The general public has developed a love-hate relationship with computers. More time is wasted trying to make them work than is saved using them. To operate them, there is a dependency on a cadre of individuals who speak strange languages and are not particularly responsive to the user's needs. The prevailing opinion is that this situation is ready for change.

Computers are becoming smaller, faster, cheaper and more powerful. Mainframe computers of a decade ago are being supplanted by desktop models, and these in turn will be superseded by handheld devices which are linked by effective networks. As well as serving as repositories of data and coordinators of activity, computers will help thinkers think. This paper examines these developments, describes current examples of the use of small computers to enhance the pathologist's work and looks forward to technologic discoveries that will affect pathology and laboratory medicine.

Try to imagine making predictions in 1898 about 20th century pathology and laboratory medicine. Most of the field as it is known today did not exist. The transistor would not be invented for another half century. The rate of technologic change has exceeded all expectations and is even more heightened now. Economic and social advances are no longer hinged on the growing availability of capital, supplies of workers or the ever-increasing utilization of natural resources. Rather, the driving forces for the coming century will be the power of ideas and the command of skills and information.

At the beginning of the 20th century, the most precious materials arrived in bags, crates, boxcars and ships. On the eve of the new century, the most eagerly sought commodities can be shipped over the Internet. New types of products and services are constantly being introduced, eclipsing those of a year ago. The impact of the microprocessor continues to broaden. Computers are disappearing from desktops into devices. Moreover, communications capabilities are being added that will make for fabulous machines. In the next decade, people will be able to speak to computers, and computers will respond vocally.

Pathology is not exempt from the dictates of this new reality. The pace of modern life, which creates and then overturns whole fields of knowledge, presents challenges and opportunities. The singular style of learning and investigation exemplified by the Association of Clinical Scientists is more compelling today than at the founding of the society. Pathologists of the next century will need a broad education, not merely a specialty. Practitioners will have truly learned to learn and will be able to communicate knowledge effectively.
Approaching the Limits of Technology

In 1965, Gordon Moore, co-founder of Intel Corporation, proffered "Moore's Law," which states that microprocessors double in power and performance every 18 months (table I).\(^3\) This growth has facilitated development of the industry (table II) but cannot continue indefinitely. The size of atoms sets an absolute limit in materials. Moore himself believes that the limit will be reached in 20 years if the same curve is maintained.\(^{14}\) Progress may slow before then. The problem is that light cannot project an image much smaller than its wavelength.\(^3,8,14\) Fabrication plants today use ultraviolet light to print chip features as fine as 350 nanometers. To go down further requires shorter wavelengths of ultraviolet light, but lenses cannot focus an image below 193 nanometers. When that occurs, the accumulated knowledge of photolithography will be exhausted. Engineers will attempt different technologies. If more transistors cannot be crowded on the surface of a chip, they will try its third dimension: building down and up, as in the subways and skyscrapers of land-starved Manhattan. Chip makers are already doing this. If silicon cannot be shrunk or drained of its heat, another semiconductor, such as gallium arsenide or silicon germanium, is a possibility. When electronics itself becomes poky, it can be set aside for photonic circuits, which run on light waves.

Sustaining Moore's Law for another 50 years will be more than sufficient to realize some bizarre dreams. By 2047—exactly one century after invention of the transistor—computer chips will be 10 billion times more powerful than they are today. The chips will also be unbelievably inexpensive on a per-transistor basis. One could toss them around with abandon. Microprocessors could literally be woven into the fabric of society—into clothing, shoes and doorknobs. Houses might keep track of the rooms being occupied and adjust light and heat accordingly. When combined with biosensors, they could continuously and unobtrusively monitor many body functions and suggest or initiate corrective action.

There are limits on software as well as on hardware. Computer systems are too complex. Mitch Kapor, president of Lotus Development Corp., echoed the sentiments of many when he said, "Not a day goes by that I don't want to throw my computer out of the window." Icons on Macintoshes freed users from memorizing commands, but computers are now so crammed with icons that it is impossible to remember what they all mean. They stifle, rather than boost, efficiency.

Software is devilishly difficult to design and update. There are humorous incidents in the attempts of factories to automate.\(^5\) At General Motors, heavy-handed robots smashed the windshields they were supposed to install and spray-painted each other rather than cars. At General Electric, robots were confined to cages after occasionally hurling hot metal parts at workers. There have been successes, but large-scale programming remains problematic. In 1996, U.S. companies canceled 40 percent of large software projects. Only 27 percent were considered successful (Standish Group International).\(^5\) Automation of hospital functions has proved particularly onerous. Many pathology groups lose a high percentage of income because of inadequate billing systems. Some difficulties result from poor coding. A more fundamental dilemma is that many problems are too complex for even the largest and fastest computers. For example, factoring a number of N digits by the trial division method requires \(10^{172}\) divisions. Accordingly, factoring a 54 digit number on a computer capable of \(10^{10}\) divisions/second would take \(10^{17}\) seconds, which is the age of the universe.

### Table I

| Moore's Law – Increasing Capacity and Falling Price of Computers |
|-----------------|-----------------|-----------------|
| Year            | 1979            | 1984            | 1997            |
| RAM             | 16K             | 128K            | 12,000K         |
| Disk size       | 128K            | 40,000K         | 10,000,000K     |
| Speed           | 2MHz            | 10MHz           | 250MHz         |
| Cost            | $5000           | $3900           | $1400           |
Problems of human organization and professional activity are typically more complex than computer engineers can comprehend. Automating such processes may never succeed.

Learning to Use the New Technology

Laboratory information systems are large multimillion dollar machines run by a cadre of specialized personnel possessed of a curious vocabulary. They are intimidating to most pathologists, but large computers are not the only systems available. In fact, Davis and Wessel have suggested that the most important benefits will be derived from small computers. They draw an analogy with the introduction of electric motors a century ago. Water wheels or steam engines were replaced by electric motors in early factories. Using a rotating shaft extending the length of the building along the ceiling, an entire factory was powered by one large motor. Each machine was driven by a belt attached to the shaft. Only when small motors were placed in each machine and tool was the real value of electric motors realized. Main frame computers are like the large electric motors that power an entire factory. Much of the benefit of computers may not be recognized until most of the large machines are replaced by small models performing specialized tasks.

During the past 20 years, in an endeavor to keep abreast of developing technology, people have been compelled to replace computers prematurely. Today this process has been slowed by a more discriminating public demanding value for individual needs. In 1997, the computer costing less than $1,000 comprised the fastest growing market segment. These machines can meet the needs of most...
users. Desktop computers are rapidly being supplanted by handheld or palmtop models. In 1997, 32 percent of laptop computers purchased were to replace desktop machines.

Early automobiles were built to replace carriages, and they resembled carriages until engineers were able to create designs that took advantage of the automobile's unique potential. Computers have developed in similar fashion. Most programs have been written to perform well-established tasks with more speed and lower cost. Adding machines, typewriters and legal records were superseded by spreadsheets, word processors and database programs. This facilitated major changes in airlines schedules, credit cards and clinical laboratory operations. Computers are now being used in ways that have no historical counterpart (e.g., the human computer interface and genetic programming). These technologies can be of considerable benefit to pathologists. According to Davis and Wessel, the primary function of computers is to help thinkers to think.5

**Definition of the Core Values of Pathology**

The future of clinical pathology is contingent upon its ability to apply this changing technology. In 1969, Peter Drucker stated that information, rather than material resources or capital, creates wealth.6 This concept has been repeatedly confirmed. In September 1998, Microsoft outranked General Electric as the most valuable company in the world. Unlike smokestack industries, Microsoft's only factory asset is the human imagination.13 The increasing importance of information services is evident in the design of research buildings. Twenty years ago, university biomedical research buildings typically comprised 60 percent wet lab space. With the greater use of computers in research, the same institutions are now constructing only 40 percent wet lab space.

Pathology has traditionally been a bridge between basic sciences and clinical medicine. Some view it as a business, aimed at producing commodity laboratory tests and low-cost histopathologic diagnoses. HMOs and automation have intensified this perception. However, many voids in medicine remain. The communications revolution offers new ways to disseminate information and expertise, and pathologists are well situated to assume a leadership role. Self-image is important (table III). If pathologists see themselves as purveyors of knowledge and services to enhance the practice of medicine, if they strive to develop better modalities of care and more efficient ways to deliver care, they would fulfill their academic and social missions and at the same time would be formidable competitors in the commercial arena.

**The Rise of Networks and Need for Standards**

In 1997, Kevin Kelly, editor of *Wired*, wrote, "The grand irony of our times is that the age of computers is over."10 He believes

---

**TABLE III**

<table>
<thead>
<tr>
<th>Principles for Thinking About the Future of Our Profession</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where the expense of turning out tests becomes trivial and regulations become oppressive, the value of information and information systems boom (Kevin Kelly).10</td>
</tr>
<tr>
<td>The only factor becoming scarce in a world of information abundance is human attention (Tom Peters).16</td>
</tr>
<tr>
<td>We are trying to sell more and more intellect and less and less materials (George Hegg).7,17</td>
</tr>
<tr>
<td>The only sustainable competitive average comes from our innovating the competition (James Morse).16,17</td>
</tr>
</tbody>
</table>
that all significant consequences of stand-alone computers have taken place. Laboratory Informa-tion Systems (LIS) offered by major vendors are mature software products, and new systems are unlikely to bring meaningful improvements to internal laboratory operations.

New technologies are the result of communications between computers. During the next year, data traffic is expected to surpass voice traffic and global telephone systems. Communication requires standards: absent a common language, individuals could not understand each other. Historically, the development of language or standards has followed the development of technology. Until the printing press mandated consistent spelling, a dictionary in the English language did not exist. The growth of networked computers has led to a pressing need for new criteria. Most medical computing applications have expanded like nomadic tribes wandering the continent with little or no interaction between them.

In many cases, the intricacy of existing systems makes the introduction of standards prohibitively expensive. The Year 2000 problem is a good example. Adapting computer systems to handle a four-, rather than two-, digit date is costing billions of dollars. Hospital laboratory systems currently face scores of parameters which will be as complex to fix as the Year 2000 date field. Consequently, these systems will never be standardized and will eventually be replaced by new systems built from the ground up. Interfaces and interface engines provide a means for small numbers of computers to communicate with each other if the records passed between them are modest and the differences in their internal systems are minor. They are not the solution to the larger needs.

Worldwide Web to the Rescue

The explosive growth of the Worldwide Web is attributed to a set of standards which enables computers to communicate with each other. The first standard is Telecommunications Communications Protocol—Internet Protocol (TCP-IP), which allows computers to find one another. Each machine is assigned an IP address, which, like a telephone number, uniquely identifies the country, region, location and, finally, the individual computer. The second standard is Hypertext Transfer Protocol (HTTP), which gives computers a common language with which to transfer information. The third standard, Hypertext Markup Language (HTML), provides instructions for displaying messages. Vexing problems such as compatibility between PC and Macintosh computers or WordPerfect and Microsoft Word documents vanish when appropriate standards are adopted (table IV).

Emerging Global Healthcare Language (Extensible Markup Language) (XML)

While HTML propelled the expansion of the Internet, its limitations have become apparent. A new standard, XML, has been developed to facilitate communication of all medical information. Some pundits believe it is perhaps the most important technological event since development of the silicone chip. XML will be able to organize and transmit all information stored in health care databases as well as point-of-care information and other items that are seldom included in the electronic record. It is an open standard that can

<table>
<thead>
<tr>
<th>TABLE IV Standards for Healthcare Information Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICD9 – Codes diagnoses.</td>
</tr>
<tr>
<td>CPT – Codes procedures.</td>
</tr>
<tr>
<td>SNOWMEDS – Codes pathologic diagnoses.</td>
</tr>
<tr>
<td>HL7 – Interface standard for medical records.</td>
</tr>
<tr>
<td>LOINC (Logical observation and identifier names and codes)</td>
</tr>
<tr>
<td>Codes laboratory tests and clinical laboratory variables.</td>
</tr>
<tr>
<td>CLIMS (Components and instruments interfaces).</td>
</tr>
<tr>
<td>ASMLM (Arden Syntrx for Medical Logic Module) standards for writing reminders, alerts interpretations, and diagnoses.</td>
</tr>
</tbody>
</table>
be used by any vendor or computer and supports all languages. When XML is fully implemented, physicians will be able to read medical records in other languages as easily as their own. This will truly transform the medical profession.

Patient identification is often the most daunting obstacle in interfacing medical computer systems with one another. Some countries (eg, Canada) assign national medical record numbers, but in the United States this proposal has been vigorously debated. The problem is not in technology; pets and farm animals are harmlessly identified by microchips placed under the skin. The difficulty with identification of humans lies in the potential for invasion of privacy. This predicament must be resolved if full benefit is to be derived from health care information systems.

Glimpse of the Future

The future of laboratory information technology is to be found in the universal availability of handheld super computers with wireless Internet connections and a complete set of communications standards. Such technology would support development of new paradigms in health care. When Kevin Kelly stated that "the age of computers is over," he was correct to the extent that existing programs have reached an advanced level of maturity for accomplishing tasks with speed and accuracy and that the foundation of major changes is in networks. However, his theories disintegrate when one considers the new types of software applications (eg, the human interface and evolutionary programming) now unfolding and the powerful handheld computers with wireless Internet connections under development.

From the outset, communication with computers has been via modified typewriter keyboards. From yesterday's punch cards to today's PCs, this keyboard has changed minimally. The mouse and other pointing devices were major advances, and progress is being made in voice recognition, visual pattern recognition and remote sensing. Physicians will be able to communicate with computers as they communicate with each other. The profession has just begun to discover the impact of this technology.

Programming by Directed Evolution

Most computer programs are based on algorithms, which are mathematical or other plans for solving problems. In many areas, systems are becoming more complex than the human mind can manipulate. H. David Shaffer of Phillips Electronics has stated that the next level of complexity can be reached only through evolutionary methods. Engineers who formerly thought in Cartesian, gears or straight lines, are finding that concepts of biological evolution are liberating the design of hardware and software.

Computer aided design (CAD) helps engineers prepare drawings, but its principals are the same as if the engineers had used pencil and paper. Evolutionary programming is modeled on genetic mutation and natural selection. The building blocks or components of a possible solution and criteria for evaluating candidate solutions are first defined. The building blocks include small segments (genes) and large segments (chromosomes). A random population of candidate solutions is then set up in the computer, and a breeding and natural selection process to optimize the products is initiated. The process includes mutation of genes (small sections) and sex (recombination of large segments chromosomes) and enrichment of the next generation with the fittest of previous generations. The computer selects the most appropriate solution at each generation to breed (recombine) for future generations.

Evolutionary computing is untidy. Programmers define only the components and selection criteria and allow programs to evolve towards optimal solutions. However, it is precisely because it is disorderly that it finds solutions that are more efficient and flexible than those written by human programmers. The principles of evolutionary computation have been understood for many years, but only recently has computational capacity increased
sufficiently for practical application.\textsuperscript{18} The Boeing 777 aircraft has the most efficient jet engines ever produced. The geometry of the combustion chambers of these engines was designed by computational evolution. At Deere and Company, which manufactures a bewildering array of custom farm machinery, daily schedules are “bred” that direct assembly lines in six factories to fill custom orders for millions of varieties of agricultural equipment. Daily production schedules are “consistently more efficient than any person could have figured out.” The NIH supports Natural Selection, Inc., in using evolutionary programming to teach computers to read mammograms with more speed and accuracy than could a radiologist. At the University of Virginia, work schedules for laboratory technologists are “evolved” by genetic programming and have proven superior to those produced by supervisors (J Boyd, personal communication).

**Future Instrumentation**

Predicting the direction of a paradigm is impossible. Nevertheless, laboratory instrumentation is following a pattern similar to that of Moore’s Law. Instruments are becoming smaller, more powerful and less expensive. There is a well-established pathway for laboratory tests. They begin as complex procedures in research laboratories. When there is sufficient interest, the procedures are transferred to reference laboratories and then to central hospital laboratories and progressively to doctors’ office laboratories, point-of-care devices and finally consumer products. With the current activity in molecular biology, one can confidently expect continuing development of new tests in research laboratories.

With this in mind, scientists can speculate on the nature of laboratory instruments in the 21st century. Handheld devices will be able to do hundreds of assays on a single drop of blood, urine, saliva or sweat. They will monitor vital signs and chemistries through the skin on an ongoing basis. They will have the power of 1980s super computers and will be able to speak, listen, call for help and dose medication. Moreover, the instruments will maintain a dynamic medical file, recording multiple parameters simultaneously and continuously. The data will become part of a national or international database for epidemiological studies and risk analysis. Together with pertinent medical literature, this information will be available on a constant basis. The problems with patient identification and confidentiality will be resolved in ways that preserve individual rights and promote public health and epidemiological research. Such devices will inevitably eliminate jobs in laboratories and may eliminate laboratories as we know them, but they will generate opportunities for new and more rewarding work. As always, the need for scholarly health care professionals will grow as technology advances.

**Current Examples**

**Voice-to-Text in Pathology**

Several companies (IBM, Dragon Systems) have made extensive advances in voice-to-text software to translate conversational English into standard text. Because these systems merely automate an existing process and do not move it forward, they have not gained wide acceptance. In fact, some experts deem them a step backwards. Medical records require more standardization and less random verbiage. However, this technology has other applications. Systems are being developed which remind pathologists of the pieces of information that need to be recorded on each specimen. If they can be combined with real-time-assisted coding and clinical alerts derived from medical records, their value would transcend merely replacing transcriptionists.

**Imaging Systems in Anatomic Pathology**

Some scientists considered imaging systems for anatomic pathology valuable for teaching but did not contribute significantly to the diagnostic process. An analogy with x-rays would disprove this conjecture. Physicians gain a bet-
ter understanding of medicine and, consequently, make better decisions when they have access to x-rays than if they had only the radiologist’s narrative report. When images in pathology become as available as x-rays, one can look forward to a different perception of pathology and an improvement in standards of practice across a broad segment of the profession.

Clinicians will enhance their understanding of pathologic diagnosis and disease processes when they are able to see diagnostic fields of biopsies regularly. The equipment has improved dramatically and at lower cost. At the University of Texas–Houston, the system is integrated with the Cerner Anatomic Pathology System. Patient registration and test results are passed to the imaging system as they become available. A digital camera is attached to a microscope. Images can be captured without disrupting the normal workflow of sign-out. The process then shifts automatically to print reports, with images of photographic quality. Images and text report can also be distributed by e-mail or other electronic means. Methodology for accessing images through the hospital’s electronic medical record are under development.

**Pathologists’ Workstation**

To make both guidelines and draft interpretations readily available to pathologists, at the University of Texas–Houston, a basic workstation with off-the-shelf components was designed to use the web hypertext technology. Employing a terminal emulator program, a PC was connected to the main laboratory computer. Initially, interpretations in word processor files were saved as they were produced, and a large collection of files covering most of the common specimens soon accumulated. These were then translated into HTML and organized with appropriate links for rapid browsing. In practice, one or more draft interpretations were selected from the HTML files and pasted on a “scratch pad,” where they were combined and/or edited. The completed interpretation was then pasted into the laboratory computer and the record immediately verified.

This simple system helped pathologists to produce reports of higher quality and at lower cost than would have been possible by dictation and transcription. Once the wording of a particular incident had been formulated, it remained easily accessible when the situation recurred. At first, there were different sets of draft interpretations for various pathologists; in time, common interpretations were adopted as more efficient.

Keeping clients advised as to payer rules, laboratory services, specimen requirements, turnaround times, normal ranges, etc., is an ongoing problem for laboratories. Electronic manuals can integrate data from the laboratory system with details on laboratory operations, personnel, hours, etc. Many hospitals now have such manuals (http:\www\emory.edu\whsc\clinlabs). In the future, information on order systems will be available so that clients will have complete data when ordering tests. In developing user-friendly means to order products, laboratories lag far behind other industries.

**Patients’ Interactions**

It is the opinion of many that ownership of electronic medical records should be fundamentally revised. Avenues are being explored to transfer responsibility for these records from health care facilities to patients. Dr. C. Edward Koop, former Surgeon General, has founded Empower Health (www.empowerhealth.com) to offer comprehensive personal health information, news, e-commerce and interactive services to individuals so that they can manage their health better. The personal medical record system is an Internet-enabled suite of applications designed to allow consumers to track and record their medical data privately and securely. When fully operational, this system will collect medical information from the patient’s health care provider and, as instructed by the patient, will
make it available to other providers. Pathologists are in a good position to benefit from this technology.

**New Paradigm for Pathology**

Since the beginning of the Industrial Revolution, people have worried that their livelihood will be replaced by automation. When laboratory computers were introduced in the 1960s, some pathologists became concerned for their jobs. The writer proposes two observations as Hunter’s Axioms. The first is: Attempts to replace professionals with automation will fail. Software designers cannot anticipate all situations confronting professionals. The second is: Attempts to enhance the efficiency of professionals by providing them with necessary data will succeed. The greatest potential lies in leveraging the intellect, ie, using computers to revamp the way people think and work together. The need for professionals will grow.

The future of the clinical pathology will be determined by its ability to adapt to advancements in technology. An anecdote of the airlines and railroads may be pertinent. In the 1950s, the airline industry experienced vigorous growth, but the railroads with its ticketing network, sophisticated communications, baggage- and freight-handling infrastructures and unlimited access to capital, were in a position to dominate. However, no American railroad established a significant presence in the airline industry because they believed they were in the railroad business, rather than the transportation industry.

If clinicians believe that they are in the business of producing test results in central laboratories, then their future will become ever more constricted. However, if they perceive their mission as that of providing information for physicians and patients on managing health care more effectively, then they will be in a growth industry for the foreseeable future. The most critical evolving use for computers may be to help thinkers think. The success of programs will be limited primarily by lack of imagination and failure to seize opportunities. As it has in other fields, information technology will change clinical pathology. However, the need for quality diagnostic information personalized and interpreted individually is intensifying.

**Reference:**