors and publishers are to be congratulated for their pioneering use of an interactive CD-ROM created as an integral part of the writing process. This allows the reader to experience rapidly the power of visualization and then to "click" one's way to the text for deeper reading. This interactive visual interface is another step toward establishing as "natural" a mode for humans to live in an information reality as they now do in the physical universe.

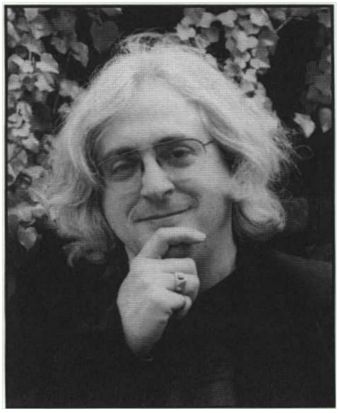
Larry L. Smarr, Director
National Center for Supercomputing Applications
University of Illinois at Urbana-Champaign

August, 1993

About the Authors



Rob Wolff is the Project Leader of Advanced Applications in Apple's Advanced Technology Group where, since 1988, he has specialized in developing prototype environments for scientific computing. Before coming to Apple, he was a planetary astrophysicist for 11 years at NASA's Jet Propulsion Lab (JPL) where he worked on the interaction of the solar wind with nonmagnetic planetary objects. He was a Guest Investigator on Pioneer Venus and a member of the Voyager Plasma Science Team during the active lifetimes of those missions. He supported his research habit by designing distributed computing environments for planetary missions. In 1980 he began working with Jim Blinn on visualizing astrophysical systems. He has produced a number of visualizations and animations and has participated in several courses and panels on visualization at SIGGRAPH. He is currently Visualization Editor for Computers in Physics and is a Co-Investigator on the Volcanology Team on NASA's Earth Observing Systems (EOS) Mission. Dr. Wolff has a Ph.D. in astrophysics from Brandeis University.



Larry Yaeger's background includes computational fluid dynamics, computer graphics imaging, and neural network research. He carried out pioneering simulations of fluid flows over the Space Shuttle, in laser cavities, and over submarines. He was Director of Software Development at Digital Productions and one of the principal architects of its computer graphics rendering software. In this role he contributed to the design and development of the software tools and production techniques used in the film The Last Starfighter and Clio-award-winning television commercials. He also combined fluid dynamics and computer graphics to create the simulation of the planet Jupiter seen in the film 2010, and was technical director for the special effects creation of the flying owl in the opening title sequence of the film Labyrinth which received an NCGA animation award. As a Principal Engineer in Apple's Vivarium Program, he built neural network simulators on Apple's Cray and applied them to optical character recognition and text-to-speech translation, designed and implemented the software to give Koko the gorilla a computer-based "voice," and built and filmed a proof-of-concept system for integrating Macintosh graphics into routine film production for "Star Trek: The Next Generation." Now as part.of the Adaptive Systems/Advanced Technology Group at Apple Computer, Inc. he is extending his character recognition work to pen-based micro-processors and he is currently combining computer graphics, neural networks, and genetic algorithms to study artificial life and artificial intelligence.

Preface

Since Apple Computer introduced the Mac II in the summer of 1987, the personal computer revolution has swept the scientific community from astrophysics to medical imaging. That year, for the first time, researchers could manipulate 8-bit color images in a low-cost, easy-to-use personal computer that had the speed of a VAX 11/750. Suddenly, the possibilities of imaging all sorts of pictorial, graphical, and volumetric data on a personal computer became real. However, two problems still remained:

- There was no way to inexpensively network the new Macintosh to existing Unix and VMS data bases, and
- There was no imaging or visualization software that ran on the new machine.

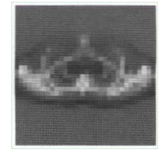
Apple and various third-party hardware companies solved the first problem by creating low-cost Ethernet cards that plugged into the Mac. However, solving the second problem was a little more difficult, since third-party software companies would not develop visualization packages for the Mac II until there were enough machines in researchers' hands to justify the development costs. For their part, researchers were somewhat reluctant to purchase a color Mac II until there were software packages that would improve their research productivity.

Apple broke this circle when it funded NCSA, the National Center for Supercomputing Applications, to develop public-domain visualization software for the Mac II. In the summer of 1988

Larry Smarr, director of NCSA, gave the keynote speech at the ACM SIGGRAPH meeting in Atlanta and, with a little help from a friend, demonstrated NCSA's visualization software on a Macintosh in front of a couple of thousand attendees. NCSA distributed its software over the Internet, and soon researchers and teachers throughout the country were creating images and animations on their desktops. At about the same time, a number of scientific software packages, like Mathematica™, were released. In addition, low-cost development systems such as Language Systems Fortran™ and Symantec's Think C™ became viable environments for the serious scientific developer. Scientists found that they could now compute, analyze, and visualize their data in classic Macintosh style. *Desktop visualization* had truly arrived and, with it, sufficient impetus for several other companies to upgrade or create software to take advantage of the new hardware.

Hardware in all areas of computing continued to improve, not only in speed, but in functionality as well. Today, personal computers run at several times the speed of the mid-1980s VAX minicomputers, 24-bit color is becoming standard, users can get up to 256 megabytes of RAM on their systems, and scientific users typically have over a gigabyte of disk space available to store data. With the introduction of Apple's QuickTime™ standard for manipulating digitized video, scientists worldwide can now create animations from data residing on Macintoshes or Unix hosts and play them back on Mac, Unix, or Windows™ machines through a wide range of software, from simple players to word processors. As a result of all of these developments, hundreds of thousands of well-endowed personal computers live on the desktops of researchers throughout the world, and there now exists a wide variety of imaging, analysis, and visualization software for the research or teaching scientist.

Visualization of Natural Phenomena (VNP) began as a project designed to teach researchers, university teachers, and students some of the basic concepts and techniques of scientific visualization. However, by its very nature of being a tightly coupled book and CD-ROM, we realized early on that an element of design needed to be incorporated that heretofore did not exist in print media. In particular, we felt that the CD should be more than just an interesting addition to the text, but should be able to stand alone as a unique product. As such we spent a fair amount of time, including prototyping several CD interfaces, trying to find the most effective way of incorporating this functionality in the design of the text. What we came up with was a system to use icons to link the text and the CD. On the CD, animations are played by clicking on an icon in a matrix, where the *y*-axis of the matrix lists the chapters of the book, and the *x*-axis denotes the number of each animation in each chapter. Thus, for example, CD 5.3 indicates the third animation in Chapter 5. In the text, the same icons from each of the animations are placed appropriately in the margin of each chapter, along with each animation's coordinates. This way users should be able to navigate between the two media without much difficulty.



CD 5.3

An icon like this one, placed in the margin of the text, indicates an animation on the CD. In this case, the animation is the third animation in Chapter 5.

Of course, our goal of including a CD with over 100 animations had technical problems of its own. Apple's QuickTime compression technology enabled us to achieve that goal, and we describe QuickTime in several places throughout the text and the Tech Notes. Unfortunately, QuickTime is not yet fully functional on Unix and Windows platforms, thus it was impossible to build a CD-ROM that ran on all environments. As a consequence, we had to ensure that the book would be a valuable product by itself. So, although the CD-ROM significantly enhances the text, it is by no means necessary in order to understand the principles, techniques, and issues discussed in the text. Correspondingly, for those Mac users who purchase the package primarily for the CD-ROM, the 100-plus visualizations and animations alone span a really interesting spectrum of science, and should be a source of entertainment and learning for all educational levels.

Selected Mathematica notebooks described in the text, as well as contributions from Doug Stein and Theo Gray of Wolfram Research and Mark Yoder of Rose-Hulman Institute of Technology, are included on the CD. Public domain and demo commercial visualization and image processing software is also included on the CD as well as sample data sets for image processing and visualization. We selected Mathematica as the general medium of exchange in this regard, since Mathematica runs on all platforms, although the Notebooks themselves only work well on Macintosh and NeXT platforms. Those without Macintoshes will be interested to know that some of the software (certain NCSA software and the commands from the Mathematica notebooks) is specifically designed to run on other platforms. However, because of our intent to make the CD work properly on as many Macintosh systems as possible, we pressed this current version of the CD in Macintosh HFS format, rather than in an ISO 9660 format. Pressing the CD in ISO format would enable text files to be read by other systems, but it would cripple the interface to the QuickTime animations, as well as severely limit their performance. We do intend to provide the VNP CD to Unix and Windows environments in some future release as soon as QuickTime technology is a bit more stable on other platforms. Right now, however, the only really solid environment for playing compressed animations with sound (and, without sound, for that matter) is the Macintosh. However, we strongly encourage all readers to send in the registration card in the back of the package so that we can keep you updated on any new versions of the CD and other product announcements.

The text itself is organized into two major parts, a main text section consisting of seven chapters and a section of Tech Notes, comprising 15 short treatises on the most important technical issues referred to in the main text. The main text itself is designed to be read fairly easily, requiring minimal computer graphics or image processing background to understand it. At the end of each chapter are suggestions for further reading for those interested in pursuing topics in more depth. In contrast, most of the Tech Notes are fairly detailed, and several require a decent understanding of complex variables, differential and projective geometry, and differential equations. Some familiarity with advanced computer graphics concepts is probably helpful, but not necessary. Liberal pointers between the chapters and the Tech Notes ensure that the interested reader understands the overall context of a given technical issue. Three of the Tech Notes are written by colleagues of ours at Apple: Scott Stein wrote one on Apple's QuickTime technology and another on networking in scientific visualization, and Peter Hughes wrote the Tech Note on terrain rendering and *Mars Navigator.*

The text is constructed around the concept of an image, and we build on that basic notion as we discuss all of the various visualization and multimedia technologies. The chapter-by-chapter breakdown is as follows:

• Chapter 1 introduces the basic structure of an image, the nature of color, and some of the more common image processing functions.

• Chapter 2 extends the image display concept to more general data sets, including data from numerical simulations and various empirical data sets that would not necessarily be considered images.

• Chapter 3 looks at the complex issue of terrain rendering and the general problem of determining the altitude of an object from images of it.

• Chapter 4 takes us through multivariate visualization, the process of finding ways to correlate and visualize multiple scalar and vector data sets.

• Chapter 5 introduces the basic concept of volume visualization, and the most widely used methods are discussed from the perspective of the needs of the scientist.

• Chapter 6 delves into polygonally based three-dimensional rendering and animation—the kind of graphics used in motion picture special effects as well as some of the most striking scientific visualizations.

• Finally, Chapter 7 looks at the relationship between scientific visualization and the efforts made by the film industry to simulate reality. Chapter 7 can stand by itself, but it also closes the loop in a number of visualization areas since entertainment and scientific computer graphics have long had a mutually beneficial relationship. On a creative level, Chapter 7 reveals certain secrets of how various special effects are created, and this is interesting to anyone who has seen a science fiction film produced in the last 15 years.

• Chapters also have references appended at the end so that interested readers can simply copy the references that they need without having to keep flipping to the back of the book.

• The Tech Notes cover a range of topics from color to image processing to sound to algorithms in volume visualization and rendering and animation. Each Tech Note is designed to give an overview of the important concepts for that subject.

• Appendix A describes the making of *Visualization of Natural Phenomena*, the various hardware, software, and data management problems we had throughout the project's development, and how we managed to solve each of them. Appendix A also lists the different commercial software and hardware packages used in the production of VNP, along with the addresses and phone numbers of the developers.

• Appendix B is a Glossary of words and concepts as well as a complete list of references for the entire book.

This project required a fairly massive technological effort, both in producing the CD and producing the images for the CD. In addition, the production of the text and still images themselves was something that we, as the authors, were involved in throughout the entire process.

We hope that you find this book both informative and attractive. We've tried to mirror the combination of information and aesthetics that one finds in the best scientific visualizations, just as these two attributes are combined in our own perspectives.

Robert spent 11 years as a planetary astrophysicist at the Jet Propulsion Laboratory, the birthplace of digital image processing (as part of the 1964 Ranger 7 moon imaging mission) and home of some of the earliest 3-D rendering for scientific visualization (Jim Blinn's Voyager mission planning animations starting in 1977), and Larry spent 10 years as a scientist and programmer in the field of computational fluid dynamics and 5 years in the field of commercial computer graphics for the film and television industries. Both of us have been performing musicians as well, and both of us have produced a number of computer animations.

As it turns out, early in our careers, we both came to understand the great value of visualizing the results of numerical computations and empirical measurements. At first that often meant using a pencil and graph paper, yet the insights offered by processing the data through the world's best pattern recognizer—the human visual system—made the effort more than worthwhile. And, as a result of our need to understand complex data structures, both of us were quick to realize the potential of the digital computer. We feel strongly about the scientific (and ultimately the sociological) value of the techniques discussed in this book, and hope you find it both valuable and enjoyable.

While we've worked hard to ensure the correctness and usefulness of this book, everything can always be improved. In a project of this scope tradeoffs are always made, and we apologize if not all of the subjects we deal with here were treated in sufficient detail for all readers. If you find areas for improvement, including any technical errors, graphics errors, or omissions, please feel free to send an e-mail to *vnp@apple.com*. As we mentioned earlier, as cross-platform multimedia delivery systems start becoming a reality, we also hope to make the CD-ROM accessible to users of Unix and other operating systems; if you're interested in such a capability, let us know at the above e-mail address. So enjoy the short movies of fluids, planets, and other natural phenomena that populate the CD. We had fun making it, and it is our wish that you have fun viewing it.

Robert S. Wolff
Pasadena, California
August, 1993

Larry Yaeger
Los Gatos, California
August, 1993

Acknowledgments

Putting together this project required the help and support of lots of people. First off, we never would have completed the project if it were not for our publisher, Allan Wylde, who supported us and showed the patience of Job from start to finish of the project. Allan understood from the start that VNP was very difficult, and that we would be pushing technology throughout the entire project. Other Springer-Verlag folks who were critical to the project were Cindy Peterson, Publishing Associate, and Sue Purdy Pelosi, Production Manager, of the TELOS office in Santa Clara, California, who helped with project administration, and Paul Manning and Jacqueline Jeng in New York, who worked on advertising and promotion of VNP.

We thank Apple Computer for its strong support of the project, in particular, our management chain: David Nagel, Rick LeFaivre, Harvey Lehtman, Mark Miller, and Jim Spohrer for their support throughout this project, as well as all of our friends and colleagues in Apple's Advanced Technology Group for their friendship, advice, and encouragement. As far as the Macintosh itself goes, we realized several months ago that VNP would have been nearly impossible to do in any other computing environment today. Yes, we certainly have a long list of things that we feel need to be fixed or improved so that other people would have an easier time of it, but overall, there is not a better development environment today for this kind of project. The fact that we were able to put VNP together is a tribute to the engineers who have helped make the Macintosh environment what it is today.

Nearly all of the line art, as well as the development of the MacroMedia Director front-end to the animations on the CD, and much of the work in editing the visualizations for the cover was done by Ming Chen. His tireless efforts, often successively refining drawings, and doing countless iterations of the CD-ROM interface, working around MacroMedia Director QuickTime and screen-refresh bugs often times late at night and on weekends, enabled us to put together a first-class looking book with a CD-ROM interface to QuickTime MooVs that we feel is about as good as can be done with today's technology.

Our production manager, Jan Benes, is another saint, who put up with constant revisions and changes while attempting to maintain some sort of production schedule. Special thanks also go out to Andrew L. Alden for copyediting and proofreading. His ability to catch illogical statements, inconsistencies, and just plain dumb errors saved us many times. We thank Jim Predny for doing the skillful and tireless QuarkXPress page formatting. Bob Meyers and his staff at Robert Meyer's Studio in Pasadena, California handled the slide scanning and color separations with exceptional dedication and professionalism. Thanks to Iva Frank who designed the cover, and Laura Bonazolli who was responsible for the complex sets of permissions required.

We extend special thanks to the technical reviewers, who put in lots of time to help us get the bugs out of the first few revisions: Mark Yoder, of Rose-Hulman Institute of Technology (who also provided the Mathematica image processing notebooks on the CD-ROM); Bob Wolfe of the University of Rio Grande; Brand Fortner of Spyglass, Inc.; Mike Norman of NCSA; Jim Knighton of JPL; Peter Hughes of Apple Computer, Inc.; Doug Stein of Wolfram Research, Inc. (who also provided the Mathematica-to-HDF file converter and the Mathematica fractal generator for the CD-ROM); and Tom Wickham-Jones of Wolfram Research, Inc.

Many people contributed images, technical support, loaner equipment, and technical advice throughout the project. Some we had known for a long time; others who we knew only through a phone call or e-mail were willing to provide hardware, software, images, and animations; and there were a few people who we got to know fairly well as a result of their generosity in providing their data.

So, special thanks to Optical Data Corporation and their wonderful laser disks; Steve Goodman of FWB for loaning us a couple of large-capacity Hammer drives; John Chan of SuperMac for getting us a VideoSpigot card when they first came out; Don Johnson of Pinnacle

Micro, for loaning us a recordable CD-ROM drive so that we could master the test CD's; Jim Blinn of Caltech and Bob Holtzman of JPL for setting the initial sparks of the visualization fire; and Tim Taylor and Sandi Reda, of Radius, Inc., who went out of their way to loan us a Radius VideoVision card (and help with technical support) during the digitizing process.

Thanks to all of the people and companies who contributed images and animations to this project. Special thanks to:

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Mike Backes, *American Film Institute*
CAROLCO
Ted Clark, *JPL's Galileo Project*
Gary Demos, *Digital Productions and Demographics*
Industrial Light and Magic
Bill Kroyer, *Kroyer Films, Inc.*
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Mark Yoder, *Rose-Hulman Institute of Technology*

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Jim Knighton, *Jet Propulsion Laboratory's Earth and Space Sciences Division,*
The Los Angeles Kings
Skip McNevin and Jurrie van der Woude, *Jet Propulsion Laboratory's Public Information Office*
Trish Russo, *The Ohio University in Phoenix*

Lastly we thank our families: Donna, Tricia, and Sammy Wolff (Robert's clan); and Levi Thomas (Larry's wife) for their patience, understanding, love, and support throughout this project. Yes, we will be spending more time at home...real soon.

We wish to dedicate this book to two special men. The first is the late Clayne M. Yeates, for many years Science and Mission Design Manager for NASA's Galileo Project. Clayne funded much of the early visualization work at JPL, without which this project never would have been. As he was with much of his work and his life, Clayne understood the vision and gave us the freedom to dream. The second is Gino Moretti, who always insisted that the results of a simulation had to be plotted to be understood. He was right.

1 Images and Image Processing

Images of natural phenomena hold a particular fascination for us, especially if they show objects and events outside our normal range of perceptions or experience. Even commonplace phenomena like the rainbow swirls of oil on water attract us with their natural complexity, organic motion, and beauty. But we all share a special fascination for the mysterious and extraordinary phenomena that our senses are not normally capable of showing us. Telescopic images of galaxies or optical fiber-based videos of dividing cells draw and hold our attention the way each new experience fascinates a child.

However, the simple notion that an image of something will tell us all, or nearly all that we need to know about it is far from true, since the fundamental nature of an image is that it is dependent on the object being observed, the wavelength of the radiation being used to make the observation, and the technology being used to collect and display the observed data.

In this chapter we discuss the fundamentals of image creation and display, color theory, image processing, and image animation. Because image processing has its roots in space exploration and aerial photography, most of the examples we use will be from those domains. Space exploration also brings us to more general astronomical data and the concept of imaging in nonvisible wavelengths such as infrared, ultraviolet, X-rays, gamma rays, and radio waves. This chapter also forms the foundation for later chapters on imaging of numerical data, terrain rendering, and volume visualization. In this context the reader will find the material on color theory, image display, and image manipulation (image processing) to be generally useful in later chapters.

We need to establish a few basic terms for those readers who are only marginally familiar with imaging technology. These terms are also defined later in the chapter in the context of specific technologies and applications, but it's best to have a common working vocabulary at the outset.

Image processing refers to the manipulation of a digital image in order to extract more information than is apparent from an initial visual inspection. A *digital image* is composed of a matrix of numbers, each of which represents a particular color. Each of the numbers is called a "*pixel*," which is a contraction of "picture element." The *resolution* of an image is generally considered to be the number of pixels in each direction or, equivalently, the dimensions of the image matrix. Each pixel can represent one of a number of colors or gradations of gray. This is essentially the dynamic range of the pixel and is generally expressed in terms of the number of *bit-planes* (or simply bits of color). Thus, for example, a pixel with $2^8 = 256$ gray levels would have 8 bit-planes of gray-scale information. Alternatively, a color image might have 8 bit-planes for each of the three red, green, and blue (RGB) color *channels* represented by the electron guns in the computer's monitor. A detailed discussion of color is provided in **Tech Note 1**.

Imaging: Another Dividend from Space Exploration

The power of an image far exceeds that of the printed word or, for that matter, the matrix of numbers that compose the data set from which the image is generated. Nowhere has this been more apparent than in the public response to images taken by the robot spacecraft Viking and Voyager in the decade beginning in 1976. In fact, much of modern image processing technology comes directly from research in space exploration in the 1960s and 1970s. Thus it's fitting that our visual exploration of natural phenomena begins with the planets. One of the most awe-inspiring pictures ever produced was taken nearly 15 years ago by a robot spacecraft that was roughly half a billion miles from Earth. The image wasn't taken with film, but with a video camera. The spacecraft was Voyager 1 and, on February 13, 1979, when the spacecraft was about 20 million kilometers from Jupiter, the imaging system took the picture of Jupiter and two of its inner satellites, Io and Europa, shown in Figure 1.1a.

There are many remarkable things about this image: the accuracy of the spacecraft trajectory, the pointing accuracy of the camera, the stability of the spacecraft, the transmission of the data from Jupiter, the sensitivity of the receiving antenna on Earth, and so forth. However, for our purpose the imaging system itself is worth a close look. Since we use a number of Voyager and Viking images as examples throughout the book, it is valuable to understand something of the end-to-end process of the production of these images.

The video cameras on board the two Voyager spacecraft were fairly primitive by today's standards, but they did a job that no other camera has ever come close to. There are two cameras on each spacecraft, a wide-angle (200 millimeter focal length and field-of-view of about 3 degrees) and a narrow-angle (1500 mm focal length and field-of-view of 0.4 degrees) camera. Each Voyager camera's vidicon tube has a resolution of 800 × 800 pixels × 8 bits per pixel. The resolution of each optical system is roughly 10 microradians per pixel for the narrow-angle camera and 70 μrad per pixel on the wide-angle camera. This means that, at 100,000 km range, the camera can distinguish objects larger than about 1 km. The 10 μrad per pixel is the same resolution as the single camera on the much more recent Galileo spacecraft. To give you an idea of the actual structure of a pixel, we'll blow up a piece of Jupiter's volcanic moon

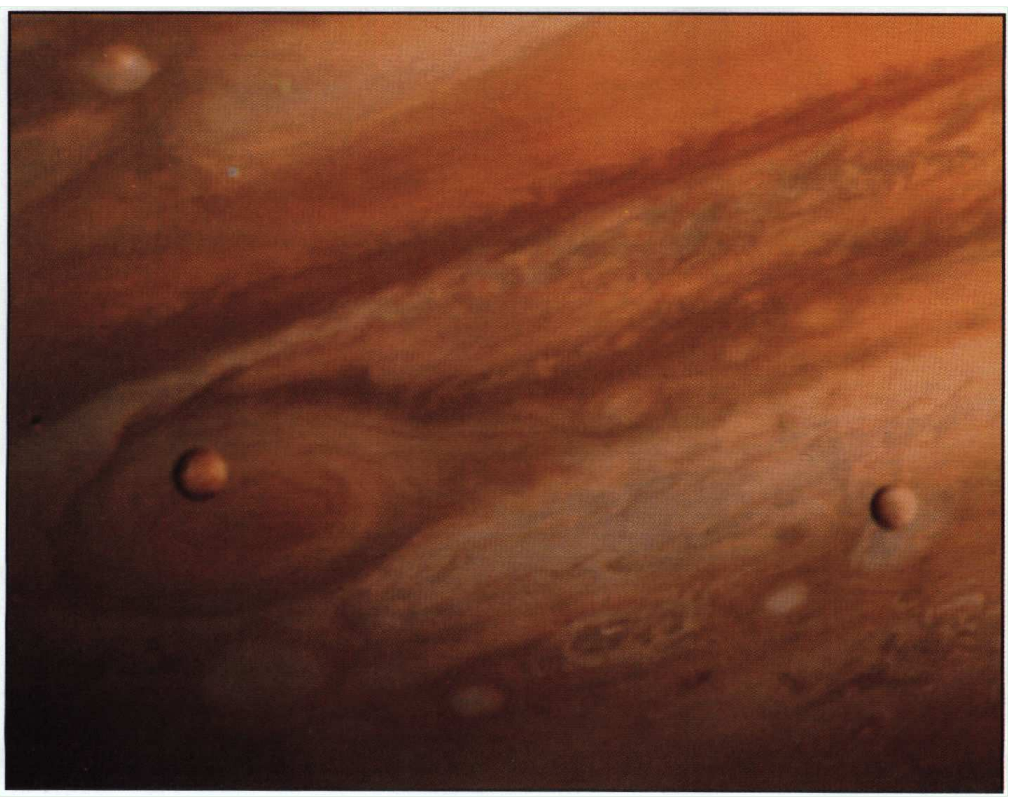


Figure 1.1a

Figure 1.1a
Voyager 1 image of Jupiter and two inner Galilean satellites, Io and Europa, taken on February 13, 1979. (Courtesy NASA/JPL)

Io (Figure 1.1b). Notice that a pixel here is simply a single gray square, and that there is absolutely no structure to it; usually there is no information about an image at resolutions below 1 pixel.

CD 1.1

The cameras are attached to selenium-sulfur black-and-white vidicon television tubes—quite primitive compared to your home video-camera but nevertheless very impressive at a range of 500 million miles from Earth. Brightness levels are recorded at each element of the vidicon to an accuracy of 8 bits (1 part in 256), and that data was either stored on the spacecraft's tape recorder or transmitted directly to Earth, depending upon where the spacecraft was relative to Earth and Jupiter and what else the spacecraft was doing at the time. Color images were achieved by combining data from different images taken successively through different colored filters and then geometrically correcting the images on the ground for the motion of the spacecraft during the time that the images were taken.

Each Voyager image has a resolution of 800 by 800 pixels for a total of 640,000 pixels. Each pixel consists of 8 bits (1 byte) per image

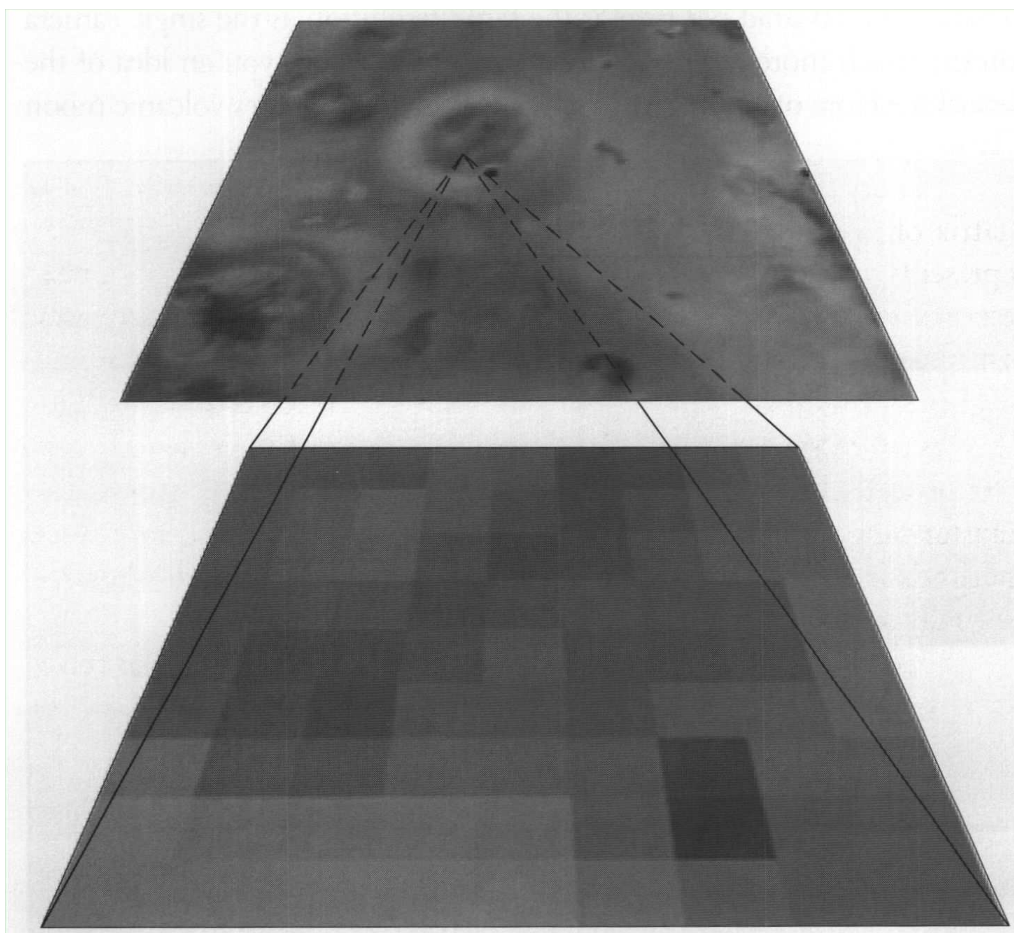


Figure 1.1b

Figure 1.1b
Magnification of a gray-scale image of Io to the pixel level, showing how an image is composed from individual pixels. The circle in the center of the image is the volcano Pele.

for a combined total of nearly 2 megabytes for each color image (three 8-bit channels) taken. Images taken by Voyager must either be transmitted directly to Earth or stored on the spacecraft's magnetic tape recorder and relayed later, as the spacecraft's active memory (RAM) is a mere 8000 bits. Obvious limitations in this process are the physical characteristics of the tape recorder and the data transmission rate from the spacecraft to Earth. In Voyager's case it took about a minute to transmit an image from Jupiter to Earth during the time that Voyager was traveling through the Jovian system.

IMAGE PROCESSING BASICS

In this section we discuss some of the concepts of image processing as a scientific computing tool:

- How a digital image is constructed from individual pixels
- Why image processing is important to scientists
- Some common image processing problems
- Basic image processing filters.

In the examples that follow, all of the image processing was performed in Adobe Photoshop™. A more mathematical treatment of image processing fundamentals is given in **Tech Note 2**. Readers so inclined will find image processing Mathematica™ Notebooks on the CD in the Image Processing folder.

Every image can be viewed as simply a two-dimensional (2-D) matrix of pixels, each with a different integer numerical value which represents a specific color or gray level. Since the eye has a nonlinear response to color, and small-scale features of a given brightness are easily lost in a sea of larger, brighter features, researchers turn to color and brightness manipulations to bring out specific features of an image. This task is made easier with the simple data structure of digital images. The process then resolves to developing mathematical methods for transforming images. The set of techniques that has evolved from these methods is called *image processing*. The individual techniques are generally termed *filters*.

Different filters are designed to perform different kinds of functions, but basically most image processing techniques fall into one of two classes:

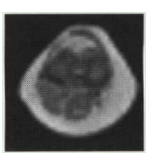
- Filters that operate on the entire set of pixels at once in an image
- Filters that operate on a small subset of an image.

Examples of the first class include simple brightness or contrast variations of an image, or functional transformations of the brightness distribution or histogram of the pixels in the image. In the second class fall such complex pixel manipulations as contouring, image sharpening or blurring, weighted averaging, and edge detection of features. These functions are discussed qualitatively later in this chapter, and the mathematical foundation of each kind of filter discussed here is detailed in **Tech Note 2**. However, first we need to get a better understanding of just why image processing is an important research tool to computational science, as well as some of the more common data analysis problems that image processing can address.

IMAGE PROCESSING AS A SCIENTIFIC TOOL

Scientific image analysis has very different requirements than, for example, artistic image manipulation. For the artist, creative control over individual pixels and collections of pixels is essential. Algorithmic manipulation of the image is of little use. In contrast, scientists need to be able to mathematically transform images from one state to another. Moreover, whereas artists usually work on a single image at a time, scientists often need to be able to apply the same set of functions repeatedly to hundreds or thousands of data sets. These distinct classes of functionality impose different requirements on an image processing system. As a result, a given commercial or public-domain image processing system cannot easily be optimized for both types of work.

In this book we're obviously concentrating on scientific computing. From that point of view we know that a scientist generally needs to perform one of two tasks with an image: (1) determine qualitatively and quantitatively the gross features of a dominant structure or phenomenon, and (2) find small-scale meaningful structures. These general requirements span the spectrum of scientific fields, from microbiology to astronomy. Given the needs of scientific image processing, the first question one needs to answer for a specific problem is whether to analyze the color or gray-scale representation of the data. Whereas it is true that intelligent use of colors can enhance specific morphological features of a given image, gray scale often provides better structural detail to the eye. This is especially true for fine details, so gray-scale mapping is often used in image analysis to pick out hard-to-discern features. Medical imaging is one area where gray-scale is used extensively, but it is used quite a bit in the studies of continuous systems, such as fluid dynamics, as well. For example, a researcher might be interested in ascertaining whether or not "artificial" numerical waves are propagating in the computational domain. A color palette designed to enhance small-scale structures, such as numerical waves, might also pick



CD 1.2

up other features, or simply produce artifacts associated with the choice of palette. Coupled with the nonlinear sensitivity of the eye, color is not necessarily the best choice for the problem. Gray-scale, which is simply related to the intensity discernible by the eye, should be much better for this task.

Many researchers in medical imaging are beginning to work with 12- and 16-bit gray-scale images, since the greater bit-depth gives a much larger dynamic range to the data represented by the image. With this dynamic range, image processing can bring out considerably finer detail than would be available with the 256 values in an 8-bit image. In the next section we'll look at a couple of examples from Earth and planetary sciences, and discuss some of the basic image processing filters that one might use to enhance small-scale and large-scale features of an image.

BASIC IMAGE PROCESSING FILTERS

Although hundreds of image processing filters have been developed over the past two decades, considerable information can be obtained from an image by the use of just a few. In particular, for the kinds of scientific problems we discussed earlier, a handful of basic filters should suffice for most applications. In this section we use some Voyager imaging data to illustrate the power of these basic tools.

As an example of the power of even simple image processing, consider Figure 1.2 where we process a Voyager image of Jupiter's Great Red Spot, first discovered by the English scientist Robert Hooke in

Figure 1.2a
Voyager 1 high-resolution image of Jupiter's Great Red Spot in natural color formed from three consecutive images. (Courtesy NASA/JPL)

Figure 1.2a

1630 and subsequently drawn by the Italian astronomer Giovanni Cassini in 1631. Figure 1.2a shows a Voyager 1 high-resolution image (that is, an image from the high-resolution camera) of the Great Red Spot with surrounding vortices (in natural color) while Figure 1.2b shows a closeup in exaggerated color—false color—as a result of manipulating the color values of the image. In this simple case, color enhancement is achieved by taking all color values in a given range and adding a number to them, thus accentuating that range from others in the image. Notice how the enhanced color brings out some of the fine structure of the atmosphere surrounding the Great Red Spot.

A gray-scale image brings out subtle differences in brightness that are often masked in a color image. In Figure 1.2c we show a gray-scale image of Figure 1.2b

A more interesting filter is contrast enhancement, wherein one simply takes all pixels with brightness levels below a certain threshold value and decreases their brightness while at the same time taking all of the other pixels and increasing their brightness. Figure 1.2d shows a contrast enhancement of Figure 1.2c. Contrast enhancement is sometimes termed "stretching" the image, since poor contrast means that all of the pixels have numerical values that fall within a narrow range.

In the pixel world one of the most useful pieces of information we can obtain is a *histogram* of the image. A histogram plots the color values of pixels in a given channel against the total number of pixels with those values in the channel. In the case where a single (gray-scale) channel is selected, the histogram gives us a distribution of

Figure 1.2b
Voyager 1 closeup image of the Great Red Spot in false color. Note how small-scale features are exaggerated compared to the natural color image in Figure 1.2a.

Figure 1.2c
A gray-scale representation is often a useful transformation to do before performing basic image processing.

Figure 1.2b

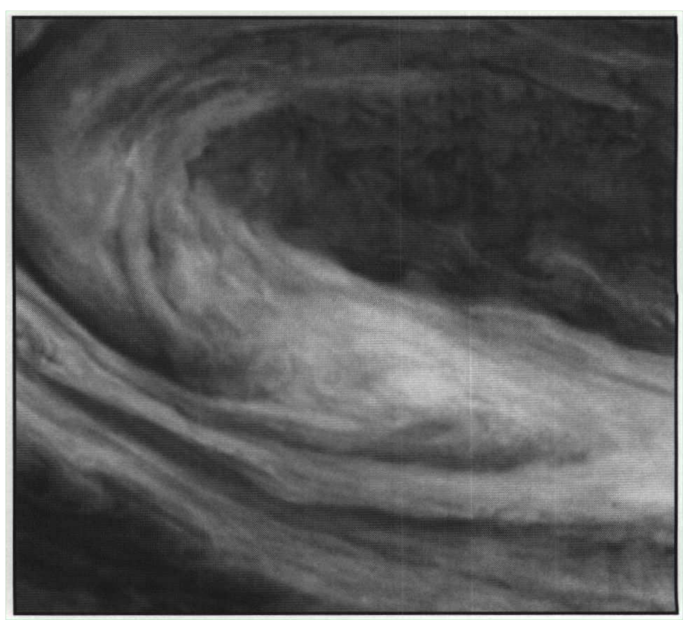


Figure 1.2c

gray-levels of the image. In terms of the histogram, increasing contrast stretches the image data out across the histogram. In the Photoshop context, 100 percent contrast yields the widest separation of grays yielding just black and white, whereas 0 percent contrast reduces all grays to a single, median gray. Functionally, most contrast enhancement functions compress all gray-level values below the threshold into a narrow range toward 0 (black) while compressing all gray-level values at or above the threshold into a narrow range toward 255 (white). The simple brightness enhancement increases or decreases the gray-level of every pixel in the image, thus shifting the entire range of grays in the histogram. Brightness filters can therefore be considered to be a subset of contrast enhancement. The histogram model shows us that contrast enhancement is basically a scalar transformation of gray-levels in an image.

We can enhance small-scale features even further by applying a simple filter, called a *histogram equalization*, to the false-color image. Histogram equalization is discussed in depth in **Tech Note 2** but, for the purpose herein, we can consider it as just a redistribution of color and intensity values of the image such that each combination of color and intensity is assigned the same number of pixels. Figure 1.2e shows a histogram equalization of Figure 1.2b.

Another powerful filter is *edge detection*. Edge detection filters look for sharp changes in color or gray-scale level in an image and blacken out the surrounding region. This tends to enhance small-scale structure of the image. In **Tech Note 2** we discuss the functional basis

Figure 1.2d
Contrast enhancement of Figure 1.2c. Notice the increased sharpness of small-scale features.

Figure 1.2e
Histogram equalization of Figure 1.2b.

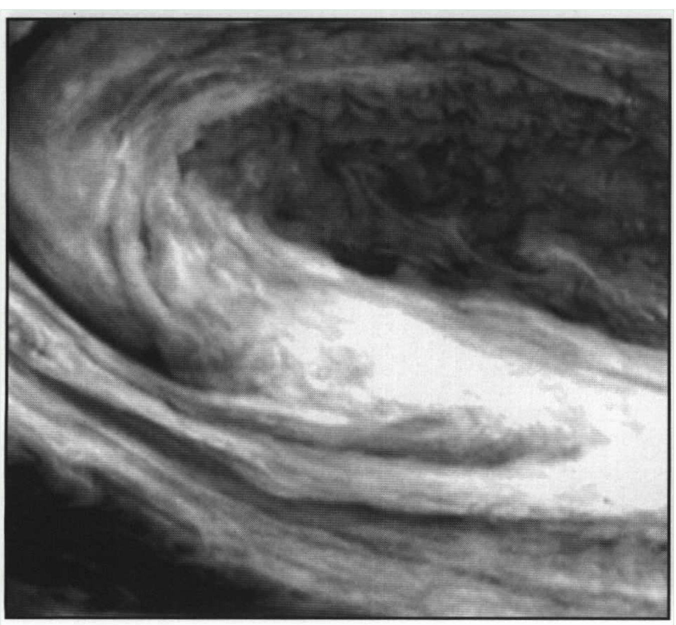


Figure 1.2d

Figure 1.2e

for edge detection. In Figure 1.2f we've applied an edge detection filter to the image to observe small-scale turbulent flow structure within the Great Red Spot.

The image processing filters discussed above can be used to "make visible the invisible," so to speak, and Voyager 1's journey to Jupiter provides excellent examples to illustrate this point. In particular, we consider the discovery of Jupiter's ring (Figure 1.3), a planned-for observation of an object that had never been seen, and the discovery of volcanic activity on Io, when the imaging system was being used not for scientific observations, but for optical navigation of the spacecraft (Figure 1.4). In the case of Jupiter's ring, the observation to search for the ring was planned for based on theoretical models of existing ring systems around Saturn and Uranus. However, in the case of Io, the discovery of active volcanism was unexpected and unplanned for. In both cases, a lot of image processing was required to determine the validity as well as the precise nature of the observations. To give you a feel for both the sensitivity of Voyager's cameras and the difficulty of observing Jupiter's ring, consider that Jupiter's ring is roughly ten thousand times more transparent than the best glass made.

Figure 1.2f
Edge detection filter applied to Figure 1.2d to bring out some of the small-scale structure of the image. Part of what we're seeing, however, is likely due to artifacts of the edge detection algorithm applied to a highly contrasted image.

Figure 1.3
This image from Voyager 1 shows, for the first time, a faint ring encircling Jupiter (thick gray line in center of image). The faint lines parallel to the ring are star tracks, and the regular array of dark dots are calibration marks on the image known as reseau marks.

MORE EXAMPLES

In this section we apply a variety of filters of the types discussed above to a couple of images. Since there is no better teacher than example, this exercise is intended to give the reader a feel for several

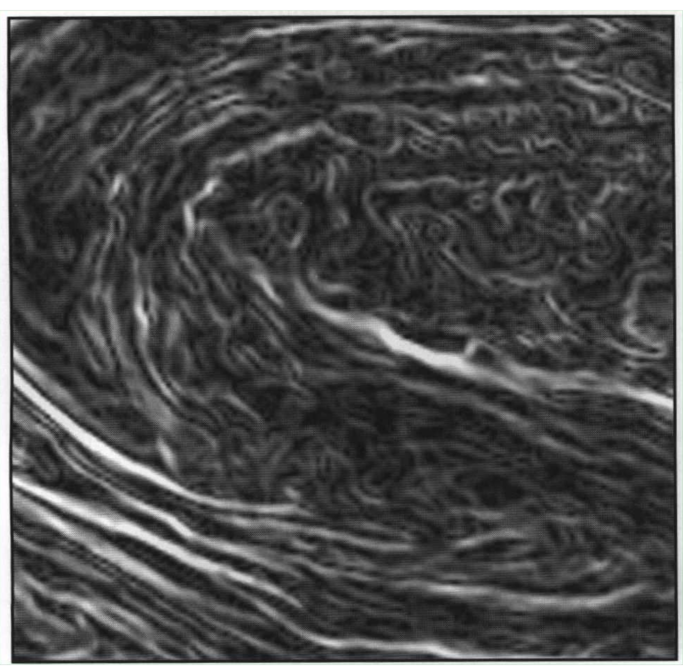


Figure 1.2f

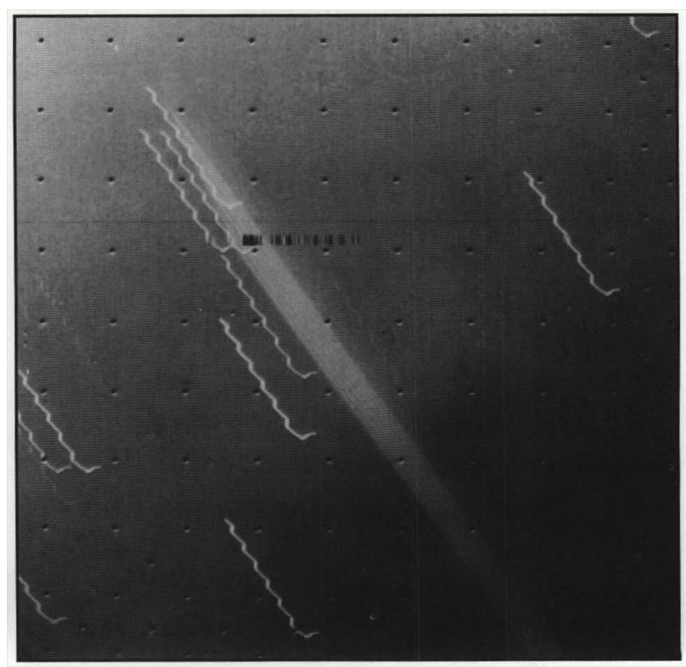


Figure 1.3

kinds of filters. One of the most dramatic examples of the success of image processing as a research tool is a Voyager 2 image of Saturn's rings taken from a range of about 3 million kilometers (Figure 1.5). The theory was that, although Saturn's rings are composed mostly of water ice, differences in color across the rings might be able to be used to determine the presence of possible trace constituents of other materials. These color differences are too small to show up in an ordinary image, but they can be brought out by special processing of the image. In Figure 1.5 the image of Saturn's B and C rings was made from three pictures taken through separate green, blue, and ultraviolet filters by Voyager and then combined to form a single false-color image later during processing at the Jet Propulsion Laboratory (JPL).

In Figure 1.6a we show the full disk of Io in natural color as imaged by Voyager on March 5, 1979. Io is the most volcanically active object in the solar system, and its color (largely due to sulfurous deposits on the surface) and pockmarked surface are principally due to ongoing volcanic activity. In Figures 1.6b, c, and d the composite image is broken down into component red, green, and blue bands, respectively. Each band has a resolution of 8 bits. In addition to getting a better feel for the color composition of the image, it's much easier to work with an individual band when performing most image processing operations. In Figure 1.6e we apply a weighted average filter to the red band. The filter sharpens the image considerably and, if we look at the region encircled in red, allows us to see a lot more structure than was apparent in the

Figure 1.4
This image taken by Voyager 1 as it flew by Jupiter, showed the first evidence of extraterrestrial active volcanism. The umbrella-shaped plume is volcanic gas and dust spewed outward by the volcano, named Pele, after the Hawaiian god of volcanism.
(Courtesy NASA/JPL)

Figure 1.5
Voyager 2 image of Saturn's B and C rings taken from about 3 million kilometers. Images from the green, blue, and UV filters were combined to produce this false color image. Notice how the fine structure of the rings stands out.
(Courtesy NASA/JPL)

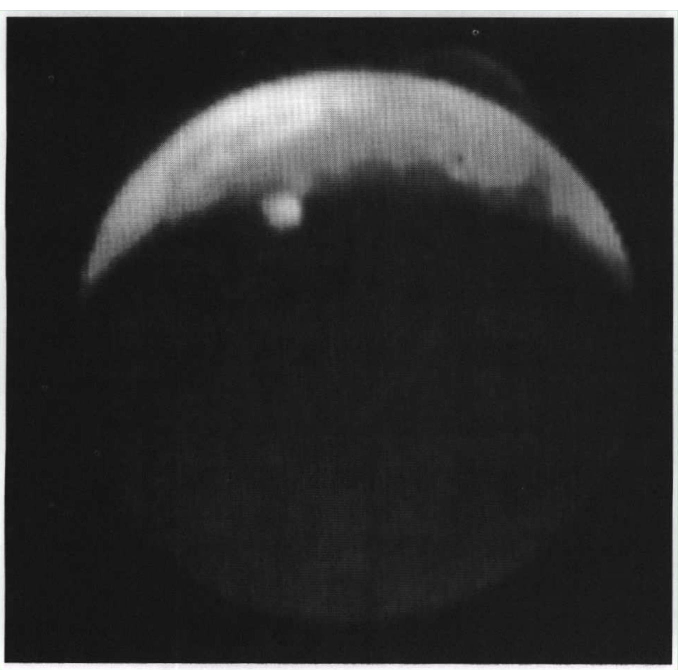


Figure 1.4

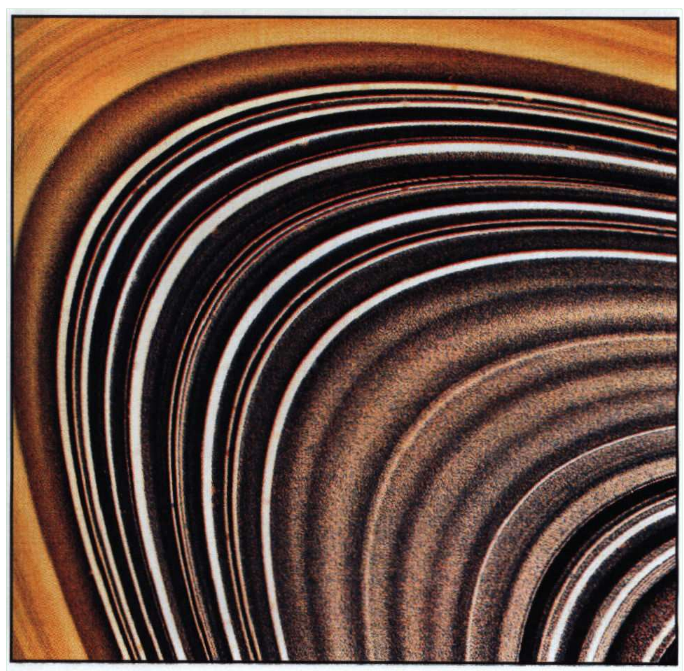


Figure 1.5

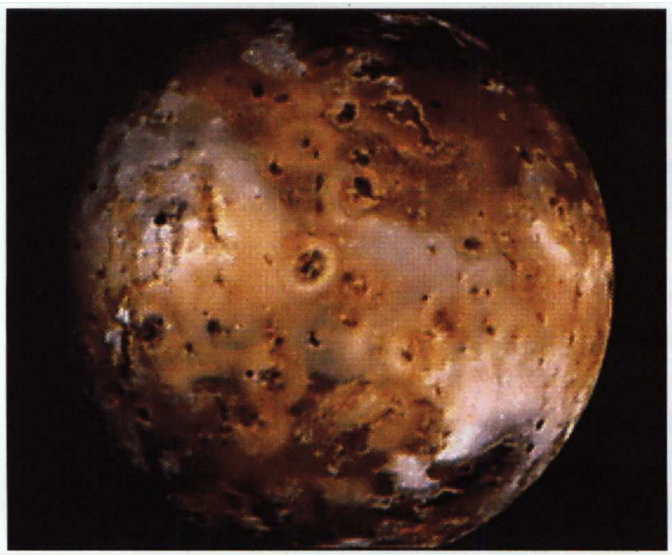


Figure 1.6a

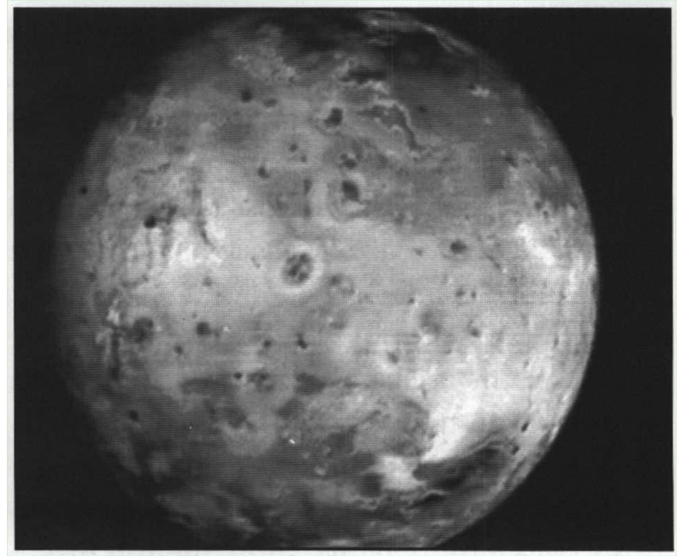


Figure 1.6b

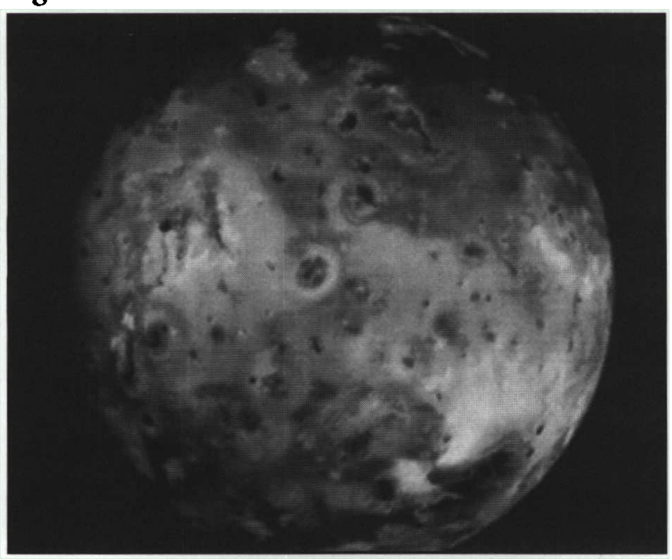


Figure 1.6c

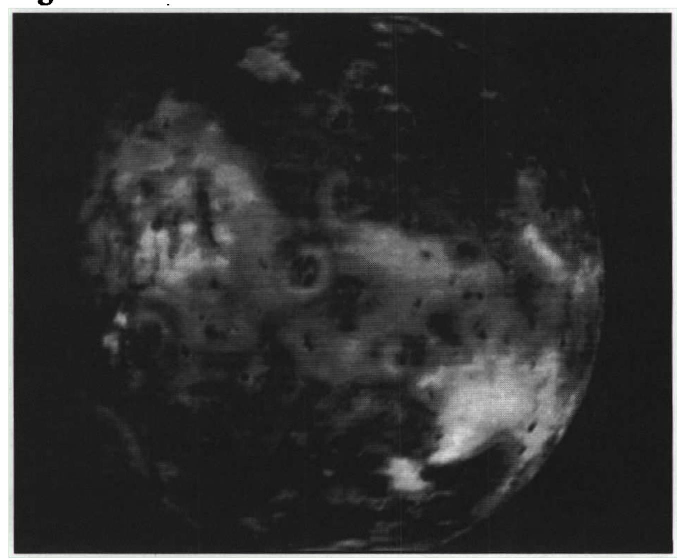


Figure 1.6d

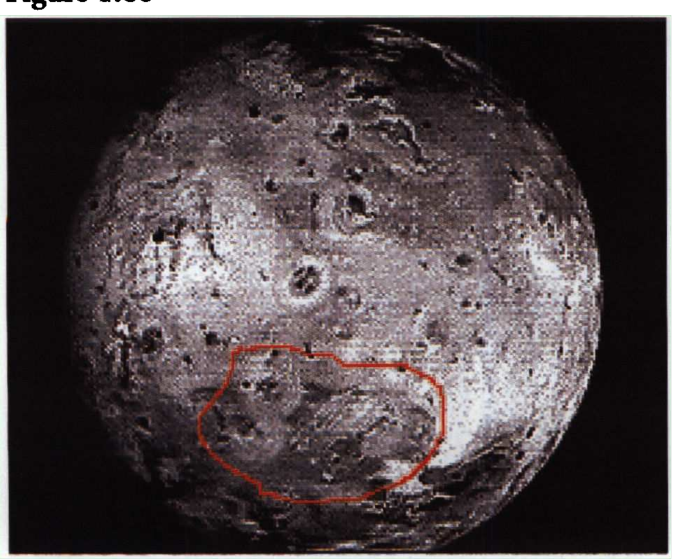


Figure 1.6e

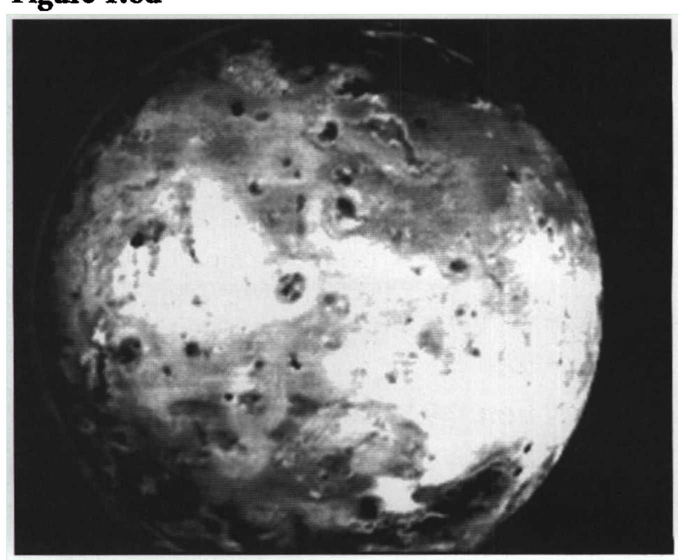


Figure 1.6f

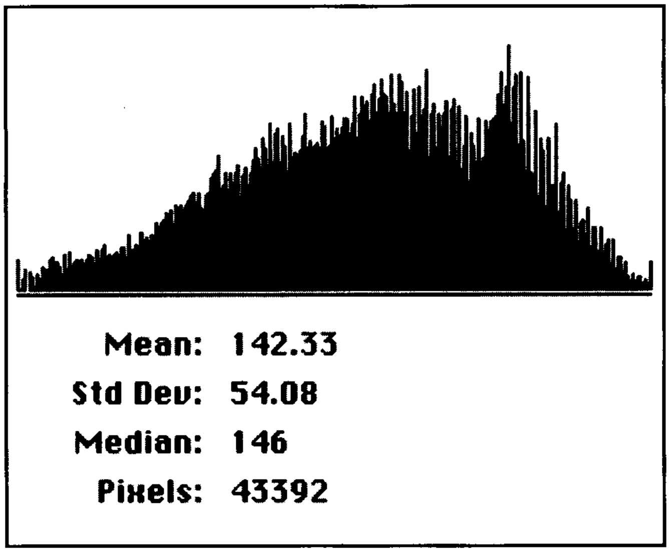


Figure 1.6g

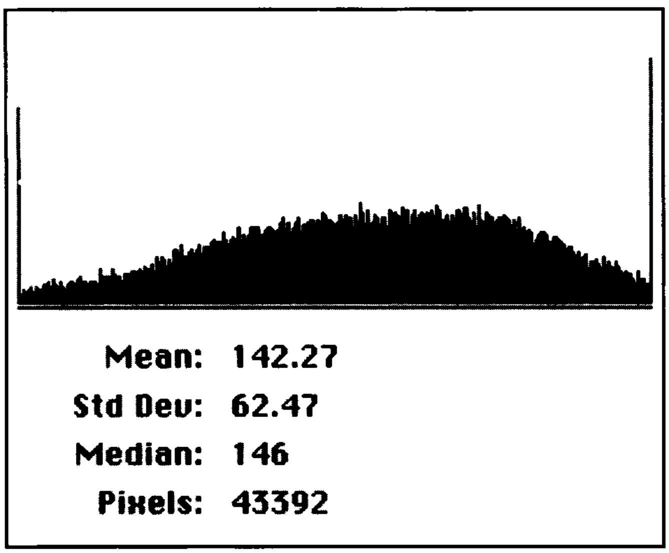


Figure 1.6h

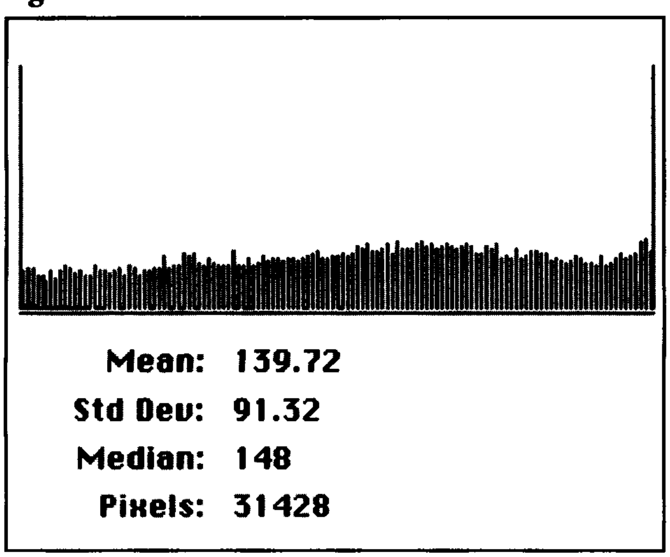


Figure 1.6i

Figure 1.6a
This image of Io taken by Voyager 1 on March 5, 1979 shows clear evidence of volcanic activity through extensive mottling and erosion of the satellite's surface, confirming a prediction made by planetary geologist Stanton Peale. (Courtesy NASA/JPL)

Figure 1.6b
"Red" channel from Figure 1.6a.

Figure 1.6c
"Green" channel from Figure 1.6a.

Figure 1.6d
"Blue" channel from Figure 1.6a.

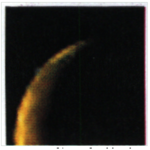
Figure 1.6e
A weighted average filter applied to Figure 1.6b. Note the sharpness of the structures visible in the red-circled region compared to the same region in Figures 1.6a and b.

Figure 1.6f
Contrast enhancement to Figure 1.6b. Although it makes the bright regions brighter, we see no additional structure beyond the previous enhancements.

Figure 1.6g
Histogram of Figure 1.6b. Note the median of the distribution at 146, with a fairly wide standard deviation.

Figure 1.6h
By applying a weighted average we can spread out the pixel distribution, as in this histogram of our test image.

Figure 1.6i
This histogram of the contrast-enhanced image (Figure 1.6f) shows how the number of pixels per gray level is spread out fairly evenly over the range of gray-scale values.



CD 1.3

original image. Finally, in Figure 1.6f we apply a contrast enhancement to the red-filtered image. Although the contrast enhancement makes the bright areas brighter by stretching out the distribution of pixels among the available 256 gray-scale values, in this case it does not provide us with any better detail of the image. That's because the weighted average filter has already brought out the interesting features in the image.

Figures 1.6g, h, and i show the histograms of pixels among the gray-scale values for Figures 1.6d, e, and f, respectively. The horizontal axis of the histogram is the gray level and the vertical axis is the number of pixels. The "mean" is the average brightness value, while the "standard deviation" and "median" are the usual definitions, and "pixels" signifies the total number of pixels in the image.

We should note, for those who want to try these exercises at home, that all processing in these examples was done in Adobe Photoshop 2.0 with a 16 MB RAM partition running on a Mac IIfx with 32 MB RAM, under System 7.0.1. The memory partition only affects the speed of the computation since, if the partition is large enough, all of the image can be loaded into memory at once. Otherwise the data must be continuously read in from disk. The other problem with Photoshop is that it creates a "virtual memory" space on the hard disk, and for large size images this could take quite a while. The virtual memory is equal to the size of the image you are opening.

Figure 1.7a
A Voyager 1 single-filter image of Saturn's ring system. Note the gross structure of a few large rings, although there appears to be a hint of some smaller scale structure. (Courtesy NASA/JPL)

Figure 1.7b
Contrast enhancement of Figure 1.7a. Radial structures (the "spokes" of Saturn's rings) appear in the center of the ring system. These structures were not visible to the unaided eye in Figure 1.7a.

Figure 1.7a

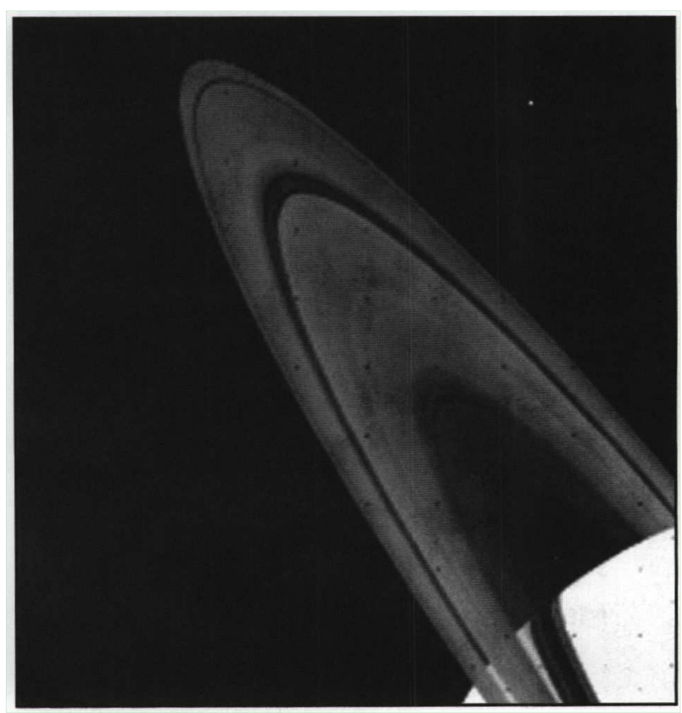


Figure 1.7b

If there is not enough contiguous space, the image opens extremely slow. The raw image data for each of these examples is provided in the CD in the "Image Processing" folder. Each particular computation that we performed here took about 5 to 10 seconds to process in this environment. However, the processing time depends strongly on a variety of factors such as the size of the image in pixels and the complexity of the algorithm.

Simple contrast enhancement and sharpening filters can be powerful techniques, as we illustrate in Figure 1.7 using a Voyager 1 single-channel image of Saturn's ring system. Figure 1.7a shows the original image, while 1.7b shows the image with a fair amount of contrast enhancement. In the original image Saturn's rings appear to be five or six fairly homogeneous structures. However, upon applying the contrast enhancement filter we can see considerably finer structure in the rings. Notice also that just inside of the dark band (the Cassini division) there appears to be a hint of radial structure in the form of dark streaks. These were identified by planetary scientists as "spokes" and appear to be dark dust electrostatically elevated above the ring plane and partially coupled to Saturn's magnetic field. In Figure 1.7c we apply a *sharpening* filter to the contrast-enhanced image in Figure 1.7b. This is another type of filter that enhances small-scale features in an image. The first thing we notice is that the ring system is made up of literally hundreds of smaller rings (as Figure 1.5 showed in detail). In addition, the spokes become a

Figure 1.7c
A sharpening filter applied to Figure 1.7b really brings out the small scale structure of the rings as well as the spokes.

Figure 1.7d
Another contrast enhancement clearly shows the two inner ringlets, which otherwise would only be faintly visible.
(Courtesy NASA/JPL)

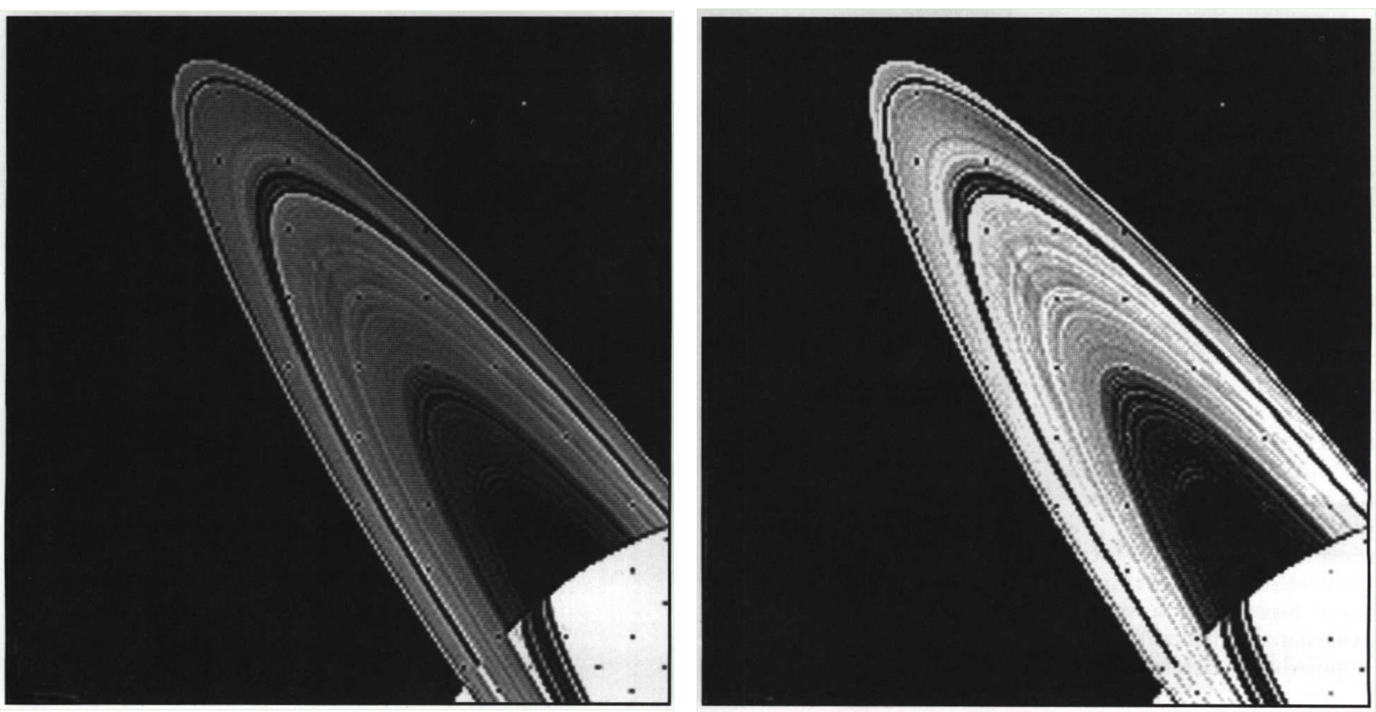


Figure 1.7c **Figure 1.7d**

bit more visible under this filter and are clearly identified as radial features. We also see some faint ring structure at the very inner edge of the ring system. Another contrast enhancement (Figure 1.7d) enables us to clearly see two thin rings at the inner edge of the ring system.

IMAGE ANIMATION

For a long time films or videos of sequences of images were considered an extravagant luxury for researchers or, at best, a tool that management and public information folks could use for public lectures and program reviews. Exceptions to this were projects like E.E. "Doc" Edgerton's work at MIT on high-speed photography; satellite-based meteorological data; and fluoroscopy for seeing a patient's gastrointestinal tract at work. But these were specialized technological approaches toward specific scientific or medical problems, and the techniques were not easily generalizable to other content areas.

However, partially as a result of Voyager's observations over the past 15 years, the attitude toward animation has changed considerably. Part of this prejudice had to do with cost: until 1990 or so it was just too expensive to create films or videotapes of large numbers of images as a regular course of research. However, today it is fairly easy for researchers and teachers to create videos of sequences of images, and since videos are a basic medium of exchange of time-dependent, visual

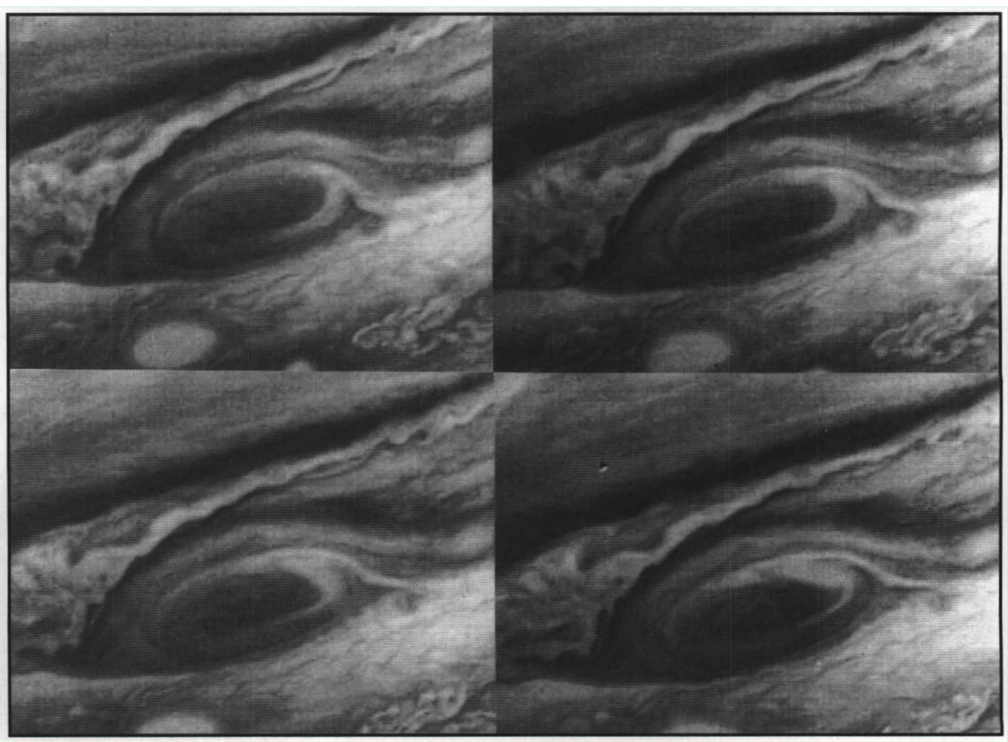
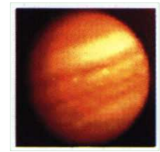


Figure 1.8

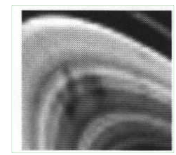
Figure 1.8
This sequence of four images taken by Voyager 1 illustrates the importance of studying the time-dependence of systems. Note the movement of the small vortex in the lower right-hand edge of the red spot. By measuring the distance that this vortex has moved over the course of the four rotations, researchers can obtain local wind-velocity information about Jupiter which would otherwise be difficult to impossible to determine. (Courtesy NASA/JPL)

information, more and more scientists are using animations as a regular part of their work. As a result, it is now widely accepted that sequences of images of phenomena in any field can clearly be of value when one is interested in time-dependent as well as spatially varying problems.

In Figure 1.8 we show a sequence of images of Jupiter's Great Red Spot that clearly shows the dynamics of the atmosphere in that region. These images were taken by Voyager 1 on its approach to Jupiter approximately 10 hours (one Jovian rotation period) apart. They were the first direct observations of dynamics in Jupiter's atmosphere, and gave researchers an opportunity to study the large-scale structure and dynamics of a planetary atmosphere other than our own. This knowledge has enabled meteorologists to gain a much broader perspective on our own weather systems here on Earth. Figure 1.9 shows the same observational technique applied to Saturn's rings; as a direct result of these images, planetary scientists found that the mysterious radial spokes were partially coupled to the rate of rotation of



CD 1.4



CD 1.5

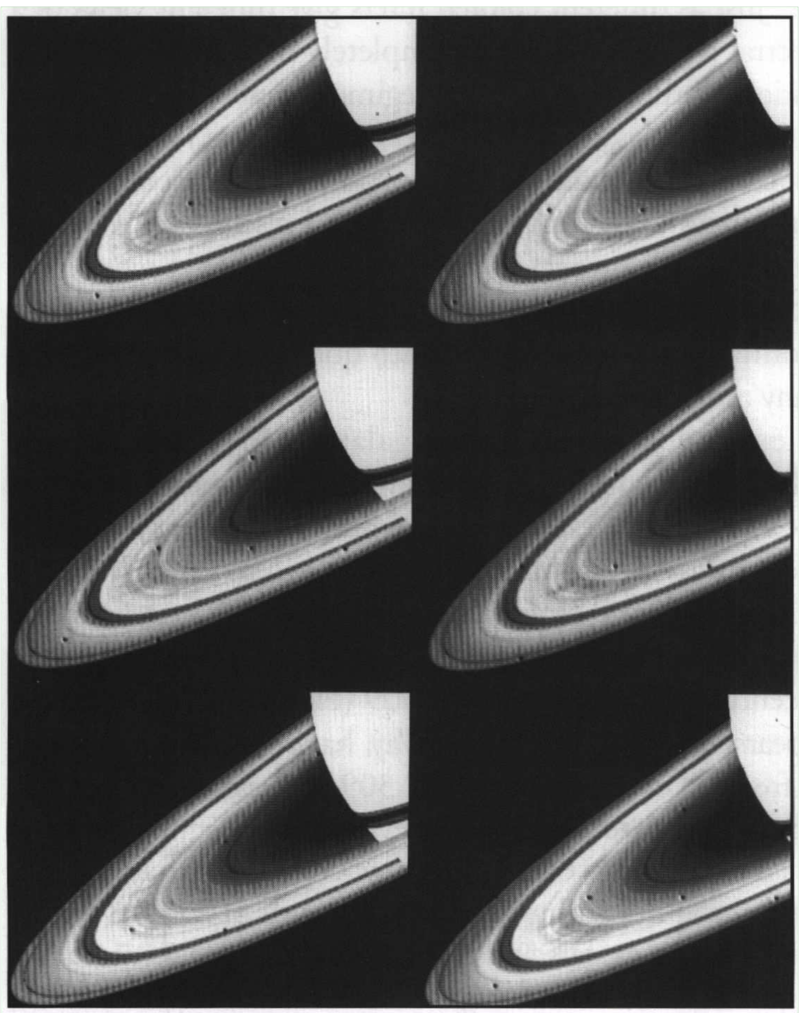


Figure 1.9

Figure 1.9
A sequence of images of Saturn's rings taken by Voyager 1 enabled researchers to determine that the spokes in the rings were tied to the rotation period of Saturn's magnetic field, rather than to the much more slowly rotating rings themselves. (Courtesy NASA/JPL)

Saturn's magnetic field. This was an unexpected result, leading researchers to consider the broader aspects of electromagnetic forces in the evolution of planetary systems.

In both of these cases, the knowledge gleaned by simply taking a time-dependent data set rather than a single image has changed our knowledge of those systems forever. In Chapter 2 we discuss the process of image animation in some detail from the perspectives of producing videotapes as well as creating sequences of digital images to be viewed on a personal computer.

Beyond Visible Images

Another variable in the imaging world is wavelength. So far we have been discussing images taken primarily in visible light. But what if we branched out from the visible spectrum and looked at wavelengths in the infrared, ultraviolet, X-ray, and radio regions of the electromagnetic spectrum? Just as different colored filters give different views of a scene, each spectral region provides a completely new window on the world. In addition, within each spectral regime different observational techniques and technologies are needed to obtain the data, and different analysis and visualization techniques are required to understand the data. Recent advances in detectors have enabled researchers in many fields to gain insight into processes and phenomena that were once hidden. Moreover, different spectral images of an object often produce such radically different results as to put into question how we classify and analyze many astronomical objects.

As an example, consider the galaxy M31, the famous Andromeda galaxy. In Figure 1.10a we show an image, taken in visible light, from the 200-inch telescope at Palomar Observatory, while in Figure 1.10b we show M31 as imaged in the infrared by IRAS (Infrared Astronomy Satellite) in 1979. Note the distinct difference in structure of the galaxy in the two wavelength bands. A more dramatic example is an image taken recently of the galaxy NGC 309 (Figure 1.10c), which in visible light appears similar to the Milky Way, having three bright arms that spiral out from a central disk. NGC 309 is classified as a classic spiral galaxy. Standard theories of stellar evolution maintain that the luminous arms are the regions of the galaxy where starbirth takes place. However, viewed in the near-infrared at a wavelength of 2.1 μm one of the galaxy's three arms disappears and the central disk appears more like an ellipsoid (Figure 1.10d). This image indicates that the galaxy could belong to an entirely different class of objects, the barred spirals, which differ significantly from classic spiral galaxies in a number of aspects. Whereas the visible image of NGC 309 suggests that the luminous arms are the likely regions of star formation, the infrared image indicates that the central ellipsoid is the principal region of starbirth.

Figure 1.10a

Figure 1.10a
The Andromeda galaxy as photographed in visible light by the 200 inch Mount Palomar telescope. (Courtesy California Institute of Technology)

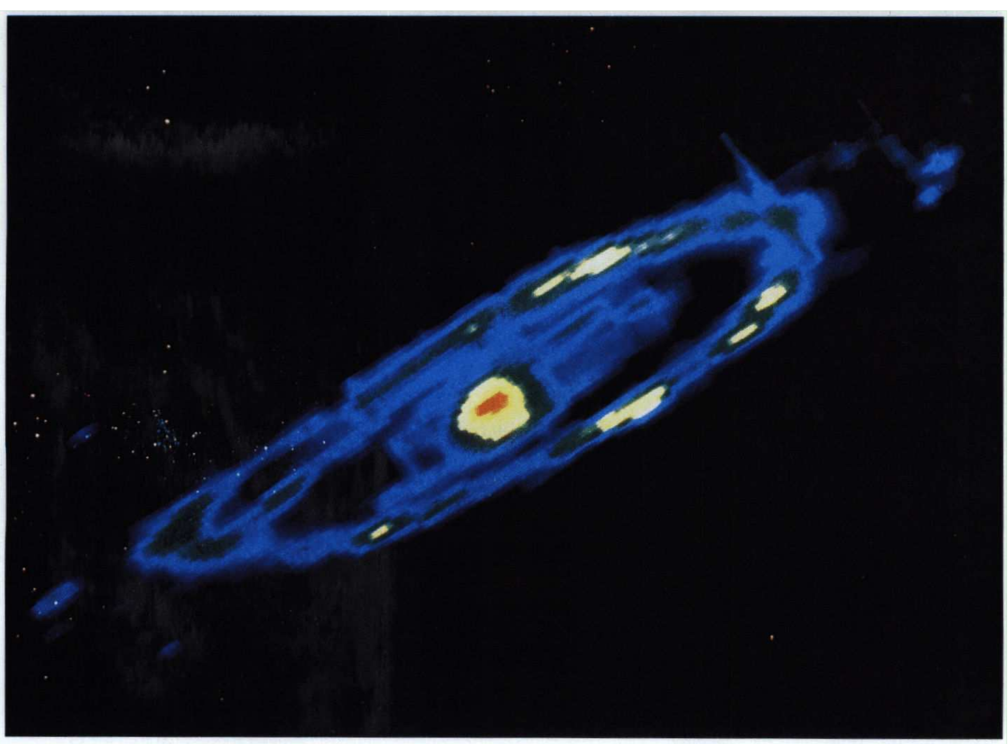


Figure 1.10b

Figure 1.10b
The Andromeda galaxy as viewed in the infrared by the IRAS satellite in 1979. (Courtesy NASA/JPL)

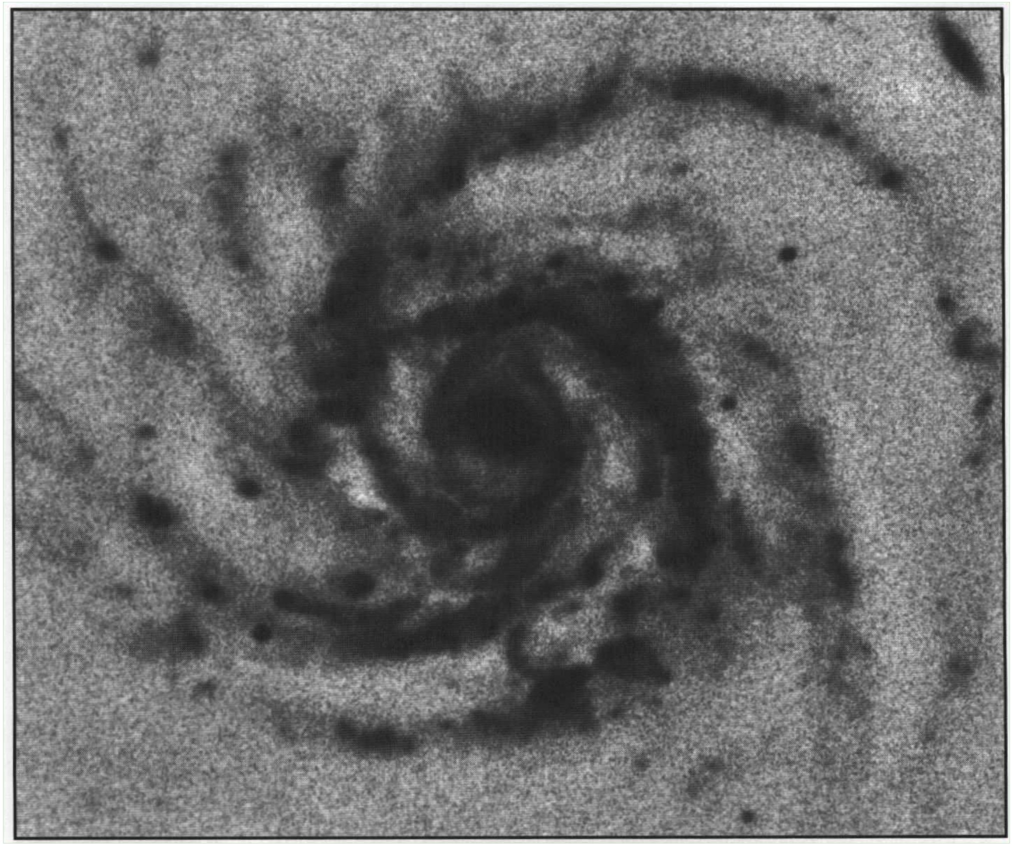


Figure 1.10c

Figure 1.10c
In visible light, NGC 309 appears to be a classic spiral galaxy with several arms. (Courtesy David L. Block, Richard J. Wainscoat, and T. Kinman)

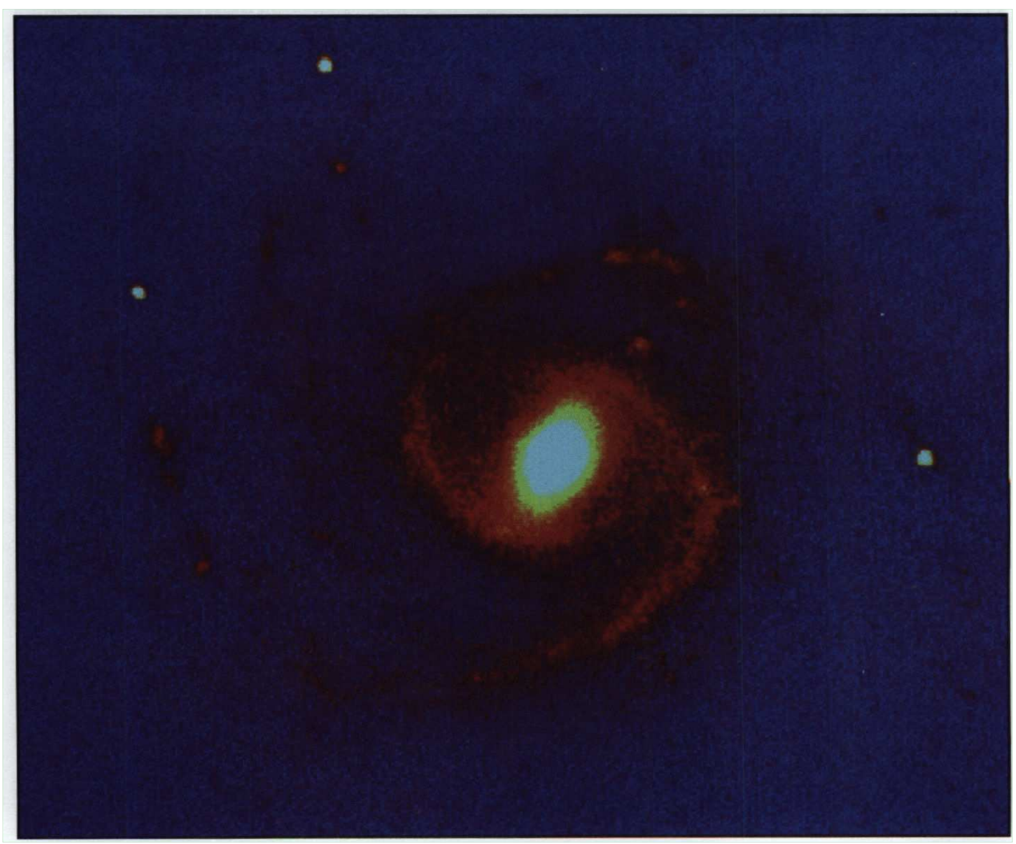


Figure 1.10d

Figure 1.10d
This image of NGC 309, taken in the infrared and shown here in color, indicates an entirely different type of galaxy than is seen in visible light, and calls into question the very process that is used to classify the structure and evolution of galaxies. (Courtesy David L. Block, Richard J. Wainscoat)