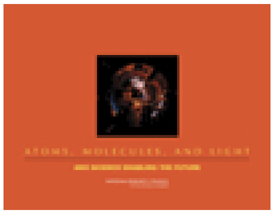
Atoms, Molecules, and Light: AMO Science Enabling the Future

Committee for an Updated Assessment of Atomic, Molecular, and Optical Science, National Research Council



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THE NATIONAL ACADEMIES
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ATOMS, MOLECULES, AND LIGHT

AMO SCIENCE ENABLING THE FUTURE

COMMITTEE FOR AN UPDATED ASSESSMENT OF ATOMIC, MOLECULAR, AND OPTICAL SCIENCE
BOARD ON PHYSICS AND ASTRONOMY
DIVISION ON ENGINEERING AND PHYSICAL SCIENCES
NATIONAL RESEARCH COUNCIL
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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This project was supported by the National Science Foundation under Grant PHY 98-12262 and the Department of Energy under Contract No. DE-FG02-94ER-14451.

Cover: NIST physicist Kris Helmerson looks at a cloud of laser-cooled sodium atoms (the small, bright yellow dot at the center of the photo) that have been trapped by a combination of laser beams and magnetic fields. The atoms, levitated in a vacuum by this magneto-optical trap, have a temperature less than a thousandth of a degree above absolute zero, yet they remain in the gas phase.

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Preface

With the publication in 1994 of *Atomic, Molecular, and Optical Science: An Investment in the Future* (the FAMOS report), the National Research Council launched the series *Physics in a New Era,* its latest survey of physics. Each of the six area volumes in the survey focuses on a different subfield of physics, describing advances since the last decadal survey and suggesting future opportunities and directions. This survey culminated in 2001 with the publication of the seventh and final volume, *Physics in a New Era: An Overview.*

Since the publication of the FAMOS report, the developments in atomic, molecular, and optical (AMO) science have been amazing. Significant advances in areas such as cooling and trapping, atom and quantum optics, single-atom and single-molecule detection, and ultrafast and ultraintense phenomena, along with the emergence of new applications, made it clear that an update of the FAMOS report was needed. With support from the National Science Foundation and the Department of Energy, the Committee for an Updated Assessment of Atomic, Molecular, and Optical Science was formed. The committee's statement of task reads as follows:

> The committee will prepare a narrative document that portrays the advances in AMO science and its impact on society. The report will:
>
> - Highlight selected forefront areas of AMO science, emphasizing recent accomplishments and new opportunities.
> - Identify connections between AMO science and other scientific fields, emerging technologies, and national needs.
> - Describe career opportunities for AMO scientists.

To accomplish its task and at the same time reach a broad audience, the committee decided to present its report in the form of a brochure highlighting selected advances, connections, and impacts on national needs. An exhaustive assessment of the field, which will fall within the purview of the next decadal survey, was not the goal of the update.

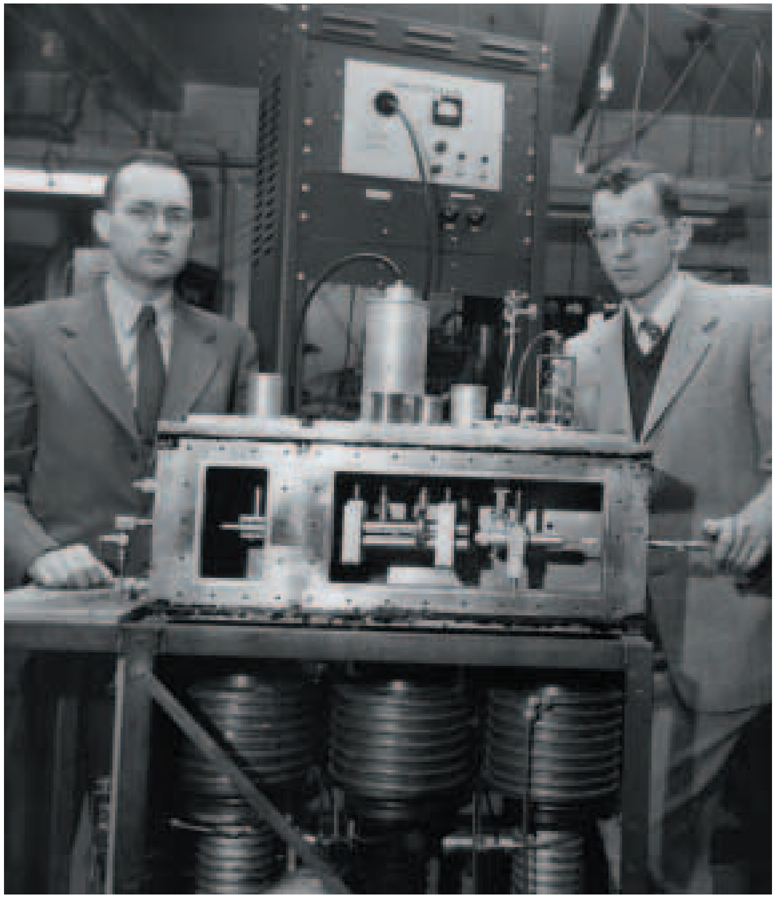
The committee would like to express its gratitude for the informative interactions it had with many scientists and policy makers. Many colleagues completed a questionnaire and suggested topics to be included in this report. The final selection of topics was made in accordance with the criteria set forth in the statement of task.

While this report was still being written, the tragic events of September 11, 2001, occurred. AMO science and its applications have already played and will continue to play a central role in our nation's response to terrorist threats from conventional as well as chemical or biological weapons. Some of the technology discussed in this report in the chapter "AMO Science Enhancing National Defense" was used successfully for the U.S. military response in Afghanistan—the Global Positioning System (GPS) and laser-guided munitions are just two examples. AMO science will also enable the development of early detection techniques that will help to neutralize the threat from biological and chemical agents.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Thomas Appelquist, Yale University; William Bialek, Princeton University; Ronald Cohen, University of California, Berkeley; Thomas Gallagher, University of Virginia; John Goldsmith, Sandia National Laboratories; Erich Ippen, Massachusetts Institute of Technology; Neal Lane, Rice University; Cherry Ann Murray, Lucent Technologies; and Richard Powell, University of Arizona.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lloyd Armstrong, University of Southern California. Appointed by the National Research Council, he was responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents



Townes and Gordon with one of their first masers (1954).

A CO_2-laser-based automobile body welding station (2001).

Introduction

AMO science—the study of atoms, molecules, and light, and the discovery of related applications and techniques—has yielded a bumper crop of innovations that have had a significant impact in many spheres:

- **the growth, vitality, and transformation of our economy**
- **our ability to provide ever-improving health care**
- **our understanding and control of the environment**
- **our national security and homeland defense capabilities**

AMO science does more than prime the pump from which our society's material wealth flows. In addition to providing the basis for new technology, it also is a source of the intellectual capital on which science and technology depend for growth and development.

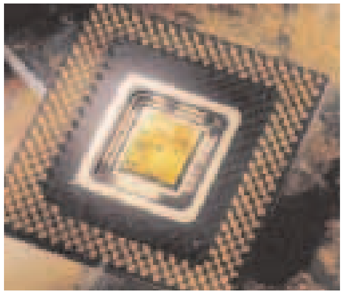
AMO activities in our universities have been key to training many of our best scientists, engineers, and technical professionals, who will continue to impact all parts of our technology-based society. The benefits of having created this intellectual and human resource capital that we value so much flow from investments made many years ago.

AMO science continues to be a frontier science that is attracting the best minds worldwide, and stunning discoveries are being reported at an ever-increasing pace. If the past pace of innovations based on discoveries and inventions made by AMO is any guide, the nation will continue to benefit handsomely through the many revolutionary applications resulting from present investments.

Alan Greenspan, chairman of the Federal Reserve Board, has observed, "New technologies that evolved from the cumulative innovations of the past half-century have now begun to bring about dramatic changes in the way goods and services are produced . . . ." At roughly $100 million per year, total federal investment in AMO research is incredibly profitable. The increasingly interconnected nature of the scientific enterprise makes an investment in a field such as AMO, with its strong enabling component, all the more valuable. Discoveries and applications from AMO science can leverage investments in other areas of physics and science as well as engineering and medicine. This is a two-way street, however, for

AMO science benefits from discovery and application in other fields as well. The investments in scientific research have led to applications that reach far beyond science per se into the diverse worlds of optical communication, manufacturing, health care, energy, and national security.

Consider the continued impact of the maser and the laser, invented over 40 years ago. The laser, which came from AMO science, was quickly embraced by the semiconductor community and has led to technologies and consumer applications that would not otherwise exist. These include the optical information storage industry, with its CDs and DVDs; the modern communication industries, with their fiber-optics-based transmission systems; and the modern printing industries, with laser printers at both the consumer and production levels. Lasers directly enable a set of industries that contributes over $300 billion to the worldwide economy.



The semiconductor processing industry, whose future has always been based on packing an increasing number of transistors and other components onto smaller and smaller chips, finds that excimer lasers based on inventions in atomic and molecular science have become the key drivers for future progress. Every single deep-ultraviolet lithography stepper (a machine that facilitates reproducing a semiconductor chip from a master) now requires an excimer laser for producing integrated circuits. New types of excimer lasers at shorter wavelengths will continue to meet the ever-more-exacting demands of the semiconductor industry, which has worldwide sales exceeding $200 billion per year.

Every year, hundreds of thousands of Americans are diagnosed with cancer or suffer from a debilitating condition. Magnetic resonance imaging (MRI) is one in a long list of medical technologies derived from AMO research that are helping many of these individuals to realize better health and a longer life. MRI can be traced back to research done in the 1930s by Stern and Rabi. Standing on the shoulders of numerous scientists before them, these early AMO pioneers developed atomic and molecular beams to measure the magnetic properties of the proton, a particle that resides in the nucleus of every atom and molecule in our bodies. It is this magnetic property of the nucleus that made possible magnetic resonance spectroscopy in the 1940s and the magnetic imaging of the human body in the 1970s. Tissues containing fat and water have typically been the targets for MRI scans because they give large magnetic resonance signals. The most recent development in MRI technology, the incorporation of polarized rare gases, now allows imaging of organs that do not contain much water, such as the lung. It was made possible by AMO research on optical pumping, which also began in the 1940s. It is important to recognize that MRI, which has grown into a billion-dollar industry that performs several million MRI scans annually, would not have been possible without the fundamental research that is now some 70 years old.

Another example of the influence of AMO science is the impact that our understanding of the physics of atomic and molecular collisions has had on improvements in the efficiency of gas discharge lamps. About 20 percent of U.S. electricity consumption is accounted for by domestic and industrial lighting. It is clear, therefore, that the use of more efficient light sources could mean significant savings for the U.S. economy. Among the new sources are high-efficiency metal halide lamps, sunlight-spectrum sulfur-dimer lamps, and white light emitting diode (LED) sources. These new sources, along with the now fairly common standard and compact fluorescent lamps, can be 3 to 10 times more efficient than standard household incandescent bulbs. Even if only some inefficient light sources are replaced with these new sources developed out of AMO research, a modest 1 percent gain in overall lighting efficiency would lead to a $4 billion annual saving in the nation's energy bill.

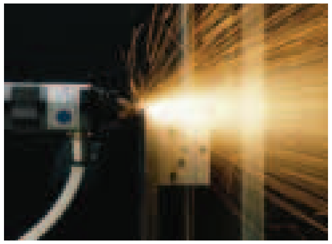
While technologies enabled by AMO science continue to make communications faster and cheaper, concerns have arisen about the confidentiality and authenticity of messages. Ensuring greater security for electronic transmissions between national security, law enforcement, and financial institutions is a growing priority as the United States is faced with one threat after another. Today's cryptographic codes, which are based on factoring very large numbers, can provide a barrier against most unauthorized intrusions, given that traditional computers cannot break these codes on any reasonable time scale. Nevertheless, breaches do occur and can go unnoticed until financial losses or other consequences are detected. Cryptography based on quantum physics, as opposed to classical physics (factoring), would not only provide a more robust way of assuring confidentiality and authenticity but would also provide a way of informing the sender and/or the receiver that an intrusion is in progress. Researchers in AMO science have given proof of principle for key processes on which quantum cryptography would be based.

Beyond developing new systems for securing information, AMO science also continues to make significant contributions to national security and homeland defense. The products of AMO science are improving our defenses against traditional threats as well as enabling reliable countermeasures against threats from biological and chemical agents.

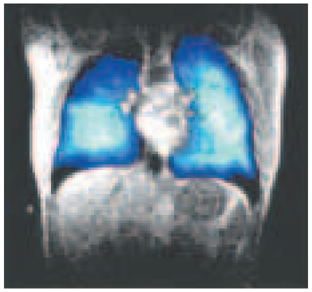
Not all of the AMO advances occurring today can or should be seen as having direct and identifiable coupling to the current economic, health, defense, or environmental needs of the nation. For example, the invention of the maser by Gordon, Zeiger, and Townes in 1954 was a fundamental breakthrough in molecular science (see image at the left on page viii). It showed for the first time the importance of a phenomenon known as "population inversion" and some years later led to the invention of lasers. Through a progression of subsequent discoveries, inventions, and innovations spanning some 20 years, the consequences of that 1954 breakthrough have affected numerous industries. For instance, automobile manufacturers now use laser-based auto body welding technologies, reducing costs and improving quality (see image at the right on page viii).

The characteristic time scale for going from discovery to deployment of basic advances resulting from science in general and AMO science in particular can be as short as a few years or as long as decades. This lag can be compared to the time it often takes to get approval for a new drug—in pharmaceutical research, such long lag times are accepted, and long-term investment strategies are the norm. Therefore, a patient investment strategy tolerant of high risk is key to ensuring that the nation benefits from AMO and other branches of science.

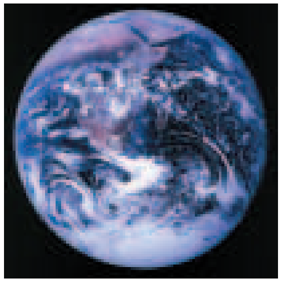
The purpose of this report is twofold: (1) to delineate the connection between AMO discoveries and technological applications throughout society and (2) to highlight recent advances that will play an important role in shaping the landscape of scientific discovery and technological invention. To underscore the breadth and importance of AMO-based applications, the committee presents a few snapshots of technology in four areas: the economy, the health sector, the environment, and national security. These are followed by an abbreviated collection of frontier investigations associated with the ability of AMO science to access and probe the ultimate limits of temperature, particle speed, and resolution. These short chapters show how AMO science is impacting life as we live it today and how contemporary investigations are revealing new understanding of nature, which—when harnessed—will revolutionize life as we live it tomorrow.



AMO science plays a critical role in the health and growth of the economy of the United States. The Internet and optical communication, the electronic industry and the Global Positioning System (GPS) are all empowered by technologies derived from AMO research. The eagerly anticipated advances that will come from the national push toward the nanoscale will certainly rely on corresponding advances in atomic, molecular, and optical science. The chapter "AMO Science Impacting the Economy" illustrates applications based on AMO research in manufacturing and processing, information technology, communications, and entertainment.

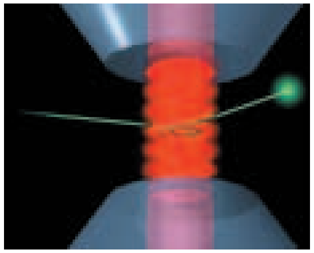


Lasers are playing a crucial role in many areas of surgery. From correcting ocular conditions to imaging damaged organs to removing tattoos, lasers are having a profound effect on health care. Breathable magnets, LASIK, and the medpen are but a few of the examples highlighted in "AMO Science Improving Health" that have enabled early detection and the development of corrective measures not heretofore possible.

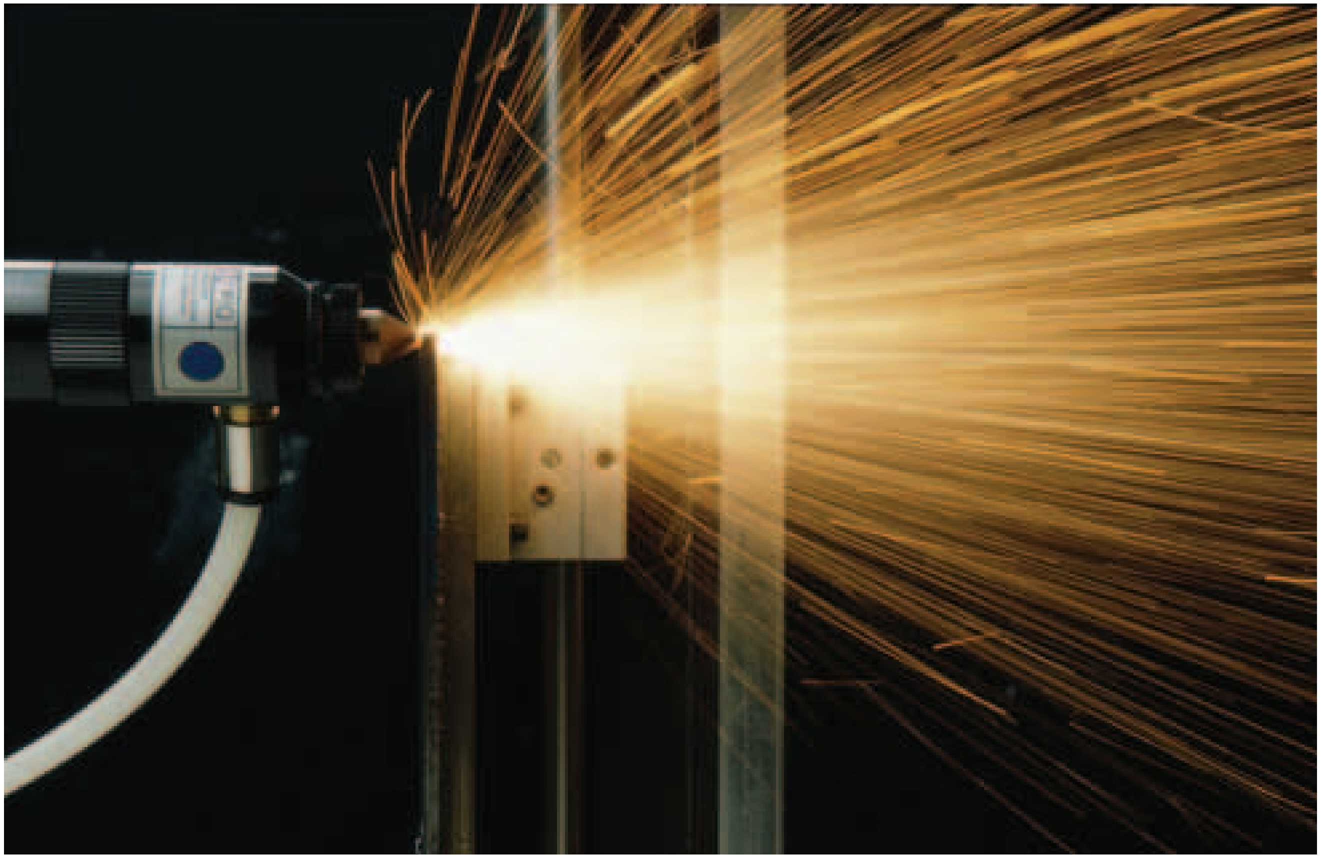


The atmosphere that surrounds Earth protects us from the harshness of space while providing an environment that sustains life. The constituents of the atmosphere—atoms, molecules, and electrons—exist in a dynamic and delicate balance that is strongly affected by pollution and sunlight. The interplay between pollution and global change—global warming and the hole in the stratospheric ozone layer—is treated in "AMO Science Protecting the Environment." AMO research not only is providing technology to measure and model pollution and the harm it causes, but it also is playing a critical role in the development of remediation procedures.

The genesis of many of the advances required to meet today's national security needs can be found in civilian research programs, and indeed the converse is also true. "AMO Science Enhancing National Defense" describes a few advances in laser science over the past decade that have led to increased security, better defense, and improved military preparedness.



The heart and soul of AMO science, discovery, is propelled by the exquisite control AMO scientists have over the properties of atoms, molecules, and light. In "AMO Science Expanding the Frontiers," the committee describes research under extreme conditions—ultracold temperatures billions of times colder than space, ultraintense light strong enough to tear even space apart, and ultrashort light pulses fast enough to stop the motion of atoms within a molecule and allow the manipulation of one atom at a time. Whether colliding atoms together or holding them in place against natural forces, AMO discovery is providing a glimpse into unexplored aspects of the basic properties of nature that are certain to have a profound effect on how we live tomorrow.



A laser cutting a sheet of metal produces a shower of sparks.

AMO Science Impacting the Economy

Whether hiking in the mountains with the aid of a handheld Global Positioning System (GPS) navigational device, surfing the Internet, listening to a CD player, or simply using the telephone, we are today surrounded by technology that in some way has benefited from the investment in AMO science and its resultant application. Whole industries, including those producing consumer electronics, media and communications companies, health care companies, and defense system contractors, have become multibillion-dollar contributors to the economy of the United States.

Much of the growth in the communications industry during the last 20 years was based on a revolution in optical communications that made the global Internet a reality today (Figure 1). Indeed, the Internet is based on an explosion of new technologies like diode lasers, the extremely bright light sources no larger than a grain of salt that send trillions of light pulses each second through optical fiber networks. The entire network is made transparent by compensating for optical absorption in the fibers with amplifiers that boost the light signals every 50 miles. Fiber amplifiers increase the range of optical communications, enabling transcontinental and global communications links. These amplifiers also allow hundreds of different-colored laser beams to be transmitted simultaneously on the same optical fiber using a single optical amplifier. At the present data rates, these optical networks can transmit the information content of the Library of Congress between New York and London in less than a second on a single optical fiber. So many optical fibers have been installed that, if placed end to end to form a single fiber, they could encircle the globe several times over. Internet optical backbone link capacity increased a hundredfold between 1995 and 1998, to 20,000 trillion bits per second. While the communications industry has recently suffered a downturn, the potential for increasing demand for capacity in the 21st century remains, with

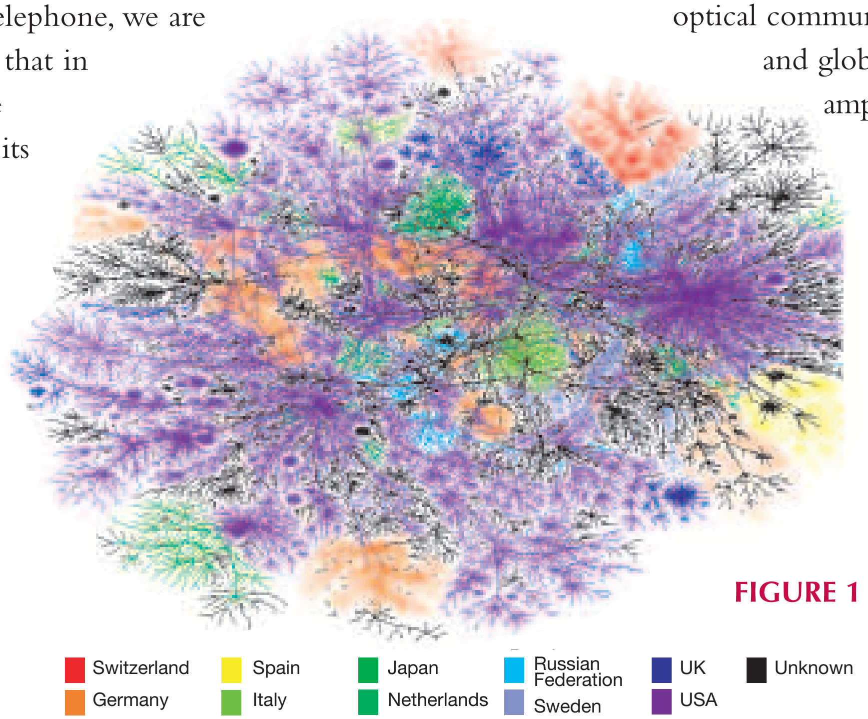


FIGURE 1

Each line on the map represents a path that e-mail might take through the global Internet. The colors indicate different geographical locations. Internet routers are located at each branch.

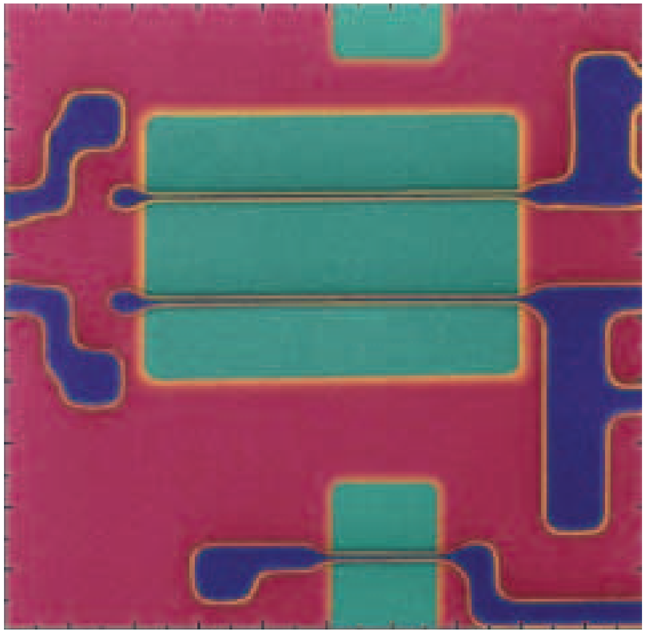
features and services such as HDTV, broadband communications, and advanced home security systems becoming more available through the use of optical fiber, wireless, satellite, and cable connections.

Paired with the growth in communications has been the growth of computers and information processing. The GPS receivers and wireless phones available today use the latest in integrated circuit technology. AMO science is playing a key role by enabling the increase in the density and speed of computer chips. As an example of what is possible even today, a tiny transistor component on a chip is shown in the electron microscope image in the box "Laser Lithography." This transistor would easily fit inside a bacterial cell.

Computer technology continues to advance, resulting in ever-faster computation speeds. This progress is based on the decreasing size of the transistors in the very-large-scale integrated (VLSI) circuits used in computers and signal processors. Transistor feature sizes in commercial production have been decreasing, from 0.35 microns in 1995 to 0.13 microns in 2002. These dimensions are nearly 1/1,000th the diameter of a single strand of human hair. One important factor limiting feature size on a chip, and thus the computational speed, is the wavelength of the light used to form the transistor patterns and interconnecting wires. The shorter the wavelength, the smaller the features.

Today, ultraviolet excimer lasers with average output powers in the 20-watt range are replacing the older mercury arc sources. It is interesting to note that it would take more than a billion 100-watt incandescent lightbulbs on at the same time to be effectively as bright as this laser source. Excimer lasers operate using the light emitted from gas molecules excited in an

LASER LITHOGRAPHY



A top-down scanning electron microscopic view of a field-effect transistor gate (green rectangle) where the source and drain for the device (narrow blue horizontal lines) are spaced by only 0.12 microns (a human hair is approximately 100 microns wide). These ultrasmall features are patterned by photolithography. Photolithography uses a patterned mask in combination with an excimer laser with a wavelength of 248 or 193 nanometers. The beam from the laser is focused through the mask to expose the features seen above. This transistor is a component in a digital signal processor fabricated at Bell Labs. It operates at 100 megahertz and uses only a 1-volt power supply. Potential applications include enabling smaller and lighter cellular phones with extended battery life. The technology also could be instrumental in data transport over wireless phones, in higher-speed Web surfing, and in video applications.

electric discharge. Their operation, and future advances, all depend on AMO science.

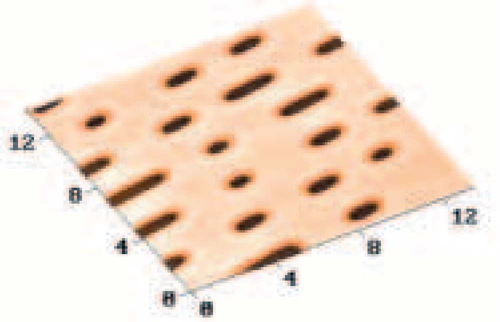
Plasma processing is used to etch many of the small features of a state-of-the-art transistor. Atoms and molecules interact with one another and with the surface of the semiconductor circuit during this processing to form or deposit the circuit components and features. The speed at which this process can take place and its uniformity over the large wafers used for making silicon VLSI circuits rely critically on our understanding of the collision and excitation dynamics of the atoms and molecules in the plasma processing environment. AMO science is now at the point of being able to predict and model these important processes in great detail. Designing future processing systems that extend the etching and deposition to ever-finer dimensions with higher aspect ratios, greater processing speeds, lower production costs, and increased uniformity will rely heavily on the insights that we are developing through these models.

The dimensions of individual transistors on computer chips are shrinking to the level of the dimensions of single atoms and molecules. For example, there are presently only a few molecules of silica glass separating the active gating structures in transistors. If the present decrease in the dimensions of transistors is to continue, transistors will have to be no bigger than a single molecule by the year 2020. At this scale, quantum mechanical processes become very important. Even the methods of computation may evolve, with quantum processing of information resulting in stunning new computing capabilities. These eagerly anticipated advances will certainly rely on advances in AMO science.

The precise control afforded by the laser has other important applications. Laser drilling can form holes smaller than the diameter of a human hair while precisely positioning them to an even better accuracy. So it becomes conceivable to construct cars from material that is cut using high-power lasers based on light emitted from carbon dioxide molecules. These lasers emit intense beams that can be

OPTICAL STORAGE

Music, data, and computer software information are often stored on CDs or DVDs. How do these information storage disks work? The key component is a tiny semiconductor diode laser that is focused to a microscopic spot on the disk as the disk rapidly rotates on the disk platter. The laser is mounted on a mobile arm so that it can track a spiral line of dimples that winds its way around the disk. A scanning probe microscope picture of these dimples is shown below for a DVD.



Each dimple on the disk is only 0.5 microns wide (a human hair is approximately 100 microns wide). The laser is tightly focused so that it reflects from only one line of dimples at a time. Laser light can be focused to a spot that is nearly equal in size to the laser's wavelength. Light wavelengths vary from 1 micron in the deep red to 0.35 microns in the violet end of the rainbow. The bluer the light, the more densely the information on the disk can be packed. DVDs use both 0.65- and 0.63-micron wavelengths (red light) and contain 4.7 billion bytes of information, nearly eight times the information on a CD.

focused extremely accurately to make precision cuts with very little waste. A laser cutting a sheet of metal is shown at the beginning of this chapter, on page 6. Clothing, too, may be cut using a laser.

Compact disk (CD) players read the billions of bits of information stored on a CD with a tiny laser that costs less than a dollar. This semiconductor diode laser emits dark red light with a wavelength of 0.78 microns. The laser is focused to a microscopic point, where it is reflected from the bits of information that are stored as dimples on the CD. The newer digital versatile disks (DVDs) can store and read nearly eight times as much information as a CD by using shorter wavelength lasers that emit at wavelengths of 0.65 and 0.63 microns (see box "Optical Storage"). Another increase in information density is expected with the advent of even shorter wavelength lasers that emit light in the blue and violet. Diode lasers are also used in laser printers and commercial printing applications.


FIGURE 2
Satellite view of lighting across the United States at night.

Anyone flying across North America at night will see from 35,000 feet a vast array of lights extending from coast to coast, as shown in the satellite photograph that is Figure 2. This lighting consumes nearly 20 percent of the total power generated across the nation. AMO science is making an important contribution to the quality and efficiency of lighting by studying the emission of light from the collision of electrons and atoms in electrical discharge lamps. At present, discharge plasma light sources—including low-pressure fluorescent lamps and high-pressure, metal-halide, high-intensity-discharge lamps—yield both good color and efficiencies that are nearly five times greater than those of common incandescent lights. There is good hope that lighting scientists will be able to increase this efficiency another two- or threefold while improving the color of the light emitted to suit a variety of applications. Research progress has been excellent in the field because of much better electron-atom collision and spectroscopic data, combined with an increase in computational power, leading to the development of more accurate lighting models. In the end, more efficient lighting will help conserve fossil fuels, reduce environmental problems, and provide significant savings to the economy.

The theme of precision measurements based on atomic, molecular, and optical science has had a dramatic impact on all our lives. Perhaps the most impressive example is the Global Positioning System (GPS), a system of 24 satellites that surround Earth and send radio messages to receivers on the ground (Figure 3). Each satellite has an ultraprecise atomic clock onboard that keeps time to an accuracy corresponding to the loss or gain of no more than a second since the time of the dinosaurs, nearly 140 million years ago. This incredible accuracy is obtained by monitoring the fundamental rhythms that beat within each isolated atom.

The need to reckon time is deeply embedded within the human psyche. The history of clocks began with Neolithic bone carvings that marked the passing of seasons. Then, in the last few

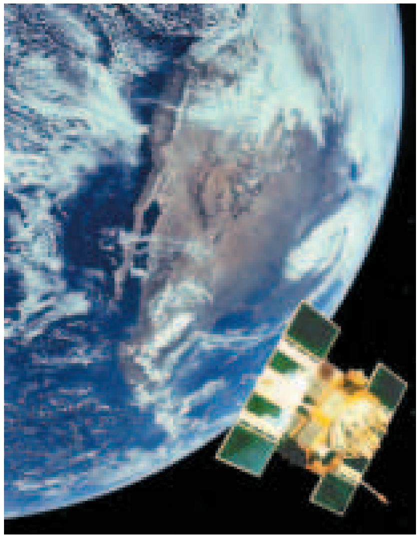


FIGURE 3

GPS satellite orbiting Earth and transmitting atomic clock information.

centuries, the precision of clocks improved, from seconds per day to seconds per decade. In the first half of the 20th century, crystal-controlled electric clocks were developed for communication and navigation. In the second half of the 20th century, there was an unprecedented advance in timekeeping—the precision jumped by a factor close to one million. One motivation for this spectacular increase was to satisfy curiosity about one of the most profound of all theories: Einstein's theory of gravity. The aim was to make a clock precise enough to reveal how time is altered by gravity—the geometrical shape of space and time. The result was the invention of the atomic clock, which has enabled the GPS system.

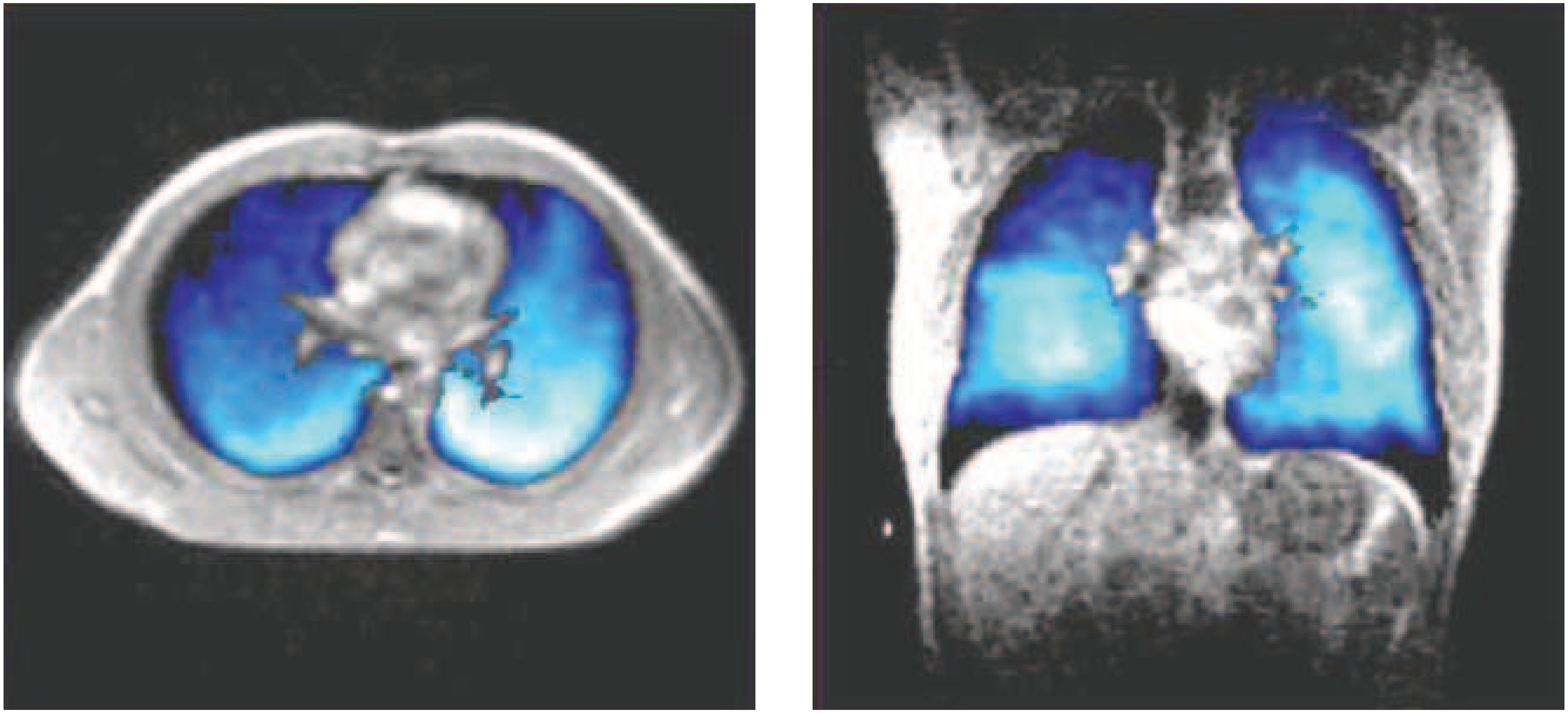
The GPS is a useful tool for a wide range of people, including sportsmen, farmers, soldiers, pilots, surveyors, delivery drivers, sailors, dispatchers, lumberjacks, and firefighters. GPS makes their work and leisure safer and more efficient (Figure 4).

There are many ways in which atomic, molecular, and optical science has profoundly contributed to our economy and way of life. The advances described here give only a conservative glimpse of what may happen in the coming few years. What will the future bring? The possibilities opened up by the Internet seem limitless. Computational speeds and information storage will almost certainly continue to increase, requiring entirely new technology to be developed at the atomic and molecular level. Improvements in the GPS should make it possible to resolve positions no further apart than the width of your finger, making such applications as self-guided cars possible.

The benefits that society will reap in the future depend on the investments it makes in the present. For example, a significant increase in demand for capacity in the global optical communications network could sooner or later strain the capabilities of low-loss optical fiber and semiconductor laser transmitters to their limits. What, then, will be the next breakthrough in this technology? It will be an exciting adventure, one that is vital to our society, to explore new high-speed optical devices and optical networks or perhaps even an entirely new optical phenomenon that one day will play a central role in global communications.

FIGURE 4

A hiker in a remote area can use a handheld GPS receiver to access atomic clocks that give his position to an accuracy of a few yards.



Today we have many exceptional diagnostic techniques to assist the medical profession in the diagnosis and treatment of diseases and to allow both doctors and patients to make more informed decisions about health care. Many of these techniques were developed from results obtained in AMO research. Novel, noninvasive imaging allows doctors to have far better control during surgery, resulting in less loss of healthy tissue. Magnetic imaging with polarized rare gases makes it possible to see the finest lesions in the lungs (see box "A Patient's Story) and may even be used to image specific brain functions. Medical diagnostics are in the early stages, and new applications of the technique are still being discovered (see box "Breathable Magnets"). Lasers are also playing a major role in many areas of surgery (see box "Improving Laser Surgery").

Since the interior of the eye is easily accessible with light, ophthalmic applications were the first widespread uses of lasers in medicine. Argon lasers are now routinely used to treat retinal detachment and bleeding of blood vessels in the retina caused by age-related macular degeneration. Today's surgeon is not limited to the metal scalpel but now has a wide array of lasers of different wavelengths to choose from to excise tissue, depending on the disease and the type of tissue involved. The use of lasers dependent on carbon dioxide or a neodymium-doped yttrium-aluminum-garnet (YAG) rod as the lasing medium to cut tissue while simultaneously sealing blood vessels has been widely and successfully applied to many surgical problems in specialties ranging from dermatology to general surgery. Tattoos can be removed using lasers whose wavelength is selected on the basis of the color of the tattoo; multicolor tattoos may be removed using several lasers. Lasers are being used for the controlled removal of the surface of the skin to reduce or eliminate wrinkles (laser skin resurfacing). Other laser systems are being used to remove unwanted body hair, to treat acne (in conjunction with a topically applied cream), to remove cancerous skin, and to excise tumors in the colon. The erbium-doped YAG laser has recently been introduced for dental applications; it promises a dramatic reduction in pain and automatic decontamination,

A PATIENT'S STORY

John has received some troubling news. He has just been diagnosed with a disease that has damaged much of his lungs, rendering large portions of them useless.

His lung surgeon is faced with a difficult operation, as the only way to save the patient is to remove the affected portions of the lung. But such surgical procedures have a very high failure rate, and it's difficult to know which sections of John's lung to remove during the surgery. Fortunately, the surgeon is aware of a new imaging technique that can let a doctor see in advance which sections of the lungs work and which are diseased. This method uses rare gas atoms prepared by a process called optical pumping to visualize the functional portions of the lung. In optical pumping, atoms are aligned, or polarized, to produce a striking result: a gaseous magnet. John need only breathe the polarized gas during an otherwise conventional magnetic resonance imaging (MRI) session. The images on page 12 superpose a conventional MRI scan of the lungs and a scan using polarized gases.

BREATHABLE MAGNETS

Medical imaging using magnetized rare gases was invented in 1994 to provide a way to study diseases of the lung, heart, and brain that depend on the flow of gas and blood through the vital organs. This marriage of AMO science and medical imaging grew out of the basic study of the atomic nucleus.

But how did this connection between AMO physics and medical imaging come about? It started with some basic research on helium by Luis Alvarez at the University of California, Berkeley, in the 1940s. He discovered a form of helium gas, ^{3}He, that behaves like a tiny bar magnet. ^{3}He is abundant in the universe but exceedingly rare on Earth—the world's supply amounts to only about 1 ton. There is more ^{3}He in the rocks on the Moon's surface than on our planet. In recent years, there has been a steady supply of the gas from an unusual source: Although ^{3}He is not radioactive, it is produced from the radioactive decay of tritium, the form of heavy hydrogen present inside nuclear warheads.

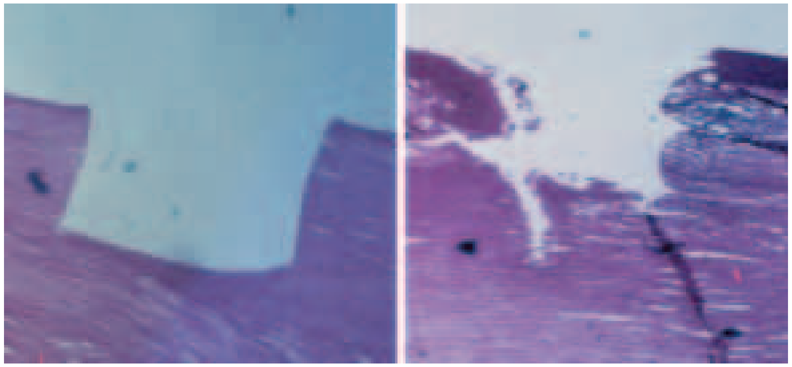
Because ^{3}He is a gas, its atoms are randomly oriented at room temperature, so the total magnetism in a bottle of it is essentially zero. However, scientists studying the basic physics of atomic collisions perfected an optical pumping scheme that uses polarized laser light to align most of the ^{3}He with their magnets pointing in the same direction. This creates a very unusual material: a gas that acts like a bar magnet. It was later recognized that this new "breathable magnet" might have marvelous properties for imaging the lung and the circulatory system. But many technical obstacles had to be overcome before this promise could be demonstrated in the 1990s, when the first magnetic images were obtained using this technique. Now, only a few years later, breathable magnets are producing dramatic images like the ones shown on the opening page of this chapter. Tiny features in the lung, brain, and circulatory system are visible for the first time.

IMPROVING LASER SURGERY

Following its development in the mid-1970s, researchers quickly discovered (in 1981) that the excimer laser, a product of years of AMO research, could be used to cut away skin tissue in a much better fashion than previously possible. This type of laser produces light in the ultraviolet region and, as shown in the image below of a cross section of a human aorta after it has been irradiated with an excimer laser, a laser scalpel of this type can produce a well-defined and controllable cut in biological tissue.

By contrast, an image of a human aorta irradiated with longer wavelength light—pulsed green (532-nanometer) light, for example—would show an incision characterized by burning and charring.

Laser surgery carried out with excimer lasers is a good example of how AMO science has led to new and improved surgical techniques. Indeed, in the ensuing years, AMO scientists collaborated further with medical doctors interested in using these effects for cutting and etching the cornea, artery walls, and skin while minimizing unwanted collateral damage.



LASER REFRACTIVE SURGERY— A FAREWELL TO SPECTACLES?

The success of laser refractive surgery is a story of sophisticated lasers that were developed for basic research and then found new applications in clinical medicine. This transition has occurred through partnerships between basic research scientists, technologists in start-up companies, and the medical community.

One of the early laser surgical procedures—utilized first in Russia—uses radial incisions directly in the cornea (radial keratotomy, or RK) to alter the curvature of the surface. This method produced vision improvement, but it was difficult to control the extent of the correction accurately.

In the early 1980s it was discovered that the outer layer of the eye's cornea is extremely sensitive to excimer laser light. The 193-nanometer light emitted by the argon fluoride excimer laser can be used to etch away corneal tissue with high precision. Medical researchers postulated that this ability to destroy tissue might be used to resculpt the curvature of the eye's optical surface with great precision and control. This idea led to the transition from RK to laser-assisted in situ keratomilieusis (LASIK), which has faster recovery times and more immediate results than RK. LASIK involves ablating tissue under the outer surface of the cornea. The corneal surface tissue is surgically opened to form a thin, transparent flap. Then, following programmed laser ablation of the underlying tissues, the flap is replaced. This is where great skill, surgical experience, and the right keratome (corneal cutting device) are critical. The results can be dramatic, especially for the severely myopic.

New technologies now being developed promise to improve this procedure further. In many cases, these technologies come directly from basic research labs, where there are similar exacting requirements for laser performance. One very recent development is the use of ultrafast femtosecond lasers to replace the mechanical blade that cuts the corneal flap. The laser uses femtosecond light pulses—a femtosecond is a billionth of a millionth of a second—to photoablate tissue at the rate of thousands of laser pulses per second. This produces smoother surface cuts than blades and virtually eliminates the risk of infection. The same technology might soon obviate the creation of a corneal flap. This is because ultrafast lasers can damage material beneath a transparent surface without harming the surface itself, through a process called nonlinear multiphoton absorption.

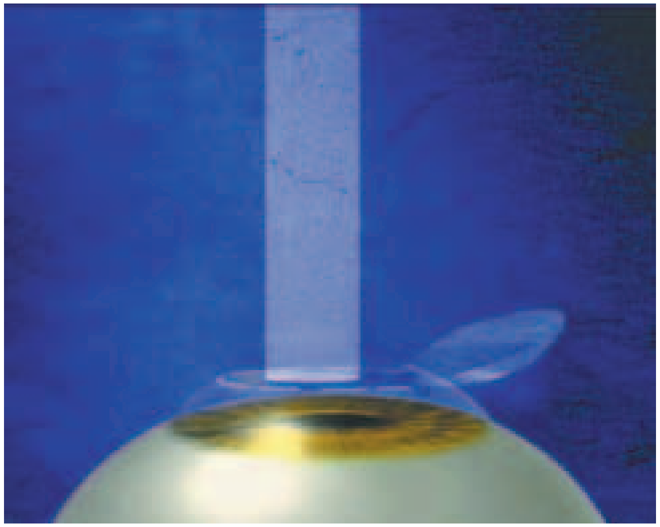


FIGURE 5

both welcome contributions to the treatment of dental disease. The days of tolerating the vibration and noise associated with drilling to prepare dental cavities for filling may be numbered.

Today, millions of people suffer from near- or far-sightedness and require either contact lenses or glasses to see clearly. Glasses, however, can be broken or forgotten, and contacts require careful cleaning. A new procedure, laser-assisted in situ keratomilieusis (LASIK), is enjoying widespread use because it is an outpatient surgical procedure that produces very good vision correction for many individuals. In LASIK (Figure 5), the surgeon uses an excimer laser to "sculpt" the structure of the eye with the goal of achieving vision correction without lenses or contacts (see box "Laser Refractive Surgery—A Farewell to Spectacles?").

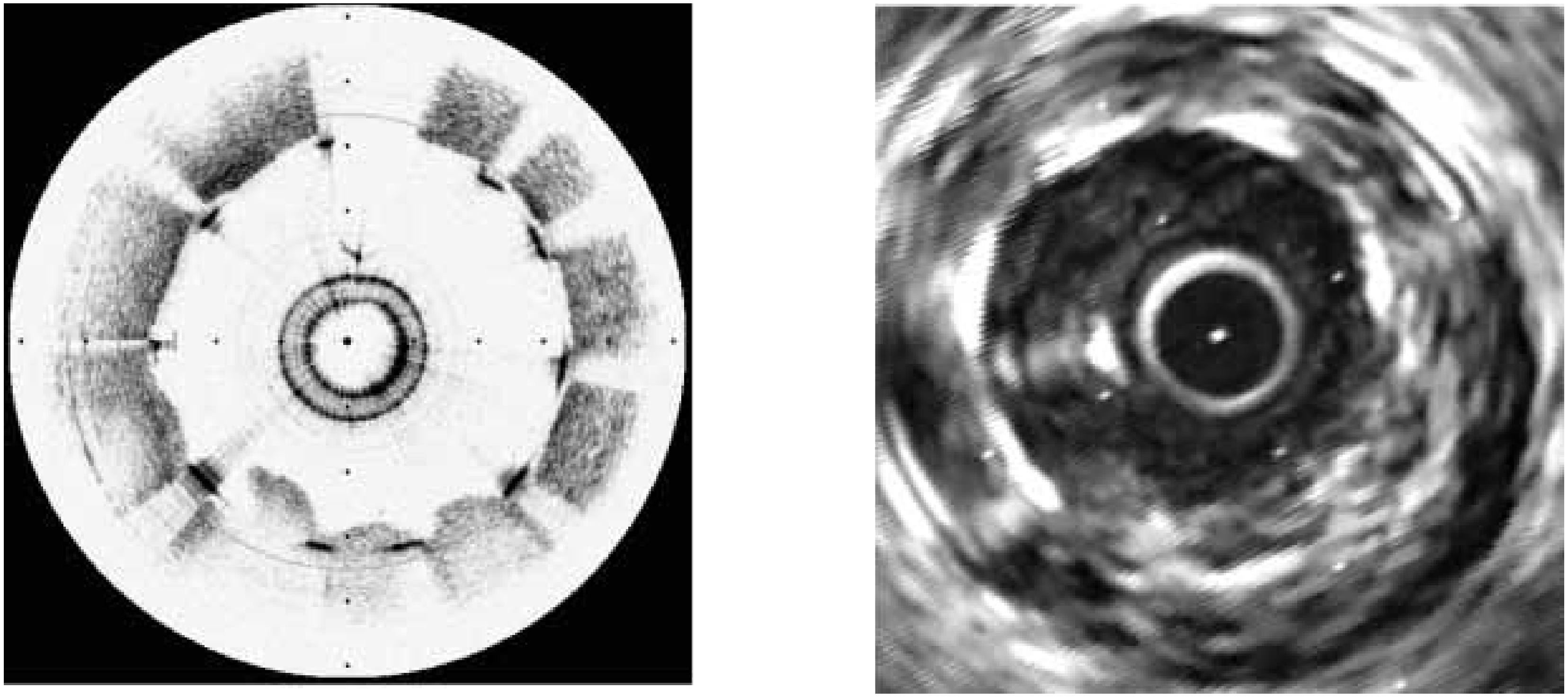


FIGURE 6

Two images of the same artery using the OCT method (left) and ultrasound (right).

Nearly 7 million Americans suffer from coronary heart disease (CHD), and nearly 500,000 die of the disease each year. CHD is caused by a thickening of the inside walls of the coronary arteries. This thickening, called arteriosclerosis, narrows the space through which blood can flow, decreasing and sometimes completely cutting off the supply of oxygen and nutrients to portions of the heart. A new optical imaging technique, called optical coherence tomography (OCT), is now being developed that promises to dramatically improve the diagnosis and treatment of this disease.

OCT uses a bright optical source introduced into an artery by a fiber catheter (the central ring in the left portion of Figure 6). A broad range of infrared colors from this bright source reflects from the various layers in the lining of the artery at different times. A detector compares these times with a reference clock to form a high-resolution map of the artery wall. As can be seen from Figure 6, the resolution is much higher than with the older ultrasound techniques. An OCT image of a cross section of an artery (left) is compared with a lower-resolution intravascular ultrasound image (right).

The images were acquired following the deployment of a stent, a wire frame tube inserted to prevent collapse of the artery and ensure the unclogged flow of blood. The individual struts of the stent are opaque to both infrared light and ultrasound, resulting in shadowing of the vessel lumen underlying them. In the ultrasound image this shadowing is less apparent than in the OCT image because of its coarser resolution. Determining that the stent struts are in close proximity to the vessel lumen is clinically very important to the stent deployment. Stents are commonly used to prevent initial or secondary heart attacks. The new OCT imaging technique will clearly improve health care for many of us.

Advances in laser technology are also enabling a new treatment of the main cause of vision loss in people over 50: age-related macular degeneration (AMD). In a patient with AMD, the central portion of the retina (the back surface of the eye responsible for vision) becomes progressively damaged by leakage of blood and fluid from blood vessels. Lasers are already used to treat this condition by making controlled scars within the eye on the retina. While this treatment controls the disease, it does so at the cost of creating some irreversible vision loss. The new treatment, recently approved by the Food and Drug Administration (FDA), uses a combination of laser light and a new drug to treat the abnormal blood vessels in the eye, which are the cause of the problem. This new drug is injected into the patient, and light from a laser is used to convert the molecules of the drug to a reactive form. This reactive form of the drug locally creates a small, highly controlled scar that is confined to the abnormal vessels. While not a cure, the treatment allows some forms of the disease to be controlled without loss of vision. In contrast to earlier laser treatments, which used large and expensive lasers, the new approach uses a relatively inexpensive diode laser, similar to those in CD players, to activate the drug. Referred to as photodynamic therapy, the technique has also been approved by the FDA for relief of the symptoms of cancer of the esophagus; it allows the patient to continue to swallow when otherwise she or he might be unable to do so. Other cancer applications are also being developed.

Future advances in medicine that will be used to treat cancers and other terminal conditions will be linked to our knowledge of the four-letter genetic code for life stored in DNA. This code is based on four molecules, called G, C, A, and T. Three billion of these molecules form the DNA present in every cellular nucleus in our bodies. Much research has been devoted to sequencing the human genome, a truly massive international effort. Knowledge of the genetic sequence for many organisms will be one of the great achievements of this new century and will lead to unimaginable new therapies for disease. At the heart of each commercial gene-sequencing machine is a device called a fluorescence spectrometer, which is an optical instrument that measures the colors of light being emitted by fluorescent molecules. To sequence a piece of DNA, each of the molecules G, C, A, and T is labeled or tagged with a different colored fluorescent dye through a chemical reaction. By reading the colors of the dyes, the sequence can be obtained. The contribution of AMO science to this work rests on pushing the state of the art with advanced light sources and detectors to achieve new levels of sensitivity and selectivity. For example, if a laser beam can be used to detect labeled bases inside of or exiting from a tiny capillary, the enhanced sensitivity allows the detection of smaller amounts of the material of interest.

Ultrasensitive optical detection has been the target of research and development in AMO science for many years, with the original goals being military applications and the quest for scientific insight that results from pushing the limits of detection all the way down to single photons from a single molecule (see box “Medpen”).

MEDPEN

A miniature development that may help save lives on the battlefield is a handheld laser called the laser medical pen, or Medpen, developed by the Air Force. It can cut like a scalpel and also stop bleeding. The purpose of the Medpen is life support in combat situations, enabling the physician or paramedic to coagulate blood and close wounds under battlefield conditions. The same device could also be used for domestic emergencies, such as stabilizing accident victims at a crash site.

Less than 12 inches long and less than 1 inch in diameter, the Medpen delivers 5 watts of continuous power at a wavelength of 980 nm (invisible infrared light). Its 3-volt battery can power it for 20 minutes, long enough for most emergency situations. Medpen is made possible by tremendous advances in diode laser technology, most notably in efficiency, reliability, and miniaturization.

Concurrently, basic AMO research has sought to understand how chemical reactions can produce light at the molecular level. Today, these disparate research efforts are being combined to generate a fascinating new array of medical applications.

One such application is the imaging of the effects of drug treatments on live subjects (Figure 7). Its goal is to understand by noninvasive means the mechanisms of disease and the complex genetic program that controls the development of mammals. This approach uses the fact that light can pass through tissues in much the same way as light from a flashlight passes through one's hand

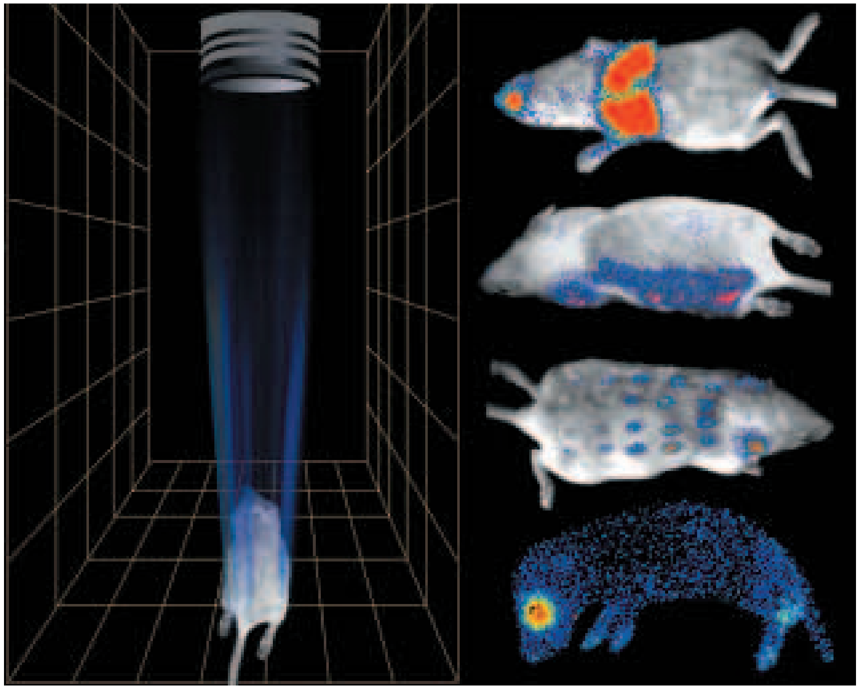


FIGURE 7

New imaging techniques capable of detecting light produced inside a living subject allow observation of the effects of antitumor drugs, antibiotics, or antiviral treatments. The images on the right are scans of living mice that would allow researchers to investigate the effects of various drugs on different parts of the body without having to resort to harmful invasive techniques.

in a dark room. The source of light in the images of live mice is internal; that is, researchers use the genes from fireflies and other glow-in-the-dark (bioluminescent) organisms to place molecular indicator lights inside mammalian cells. These labeled cells are then used in combination with pathogens and drug treatments in animal models of human disease. The light that comes through the skin from the marked chemiluminescent cells is extremely weak, but it can be detected one photon at a time with an ultrasensitive imaging detector to reveal growth rate and movement of the cells within the living animal. This level of sensitivity is comparable to that of the human eye after full adaptation to the dark.

Using this novel approach, it is now possible to observe the effects in the body of antitumor drugs and antibiotic or antiviral treatments. Indeed an ultimate goal is to make the body essentially transparent for medical diagnostics, and to use advanced optical tools to understand how pathogens cause disease and how the host organism responds to pathogens and treatments, without having to resort to invasive surgical techniques.

AMO Science Protecting the Environment

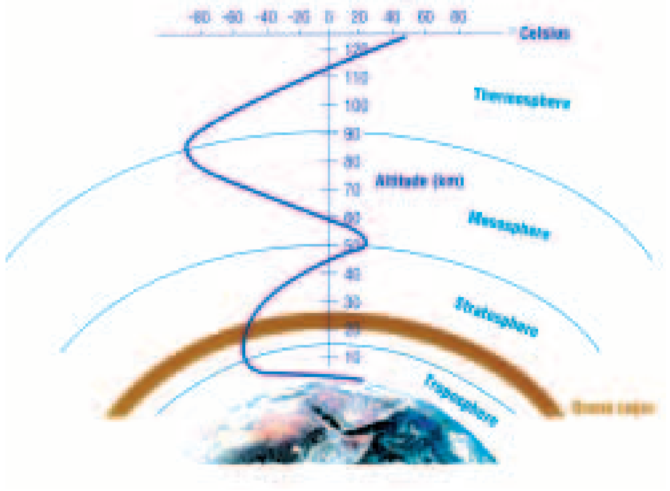
...Pollution, pollution, wear a gas mask and a veil.
Then you can breath as long as you don't inhale....

— Tom Lehrer from "Pollution" (1965)

Earth is a wonderful place, an exquisite menagerie of truly remarkable features with virtually unlimited possibilities for satisfying the human need for exploration and creativity. Human endeavors can put a strain on the environment, however: Transportation, industry, and activities associated with agriculture all release harmful substances into the atmosphere that can cause illness and damage our environment. These substances can also react among themselves in the presence of sunlight to produce new and potentially more dangerous compounds.

When flying into major metropolitan areas we are not surprised to find ourselves descending into a pall of smog, a reddish-brown haze. Smog consists of the visible products of the reaction of nitrogen dioxide, hydrocarbons, water vapor, and invisible gases such as ozone, as well as airborne particulates. It is corrosive and irritating to the eyes, throat, and lungs. Other forms

EARTH'S ATMOSPHERE



The atmosphere that surrounds Earth protects us from harmful radiation and extreme temperatures of space while providing an environment that sustains life. The diagram shows the layers of the atmosphere and how temperature varies with altitude. Earth's gravity causes the densities of atmospheric molecules (oxygen, nitrogen, water, etc.) to be greatest near Earth's surface and to decrease with increasing altitude. The interplay of the molecular densities and the solar radiation penetrating to each layer is one of the most important determinants of the unique physics and chemistry within each layer.

The troposphere, which is closest to Earth, is the most complex region of the atmosphere. It is affected by the oceans and landmasses as well as plant and animal life. This is the region where we experience weather, from the blizzards of winter to the blistering heat of summer. Above the troposphere is the stratosphere, which contains a high concentration of ozone molecules and is sometimes referred to as the ozone layer. These ozone molecules shield Earth's surface from harmful solar ultraviolet radiation, exposure to which has been linked to skin cancer, eye disorders, and changes in plant growth patterns. Above the stratosphere is the mesosphere and above that, the thermosphere, the layer in which many satellites and the space shuttle orbit. Present within the mesosphere and the thermosphere is a dilute plasma, a collection of ions and electrons created by radiation from the Sun. This plasma, known as the ionosphere, enables radio communications around the globe.

of air pollution can be invisible, and while they may not be harmful to breathe, they can have an unacceptable effect on our global atmosphere. Chlorofluorocarbons (CFCs), for instance, released from refrigerants and cleaning agents, are associated with the destruction of ozone in the stratosphere, and carbon dioxide contributes to global warming.

To keep Earth safe and habitable, we need to improve our ability to monitor and control human-induced pollution and to understand how various pollutants interact among themselves and how they affect different parts of the atmosphere (see box "Earth's Atmosphere"). This chapter describes how AMO science provides the essential data for atmospheric models and a variety of innovative techniques that are used to monitor pollution quantitatively.

Understanding the Atmosphere and Climate

Atmospheric science (and other environmental sciences) is different from many other areas of science in that controlled large-scale experiments are often difficult if not impossible. Nevertheless, microscopic physical and chemical processes that affect the climate occur constantly throughout the atmosphere, the oceans, on land, and in the biosphere. Atmospheric scientists strive to understand these processes in conjunction with sunlight and human activities such as transportation, combustion, industry, and agriculture and to determine how their interaction globally influences the atmosphere and climate.

The complexity of the atmospheric system makes it difficult to describe all of its behavior using a small number of theoretical expressions. Therefore, comprehensive numerical models play an essential role (see box "Scientific Models"). Atmospheric scientists must also make extensive use of data provided by laboratory experiments as well as information and parameters obtained from monitoring the atmosphere from the ground, balloons, aircraft, and satellites. AMO science makes an important contribution to instrumentation, data collection, and analysis in atmospheric science.

To be a reliable, predictive tool, a model must include as completely as possible the phenomena affecting the system, and it must be based on accurate data. Models of the upper atmosphere (the mesosphere and thermosphere) require knowledge of the intensity of the Sun's radiation as a function of wavelength, densities of constituent molecules and atoms (primarily N_2, O_2,

SCIENTIFIC MODELS

A model is a collection of mathematical expressions that describe what we know about a system. Models allow scientists to carry out controlled virtual experiments on computers to determine how a system will behave under various circumstances.

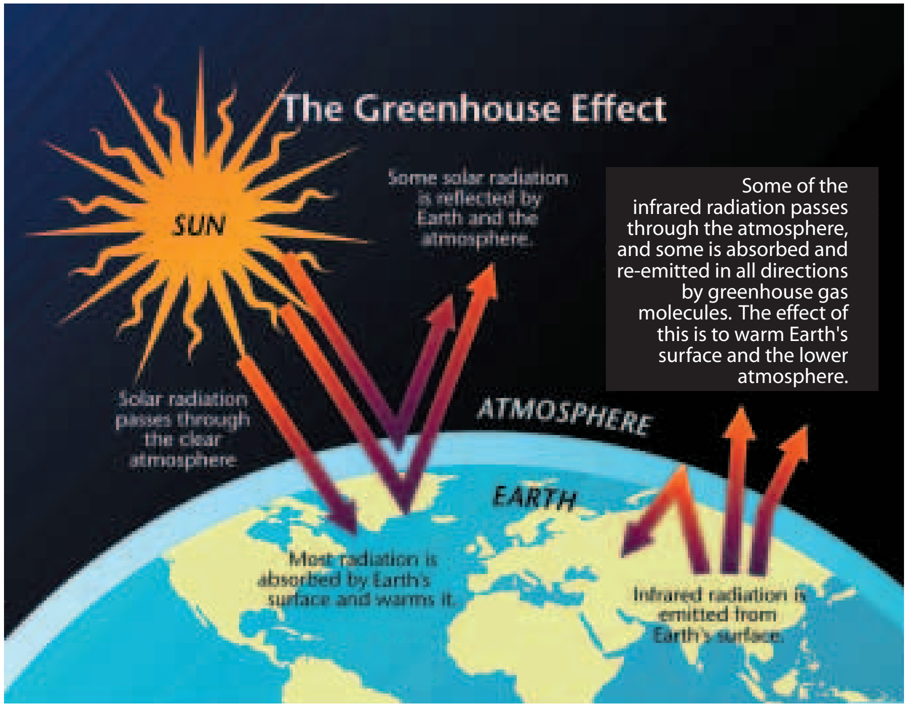
The power of a theoretical model lies in the predictions it makes and its ability to identify key relationships between physical and chemical processes. Differences between the model's predictions and the measured parameters are used as a guide to further our understanding of the system and to improve the model.

Atmospheric models have had a critical impact on national and international policy. The implication of chlorofluorocarbons (CFCs) in the destruction of the ozone layer—which led to the Montreal Protocol, an international treaty banning the manufacturing and use of CFCs—is a success story to which AMO instrumentation and research made a significant contribution. Three chemists were awarded the 1995 Nobel Prize in Chemistry for their work on the formation and decomposition of ozone.

O, and He), the probabilities for atoms and molecules to absorb light of a particular wavelength, and ion-molecule and electron-molecule collision rates. Fundamental AMO research in collision physics, in the spectroscopy of atoms and molecules, and in chemical reactions is providing data central to atmospheric modeling.

Generally, atmospheric models become increasingly complicated as the altitude decreases because there are more constituents to include and additional effects to take into account. Modeling the stratosphere and troposphere requires fast supercomputers to run huge computer codes that incorporate thousands of chemical reactions, detailed global wind patterns, and abundances of large numbers of trace species. Sophisticated atmospheric models are used to help guide policy makers in drawing up recommendations governing the burning of fossil fuel and the manufacture and use of ozone-destroying chemicals.

Although carbon dioxide is an integral part of plant and animal metabolism and therefore occurs naturally in the troposphere, significant increases in carbon dioxide may cause problematic atmospheric and climatic changes on a global scale. Over the last century, increased burning of fossil fuels—particularly in the generation of electric power, in the heating of homes with oil or natural gas, and in automobile combustion engines—has led to a buildup of carbon dioxide in the atmosphere. Models incorporating data from AMO science predict that as the concentrations of carbon dioxide and other gases such as methane, ozone (from pollution), and the CFCs increase, more of the infrared radiation coming from Earth will be trapped near the surface. Trapped infrared radiation leads to warming of the troposphere and the surface of Earth, known as the greenhouse effect (Figure 8).



Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm Earth's surface and the lower atmosphere.

FIGURE 8

The natural greenhouse effect of Earth's atmosphere.

While the effects of water vapor in our atmosphere produce a natural greenhouse effect—and indeed the effect makes our planet suitable for the type of life that has evolved on it—a rapid increase in heating will affect ecosystems in ways that are at best poorly understood. For instance, evaporation rates would increase substantially, with a resultant increase in rainfall. These rapid changes might also put human populations at risk. In any case, managing their effects will certainly incur costs that are difficult to predict. The warming may already have started, as the mean global temperature has risen by approximately

0.5°C during the past 100 years. The consequences of such warming can be very dramatic and might include the thinning of the polar ice caps.

Although ozone (O_3) near the surface of Earth is a pollutant and contributes to global warming, O_3 in the stratosphere screens our planet from harmful ultraviolet sunlight. Ozone is produced naturally in the stratosphere and is destroyed by a complex series of chemical reactions, some of which are fueled by man-made chemicals.

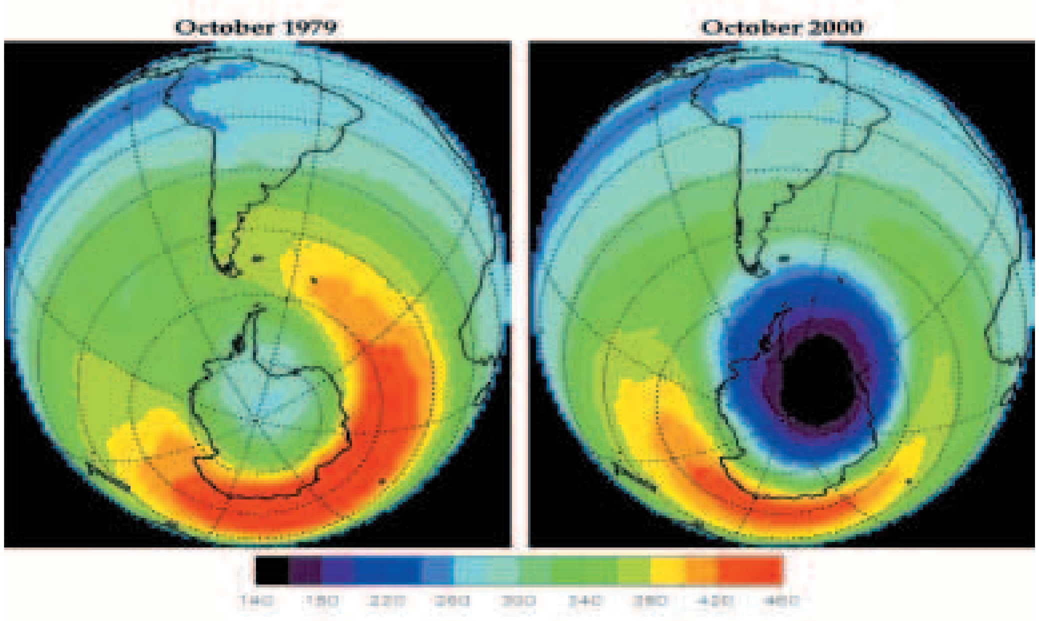


FIGURE 9

Measurements of ozone concentrations over Antarctica from natural springtime minimum conditions in 1979 (left) to the extensive ozone hole recorded in 2000 (right).

Global concentrations of O_3 in the stratosphere are monitored by NASA and the National Oceanic and Atmospheric Administration (NOAA) using satellite-based spectrometers. The data show a dramatic seasonal loss of O_3 over Antarctica during the polar spring (October-December). While the formation of the Antarctic ozone hole is cyclic, over the last 21 years the hole has grown larger and is more depleted in O_3 and more persistent (Figure 9).

Using a variety of measuring techniques based on AMO science, atmospheric scientists have discovered a sequence of chemical reactions occurring in the polar stratosphere during winter, when no sunlight is present. These reactions, which produce chlorine molecules (Cl_2), occur on the surface of polar stratospheric clouds of ice crystals. In spring, when sunlight penetrates the region once again, the Cl_2 molecules break apart. The Cl atoms then react with O_3, destroying it and causing formation of the ozone hole.

It has recently been recognized that carbon dioxide (CO_2) also plays a role in the growth of the ozone hole. Paradoxically, while CO_2 contributes to global warming near Earth's surface, it causes cooling in the stratosphere. Carbon dioxide molecules generated at ground level can eventually migrate to the upper layers of the atmosphere, where they collide with oxygen atoms. During the collision, the colliding atoms lose energy (i.e., they cool), while the CO_2 is transferred to an internal excited state. The excited CO_2 then radiates, causing a net cooling of the upper atmosphere. In the stratosphere this cooling contributes to the enhanced formation of polar stratospheric clouds, leading to greater ozone depletion. Models suggest that the doubling of CO_2 in the atmosphere, as is predicted to occur over the next century, will result in significant amounts of cooling in the upper atmosphere and, in turn, more O_3 depletion.

Laser Altimetry

The ability to assess, model, and identify various pollutants and their influence on the environment is a direct result of decades of fundamental AMO research. Autonomous, unattended measurements to monitor pollution over large regions have been made possible through advances in laser spectroscopic tools such as lidar—light detection and ranging (see boxes "Lidar," "Lidar Mapping of Pollution," and "Lidar Mapping of Los Angeles Pollution"). The compact nature of a lidar spectrometer allows it to be deployed on satellites and airplanes.

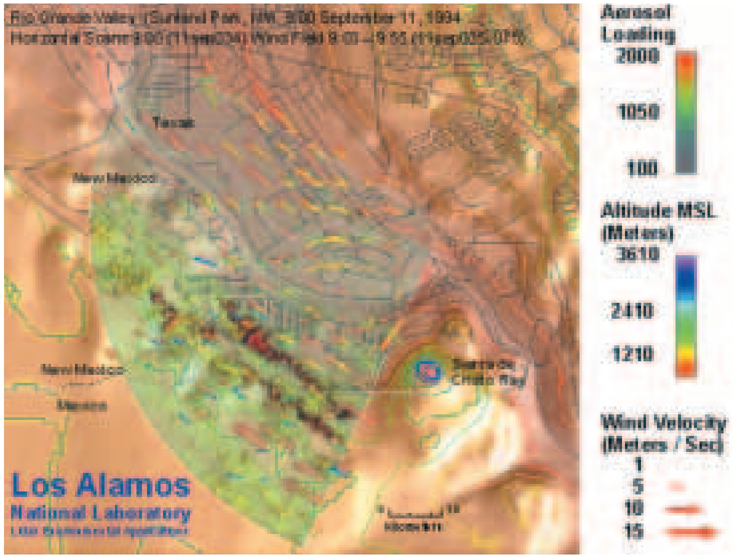
A lidar-enabled technique, laser altimetry, is being used to monitor the health of Earth's polar ice caps. Accurate knowledge

LIDAR

Lidar can be thought of as radar with laser beams. While radar can image large objects such as aircraft, lidar can be used to map the location and concentrations of atmospheric molecules and aerosols as well as landmasses. In lidar, pulses of light are transmitted into the air, where they are scattered or absorbed and re-emitted by atmospheric constituents. Light returning to the transmitter is collected by an optical receiver and analyzed to extract details about the state of the atmosphere at distant points. The distance to a suspicious plume, for example, can be obtained by measuring the time delay between emission of the laser light and collection of the back-scattered light. The concentration of atmospheric molecules can be obtained by using twin laser beams, one of which is tuned to a wavelength the molecule in question likes to absorb. Advances in laser technology, electro-optical materials, and high-powered, low-cost lasers in the eye-safe 1.5-micron band now permit remote mapping of lower concentrations of atmospheric constituents at increased ranges.

LIDAR MAPPING OF POLLUTION

The image below shows the striking ability of lidar to measure pollutants in the atmosphere, along with their distribution and circulation. Horizontal lidar scans over El Paso, Texas, provide graphic evidence of pollution transport and how the circulation patterns are affected by the terrain, the transportation system, and political borders. Dense plumes of pollutants (red) moving northwest are coming from identifiable sources to the south. Lidar wind-field measurements in the image are indicated by the position, length, and direction of the arrows, while the altitude of the measurement is indicated by its color. These wind measurements also show atmospheric flows through the Rio Grande Valley basin, which are influenced by the local terrain. These flows are responsible for the transport and dilution of pollutants in the area. Wind measurements with aerosol lidars can capture even small-scale atmospheric flows, such as the turbulence downwind of the Sierra de Cristo Rey peak and the channeling of the low-level flow through the valley basin.



of whether or not the polar ice caps are changing in size has been a scientific goal for decades. Changes in the thickness of the polar ice cap would also be an unavoidable consequence of any large-scale climate changes that may be occurring in our atmosphere. While accurate measurement of polar ice cap thickness is very difficult, the Greenland ice sheet, second in size only to the Antarctic ice sheet, lies on land above sea level and provides a stable measuring platform (Figure 10). Laser altimetry exploits the

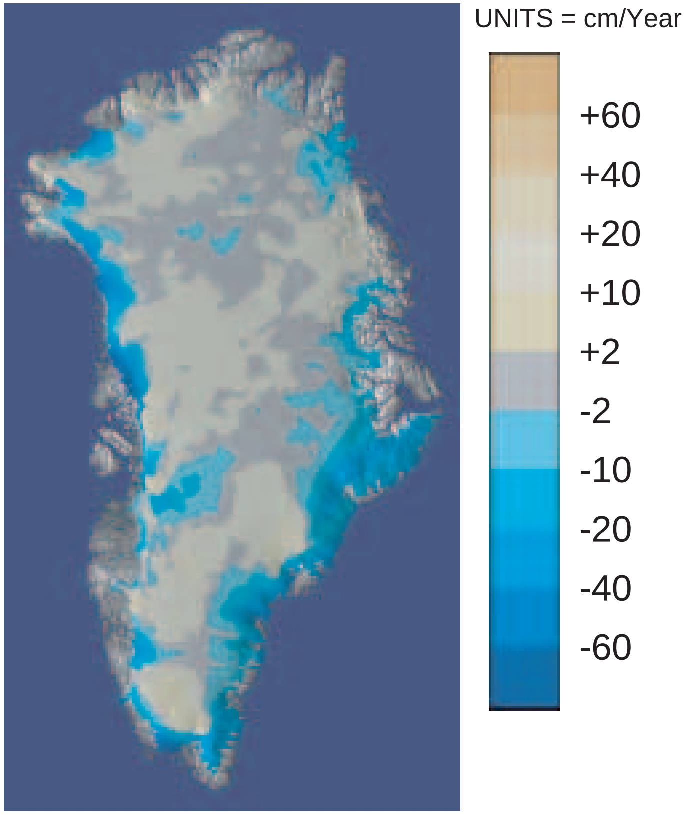
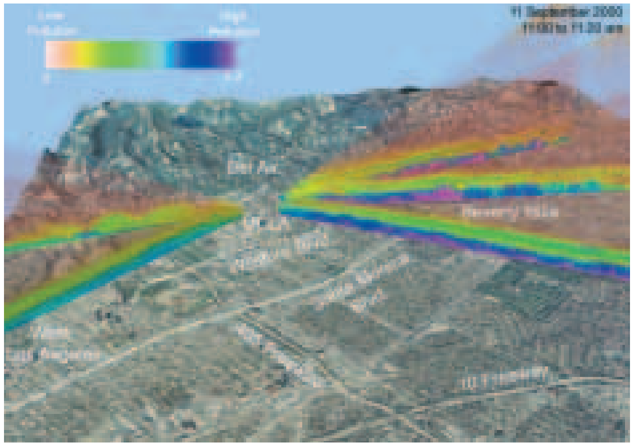


FIGURE 10

This map shows that the Greenland ice sheet is thinning, primarily along coastal regions, and thickening in some inland areas.

LIDAR MAPPING OF LOS ANGELES POLLUTION



Sunlight reacts with emissions from cars, trucks, and smokestacks to create smog. Lidar helps us to identify where smog is created and to see how pollution is transported by the wind. This image shows a series of vertical scans taken by an eye-safe lidar located in metropolitan Los Angeles. Purple areas indicate high levels of airborne particulates; there are several such patches as the lidar looks east into the densely packed streets of Beverly Hills. One particularly prominent plume of pollution appears at the intersection of Wilshire and Santa Monica boulevards, two arteries with a lot of stop-and-go traffic. Westward at the 405 Freeway, the particulate level actually drops. This is because winds from the Pacific Ocean help to mix and disperse the pollutants and because the traffic was moving smoothly on the freeway when the measurement was taken. Notice also the layer-cake structure of the atmosphere. The data were acquired within a few minutes of one another and represent a snapshot of the atmosphere. Successive scans can be combined to create movies of how the air around us behaves and ultimately can be used for urban planning and decision making.

Global Positioning System to precisely assess, every few years, the rate at which the elevation of the entire ice sheet is changing. These measurements indicate that the sheet is thinning along some coastal regions.

Internal combustion engine exhaust is a major contributor to ground-level air pollution and smog. One of the most important factors limiting the design of modern, cleaner-running diesel engines is the amount of nitrogen oxides that these engines emit.

The combustion environment inside a diesel engine can vary dramatically in both the location of the combustion and when in the engine cycle it occurs. The chemistry is complex, involving mixtures of hydrocarbons, molecular oxygen, molecular nitrogen, and water vapor. Sensitive techniques such as laser-induced fluorescence are needed to study the formation of these and other chemical species during combustion processes (see box "Laser-Induced Fluorescence" and Figure 11).

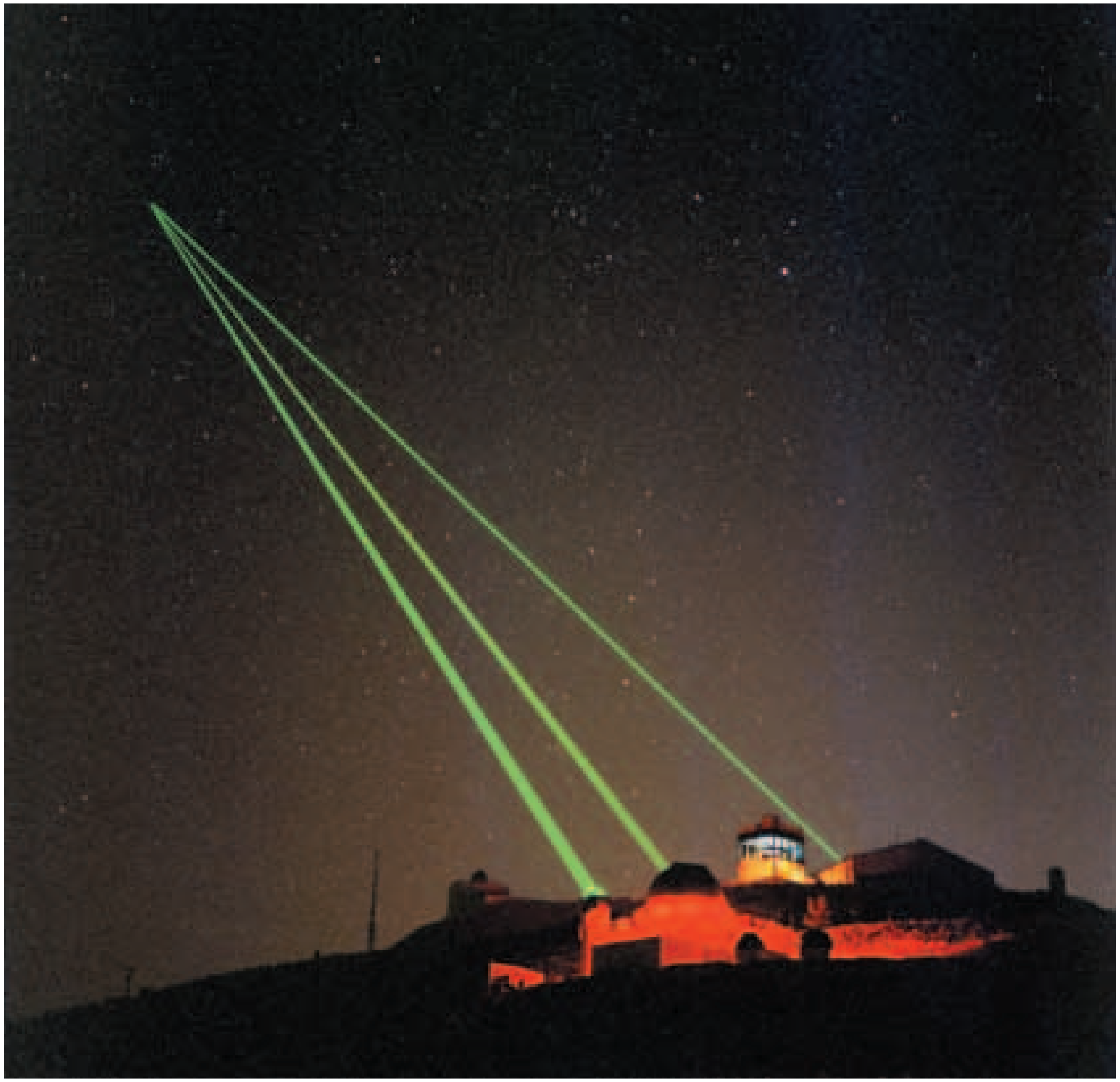
LASER-INDUCED FLUORESCENCE

AMO scientists developed laser-induced fluorescence several decades ago to investigate atoms and molecules that were hard to detect or otherwise invisible. In planar laser-induced fluorescence (PLIF), the output of a laser tuned to a wavelength absorbed by an atom or molecule of interest is formed into a thin sheet of light and sent through the combustion region. Fluorescence emitted by the atoms or molecules in the path of the sheet of light is detected at right angles with a very sensitive camera to produce the spatial images shown above. This pair of PLIF images shows the formation of NO in a diesel engine near the beginning (left) and near the end (right) of the combustion cycle.

Planar laser-induced fluorescence (PLIF) is a technique being used to determine temporal and spatial maps of nitric oxide (NO) in an operating diesel engine. These images, along with detailed knowledge of collision cross sections of the molecules in the combustion chamber, are used to extract NO concentrations from PLIF images like those shown in the box. What we have learned from these images reveals that NO forms progressively during combustion, with approximately one-half to one-third forming at the end of the cycle. Such results have already impacted research directions of engine manufacturers as they work to produce engines with reduced emissions.

FIGURE 11

An actual diesel engine modified for planar laser-induced fluorescence imaging.



The night sky illuminated in a Guide Star demonstration. Inelastic scattering of the outgoing laser beams by the atmosphere makes them strikingly visible.

AMO Science Enhancing National Defense

AMO Science, National Defense, and Security

Lasers can deliver large amounts of power at long distances almost instantaneously. These exotic qualities of laser weapons seem to belong more to the world of science fiction than to the world of national defense. But the same properties that have made lasers indispensable tools in industry and medicine also make them especially useful tools for the military. Advances in laser science over the past decade have led to increased security (see box "Homeland Security"), better defense, and improved military preparedness in many areas. Many of the advances needed for national security have come out of civilian research programs; conversely, many of the advances from national security-related research programs have had a significant impact on civilian technologies. Here the committee describes just a few of the AMO science advances that have contributed to our national defense.

Imaging Through a Turbulent Atmosphere

Scanning the evening sky in the early 1960s one might have caught a glimpse of the Echo satellite as it passed overhead. Today's near-Earth orbits are filled with communications, military, and research satellites. Being able to see an adversary's satellites is an important national security priority. Optical telescopes, no matter how powerful, are limited in their resolution by atmospheric turbulence. Now, lasers and atomic physics are changing that. One approach to overcoming the problem of atmospheric turbulence is through the use of atomic physics and the technology developed originally for high-power lasers.

In one such application, called Guide Star, a powerful laser is directed skyward to more clearly resolve images of satellites in Earth orbit. As it propagates through the atmosphere, the laser beam encounters a layer of sodium atoms at an altitude of about 50 miles. Formed by the breakup of meteors entering Earth's atmosphere, the sodium atoms in the layer absorb and then re-emit some of the light, which appears to an earthbound telescope as an artificial magnitude 7 star (a factor of 100 weaker than Polaris, a magnitude 3 star). This light intensity is too weak to be observed by the naked eye but more than sufficient for our purposes. If the artificial star is located at about the same position in the sky as a passing satellite, then light from the object and light from the artificial star will both be subject to the same amount of atmospheric distortion. One can calculate what the artificial star should look like in the absence of atmospheric distortion. Consequently, a telescope equipped with a deformable mirror that is viewing both objects can change the shape of its mirror under computer control to correct the image of the artificial star for the effects of atmospheric distortion. In doing so, it also resolves the image of the passing satellite. Satellite features as small as a basketball 1,000 miles away can be observed using this system. Such

HOMELAND SECURITY

Three-dimensional imaging (holographic) and scanning technologies improve hands-off detection.

The events of September 11, 2001, made us recognize that the United States is vulnerable to new threats to the security of its people, economy, and infrastructure. These threats go substantially beyond traditionally recognized concerns. To anticipate, respond to, and prevent future occurrences of the type that took place on that day, the United States is creating an administrative structure called Homeland Security.

Responses to potential threats include the creation of systems capable of securing our nation's communication systems from infiltration, safeguarding our transportation systems from disablement, and preventing harm to our people from various weapons, including chemical and biological agents.

Technologies enabled by AMO science continue to make communications faster and cheaper, and the use of new cryptographic codes based on quantum physics rather than classical physics promises to better protect our national information infrastructure from unfriendly intrusions.

AMO science continues not only to make our more traditional defense systems better but also to give us increasingly sophisticated and effective sensors for the early detection of threats to both civilian and military populations from chemical and biological agents. AMO science's continuing progress in detection systems offers a significant boost to the development of early and effective countermeasures against such threats.

good resolution has allowed improved identification of satellites and their closer scrutiny, enabling us to more clearly determine their intentions and functions.

Lasers and Atomic Physics Help Achieve Nuclear Arms Reduction and Safeguard the Nation

Nuclear nonproliferation is one of our most important national security goals. One of the challenges of the nonproliferation effort is how to assure the safety and reliability of our remaining nuclear weapons, an effort known as stockpile stewardship, without having to resort to testing through the detonation of nuclear warheads. Advances in AMO science have aided this effort, particularly in two areas: (1) the development of large solid-state lasers that can help simulate conditions found in thermonuclear explosions and (2) the formation of more accurate theories of how atoms behave at high temperatures and pressures.

One of the reasons lasers are an exciting tool in the laboratory is their capacity to concentrate energy in space and time in the form of focused high-intensity beams of coherent light. This capability has led to the development of several new types of experiments, including programs that began in the early 1970s whose aim was to simulate small thermonuclear detonations in the laboratory. Continued progress eventually led to the construction of what was then the world's most powerful laser: Nova (Figure 12). Nova was capable of generating power equivalent to several hundred times the electrical power output of the United States for about one billionth of a second. The first laser to achieve the conditions needed for thermonuclear fusion in its focus, it gave the nation the potential ability to study aspects of nuclear weapons without conducting tests.

The physics of nuclear weapons is very complicated and not completely understood. In the past, underground nuclear tests were conducted to determine how weapons would work. Now that testing of nuclear weapons has stopped, our nation's security depends on learning how to predict their performance through numerical simulations and experiments not involving the detonation of weapons. To study conditions inside a thermonuclear explosion, ten powerful laser beams are focused into a small, hollow gold cylinder about the size of a dime. Each cylinder contains a small BB-size capsule filled with a small amount of nuclear fuel. The multiple laser beams enter from both sides and impinge on the inside of the cylinder.

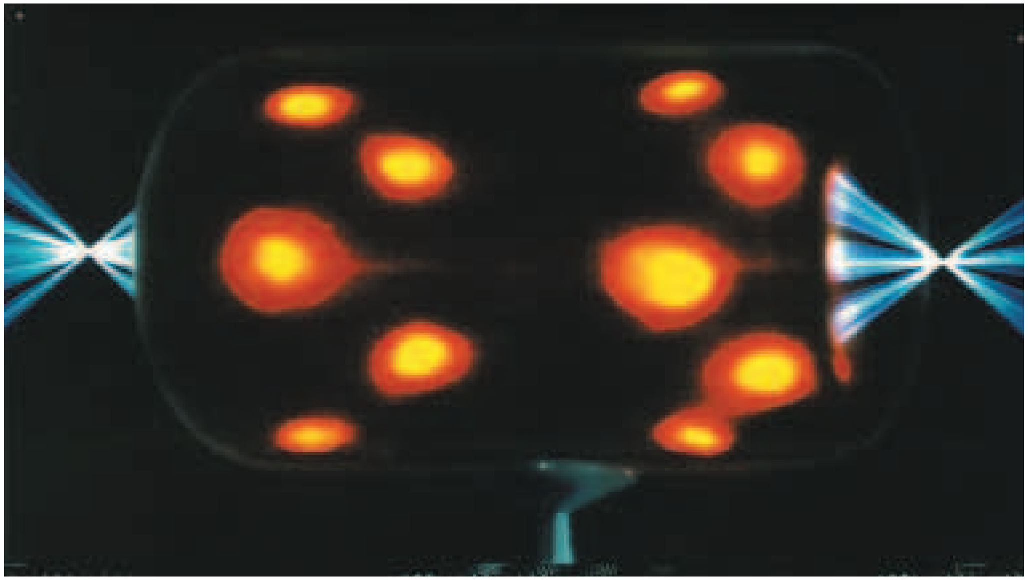


FIGURE 12

The Nova laser heats a hohlraum target to several times the temperature of the Sun.

This vaporizes the gold and creates intense x rays, which compress the capsule. The total energy contained in the beams is typically about 40,000 joules. Although this is equivalent to the energy released from burning only 1 gram of coal, it is delivered in such a short period of time and in such a small volume that the fuel inside the test sample is heated to several hundred times the temperature of the Sun.

Data from experiments with Nova have improved our understanding of the underlying physics of dense heated matter and what happens during a nuclear explosion. These results are being used to test computer calculations of atomic processes like turbulent mixing and x-ray opacity. This provision of experimental data for the confirmation of numerical simulations is an important contribution that AMO science makes to our national security as we strive to reduce the risk of global nuclear war. Future projects such as the National Ignition Facility laser, currently under construction in California, will continue this partnership in the 21st century.

Laser Range Finders and Target Designators

Lasers and optical technology have had a major impact on conducting modern warfare while minimizing unintended damage. Laser technology has helped in two significant ways, precision range finding and target designating, allowing the substitution of precision for quantity (force).

The laser range finder for tanks and aircraft has been used extensively for 30 years. The combination of laser range finders, which have an accuracy of ±60 centimeters out to a distance of 10 kilometers, and infrared sensors has made tanks a formidable mobile artillery weapon. The military edge gained from this combination, called a force multiplier, makes U.S. tanks up to five times more capable than the less advanced tanks of adversaries.

For aerial bombing missions, the laser range finder plays a different role: It becomes a laser designator for ground targets. This advance has led to remarkably improved target accuracy. While it is possible to build very precise bomb aiming and release mechanisms and bombs with finely designed aerodynamic characteristics, the wind in the atmosphere between the aircraft and the target is unpredictable and limits the accuracy of a bomb hitting its target. With the accuracy of targeting typically decreasing by ±50 meters for every kilometer of altitude, true precision bombing without the use of laser designators could only be achieved by bombing at very low altitudes to minimize the effect of wind. Low-flying bombing runs make an attacking aircraft an easy target for modern antiaircraft defenses. Retreating to safer altitudes above the range of ground-launched missiles and antiaircraft fire, typically 10 kilometers or higher, leads to an average targeting uncertainty of 500 meters or more. The potential for unintended casualties would be unacceptable.

Laser target designators have changed this situation completely. The designation is done by shining a laser beam on the target, often from an airplane located outside the range of the aerial defenses. Sensors inside the bomb detect the reflected light, which enables automated steering for precision strikes. A number of variations on this theme, such as guidance from observers on the ground, have given us the ability to provide close bombing support for friendly forces that are under attack. Moreover, this increased accuracy means that a single, moderate-sized bomb can give a better result than multiple strikes with larger, nonguided bombs. It minimizes the number of missions necessary and the amount of damage to unintended targets.

Laser Technology for Theater Missile Defense

Directed energy weapons such as space- and land-based lasers were considered potential weapons for destroying incoming ballistic missiles during the late 1980s as part of the Strategic Defense Initiative. Lasers can deliver lethal doses of energy over long distances with minimal delivery time (i.e., the speed of light). Electrically excited lasers, including carbon dioxide lasers, free electron lasers, and chemical lasers such as the HF/DF and the chemical oxygen/iodine laser (COIL), have been considered as potential systems (Figure 13). Key issues in the development of laser-based missile defense systems for target destruction are laser power; laser efficiency; laser wavelength, which determines the size of the final focusing mirror; the engagement distance to the target; and the need for corrections for turbulence in the intervening atmosphere. While no weapons have yet reached the level of maturity needed to field them in a combat environment, billions of dollars are being invested to continue research into systems that could be developed for deployment. AMO science and scientists are contributing significantly to this effort.

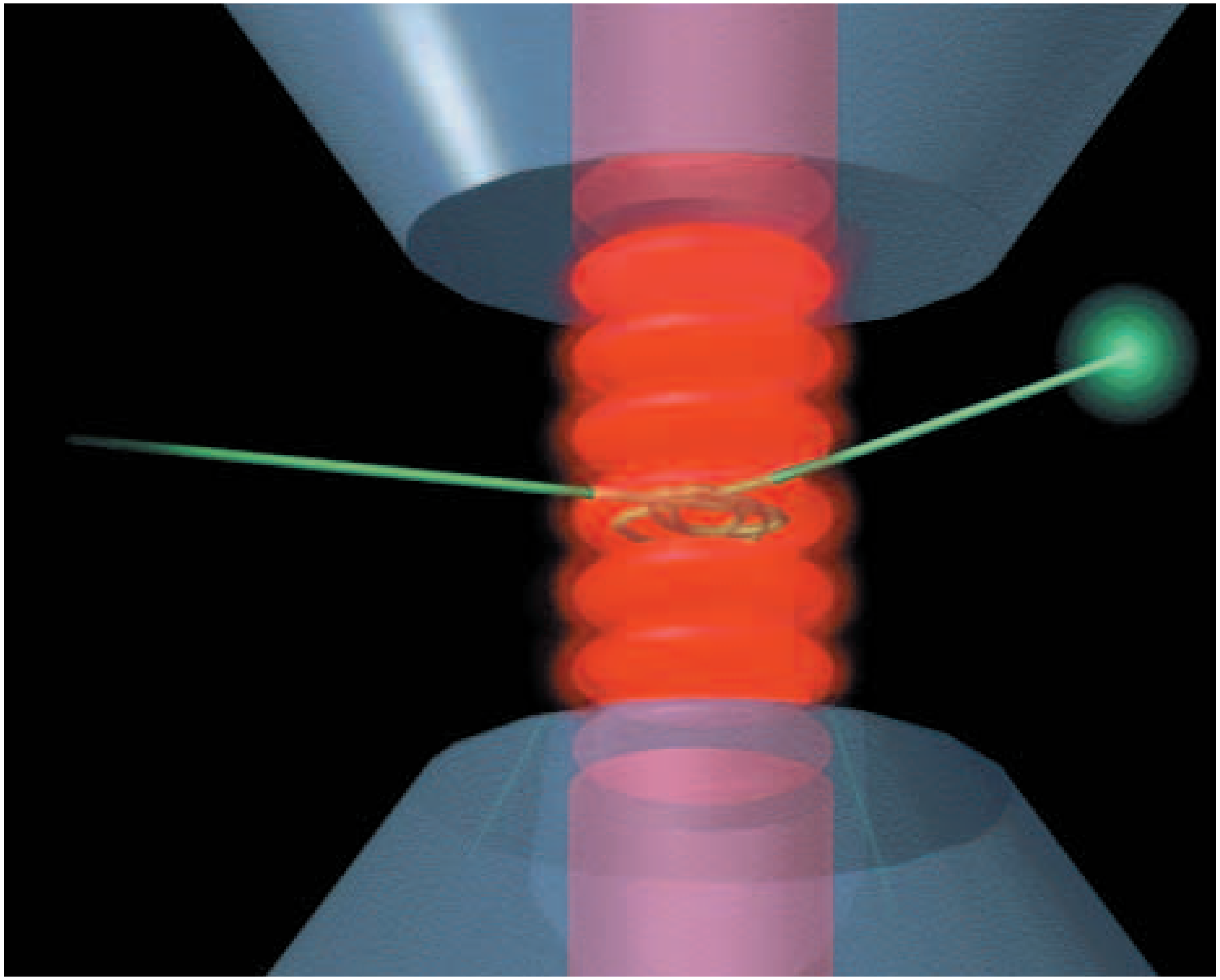
Airborne Lasers

Following the deployment of the Patriot theater ballistic missile (TBM) as a defense against SCUD missiles during the Gulf War, the airborne laser (ABL) project was initiated to investigate alternatives to the use of TBMs on and off the battlefield. As conceived, the ABL will be a high-energy COIL carried aboard a modified Boeing 747. Sensors on the plane will locate and track missiles soon after launch. If a missile is hostile, the laser will be aimed and fired at it, destroying it in its boost phase near the launch areas. The ABL will be capable of producing a beam to deliver several tens of kilowatts of continuous or pulsed power and projecting the beam up to hundreds of kilometers away, using optics that employ deformable mirrors to compensate for intervening atmospheric turbulence. Other potential applications of laser weapons, either on the ground or mounted on an airborne platform, include the destruction of short-range rockets.

Development programs for other laser weapons are not likely to result in a reliable system for several years. Formidable challenges remain, including the successful delivery of sufficient energy over long distances through an absorbing and distorting atmosphere and the field reliability of lasers. AMO science will play a central role in developing the systems and technologies that might lead to deployable weapons systems.

FIGURE 13

Katyusha rocket being destroyed in midflight (left) using a DF laser beam from the facility shown in an artist's rendering (right).



Artist's rendition of the trajectory of an atom, drawn in green, as it is being temporarily trapped in a red light field in a cavity quantum electrodynamics experiment.

AMO Science Expanding the Frontiers

Discovery

This chapter presents some vignettes of research at the frontiers of AMO science. The prefix ultra and the adjective extreme appear frequently, for these frontiers really are astonishing: Ultracold temperatures are a billion times colder than interstellar space. Ultraintense light is strong enough to rip apart atoms and even space itself. Ultrashort light pulses are so fast that they can "stop" atoms as they move within a molecule. Ultraprecise atomic clocks are so accurate that they vary by less than a second in a hundred million years.

The goals of AMO science, however, are not just to generate "ultras," but to understand atoms and light at their deepest level, to probe the fundamental laws of physics, to push the frontiers of our understanding, and to develop new techniques for measuring and manipulating light and matter. AMO research studies the basic symmetries of nature; the properties of space and time; unexplored aspects of quantum mechanics; the interaction of matter and light under extreme conditions; the structure and interactions of atoms and molecules; new forms of matter such as coherent atoms and superfluid atomic gases; and the deep connections between physics and information. Basic research often leads to totally unexpected applications, and while it is too early to judge the ultimate payoffs that may result from the advances and developments reported in this chapter, the joyful quest for knowledge and the promise of new technologies continue to drive and animate AMO science.

Theory Versus Hypothesis

Theories are the means by which physicists understand and describe the world. Some theories are limited in scope and seek only to describe a narrow class of physical phenomena. Other theories are more ambitious and seek to describe such a wide range of physical phenomena that they are called fundamental theories or physical laws. But no matter what the scope of a theory is, all theories have one feature in common: They make predictions that are open to experimental verification. Indeed, before a theory's predictions can be experimentally verified, it is only a hypothesis, a speculation that over time and after rigorous experimental scrutiny will come to be either widely accepted, or rejected.

Physical theories are not immutable—they only represent our current understanding of the world. As this understanding matures, theories change, become more complete, or are supplanted by other, "better" theories. It is a dynamical process that has occurred several times in the last century. Finding the limits of a theory, and pushing it outward just a little bit to discover something new and different, is part of the excitement and joy physicists feel when doing research.

Practically Perfect

A mathematical theorem is either perfectly true or it is false; a circle, by definition, is perfectly round. Physical theories, in contrast, are never exactly true. One finds new physics by probing the limits of presently known physical laws.

These ideas thread through an area of atomic and optical physics that is loosely described as fundamental tests and high-precision measurements. Its origins can be traced to the 19th century, when Michelson developed an interferometer to detect a predicted spatial anisotropy of the speed of light. His failure to find any effect was actually a success: It is often taken as the starting point for explaining Einstein's Special Theory of Relativity.

The tradition of fundamental tests leading to new science and new technologies is alive today. For example, experiments on the spectroscopy of hydrogen have long been a testing ground for basic theory and a driving force for new experimental techniques. The development of the needed laser technology has made it possible to measure the frequency of an absorption line of atomic hydrogen (even though light waves oscillate with a corresponding period of about a femtosecond, a billionth of a millionth of a second) to better than 2 parts in 10^{14} (1 followed by 14 zeros)—about the same as one drop of ink in 10,000 swimming pools! This new capability has potentially revolutionary implications for the science of measurement and atomic clocks, as well as in the communication and navigation applications discussed in the chapter "AMO Science Impacting the Economy."

Another example of fundamental tests is related to theoretical predictions about the nature of the force between the nucleus of an atom and its orbiting electrons. In addition to the dominant electrostatic force, there is the small contribution of a short-range force called the weak interaction. According to the Standard Model of high-energy physics, this interaction has handedness—a property that distinguishes your hand from its mirror image.

In addition to its color and direction of propagation, light is characterized by its polarization, which can be conveniently thought of as an arrow rotating either clockwise or counter clockwise. A consequence of the handedness of the weak interaction is that atoms absorb light that rotates in one direction more easily than they absorb light rotating in the other direction. This effect is minuscule, no more than a part in 10^{12} (one drop of ink in 100 pools). Yet it not only has been detected but also has been measured accurately using laser spectroscopic techniques. Thus, a tabletop atomic physics experiment has provided a test of a fundamental theory; such tests normally require gigantic particle accelerators.

Another puzzle that physicists are interested in is the observation that the basic laws of physics do not seem to depend on the direction of time. To test this observation, AMO scientists are looking at the shape of the neutron. If physical laws do depend on the direction of time, the neutron would behave as if it were not perfectly spherical. The test of this physical law, performed with AMO techniques, is among the most sensitive ever carried out in physics. It shows that if a neutron could be enlarged to the size of Earth, it would be perfectly round, to within the thickness of a human hair. As a sphere, the neutron seems to be practically perfect. When any imperfection is found, physics will take another step forward, and our understanding of the physical world will deepen.

Ultrashort Times

Amazing progress has been achieved in the last 150 years in the study of fast phenomena. Figure 14 shows a sequence of pictures taken by the British artist, photographer, and inventor Muybridge. In the 1870s he was first to capture motion through photography, with a resolution of a fiftieth of a second or so.

FIGURE 14
Muybridge's horse in motion.

Figure 15 is a famous 1957 photograph by Edgerton, the inventor of stroboscopic flash photography, which allowed for resolutions on the order of millionths of a second (microseconds). It shows the splash of a milk drop "stopped" by light from a stroboscopic flash, providing a totally new way to see a familiar event. The exposure time was 0.3 microseconds, several hundred times faster than possible with a mechanical shutter.

FIGURE 15
Edgerton's milk drop.

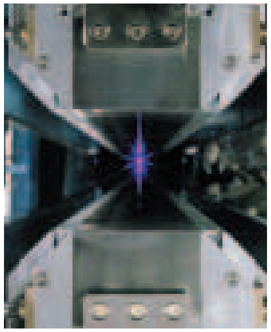
Today, we can view things on a time scale so short that it would make the fastest stroboscopic flash seem interminable. Light pulses of a few millionths of a billionth of a second (femtoseconds) have been generated using ultrafast laser techniques. Femtosecond light pulses are so fast that they can reveal the inner workings of the fastest electronics circuits and "stop" chemical reactions.

Physicists and chemists are now using femtosecond lasers to unravel the complex dance that atoms perform during chemical reactions. The bonds that bind atoms within molecules are made and broken on the femtosecond time scale. For example, the protein bacteriorhodopsin absorbs light to provide energy for a cell. Femtosecond pulses allow scientists to probe and understand how the protein absorbs light, important information when investigating how our eyes work or how plants absorb energy from sunlight during photosynthesis.

As usually occurs when a new technology is created, many new applications suddenly appear. This brochure highlights several such applications in various fields. Shorter and shorter pulses are being exploited in communications. They may be used to monitor water content in plants and food and will form the basis for the next generation of ultraprecise clocks and GPS systems. They might also find application in drilling the smallest, most precise holes for use in microsurgery and micromachining.

Ultrahot and Intense

Earth is a tranquil, relatively nonviolent part of our universe—a veritable backwater near the edge of an average spiral galaxy. If we look outward, we see astrophysical environments completely outside of our experience—hot, violent, and totally inhospitable. At very high temperatures, atoms are stripped of many or all of their electrons. The resulting hot soup of ions, electrons, and photons, which is found, for example, in supernova remnants, is called plasma.



AMO scientists and engineers invent tools that produce ultraintense pulses of light, which can create environments hotter and denser than the interior of the Sun. They also use accelerators and state-of-the-art synchrotron light sources to study the processes that occur in high-temperature plasmas. This allows them to understand how ultrahot electrons, ions, and photons interact and collide with one another in these extreme environments.

Imagine a laser beam focused onto a spot on a solid surface smaller than the diameter of a human hair. As we begin to increase the laser pulse energy, we first vaporize the spot and create a crater (Figure 16). At still higher energies, the laser continues to heat the vapor from the crater until atoms and molecules explode into electrons and ions, forming an ultrahot, ionized plasma with a temperature of millions of degrees, similar to a star's interior. We can turn up the laser pulse energy even higher, so that the laser light pushes the electrons and ions around so violently that they accelerate to relativistic velocities close to the speed of light, hardly interacting with each other at all. In this regime, even the concept of temperature loses its meaning.

Finally, we have lasers with such incredibly high energies that we can literally rip apart empty space to form new matter and light where none previously existed! The ultrashort pulses of light that can accomplish these wonderful phenomena are generated with equipment that would fit on your kitchen table.

As well as providing new tools with which to understand our universe, ultraintense lasers have many practical applications. The craters formed by laser beams have edges smooth enough to be used in eye surgery or for the drilling of microscopic holes or the cutting of materials in industry. Laserlike beams of x rays can be generated and used to "see" atoms and molecules as they move about in chemical reactions. Finally, intense lasers can be used to accelerate beams of electrons to the ultrahigh energies required to study the fundamental constituents of matter. These new x-ray and matter beams may be used in the future for applications such as building smaller, faster electronic circuits or higher-resolution microscopes.

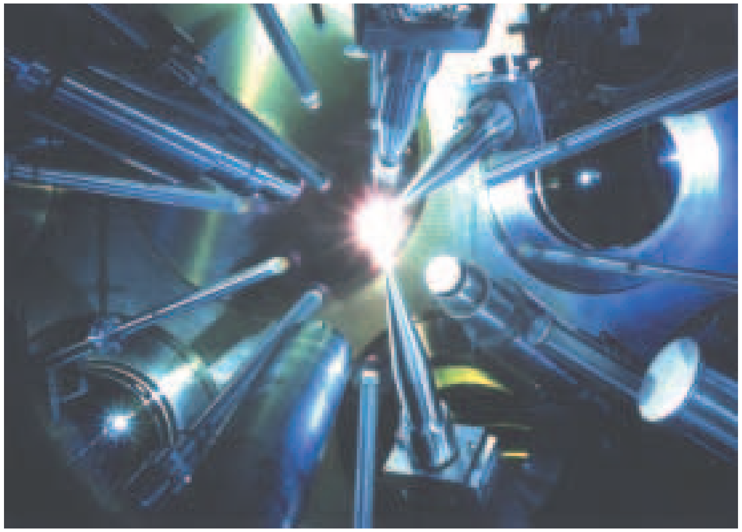


FIGURE 16

Ultraintense laser pulses vaporizing a target.

One at a Time . . .

Atoms are so small that we usually encounter them in astronomical numbers. A cubic centimeter of a solid, for instance, typically contains about 10^{23} atoms (1 followed by 23 zeros); the smallest speck discernable with an optical microscope contains more than a trillion atoms. In view of such numbers, the idea of carrying out an experiment on a single atom seems most improbable. Nevertheless, AMO experimentalists can isolate and manipulate not only single atoms, but also single electrons, single ions, single molecules, and even single photons (see Figure 17).

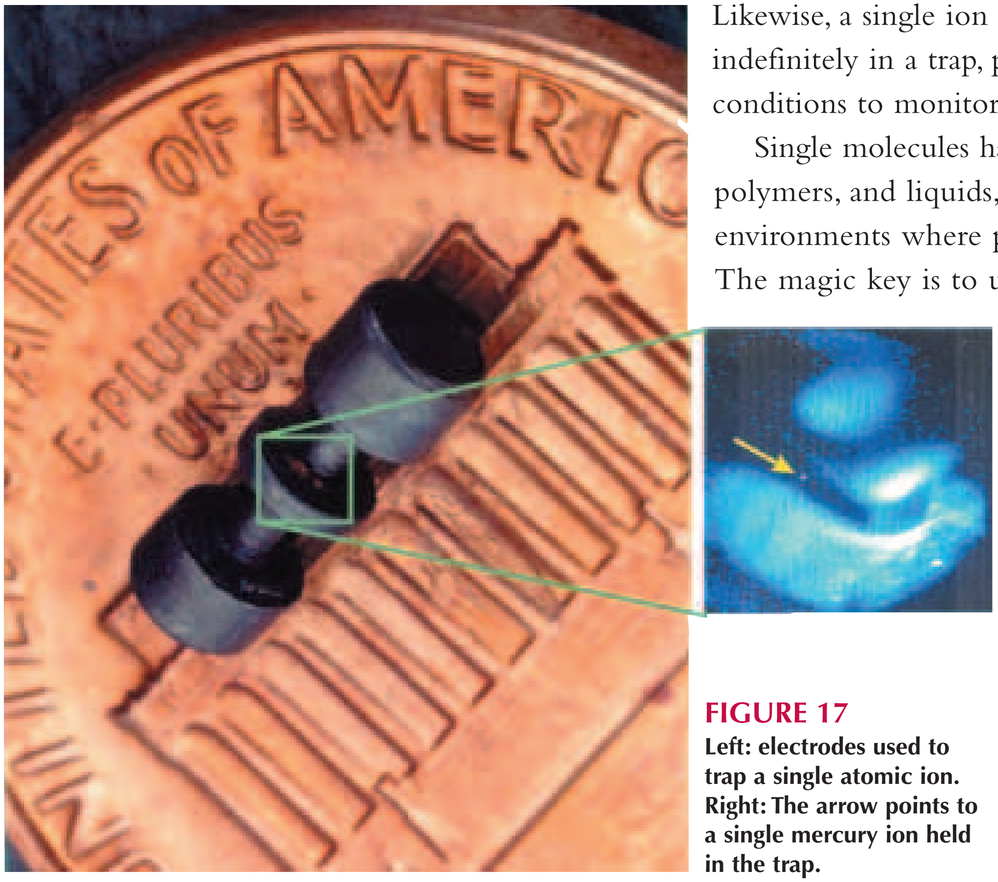


FIGURE 17
Left: electrodes used to trap a single atomic ion. Right: The arrow points to a single mercury ion held in the trap.

Physicists have dreamed of experiments with single particles for a long time. The use of single particles eliminates unwanted interference by other particles. It also emphasizes the quantized nature of light and particles and reveals the quantum effects that are washed out in large ensembles.

A lone electron, trapped and observed for months, has provided the most precise test of theory in the history of physics: Quantum electrodynamics was verified to a precision of 2 parts in 10^{12}. A single photon, generated in a one-atom maser, has been trapped in a superconducting cavity for times approaching a second. If free, it would have traveled 300,000 km during this time. These trapping methods are being applied to new types of quantum systems, advancing our understanding in areas of quantum communication and quantum information processing. Likewise, a single ion or several ions can be held indefinitely in a trap, providing essentially ideal conditions to monitor their behavior.

Single molecules have been observed in crystals, polymers, and liquids, and even in biomolecular environments where proteins and DNA are found. The magic key is to use a molecule that emits light when pumped by a laser beam. Light from the single molecule can then be detected while the possible interfering signal from nearly one trillion other molecules of the nearby host material is rejected. This represents truly ultrasensitive detection.

Single-molecule investigations are opening new areas of biology, physics, and chemistry. They challenge scientists to develop a far more accurate picture of how an ensemble of molecules works. These insights will be crucial in the future drive toward molecular machines at the nanoscale.

Ultralarge: AMO Science in Astrophysics

It is perhaps surprising to realize that much of our understanding about the universe, its origins, and evolution relies heavily on our knowledge of atomic and molecular science. Almost all of the information that we receive about the vast array of astronomical objects in the universe comes to us through the light waves detected by ground-based telescopes and telescopes orbiting high above Earth. Thus, spectroscopy is an important fundamental tool in astrophysics. It is through spectroscopic observations of the early universe, galaxies, stars, supernovae, molecular clouds, and planets, for instance, that one can deduce temperatures, element abundances, and gas densities in such objects—provided that the necessary atomic and molecular studies have been carried out to obtain the relevant spectroscopic data.

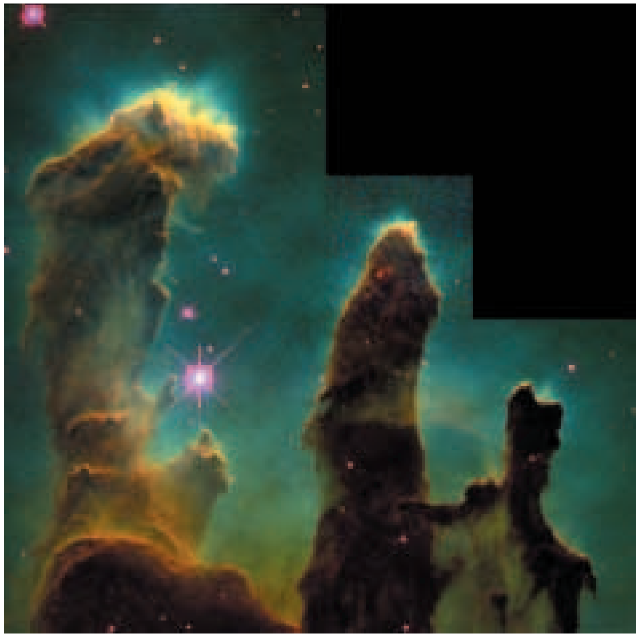


FIGURE 18

New and exciting observations often point to the need for new atomic data. In 1996 astronomers detected x-ray emission from comet Hyakutake. Comets are known to radiate light, either scattered sunlight or solar radiation first absorbed and then re-emitted by gas in their atmospheres, but the origin of these x rays was a mystery. The theory that was developed suggests that x rays are emitted by highly charged ions in the solar wind excited in collisions with neutral species in the comet's atmosphere. The Chandra x-ray satellite, carrying instruments with improved resolution, has confirmed the general predictions of the theory. However, to identify individual x-ray features that are now observed, further laboratory experiments on these ion-molecule collisions will be essential. Meanwhile, x-ray emission has now been observed from several more comets.

In another example, in the last few decades a variety of unusual molecules have been discovered through their radio-emission spectra to exist in interstellar clouds and circumstellar shells. A vast majority of these molecules are hydrocarbons, and a few are the same as simple organic molecules that form the basis of life on Earth. Figure 18, a picture taken by the Hubble Space Telescope, shows a glowing sky surrounding dark regions where there is no visible radiation. These regions are dark because starlight is obscured by large quantities of dust. They do, however, emit radiation at infrared and radio frequencies. It is in such dusty, dark clouds that astronomers have detected a rich array of molecules; in some cases molecules that had never before been seen on Earth were identified in interstellar clouds. Laboratory scientists have since been able to produce them. Aided by computational studies, they have confirmed the composition and structure of these molecules. Further work on atomic and molecular processes contributing to molecular formation will allow scientists to understand the fascinating physics that controls the dynamics and evolution of these interstellar and circumstellar regions. Because interstellar clouds are the birthplace of stars, knowledge of molecular physics will help to unlock the secrets of star formation and stellar life cycles.

Ultracold—Approaching Absolute Zero

Whenever the frontiers of temperature are pushed downward, new physics emerges. Thus, for physicists it is never too cold. When temperatures of a few kelvin were reached (room temperature is about 300 kelvin, or 300 degrees above absolute zero) amazing quantum phenomena were discovered—superconductivity, in which an electrical current flows with zero resistance, and superfluidity, in which liquid helium flows with zero friction.

In a series of developments starting in the mid-1980s, novel techniques based on laser cooling and evaporation moved the low temperature frontier into the nanokelvin (billionth of a degree) regime.

Low temperature means low energy, for temperature is a measure of the energy in a system. The lower the temperature, the less random thermal motion is present. For this reason, access to the ultralow temperature regime has provided many payoffs. For example, atomic motion is an impediment to many precise measurements. However, at ultralow temperatures, atoms move very slowly or can even be made to stand practically still. This slow motion has already been exploited to develop a new type of atomic clock with unprecedented precision. In another application, laser cooling was used to create atomic gyroscopes that have the potential of exceeding the best gyroscopes ever made.

At ultralow temperatures, energy can be so scarce that a gas of atoms forms a new state of matter—a quantum gas. In particular, one class of atoms called bosonic atoms can undergo a transition to what is known as a Bose-Einstein condensate.

Bose-Einstein condensation (BEC) is one of the few known phenomena where quantum mechanical behavior—usually only relevant on a microscopic scale—manifests itself macroscopically (see Figure 19). Research on BEC has provided new insight into the quantum world and has led to a new technology for atoms and atom optics. The 2001 Nobel Prize in Physics was awarded to three physicists for the first demonstration of BEC in 1995.

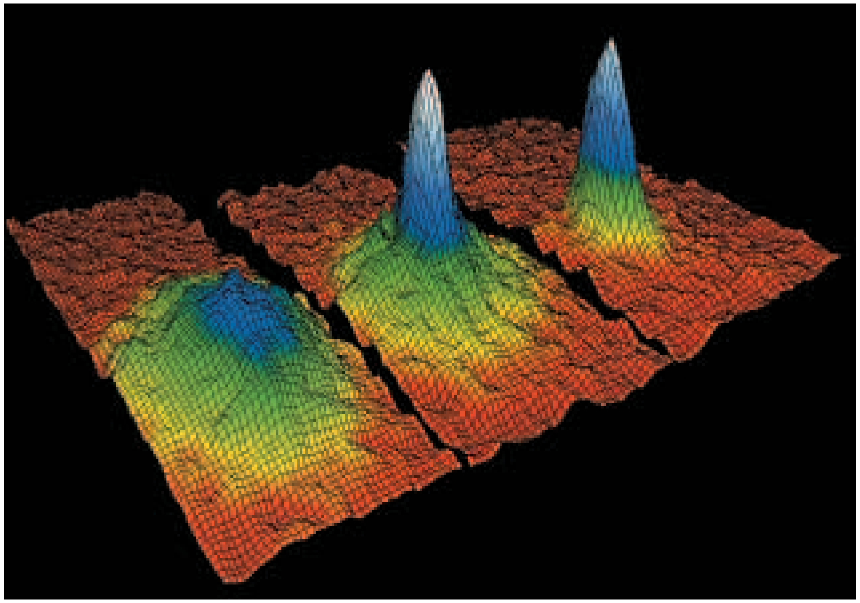


FIGURE 19

The velocity distributions in this figure illustrate the transition from a normal, albeit ultracold, gas to a Bose-Einstein condensate. The broad distribution at the left is characteristic of an ordinary collection of atoms. The narrow, peaked distribution at the center and right represent the condensate, some of the coldest matter in the universe. The vertical axis in the distributions corresponds to the number of atoms, while the horizontal axes correspond to two of the velocity components.

Quantum Weirdness

Computers operate by manipulating sequences of elementary objects, called bits, which can take one of two values, zero or one. By contrast, the equivalent quantum object, a qubit, can be in any superposition of these two values. This is a bizarre consequence of an aspect of quantum mechanics that allows a quantum system to be in two different states at once. For instance, a quantum particle can find itself in two positions, or have two velocities, at the same time. This is the origin of the famous paradox of Schrödinger's cat, which can be simultaneously alive and dead!

Even stranger are the properties of pairs of quantum particles, such as the light produced by an optical parametric amplifier, illustrated in Figure 20. This device emits photons in pairs, for instance a blue and a red photon, or two green photons. Photons, the elementary particles of light, are characterized by a polarization, which can be thought of as an arrow pointing up or down along some direction. If a pair of green photons—the two bright green spots on the picture—is emitted by that optical parametric amplifier, it is fundamentally impossible to know with certainly the polarization of either one. However, if we determine that one of the photons has "up" polarization, we can be sure that the other has "down" polarization. Pairs of quantum particles with this type of correlated properties are said to be entangled. They are so intermixed that there is no way to describe either separately.

Entangled pairs of particles lead to apparently paradoxical and counterintuitive effects, such as the "spooky action at a distance" that so disturbed Einstein. The distinction in the behavior of pairs of classical and quantum particles was quantified in a mathematical form called Bell's inequalities, which are satisfied classically but violated in the quantum world. This violation has been unambiguously demonstrated in a series of beautiful atomic physics experiments.

At the fundamental level, these recent advances have shed light on the mind-bending transition from the microscopic to the quantum world. On the practical side, they are opening up the way to a technological revolution: quantum information technology. They have led to the first demonstrations of quantum teleportation, which allows a quantum system to be exactly reproduced at a distant location. Another application, quantum cryptography, allows the development of unbreakable protocols to secretly exchange information. And someday, quantum computers, which are based on qubits instead of bits, could implement the quantum algorithms being developed for tackling problems that are unsolvable using classical computers.

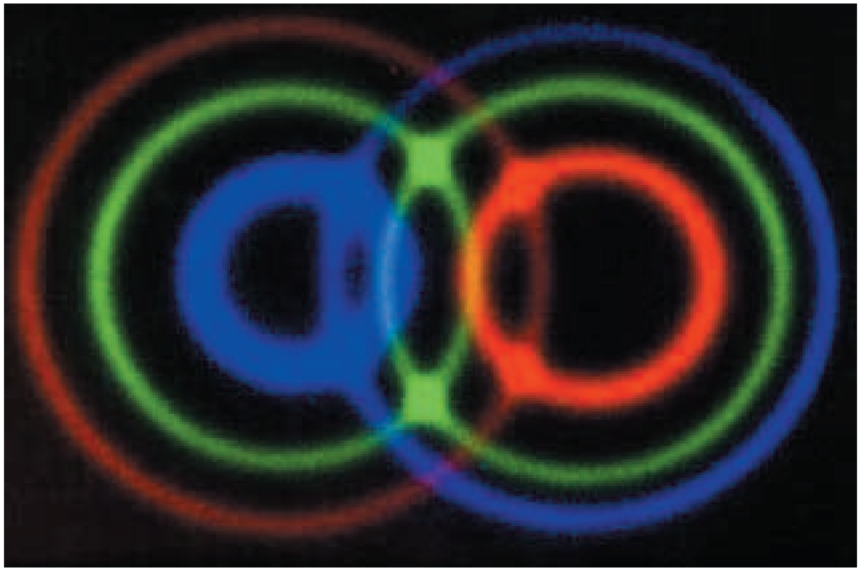


FIGURE 20

Light from an optical parametric amplifier. The bright green spots correspond to the emission of a pair of entangled photons.

Epilog

The breadth of AMO science and its impact have made the discipline attractive to a large number of support agencies. Support comes mainly from the National Science Foundation, the Department of Energy, the Department of Defense, the National Aeronautics and Space Administration, and the National Institute of Standards and Technology. Additional support is realized through active research programs at federal and industrial laboratories.

AMO science is dominated by the work of single investigators and small groups. This mode of operation, often called "small science"—in contrast to large-scale science such as experimental high-energy physics and space-based science—has fostered the creativity and innovation that produce notable discoveries year after year. Students trained in AMO science graduate with a vast range of skills and capabilities, making them valuable contributors to our economy. The vitality of AMO science as a fundamental science as well as a fertile training ground has contributed to the recent birth and expansion of AMO programs in academic institutions across the United States.

We continue to be dazzled by the progress of technology and its huge impact on the economy, health, environment, national security, and homeland defense. It is not possible to fathom the wonderful new ideas that will invariably arise from the basic research currently under way. But more important than the tangible aspects of the progress brought about by discoveries and inventions is the pioneering spirit enkindled by scientific exploration. This pioneering spirit is the key to our nation's continuing security, health, and economic success.

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