Computing & Computers

Weapons Simulation Leads to the Computer Era

by Francis H. Harlow and N. Metropolis

From the beginning, research at Los Alamos has exploited the happy interrelationship among experiment, field observation, and theory. Each of these has its tools; for theoretical investigations the most important are the indispensable calculators and computers.

Until the age of computers, the classical approaches to theoretical investigations centered on the mathematical techniques of perturbations and linearization. Complicated nonlinear interactions usually could be examined only for special circumstances in which the behavior departed slightly from an equilibrium or otherwise solvable configuration. There were, and still are, many interesting problems of this kind, and where nature did not cooperate with this type of simplicity, there were experimental data and empirical models to help advance the technology.

With increased sophistication, however, the needed answers became much more difficult and expensive to obtain. In the case of weapons calculations, for example, intractable nonlinearities in the mathematical expressions of natural laws could no longer be avoided. Numerical techniques were required for solving the equations, an approach that was extremely time-consuming if carried out by hand. The first rudimentary computers came along just in the nick of time, especially for the wartime research at Los Alamos.

During World War II, the primary mission at Los Alamos was to design, build, and proof-test a fission bomb. The problems presented a variety of technical challenges, both experimental and theoretical. They were hard but eventually proved solvable. Some of the theoretical analysis was accomplished by analytical procedures, but most required tedious numerical evaluations cranked out on desk-top calculators or on electromechanical business machines using punch cards and sets of plug boards appropriately wired for different types of calculations. These last devices, with a separate machine for each functional or calculational step, constituted the Laboratory's first rudimentary computer. Stored-program, high-speed, electronic computers were not used until after the war; they simply didn't exist. However, this experience of the war years was enough to excite the involved scientists and engineers to the power of mechanized calculations and acted as a tremendous spur to the postwar development of the modern computer.

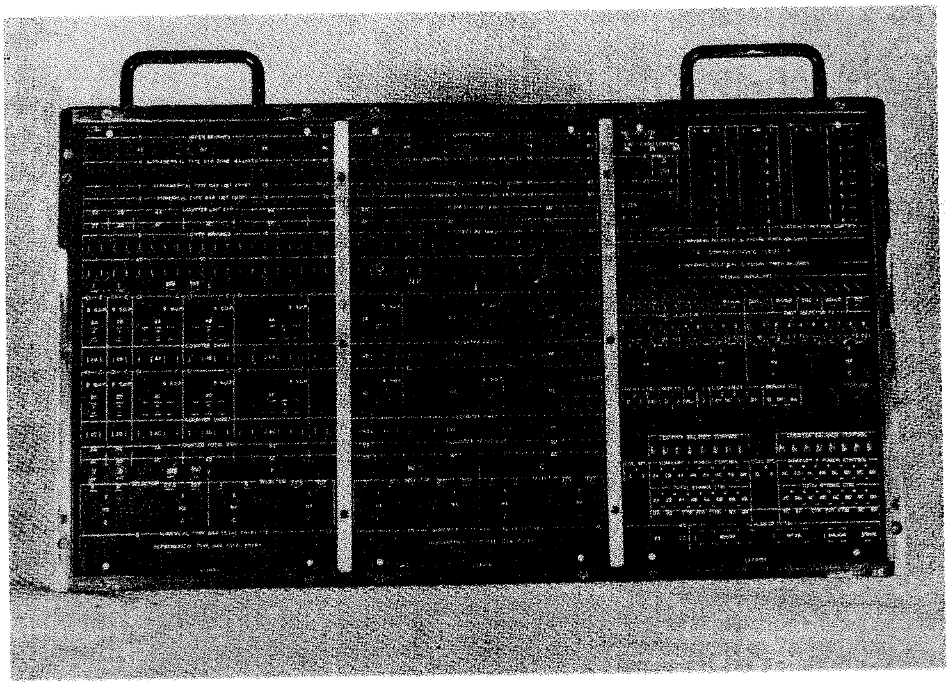
Bomb Design and Computer Development

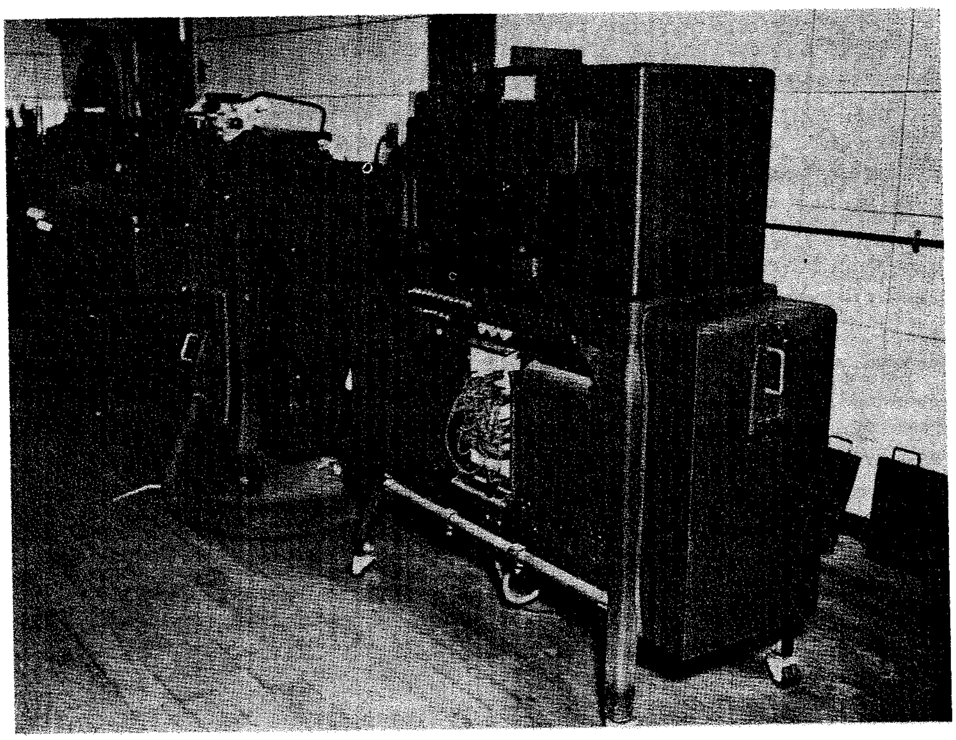
In 1943 the main theoretical task at Los Alamos was to compute the dynamic behavior and explosive power of a nuclear detonation. The issues to be resolved centered on the following.

- The physical and chemical properties of materials at extremely high temperatures and pressures: equations of state, reaction cross sections, and explosive detonation chemistry.
- Fluid dynamics in its most general sense: the motion of highly deformable materials in the presence of chemical and nuclear energy release.
- Neutron transport: the processes of nuclear fission, the maintenance of a chain reaction, and the prediction of energy release.

All three of these topics involved difficult mathematical problems. The issues of nonlinear equations, coupling among many variables, and time-varying singularities all required resolution. Numerical solutions were the only way to make progress.

To appreciate the need for numerical solutions, it is sufficient to recognize that the very nature of the Laboratory's objective—an atomic bomb—precluded extensive field testing. Would vital factors be overlooked or even unsuspected? To avoid this possibility, numerical methods had to be developed that simulated weapons experiments. Then a whole series of designs could





Electromechanical business machines. The lower photograph shows an IBM 513 reproducing punch and, in the background, an IBM 405 alphabetic accounting machine, which could add or subtract and list results with its printer (on top of the machine). The machines were programmed with interchangeable plugboards (upper photograph) that were wired appropriately for the desired calculations or machine operations. A small plugboard is in place on the front of the reproducer and two larger plugboards of the type used in the accounting machine are propped against the wall to the right.

be calculated and carefully studied. To carry out such model simulation, computational methods had to be established in which there could be no pitfalls due, for example, to calculational instabilities; the possibility of physical instabilities was complexity enough to contend with.

Associated with these problems were the incredibly complex matters of weapons engineering, together with the overwhelming logistic problems arising from the necessity for success and speed. Today, engineering and logistic problems, too, are greatly aided by computers, but our discussion will focus on the central issue of bomb design, together with the astonishing spin-off to all branches of science and technology that came from the Los Alamos developments for computing bomb designs.

A modest beginning for numerical computation at Los Alamos was made with a batch of various models of desk calculators. It soon became clear that these would be totally inadequate. In addition, these machines often broke down and were initially shipped back to the factory for repair. When the drain became serious, Richard Feynman and one of us (Metropolis) undertook a self-inflicted repair service, mostly by comparing the mechanical motions of a properly operating machine with a faulty one. This trial-and-error method stemmed the outward flow. However, the administration discovered this extracurricular service and when some critical eyebrows were raised, the activity was interrupted. Then, as the number of working calculators dwindled again, criticism turned to pleas to restore the status quo.

Dana Mitchell of Columbia University proposed that the electromechanical business machines be considered. The idea was suggested by the fact that Wallace Eckert, a colleague and astronomer, had been using them for calculating various astronomical tables called ephemerides. Stanley Frankel and Eldred Nelson were assigned to select the first group of such machines. Because the shipping crates arrived before the maintenance man was cleared by the Army, Frankel and Nelson, assisted by Richard Feynman, unpacked the crates and attempted to assemble the machines using only the wiring blueprints to guide these theorists turned would-be experimentalists.

At this same time in 1943, the mathematician Donald Flanders (affectionately known as Moll) organized and trained a formal hand-computing group; its members were principally recruited from the wives of the local scientists. This group made an important contribution to the overall effort. The focus of their work was the more complicated, but less repetitious, algorithms that were not tractable by the relatively primitive electromechanical machines. Typical problems were the geometric analysis of a measurement of a nuclear cross section or data reduction from experiments, requiring a fraction of a day to a few days for one person to complete. However, this group also computed several sequences of repetitious calculations that were used to certify that the electromechanical machines had been assembled correctly and were operating properly. For this calculation a production line was set up, each member of the group computing one step of the calculation corresponding to one machine operation. Feynman turned this into a lively competition, and his contagious enthusiasm and cheering spurred the group on to an early lead over the machines. After a while the repetitiveness of the hand calculations began to have its effect. But the task had achieved its purpose.

The problem of highest priority for the business machines was simulation of implosions, which involved integrating a coupled set of nonlinear differential equations through time from a prescribed initial configuration. The numerical procedure used a punch card for each point in space and time; a deck of cards represented the state of the implosion at a specific instant of time. Processing a deck of cards through one cycle in the calculation effectively integrated the differential equations ahead one step in the time dimension. This one cycle required processing the cards through about a dozen separate machines with each card spending 1 to 5 seconds at each machine.

The machines were relatively complex, each one containing several hundred relays as the primary computing element. The constant New Mexico dust frequently caused intermittent errors—at least one in every third integration step—by sticking to the relay contacts. Fortunately the computational procedure was very stable and insensitive to small errors; only errors in the more significant digits were corrected.

The use of three work shifts and the acquisition of triple-product multipliers and division machines rapidly increased the amount of machine computation that could be accomplished. Much of the necessary staff expansion was taken up by a group of bright young men in military garb, the Special Engineer Detachment.

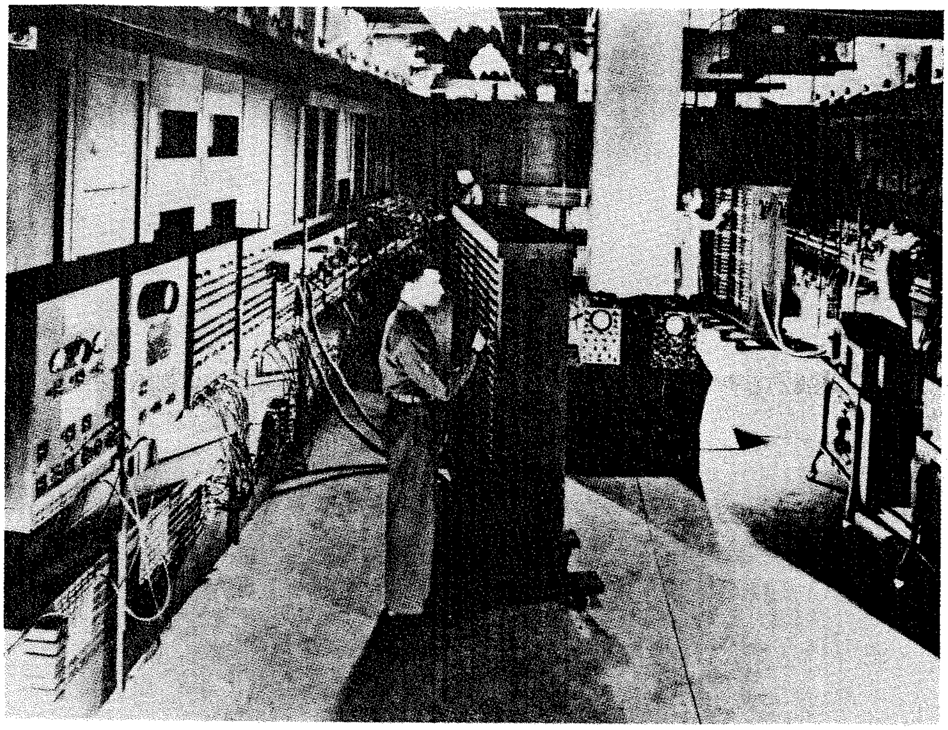
By the time of the Trinity test, the simulation approach to weapon design had not only proved its effectiveness but had also established the roots of some impressively powerful new computing techniques. Many theorists and experimentalists first learned of numerical methods and computing doing this research. Before the war only a few scientists had considered such techniques, but a new cadre graduated from the war effort eager to use their knowledge on a variety of scientific problems as well as to extend the numerical methods and improve the calculating machines.

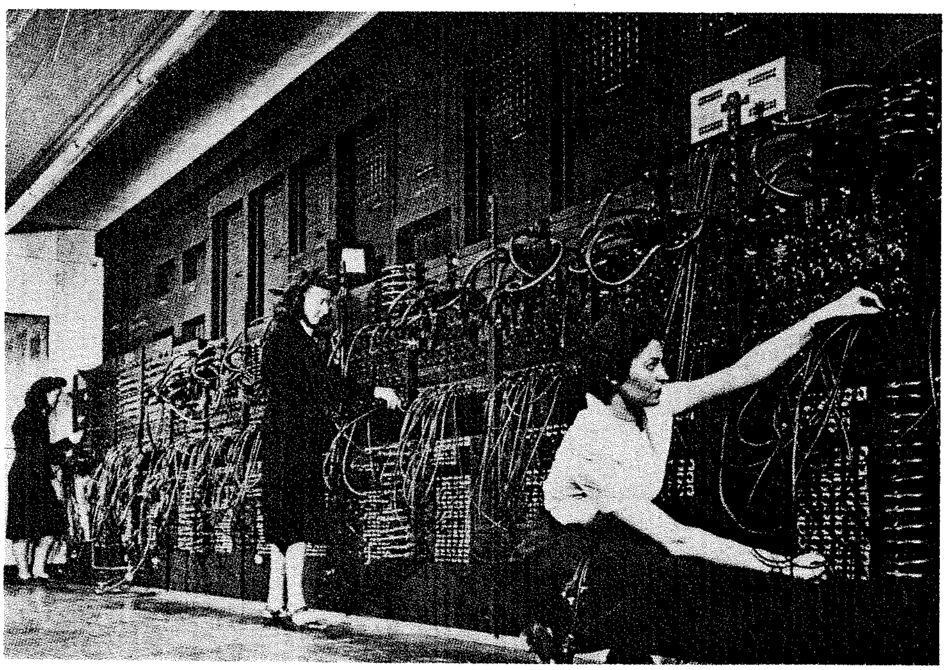
One who had a great influence on the subsequent development was the distinguished mathematician John von Neumann. It was he who first advised Los Alamos scientists of the ENIAC (electronic numerical integrator and calculator) project at the University of Pennsylvania. The goal of the project, supported by the U.S. Army Ballistics Research Laboratory in Aberdeen, Maryland, was to create a computing machine to solve ballistic trajectory problems. The result was the first large-scale electronic computer, employing electron tubes rather than relays or mechanical counters. Programming was achieved by using cables to interconnect electron tube registers in a manner similar to the plug boards in the electromechanical business machines. Because the ENIAC computed at electronic speeds, it performed in minutes computations that took days on the business machines.

Even before the Trinity test, as the ENIAC was nearing completion in early 1945, von Neumann raised the question with Frankel and Metropolis of using the ENIAC to compute the first set of problems on thermonuclear designs. The response was immediate and enthusiastic. Arrangements were made by von Neumann, who was also a consultant to Aberdeen, using the argument that the "Los Alamos Problem" was a more comprehensive test of the computer since its complexity was at least an order of magnitude greater than the computation of firing tables.

The experience of using the ENIAC, which occurred at about the same time as the Trinity test, was, for the participants, as memorable as that of the first atomic explosion. Electronic equipment, bristling with 18,000 electron tubes and a half-million solder joints, filled one large room and was joined together to operate as a single unit. Attending this equipment was a cadre of very earnest people who wanted the machine to give real answers to real problems, and their immersion in electronic computing was total. The computer age had begun in earnest.

Von Neumann made many contributions to the computer discipline, including his idea of the single-address instruction code, which evolved from his own frustrating experiences with the business machines. But one must not forget that he accelerated greatly the whole development by the mere fact that he had taken such a great interest in the subject. That a mathematician of his stature should do so attracted many other capable scientists





The ENIAC in operation at the University of Pennsylvania. This first large-scale electronic computer was tested in 1945 with the "Los Alamos problem," calculations important to the design of thermonuclear weapons. The lower photograph shows how the ENIAC was programmed by interconnecting the electron tube registers with cables inserted in plug boards.

to the field.

In the spring of 1946, when the series of ENIAC computations of one-dimensional thermonuclear burning of deuterium and tritium had been completed, a conference was held in Los Alamos. It was organized by Edward Teller with, among others, Enrico Fermi and John von Neumann participating. The principal purpose was to discuss the computational results and to assess the prospects for a physical realization of a thermonuclear device. Despite the simplified but nonetheless relatively ambitious nature of the model, the general consensus was that the preliminary results were encouraging. Several comprehensive documents were prepared as the first phase of the Los Alamos project came to a close.

Even before the completion of the ENIAC, the group associated with its development was discussing the logical and engineering design of the next-generation electronic computer, the EDVAC (electronic, discrete variable automatic computer) project. By good fortune, Frankel and Metropolis were able to participate in some of those discussions, particularly with Mauchly and Eckert, who were monitoring the debugging phase of the ENIAC with the "Los Alamos Problem." Originally the ENIAC, its techniques, capabilities, even its very existence, were classified. However, in 1946 it was declassified, and a spate of efforts emerged in several parts of the country, as well as in Europe. Soon after the war, a project was also started at the Institute for Advanced Study in Princeton by von Neumann. Both projects were interested in the concept of the stored program, in which the computer program itself was recorded electronically in the same form as data. This storage allowed for the possibility of the program's modifying itself on the basis of contigencies as it was running. This feature increased enormously the programming capabilities of a computer.

In early 1949 a group was formed by Metropolis in Los Alamos to pursue a computer development parallel to that of Princeton. To replicate is much easier than to design and develop; so before long Los Alamos had caught up with the construction of that part of the computer called the arithmetic processor. Difficulties were encountered at Princeton in the development of the memory, and Los Alamos and Princeton followed separate courses, each developing their own. As a result, controls and input-output components were also tailored differently to be compatible with the different memory components. In March 1952 the first large-scale hydrodynamic calculation was completed in Los Alamos on the new computer, the MANIAC (mathematical and numerical integrator and computer).

In addition to a variety of Laboratory weapons problems, many interesting computational efforts were being prepared in the wings for the MANIAC. These included

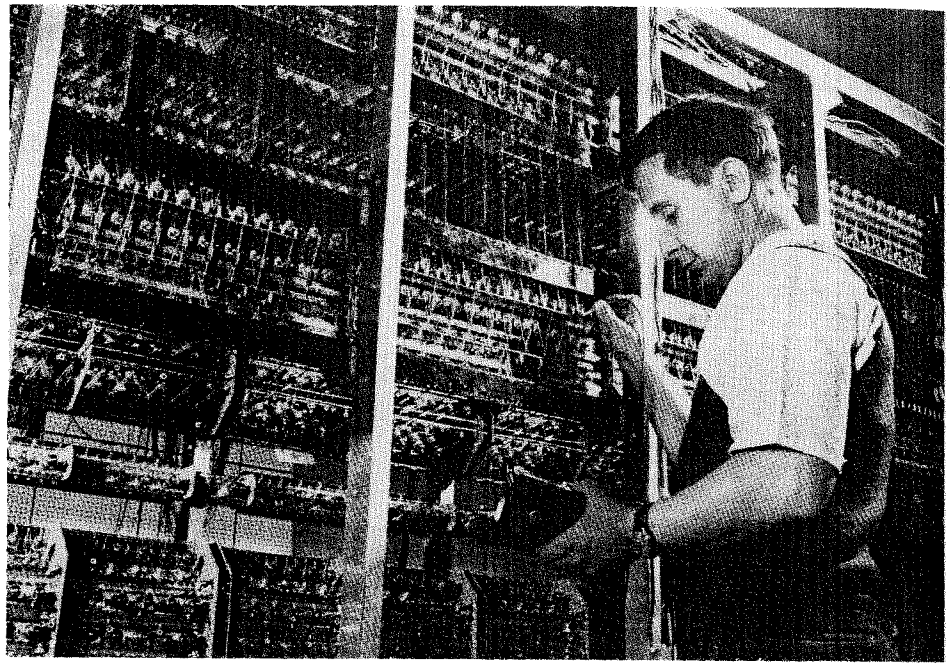
- phase-shift analysis of pion-proton scattering,
- vibrational studies of a nonlinear chain,
- the first chess-playing program on a 6 by 6 board,
- attempts to decode DNA sequences, and
- applications of Monte Carlo techniques to phase transitions.

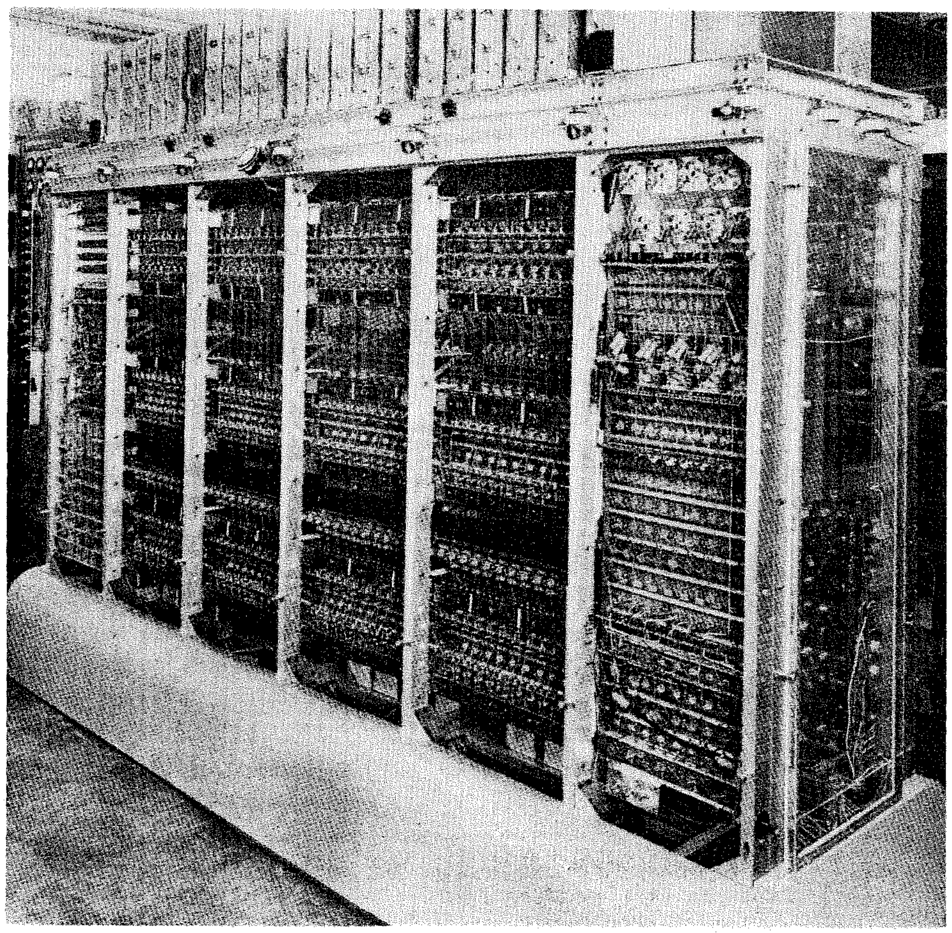
Thus a wide spectrum of problems tested the versatility and capability of the logical structure and engineering design of MANIAC.

In about 1953, John Jackson initiated research on programming languages at Los Alamos. Also, Mark Wells and collaborators started, long before it was fashionable, an impressive development of a high-level programming language and operating system, eventually known as Modcap. Such language development was critical since the computer's potential could not be realized without a convenient way to communicate with it.

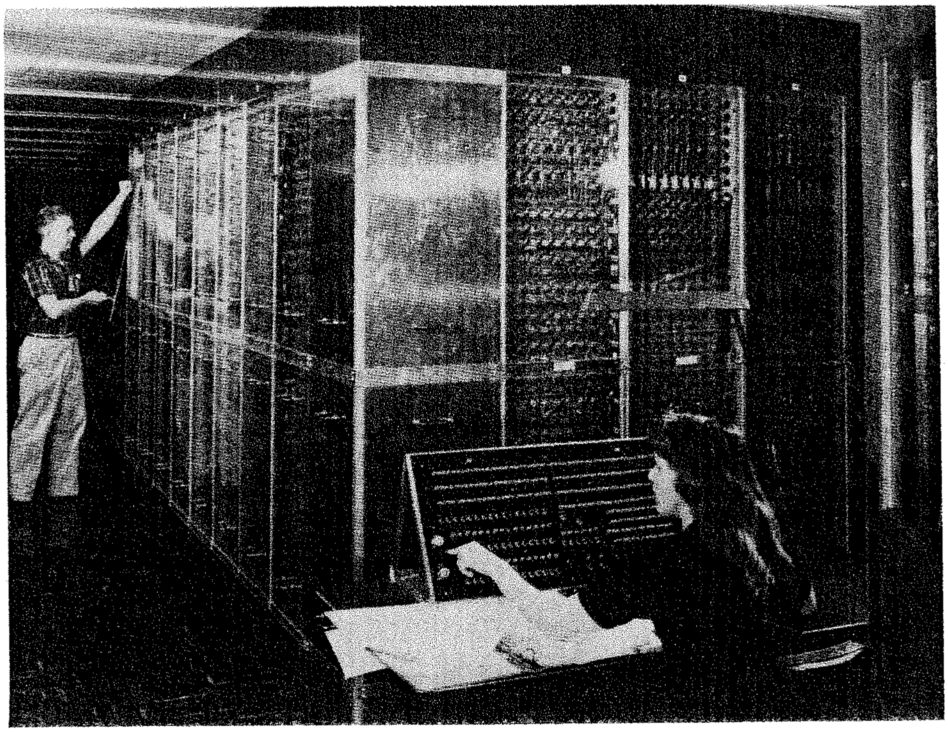
By 1957, with the advent of MANIAC II, the first modest experiments on man-machine interactions were started in which the programmer could direct the computer during the course of a programmed calculation. These experiments played an essential role in the discovery of the so-called universal functions, which are now becoming so important for the analysis of chaotic behavior.

The main use of these developments was, of course, weapons simulation, especially for thermonuclear weapons. It is here that the full scope of Los Alamos accomplishments during this period can be especially appreciated. In a thermonuclear weapon there may be two stages, the first a fission bomb with the secondary stage nearby. Radiation from the fission explosion can be contained and used to transfer energy to compress and





The Los Alamos MANIAC I during construction (upper photograph) and in 1952 after its completion. The banks of vacuum tubes in the middle four panels make up the arithmetic processor; the side panels and the back contain the controls; the row of switches on the far left is the user's console; the boxes on top, each containing a 2-inch electrostatic cathode-ray storage tube, constitute the memory. Neon lights attached to each tube allowed the binary digits contained in the registers to be seen directly, and, as a result, the contents of a register could be changed by shorting one side of a vacuum-tube flipflop with clip leads.



The MANIAC II, used at Los Alamos from 1956 to 1977, was more powerful and easier to use than MANIAC I, especially since it included floating-point arithmetic. One of the first programming languages, eventually known as Modcap, was developed for this computer and, in fact, evolved and improved over the years as ever more sophisticated algorithms were used in the calculations.

ignite the secondary component containing thermonuclear fuel. Thus, the investigation of radiation transfer and thermonuclear fusion were added to the original list of theoretical issues to be resolved. As bomb design requirements became more demanding and the problems more complex, reliance on numerical solutions by high-speed computer became even more critical. At every stage the stronger the computer, the greater the complexity that could be tackled successfully. While most of the scientific and technological world maintained a disdainful distaste (or at best an amused curiosity) for computing, the power of the stored-program computers came rapidly into its own at Los Alamos during the decade after the War.

In the early 1960s Los Alamos collaborated in the planning of the Westinghouse Solomon computer, which explored the early uses of parallel processing. For this purpose Los Alamos provided a PIC (particle-in-cell) code for fluid dynamics analysis as a challenge to Solomon's capabilities. The PIC method is basically a technique whereby one can account for very strong distortions in a swirling fluid by using not only a mesh of calculational cells but also marked particles that could move among cells and so avoid a meaningless tangle in the calculational mesh. As a result of its ability to deal with complex fluids, this type of code was used extensively for a wide variety of applications. The translation of the code into Solomon's language was successful, generating considerable excitement for the value of parallel processing.

Gradually, industry began producing more powerful electronic computers, and the Laboratory updated its complement of computers with these. However, Los Alamos scientists remained at the forefront of computer science by contributing to design innovations and improvements in the computers produced by the corporations. The demand for more computing power never stopped growing; today it is still expanding.

Many of the early computers were from International Business Machines (IBM), including the original wartime electromechanical machines. In 1953 the Laboratory acquired the IBM 701. Later several copies of an improved version, the 704, were purchased, followed, in turn, by the so-called Stretch. This last computer, occupying several rooms, was the first all-transistor computer and the first to use a 64-bit word, thus allowing greater accuracy. The giant manufacturer began to mature with the impressive 709 and its subsequent transistorized version, the 7090, acquired by Los Alamos in several copies.

At this juncture the Laboratory turned to the Control Data Corporation (CDC). The newly developed 6600, the supercomputer of the 1960s with increased processing speed, made its appearance here in 1966, again with replication. The next step was an improved version known as the 7600. The Laboratory bypassed, however, the more ambitious CDC attempt named the STAR (string array), which seemed to possess supernova characteristics. Eventually, several Crays, designed by Seymour Cray, formerly of CDC, were acquired; these are the most ambitious of all industrial efforts and push electronic switching speeds to the limit except possibly for superconducting Josephson junctions, which have not yet been implemented on a commercial basis.

Notwithstanding all this computer power, much more will be needed for the various Laboratory problems that are awaiting the next qualitative step in computer research and development. Especially important are multi-dimensional problems, for example, the study of nuclear fission when particles are expelled laterally from an oscillating, liquid-drop model of the nucleus.

The next steps in computer development, like their predecessors, seem promising for dealing with the latest complexities. The fantastic progress in very large integrated circuits encourages the concept of multiprocessing, perhaps at the level of several thousand-fold, in which calculations over a three-dimensional mesh are carried out by sweeping through the mesh with parallel calculations taking place simultaneously. Multiprocessing must be coupled with high-level language development so as to deal with the problems of data synchronization.

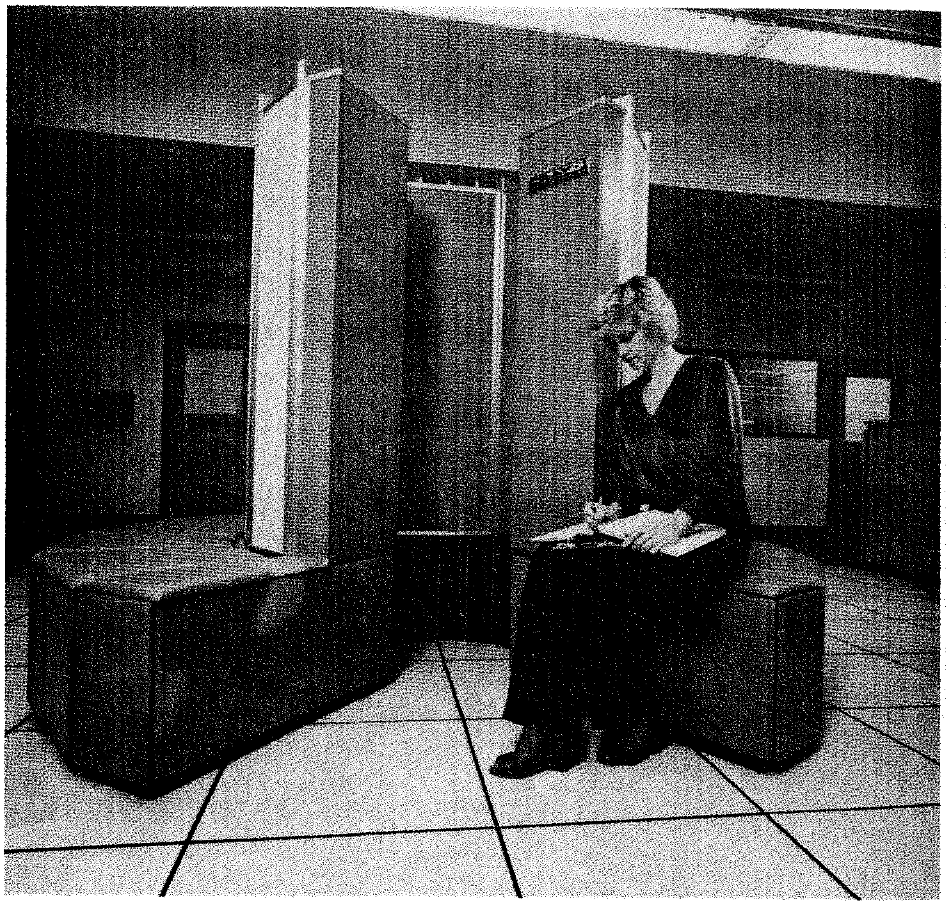
Perhaps these developments will stimulate a qualitative change in our approach to numerical methods that will reflect these potential parallel capabilities. In that regard, it should be remarked that the increased computing capability to deal with ambitious problems should focus attention on the ubiquitous need to assign variances to all computed quantities. This need still remains a central challenge, and only when it is answered will computer science have achieved maturity.

Numerical Analysis

In perspective, this forty-year period of computer development is recognized as one of this century's truly remarkable spurts of technological advance. Equally spectacular has been the development of new techniques for the *use* of the computers.

Theory, described in its most homely terms, is the cataloguing of correlations, and mathematics is the language whereby these correlations can be expressed with precision. The laws of nature (such as Newton's laws or the laws of thermodynamics) are the most fundamental of the correlative descriptions. In principle, they describe a large proportion of the processes of interest to science and technology. In practice, much work is required to translate these laws into detailed descriptions of particular events. Tractability requires approximations; experiments guide the formulation of these approximations and furnish data for their validation. In turn, the theoretical predictions suggest additional requirements for hard data, and so the crucial cooperation persists. Sometimes nature reveals its secrets with grudging reluctance, thrusting numerous false leads and pitfalls in our pathway to the successful analysis of complicated problems. Numerical instability is a classic example.

To see what is involved with numerical instability, it is useful to visualize the way in which a computer calculation resembles a laboratory experiment. Consider, for example, the wind-tunnel testing of forces generated on an obstacle placed in the flow path. A typical experiment requires a long box to confine the wind, a fan to drive its flow, a generator of smoke filaments to make the flow paths visible as the air is deflected around the obstacle, a camera to take movies



The Cray computer is the most recent and most powerful of a series of electronic computers produced by industrial corporations and used at the Laboratory.

of the flow lines, and various instruments to record pressure, temperature, local velocity, turbulence intensity, and net force on the body.

By analogy the calculation requires equipment (the computer code), a box with inflow and outflow (the mathematical boundary conditions), flow visualization techniques (a careful accounting of the motion of representative elements of fluid), and recording devices (the printed output and computer-generated contour and velocity-vector plots).

The experiment is performed in the laboratory by switching on the start buttons and letting the configuration develop. The same is true with a calculation; we supply initial conditions and the computer advances the whole flow pattern step by step through a sequence of time cycles closely resembling the frames of a motion picture. Indeed the results can be recorded on film and projected—a very meaningful way for the investigator to absorb the results without bogging down in a morass of detail. In contrast to an artist's animation of speculated behavior, such movies describe the actual solutions of sets of complicated coupled equations, representing the consequences of fundamental natural laws.

The analogy can be pressed even further.

Suppose that the bearings in the fan motor start to fail. The fan will oscillate with increasing amplitude and, if left alone, may shake the whole structure into self-destructive pandemonium. A similar process occurs with numerical instability, manifesting itself at first as seemingly benign localized oscillations in, for example, the velocity vectors, but then growing with alarming speed to a catastrophic overflow with numbers exceeding the national debt expressed in pennies. Whereas fan motors burn out rather rarely, numerical instability is a chronic threat with a propensity for occurrence in the least expected and most exasperating circumstances.

However, the cure of this nemesis to good computing is not the only goal of numerical methodology development. Good computing requires a firm foundation in the principles of natural behavior. It inevitably requires a careful choice of good approximations, as well as a cunning insight into the precarious balance between the mutually exclusive needs for finely detailed resolution and economically feasible progress. The required attributes for skillful computer utilization are many, although for some purposes even the novice can solve useful problems with existing techniques and codes. It is a stunning tribute to Los Alamos bomb designers and their colleagues that many of the most powerful procedures for taming computers to the myriad tasks of modern science and technology were developed right here during the forty years commemorated by this issue of *Los Alamos Science*. Some outstanding examples can be cited in the following fields.

PHYSICAL PROPERTIES OF MATERIALS. Critical data for the analysis of fission and fusion bomb dynamics are contained in the equations of state for the various materials, the neutron cross sections, the radiation transfer properties, and the rates for chemical and nuclear reactions. For ordinary circumstances these data can be gathered by relatively simple laboratory experiments; the extreme conditions in a bomb, however, are a whole new ball game. The Thomas-Fermi model of the atom for zero-temperature equation-of-state analysis, for example, required extension to temperatures comparable to those in the sun; Los Alamos devised the necessary theoretical techniques and implemented them with computers. While much of the material-properties analysis is zero-dimensional, it is not without its perplexing challenges. Hartree-Fock models for low density or spectroscopy studies were notoriously unstable when solved on the computer, until Los Alamos investigators discovered the elusive trick required for proper numerical behavior, which involved modifying the troublesome inhomogeneous terms in the differential equations so that the equation became nearly homogeneous.

For material-properties analysis the computer also serves science in two seemingly mundane but crucial ways apart from the basic derivation of the data. First, the incredible calculational speed enables the investigation of numerous elements and compounds for all ranges of temperature and pressure of interest, a task that would take centuries if undertaken by hand. Second, the computers serve as data storage and management centers, affording readily accessible information for other computer codes or whatever purpose may be required.

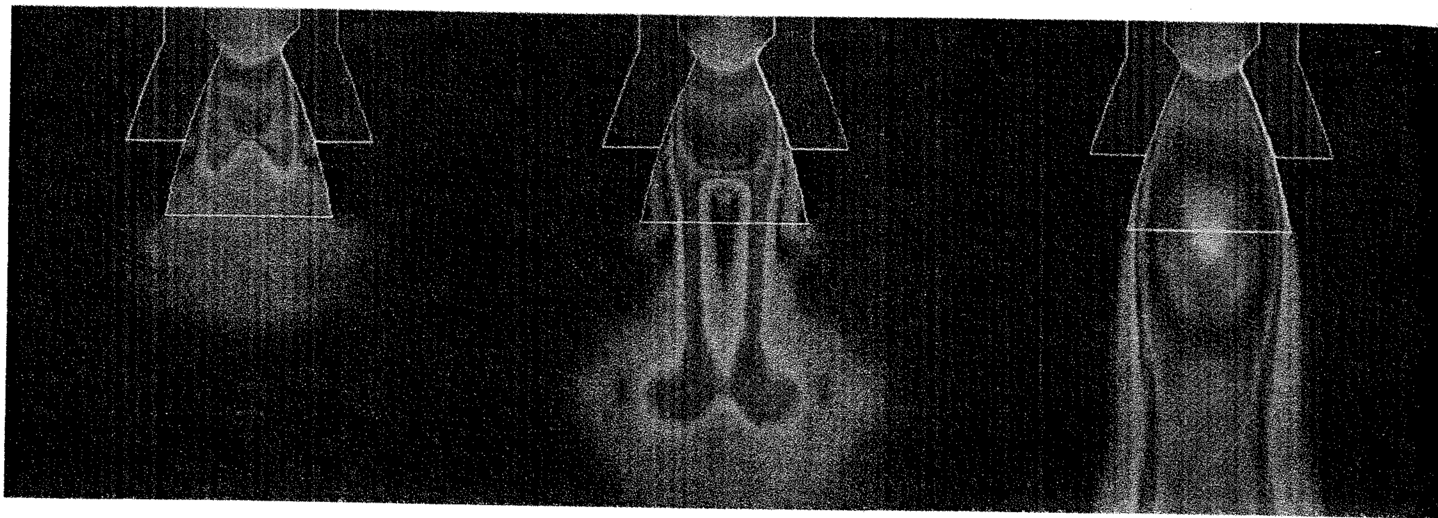
The Los Alamos experience in this last regard has found spin-off in numerous directions, most recently in the newly established worldwide genetic sequence data bank at Los Alamos for DNA and RNA information.

FLUID DYNAMICS. Calculations of the first fission bomb implosions were accomplished with the converted electromechanical business machines. However, the high-explosive shock was advanced through the material by means of the more complicated equations that required hand calculations, each calculation checked and rechecked with the slow desk-top calculators of the era.

With the postwar responsibility to investigate the feasibility of a two-stage thermonuclear weapon, the fluid dynamics problems became enormously more complicated. The primary and secondary portions of the weapon sat apart from each other. Instead of the simple, single-stage fission-bomb configuration, the dynamics of the separated stages required the analysis of potentially strong distortions of materials moving with incredibly greater complexity. The calculation of non-steady multi-dimensional fluid dynamics became the challenge.

To meet that challenge, the Los Alamos investigators worked with two fundamental viewpoints, Lagrangian (in which volume elements are carried along with the fluid) and Eulerian (in which material flows through volume elements fixed in space), together with various innovative hybrids. First applied to the high-speed flows required in bomb design and weapons-effects analysis, the techniques soon were extended to low-speed (incompressible) flows for wave studies and to the broad field of interpenetrating (multiphase) flows like that of raindrops falling through the air. Through the 1960s and 1970s these newly developed computing techniques found their way to laboratories throughout the world, where the Los Alamos innovations remain today the basis for much of the analysis of fluid dynamics in such diverse fields as weather forecasting, continental-drift analysis, blood-flow studies, rocket nozzle design, geothermal energy extraction, oceanographic problems, nuclear reactor safety, and a host of other applications.

NEUTRON TRANSPORT. Neutronics, evolving from a central concern in fission-bomb design, lies at the heart of nuclear reactor analysis, which is a crucial facet of the studies so essential to alleviation of the world's energy crisis. The first really effective way to calculate the dynamics of neutrons, the SN method, is a Los Alamos product. Even today the SN technique, which deals



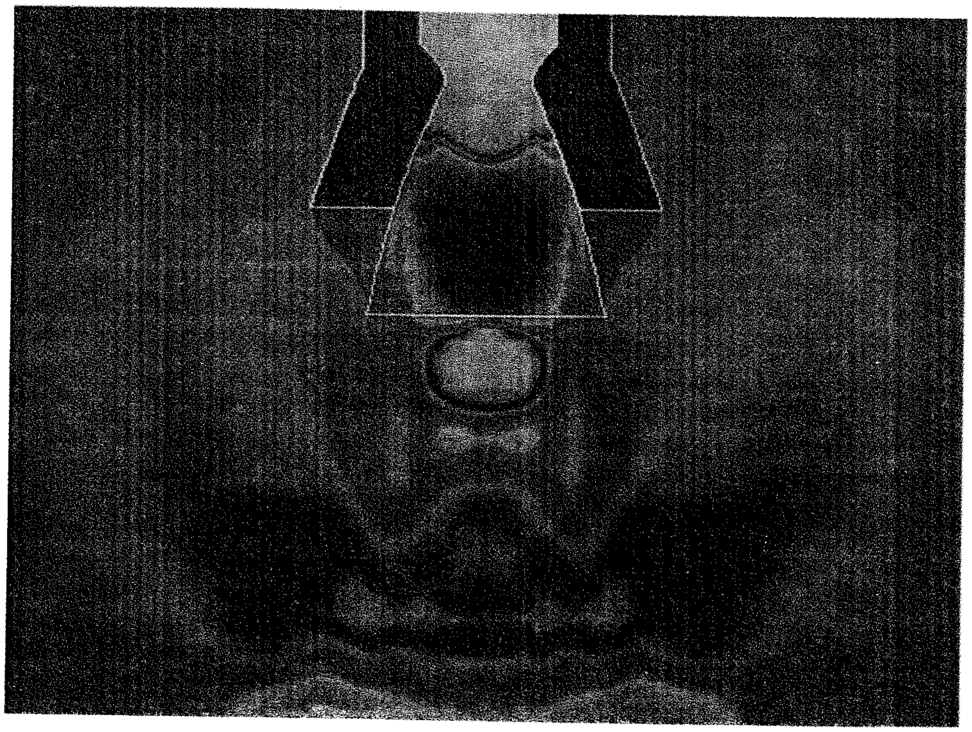


Fig. 1. Analysis of a Space Shuttle problem. These computer graphics illustrate calculations of the flow of gases from the propulsion nozzle on the Space Shuttle Solid Rocket Booster at times during about the first two hundred milliseconds after ignition. The calculations were part of a joint study with the NASA Langley Research Center to determine the cause of an unusually large overpressure on the first Shuttle flight that exceeded preflight predictions by as much as 5 to 1. In each picture the nozzle entrance plane is at the top with the flow exhausting downward. The upper frames show Mach number with time increasing from left to right. The lower frame shows pressure contours, and the overpressure appears as the yellow area. Features of this complex flow problem

Fig. 1

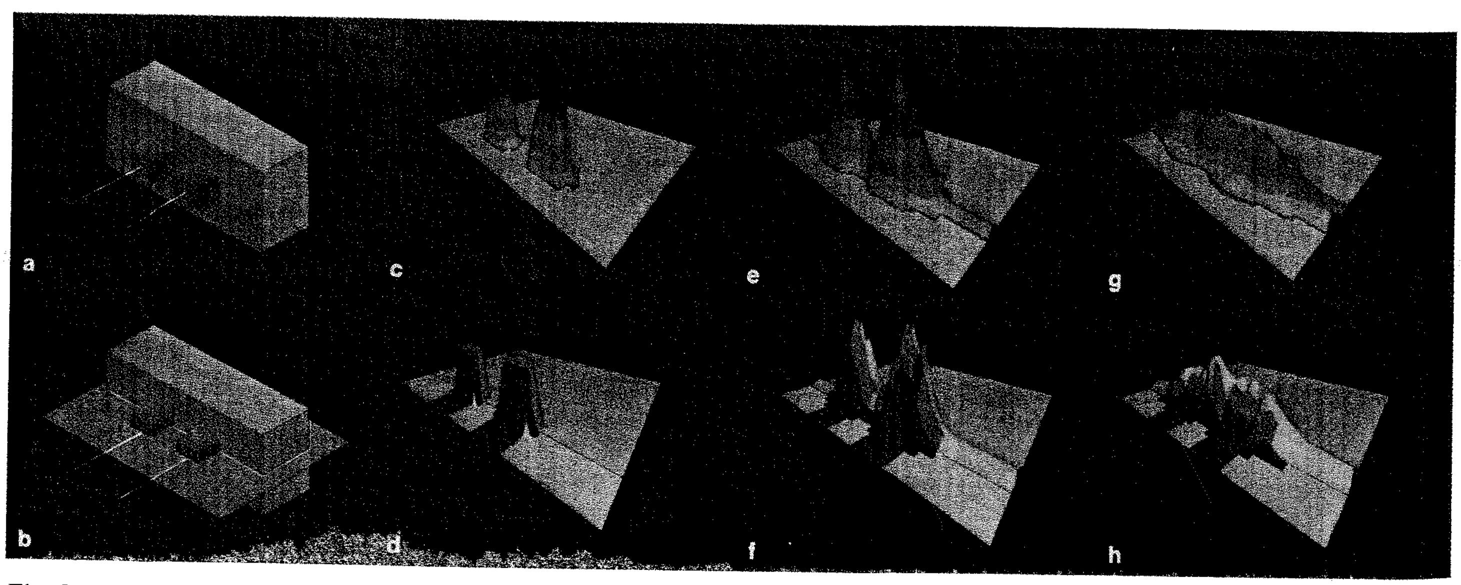


Fig. 2

were not truly understood until such color-coded graphics, along with color movies, had been generated. In fact, the first graphics in this study immediately suggested improvements that could be made to the calculations themselves. The Los Alamos code (VNAP2) used here solves the 2-dimensional (axisymmetric), time-dependent, compressible, turbulent flow equations. (Research by Michael C. Cline, Los Alamos, and Richard G. Wilmoth, NASA Langley Research Center; graphics by Eric Everton, Computer Science Corporation; work supported by DOE and NASA.)

Fig. 2. Computer graphics of results from a 3-dimensional Eulerian hydrodynamic code, SOIL3D. This impact modeling code simulated the collision with an aluminum target of two 25-gram steel cubes moving at 4 kilometers per second (depicted in a and b). The calculation of material velocity, density, pressure, temperature, internal energy, stress, and composition during the first 2.5 microseconds of the impact required 30 minutes of Cray-1 computer time to model. Data in c through h are displayed as a function of position in the horizontal symmetry plane in which the maximum pressures and stresses occurred (green in b). The pressure, whose distribution is shown in c, e, and g at 0.3, 1.3, and 2.3 microseconds, respectively, peaks in e at 450 kilobars (red), about 66 times the yield strength of steel (magenta). The same pressure distributions, displayed in d, f, and h with colors now representing material composition, show the regions in which steel and aluminum have mixed (pink). (Computer solution by Alden Oyer; graphics by Bill Wheat.)

with neutron flow, scattering, absorption, and generation as a function of such variables as direction and energy, is the basis for neutronics calculations throughout the world.

Also developed originally for neutronics is the famous Monte Carlo technique, whose descendants are employed for stochastic-event analyses in a remarkably diverse set of disciplines. As the name suggests, Monte Carlo is a game of chance. For neutronics, the technique follows the trajectories of representative individual neutrons moving through a material and interacting with nuclei along the way. Appropriately weighted random numbers generated by the computer describe the outcome of each interaction. The collective action of countless neutrons in a real situation is approximated with greater and greater accuracy as the relatively small number of sample trajectory calculations increases. For neutronics, Monte Carlo techniques furnish very accurate standards with which the results of faster SN calculations can be compared. Los Alamos played a seminal role in the history of Monte Carlo calculations and is largely responsible for its use throughout the world.

RADIATION TRANSPORT. Computation of the containment and transfer of radiation in a thermonuclear weapon is a challenge for the most ingenious inventor of computer techniques. Plagued by potential numerical instabilities, the accurate calculation requires not only a detailed knowledge of the interaction between radiation and materials, but also a sophisticated around-by-the-back-door type of circuitous mathematical logic for the numerical analysis.

While the opportunities for spin-offs of this very-high-temperature technology seem at first limited, they are actually very extensive. Los Alamos calculation techniques for radiation transport have been applied, for example, to astrophysical problems, lasers, and plasma dynamics problems for controlled thermonuclear fusion.

NUCLEAR PHYSICS. Thermonuclear fusion is only one of many fascinating problems in nuclear physics treated by the Los Alamos computers. At the extreme circumstances of highly relativistic nucleus-nucleus collisions, for example, nuclear physics and fluid dynamics become appropriate bedfellows. A nucleus with many neutrons and protons acts classically, resembling a liquid drop with surface tension, viscosity, and so forth; the quantum aspects enter only in this collective fashion. In high-velocity collisions, the nuclei can be described as relativistic fluids and they behave like strange raindrops that pass through each other. Computers offer the only means for boiling down the complicated equations that describe such collisions to numbers that can be compared (very favorably) with experimental results.

In an article of this length, we can, of course, only touch lightly on a few selected topics in the history of computers and computing at Los Alamos. Even with this limited discussion it should be apparent that Los Alamos has been a leader in developing many of today's most versatile and powerful analytical techniques. Commencing with fission bomb technology and advancing through the era of thermonuclear weapons design, the results of computer technology development at Los Alamos will continue for a long time to solve problems in the most astonishing array of spin-off fields. ■

Further Reading

N. Metropolis, J. Howlett, and Gian-Carlo Rota, Eds., *A History of Computing in the Twentieth Century*, (Academic Press, New York 1980).