# ◆ Bell Labs Innovations in Recent Decades

*"Bell Labs Innovations." The phrase is new to company logo, but the reality it suggests is legendary. Indeed, Bell Labs, Lucent Technologies' R&D unit, sustains a long and distinguished history of innovations. We are pleased to begin this special issue commemorating the 75th anniversary of Bell Labs by highlighting innovations associated with the tenures of Bell Labs' most recent past presidents—William O. Baker, Ian M. Ross, John S. Mayo, and Daniel C. Stanzione. Each past president provides perspectives on innovations of special economic and technological impact advanced during his time in office.*

*(Bell Labs' current president, Arun N. Netravali, reflects on future innovations at the end of the issue.)*

**William O. Baker**
**President, Bell Labs**
**1973–1979**
**Chairman**
**1979–1980**

As we approach the maturity of the Information Age, it is especially gratifying to have the opportunity to identify two examples among those major technologies launched in an earlier time that have helped lay the foundation for this Age and that are continuing to have far-reaching commercial and social impact today: cellular wireless communications and photonics. Both occupy prime spots in the continuum of escalating capabilities in telecommunications, and they build on earlier notable solid-state and radio research.

The primary systems experiment in mobile radiotelephony took place in 1976, with a cellular wireless trial following in 1978. Also during this time frame was the operation of a total transmission system based on the first functional photonics, including lasers and optical fibers. (The introduction to telecommunications of photonic transmission in open space also took place during this period, and the concepts are currently being applied in Lucent's new WaveStar™ OpticAir™ system for transmitting high-speed data in metropolitan areas and campus environments.)

It is also desired at this 75th anniversary of Bell Labs to pay tribute to colleagues, too numerous to be named, who have sustained us in the technical decisions and developments advancing these technologies. They have created experimental evidence that the workable systems predicted by our basic knowledge from the first three-quarters of the century could, indeed, be pursued to implementation. Thus was practiced an early form of "futurism.com"—with only the ingenious Bell Labs creators confident of a successful "IPO."

The output from Bell Labs is of course the product of individuals and groups—the human aggregate—in contrast to any disembodied institutional product. Accordingly, the issue of what we knew or did not know at the long-passed time of technical decision-making is an intriguing exercise in human fallibility, spread among personalities and individual achievement and knowledge. Correspondingly, the total basis for a risky decision has to be an informed balance between the improbable and the impossible. This balance is weighted heavily with our knowledge of the impossible, which has grown dramatically with the maturing of telecommunications and with advancing skills and worldwide application in electromagnetism and materials.

Let us first turn to photonics, which built on the aggregation of many seminal inventions. The long search for a workable incarnation of Dr. Alexander Graham Bell's photophone took a new path with the discovery at Bell Labs of the laser—or "optical maser"—by Arthur Schawlow and Charles Townes and with the subsequent creation of coherent optics. Thus, by 1974, Bell Labs researchers had created integrated optical circuits. Moreover, extensive Bell Labs research in the chemistry and engineering of silicon itself yielded optical fibers generated by modified chemical vapor deposition. These fibers, also in 1974, became the first with a loss of less than 2 dB/km, a major milestone toward practical photonic transmission systems. These advances came along with passive, mode-locked lasers and picosecond light-pulse generators. Finally, the Burrus light-emitting diode and the proposal and patenting of broadband wavelength division multiplexing (WDM) then established the foundation for the vast bandwidth and data-handling capabilities of today's backbone optical networks. Coordinate with these transmission capabilities were a host of devices and physical controls, including distributed feedback lasers and support units, connector and splice-loss measurements and controls, and an array of other engineering advances basic to a definitive optical systems trial.

The experience and knowledge from this background led to the digital transmission systems experiment in Atlanta that introduced photonics as a generic communications capability. It was decided in January of 1976 that this experiment would function at 44.736 Mb/s, with a cable of 144 fibers, and terminal circuits matching the transmitted signals. The Bell Labs engineers planning and conducting this experiment were especially oriented toward the challenging questions of cross talk as well as fiber joining and splicing and other previously unknown features of optical fiber communications. The Atlanta experiment and the subsequent system trial in Chicago were successful in establishing photonics as the new, highly reliable, high-capacity communications medium. The report in the *Bell System Technical Journal* (Vol. 57, No. 6, Pt. 1, pp. 1717-1898) of the Atlanta experiment provided a particular commercial impact.

The experiment also demonstrated how a total systems synthesis and engineering could be done independently of extensive and prior field experience and operating methods. Thus, it appears that, somewhat separately from the specific innovation of photonics, there was also the innovation of a new project-management system employing the aggregated skills and organization of Bell Labs. Accordingly, the Atlanta model enhanced the Lucent capacity for designing and implementing totally new commercial systems.

Let us turn now to mobile radio telecommunications. Bell Labs had a long history of radio research, but the orientation of this pursuit changed drastically around 1955, with the solid-state era and new theoretical telecommunications principles. The long-recognized service and technological potentials of mobile radio telecommunications were thus supported by many years of Bell Labs research and development.

Novel experimental action resulted from the decision of the mid-1970s to inject new engineering and science of switching, transmission, computer functions and radio techniques into a newly combined system that was based on cellular radio concepts put forward at Bell Labs in 1960. This action took the form of a Bell Labs initiative to construct and install a full-scale operational trial of advanced mobile telephone service. The trial applied the probable—although not assured—allocation by the Federal Communications Commission (FCC) of an 850-MHz band with 75-MHz frequency for common carriers. Obviously, this exercise, which was to be done in Chicago, involved the high risk of providing large, reliable service capabilities that would satisfy long-delaying regulators as well as the difficult economics of Bell Labs' owners and supporters, AT&T and Western Electric. Accordingly, detailed integration with new radio research and development was also required.

Thus, the 40-MHz channel in the 850-MHz band first granted by the FCC in May of 1974 had to be expertly exercised. There was little room for failures or deficiencies, because this Chicago field experiment in 1978 not only completed a saga begun with mobile telephone service in 1946. It also represented the emerging universe of cellular radio in its most sophisticated embodiment. This era became, as well, the classic case of regulatory delay—of restrained radio frequency, in which governmental regulation had severely limited customer access and use.

Clearly, the influence of regulatory restraints and other uncertainties helped drive the gathering of experimental evidence of reliability and quality prior to the long-delayed commercial adoption of public cellular services in the United States. For example, FCC authorization for the tests begun in Newark followed extensive system preparations, including the only U.S. proposal to the FCC by December of 1971. In response to this proposal, the FCC authorized tests in the 825- to 845-MHz mobility base and 870- to 890-MHz-based mobile. Even then, actual trial uses were turned on only in December of 1978, furnishing 136 voice channels operating through a central switch in Oak Park, Illinois. Moreover, the Bell Labs Advanced Mobile Phone System (AMPS) was shown to be superior to spread-spectrum utilization of frequencies, despite proponents to the contrary. This argument alone had been the cause of considerable delay in the FCC acceptance of our plan. Finally, even though the Chicago trial results worked directly for commercial use, these public services, when introduced in October of 1983, lagged behind the first network in Japan by four years and the availability of NMT 450 in Scandinavia by two years. Nevertheless, there were over one million subscribers in the United States by the end of 1987 and nearly 34 million by the end of 1995, with about 80 million in 1998.

The cellular experiments in New Jersey and Illinois had broad implications for general digital as well as analog telephony and telecommunications and information handling. They also had implications for the challenges that the systems offer today. Indeed, the cellular system at the center of these experiments was, in the words of I. M. Ross, Bell Labs' sixth president, "a synergistic combination of switching, transmission, computer, and radiotechnologies." In addition, great care was required to build these qualities of excellence into the ultimate experiment in order to gain the influence, fundamentally and publicly, that was justified.

Moreover, the simultaneous pursuit of digital techniques in cellular mobile radio not only led to the careful introduction of digital systems for mobile telephony, but also expedited the global spread of personal communication networks (PCNs). This work, in turn, drove our plan of the mid-1970s in showing that a limited-range radio signal—analog to begin with—favored the high-megahertz radio frequencies for implementing signaling among cells. The signals were then handed over to advanced switching as the way to move ahead in this dynamic market.

The approach decided upon, for initial cell size of about 8 miles in radius, with omni-directional antenna transmission, functioned as planned, including new software for interconnection to the fixed telephone network via mobile telephone switching office (MTSO). The FM channels of 30-kHz width were all managed by control channels fitting the expanded volume and versatility of the cellular wireless system. Particularly, long-debated spectral usage was optimized through a function of the communication capacity per unit bandwidth.

Both the radio technology of high frequencies and the control and switching system of cellular science and engineering combined to trigger a mobile phone sector growth of more than 50% in 1998. The cellular telephony achievement has been substantiated by numerous basic patents in the mobile and cellular fields and recognized by many awards in Bell Labs—including the Alexander Graham Bell Medal of the IEEE and the U.S. National Medal of Technology covering this wide domain.

Importantly, each frontier in the broad field of cellular telephony had been well identified so that synthesis for the Chicago experiment was relatively complete. The system was thoroughly analyzed during the planning and execution of the trial, and the analysis showed how digital schemes offered efficient spectral usage as high-speed digital circuitry was being attained.

Overall, the concept and execution of this cellular wireless trial have underlain the multibillion-dollar global wireless/cellular market in which Lucent plays such a major role today. Together with the technology of photonics, cellular telephony has helped lay the foundation for today's maturing Information Age. ◆

**Ian M. Ross**
**President, Bell Labs**
**1979–1991**

Perhaps the most fundamental technical innovation in the history of the Bell System's network was its conversion from essentially all analog to all digital. This involved converting from equipment based on relay and vacuum tube components to microelectronic components, together with developing extensive software systems to customize the hardware and to facilitate both network and business operations.

The technical underpinning for this work took place at Bell Labs over several decades. It started with invention and development of semiconductor devices, with dominant Bell Labs contributions in the early years and continuing contributions to this day. The pioneer of digital transmission systems, T1 carrier, was put into service in 1962, and the world's first digital switch, 4ESS™, was cut over in Chicago in 1976. However, I think it is fair to say that the major implementation of digital networking took place in the 1980s. Regardless of the exact dates, this important innovation should be covered somewhere in this publication, and I will attempt to do just that.

In the early 1980s, planning was under way for evolution of the end-to-end digital network, followed by extensive implementation. Between 1987 and 1989, AT&T alone spent about $8.7 billion on network evolution, mostly for digital switching and transmission and for software for intelligent functionality in new digital facilities. By mid-1990, the more than 1.8 billion circuit miles of AT&T's domestic network were all digitally transmitted.

Despite the success of T1 carrier systems for major urban areas, digital voice transmission was not considered competitive for long distance networks until the development of optical fiber technology. The first long distance application for digital fiber was in short spans between the toll switches of the Northeast Corridor of the United States. In 1986, AT&T's first application of coast-to-coast fiber connectivity was installed for General Motors, and by 1990 nearly all FT Series G lightwave systems were upgraded from 417 Mb/s to 1.7 Gb/s.

A major milestone during this period was the 1982 commercial introduction of the 5ESS® Switch, the first time-division, digital switching system AT&T designed for local and toll offices, as well as for private network and stand-alone applications.

The 5ESS Switch employs a modular hardware and software architecture, which improves its economics, allows more flexibility for growth, and simplifies the development process to introduce new technologies into the switching system and add new features. Structured programming techniques, high-level languages and modular design were used to achieve high capacity, functionality, and reliability. Specifically, one key is that the operational software architecture is organized with a generalized operating system and database manager in order to achieve a high degree of hardware independence.

Now, the software systems for switches such as the 5ESS were among the largest and most complex of their time, and therefore were the largest part of the development effort. It was a daunting challenge to design and develop a software system consisting of millions of lines of code for a switch with a reliability objective of no more than two hours total system downtime in 40 years—equivalent to three minutes downtime per office per year. Moreover, new features must be introduced by means of software, not hardware, changes.

Meeting the challenge of rapid feature addition demanded approaches such as the combination of sophisticated operating system, high-level language, and modular design. In fact, the software environment is essentially the same in the various modules of the switching system, enabling software to be ported among the modules as architecture and feature needs evolve. Since maintenance routines constitute more than 50% of the system's software, these routines are also designed to facilitate changes. The operating system, among other things, allows the view of the switching system as a collection of independent processors with well-defined interfaces via a concise message protocol. In essence, the system design can be viewed as a collection of independent switches administered as one switching center.

Over the years, the 5ESS Switch has grown in capacity and features and has become Lucent Technologies' flagship product, with well over a hundred million lines deployed around the globe. Because the 5ESS is the industry's most reliable switch and because its architecture has enabled its evolution to handle packet communications, Lucent sales teams sell more than one 5ESS Switch every day, including weekends and holidays, to both new and experienced service providers.

Digital switching was introduced not only in the public telephone network, but also in enterprise networks, with AT&T's System 75 and 85 digital PBXs. The System 85 was introduced in 1983 for large applications of up to 32,000 lines and 6,000 trunks, and a year later the System 75 was introduced for intermediate applications of up to 800 lines and 200 trunks.

The PBXs played an expanding role as a simple, manageable, and economical way of connecting a customer's computers and terminals to handle the growing volume of information flow in businesses. Both of these PBXs integrate voice and data processing and interconnect a large selection of voice/data terminals and data-only terminals.

The role of computer-based operations support systems expanded during this period from providing cost-effective network operations to also helping accommodate the increasingly rapid introduction of complex, new customer services as well as new and diverse network technologies. In the past, typical functions of operations support systems included electronic record management, centralization of operations personnel, automated circuit testing, and planning. In the new environment, operations support systems also made possible features such as customer-initiated testing and access-line monitoring, in addition to elements of the provisioning function.

During this period, major advances were made in operations support system (OSS) design and development, resulting in their rapid deployment to meet new network and sophisticated service needs. Major OSS productivity enhancers are standard run-time and development environments based on the UNIX* operating system, which was invented at Bell Labs—together with modular software architectures that effectively reuse system requirements, designs, and software code. Because of its growing importance in switching, transmission, and operational support systems, software ultimately accounted for 50% of Bell Labs' end product, up from about 10% at the beginning of the decade.

Following the 1984 divestiture of the telephone companies from AT&T, and particularly the establishment of business units within AT&T, it was clear that major changes were needed in the organization of Bell Labs. The existing functional organization had served the Bell System's regulated monopoly and its principal organizations—AT&T, Western Electric, and the Bell Telephone companies—with an excellent record of R&D innovation. But the organizational structure did not provide the business units with the accountability and rapid response time they needed to prosper in a competitive marketplace.

Clearly, the organizations doing the development for individual business units would need to be funded by those units and report directly to them. Equally clearly, it would be very valuable to preserve the benefits of certain fundamental functions such as research and quality procedures. It would also be desirable, if possible, to preserve the communications, cooperation, and sense of community that existed across Bell Labs—intangibles that have been a hallmark of Bell Labs and one key to its invention and innovation from the earliest days.

There were a number of differing viewpoints as to what should be done, with much heated discussion among the many people involved. Within Bell Labs, major contributions were made by Saul Buchsbaum, John Mayo, and Dan Stanzione, just to mention a few. Eventually, some key decisions were made and implemented. The development organizations would transfer into the business units. Some core functions, importantly including research, would remain in the Bell Labs Division and would be funded by AT&T at a level determined by its Chairman. The President of Bell Labs, reporting to the AT&T Chairman, would also be responsible for retaining the Bell Labs sense of community across all of AT&T's R&D.

Given AT&T's approval, the implementation of this plan was begun during my tenure and was largely completed while Mayo was President. This was, in many ways, an organizational innovation. Most high-tech companies have their development activities report to their business units. Few companies, however, have managed to preserve their research activities, and I believe none of those are substantially corporate funded. Retaining the sense of community is probably unique. This structure provided a base from which the management of Lucent could build and evolve its R&D resources to best meet the needs of its business.

In sum, major technological and organizational innovations took place during the 1980s. The microelectronics revolution enabled end-to-end digital network evolution with advances in digital switching and transport. Photonic system deployment gained momentum. The 5ESS Switch joined the 4ESS to provide digital switching for both local and long distance applications. Moreover, increasingly versatile operations support systems helped operate and manage the network, perform business functions, and deliver complex, new services.

Against this backdrop, Bell Labs began the dramatic transformation that would take it into the competitive era with the organizational structure that is so vital today to its role as the innovation engine of Lucent Technologies. That structure also enables Lucent so effectively to include the phrase “Bell Labs Innovations” in its logo. ◆

**John S. Mayo**
**President, Bell Labs**
**1991–1995**

The key to modern telecommunications is worldwide, high-speed digital networking connectivity. In the late 1980s and early 1990s, the combination of two key technologies drove this trend—networked microcomputers and high-speed optical transmission systems, both of which were pioneered by Bell Labs.

Together, these technologies laid the foundation for ever-increasing network capabilities, such as today’s expanding family of digital services and tomorrow’s networked multimedia communications—which will give us voice, data, images, and video in any combination, anywhere, anytime, with convenience and economy.

Certainly, the biggest innovation was the move away from a large, centralized processor controlling a local environment to networks of microcomputers controlling not only the local environment, but also interconnecting regionally, nationally, and globally. During this period, microcomputer systems were doubling their processing power every year, compared to every three years for mainframe systems. Microcomputer systems also were using ever larger numbers of processors per system.

A major example of this trend was the 5ESS® Switch, which was developed by Bell Labs to meet growing demand by service providers for a digital switch controlled by a stored program of instructions. It went from 2,500 microcomputers in 1987 to 5,000 microcomputers by 1991. Such microcomputer clusters achieved processing power of over 10,000 millions of instructions per second (MIPS). These fleets of microcomputers also gave the 5ESS Switch the flexibility for orderly evolution that later enabled its circuit-switched technology to accommodate newer packet technologies—thereby protecting the investments of service providers.

Such distributed computing and intelligence laid the groundwork for network resources on demand for an increasingly widespread range of needs. This is a capability, for example, that would enable network users to access and pay for the exact amount of bandwidth they needed for specific applications, such as videoconferencing, and to get that bandwidth when they needed it and for however long they needed it.

As part of such network resources on demand, most services were also becoming preprovisioned. One of the challenges in network evolution was to reduce the substantial labor and time needed to provision network services. Distributed network intelligence allowed a single technician using a console and software to do what formerly took many technicians and a fleet of trucks visiting various sites in the field—thereby eliminating the bottlenecks of geography, labor, and time. The capability to provide a broad spectrum of services was set up in advance so that the user or service provider could activate it on demand, much as electrical service to homes and businesses is preprovisioned and then activated when needed.

Distributed network intelligence also began extending this software provisioning to make possible an increasingly wide range of adaptive, logically provided services. These services, adapted to the needs of each customer, would be activated and implemented by software commands in intelligent switches and other network elements. Such growing network flexibility meant the customer, increasingly, could utilize the entire range of possible services at home or in the office.

In addition to the worldwide, distributed processing power of networked microcomputers, the second key technology driving global digital networking connectivity was high-speed optical transmission. During the late 1980s and early 1990s, the capacity of optical transmission systems continued to double every year, as it had for well over a decade previously. Moreover, the 1989 introduction of optical amplifiers—pioneered by Bell Labs to control light by light—brought about a revolutionary improvement in lightwave transmission.

Much of the revolutionary impact of optical amplifiers derives from the ability of just one amplifier to boost signals carried by many different wavelengths or "colors" of light. This capability is especially important for optical transmission systems using the capacity-building technique of wavelength division multiplexing—also pioneered by Bell Labs—in which many different "colors" of light are sent down the same fiber, each carrying different information. Thus, optical amplifiers made wavelength division multiplexing economical as well as practical. That meant that we could continue to increase optical system capacity—almost arbitrarily. Indeed, the control of light by light, with the full range of opportunities it may open, is potentially even more capable than all of the systems and devices based on electronic control.

As digital technologies emerged, they were initially local in reach, such as the T1 transmission system, with its 25-mile range. The aggressive Bell Labs vision of global digital networking connectivity, which laid the foundation for future powerful, worldwide networks of networks, could only be realized by photonic systems using optical amplifiers.

In 1992, in laboratory system test beds, Bell Labs and a Japanese partner successfully tested an optical amplifier that enabled error-free transmission over 9,000 km—initially at 5 Gb/s and later at 10 Gb/s. At the time, this was one of the world’s longest and fastest optically amplified fiber-optic systems.

An associated driver of global digital connectivity was the worldwide push toward common standards. For example, a set of common standards was necessary to interconnect photonic systems operating at many different speeds. Such standards are always difficult to achieve, but despite much controversy, the communications industry emerged with a single set of standards able to support today’s optical networks. The standards enabled service providers to use photonic transmission equipment from many different vendors without worry about compatibility, and they also laid the groundwork for simplified networks and efficient transport of broadband services, helping make possible high-data-rate services.

This was a period not only of intense technological change. It was also a period of repositioning in the marketplace by AT&T, as a result of AT&T's 1984 divestiture of its local Bell Telephone companies and the associated growth of competition in the provision of long distance communications service. The extremely productive Bell Labs R&D environment of the regulated era had to yield to an equally, if not more, productive environment geared to an era of intense competition. Time to market thus became a much more significant driver and led to the creation of a new R&D paradigm. Key elements of the new paradigm were to align R&D, manufacturing, and business management into small, highly focused, nimble teams; to develop and use a family of reusable processes and other assets; to conduct research and development concurrently while still managing research centrally and holistically; and to avoid serial handoffs in the product realization process.

Creating the new paradigm was particularly difficult, because it had to emerge simultaneously with new families of products, including systems based on the key technologies of networked microcomputers and high-speed optical transmission. Nevertheless, the new R&D paradigm would be vital to establishing the technological foundation for what, in 1996, was to become Lucent Technologies. ◆

**Daniel C. Stanzione**
**President, Bell Labs**
**1995–1999**

The last decade of the twentieth century has seen profound changes in communications, perhaps more profound than in any decade since the early part of the century, when the notion of "universal service"—the idea that any person in the United States would be able to talk to any other person in the United States—was introduced. We ended the century with the notion not just that any person in the world could talk to any other person in the world, but that any person could almost instantaneously access any information any place in the world. The profound communications changes of the last decade include not only remarkable changes in technology, but also in the ways we think about the market, how we conceive of networks and computing, and how we behave and compete in the marketplace. To me, what is maybe even more remarkable is that the marketplace trends and the technology curves state quite clearly that the years ahead will see change that is even more profound and happening at an even faster pace.

Let us first consider the technology changes and begin with the shift from electrons to photons, the impact of which we are just beginning to see. Signals now travel mostly over optical fibers in core and backbone networks. Increasingly, they will travel over fibers in metropolitan, local loop, and enterprise networks. The growing ubiquity of broadband optical transport will bring people low-cost multimedia communications at home and at work, along with pervasive high-speed Internet access.

One of the enabling forces behind this drive for ubiquitous optical transport is dense wavelength division multiplexing (DWDM). For backbone and long haul applications of DWDM, Bell Labs developed the WaveStar™ OLS 400G, which transmits up to 80 wavelengths and 400 Gb/s over a single fiber. For metropolitan and enterprise networks, we have developed the WaveStar™ OLS 40G, which sends up to 16 wavelengths and 40 Gb/s of traffic per fiber.

The shift from electronics to optics is nowhere more apparent than in the new WaveStar™ LambdaRouter, which is a true optical cross connect with an optical—rather than an electrical—switching fabric. It directs light using an array of hundreds of electrically configurable, microscopic mirrors that are fabricated on a single substrate. The freely moving mirrors rotate around micro-machined hinges.

What is important about the device is that it eliminates today's optical-to-electrical-to-optical conversions required for signal processing. Signals remain all optical throughout the entire connection because the LambdaRouter switches wavelengths of light, which is clearly the way of the future for optical networking. Because of this, the device also operates independently of bit rates and protocols. This particular approach uses just one of many "early-stage" technologies that integrate optics with electronics. The research tells us that the shift from electronics to optoelectronics—combined silicon electronic and optical circuits—on the way to pure optical circuits has only just begun, yet the changes have already dramatically affected the performance and costs of networks.

A second technology shift is from wireline to wireless. We see it most readily in the explosive growth of familiar technologies like Global System for Mobile Communications (GSM), code division multiple access (CDMA), and time division multiple access (TDMA), and in Lucent's successful line of products for mobile networks. We also see it in the marketplace, where a few countries around the world have already reached the point of having more wireless subscribers than wireline—with more countries crossing this threshold every year.

One of the interesting developments is the WaveStar™ OpticAir™ Optical Line System, which not only exemplifies the shift to wireless, but also represents a convergence of wireless with optical. The OpticAir system uses DWDM to transmit voice, video, and data over different wavelengths of light directly through the air. So it is both wireless *and* optical. It has potential uses for bringing people broadband network access, for example, within a business park, for high-capacity connectivity within an enterprise campus, for links overcoming geographical constraints, and for short-term uses such as disaster recovery and special events. Third-generation wireless networks will transform how we think of accessing networks over the next few years, and the two technologies of optics and wireless will compete to eliminate the phrase "the last mile" from communications lingo.

The third technology shift represents perhaps the most far-reaching change in networking—and that has been the ongoing shift from circuit to packet transport and switching. Even more significant than the rise of packet networking is the associated market phenomenon that has led this change. That is, of course, the phenomenal growth of the Internet, stimulated by browsers and the World Wide Web, of e-commerce, and of data traffic in general. More and more people are gaining on-line access to a virtually unlimited wealth of information and products. This new instant availability of information and products is dramatically changing the way people learn and how they communicate, shop for various goods, and conduct transactions, to cite just a few major changes.

Bell Labs has developed a number of major products to help drive the shift toward packet transport. One breakthrough product has been the Lucent Softswitch, which enables seamless connectivity between public telephone networks and various Internet telephony networks. This software product gives Internet service providers the "glue" they need to make Internet telephony equipment work together and to allow people to make Internet phone calls that look, feel, and work like regular phone calls placed over traditional phone networks.

The Lucent Softswitch also enables traditional network providers to offer Internet phone customers the same advanced services they offer other customers today. Thus, providers can offer their customers intelligent network services—such as call waiting, call forwarding, billing, and operator assistance—over either traditional networks or the Internet. Then, too, service providers can access and use existing directories and databases on both the Internet and public phone networks.

Moreover, it is important that programming interfaces of the Lucent Softswitch enable both network operators and independent software vendors to quickly create new Internet-based services that operate across public phone networks and the Internet. This capability will make possible individualized custom services for customers—a trend that will grow during the next decade.

Another driver of the shift to packet transport is the 7R/E™ Packet Solutions, a portfolio of packet data networking solutions that delivers traditional telephony and data services within a packet environment, transforming today's central offices to "packet central offices." It supports convergence at the core of the network, enabling the creation of a new packet local, tandem/transit, or long distance network. Its Call Feature Server processes calls in packets from one end of the network to the other, spanning local, long distance, or international networks. The 7R/E technology also enables existing circuit networks to evolve to converged voice/data packet networks.

Another notable driver of the packet transport trend is the revolutionary PathStar™ Access Server—enabling the world's first full-featured IP central office. It can serve cable or telephone carriers building new next-generation IP networks. It sits on the edge of the public network and converts data and voice traffic from phones, fax machines, or PCs to IP and routes the packets to an IP network such as the Internet. It also provides highly scalable, high-capacity access to the Internet, allowing the integration of voice and data into a single, low-cost access server at the edge of the network.

The PathStar Access Server is the only IP-based access server that has direct access to the existing copper local loop, which eliminates today's two-step dialing and also helps relieve congestion on traditional public networks on the way to an IP network. Importantly, it is an integrated routing IP platform that handles a variety of traffic, from "plain old telephone service" (POTS) and integrated services digital network (ISDN) to the various digital subscriber line technologies (xDSL), along with services including 911, billing, call waiting, call forwarding, and operator assistance.

These, then, are the major shifts in the technology of networking over this last decade: optical networking, wireless communications, and packet switching—each building in its own way on the continuously increasing power provided by the fundamantal technologies of silicon and software. As great as the changes in technology have been, they are dwarfed by the local and global changes in our environment and the marketplace. The market has truly become a global one. A new communications company called Lucent Technologies has been created in a marketplace where global competition has been at a fever pitch. A "new" company—albeit with a long, distinguished heritage—in a new environment placed new demands on Bell Labs. The competitive landscape has taken on an "'hourglass" shape, where large companies from both the communications and computing segments, drawing on enormous resources, compete side-by-side with startups. Those startups, as well as the demands of the marketplace, have brought changes in R&D models, including processes and behaviors, that few could have contemplated even five years ago.

One important marketplace change is the truly global nature of both our customers and our competitors. To better serve Lucent's global thrust with "local" R&D resources close to customers around the world, Bell Labs rapidly expanded its global presence. That presence grew from only a handful of countries ten years ago to 15 countries when Lucent was launched to 25 countries today, with more than 3,500 Bell Labs people now working outside the United States. The spread of new laboratories to Europe and Asia means that we are much more in touch with the marketplace in those regions. Moreover, being near customers not only gives us better insight into their needs, it also allows us to draw from local markets for the most talented people.

Throughout the history of Bell Labs, there have been those times when major upheavals in technology, in society, and/or in the marketplace have required significant change in the Labs. Perhaps one of the greatest traits of success is to know when to change and to have the ability to rapidly do so. There are many examples in recent decades. In the 1970s, under Bill Baker's leadership, a sizable shift from work for the government to a clear focus on digital, wireless, and photonics telecommunications technology occurred. During the 1980s, Ian Ross led Bell Labs through extraordinary change, as software work, especially large software projects, became a fundamental part of telecommunications technology. And in the early 1990s, John Mayo, who had been so key in technological and process changes during his career, was instrumental in leading major organizational change as the development units in Bell Labs became more closely aligned with the business units. In the last few years, the networking technology shifts, together with the intensely competitive global marketplace, have dramatically changed the way technology must be created, managed, and brought to market. To do this with the greatest speed and effectiveness has again required broad behavioral shifts among the people of Bell Labs. I believe these behavioral changes have been even more impactful than the technological changes.

Behavioral changes are often hard to characterize. Certainly they include a sharper focus on the marketplace and on the team sport of innovation, which goes beyond invention, causing change that benefits customers to occur in the marketplace—and doing it more rapidly than our competitors. Perhaps the biggest behavioral change has been the close working relationships developed across functional lines—for example, between researchers and sales people and extending to customers themselves. Arun Netravali personally led much of this change, as head of Bells Labs Research.

The focus on customers and the marketplace has resulted in a much greater emphasis on speed to market. We have facilitated this increased speed through concurrent engineering and a different mindset. Projects such as WaveStar™ OLS 40G, PathStar™ Access Server, and the Lucent Softswitch all went from concept to first market application in about twelve months or less.

The behavioral changes in the people of Bell Labs are perhaps the most significant changes of all in preparing us for the R&D challenges of years to come. That is because the vital hallmarks of Bell Labs, its technical excellence and innovation, are embodied in its people. Most basically, the technology that is at the heart of Bell Labs' output is not rooted in technical papers or patents or even its products. Rather, it is embodied in the people of Bell Labs. The fundamental strength of Bell Labs, now and in the future, lies quite simply in the talent that we have and the environment that nurtures talent and attracts new people. While the technology evolves ever more quickly, and the marketplace changes even more dramatically, and the business models for R&D transform still further, the fundamental of having truly world-class people in every phase of our work will remain with us as *the* essential characteristic of Lucent's Bell Labs. ◆

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