Metropolis, Monte Carlo, and the MANIAC

by Herbert L. Anderson

In 1942 Nick Metropolis was working with Edward Teller on the reactor project at the University of Chicago when J. Robert Oppenheimer invited the young physicist to continue his collaboration with Teller, but at Los Alamos. There Metropolis joined the Manhattan Project as a member of the Theoretical Division, having been encouraged by Teller to move from experimental to theoretical physics. His first assignment was to develop equations of stale for materials at high temperatures, pressures, and densities.

Over the years Metropolis turned increasingly to mathematics and computer design, and by 1948 he was leader of a Los Alamos team that designed and built the MANIAC, one of the first electronic digital computers. Many of the country's foremost scientists were eager to try their experiments on the wonderful new machine and came to the Laboratory to work with Metropolis. A few years later, together with Teller, John von Neumann, Stanislaw Ulam, and Robert Richtmyer, Metropolis developed techniques and algorithms for using the Monte Carlo method (so named by Metropolis) on the new computers.

The Monte Carlo method is an application of the laws of probability and statistics to the natural sciences. The essence of the method is to use various distributions of random numbers, each distribution reflecting a particular process in a sequence of processes such as the diffusion of neutrons in various materials, to calculate samples that approximate the real diffusion history. Statistical sampling had been known for some time, but without computers the process of making the calculations was so laborious that the method was seldom used unless the need was compelling. The computer made the approach extremely useful for many physics problems.

Metropolis was also involved in the development of an importance-sampling scheme, called the Metropolis algorithm, that improves the effectiveness of the Monte Carlo method. In the past twenty years his work has included nonlinear problems and combinatorial theory as well as Monte Carlo calculation. He was named a Senior Fellow of the Laboratory in 1980.

In September 1985 more than one hundred researchers from around the world met in Los Alamos for a four-day conference, in honor of Nick Metropolis, on the frontiers of quantum Monte Carlo. One of the speakers was Herb Anderson, from the Laboratory Physics Division, Anderson's presentation was a fascinating reminiscence about the first modern calculating machines and the scientists who used them, about the intellectual ferment in the physics community that began early in this century and still continues, and about Nick Metropolis and the MANIAC. This article is adapted from Anderson's presentation.

Conversion of input to hexadecimals
Punching input

This story is about the MANIAC and about Nick Metropolis, who conceived the MANIAC, built it, and saw how to use it for a wide variety of problems. In the period just after World War II, other computers were being built, many of them, like the MANIAC, modeled on the von Neumann principle, the principle of the stored program. Von Neumann organized a group at the Institute for Advanced Study and started building a computer based on that principle. Other institutions got into the act, too, because they all realized the importance of building computers. There was one at Argonne called the AVIDAC and one at Oak Ridge called the ORACLE. Then there were the SEAC at the National Bureau of Standards and the ILLIAC at the University of Illinois. But the MANIAC at Los Alamos was special.

You see, the circumstances in postwar Los Alamos were special. The war had brought together there an exceptional group of scientists, with whom Nick had established a close relationship. John von Neumann, Enrico Fermi, Hans Bethe, Edward Teller, Stan Ulam, Dick Feynman, George Gamow, Tony Turkevich, and Robert Richtmyer, among others, were drawn to Nick because they enjoyed working with him. When you went to Nick with a problem, he took a deep interest in it and worked hard on it with you, invariably making some essential contribution. It was a treat to work with Nick, and, if you understand that, you will understand a lot about how this story evolved.

Those who returned to Los Alamos after the war were drawn irresistibly to Nick and his MANIAC, to what this wonderful electronic computer could do for them. They went away enriched by their new experience and rewarded by new scientific results in their fields of interest. This is a happy tale of how one of the first of the modern computers got its start and what it was able to do in its early years.

Fermi's Brunsviga

Let's go back about forty-five years to the beginning of World War 11. Nick was twenty-five years old. In those days we had no computers as we now know them. We used slide rules and adding machines—hand-operated machines. Machines with electric motors were the exception rather than the rule.

I remember particularly the hand-operated machine that Fermi used with remarkable deftness. It was made by Brunsviga, a German firm in the town of the same name, famous as the place where Gauss was born. This machine had a crank that you rotated by hand. To multiply, for example, you set the machine and then rotated the crank the number of times called for by each digit of the multiplier, shifting the carnage for each successive digit and turning the crank again. Fermi had one of those machines when he was working in Rome and brought it along with him when he came to Columbia University in 1939. He was using it when I started working with him on the chain reaction, soon after his arrival. Whenever I used my slide rule to make a calculation, he started cranking his machine. By the time I announced my result, he was waiting—and grinning. He could beat me every time. But that situation changed when I got myself a Marchant. When it became clear that he couldn't even keep up with me, let alone beat me. he gave up the Brunsviga and got a Marchant of his own. Fermi could never resist the opportunity to calculate faster.

It seemed to me that Fermi was always calculating something. It was Fermi's view that Nature revealed itself through the experiments you devised to test it. You can construct a theory to explain what is going on, but unless the numbers come out right, you can't be sure the theory is right. So you have to do a lot of calculations.

Fermi Monte Carlo

You might be interested to know that Fermi was one of the first to use the Monte Carlo method—in a rather simple form and hand-calculated—long before it had a name. I don't know whether he was the very first, but the story comes from Emilio Segre, who told me that Fermi used that statistical sampling technique as early as 1934, when he was working on neutron diffusion in Rome.

In 1933 Frederic Joliot and Irene Curie had discovered the radioactivity induced in light elements by bombardment with alpha particles. The neutron had been discovered just one year before. These two facts gave Fermi the idea that neutrons, having no charge at all, would be much more effective than alpha particles in producing nuclear transformations. They would not be repelled by the Coulomb barrier and could therefore penetrate the nuclei of all atoms, whatever their charge, whereas the alpha particles could only get into the nuclei of light elements.

It was an exciting idea. He got a radon-beryllium neutron source and began a series of experiments with some of his young and enthusiastic collaborators: Amaldi, Segre, Pontecorvo, d'Augostino, and Rasetti. Early in the course of their work, they found they were getting some very peculiar effects. The radioactivity they obtained depended a whole lot on where the irradiation was carried out. In particular, the activity induced in silver was much greater when they did the irradiation on a wooden table than when they did it on a table with a marble top. That was a great puzzle. They couldn't explain it. Then Fermi began to tell them that they didn't know how to experiment very well and that they didn't really do things properly. Of course this didn't make them very happy. To clear up the puzzle, Fermi decided to try filtering the neutrons through various substances. His first idea was to use lead, but then at the last minute, for no apparent reason, he substituted paraffin instead. The increase in the activity of the silver was phenomenal. Everyone went home mystified.

Now, one of Fermi's characteristics was that he liked to come into the lab early in the morning and surprise his colleagues

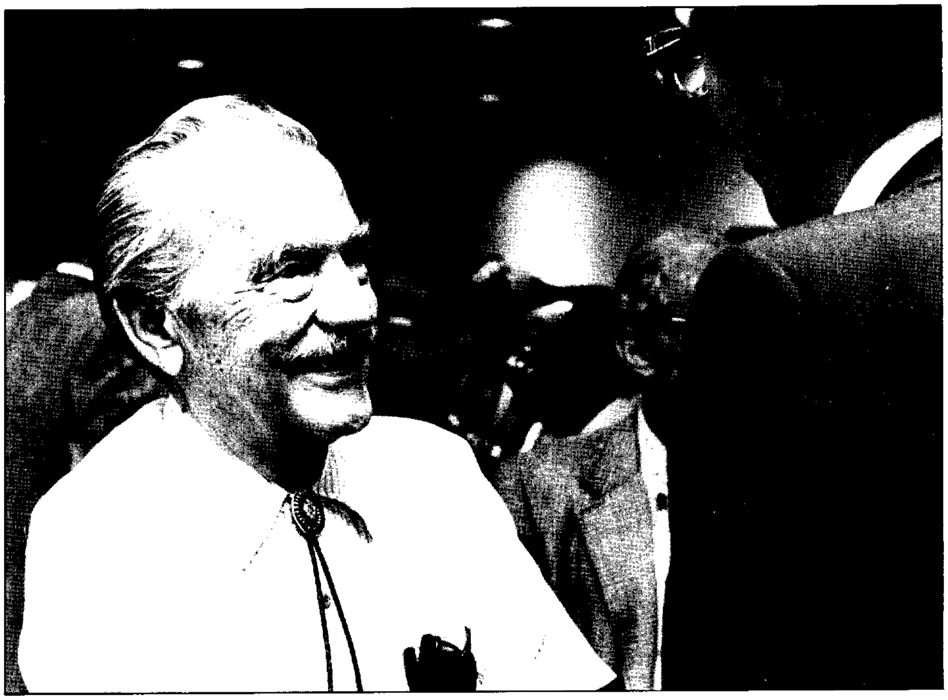

Photo by Fred Rick

Nick Metropolis enjoying a break in the quantum Monte Carlo conference, September 1985.

with the answer to whatever problem they had been worrying about the night before. Unlike—or like—the early bird who catches the worm. Fermi had an affliction that helped him do this. He had insomnia, and he always got up at four in the morning. Now what do you do if you are wide awake at four in the morning? Well, in Fermi's case he either did theory or he did calculations. For making quick calculations he had a whole bag of tricks, and the hand-calculated Monte Carlo method was one of them.

On the morning following this great puzzlement in the lab he got up at four as usual, and in thinking about the problem he decided he knew what might be happening. Maybe the neutrons were being slowed down as they went through various substances, and if they were, then hydrogen nuclei would be especially effective. And with a greater slowing, you could expect a higher level of induced activity in the silver. Well, he came into the lab and made this pronouncement, and everyone was struck by the simplicity of it all and the theory turned out to be quite plausible.

Then Fermi, in working out the detailed theory, used Monte Carlo calculations to give him a physical insight and to help him choose a suitable functional form, Gaussian, exponential, or other, for representing the slowing down process.

The slowing down turned out to be a major discovery. Slow neutrons have very large cross sections for nuclear reactions. and with them Fermi produced a large number of new radioactive isotopes. This work won him the Nobel Prize in 1938. It led directly to the chain reaction in Chicago in 1942 and to the establishment of Los Alamos in 1943.

Fermi never wrote up his use of the Monte Carlo method, but he told the story to Emilio Segre many years later when computers had made statistical sampling practical and the technique was coming into wide use. Segre mentions it in his introduction to the neutron papers in *The Collected Works of Enrico Fermi.*

The Marchant Repairman

Now- let's get back to Nick Metropolis. It is 1944, and the scene is Los Alamos. What is Nick doing? He is busily repairing Marchant calculators. And how did he get into that business? Well it happened in the following way. When Los Alamos was set up in 1943 there were no calculators. There was, however, an obvious and urgent need to carry out a lot of calculations, and the Lab went out and bought a whole lot of calculators-Marchants and Fridens, which were the best mechanical calculators at the time—and set up a hand-computing facility. The machines were heavily used and soon began to show signs of wear and tear. Too many were out for repair, and it took too long to send them to the manufacturer to be fixed. So Nick, together with Dick Feynman, set up a little repair shop. They took the machines apart and traced the mechanical linkages to find the sources of jams and slippage, and of course they learned how the machines worked, Pretty soon they could identify the difficulty rapidly, and the machines sent to their shop were quickly repaired and returned to service.

When the administrators came across this curious extracurricular activity, they regarded it as a problem. They issued some sharp criticism and stopped the repair service. But not for long. The demand for working machines was so great that the administrators decided they had better not interfere. and the service was soon reinstated.

In the fall of 1943 it became apparent that large computational problems were straining the capacity of the hand-calculators. That's where Dana Mitchell comes into the picture. I mention his name with great fondness because he was the man who got me into physics. He had come to Los Alamos to help with procurement. and he was familiar with the IBM punched-card machine. Soon a whole set of those machines arrived at the Lab. Metropolis and Feynman immediately decided to see whether these punched-card machines were really faster than their team of Marchant hand-calculators. They set up a test in which the two groups would calculate the same problem. For the first two days the two teams were neck and neck—the hand-calculators were very good. But it turned out that they tired and couldn't keep up their fast pace. The punched-card machines didn't tire. and in the next day or two they forged ahead. Finally everyone had to concede that the new system was an improvement.

As the atomic-bomb project entered its final phases in late 1944, the pressure for computation increased sharply. Nick became more and more involved in punched-card operations with Dick Feynman, who was put in charge. Their work continued at a frantic pace during 1945 until the Japanese surrendered on August 15, after which they began to relax a bit.

The ENIAC

The great step forward in computing was the introduction of' electronics, and now the ENIAC entered the scene. The ENIAC was the first electronic, digital, general-purpose, scientific computer. It was designed and built for the Aberdeen Proving Grounds by a group of engineers under the direction of Pres Eckert and John Mauchly. It had 18,000 vacuum tubes and computed 1000 times as fast as its closest electromechanical competitor. The machine was built during wartime on the promise that it would calculate ballistic trajectories at least ten times faster than the mechanical differential analyzers then in use. As things frequently turn out, the machine was now working as promised—but the war was over, and suddenly no one cared that much about calculating ballistic trajectories.

The connecting link between the ENIAC and Los A1amos was Johnny von Neumann, who was a consultant both at the Aberdeen Proving Grounds and at the Lab. He was tremendously excited about the ENIAC. He took a deep interest in its design and thought a good deal about what could be done with it. When he came to Los Alamos early in 1945, he told Nick. Edward Teller, and Stan Frankel about what the Eckert and Mauchly team was doing. They were enchanted. You know how things sometimes work out if you are in the right place at the right time—and prepared for the opportunity. Well, von Neumann suggested that perhaps Los Alamos had a problem that could be worked out on the ENIAC and invited Nick and Stan to try the new machine. It was a great opportunity, and they seized it eagerly. And so it turned out that the first serious problem the ENIAC solved was the one Metropolis and Frankel put to it regarding the "super," the thermonuclear bomb.

By this time the idea of the stored program had already been conceived. principally by John von Neumann and his collaborators on the ENIAC. They had already begun to design the EDVAC, a computer that would have a stored program. The ENIAC was programmed by connecting cables and wires and setting switches on a huge plugboard that was distributed over the entire machine. Figure 1 is a photograph showing young women programming the ENIAC by interconnecting the electron tube registers with cables inserted in plugboards, It was an awkward and tedious way to tell the machine what to calculate and what to do with the results. When von Neumann was in Los A1amos, in about 1947. he described a suggestion made by Richard Clippinger of the Ballistic Research Laboratory on how the ENIAC might be converted to a limited stored-program mode. The idea was to rearrange the so-called function tables, normally used to store 300 twelve-decimal-digit numbers set by manual switches. to store up to 1800 two-decimal-digit numbers. each pair of numbers corresponding to an instruction. A particular problem would correspond to a sequence of' such instructions. This sequence would be set on the function tables. A background control would interrogate these instructions sequentially, including so-called loops of instructions. Changing from one problem to another would be achieved by resetting the switches of the function tables to correspond to the new sequence of instructions. Figure 2 shows the function tables of the ENIAC.

This suggestion made a deep impression on Nick, but there was a missing element—the background control. On a visit to the ENIAC in early 1948, Nick learned that a new panel had been constructed to augment one of the logical operations. It was a one-input, one-hundred-output matrix, and it occurred to Nick that this matrix could be used instead to interpret the instruction pairs in the control mode proposed by Clippinger. Such a panel would greatly simplify the implementation of a background control. He told von Neumann about it and was encouraged to go ahead and try-and so he did. The scheme was implemented on the ENIAC forthwith, and Nick's set of problems-the first computerized Monte Carlo calculations—were run in the new mode.

The MANIAC

After the war Nick joined the faculty of the University of Chicago, to help set up a major computing facility. When that didn't materialize as quickly as he had hoped, he began to think of other possibilities, and about that time he got a call from Carson Mark, head of the Theoretical Division at Los Alamos. suggesting that he set up a computing Facility here. Nick was ready, willing. and able. The moral of my story is that fortune favors the prepared mind. Nick was right there. well prepared to do just what he was asked to do, and that's how the MANIAC was born.

The Mathematical and Numerical Integrator and Computer—the MANIAC—was designed according to von Neumann's principles. which had been set forth in a remarkable publication by Arthur Burks.

Herman Goldstine, and Johnny von Neumann. The MANIAC borrowed heavily from the IAS, the computer being built at the Institute for Advanced Study under von Neumann's direction. But because the MANIAC came later, Nick was able to avoid many pitfalls that delayed the IAS.

As I have mentioned, many computers were built in this outburst of activity' after the end of the war. The ENIAC had started a revolution that continues to this day, with no end yet in sight. But the unusual success of the MANIAC was due primarily to the personality and motivation of Nick Metropolis and to the group of highly capable engineers and programmers he assembled at Los Alamos to help him build the machine and make it run. The original engineers were Dick Merwin, Howard Parsons, Jim Richardson. Bud Demuth, Walter Orvedahl, and Ed Klein. The importance of programming aids was recognized early on. About 1953 John Jackson led a study of assembly languages, and an assembler was produced, Mark Wells and others launched the development of the MADCAP, a high-level programming language and compiler. This was a critical development because it provided a convenient way to communicate with the MANIAC.

Fermi and Metropolis

Enrico Fermi had been at Los Alamos during the war and liked it so much that he claimed he would not have left if only the Lab were a university. Since it wasn't a university, he made the best possible compromise by accepting a position at the University of Chicago and spending his summers at Los Alamos.

When he came to Los Alamos in the summer of 1952, the MANIAC was up and running, and it would hate been very hard to keep Enrico from that machine. He though the MANIAC was just wonderful. He could hardly wait to get his hands on it. I've told you how he loved to calculate, the faster the better, and here was his good friend Nick Metropolis with the fastest machine in the world, offering to introduce him to its mysteries and let him run it himself.

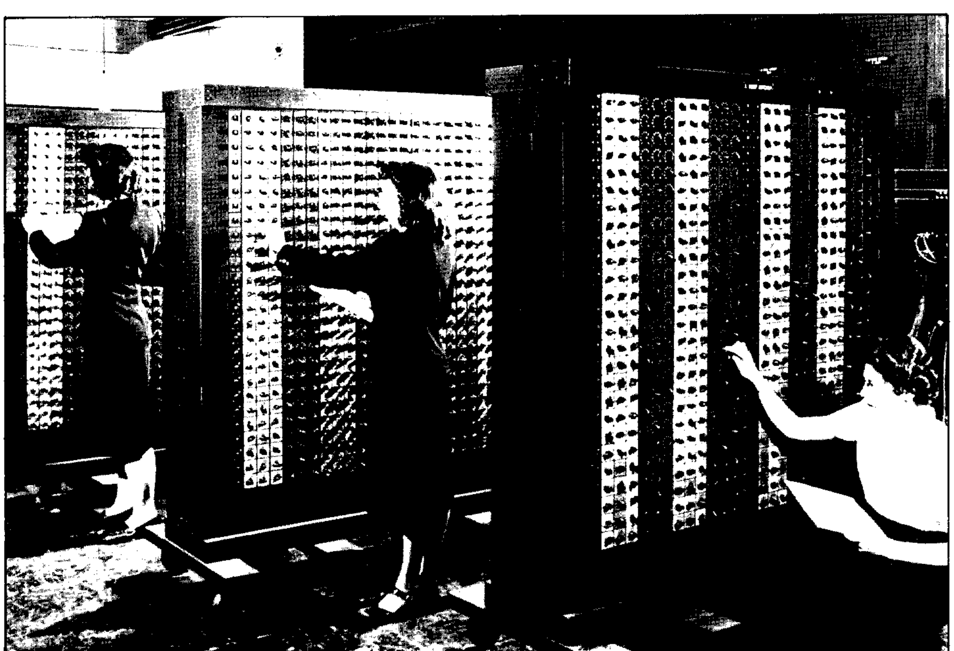

Fig. 2. Function tables of the ENIAC.

Nick must have been pleased by the praise and interest shown by so many of the illustrious scientists he had worked with in wartime Los Alamos, but the supreme accolade came from Enrico Fermi. When you build something. what could be more satisfying than to have one of the world's greatest physicists tell you not only that it's a great machine but that he wants to use it. Moreover, Fermi had a problem that was ideally suited to the machine. He wanted to analyze the pion-proton scattering experiments he had been carrying on in Chicago with his collaborators at the new 450-MeV synchrocyclotron.

My connection with this story is analogous to Nick's except that in this case I had built the cyclotron. I also helped build the apparatus and carry out the measurements. The other collaborators were Darragh Nagle and Earl Long. on the faculty and my graduate students. Ronald Martin, Gaurang Yodh, and Maurice Glicksman.

The results of our pion-proton scattering experiments had been as striking as they were surprising. The large scattering cross section at a specific energy indicated the presence of a resonance. It was a major discovery, an excited state of the proton. We had uncovered a new particle now known as the delta. and it attracted the attention of the entire high-energy physics community. In order to extract the appropriate quantum numbers of the delta, Fermi wanted to do what he called phase-shift analysis, which tells you which quantum states have the biggest scattering amplitudes and which have the smallest.

I should mention that Fermi had a knack of coming up with problems whose computation matched the means available. Some years before, when the punched-card machines were the principal means for computing, Fermi posed the problem of calculating a table of atomic masses using a semiempirical mass formula he had devised on the von Weizsacker model. Nick organized the calculation and the preparation of the tables.

The tables turned out to be very useful and were widely used. I still have my copy.

So anyway, Fermi came to Nick with his phase-shift problem. As always, Nick was extremely helpful, and they carried out the work. I learned all about it when Fermi returned to Chicago in the fall of 1952, so steamed up about computers and the MANIAC that he announced he would give a series of lectures on digital computing. We were treated to a magnificent course—Fermi at his best. We learned for the first time about binary and and hexadecimal arithmetic, Boolean algebra, and linear programming. With this kind of introduction, we were easy converts to the cause of computers in science, and we even began to go out to Argonne, whereby that time the AVIDAC was running, to learn how to program and run that machine. The gospel according to Nick Metropolis was taking effect.

There's an amusing story about Edward Teller that fits in here. Remember that Nick had been a member of Teller's group when they were working on the "super." Now, Teller was not one to let Fermi leave him behind. Anything Fermi could do, he could do too. So Teller also became a student of Nick's and learned how to program the MANIAC. When he came back to Chicago—he was on the faculty then—not to be outdone by Fermi he announced that he would give a colloquium on the subject of computers. But when the colloquium notice appeared, it didn't convey exactly the impression he had intended. It read,

Edward Teller

The MANIAC

To show how closely Fermi interacted with the MANIAC, I want you to see some of his programming efforts, done in his own hand. Remember, these were the days before FORTRAN. Programming was done at the lowest level, in machine language. Figure 3 is a subprogram Fermi wrote to convert the data in memory into decimals and to print the results. Figure 4 is a block diagram of the program for calculating the phase shifts by finding a minimum chi-squared in a fit to the data. And Figure 5 is a printout of the program from the MANIAC. Note the use of hexadecimal numbers. The comments are written in Fermi's hand.

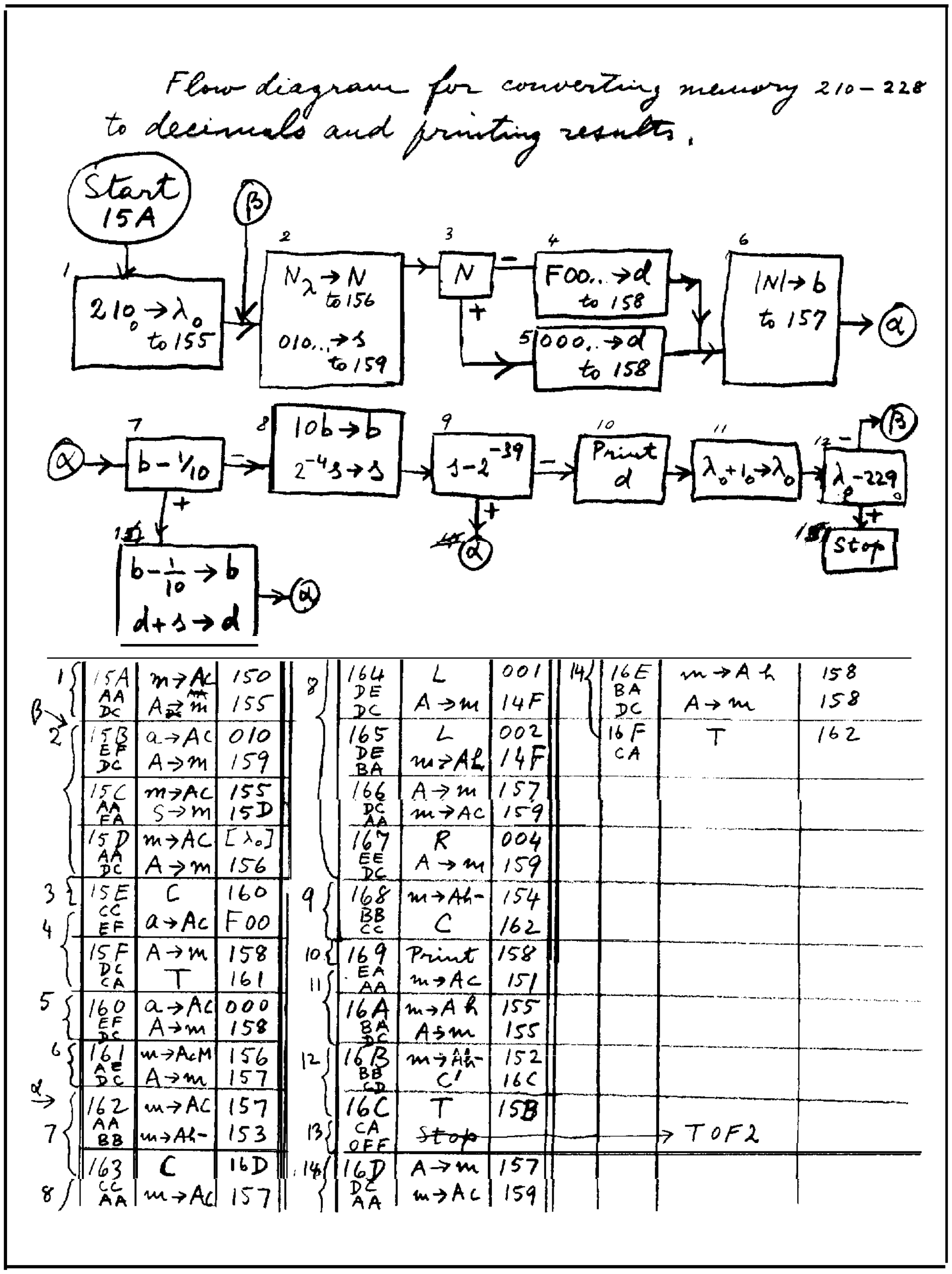

Fig. 3. A subprogram written by Fermi for converting data in memory from hexadecimal to decimal form and printing the results.

Phase-Shift Analysis

In this period, 1953 and 1954, phase-shift analysis was such a hot subject that it occupied center stage in the elementary particle physics community. At the Rochester Conferences held in those and subsequent years, you could talk about alpha three three and alpha three one, and everyone understood that these were the phase shifts of the pion-proton scattering. The physics was important-the delta was a new particle.

In working with the phase-shift analysis program, we encountered, for the first time, solutions in hyperspace, many-functional space. You had to get used to the fact that this kind of space has its own problems of minimization, that you could easily fall into the wrong minimum and end up with wrong solutions. The virtuosity of the computer almost made us lose sight of the discovery of the proton

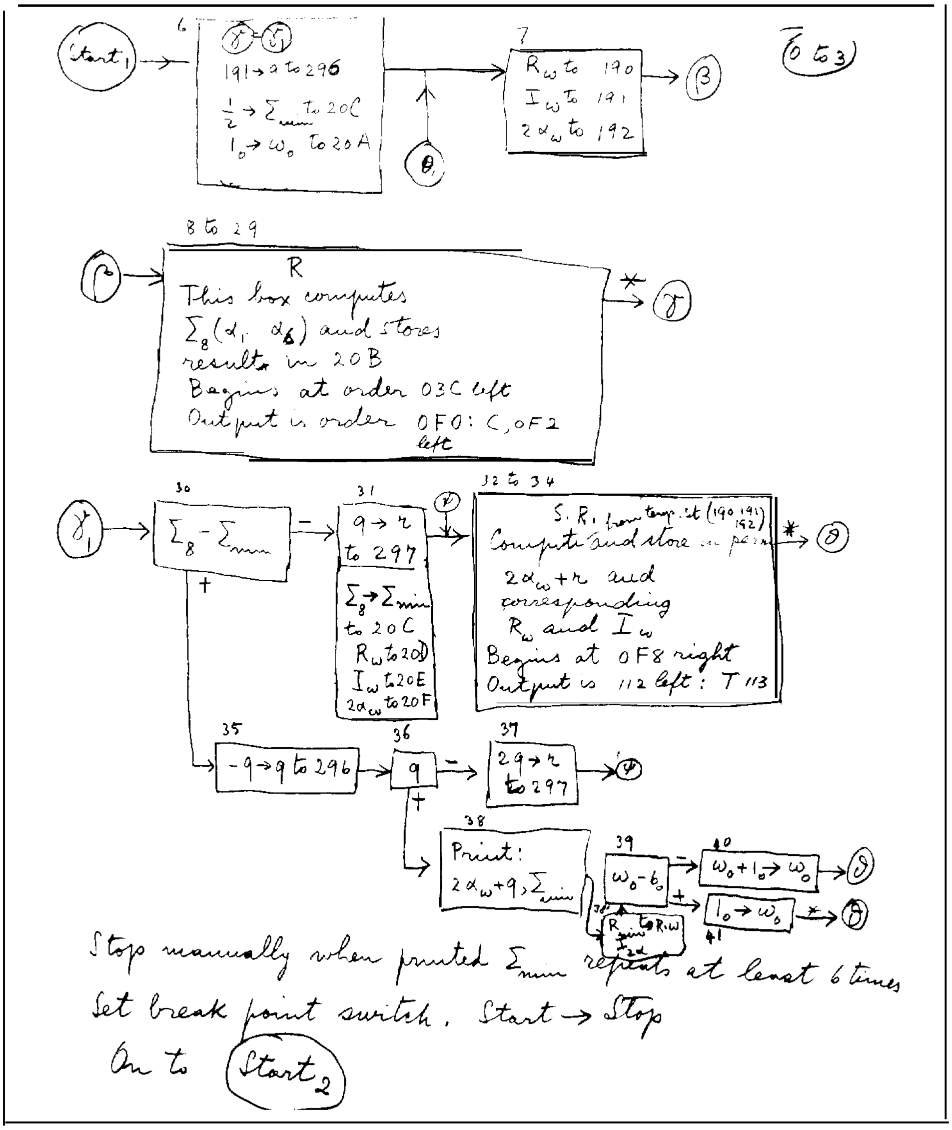

Fig. 4. A subprogram written by Fermi for calculating phase shifts by finding a minimum chi-squared in a fit to the data.

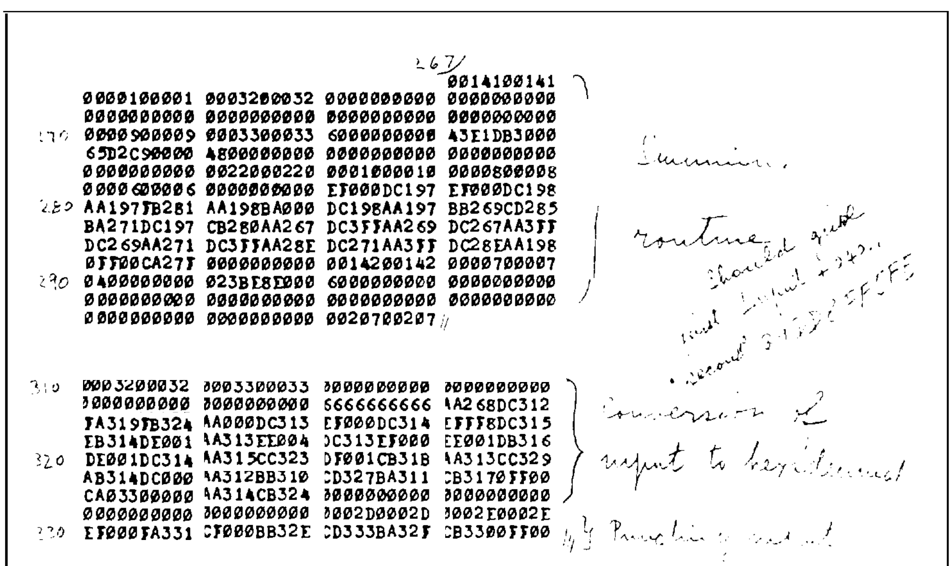

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Fig. 5. A portion of the printout of the program containing the subprograms described in Figs. 3 and 4. The program is written in machine language in hexadecimal numbers.

resonance because the computer would find solutions that we didn't expect were there. We would put a program into the machine fully expecting the quantum state of the resonance to emerge. But no. A computer doesn't pay any attention to what Nature would like the solution to be; it has its own way of finding solutions. And all of a sudden it began to find solutions, many of them—six of them—that had nothing to do with the resonance. It found many sets of phase shifts that gave good fits to the data, leaving open the question whether the resonant solution was the correct one. The resonant solution was appealing in that it accounted for all of the unusual features found in the experiments, but the nonresonant solutions were not easy to rule out.

I won't say that this confused Fermi—that would be a little too harsh—but the result of all this was that he couldn't claim with certainty that we had discovered a resonance in our experiments. As long as the computer was turning out solutions, good fits of the data, good chi-squareds, that were nonresonant solutions, he was always forced to conclude that the result was ambiguous.

Now Hans Bethe, who had been head of the Theoretical Division at Los Alamos during the war, decided to get into the act. He made himself a great expert in phase-shift analysis. He wasn't satisfied with the way Fermi was handling the problem, and he went in with the idea that he wasn't going to be that naive and that he could do better by including additional physics arguments. So he enlisted Nick's aid and, with Fred deHoffmann to help him, mounted a second program in phase-shift analysis. So here we had Nick on both sides of the competition, an odd situation that only someone like Nick could handle. In matters of science, Nick had no favorites. In the end, I think, the problem was handled best by two of my graduate students, Ronald Martin and Maurice Glicksman, working separately. They didn't have a fancy computer and therefore had to use much simpler approaches to the problem. By using graphical methods with simplified but plausible assumptions, they came up with the resonant solution that turned out to be the correct one. It was a lesson in the use of computers that should be a caution to us all.

Scientific Triumphs

The nice thing about having the first computing machine is that almost anything you do on it is new and important. In Fig. 6 I have listed ten of the many scientific uses of the MANIAC. I chose these to emphasize the distinction of the men who came to work with Nick and the variety and importance of what they were able to accomplish. These projects are also examples of how the computer opened new possibilities for scientific investigation, sometimes with surprising results.

Pion-proton phase-shift analysis (Fermi, Metropolis; 1952)

Phase-shift analysis (Bethe, deHoffman, Metropolis; 1954)

Nonlinear coupled oscillators (Fermi, Pasta, Ulam; 1953)

Genetic code (Gamow, Metropolis; 1954)

Equation of state: Importance sampling (Metropolis, Teller; 1953)

Two-dimensional hydrodynamics (Metropolis, von Neumann; 1954)

Universalities of iterative functions (Metropolis, Stein, Stein; 1973)

Nuclear cascades using Monte Carlo (Metropolis, Turkevich; 1954)

Anti-clerical chess (Wells; 1956)

The lucky numbers (Metropolis, Ulam; 1956)

Fig. 6. Scientific triumphs achieved with the MANIAC. Nick Metropolis was a co-author of the publications resulting from these studies except for the ones on nonlinear coupled oscillators and anti-clerical chess.

Nonlinear Oscillators. I have already discussed the first two calculations listed in Fig. 6. The third, the Fermi, Pasta. and Ulam study, turned out to be extraordinarily important. In the summer of 1953 Fermi raised the question of the nature of the approach to equilibrium of a vibrating, nonlinear string, initially in a single oscillatory mode. He thought it would be fun to use the MANIAC for this experiment, so he and Stan Ulam and John Pasta set up a test problem and began to run it. As they expected, the computations showed that the initial vibrational energy gradually transferred into neighboring modes and eventually achieved equilibrium, the time taken being the so-called relaxation time. Everybody was really quite happy with the result.

But the completely unexpected happened one day when they were computing a typical problem. While the machine was grinding away at this problem, they became engrossed in a heated discussion and let the computer go beyond its usual turn-off point. When they finally got around to looking at it, they found that the vibrational energy had returned to within a few percent of its initial state. Well, that was

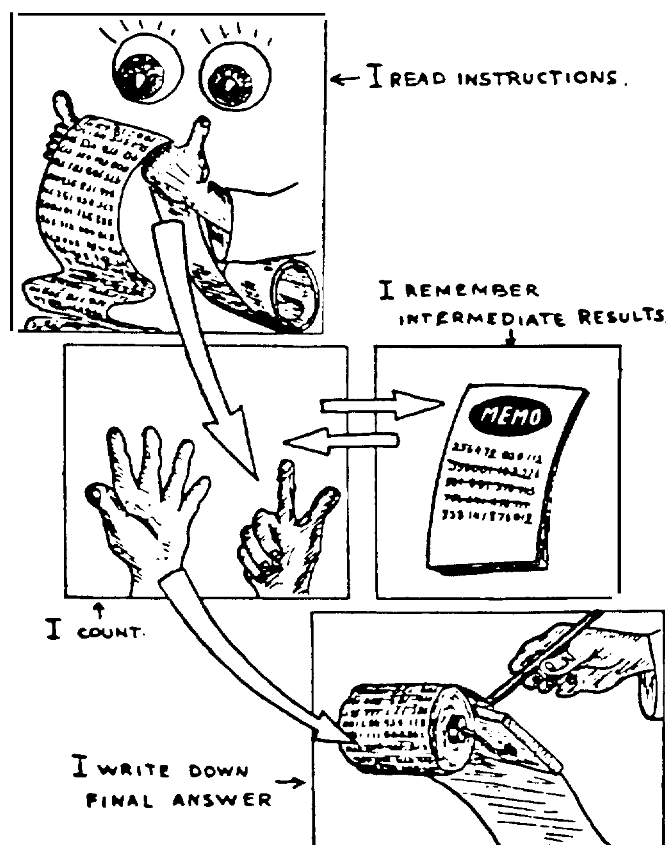

Fig. 7.

(For simplicity numbers in Fig. 7 are given in the decimal and not in the binary system.)

Fig. 7. Mr. Tomplins Iears how the MANIAC works in an illustration from *Mr. Tompkins Learns the Facts of Life* by George Gamow. (Copyright 1953 by Cambridge University Press; reprinted with permission.)

Fig. 8. Paul Stein (left), Nick Metropolis, the MANIAC, and the 6-by-6 "anti-clerical" chess board.

such a tremendous surprise that at first they thought the machine had gone awry. They ran the problem again, and 10 and behold, given enough time, the amplitudes all went back to the initial state, and then more new and surprising things happened. The rest is history-nonlinear systems were shown to have many fascinating aspects. The ideas of soliton theory emerged, and the subsequent outpouring of papers became a minor industry. Today this classic work is known as the FPU (Fermi-Pasta-Ulam) problem.

The Genetic Code and Mr. Tompkins. The Metropolis circle of famous scientists included George Gamow. At the time Gamow was introduced to the MANIAC. his interest had turned to biology, and so he got Nick to help him work on some problems of the genetic code. He was one of the first to have the idea that the genetic code was vested in four nucleic acids. which somehow were able to code for the twenty amino acids from which proteins are made. So some of these early studies of the genetic code were carried out on the MANIAC.

On the lighter side Gamow was writing a book called *Mr. Tompkins Learns the Facts of Life.* Gamow was so fascinated by the MANIAC that he decided to include the machine in his book. So when Mr. Tompkins is to learn how the brain works, Gamow introduces him to MANIAC and has the computer explain how his electronic brain works. Figure 7 is an inimitable Gamow cartoon from this delightful book: notice how appealingly the essentials are presented.

Importance Sampling. A significant advance in the use of the Monte Carlo method came out of Nick's collaboration with Edward Teller. Teller, obviously delighted at gaining access to such a marvelous toy, proposed that the MANIAC, and the Monte Carlo method, be used to carry out calculations on the equation of state in two dimensions for hard spheres. These calculations introduced the idea of what is now known as importance sampling, also referred to as the Metropolis algorithm. The scheme. which reduces the statistical error and thereby greatly improves the effectiveness of the Monte Carlo method, is widely used today, as participants in this conference have made evident.

Two-Dimensional Hydrodynamics. I won't say too much about two-dimensional hydrodynamics because it was always a major problem at the Lab-and still is. But Johnny von Neumann was one of the great experts in the field, and he showed how to attack the two-dimensional flow of two incompressible fluids under gravitational and hydrodynamic forces.

Iterative Functions. A striking thing about these early computer experiments is that in some cases the importance of the work wasn't recognized at the time the work was done. It was immediately obvious that the pion-proton phase-shift analysis was going to be important. But when Paul Stein, Myron Stein, and Nick Metropolis began to look into the problem of iterative functions, it was mainly to satisfy their curiosity. Quite some time later, this problem unexpectedly turned out to be very important.

One of the surprising consequences of these early studies of iterative transformations was the discovery of their universal properties. This work was an inspiration to Mitchell Feigenbaum, who took it up a few years ago and used it to show how such functions lead to a theory of the onset of turbulence and chaotic behavior. This subject has turned out to be as important as it is exciting. It has fired the imaginations of many who are intrigued by the curious aspects of nonlinear behavior. It is currently being widely developed, a good example of computer-driven mathematics.

A Few Others. Another noteworthy study was the classic study of the nuclear cascades induced by bombarding heavy nuclei with high-energy particles. Nick did this study with Tony Turkevich, using Monte Carlo techniques.

Then Mark Wells and others prepared the first program to develop a strategy for "anti-clerical" chess. This game was played on a 6-by-6 board with bishops removed. It was a highly amusing experience and had many implications for subsequent games of strategy. Figure 8 shows MANIAC I. Paul Stein. Nick Metropolis, and the chessboard.

Finally, I must mention some interesting work in number theory in which Stan Ulam and others introduced the notion of "lucky numbers," a generalization of the ordinary prime numbers with many similar properties. That was an attractive piece of work.

This list often is just a small sample of' the many scientific uses of the MANIAC, and it includes only the most prominent names associated with Nick on those projects. These I think were the most important works—or at any rate the most interesting.

Death of MANIAC

Before closing, let me make clear how the MANIAC evolved over the years. MANIAC 11 succeeded MANIAC I in Los Alamos in 1956. The second MANIAC was more powerful than the first and, because it included floating-point arithmetic, was easier to use. MANIAC III, with the latest in solid-state circuitry, was developed at the University of Chicago when Nick returned there to head the newly formed Institute for Computer Research.

In 1965 Nick returned to Los Alamos from Chicago, but by this time the computing needs of the Laboratory had increased dramatically and were being supplied by commercial machines. Unfortunately, in this climate the decision was eventually made to abandon the kind of original research that was special to the computer project, and in 1977 MANIAC II was turned off.

To conclude this story on a happier note. I remind you that it's Nick's birthday. I've always had the idea that when there is a birthday there ought to be a poem. Here is my own modest offering.

Monte Carlo Metropolis

Nick, you'll remember those halcyon days;
The Monte Carlo method was in its earliest phase.
You went to the ENIAC and got it to load
Problems you wanted in a stored-program mode.
The Monte Carlos you gave it opened a crack
That helped you decide to build MANIAC.
MANIAC came out as a marvelous toy,
A machine you could work with and really enjoy.

You called on your friends to, join in the fun,
And it wasn't too long before they'd begun.
There was Teller, Gamow, Turkevich too.
Of others not mentioned there were quite a few.
But these in particular knew that their goal
Was through Monte Carlo in the MANIAC's soul.
Those were seminal papers, seeds had been sown;
That how Monte Carlo came into its own

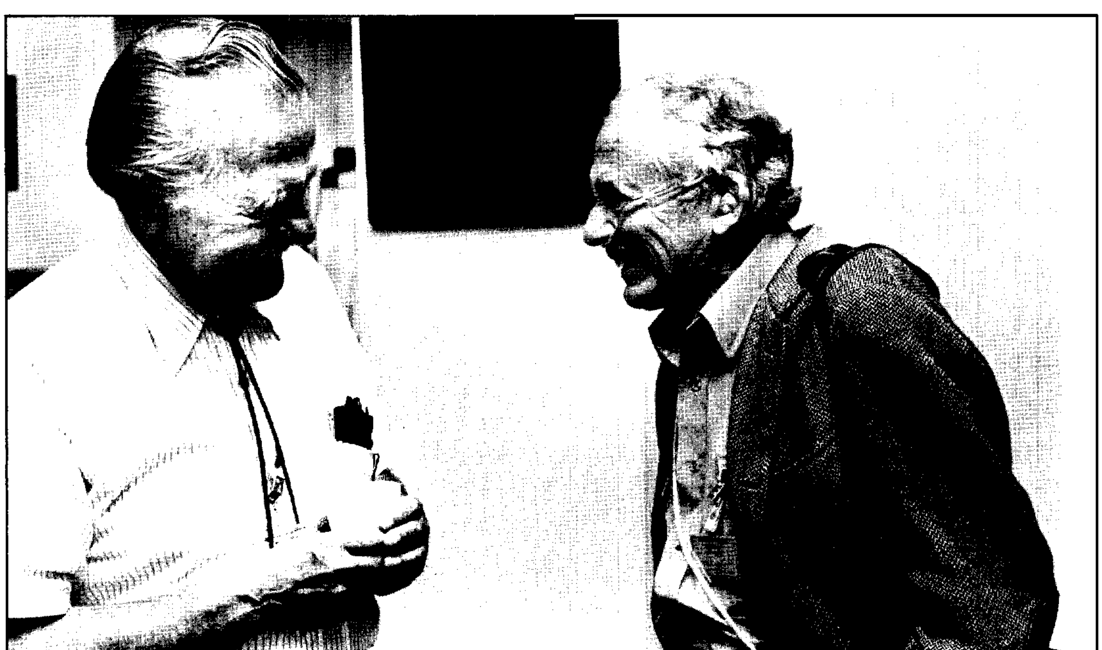

Photo by Fred Rick

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Historical illustrations for this article were published by N. Metropolis.

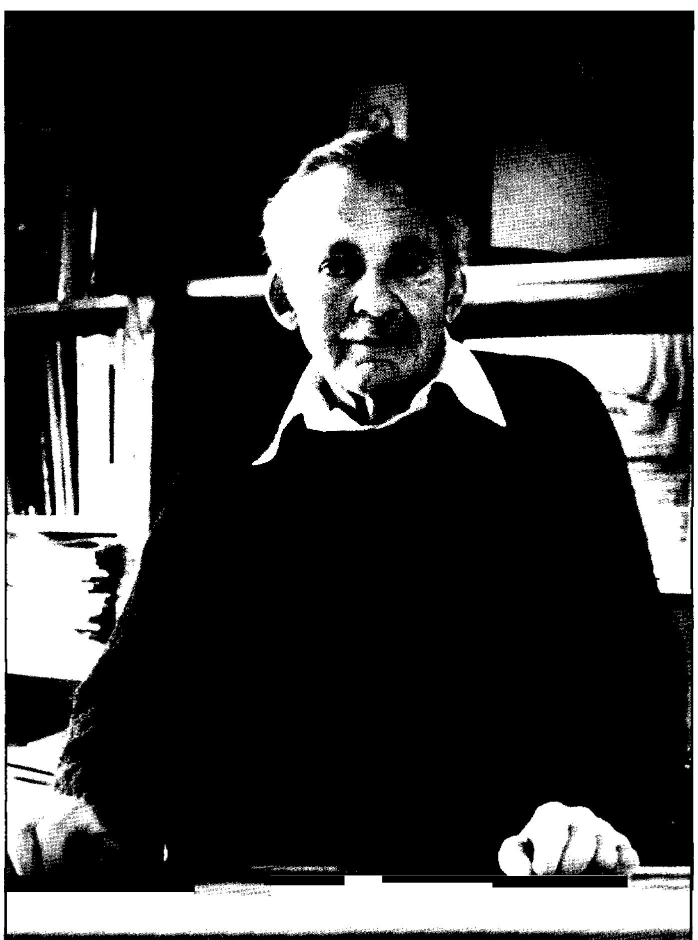

Photo by Fred Ri:k

Herbert L. Anderson received his Ph.D. in physics from Columbia University in 1940. As a graduate student he assisted in the construction of a 37-inch cyclotron at Columbia. He also began a close association with Enrico Fermi that lasted until Fermi's death in 1954. Anderson was the first in the United States to demonstrate the energy release in the fission of uranium in an ionization chamber/linear amplifier combination. He participated in the original experiments on neutron reproduction in uranium. which led directly to the development of the nuclear chain reaction. These experiments included the early studies on the fission of uranium. the emission of neutrons by uranium. the slowing down of neutrons in carbon, and neutron reproduction in a lattice of uranium and graphite. During 1942-44 he had a major role in the design and construction of the first chain reacting pile, in Chicago, the second (CP-2) pile at Argonne, and the Hanford piles. At Los Alamos his experiments at the Omega reactor helped establish the critical size for nuclear explosions in uranium-235. His measurements at Alamogordo, New Mexico, in which he used fission-product analysis, established the field of the first nuclear explosion in 1945. The method, adapted to air sampling, became a principal means for detecting and analyzing nuclear testing carried out by foreign countries. He returned to Chicago in 1945 as a member of the newly formed Institute for Nuclear Studies. He served as Director of the Enrico Fermi Institute from 1958-62. He was appointed Guggenheim Fellow in 1955-57 and Fulbright Lecturer in Italy in 1956-57. He was elected to the National Academy of Sciences in 1960 and to the American Academy of Arts and Sciences in 1978. In 1982 he received the Enrico Fermi Award. During the years in Chicago, he was a consultant and Visiting Fellow at Los Alamos, and in 1978 he joined the Laboratory as a staff member. He was appointed a Los Alamos National Laboratory Senior Fellow in 1981 and Distinguished Service Professor Emeritus at the University of Chicago in 1982. In the Physics Division at Los Alamos, he is currently working with an instrument of his own design to analyze the proteins made by living cells. The proteins are separated by two-dimensional electrophoresis, and the protein analyzer measures them by direct beta-ray counting. In a collaboration with biologist Theodore T. Puck, he is trying to identify the proteins specific to three human chromosomes.

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