Computer and software support of data-handling systems in high-energy physics

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Computer and software support of high-energy physics experiments is realized as an environment in which human beings, computer systems, detectors, programs, algorithms, and information interact. These systems are created on the basis of mainframes, distributed computing, workstations, and networks using CASE (Computer-Aided Software Engineering) and artificial intelligence tools. This review discusses the problems related to the creation of such systems: the processing and analysis of data in high-energy experiments and the requirements on computational resources; the characteristics of computational centers at high-energy physics laboratories; the role of mainframes, distributed computing systems, and workstations; the effect of the RISC revolution on computer models of experiments; the problems and structure of software support and possible developments of it; the computing strategy of the next generation of modern experiments in high-energy physics.

The processing of the data obtained in modern experiments in high-energy physics requires not only powerful computer systems and large amounts of software, but also the solution of a wide range of problems related to the enormous amount of information obtained, the organization of the work of large international collaborations and exchange of data between their members, and providing the participants with effective tools for data analysis so that physical results can be obtained very rapidly after completion of the data collection. For example, about 500 million photoproduction events were obtained in the E687 experiment at Fermilab in 1990–1991. The reconstruction of these events was completed 7 months after the end of the run. Of course, the analysis of such an enormous amount of data is impossible without a powerful and efficient computing environment.

The basic problem arising when computer and software support play a fundamental role in experiments has been described in a statement about experiments at the large electron-positron collider at CERN:[4]

"From the very start of the planning of experiments at the large electron-positron collider at CERN it has been realized that there is a problem with providing computational resources (the "LEP computing problem"). Discussions in 1984 and 1985 revealed that in recent years it has come to be widely and incorrectly assumed that this problem is exclusively financial in nature. Therefore, the discussions had essentially reduced to the discrepancy between the available and needed computational resources. However, now the understanding of this problem has changed radically. It has become clear that the problem is more complicated than appeared earlier, and its solution does not require just an increase in computing power for package processing. In addition to this, it is necessary to consider the problems of massive memory; the role that can be played by fermi processors; data transmission networks both inside and outside the experimental laboratory; and also workstations for interactive analysis of results."

To this should be added the software support of these systems and the whole set of related problems mentioned above. In other words, the development of computer support for modern high-energy physics experiments involves the creation of an environment in which human beings, computers, experimental setups, algorithms, and information interact. Below we shall refer to this as the computing environment.

Thus, the computing environment in high-energy physics (HEP) is understood to be the wide range of issues related to the use of computers for solving various types of problems in this field. What is presently meant by this term can be judged from the topics of the reports presented at the conferences "Computing in High Energy Physics," which have been held regularly since 1980, and also the conferences devoted to detector development.[1–12]

At these conferences a great deal of attention has been given not only to the actual computer and software support of research, but also to the full range of problems somehow related to the use of computers in this area of scientific research. This includes the computational facilities at physics laboratories connected to form distributed computing systems together with their software support, programming languages and methods; systems for analytic calculations, algorithms and methods of solving physical problems; and problems associated with the use of expert systems and other elements of artificial intelligence in research. For example, at the computing conference in 1992 there were, in addition to the plenary sessions devoted to general problems in HEP computing, 15 parallel sessions devoted to the following topics:[12]

Triggering and data collection;
Libraries and program packages;
QCD calculations, architecture, and experiment;
Data-transmission networks;
Computer-aided detector construction;
Graphics and visualization;
"Inexpensive" packaged software;
Object-oriented applications;
Data bases;

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CASE (Computer-Aided Software Engineering) technology;

Public software support and distributed computing;

Neural networks;

High-speed communications;

The technology of massive memory;

Data management.

In this review we discuss data analysis in HEP experiments from the viewpoint of their computational requirements, including techniques for estimating the computational resources needed, the characteristics of various computational centers at HEP laboratories and specialized computing systems, and the role of mainframes and distributed computing systems. For the example of the LEP experiments we review the evolution of distributed processing systems, from the initial designs to the final realization. The concluding section of the review is devoted to questions of computing strategy and the methodology of developing software support for the next generation of experiments.

1. SOME FEATURES OF EXPERIMENTAL RESEARCH IN HIGH-ENERGY PHYSICS

The object of high-energy physics research is the quantum world of elementary particles. This research requires powerful accelerators at high and superhigh energies; complicated, expensive detectors; powerful computing systems with massive memory capable of processing and storing enormous amounts of information; data-transmission networks which operationally link the members of large international collaborations; and the corresponding software support.

Because of all these factors the computing systems for processing and analyzing experimental data and the data transmission networks have come to be considered, along with detectors and accelerators, as fundamental components of HEP experiments.[20]

1.1. Measurements in the quantum world of high-energy physics

The requirements which HEP imposes on data-processing systems, computing resources, massive memory devices, and data-transmission networks are constantly growing owing to the ever increasing amount of experimental data. The need to process ever greater amounts of data arises not only from the complexity of individual particle collisions at high energies, but also from the nondeterministic nature of the observable results. The latter arises because even when we fully understand the physical processes occurring in a high-energy particle collision, we can predict only the probabilities of various final states (the types of particle and their momenta) which can arise in, for example, electron–positron collisions at an energy of about 100 GeV in the c.m. frame. However, since actually the physics of such phenomena is not known well enough, to test theoretical predictions it is necessary to experimentally measure the probabilities of various processes, which requires the recording of tens and even hundreds of millions of events.[16,143]

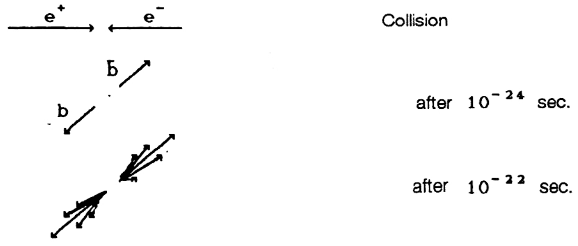

FIG. 1. Why the process e^+e^- cannot be measured directly.

1.2. Smearing of interaction results in the measurement process: the need for modeling

The features of the processes studied and of the detection apparatus do not allow us to observe a picture of what actually occurs in a high-energy particle collision. Quarks are viewed as fundamental particles, but we cannot observe them directly because the speed with which physical processes occur makes it impossible to fix and directly measure the characteristics of primary interactions. This is illustrated in Fig. 1, where we show three "instantaneous" snapshots of an e^+e^- collision producing a quark-antiquark $(b\bar{b})$ pair which undergoes fragmentation into jets of other particles in a time interval so short that no measurements can be made during it. However, even if we could compute this process and measure the characteristics of all the particles produced, we still would not be able to identify jets from $b\bar{b}$ fragmentation for each event studied. This problem must be solved statistically using the special features of the fragmentation process for this type of quark.[16,17]

Quark fragmentation is a typical example of how the physics of a process smears the initial picture of an interaction which must be reconstructed from the results of measurements of the secondary reaction products.

The nonideal nature of detectors also contributes to the distortion of the data for many different reasons (dead zones, inadequate resolution, background, etc.).[17,19]

Therefore, the natural approach in this case is to model physical processes in order to study the relation between them and the experimentally observed "picture." This makes it possible to evaluate the possibility of discovering particular processes (hypotheses) and to find criteria for isolating them statistically.

In relation to this, the detector is viewed as a device with particles at the input and signals at the output, and its properties are described in terms of a response function which determines the probability for a signal with given characteristics to appear in the detector when particles of given properties encounter it.[18] This problem is solved in the modeling process by generating the events to be studied and the results of "measurements" of them by allowing the generated particles to pass through the detecting apparatus. This makes it possible to determine the relation between the quantities which we can measure and the fundamental physics which we want to understand. By comparing the results of the modeling and of experiment we can arrive at conclusions about the nature of the observed processes. This has led to the

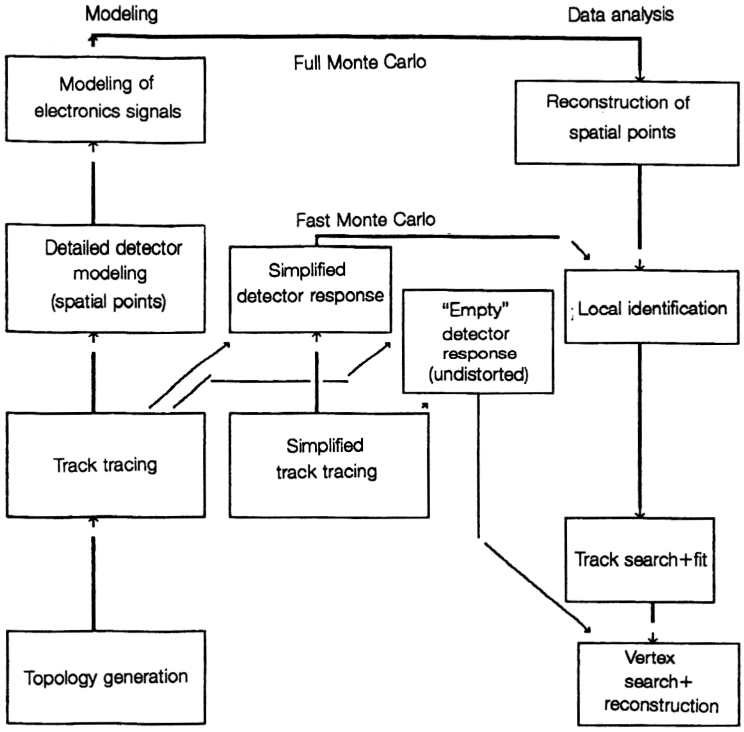

FIG. 2. Relationship between modeling and data analysis processes.

appearance of the following rule in HEP, which of course is not absolute:

"In high-energy physics experiments there is no result without modeling" (Ref. 17).

The computational resources required for full modeling, from stating the physical hypotheses to the final reconstruction of the "measurement results" (Full Monte Carlo) are quite large. Therefore, for some problems the required resources are decreased by using "partial" or "fast" modeling (Fast Monte Carlo), where only part of the process is modeled. For example, to estimate the probability of detecting certain particles in the detector it is sufficient to obtain their characteristics and "pass" them through the detector. The fundamental difference between full and fast modeling is shown in Fig. 2 (Ref. 4).

1.3. Physical analysis of the data in HEP experiments

The basic scheme for analyzing data in HEP experiments is shown in Fig. 3 (Refs. 16 and 17).

After the collection, filtering, and preliminary processing of the detector data performed by the Data Acquisition System, the information about a single event is added to the set of raw data and written in memory.

The detector parameters and relative locations of the detector elements needed for event reconstruction are determined in the course of detector calibration and stored in a data base (DB) to which the reconstruction, modeling, and analysis programs have automatic access.

In the course of reconstruction the spatial picture of the event is reconstructed and the parameters of the particles involved in it are found.

In the concluding stage of the analysis the distributions and correlations of these fundamental quantities are compared for the actual and the simulated events.

The fundamental tools used in the physics of data analysis in HEP experiments are powerful graphics workstations, which are used for event selection and analysis and to study the spatial picture of events.

1.4. Some problems in the organization of collaborations in HEP

Owing to the increase in the accelerator size and the energy of the colliding particles, the experimental equipment used for research in HEP has become huge, complicated, and expensive. Modern detectors weigh thousands of tons and occupy thousands of cubic meters, the number of fast electronic channels is hundreds of thousands, and the cost is tens and hundreds of millions of dollars.[21]

The amount of initial data and results is of the order of tens of terabytes. The processing and analysis of such huge data flows requires enormous computing power (measured in thousands, and for experiments currently in the planning stage, millions of MIPS) and hundreds of highly qualified specialists.[16,20]

Owing to these factors, experimental research in HEP is carried out at a small number of centers.[20] For example, at present there are plans to build only a single large hadron collider (LHC) at CERN (Geneva) with colliding proton energies of 7+7 TeV, although as recently as 1993 there were plans to build two colliders of this type.

Hundreds of specialists from dozens of institutes and organizations of various countries participate in preparing and carrying out HEP experiments. For example, the L3 experiment involves about 500 physicists from 42 institutes and universities in 14 countries.[16]

The software support of HEP experiments involves hun-

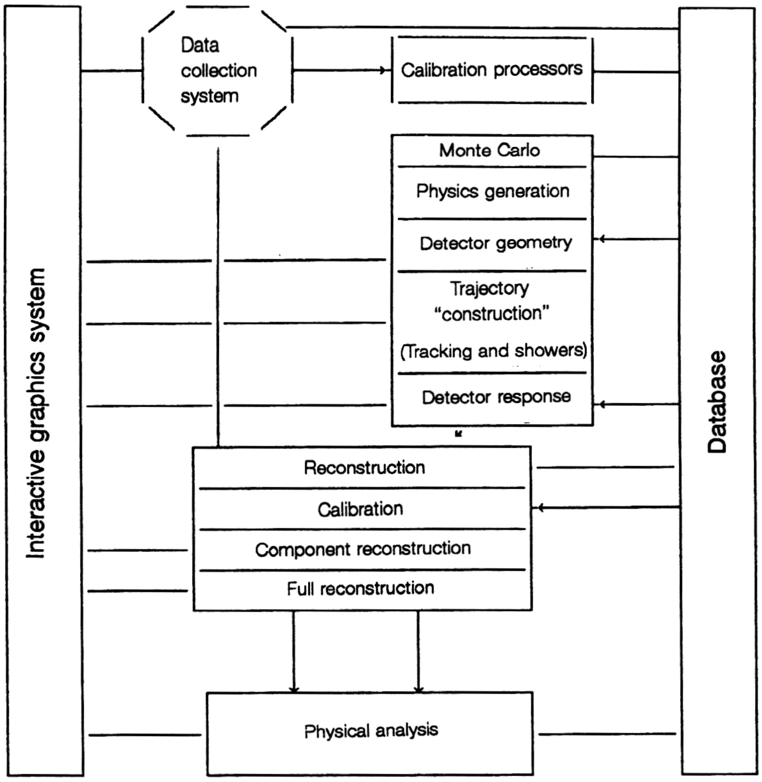

FIG. 3. Basic scheme for data analysis in HEP experiments.

dreds of thousands of codes, and its development requires several hundred human-years.

Data processing and analysis by such large international collaborations requires recording of the initial data, event reconstruction, processing of the reconstruction results, and distribution of these results among the members of the collaboration for physical analysis.

Therefore, on the one had there is a data base and tens of thousands of information carriers, while on the other there are hundreds of physicists from dozens of institutes in various countries. The problem is to organize a distributed system of data processing over these many countries in different continents. The solution of this problem naturally involves a large number of technical, organization, and sociological problems.[17]

For organizing the efficient operation of large international HEP collaborations, in 1989 it was proposed that they be divided into participants of the following three categories: those at the experimental site (the main center), those at home sites (regional or national centers), and those at universities.[2,4]

The main center (for example, in the L3 experiment) is responsible for the operation of the accelerator and part of the most important technical support of the experiment, but to only a small degree for human resources.[16] As far as the event reconstruction is concerned, initially it was assumed that such an important center as CERN would be responsible for processing 1/3 of all the recorded events, the storage of the initial data, the combined results (Master DST), the data bases containing the calibration results, and the dissemination of information between the members of the collaboration.

The regional or national centers (home sites) should make the fundamental contribution to the preparation of the experiment and the processing and analysis of the results.[11]

As far as universities or small institutes are concerned, they are responsible for solving specific problems in accordance with their available resources and for supplying the research with the intellectual resources of a university.

However, owing to the extremely rapid development of inexpensive, workstation-based computing systems, which are comparable in power to large mainframes, the situation has changed fundamentally. For example, the LEP experiments have acquired their own computing systems allowing them to perform event reconstruction during the course of several hours after recording the event.[13,16]

2. THE VOLUME OF DATA AND REQUIREMENTS ON THE COMPUTATIONAL RESOURCES IN HEP EXPERIMENTS

HEP computing differs from many other types of "scientific" computing in that here special attention must be paid not only to the actual calculations, but also to the organization of the entire process itself.[16] This is required because of the huge amounts of initial data and final results, the enormous computations, and the involvement in the process of hundreds of people working at different sites. To evaluate and understand the problems encountered in processing large amounts of data, it is necessary to learn to model the processing and to estimate the amount of results that will be obtained and the computational resources needed.

It should be noted that in experimental physics it is rather difficult to project the computational resources which will be needed, especially when dealing with a new generation of experiments. This is because many things can change not only in the course of preparing an experiment, but also during the experiment itself. Therefore, the results of the modeling and the estimates are rather qualitative, but still they are useful for guessing which problems will arise and for helping to solve them.[4]

2.1. The technique of estimating the computational resources for off-line processing of experimental data

Let us consider the fundamental approach to estimating the computational resources needed for off-line data processing in HEP experiments for the example of the electron-positron collider HERA (DESY). This approach is discussed in the book *Computing at CERN in the 1990s* (Ref. 12).

The basic arguments are the following.

1. A detector will on the average record one event per second and will operate six months a year. Thus, the total number of events obtained in it in a year will be 1.5×10^7. If 1.5×10^6 events are selected for the Master DST, and the average lengths of an event in the tapes of initial data and the Master DST are 100 and 20 Kbytes, respectively, the total volume of initial data obtained in a year will be 1500 Gbytes and that added to the Master DST per year will be 30 Gbytes. If the reconstruction of a single event on a computer like the IBM 370/168 takes 20 seconds of machine time, the reconstruction of all the events will require 12 such machines (12 CERN units of computing power) if each computer operates 290 days a year.

2. A number of events equal to the number of real events will be generated by the Monte Carlo (MC) method and selected for the Master DST, i.e., 1.5×10^6 MC events per year. Of these, 30% will be from full modeling and 70% will be from fast modeling. If the length of an event generated by the full modeling is 100 Kbytes and that from fast modeling is 20 Kbytes, the average length of a single event on the MC Master DST will be 44 Kbytes and its volume will be 66 Gbytes. If the average time to generate a single MC event is 60 seconds, the event generation and subsequent reconstruction will require four units of computing power. The procedure of modeling this number of events will be repeated 2.5 times.

3. The reading of the Master DST to support the work of a single physicist requires about an hour of machine time, and for two hundred physicists taking into account the computer efficiency (0.85) about 200 hours a day or 10 CERN units of power (200 hours/24/0.85) are required.

Therefore, with these assumptions the off-line data processing will require $\sim$32 units of computing power and $\sim$1800 Gbytes of memory for storing the initial data and the final results.

This example illustrates the fundamental approach to estimating the needed computational resources and the set of assumptions (models) and values which must be specified to obtain the estimate.

Naturally, the situation in real life can be much more complicated. Therefore, for modeling this process and studying the effect of various factors on the quantities of interest in physics it is necessary to construct an algorithmic model of the process taking into account various submodels, to specify the initial data, and to select software for solving this problem, preferably interactively.

Electronic tables are a convenient tool for solving problems of this type.[24] The use of these tables makes it possible to solve this problem even using something like an IBM PC, where results can be obtained several seconds after interactively formulating a model of the process and specifying all the needed data.

By including in the table data on the cost of computing systems and various types of computers, rates of information transfer along communications lines, and so on, it is possible to solve a wide range of problems related to the modeling of the off-line data-processing process, to choose the optimal version of computing systems taking into account cost, and so on. By introducing changes in the submodel and initial data, it is possible to study the effect of various factors on the final results, represented as tables or graphs, several seconds after introducing the corresponding data into the table. This allows the efficient and rapid solution of the problem of modeling the off-line processing, the study of various models of the process, and the selection of the optimal type of computing system.[25] The basic scheme of the algorithmic model for this process is shown in Fig. 4.

2.2. Fundamental requirements on the computing resources for LEP experiments

A special conference has been devoted to the study of the problems related to the off-line processing of experimental data and estimates of the computing resources needed to perform experiments in the large electron-positron collider at CERN: "Meeting to Understand the Specific Computing Needs of the LEP Experiments" (April 1987; Ref. 4).

The main result of the conference was a clear understanding of the need for a complex approach to solving the problems of off-line data processing and the scale of computational resources needed for this.

In the summary document of this meeting and several subsequent publications, a model of this process was discussed for LEP experiments and estimates of the required computational resources made on the basis of it were given (Refs. 4, 12, and 23).

The specialists at CERN calculated that the realization of their physics program for 1991–1992 would require 600 CERN units of computing power instead of the 74 units available by the end of 1988.

A rough estimate of the cost of a CERN unit of computing power for large computers (CRAY, IBM, VAX) at that time was $\sim$300 thousand dollars. In Table I we give data on the development of the CERN computational center during the period from 1988 to 1991, and in Table II we give the costs of the various computational devices (in millions of Swiss francs) acquired by CERN in 1988 and 1989 and planned for 1990 and 1991.

We see from the data given in these tables that even a significant increase in investments in large computers over several years would not allow CERN to reach the needed level of computational power in mainframes.

Since the computational resources required by the physics program significantly exceeded the level of planned ex-

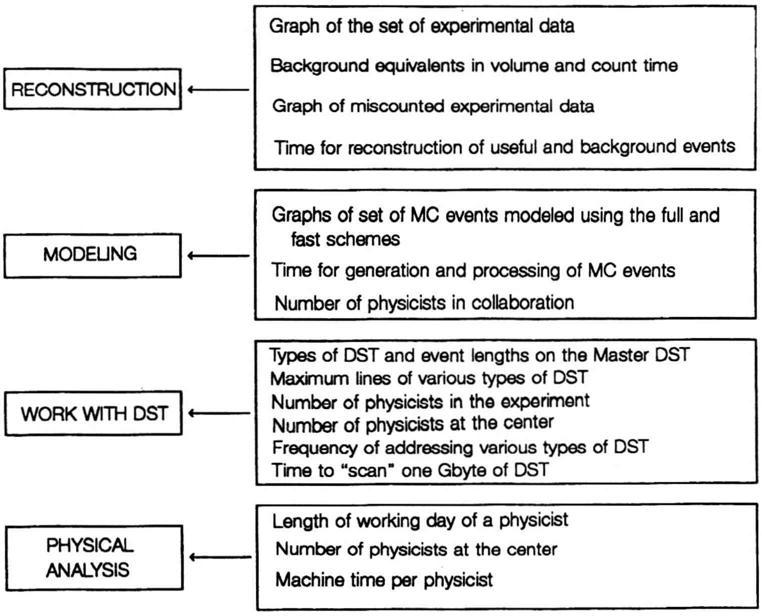

FIG. 4. Basic scheme of the model for off-line processing of the data of an electronic experiment.

penditures for this purpose, the concept of distributed data processing was proposed. According to this, CERN would be responsible for processing at least one third of the data obtained and would supply the other participants in the collaboration with the information needed to process the rest of the data and analyze the DST of the experiment.[12]

CERN promised to increase the power of the large mainframes at the computational center for 150 units for this purpose in 1992.

The other collaboration members were to supply 300 units, and the remaining 150 units were to come from parallel computing systems.

Along with this the following trends were noted in the evolution of the organization of distributed computing:

1. The next five years will be a period of development of computing for off-line data processing for HEP experiments owing to progress in the development of a distributed computing environment and exploitation of the rapidly developing technology of workstations and data-transmission networks.

2. The main elements in the evolution of centrally organized computing at CERN, at national and regional centers, and at universities will be the following:

•Growth of computing power for packaged data-analysis software, including the use of ordinary, general-purpose computers, widespread use of inexpensive parallel computers, and the integration of the latter with cartridges and disk memory at the scales needed for high-energy physics.

•The establishment of personal workstations as the fundamental tool for interactive data analysis. The development of distributed joint processing for interactive data analysis, when different components of a program are simultaneously running at powerful work stations and at one or several central mainframes and file stations.

•The introduction of high-speed global data-transmission networks which allow physicists to work efficiently at their own workstations.

The following have been singled out as key elements in the computing plan at CERN:

An order-of-magnitude improvement of the computational possibilities between CERN and collaborating institutes to ensure decentralized data processing and analysis.

On the basis of the estimates that were made, the following recommendations were made to ensure fulfillment of the CERN requirements on massive memory devices during 1991–1992:

A quantity of cartridges and disk space sufficient for processing at least 50 Terabytes of data (about 250 thousand cartridges) should be provided.

TABLE I.

Computer	end of 88	end of 89	end of 90	end of 91
IBM compatible	36	60	57	54
Cray	32	32	32	90
DEC	6	10	10	10
Total power	74	102	99	154

TABLE II.

	Cost		
	1989	1990	1991
New projects for real-time systems	0.5	1	1
Disks for massive memory	9	11	11
Automated cartridge loading	1.4	0.6	2
Power of large CPUs	2	21	25
Parallel processing	1	3	6
Global data-transfer network			
Interfaces at CERN	1	1	1
Line cost	4	10	12
Tape copying service	0.5	0.5	0.5
Infrastructure (buildings, tape archives)	1	1	-
Total:	20.4	49.1	58.5
in millions of dollars	~13	~30	~36

CERN should be equipped with automatic cartridge loaders capable of processing 8 Terabytes (40 thousand cartridges).

Copying of cartridges onto tapes and their distribution among members of a collaboration should be ensured.

About a terabyte of disk space should be provided at CERN for arranging fast access to the most active part of the data from a central storage device.

In connection with this, the question arose of creating a general computational infrastructure at CERN for ensuring the operation of a distributed computing complex involving various types of computer connected by data-transmission networks.

For remote centers to be able to actively participate in the analysis of the experimental data from the LEP experiments, their computing resources must satisfy the following requirements:

A computing power of 20 units;

Disk space of 100 Gbytes;

Automatic loader for 5 thousand carriers.

Because the analysis of the requirements on computing resources for the LEP experiments showed that they significantly exceed the resources available at the CERN computational center, physicists began seeking ways of increasing the computing power by designing specialized computing systems. This in the end led to the creation for large-scale experiments of computing systems ensuring event reconstruction and organization of physical analysis (Refs. 14, 17, and 143).

Therefore, the development of computational systems to support electronic experiments in 1988–89 displayed two trends. One was the increase in the power of mainframes at the main center and at the home sites of the collaboration members, and the other was the creation of parallel computing systems incorporated into the computational infrastructures of the main centers.

2.3. The volume of data recorded by detectors in high-energy physics

The large detectors used to make measurements in the energy range 100–1000 GeV in the c.m. frame have ~200 000 sensitive elements, which allows them to easily distinguish the energy contributions of adjacent particles forming jets and showers. Readout from these elements occurs each time the trigger system of the detector finds an interesting event. Here a single sensitive element can transmit from one to several hundred bytes of information. Therefore, the raw data from large detectors contain over 1 Mbyte per event. However, since the particles produced in a collision do not strike all the sensitive elements and the output from elements with a null result is discarded, the amount of data recorded for a single event is decreased to 100–200 Kbytes.

TABLE III. Basic components of the UA1 detector and event dimensions (Ref. 26).

Detector	Number of channels	Data, kbytes "raw"	Data, kbytes formatted
Central detector-drift chamber	6 200	1600	≈80
Hadron calorimeter	1 200	2.4	2.4
Electromagnetic calorimeter	2 200	4.4	4.4
Calorimeter position detector	4 000	8	8
Forechamber	2 000	32	8
Drift (muon) chamber	6 000	1	1
Streamer tubes	50 000	50	≈4
Uranium calorimeter	20 000	80	8
Total		≈1770	≈140

In Table III we show data demonstrating the results of information compression for the UA1 setup with 4π geometry.

Future detectors for the next generation of accelerators at higher energies will have a larger number of sensitive elements and it is expected that for them the size of an event after the first compression will be ~1 Mbyte.

In Table IV we give data showing the event length under various experimental conditions.[27]

2.4. Computing power needed for the reconstruction and modeling of events in high-energy physics

The reconstruction of a typical event produced in a collision of 100–200 GeV particles by a general-purpose detector requires from 50 to 150 HEP-MIPS seconds and at present can in most cases be completed several hours after the recording of the event. During the subsequent analysis the values of the calibration constants are refined and the algorithms and programs are improved. This can lead to a repeated reconstruction of all or a large part of the recorded events, which is in fact what is usually done.[16]

The modeling of modern HEP experiments presently requires a very large amount of computational resources, which during the last 15 years has increased by 3–4 orders of magnitude. On the one hand, this increase is due to the fact that many of the experiments carried out are precision searches requiring the modeling of large numbers of complicated events, and, on the other, it is due to the sharp drop in the cost of computational devices, which has made it pos-

TABLE IV. Data on event sizes for various experimental conditions (Ref. 27).

Accelerator	Luminosity ($cm^{-2}sec^{-1}$)	Physics: Cross section	Detector: Average number of channels	Frequency	Event size, kbytes	Interaction rate
LEP	10^{31}	32 nb	150 000	45 Khz	50–100 Kb	1 000 Hz
HERA	$2*10^{31}$	15 μb	260 000	10 MHz	125 Kb	10 000 Hz
LHC/SSC	10^{34}	60 mb	10^7	65 MHz	1–10Mb	65 MHz

TABLE V. Amount of data and requirements on the computational power for current and future large HEP experiments.

	Current			Future	
Particle	e^+e^-	$e\bar{p}$	pp	pp^-	e^+e^-
Energy in c.m. frame (GeV)	100	300	2000	(16–40) K	(0.5–2) K
Raw frequency of interesting events (Hz)	⩽1	1-1 000	$1–10^6$	$1–10^8$	⩽0.001
Frequency of writing on tape (Hz)	~1	~1	~1	10–10 000	~1
Event size (Kbytes)	100–200	~100	~100	(1–10) K	(1–10) K
Event-reconstruction time (HEP-MIPS sec.)	50–100	~100	~200	500–5 000	500–5000
Time for detailed modeling of an event (HEP-MIPS sec.)	(2–5) K	(2–5) K	~5 K	(20–200) K	(20–100) K
Yearly amount of data (Tbytes)	1–10	1–10	~10	⩾1000	~10
CPU resources (HEP-MIPS)					
Reconstruction and analysis	50–150	30–100	30–100	⩾100 K	~200
Modeling	200–2000	100–1 000	50–500	⩾100 K	~200

sible to carry out modeling for new problems which were previously impossible to tackle. Most of the computer time is spent on modeling showers generated when particles pass through the detector. If high accuracy is required, the amount of computer time needed becomes roughly proportional to the total energy deposited in the detector. For example, at 40 GeV it can take hundreds of HEP-MIPS hours to model a single event.[16] As far as the cost of computing power is concerned, judging from the data presented in Refs. 2, 20, and 33, the cost of a single MIPS of a mainframe (like an IBM) fell by almost a factor of four from 1987 to 1991 and in 1991 became 40 thousand dollars. Meanwhile, the cost of a single MIPS for workstations was lower by a factor of ten or more.[33]

In Table V we present data on the yearly amounts of information collected and the requirements on the computing power for current and planned HEP experiments based on the event-recording rate, the time the detector operates in the accelerator, and the characteristics of the studied events. In the calculations it was assumed that the operating times of various detectors in the beam were roughly identical and equal to about 2000 hours per year. This number was obtained on the basis of the following figures. Usually half a year is scheduled for a physics experiment at an accelerator. During this time the accelerator operates 24 hours a day, but in the opinion of physicists the efficiency of operation of the accelerator plus detector is no more than 50% (Ref. 16).

2.5. Units of measurement of the computing power

Until recently, in HEP, as in computational technology as a whole, it was standard to use the historically evolved measurement of the operating speed (power) of a computer in millions of instructions performed by the processors per second (MIPS). However, now, because of the great diversity of command sets for different processors of greatly differing architecture, this indicator has ceased to be an objective criterion. Therefore, for an objective estimate of the power of a computer it is best to use a set of computations typical for standard problems of specific applications. The computer power is now measured using special tests (Benchmarks), which consist of some mixture of operations determined for a given test and characteristic of a certain class of problems.[29–31]

Units used in HEP at present, in addition to MIPS, are HEP-MIPS (CERN), SSCUPS (SSCL), VUPS (VAX units of performance), and others.[16,32]

The following approximate expression can be used to compare computer powers expressed in different units:[32]

$$1 \text{ SSCUP} \approx 1 \text{ SPECmark} \approx 0.25 \text{ CERN unit} \approx 1.4 \text{ MIPS}.$$

Examples of the computer power for various tests are also given in Tables VI and VII.

3. THE COMPUTING ENVIRONMENT OF HEP EXPERIMENTS

Owing to the large diversity in computing resources required by HEP experiments, the time spent to process the experimental data and obtain physical results is to a large degree determined by the "computing environment."

TABLE VI. Examples of the relative power of computers for typical HEP programs in HEP-MIPS and MIPS units (Ref. 16).

Computer		Power	
		MIPS	HEP-MIPS
IBM 3090–600E	(1 processor)	6.5	25
Cray XMP-48	(1 processor)	8.0	30
Apollo DN 10000	(1 processor)		15–25
HP 9000/720			24–35
IBM RS 6000-320		1.0	10–13
VAX 11/780 (with floating-point command speedup)			1

TABLE VII. Computer powers for various benchmark tests (Ref. 32).

Machine	SSCUPs	SSCUPs (optimized)	SPECmarks	MIPS	CERN
VAX-11/780			1.0	1.0	
VAX 6410	7.0	8.4		7.5	1.9
SGI 4D/35S	15.3		23.0	33.0	
SGI 4D/310	13.5	21.6	18.5	30.0	5.3
IBM RS/520	11.9		22.0	29.5	
IBM RS/530	14.3	21.3	28.6	33.0	4.9
SUN Sparc 2	11.8	16.3	21.0	28.5	3.5
DEC Stat. 3100	6.4	10.0	10.8	14.0	2.8
DEC Stat. 5000	10.5		18.5	24.0	4.4
Apollo DN 10000	11.6	18.6	17.4	22.0	4.9
HP Apollo 9000/720	22.7	29.4	55.7	57.0	

3.1. Basic scheme of the computing environment of HEP experiments

The basic scheme of this environment realized for the L3 experiment (LEP,CERN) in 1989–1992 is shown in Fig. 5. It involves mainframes, systems of special processors designed to solve particular problems, workstations, and a large number of peripheral devices for data recording, storage, and selection. "Superminicomputers" (mainly VAXes) are used for data collection, detector calibration, and the solving small test problems. Most of the development of the software support and physical analysis of the results is done using personal workstations.

The elements of the computing environment of an experiment at the main laboratory (the experimental side) are linked together by local data-transmission networks and linked to the computing systems of the collaboration members by regional or global networks.

In the 1970's and early 1980's the large HEP laboratories were constantly acquiring powerful and accessible mainframes, since there were no other alternatives for increasing the computing power at that time.

Around 1976 several small groups of physicists realized that even though mainframes are quite suitable for calculations involving large amounts of input and output, there are problems which can be solved more quickly using inexpensive CPU power (emulators).[118–122] Although this involved certain inconveniences, they nevertheless came to be used in a number of experiments.[16]

By 1985 it had become clear to physicists that they needed to find a way of obtaining relatively inexpensive computational resources in order to avoid future problems related to processing large amounts of data. The appearance on the market of RISC computers (Reduced Instruction Set Computers) with a cost/efficiency ratio significantly better than that of mainframes made it possible to solve the computing problem in HEP experiments by using these machines as the basis of powerful computing systems (Fig. 6).

Work on creating such a system (the Advanced Computing Project at Fermilab) began at FNAL at the time when mainframes still dominated in HEP.[132]

The second generation of ACP systems used processor chips of the R3000 family from the MIPS corporation. Each processor could have from 8 to 32 Mbytes of memory and a CPU power of 10–12 HEP-MIPS. Over 200 ACP/R3000 processors were built and used as the basis for systems which became widely used for data processing at FNAL and a number of universities beginning in 1991 (Ref. 16).

The creation of distributed computing systems on the basis of inexpensive processors significantly changed the computing environment of experiments and, in particular, the actual model of HEP computing, which was proposed in 1987 (Ref. 4).

3.2. Examples of models for HEP computing

The creation of relatively inexpensive computing systems based on microcomputers and their linking to the computing systems and mainframes of central computational centers of laboratories by local data-transmission networks led to the development of a new model of computing for HEP experiments. The basic scheme of this model is shown in Fig. 7. At its center is a powerful data server with a large

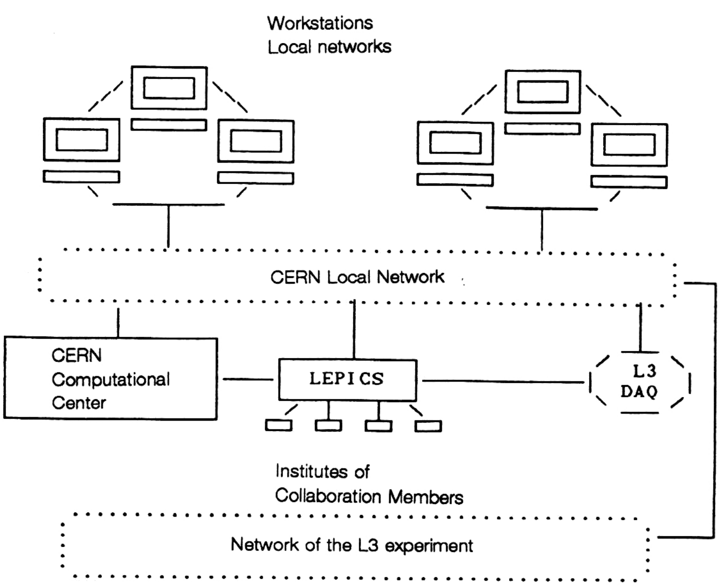

FIG. 5. Basic scheme of the computing environment of the L3 experiment.

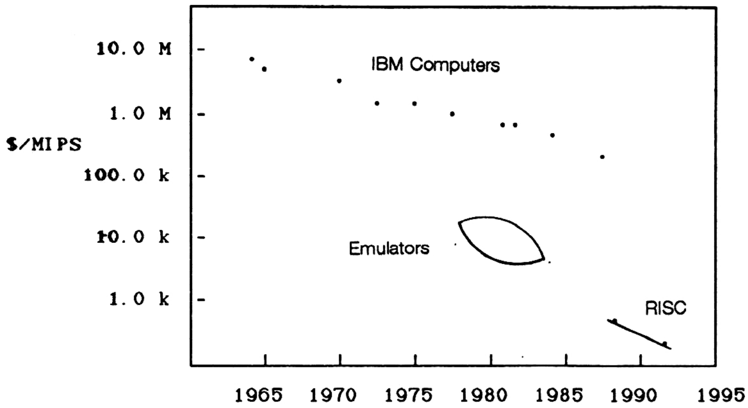

FIG. 6. Decrease with time of the cost of various computational systems (IBM computers, emulators, and RISC work stations).

amount of disk memory and a large library of information carriers, and it is surrounded by a network of powerful workstations.

This model is an idealized and simplified scheme constructed on the basis of the computing systems of several HEP experiments. Let us therefore consider several examples of its actual realization.

For example, LEPICS (L3 Parallel Integrated Computer System) included an IBM 3090 connected to a series of HP/Apollo DN 1000 RISC workstations using a Stollmann GmbH interface. The linked processors can solve reconstruction, modeling, and analysis problems in parallel. They had access to thousands of tapes mounted by a robot and tens of thousands of tapes mounted by operators. The linking network was provided by the FDDI, the Ethernet, and the Apollo Token Ring (12 Mbits/sec), and the high-speed (1–2 Mbytes/sec) links were provided by a Stollman interface connecting the DN 1000s to the IBM 3090. The total CPU power of LEPICS was about 500 HEP-MIPS (Ref. 16).

In Fig. 8 we show the flow chart for the data used by the reconstruction and off-line processing systems of the ALEPH detector (LEP, CERN).

The data-collection system (a VAXcluster) sends raw data files via two-port disks to the event-reconstruction system Falcon (Event Reconstruction Facility-Local Area VAXcluster). In 1989–1990 the system was based on 12 processors of the VAX stations 3100/30 without disks or screens, and its power was 24 HEP-MIPS. In 1992 it was raised to 90 HEP-MIPS by using more modern VAX stations.

The reconstruction results ready for physical analysis were sent via the Ethernet to the disks of the CERN IBM 3090/600 and the ALEPH Off Line VAXcluster. The IBM disks could also use the CERN CRAY XMP/48. The IBM was used for compressing and classifying the data and writing them on cartridges for dissemination among the collaboration members. The control of the movement of the data between the various systems was completely automated and made it possible to obtain reconstruction results for physical analysis several hours after recording the event.

For the repeat of the data processing after the introduction of refinements into the algorithms and constants the CERN CRAY was used as the data server, providing Falcon with access to the tapes of initial data.

The farm for event reconstruction in the DELPHI experiment, DELFARM, is a mixed system consisting of nine VAX stations and 13 DEC 5000 stations. The former control the operation of the system and the data input and output, and the later perform the computations. The possibilities offered by the system can be judged from its operation in 1992. During that year, 9 000 000 triggers were obtained, and their reconstructions were completed in a matter of days after the data collection. Two reprocessings were carried out as the

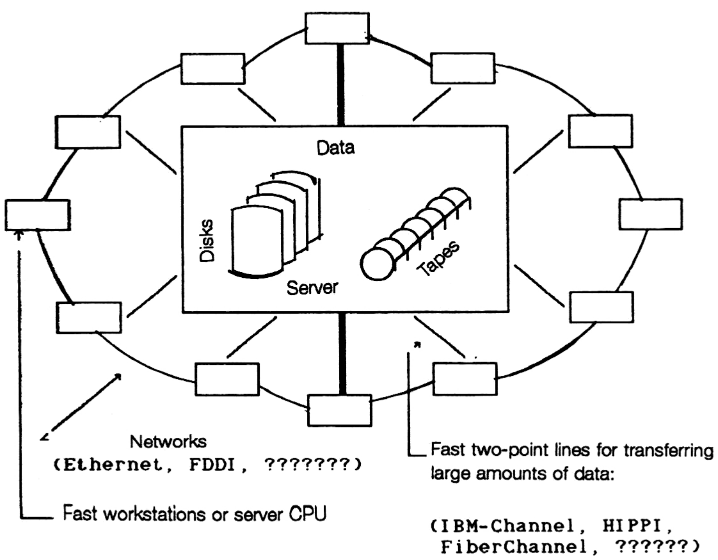

FIG. 7. Model of HEP computing. The data servers and powerful workstations are shown.

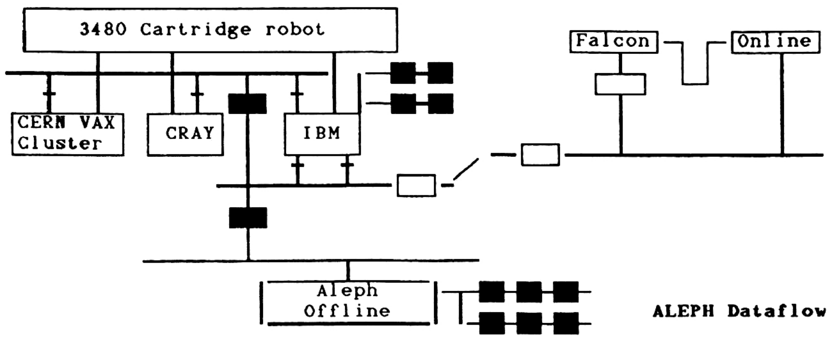

FIG. 8. Scheme of movement of data used by the reconstruction and off-line processing systems of the ALEPH detector.

constants were improved. The DST was stored both at the CERN Computational Center, and at a special DST farm. The latter consists of six DEC stations with 70 Gigabytes of disk space, which is sufficient for storing all the 1992 data and providing easy access to them. When either of these two farms becomes free, it is automatically switched over to event modeling and it also is automatically switched over to solving fundamental problems as needed. The data needed by the institutes involved in a collaboration are copied onto 3480 cartridges at the CERN Computational Center or onto Exabyte cassettes at the DST farm.[143]

The development and implementation of this type of system considerably shortened the time needed to obtain physical results. This is indicated, in particular, by the unprecedented rate at which physical results were obtained in the LEP experiments.[133] There are also other examples. For example, the E687 experiment at Fermilab obtained more than 500 million events, whose reconstruction was completed 7 months after the end of the final accelerator run, and soon after this the search for candidates for charmed particles and creation of the DST were completed.[134]

At the present time distributed computing systems are the main suppliers of computing resources in HEP and they have rendered mainframes obsolete. For example, in 1992 about 90% of all the MIPS needed by experiments were provided by distributed computing systems.[16]

3.3. The role of personal workstations in the computing environment of a HEP experiment

A workstation in HEP is a computer which has sufficient memory and power of the central processor to be used to develop software support for experiments and to execute the corresponding programs.[16]

Graphics workstations are most often used to develop software support, especially stations with high-resolution screens, multiwindow operating systems, file-control systems, systems for controlling joint processing using local networks, and extended graphics possibilities. Powerful graphics workstations with three-dimensional graphics have also become fundamental tools for processing very complicated events, data representation, and interactive analysis.[20]

When preparation for the LEP experiments began in 1982, many physicists were very worried about questions of precision measurements and software support owing to the appearance of problems considerably more complicated than those they had faced previously. Fortunately, the arrival of workstations and computational power which was relatively inexpensive compared to that of mainframes transformed HEP computing and made it possible to solve many problems in detector design more efficiently than in the 1970s.

Personal computers made it possible to significantly shorten the cycle of editing-translation-loading-execution of a program and supported interactive loading much better than a simple terminal. Here the most important issue is the fact that a PC allows graphics to be used to understand what the program is doing. Each program element can be constructed such that it gives results in a form suitable for visualization, thereby making it possible to evaluate the result not from tables of numbers, but by studying two- or three-dimensional "pictures" in the detector. Naturally, this approach combined with the possibilities of interactive program editing and execution creates qualitatively new possibilities of designing software support for HEP experiments. The advantages provided by the graphical capabilities of PCs became available also because from the very beginning applied programs were oriented toward the use of PCs. Graphics make it possible to understand how the detector and programs actually work.

In 1992 "low-end" personal computers which cost about 7000 dollars had a monochrome screen, 16 Megabytes of memory, a 400-Megabyte disk, and 12 HEP-MIPS of CPU power. More powerful machines costing about 30 000 dollars had a 1280*1024 color screen, three-dimensional graphics, a disk larger than 1 Gigabyte, and at least 30 HEP-MIPS of CPU power.

In the future low-end machines will apparently be used as complex terminals to perform editing, partial compilation, and physical analysis, and all problems requiring large CPU power will be transferred to more powerful machines. In this case the purchase of one powerful PC and several X-terminals can allow small groups of physicists to participate in HEP experiments.[16]

X-terminals are something between powerful workstations and inexpensive terminals. They operate with a graphics protocol which allows the computational functions performed by the leading computer to be separated from the information display realized by the X-terminal. The X-terminals produced by IBM are called X-stations.

X-stations are devices forming part of a local network which provide the functional possibilities and power of full-scale workstations, but cost much less per user.[136]

3.4. Data-transmission networks in HEP experiments

Networks can be classified as global, regional, or local, depending on the geographical area they cover.[114]

Global networks link subscribers located in different parts of the country, continent, or world. They make extensive use of satellite communications. Examples of such networks are the international networks of national airlines, computational networks linking centers carrying out fundamental research in certain scientific fields, for example, HEP, networks linking academic centers, and so on.

Regional networks link computational systems within a particular region (a country, province, group of institutions, etc.).

Local area networks (LANs) connect computers located at different sites within a single institute, enterprise, or even a single building.

In HEP LANs serve to connect devices both for a single experiment and for an entire laboratory.

Local and global data-transmission networks are fundamental computational tools in HEP.

The basic scheme for a data-transmission network of a typical HEP experiment is shown in Fig. 5. The elements of the computing environment of an experiment are linked to each other and to the central computational center using local networks with, as a rule, high rates of information transfer (from 10 kbits/sec to 100 Mbits/sec). If several local networks are used in an experiment, they as a rule are linked together and to global networks.

Data-transmission networks offer the following possibilities in physics:

•Access from terminals to remote computational resources existing both at the experimental site and at the organizations participating in the collaboration;

•Electronic-mail links to colleagues all over the world;

•File exchange between any two computers used by collaboration members for

•collaborative development of software and data analysis;

•access to remote data bases and analysis programs;

•access to remote program libraries;

•dissemination of small sets of events for analysis at remote laboratories;

•Running problems at remote computers;

•Automatic sharing of program libraries and data bases among members of a collaboration;

•Information exchange between jobs being run on different computers for the following:

•managing the course of experiments from remote laboratories;

•distributed data processing for the effective use of available computer resources;

•Transfers of large amounts of experimental data;

•Organizing teleconferences.[20]

There has recently been great interest in fiber-optics data-transmission systems in the FDDI (fiber distributed data interface) standard with a rate of 100 Mbits/sec. The main areas of application of FDDI at CERN are:

•Use as a fast central network linking local Ethernet networks;

•Providing a high-speed link between workstations and powerful computers.

Most workstations and personal computers will apparently continue for a long time to be based on the Ethernet, but future powerful work stations, the file servers connected to them, and high-speed access to central resources will be based on the FDDI (Ref. 112).

The CHEOPS project proposed by the European Space Agency (ESA) has begun to be realized for the purpose of eliminating differences in the rates of data transmission between members of collaborations engaged in HEP research in Europe. The Olympus satellite is to be used in this project. During several hours at night its channels with a speed of up to 8 Mbits/sec can be used to transfer data between collaboration members. Realization of this project will allow CERN to be linked with institutes at the periphery of Europe for which hard-wired links are either absent or cost too much (Greece, Finland, and Portugal).[116,135]

The EARN and BITNET networks have become widespread in Europe and the United States. They link academic and scientific-research organizations by dedicated telephone lines and allow file exchange and electronic mail between IBM, VAX, and several other computers.

Commenting on the network situation in HEP, in 1991 Fluckiger noted:

1. The era of megabit data-transmission rates has arrived. In Europe it connects research institutes in France, Germany, Switzerland, and CERN.

2. The transmission rates of trans-Atlantic lines have also reached megabyte speeds.

3. Institutes in central and eastern Europe are also connected to the HEP network, but with lower transmission rates.[116]

Studies have shown that the participants in HEP experiments require:

•Integrated local and global computational systems;

•Easy access to amounts of data ranging from 1 to 40 Terabytes;

•Computing powers of 1000 and more MIPS with easy access to data;

•A user interface and graphics capabilities at the level of modern workstations.

Systems for carrying out video teleconferencing are also being created to ensure operational links between participants in HEP experiments.[117]

It should be noted that owing to the high cost of network services, the issue of the transfer of large amounts of information by magnetic carriers has not waned in importance.

3.5. Examples of computing environments at HEP centers

The leading international center for fundamental research in various areas of physics including HEP is CERN. In recent years the development of its computing environment has displayed the following trends:

1. Growth of computing power from the use of mainframes, which continued until 1992, in accordance with the plans for performing the LEP experiments developed earlier.

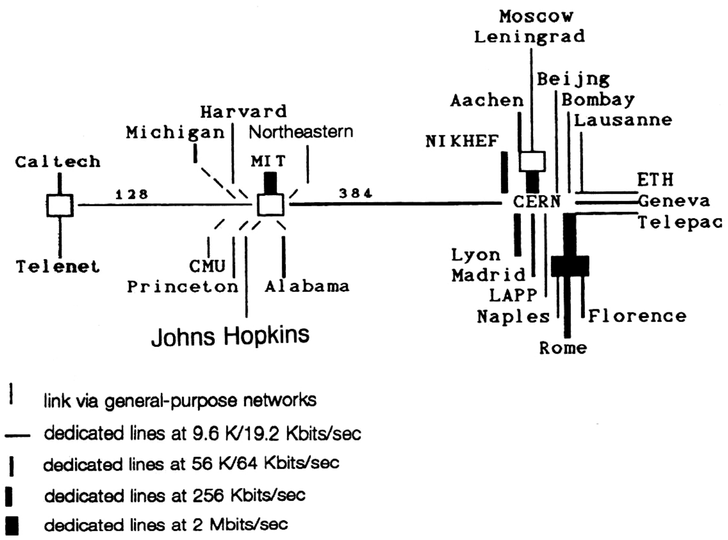

FIG. 9. Topology of the network of the L3 experiment (LEP3NET topology) as of March 1991.

2. Creation of distributed computing systems for satisfying the computing requirements of the LEP experiments.

3. The beginning of a gradual shift from mainframes to distributed computing systems.

In 1989 the central computing power of CERN was ≈88.5 CERN units, provided by the following computers: the Cray X/MP-48 (32), the IBM 3090-600E (39), the Siemens 7890 (13), and the VAX Cluster (≈4.5). (It should be recalled that the CERN unit of computing power is the power of an IBM 370/168 or a VAX 8600.)

The IBM 3090/600E and Siemens 7890 were used for basic packaged programs and interactive inquiries. These machines had access to 25 tapewinders and 32 cassette devices and disk space (205 Gigabytes).

The VAX Cluster provided the main interactive service.

The local X25 network was connected to 12 external dedicated channels, including one satellite channel and one channel with a deep-sea line to the United States. The Swiss EARN node was located at CERN and also connected to 12 dedicated channels.

Most of the large experiments had at least one powerful 32-bit computer. This was usually a large VAX, and also there were a number of small machines, usually connected to form a cluster. These computers were used to solve many problems, including data collection during detector testing and calibration runs. There were at least 100 VAXs and microVAXs and 20 Nord Data computers (including six 32 Nord-500s) used in the experiments.

It was estimated that in 1989 CERN had at least 2000 Apple PCs based on the Motorola 68000 microprocessor (Macintoshes) and at least 8000 IBM-compatible PCs, more than 120 Apollo workstations, and at least 250 VAX stations. About 65 Apollos were on the main network and were used by physicists and some of the DD personnel for developing software support and physical analysis, 20 were used in the LEP management system, and about 7 were used in electron-

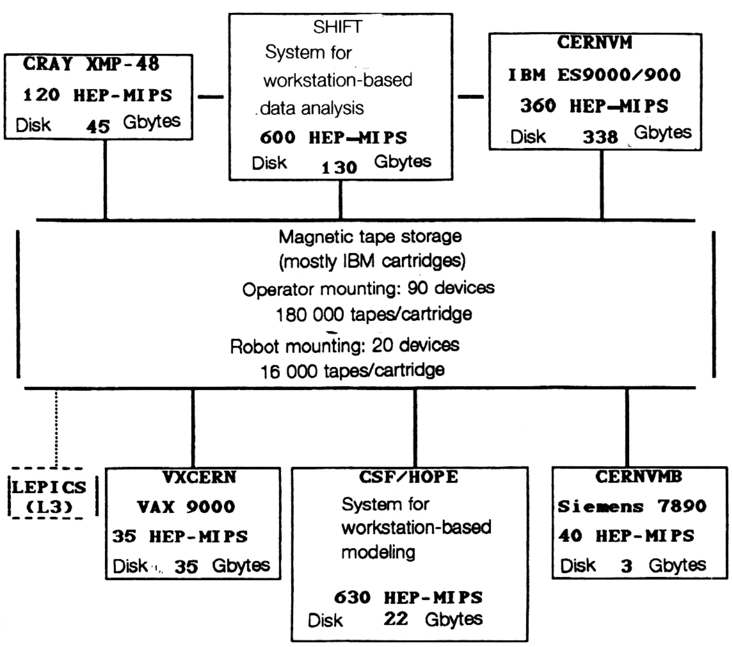

FIG. 10. Simplified scheme of the CERN computational center showing its basic possibilities at the beginning of 1992.

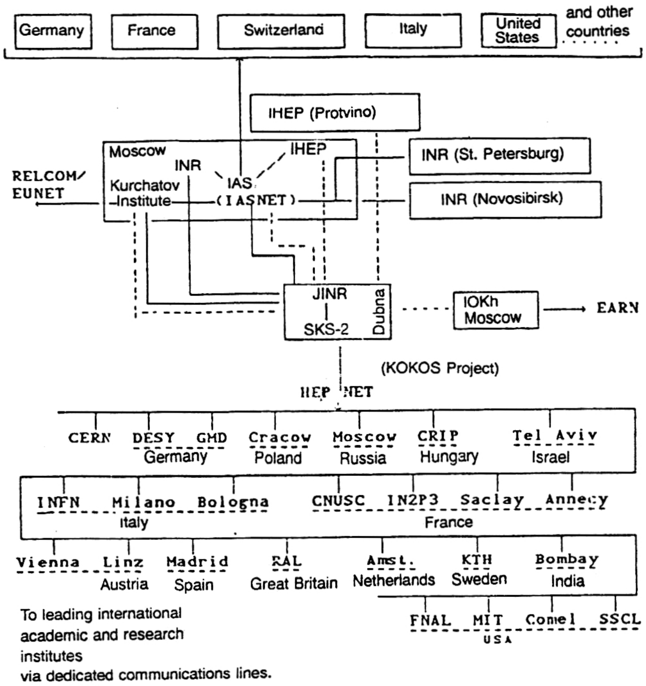

FIG. 11. Schematic view of links between JINR and the international computer networks of Europe, the United States, and nuclear centers in Russia.

ics design systems. The VAX stations were mainly used to develop software support and for physical analysis.

By 1992 the total computing power of the CERN Computing Center was about 2000 HEP-MIPS, of which ~60–70% was from distributed computing systems (Fig. 10). The total amount of disk memory was greater than 550 Gbytes. The magnetic tape storage amounted to about 200 thousand magnetic tapes and cartridges. For the three thousand personnel and four thousand visitors there were more than five thousand personal computers and workstations of various types.[16]

Therefore, the main components of the CERN Computing Center in 1992 were a central library of magnetic tapes and cartridges, including automatic loaders, general-purpose mainframes, and workstation-based systems, which have come to play a more and more important role.

In addition to the development of the CERN Computing Center, the large-scale electronic experiments were provided with their own computing systems, examples of which were given above.

In 1992 it was becoming clear to specialists at CERN that the epoch of mainframes and supercomputers in HEP was coming to an end and that it was necessary to seek replacements for them.[143]

In April 1992 it was announced that CERN would no longer use the CRAY X-MP/48 and that it would replace CERNVAX by more powerful machines with RISC architecture, called DXCERN (Ref. 144).

In March 1993 the CRAY X-MP/48 was replaced by clusters based on the IBM RS6000 and the HP9000/700 (Ref.144).

In Fig. 11 we show the international communications links connecting CERN to members of the HEP community around the world at the beginning of 1992. Most of these links were originally used for experimental research in HEP, but the 1 554 Kbit/sec line at Cornell University in the US is an example of a line financed by other sources. This link was set up in order to make use of the advantages offered by CERN as the center of the European network. The large spread in data-transmission rates for data coming from CERN is a reflection of the fact that these lines are entirely financed by the agencies responsible for the remote ends, and

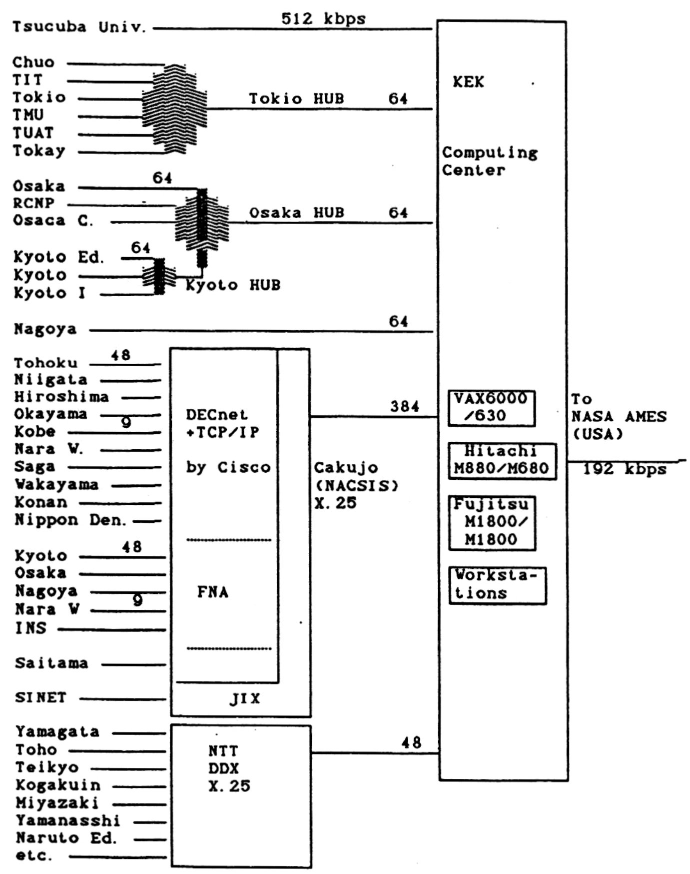

FIG. 12. Network linking the HEIF of Japan.

TABLE VIII. Central computer system of KEK.

	M-880/210 (Hitachi)	M-680H (Hitachi)	S-820/80 (Hitachi)
CPU performance	93 Mips	56 Mips	3.0 Gflops
Main memory	256 Mbytes	28 Mbytes	512 Mbytes
External memory	1.5 Gbytes		2 Gbytes
Operating system	VOS3/AS	VOS3/AS HI-OSF	VOS3/AS
Files (for three computers)			
Magnetic disk for users		180 Gbytes	
Tape library		2.2 Tbytes	
Tape units		14	

TABLE IX. Computer system of TRISTAN.

	Batch system M 1800/30 (Fujitsu)	TSS system M 1800/10 s (Fujitsu)
CPU performance (proposed)	140 Mips	33 Mips
Main memory	128 Mbytes	256 Mbytes
Operating system	OS IV/F4 MSP	OS IV/F4 MSP UXP/M(UNIX)
Disk memory system	234 Gbytes	
Transfer rate	9 Mbytes/sec	
Library of VHS tapes	3 units	
Total capacity	1.8 Tbytes	
Transfer rate	3 Mbytes/sec	
Cluster of work stations		
S-4/10 model 40	11 machines 96 Mips/machine	

it is their financial input which determines the line speed.

As an example of a computing environment of a national center, let us consider the national HEP laboratory of Japan, KEK (Refs. 131, 137, and 146).

Research in high-energy physics in Japan is carried out at the e^+e^- collider TRISTAN and the proton synchrotron (the 12 GeV PS) by two national and one international collaborations.

Universities and institutes in Japan, including KEK, participate in experiments carried out at other HEP centers around the world: CDF (FNAL), OPAL (LEP), ZEUS (HERA), SLD (SLAC), and so on. Altogether, there are 45 institutes in Japan involved in high-energy physics. Most of the data obtained in these experiments are processed at the KEK computational center.

KEK possesses most of the computational resources devoted to HEP in Japan, which satisfy the requirements of not only the laboratory itself, but also of other organizations involved in HEP experiments, which have access to these resources via a computer network linking all the HEP computers in Japan.

The main characteristics of the central computer system of KEK are shown in Table VIII.

The central computing system on KEK consists of two universal computers (HITAC M-680H and M-280H) and a vector processor (HITAC S820/80). The maximum efficiency of the M-680H is 31 MIPS and that of the M-280H is 14 MIPS. The peak speed of the S820/80 is 3.0 Gflops. Since June 1992 these three computers have formed a loosely connected multiprocessor (LCMP) system for shared use of the large disk space.

The TRISTAN computing system is designed for support of the collider experiments carried out there. It consists of two computers: one operating in time-sharing mode (FACOM M-780/10S) and the other in packet mode (FACOM M-780/30). The characteristics of these systems are given in Table IX of Ref. 146.

At the beginning of 1993 the power of this system was increased by about a factor of 1.7, the total disk space was increased to 230 Gbytes, and the amount of tape storage was increased to 3.3 Terabytes.

In addition to the mainframe complex there is a cluster of eleven S-4/10 (Fujitsu) SUN-compatible workstations, each supplying 96 MIPS.

The KEK computer network HEPnet-J (High Energy Physics network-Japan) connects the center to other Japanese and international institutes carrying out research in HEP and nuclear physics. HEPnet-J is linked through KEK to the US via a dedicated international line, and via the US to Europe, thus forming an international HEP network which has been functioning since June 1992 (Fig. 13).

The possibility of establishing computer links with Russia and China is being considered.

Since December 1991 a teleconferencing system has been in operation at KEK. It is often used by the Japan–US collaboration and has a good reputation. On the average it used about 25 hours a month.

Collaborators at universities use their own computers not only to solve their own local problems, but also as remote nodes of the computing network, ensuring access to the mainframes of the central computational system of KEK. They can send jobs to be run in packet mode and receive the results over the network.

The future experimental research program in HEP at KEK will be oriented both toward the development of its own accelerator base, and toward participation in international collaborations.

Let us conclude this section by reviewing the status and perspectives for the development of the informational–computational infrastructure of the Joint Institute for Nuclear Research.

The scientific research program at the JINR includes experimental and theoretical studies in the following areas:

•Intermediate-energy physics;
•Heavy-ion physics;
•Neutron nuclear physics;
•Elementary-particle physics;
•Relativistic nuclear physics;
•Condensed-matter physics.

The JINR also continues to play a key role in coordinating research carried out by scientists of the 18 member-countries in the JINR and the supporting the broad scientific collaboration of institutes from these countries with leading physics centers around the world and international organizations. The institute also has a special agreement regarding

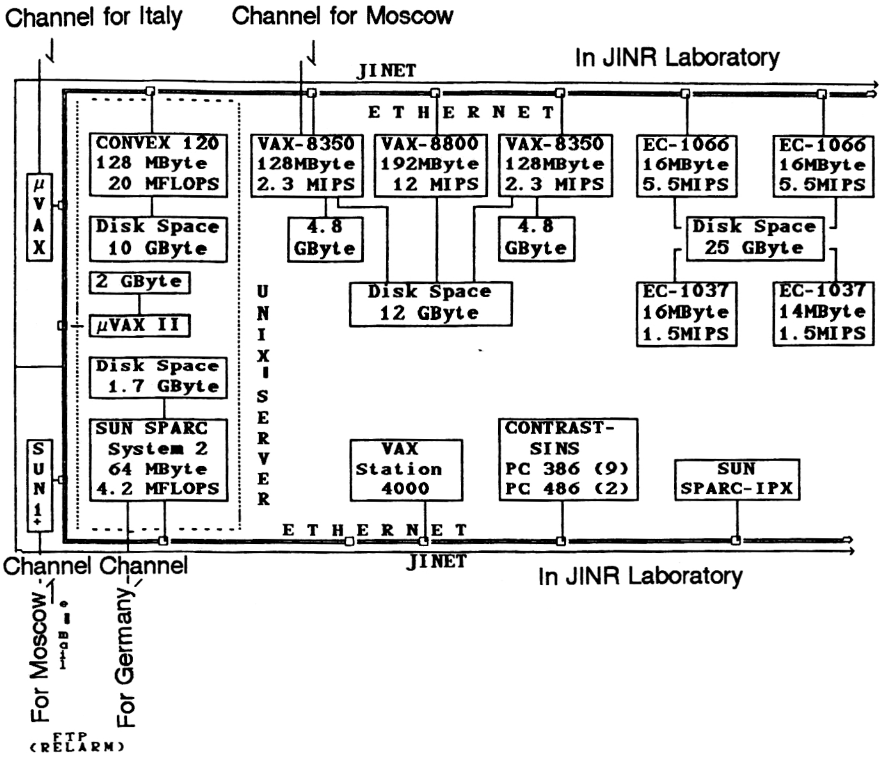

FIG. 13. Central computational complex. Joint Institute of Nuclear Research.

joint research with CERN and research centers in the US, Germany, France, Italy, and Hungary.

All these activities require adequate support from the informational-computational infrastructure of the JINR. The adequacy with which the computer resources of the JINR satisfy the requirements imposed on an international center of fundamental research can be judged from the following figures.

The informational-computational infrastructure of the JINR is based on the JINR Central Computing Complex (CCC), local measurement–computational centers inside laboratories and subsections of the institute, and both computer and terminal links.

The JINR CCC contains the following (Fig. 13):

•A distributed UNIX server based on the CONVEX-C120, SUN SPARC Station II, and microVAX computers;

•A cluster of three VAX computers;

•A complex of ES computers containing two matrix processors with a power of up to 20 MIPS for vector operations;

•A VAXstation-4000;

•Two SUN SPARC-IPX stations;

•A complex of CONTRAST-SINS workstations.

Magnetic tapes of various densities (from 800 to 6250 bpi), cartridges, EXABYTE-8500s, and CD-ROMs are used for the archiving, storage, and processing of large amounts of data.

The main task of the UNIX server is to provide users of the local JINR network access to computational, software, file, and information services on the basis of a unified interface in the UNIX medium. There are further plans to acquire an integrated multiprocessor system based on the C220 with two HP/735 RISC processors and a SUN SPARC 1000 multiprocessor server, to increase the disk space, and to create a massive memory system based on devices of the EXABYTE-8500 type.

The computing devices of subdivisions of the Institute (the computers belonging to the measurement-computational centers of laboratories, SUN and VAX stations, microVAXes, personal computers like the IBM PC XT/AT/286/386/486) are all linked by the JINET (Joint Institute NETwork) network and Ethernet, which provides access to the resources of the central computers in the CCC of the Institute. In addition, these devices can exchange electronic mail, order preprints from the scientific-technical library, receive information bulletins, news concerning networks and computers, seminar notices, administrative notices, etc.

The software support of the complex includes network packages; traditional programming systems, SUBD, the program libraries CERNLIB, NAGLIB, and other applied software support used in physics centers for carrying out experimental and theoretical research, including program packages for data analysis and control, experimental modeling, support of large software complexes, data representation, and so on. An archive of free software support is maintained on the CONVEX computer.

Workers at the Institute have access to PPDS, the particle-physics data base, the INIS informational subsystem, and the international system WWW.

The local network infrastructure of the JINR is linked to international computer networks via dedicated and commutable surface and satellite links (Fig. 10). There are two dedicated computer lines to Moscow, one with a transmission rate of 9600 bits/sec and the other with one of 19.2 Kbits/sec. The channels use the TCP/IP protocol and allow remote log-on to computers (including ones abroad) and exchange of electronic mail, teleconferencing materials, data files, and programs. These communications systems allow electronic mail exchange and remote sessions between users of the local networks JINET and the JINR ETHERNET and subscribers or computers at the main physics centers in Russia (IHEP in Protvino, ITEP, the Institute for Nuclear Research, the Kurchatov Institute, and the Lebedev Institute in Moscow, the Nuclear Physics Institute in Gatchina and in Novosibirsk, etc.) and abroad (Germany, France, Italy, Switzerland, the United States).

In order to provide participants in international collaborations with more efficient links to the JINR base, the Cosmic Link Station at Dubna (SKS-2) and the Tensor enterprise have set up two satellite communications channels.

One provides direct access to computing centers in Germany and the other to Italy, and via them it is possible to access other international computer networks.

The following services are provided through these channels:

•Operational information exchange via electronic mail;

•Access to data bases;

•Shared use of computing power of the computers on the network;

•Data transfer for off-line processing;

•Transfer of facsimile information, texts of articles, teleconferencing.

The rate of data transmission on the network via these channels is 64 kbits/sec, and may be increased in the future.

These channels provide JINR workers with access in the interactive mode to the powerful computers and databases of the scientific centers in Europe and around the world. The possibility of using a satellite channel to Potsdam for teleconferencing between the JINR and scientific centers in Germany is under consideration.

Therefore, although the computing environment of the JINR ensures the participation of Institute workers in international collaborations, its resources are considerably more scarce than those of other leading scientific centers. The biggest problems are the lack of disk space for the central computers, the speeds of data transmission on existing communications channels, and the lack of modern personal computers and workstations at work sites. However, it should be noted that in recent years significant steps have been taken toward the solution of these problems and toward increasing the productivity of the Central Computing Complex.

4. SOFTWARE SUPPORT FOR DATA ANALYSIS IN HIGH-ENERGY PHYSICS

The software support for HEP experiments consists of a large and complex set of a wide variety of programs, packages, and systems designed to perform the following tasks in data processing and analysis:

modeling;

event reconstruction;

organization of data structures;

interactive analysis and representation of data;

organization of and working with data bases;

statistical analysis and calculation of the characteristics of the physical processes studied.

4.1. Some special features of the software support for HEP experiments

The problems arising in providing software support for the large detectors in current and future HEP experiments have been discussed by Bock[85] at the 1987 computing conference.[3] In particular, the need was noted for closer collaboration in this area between "experiments" and large institutes; the possible elimination in software support of situations difficult to control by the introduction of modern techniques into programming practice; the need for a small number of specially trained, experienced programmer leaders to monitor the activity of traditional physicist volunteers; and also the need for greater contacts both within the HEP community and with people working in other sciences, including computer science, and industry.

In judging the meaning of the term "large" as applied to HEP experiments (How large is Large?), Bock notes that it can be characterized by the following data:

•A typical collaboration associated with a large detector contains 100 to 400 physicists. Half of them usually contribute to the development of the software support, and a dozen or more contribute to the solution of problems of responsibility or coordination.

•The number of computers in a typical experiment is $\geqslant$100.

•The amount of software support of a HEP collaboration is from 100 to 500 thousand lines. Of this, 2/3 is executable code, 1/10 are operator declarations, and 1/4 is commentary. This, of course, pertains to the programs of that time, which were written in Fortran.

•Data-analysis programs usually consist of several hundred subprograms, of which from 10 to 20% are written directly by physicists. The rest contains program elements from general-purpose libraries supporting experiment which belong to the collaboration or are even commercial.

The current status of activity in this area in 1991–92 has been discussed in the reviews of Mount[16] and Kunz.[38]

Characterizing the state of affairs regarding software support of HEP experiments in 1992, Mount noted that in spite of the very large amounts of software support (hundreds of thousands and millions of lines of program codes) which participants in HEP collaborations must write, usually only a very small fraction or none at all of these participants are professional programmers.

Most physicists working in this area of research are programmers, and they all clearly understand that neither their own codes nor those from a software library can be error-free.

There is another important factor which cannot be ignored. Whereas in the not-so-distant past the skill of a programmer was judged from his ability to enter the maximum amount of code into the minimum amount of computer memory, and the "readability" of the text by other people was generally of no particular value, at the present time the situation has greatly changed. The question of "clarity versus efficiency" has essentially been answered in favor of the former, which is natural when a reasonable comparison is made. Moreover, in most collaborations formal or information attempts are made to get the programmers to write pro-

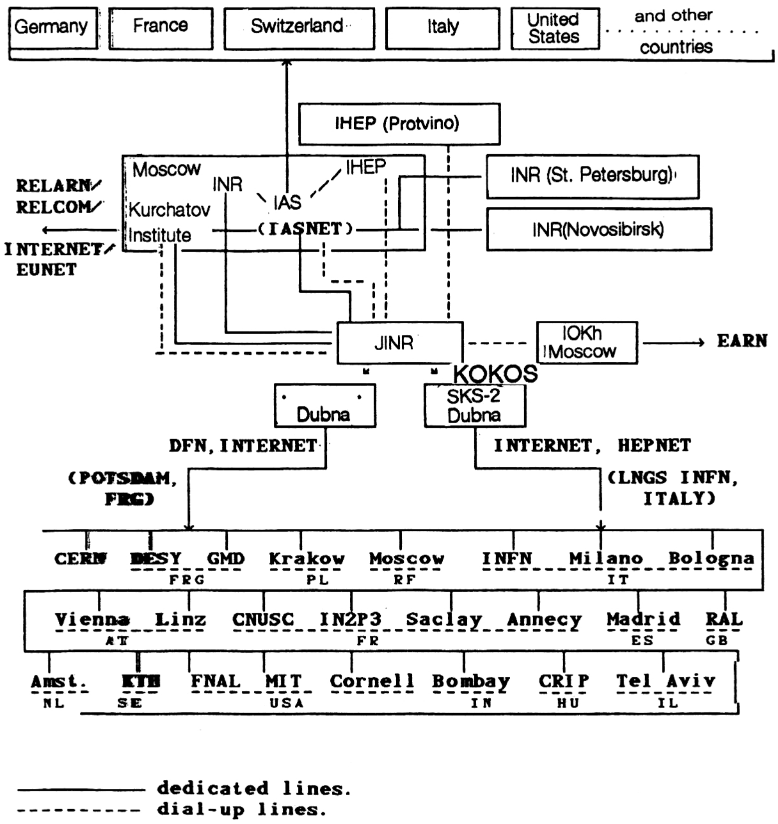

FIG. 14. Schematic view of links between JINR and the international computer networks of Europe, the United States, and nuclear centers in Russia.

grams such that their texts can be understood by others, in particular, graduate students at universities.

Fortran is the main algorithmic language used in HEP, and attempts to replace it have so far not met with any success, although there are some changes in this direction, and alternatives to Fortran are discussed at the conferences on computing in HEP (Refs. 34–38). Fortran is a convenient programming language for scientific calculations, but from the viewpoint of HEP it has a number of drawbacks. Special methods have been developed for eliminating them, in particular, for the management of data structures and machine-independent input/output, and it is these which to a large degree have ensured the survival of Fortran.[16]

4.2. Software tools in high-energy physics

Software tools in high-energy physics are divided into the following three categories:[16]

1. Tools for overcoming the limitations of Fortran. Examples are the ZEBRA package,[39] and also its predecessors: HYDRA,[40] ZBOOK,[41] and BOS.[42] ZEBRA (the data structure management system) was developed at CERN to overcome deficiencies of Fortran in organizing dynamical data structures.

2. Tools ensuring machine-independent functions such as managing codes, databases, and general-purpose program libraries, which provide the basis for creating specific applied programs.

The first example of a tool for managing codes was the PATCHY system.[43] This program, oriented toward card readers, for more than twenty years provided software development and support and was adapted to each type of computer used in HEP, including the BESM-6 (Ref. 44).

At present this function is performed by a new code-management system CMZ (Code Management System using ZEBRA). This is an interactive, fast, machine-independent, PATCHY-compatible system of managing and tracking source texts in Fortran 77 and C. It provides developers with effective support tools for creating a software product beginning from its development and ending with its tracking.[45]

Another example of tools of this type is the HEPDB database management system, which is designed to store calibration constants and provide a system for using them. It is created on the basis of the systems DBL3 and OPCAL (Refs. 46–48) developed for individual HEP experiments. HEPDB uses the possibilities of direct access of the ZEBRA system, ensuring machine independence and support of access to data using Fortran tools (Refs. 42, 73–80).

The third example of tools of this category is the CERN KERNLIB, a compact nucleus of libraries of frequently used service and computational programs and subprograms. This library can be put on nearly all types of computer and is the most important element of the CERN program library.[86] Most of the packages of applied programs of CERN and other laboratories have been created using it.

At the present time the library of CERN programs (CERNLIB) extends to nearly 600 laboratories and institutes in 55 countries (Refs. 86, 88, and 89).

The structure of the library is shown in Fig. 15. Its various components add up to more than 1 million lines including test programs, most of which are written in Fortran 77.

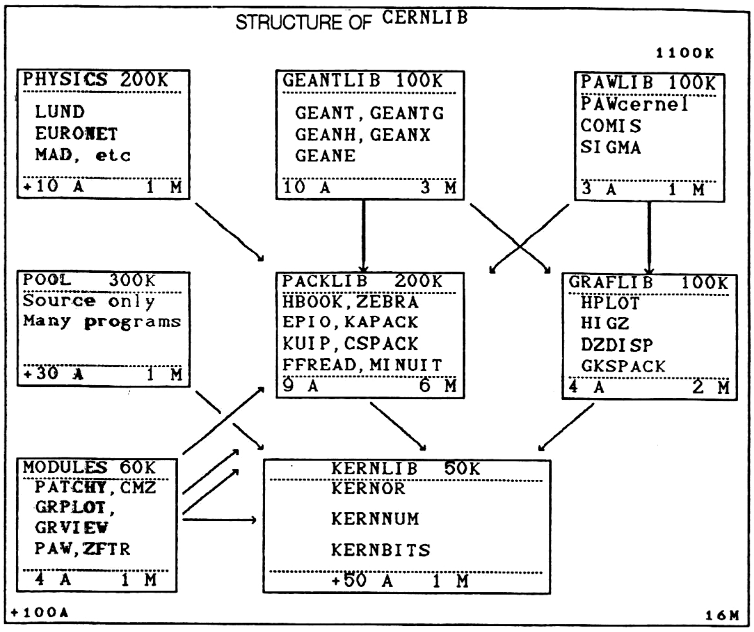

FIG. 15. Structure of the CERN program library (1100 K).

Some of the programs in KERNLIB (~5000 lines) are written in assembly language. PACKLIB, GRAFLIB, and KERNLIB contain an ever-increasing number of subprograms written in C(~10 000 lines). The estimated number of lines contained in each library component is given in the upper right-hand corner of the corresponding box. The total number of authors in the library is more than one hundred. The estimated number of authors in each component is given on the lower left, and on the lower right is the number of people involved in the development and continuing support of the corresponding component.

A special system of automatic generation of program documentation SIM (A Software Information Manager) has been developed for obtaining documentation on programs in the library.[87]

3. Specific software tools for HEP. This large category includes programs and utilities specially written for many experiments or for specific ones.

In Fig. 16 we show the basic scheme of the data-analysis chain in HEP and give the names of some of the widely used programs at the stage for which they are used, together with the name of the laboratory at which they were developed.

During the particle-generation stage a primary interaction leading to particle production is modeled together with decays of short-lived particles. The result is the 4-vector of the long-lived particles. This is done using the LUND program[81] or other similar programs which ensure particle production (Monte Carlo and the like).

Many of the components in event modeling are common to many experiments. Event generators are combined into packages which model known or hypothetical cases of particle production in individual e^+e^-,e^-p,pp, or $p\bar{p}$ collisions.

Examples of widely used event generators are the following: LUND (Ref. 69), KORALS (Ref. 49) and KORALB (Ref. 50), JETSET (Refs. 51 and 52), HERWIG (Refs. 53–

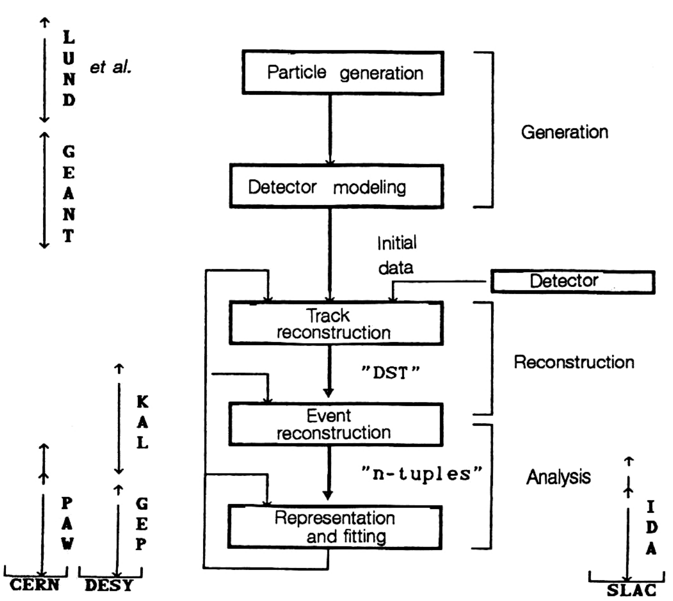

FIG. 16. Schematic diagram of the analysis chain showing the programs commonly used in its various stages.

57), PYTHIA (Refs. 58–60), ISAJET (Ref. 61), MARS (Refs. 71 and 72), EGS (Ref. 64), and GHEISHA (Ref. 65).

In the next stage the behavior of the event in the detector is modeled. Here the particles are "passed" through the detector, and spatial points and detector "responses" are generated and written in a result file in the same form as for real detectors. The GEANT package is widely used for this.[62]

The stage of track reconstruction solves the problem of recognition of elements of an event recorded in the detector, reconstruction of track segments, and preliminary identification, during which a list of probabilities for the track to belong to a certain type of particle is compiled.

During the event reconstruction stage the tracks reconstructed on the basis of the identification data are assigned values of the mass and their 4-vector is constructed. Hypotheses about the vertices and event topology are made using combinations of these. The results of this stage are represented in the form of histograms and n-tuples. The latter are two-dimensional structures characterized by two numbers. The first is the number of entries for one element of the structure, and the second is the total number of elements. Each element of the n-tuple can be viewed as a physical even characterized by a small set of physical quantities (entries).

An example of a software tool for event reconstruction is the KAL packet developed at DESY.[83]

In the final stage (representation and fitting) the statistical data collected at the earlier stages are represented as histograms, scatter plots, and so on.

PAW, GEP, and IDA close the chain.

PAW is a set of packages for interactive data analysis, including generation and representation of histograms and graphs. It requires that the physicists write a program to extract from the complicated data describing each event a small number of variables per event (an n-tuple), which can then be used to analyze the event.[68]

GEP is an interactive analysis program for analyzing data in HEP. It was written at DESY. It allows the user to perform many operations on the data, to obtain histograms, scatter plots, graphs, perform interactive data fitting, and generate new histograms or scatter plots from multidimensional distributions.[82]

IDA is an interactive system for analyzing data in HEP. It is widely used at SLAC for DST analysis.[84]

The GEANT package is currently a component of most Monte Carlo programs for current and future experiments. The GEANT subprograms "lead" particles through the detector taking into account the interaction cross sections in the sensitive and nonsensitive detector elements. These data are then transformed into responses of the detector elements.[62,63]

A typical collaboration working in HEP includes hundreds of physicists from dozens of institutes. The computations for these experiments are performed both at the main center, and at the institutes of the collaboration members, forming a distributed data base which requires management and access to the large amounts of data stored in the various devices spread out over a large geographical area. A special system has been developed for solving this, the FATMEN Distributed File and Tape Management System (Data Management, Access, and Presentation in a Distributed, Heterogeneous Environment).

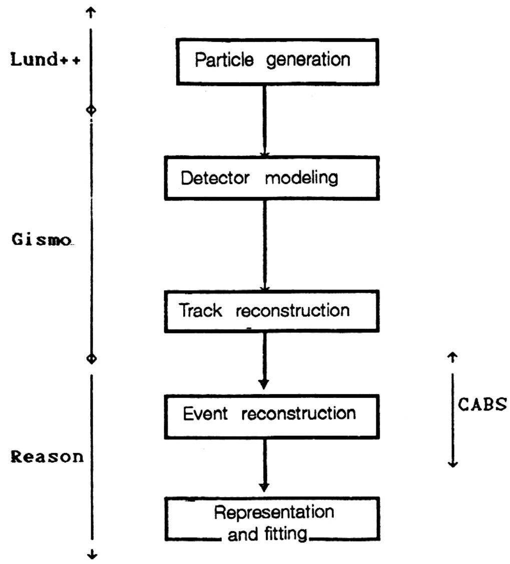

FIG. 17. New methods of data analysis in the 1990s.

FATMEN is a catalog of data sets, which is a new tool constructed in order to solve the problem of managing and addressing hundreds of thousands of data sets distributed (and probably duplicated) among many computers. FATMEN provides the user with access to data independently of the host system at which the user works, or distributes the data themselves. The data can be stored on a local or remote machine on a disk, tape, or other storage device. In all cases the user interface is the same. FATMEN performs three basic functions: data naming, access, and management.[66,67]

4.3. Future software tools in HEP

Considering the possible paths of development of software tools in HEP, Kunz[38] notes that no one can with certainty predict the future, because in computing technology both hardware and software are undergoing very rapid development. In his opinion, the key question is the path along which software support will develop.

The evolutionary approach will imply a gradual transition to Fortran 90 with its new possibilities, which will simplify the problem of writing programs for physical analysis and analyzing tools.[90]

The revolutionary approach implies a change in programming language and the use of object-oriented paradigms. Both of these will increase the graphics interface tools available to the user of GUI (Graphic User Interface).[138]

Until recently, almost all of the software tools for physical analysis were constructed using Fortran and the auxiliary tools which enhance its possibilities, as described above.

Many researchers outside HEP have found that the approach of object-oriented programming (OOP) is a better paradigm for creating modeling and analysis software. This is a real revolution in programming. The OOP paradigm is not related to any particular language. It is realized in analysis systems outside HEP using the languages Objective-C, C++, Small Talk, and Eiffel.[16]

In connection with the move in HEP toward greater use of UNIX systems,[106–111,139] the use of C for creating window control systems and operating and network systems is growing. It is also used by many physicists to create data collection systems. So the big equation about the future is: will Fortran 90 survive the migration to C (Ref. 91)?

However, C does not solve the problem of the input and output of data structures. This is solved using the system Cheetah, which provides the user with a set of C functions for managing these structures.[92]

The technology of object-oriented programming makes it possible to design complex programs with minimal expense.[93–96]

The universal programming language C++ is a development of C toward object-oriented programming and includes mechanisms for type control, data abstraction, and combining operations.[97]

Prototypes of potentially revolutionary new software tools for physical analysis have been discussed by Kunz in Ref. 38.

In Fig. 17 we show a schematic diagram of these tools encompassing the entire analysis cycle beginning with event generation and ending with data representation and fitting.

Lund++ is a program for modeling particle production processes.[98,99] The initial version of the program was written at SLAC using Objective-C. It was later rewritten in C++. These prototypes showed that the OOP approach is a powerful tool for solving the modeling problem.

Gismo is a package of programs for detector modeling and track reconstruction.[35]

The project Reason was begun in the summer of 1989 for studying the possibility of using the technique of visual programming.[100]

CABS is an example of the use of OOP for the physical analysis of B-meson decays.[101]

At the conference on computing in HEP in 1992 there was a special session (OBJECT ORIENTED DEVELOPMENTS) devoted to examples of the use of OOP at which 11 reports were presented. This indicates the ever growing role of these methods in HEP.

Work is being done on automating the process of generation of chains of programs for data analysis using Fortran, for example, CAB (The Cosmos Application Builder).[102]

Therefore, at the present time the development of software support for HEP experiments is following two directions which live together in "peaceful coexistence."

4.4. Access to terabytes of data

At the present time and probably during the next 20 years a great problem in HEP computing will be providing access of hundreds of physicists to large amounts of data stored in various types of storage devices.

This problem is solved using various types of information storage (magnetic tapes, cartridges with automatic loading, EXABYTES) along with magnetic disks, on which information in current use is written. Approaches based on the use of specialized databases have been developed to organize access to the data.[103,104]

It is possible that when the cost of direct-access devices is lower, these data will be stored on devices permitting direct access. Accordingly, it is apparently useful to consider optical disks, which at present are the most promising device for the storage of large amounts of information. Compared to magnetic storage devices, they at present are characterized by long access times and higher cost. However, the development of operating systems, common databases, and image-processing systems may lead to a shift of the economic balance in favor of optical memory. There is no other technology at present that can compete with the technology of optical memory in situations where the daily information writing is measured in gigabytes. The introduction of rewritable optical systems allowing one to actually work with unlimited amounts of information may create favorable prerequisites for the future introduction of this technology into HEP (Ref. 105).

A partial solution of this problem might be based on the fact that not all the available data are needed equally often in an analysis. Some events need to be studied more often than others. In addition, in each event there is a fraction of the initial or reconstructed quantities which is used more often than the rest.

One special version of solving the problem of data management may be the not very flexible solution used in the L3 experiment. It amounts to the following. The data after reconstruction are divided into 27 separate flows. One half of the flows contains complete information about the events, and the other half contains only the part corresponding to the most often used structures of the reconstructed data. The information contained in each flow is combined into sets of 200 Mbytes each, written on cartridges, and when needed copied from them onto a disk for subsequent transfer to the physicist's workstation. Systems of this type use special catalogs to provide physicists with access to data and the corresponding devices.[66]

The diversity of operating systems with which physicists must deal leads to certain difficulties. The situation is changing owing to the use of the UNIX operating system (Refs. 16, 106–111, and 139).

5. DATA SUPPORT OF HEP EXPERIMENTS AND INTERNATIONAL INFORMATION SYSTEMS

The problems associated with the data support of research in HEP deserves special attention. This arises, in particular, in the creation of specialized databases and information-search systems, for example, FreeHEP, QSPIRES, PPSD, and WWW.

To collect information on the software support of HEP experiments the special organization FreeHEP has been created, with access to its information store via electronic mail.

FreeHEP is an organization devoted to providing the HEP community with information about available software support, which can be of interest for research in high-energy physics, and the organization of easy access to it for users and developers.

Since the information collected by FreeHEP must be as complete as possible, it includes all the software support which can be useful for HEP.

For this reason, no requirements are imposed on the methods of transmission, formulation, documentation, language, machine support, and so on. All this is left to the authors. The development and maintenance of software support is not the problem of FreeHEP. Its role is limited to collecting information, providing easy access to it to interested users, and helping authors and users to establish contacts.

The main components of FreeHEP are the following:

(a) Global compilation of software of interest for HEP.

(b) Easy access to information.

(c) A user network news group for users and authors to discuss problems, suggestions, new ideas, etc.

(d) A set of directions for various general topics such as "how to use electronic mail" and "how to work with FreeHEP," and so on.

To contribute information to the FreeHEP store or to remove information from it is necessary to contact one of the editors by electronic mail.

FreeHEP currently contains the following divisions: Graphics, Visualization, GUI; Detector Simulation; Data Acquisition; Analysis and Data Reduction; Event Generators and Software Engineering; General Libraries; Parallelism and Distributed Computing; Software Engineering; Software Compilation; Event Generators; Data Bases; CAD/CAE systems.

The suggestion to create this system was made at the HEPLIB conference held at the SSC Laboratory in January 1991 and then discussed at the conference in La Londe. Its initiators and the authors of the original version are Tony Johnson, Andrea Palounek, and Saul Youssef.

An information-search system oriented toward physics research is QSPIRES (Stanford Physics Information Retrieval System).[141] This system consists of several databases supported by SLAC in collaboration with DESY, LBL, and several other institutes. Access to it is provided through a remote server located at the BITNET node SLACVM, and information searches can be performed interactively. JINR is located rather far from this node, and access to it is currently provided via electronic mail. Inquiries are answered within two or three days, and the amount of information sent is limited. Nevertheless, the latest information put on the system can be received at JINR much more quickly than by any other method.

The Institute of High Energy Physics (IHEP) at Protvino is carrying out the KOMPAS project, the goal of which is the development of the idea, which originated with the LBL (United States) and RAL (England) systemization groups, of creating a system of particle-physics databases for collecting and evaluating experimental data and providing the physics community with access to it.[142]

The creation of international computer networks connecting the worlds of science and business and the distributed information systems based on them have led to the creation of specialized information-search systems (GOPHER, WISE, and WWW).

Let us explain their use for the example of the INTERNET (Ref. 148).

The Internet system is not simply electronic mail. Companies all over the world use it to search for and obtain information of various types. Using this world-wide high-speed information route one can find anything, from the latest articles on universal reason to the texts of popular songs.

However, it is not always simple to find the needed information. Because there are thousands of data bases and dozens of navigational systems, a search on the multi-branched Internet can take hours or even days. Fortunately, there are some convenient auxiliary programs for the Internet which help one to rapidly find the required information.

Internet can work with three basic information search and retrieval systems: The Gopher, Wide-Area Information Servers (WAIS), and World-Wide Web (WWW).

Gopher is the most commonly used tool for Internet searches. It allows one to find information using key words and phrases. Work with the Gopher system begins by scanning a table of contents, where the user can scan through a series of menus and choose the topic needed. There are currently more than 2000 Gopher systems on the Internet. Some of them are narrowly specialized, while others contain information of broader interest.

Gopher can be used to obtain information without specifying the names and addresses of the authors, so that the user does not spend much time and effort. The user simply asks the Gopher system for what he needs, and the system finds the corresponding information.

The software support for creating a Gopher server is freely disseminated on the Internet system, but if the user sets up his own gopher he must buy a license from the University of Minnesota.

WAIS is a tool for obtaining information more powerful than Gopher, since it searches for key words in the full text of a document. Questions are sent to WAIS in simplified English. This is considerably easier than formulating a question in logic algebra, and it makes WAIS more attractive for casual users. There are more than 200 WAIS libraries, the information to which is provided mainly by workers at academic organizations on a voluntary basis. Therefore, much of the available material pertains to research and computer science.

WWW, World-Wide Web, is one of the distributed information systems whose development was initiated by CERN in 1992. WWW is distributed hypertext, that is, a (very large) set of servers throughout the world, which are associated with clients using the network protocol TCP. The servers, as a rule, have on their computer some set of documents to which a given organization provides access to the rest of the world. The distinguishing feature of these documents is the possibility of containing references to other (perhaps located in another country) documents or parts of documents. This feature is what produces the "web" which interlinks documents, which can contain INLINE graphics, sound, etc.

WWW is very actively used in research circles, in particular, at CERN, for organizing the interaction and a common information base for working groups, for example, ATLAS. Access to this system is possible from JINR (Ref. 147).

These information systems are well acquainted with each other and can interact effectively. As a rule, they sit on a common pile of documents. There are associated archival and reference services (ARCHIE, FTP) in addition to the databases, in a word, an entire information conglomerate, which helps the user to rapidly and effectively extract anything desired.

6. THE NEXT GENERATION OF HEP EXPERIMENTS, THEIR COMPUTING REQUIREMENTS, AND THE PURPOSE OF CENTRAL COMPUTING SYSTEMS

The problems posed for computing by the building of new accelerators (LHC and SSC) and the experiments planned for them were discussed in 1990 at a symposium devoted to detectors for the SSC (Ref. 140). In spite of the halt of the construction of this detector in 1993, the problems raised at the symposium remain important, since they essentially concern the computing environments of the next generation of HEP experiments and ways of solving the computing problem for rapidly developing physics research. In addition, the full range of problems raised at the symposium is important not only for experiments planned for the LHC, but also for other large electronic experiments, since the method of solving the computing problem under the new conditions is rather general in nature.

Among the main characteristics of the computing problem for the next generation of colliders are the following:

1. Each experiment will generate from 10 to 100 Terabytes of unprocessed data per year. In addition, in the processing of a typical event the amount of information per event will double. The physicists at the main laboratory and their coworkers at remote institutes must have access to these data.

The data management system will have to satisfy the following requirements. The solution of problems requiring large statistics requires the "scanning" of large amounts of data event by event, and choosing only a few numbers pertaining to each event. On the other hand, in studying rare processes it is necessary to search for isolated events in a large amount of data in order to be able to analyze all the data pertaining to the event. The organization of the data must ensure the efficient search for these two types of information.

2. Physicists will require good interactive computing and efficient access to large databases. The software support will have to include statistics packages and powerful graphics and user interfaces for constructing complex programs from simple modules. An important goal of future software systems which must be realized will be the organization of the running of a program such that it appears to be running on the local workstation of the user. The use should not have to think about where the program is running and where the data used is stored.

3. The text of the software support for current HEP experiments amounts to millions of lines of Fortran. The development of such software systems is a complicated problem for any group. To make sure that the created software support is reliable and that not only the authors are involved with it, it is necessary to use modern development tools in the construction, documentation, and testing of programs, and also to introduce standards and industrial developments.

Since the creation of distributed systems based on RISC processors and powerful workstations provides the computational resources of HEP experiments, the solution of the computing problem reduces to the solution of the following problems:

•Data organization, storage, and management;

•Creation of the corresponding computing environment;

•Introduction of modern methods of software support development.

It was further noted that the development of software support systems for new HEP experiments also requires a change in the style and working methods of physicists. A solution of this problem must be produced by the combined efforts of three groups; the experimentalists themselves, the programmers of the main laboratory, and the computer industry.

The tasks of the experimentalists are the planning, designing, and financing of computer systems and also detectors. At the same time they, together with the laboratory directors, must determine the requirements on the computer systems and software support which must be met by the central computational complex.

The tasks of the laboratory are ensuring the centralized support of experiments by providing the corresponding hardware and software systems and developing and introducing methods for creating them on the basis of the latest technology and industrial developments.

The laboratory must also develop a mechanism by which experiments can guide the selection of the systems supported at the laboratory level, and also ensure the support of suitable standards and the monitoring of the corresponding developments in the computer industry.

The experience of CERN and other leading physics centers shows that even providing large electronic experiments with their own computational resources, including rather powerful systems, does not slow the rate of development of central computing systems. Moreover, the increasing complexity of experiments leads to new requirements on the central computational resources. Therefore, increasing the central computational resources remains an important problem, and its solution will require learning to evaluate the real requirements of experimental groups and the dynamically developing computer market.[33]

Another aspect of the activity of the central computational complex is the storage of and ability to rapidly search through large amounts of data.

An obvious task of the central computational complex is the organization of communications between the center and the worldwide scientific community.

The presence in an institute of a large group of different computers also requires centralized hardware and software support.

The intensive development of computer science, including the development of qualitatively new technologies for developing software systems, should be put into practice.

Examples are the development of graphics interfaces, which are the decisive factor in improving the quality of the software support for scientific research, the use of standards, and the search for more suitable commercial and freely available products.

For example, the popularity of graphical interfaces on the personal-computer market demonstrates that it is important to follow this example when developing software for HEP.

Another new product which will probably strongly affect scientific computing is the Application Visualization System (AVS) from Stardent Computers. Using AVS, a physicist can develop complex graphical applications without writing code. This product has been used in the D0 experiment for 3-dimensional event displays. This approach is very promising and is used for the development of more general tools.

The current generation of experiments already covers a time greater than one cycle of computer technology. This creates new problems for developers of software support. In order to ensure the "survivability" of systems under changes in technology, new software support must make as extensive use as possible of commercial products. All software, both developed and purchased, should be based on standards.

Under these new conditions, a central computational complex will not only solve the traditional problems of providing computing resources, data storage and transmission, and network support, supplying experiments with information, and organizing and coordinating the work of physicists and industry, it will also play the role of the central "brain" which develops and introduces new technologies into the systems for the processing and analysis of experimental data which to a large degree are based on promising developments in hardware and software tools.

CONCLUSION

The evolution of computing in HEP in recent years has been characterized by the following trends:

1. Progress in the development of distributed computing systems and the exploitation of the rapidly developing technology of workstations and data-transmission networks.

2. The growth of computational power for packet data processing, including ordinary general-purpose computers and the development and large-scale exploitation of inexpensive distributed computing systems, which in the final analysis has led to the question of replacing mainframes by distributed computing systems based on RISC processors and powerful workstations.

3. The establishment of the personal workstation as the fundamental tool of interactive data analysis.

4. The introduction of local and global data-transmission networks.

The focus of HEP centers is the preparation and carrying out of research by scientists from different institutes and higher educational institutions, who are provided with the possibility of participating in data analysis from the work sites.

Active participation in HEP experiments requires good means of computer communication, the corresponding computational resources, disk space, massive memory systems, and graphics work stations.

The creation by experimental groups of their own powerful computing systems for the reconstruction and physical analysis of data has not slowed the rate of development of central computational complexes, but it has somewhat changed their function.

In conclusion, the authors is deeply grateful to V. V. Kukhtin for useful advice and recommendations, and to A. G. Zaikina and O. I. Popkova for their help in the layout of the study.

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