Particle physicists were quick to recognize the enormous potential of computers when the first machines became available about 40 years ago. Initially used to reduce the tedium and increase the speed of performing calculations, ‘computing engines’ were rapidly assimilated into the essential tool kits of high energy physics. The data handling needs of particle physics, always at or beyond the leading-edge of technology, have stimulated many pilot projects, often carried out in symbiosis with hardware and software vendors.

It is impossible to estimate by how much the ‘hi-tech gadgets’ furnished by the computer industry have accelerated the evolution of particle physics. They enabled, for example, the semi-automated measurement of particle tracks in bubble chamber photographs, and with the invention of all-electronic detectors such as wire chambers, allowed experimenters to handle ever increasing amounts of digital data with ease. There followed intelligent terminals, networks, graphics stations and more besides. Recent technological advances have perhaps been amongst the most radical of all, and today, processors of all shapes and sizes, visibly present or discreetly integrated, are as necessary for particle physics as are accelerators.

From holes to e-mail

The pioneering work in physics computing was based on centralized processing of batches of jobs with programs punched as holes in paper ribbons or decks of cards. Program editing was as like as not done with scissors and sticky tape, and dropping the program on the floor could seriously delay things until the paper ribbon was carefully rewound or the card deck reshuffled.

When it became possible to store programs on a magnetic disk, editing could be done using terminals, originally located at the computer centre, later in counting rooms and finally in offices. As central computing power increased, physicists began to interact with their executing programs in a breakthrough which totally revolutionized the analysis of physics events. In the 1980s the advent of electronic mail and networked file transfers changed forever the way the international high energy physics community conducts its business.

Some very profound changes have occurred in computing methods during the last five years or so. Not since the advent of minicomputers in the late 1960s has there been such a complete shift of perspective. Developments at the CERN Computer Centre vividly reflect what has been happening.
From workhorses to workstations

In the mid-80s, the Big Blue Boxes in the Computer Centre were the workhorses of CERN computing and the repositories of files, programs and data for the entire user community. The timeshared operating system CERNVM provided a switch-yard for news, mail and file transfers, and was the program development and text processing tool for thousands of users every day. In 1988 the Centre moved into the ‘supercomputer’ league with the installation of a Cray and a super-IBM that together delivered 60 CU, CERN Units of scalar processing power measured using bench-mark physics programs.

By the end of 1993, the Cray had gone and the IBM had been upgraded to 120 CU. However, the total capacity of the Centre had been increased by a factor of 25 to some 1500 CU. The enabling technologies for this stupendous growth are those of personal computers and Reduced Instruction Set Computer RISC workstations, and of improved network connectivity and capacity. The computer industry sells tens of millions of personal computers annually and it is this scale of marketing which has been both the cause and effect of extraordinary improvements in the quality and price/performance ratio of small computer technology, most notably of disks.

The CERN Computer Centre now has networked workstation clusters performing event simulation, physics analysis and engineering calculations. Even event reconstruction, perhaps the last preserve of the ‘mainframes’, is now mostly done on dedicated multi-workstation ‘farms’. These innovative architectures, such as the mixed-manufacturer Scalable Heterogeneous Integrated Facility SHIFT, and the codes which they run, such as the Physics Analysis Workstation PAW software, have been replicated many times over in the world’s high energy physics institutes and laboratories, at great cost saving to the community.

From links to nets

Interactive computing some five years ago still largely involved logging in to the mainframes from ‘dumb’ terminals. The number of dumb terminals on site steadily declined from its peak of 4000 in the late 80s to 2400 in 1993, and the associated INDEX links service was then terminated, after all remaining terminals had been connected to the site-wide Ethernet.

During the same period, the number of computers attached to Ethernet increased from 1000 in 1988 to some 5500 on more than 100 bridged segments in 1993. Today, thousands of users log in to powerful personal computers and workstations, interconnected by CERN’s networks. These desktop machines carry a substantial portion of the routine workload, especially for office computing and scientific or engineering work that makes heavy use of graphics.

Underpinning this latest computer revolution are truly dramatic developments in networking hardware and software. This has also allowed a steadily increasing number of ‘server’ workstations to be distributed around the site handling tasks on behalf of many ‘client’ stations. The services offered range from mail routing to file storage and program library access. The compact, high-capacity disks associated with the workstation revolution have vastly increased the on-line storage space available, while file access software such as the Network File System and Novell Netware have come to support distributed file sharing. More recently, the Andrew File System has begun to fulfil the promise of a transparent and consistent CERN-wide distributed file base. An important network capacity improvement has been afforded by the introduction of a 100
The dramatic evolution of networked desktop computing at CERN is putting great strains on 'classical' cabling such as this. Still in daily use, such a support engineers' nightmare is being replaced by the more structured alternative seen below.

Megabits per second 'backbone' – $10^8$ bps – enhanced by a 3 GigaBits per second switch – $3 \times 10^9$ bps.

A huge expansion in external networking connectivity and capacity has led to a cultural shift in the computing habits of collaborating physics institutes. Electronic mail now reaches almost all corners of the world and individual line speeds have risen from the 64 kilobits per second that was becoming common in 1988 to the 34 Megabits per second link between Lyon and CERN that was tested in 1993. Excluding this test, the total installed bandwidth has risen from 600 kbps to over 16 Mbps in five years.

From the past to the future

These far-reaching changes have allowed the basic needs of CERN's physics programme to be fulfilled in ways that were only dimly perceived a few years ago and within a constant resource envelope. They have also established computing as an important tool in many new fields of activity such as engineering and administration. A lot of effort is still needed to supplant the formidable range of coherent facilities built up over the years on the mainframes. CERNVM still has some 4,200 users per week, using an integrated range of day-to-day services not yet entirely available in the disjoint world of distributed computing. Nonetheless, these faith-ful old servants will soon cease to play any significant role in batch processing and will surely vanish from the interactive computing scene within a few years.

Looking ahead to computing needs in the LHC era some influential factors are already apparent, namely the volume of data and, so to speak, the volume of physicists. The volume of data generated by an LHC experiment – between $10^{15}$ and $10^{16}$ bits per year – will be 100 to 1000 times that produced by one of the LEP 'giants'. This will put new demands on all manner of data handling technologies, from primary storage methods at the experiments to transmission techniques for both on-site and inter-institute networks. The volume of physicists at each large LHC experiment – between 1000 and 2000 collaborators – will be 2 to 4 times bigger than at a LEP experiment, and their home bases will be spread more widely around the world, possibly anywhere between Australia and Alaska. This will necessitate some new approaches to human communication, such as video-conferencing which is already being tested by the emergent collaborations, heralding another round of dramatic sociological changes in high energy physics.

Recent technological developments in computing have been quite radical, and the rate of progress, driven by burgeoning commercial markets, continues unabated. As in many other hi-tech areas, the particle physics community is ready to exploit every advance. With further improvements announced almost daily by the computing industry, we are confident that the kind of computing and communicating infrastructures needed to do physics in the LHC era will be available and that we will be able to keep abreast of the exciting challenges ahead.