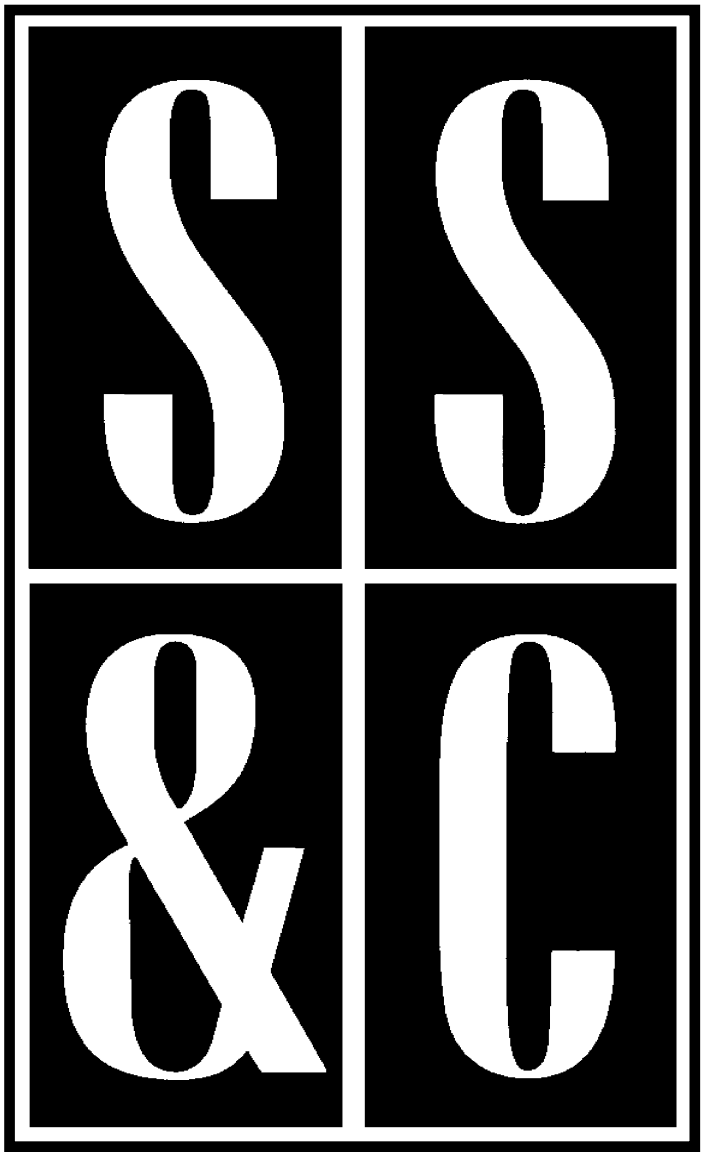
Scope, Sequence & Coordination

A National Curriculum Development and Evaluation Project for High School Science Education



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Scope, Sequence & Coordination

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Student Materials

Learning Sequence Item:

966

Radioactivity, Time and Age

March 1996
Adapted by: Nancy Reclusado, Don Warner, Dorothy Gabel, Thomas Goldsbury and Linda W. Crow

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Contents

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Student Sheet

Science as Inquiry

Stand ‘Em Up, Knock ‘Em Down

How can dominoes simulate nuclear fission?

Overview:

You have a cold/flu and give it to two people. Those two people, in turn, give it two more people. Before you know it, the entire class and eventually everyone in school is sneezing. You have set off a chain reaction.

Procedure:

How would you simulate a chain reaction by setting up an arrangement of dominoes? Set up two designs as specified by your teacher. For each design record the time it takes for all the dominoes to fall.

Questions:

1. In which arrangement did it take a shorter time for all the dominoes to fall?

2. How did the number of dominoes being knocked over per second change in each arrangement?

3. Are the reactions “expanding” or “limited” chain reactions? Why?

4. What makes the reaction stop?

5. Of your two arrangements, which do you think models what happens when a nuclear bomb explodes? Explain your answer.

6. Which arrangement models what occurs at a nuclear power plant? Explain your answer.

Science as Inquiry

Snapping Traps

How do snapping mousetraps simulate a nuclear chain reaction?

Overview:

Set up linked mousetraps to simulate a nuclear reaction!

Procedure:

Attach the mousetraps together with string. The strings from the gate of the first trap can be attached to one or two triggers of one or more traps as shown by your teacher. Continue until all the mousetraps have been used. The strings need to be fairly taut, otherwise the first trap may not spring the others. Design and set off at least two different arrangements. Time how long it takes for each arrangement to complete the chain reaction. Count the number of traps that sprang.

Caution: Mousetraps are extremely sensitive. Do not place your fingers in the way of the gates.

Questions:

1. Sketch your arrangements.

2. In which arrangement did it take a shorter time to spring all the traps?

3. How did the number of traps springing per second change in each arrangement?

4. Are the reactions “expanding” or “limited” chain reactions? Why?

5. What makes the reaction stop?

6. Of your two arrangements, which do you think models what happens when a nuclear bomb explodes? Explain your answer.

7. Based on the results of this activity, make a statement concerning the importance of controlling nuclear weapons.

Science as Inquiry

Crumpled Paper

How can crumpled paper be used to illustrate a nuclear chain reaction?

Overview:

During this activity you will participate in a chain reaction.

Procedure:

Extend and flex your biceps. Repeat this movement with your wrists. Get yourself ready for a paper toss! Stand and close your eyes. When you are hit with a wad of crumpled paper, toss your paper out in any direction.

Questions:

1. Just before you began the activity, your teacher had you sketch the positions of your classmates. Was there a chain reaction when students were in these positions? Explain.

2. You again sketched the positions of your classmates at the end of the activity. Was there a chain reaction when students were in these positions? Explain.

3. Compare this chain reaction to a nuclear fission reaction. What were you the equivalent of? What were the paper wads?

4. What differences are there between this simulation and nuclear fission chain reactions?

Science as Inquiry

Light My Fire

How does a spreading fire simulate nuclear fission?

Overview:

Students set up and light matches in different arrangements to simulate a chain reaction.

Procedure:

Observe several demonstrations of fires in which matches are set in different arrangements and at different distances from one another. Time how long it takes for the matches in each arrangement to light. Count those that light in each arrangement.

Questions:

1. Sketch the arrangements of the matches.
2. Tell what happened and why.
3. Which arrangement(s) produced a chain reaction?
4. Which arrangement produced the fastest chain reaction? Explain why.
5. Which arrangements did not produce a chain reaction. Explain why.
6. How does this demo relate to nuclear fission?

Science as Inquiry

Radioactivity, I

Procedure:

Gather your materials and place the pennies "heads-down" in a shoe box. Cover the box with the lid and shake it. Open the box and remove all the "changed" pennies (those that landed "heads-up"). Count the number of "unchanged" pennies remaining in the box and record this information on a data table. Repeat the procedure until all the pennies have changed, recording each trial and each result.

Questions:

1. What is the half-life of pennies? (This is the number of shakes it took for approximately 50—or half—of the pennies to change.)

2. How are half-lives used to determine the absolute time of various geological processes such as erosion, deposition, land uplift and volcanic eruption?

Student Sheet

Science as Inquiry

"Seeing" the Invisible

Procedure:

Your teacher has set up a cloud chamber demonstration. Make observations of what you see. Do all the tracks look identical?

Questions:

1. Describe any differences that you see in the tracks. How might you account for the differences?

2. What are you observing when you see the tracks? Are you observing atoms? Are you observing parts of atoms?

3. What do you think caused the tracks and why do you think this?

4. Why is dry ice used in the cloud chamber?

5. Why is this device called a cloud chamber?

Science as Inquiry

Half-life of Peas

Procedure:

Obtain a small cupful of peas. Make a data table to record the trial and number of unstable or radioactive peas. The peas are going to represent atoms, so create a name for your element. Count the number of atoms in your cup and record the number as Trial 0. Note the time (to nearest second) and then pour the cup full of atoms into a tray (or onto a piece of paper). Then separate the atoms into two categories, radioactive or decayed (stable) by the following criteria: if the flat side of the pea is up then the atom is radioactive. If the flat side is down then the atom is decayed (stable). Place the decayed atoms in one cup. Count the radioactive atoms place in the other cup. This cup of radioactive atoms is then poured out again, counted, and recorded for as Trial 2. The process is repeated until you are down to the last atom—that is—until all of the radioactive atoms have become stable by decaying. The decayed atoms are always added to the cup containing the decayed atoms from previous trials. The radioactive (unstable) atoms are put into a cup which is again poured into the tray. This sequence is repeated until no more radioactive atoms remain. The final time is then recorded.

Questions:

1. Using your data, calculate the half-life of the atoms—that is divide the total time by the number of trials.

2. How does your half-life compare to that of other student groups? Should all of the half-lives be the same? Explain.

3. Radioactive carbon has a half-life of 5,730 years. During that time half of the carbon-14 atoms change into nitrogen-14. Compare the activity using peas to the radioactive decay of C14. What represents the carbon? What represents the nitrogen? How do the half-lives compare?

4. Describe ways that this activity using peas differs from natural radioactivity. How does the analogy not match the real thing?

5. If a sample contained 100 grams of C14, in what century would there be less than 1 gram remaining?

6. Make a graph with the time on the horizontal axis, and the “radioactive atoms” on the vertical axis.

7. Describe what is happening over each time interval of your graph.

8. How many of your atoms would be radioactive after three half-lives?

9. In what year would a sample of 6 million peas disappear?

Student Sheet

Science as Inquiry

Getting Shorter All the Time

Procedure:

Measure and record the length of the entire piece of licorice. Change the name of the licorice to be more like the name of an element. Note the beginning time to the nearest second. Then cut the piece of licorice in half and record the trial number and the remaining length. (You may eat the other half if this if approved by your teacher—or save it and form a licorice graph.) It represents the mass of the radioactive element that has disintegrated. Continue halving the remaining piece. Each time you cut the remaining piece in half, measure it, record its length and trial number. The other half is eaten or saved for the licorice graph. Continue the process until the remaining piece is too small to be cut in half. Then record the final time.

Questions:

1. Using your data, calculate the half-life of the licorice, that is, divide the total time by the number of trials.

2. How does your half-life compare to that of other student groups? Should all of the half-lives be the same. Explain.

3. Radioactive carbon has a half-life of 5,730 years. During that time half of the carbon-14 atoms change into nitrogen-14. Compare the activity using licorice to the radioactive decay of C^{14}. What represents the carbon? What represents the nitrogen? How do the half-lives compare? What does the length of the licorice represent?

4. Describe ways that this activity using licorice differs from natural radioactivity. How does the analogy not match the real thing?

5. If a sample contained 100 grams of C^{14}, in what century would there be less than 1 gram remaining?

6. Make a graph of with the time on the horizontal axis, and the length of the radioactive licorice on the vertical axis.

7. Describe what is happening over each time interval of your graph.

8. What length of licorice would be radioactive after three half-lives?

9. In what year would a sample of 6 kilometers of licorice disappear?

Student Sheet

Science as Inquiry

Rocks With A Past

Overview:

All of us have heard of methods used to determine the ages of rocks. Can these methods be used on all rocks? What do these rocks look like? This activity will allow you to examine rocks that can be used in the radioactive dating process. Don't worry—they cannot harm you, but they can tell you their age.

Procedure:

Examine the rock samples and use the keys to identify the samples. Look closely at color and how the rock appears. Is it made of pieces of crystals locked together like a jigsaw puzzle? Or does it look like it has no pieces because they are too small to see?

Questions:

1. How do igneous rocks compare to metamorphic rocks?

2. All of these rocks can be used in the radioactive dating process. How would you describe the entire group?

3. How are igneous and metamorphic rocks formed?

Student Sheet

Science as Inquiry

The Case of the Melting Ice

Procedure:

Frosty the Snowman lies melting in the funnels around your lab room. There were no eyewitnesses, but there are several suspects. Each of them has holes in the alibis. It is necessary that it be determined at exactly what time Frosty was dismembered and put in the funnels to melt away, leaving no trace. Immediately record the volume of Frosty's melted carcass in your graduated cylinder and note the time. Make a chart, and at regular intervals (you decide how long) record the time and volume. After about 45 minutes, make a graph from your data.

Questions:

1. What was the exact time of Frosty's demise?

Science and Technology/
Science in Personal and
Social Perspectives

Chain Reaction: The First Half-Century

When a team directed by Enrico Fermi created the first controlled, self-sustaining nuclear reaction in a squash court under the football stadium at the University of Chicago on 2 December 1942, the group was elated. The achievement was a key step in the Manhattan Project to develop a weapon—the atomic bomb—that would win World War II, and it promised a wealth of cheap electricity down the road. “There was no ambivalence toward the project. The consequences of losing a nuclear race with Germany were unthinkable,” says University of Chicago physicist Roger Hildebrand, who, as a 19-year-old student, developed uranium fuels for reactors.

What a difference time can make. Last week, on the 50th anniversary of the so-called Fermi experiment, a series of meetings, briefings, and public protests across the country reflected the mixed feelings—at best—now attending the nuclear enterprise. Many scientists are now trying to dismantle the nuclear enterprise with the same fervor Fermi and his colleagues showed in building it. In Washington, D.C., for example, Physicians for Social Responsibility used the occasion to publicize its “Manhattan Project II,” an international campaign to prevent the proliferation of nuclear weapons.

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Science and Technology/
Science in Personal and
Social Perspectives

The Birth of the Nuclear Age

Fifty years ago last month Enrico Fermi demonstrated that a self-sustaining nuclear chain reaction could be produced and controlled. It was a quantitative experiment, and it was Fermi who decided upon all the cautious steps to be followed and all the measurements to be made.

I had joined Fermi's group at Columbia University as a young physicist in January 1942. The following account draws on my personal experience and on the well documented historical record. Most of the 40 people who witnessed the historic culminating experiment under the grandstand of the University of Chicago's Amos Alonso Stagg Field on 2 December 1942 were physicists. But this final success could not have been achieved without the indispensable efforts of engineers, chemists and metallurgists, or the especially pure materials produced for us by American industry.

It was Leo Szilard who had the foresight to enlist the help of industry in producing the required high-purity materials. Szilard was a brilliant visionary. In fact he really was the inventor of the nuclear chain reaction. In 1933 Ernest Rutherford remarked in a public lecture that anyone looking to nuclear reactions for useful energy was "talking moonshine."' Szilard took this as a personal challenge. He had read a book, written in 1914 by H. G. Wells, called *The World Set Free*. In this fantasy, nuclear bombs are developed and used to destroy cities. This brings humanity to the realization that war is impermissible in a world with nuclear bombs. So an international government is set up, and the book has a utopian ending. Szilard maintained the hope over decades that a nuclear bomb could lead to a more peaceful world.

As early as 1934, Szilard took out patents relating to possible nuclear chain reactions. He assigned the patents to the British Admiralty to prevent the publication of information that might have-important military consequences.[2] In his 1936 patents Szilard proposed using neutrons to initiate a nuclear reaction that might emit enough additional neutrons to start a nuclear chain reaction. But he didn't just leave it at that: Szilard sought financial support to develop these hypothetical processes, and he arranged for physicists to perform relevant experiments.

Szilard and the Columbia Group

In January 1939, when Niels Bohr brought the news of Otto Hahn's discovery of uranium fission to Washington, Szilard was already primed to use the fission reaction to implement his ideas on nuclear chain reactions. The crucial question was whether a fissioning uranium nucleus emits enough neutrons. So Szilard went to Columbia University and joined forces with Walter Zinn, who was doing neutron experiments. Using Zinn's neutron detector and two

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grams of radium Szilard had rented on borrowed money, they found that uranium fission did indeed produce neutrons—about two for every fissioned nucleus.

Fermi had just arrived in the US to work at Columbia. He had gone to Stockholm the previous month to receive his Nobel Prize with the secret intention of leaving Fascist Italy for good. On 26 January Fermi attended the historic Fifth Washington Conference on Theoretical Physics in Washington, DC, but he left early to do experiments with Herbert Anderson at Columbia, who had also demonstrated that neutrons were emitted in the fission process. Szilard cajoled Fermi and Anderson into working with him and Zinn. Thus in 1939 and 1940 the Columbia group consisted of Anderson, Fermi, Szilard and Zinn.

Uranium fission occurs in the relatively rare isotope ^{235}U (less than 1% of natural uranium), not in the common isotope ^{238}U. The neutrons emitted in the fission process are fast, but the cross section for fission is much greater for slow than for fast neutrons. That's true of many neutron induced reactions. It posed the problem of how one might slow down the neutrons emitted during fission. Another problem was to minimize the absorption of neutrons in parasitic nonfission processes. Resonant absorption of neutrons by ^{238}U, for example, would be a very serious source of parasitic loss. But that process turns out to be not altogether undesirable. When ^{238}U absorbs a neutron, it â-decays to neptunium, element number 93, which in turn â-decays to ^{239}Pu, a fissionable isotope of plutonium, element number 94.

The Columbia group decided to use graphite as the moderator to slow down the neutrons. To reduce the probability of resonant absorption loss, Fermi and Szilard separately came up with the idea of separating the uranium (in the form of the oxide $U_3 0_8$) and the graphite into different regions. Fermi proposed alternating layers of graphite with layers of uranium oxide. Szilard prevailed with the idea of using a lattice of uranium oxide in the graphite.[3]

Late in 1939 Szilard wrote up his theory of a nuclear chain reaction in graphite and uranium. But he withheld it from publication to keep it from the Germans. After the war, he submitted it for declassification, but the Manhattan Project authorities denied the request. His theory eventually appeared in part III of his collected works.[3]

The first experiments using stacks of graphite blocks to measure the neutron cross-section of graphite were discouraging.[4] The problem was the presence of impurities in the graphite. So Szilard went to the National Carbon Company and other industrial firms to discuss details of the manufacturing processes. His efforts led to a great improvement in the purity of the graphite, particularly a large reduction of the boron contamination. Boron has a very large neutron absorption cross section.[1]

The following story gives an insight into Szilard's personality. He became annoyed with the Manhattan Project's reports of events and decisions. So in the 1940s he wrote a set of memoirs, calling them "My Version of the Facts." He showed them to Hans Bethe, who asked him what he intended to do with the material. Szilard said he wasn't going to publish it; he just wanted God to know the facts. When Bethe asked, "Don't you think God already knows the facts?" Szilard replied, "But He may not know my version."[1]

Fermi's Piles and Style

In the earliest uranium-graphite "piles" used to measure the

multiplication of neutrons, the uranium oxide was in metal cans, but the metal of the cans absorbed neutrons, causing parasitic loss.[4,5] So the group decided to press the uranium oxide into cylinders; later a switch was made to baseball-size hexagonal cylinders called "pseudospheres." Holes were drilled in some of the graphite blocks to hold the shaped uranium oxide.

The early piles containing the oxide-graphite lattice were 8 feet by 8 feet on a side and 10 or more feet high. Neutron sources consisting of radium and beryllium powder were put in a graphite pedestal at the bottom of the pile. The piles were covered with cadmium foil (cadmium is a strong neutron absorber) to create a good boundary condition, with no stray neutrons reflecting from the walls or the air.

The neutron flux in such a lattice obeys a second order time-independent diffusion equation. With the rectangular pile geometry, it yields solutions that have cosine distributions laterally and an exponential fall off with increasing height. That's why these structures were called "exponential piles." If there is good neutron multiplication in the lattice, the exponential falls off slowly.

The neutron multiplication factor was obtained by measuring this exponential distribution as a function of height. To permit the necessary flux measurements, horizontal slots were left in the side of the pile into which one could insert indium foils all the way to the central axis. The radioactivity induced in the indium foils was proportional to the neutron flux.

By the time I joined the Columbia group in 1942, Fermi had established a regular ritual of measurements.[5] The indium foils were as identical as we could make them, and they were cross-checked experimentally. The foils were irradiated in the exponential piles for fixed times to provide the desired statistical accuracy. After removal from a pile, a foil was immediately rolled into a cylinder and then slid over a Geiger counter. The counting rates were measured for precise, fixed amounts of time. Before a counter was used, it was always checked to determine the room background. After the measurement the background was checked again. The reliability of the Geiger counter was also checked with a naturally radioactive standard for every measurement. The ritual was repeated several times to establish that the measurements were reproducible within three standard deviations.

In all his experiments, Fermi was constantly checking to make sure that the instrumentation was functioning reliably. If there was any discrepancy, he would discuss with the group all the possible sources of the error. Fermi did the same work as everyone else. If we were stacking piles of graphite bricks, he would join in; if we were pressing the uranium oxide into shapes, he would help with that.

The measuring went on 24 hours a day, but Fermi worked only during the day. We younger people took the night shift. Every morning Fermi would check all the numbers we had gotten to make sure we hadn't made a numerical or clerical mistake. Then he made a personal summary of the measurements.

In January 1942 the group consisted of Fermi, Anderson, Zinn, Bernie Feld, George Weil and me. The immediate goal of our group at Columbia was to develop a controllable nuclear chain reaction. But the world was at war, and the ultimate objective was an *uncontrolled*

nuclear device—an atomic bomb. Many experimental groups were involved in that effort, including groups at Chicago and Princeton.[4] In February the decision was made to move the Princeton and Columbia groups to the University of Chicago. Harold Agnew and John Marshall, who joined us that month, were sent from the University of Chicago to help us complete our measurements before the move. Note that Szilard is not listed as part of the experimental group. After one try at working with Fermi on an experiment, he hired somebody else to do his share of the physical work.[7] Szilard felt his contribution should be confined to thinking and making arrangements with industry and others. Szilard's efforts at arranging things complemented Fermi's laboratory efforts. They were both essential to our success. In the first years, for example, Szilard convinced Albert Einstein to help us get government financial support.

On to Chicago

In the first week of April 1942 Fermi, Feld and I arrived in Chicago, where we took up residence at International House on the campus. Fermi's family did not come until the end of the school term. Feld became a full-time assistant to Szilard.

At Chicago Fermi's experimental physics division included two large groups, one under Anderson and the other under Zinn. (Figure 1 shows some us gathered for a reunion after the war.) I became a member of Zinn's group, which also included several young people from the university, a wonderful millwright named Gus Knuth and, beginning in September, about 20 "back of the yards" high school dropouts. Knuth set up woodworking machinery for cutting, planing and machining the graphite blocks. Zinn's group was responsible for building and helping to measure exponential piles, machining 200 tons of graphite blocks and pressing about 15 000 pseudospheres of $U0_2$. Walter Zinn's enormous contributions and ingenuity in this project have not always been adequately appreciated and understood.[8] He had a full grasp of the physics involved and of the steps and processes needed to build the piles. He was exceptional at devising efficient solutions to an enormous variety of physics and engineering problems, as well as at arranging for the equipment needed to get the job done. Zinn's group performed a major share of the physics measurements for the exponential-pile program.

The exponential-pile experiments at Chicago continued to show improvement in the purity of the graphite and uranium oxide that we were receiving. We carried out the experiments in a squash court under the grandstand of the football field. The University of Chicago had recently abandoned varsity football. In August the exponential piles with purer graphite and uranium oxide began to give multiplication factors greater than 1, which meant that a large enough pile of natural uranium and graphite could sustain a chain reaction.

At the end of September 1942 we built exponential pile number 18 with even purer graphite, and we found that the improvements in the lattice and the materials were sufficient to give a multiplication factor that meant success was not far off.[8] We knew then that we could build a self-sustaining chain-reacting pile with the uranium oxide and the graphite that we would have on hand by Decem-

ber. Our estimate included the improvement in the multiplication constant we could get by removing atmospheric nitrogen from the porous graphite blocks. To this end the reactor was to be housed inside a balloon that could, if necessary, be filled with CO_2. When Anderson contacted a balloon company to place the order, they couldn't believe that anyone would want a cubical balloon.

For eight weeks in September, October and November, Fermi gave a series of easily understood lectures to those of us who were working on the exponential piles and on the first chain-reacting pile.[5] The latter was designated Chicago Pile 1, or CP-1. From these lectures we understood the implications of what we had been measuring, and we became convinced that CP-1 would be a controllable chain-reacting pile.

Anticipating the limited amount of graphite and uranium oxide that would be available, Fermi decided to build the chain-reacting pile in a spherical shape instead of a cube, because the spherical solution to the second order differential equations minimizes the volume. Construction was begun within a wooden framework of four-by-fours to support the spherical pile. As the pile grew, Knuth gradually added to this scaffold. The first layer of CP-1 was put inside the balloon on 16 November.

Graphite layers containing uranium oxide formed into pseudospheres alternated in the pile with layers of pure graphite. The graphite blocks were 4 l/8 inches high and 4 1/8 inches wide. Each layer sat directly on top of the one below, with no intervening space.[7]

During the autumn of 1942, cast uranium metal also began to arrive. Metallic uranium yields a much larger multiplication factor than does uranium oxide. By including some metal, we were able to make the pile somewhat smaller than we had originally expected.

Every day Fermi prescribed what materials were to be placed in that day's layer of the reactor. The most efficient arrangement was to put the purest material near the center of the reactor, with the earlier, less pure materials near the outside. Fermi gave his instructions to Zinn and to Anderson every morning. Zinn's group had the day shift, and Anderson's had the evening shift. Zinn's group continued to run the factory that machined the graphite and pressed the pseudospheres.

After the first few layers had been put into place, we took precautions to ensure that the pile would not become reactive. Slots were machined in the graphite so that strips of cadmium attached to rectangular wooden rods could be inserted into the pile. Cadmium is an excellent absorber of neutrons; therefore the neutron multiplication was reduced when a cadmium rod was in the pile.

Every evening as the pile progressed, Anderson's group would remove all the cadmium rods and check the neutron intensity. At first a radium-beryllium source was needed to provide the initiating neutrons. But eventually there were enough source neutrons just from spontaneous uranium fission. In addition to the indium foils we also used a boron trifluoride proportional counter to measure the neutron flux directly. Fermi used these neutron measurements to estimate at which layer the pile would go critical—that is to say, the point at which the neutron flux would begin to increase without limit.

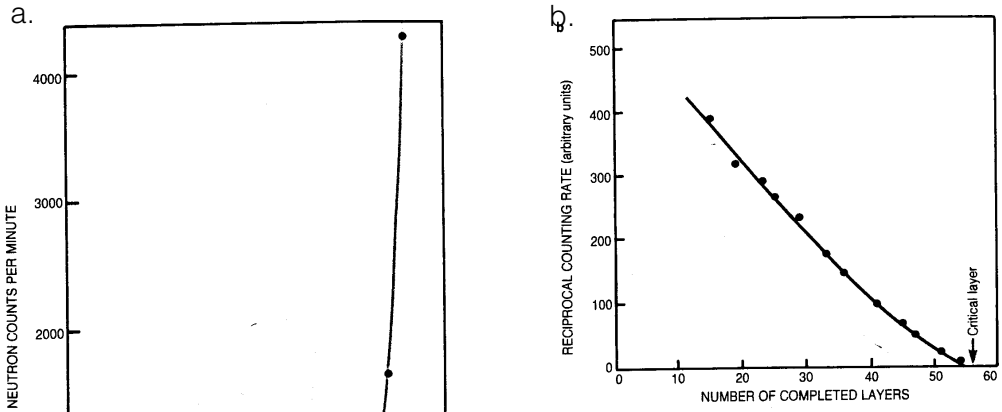


Figure 1. Approach to criticality during the construction of Fermi's CP-1 pile is seen in these plots of neutron intensity against the number of completed layers in the pile. a: The counting rate of the BF_3 neutron counter grew very large as the number of layers approached 60. b: Fermi's graph of the corrected reciprocal counting rate, as measured by the indium foils, plotted against the number of completed layers. This plot of 1 /N gave a more precise extrapolation to criticality. It indicated that the pile would go critical when layer 56 was complete. (Adapted from ref. 8.)

The operative equation reads

$$N = \frac{N_S}{1 - k}$$

where N is the neutron flux measured in the pile, N_S is the neutron flux from a source in the pile, and k is the pile's effective multiplication constant. As the number of layers increases, k also increases. When k reaches unity, the denominator vanishes and the pile goes critical. **Figure 1a** is a plot of the increasing counting rate the group observed as additional layers were added to CP-1. N, as measured by a proportional counter filled with BF_3, is plotted as a function of the number of layers in the pile. To see the approach to criticality more precisely, Fermi, in effect plotted $1/N$, as measured by the indium foils, against the number of completed layers. Fermi's plot of the reciprocal counting rate, shown in **figure 1b**, clearly extrapolated to 0 at layer 56. That meant the pile would reach its critical height during Anderson's shift on the night of 1 December. Fermi told Anderson to add layer 57 for good measure. This little excess of reactivity would ensure that the rate of rise of the critical pile's neutron flux would not be painfully slow. He made Anderson promise not to take the cadmium rods out of the pile. The word was spread to those of us who had been working on CP-1 that the removal of the rods would take place on 2 December. Fermi himself would take the completed CP-1 to the critical condition.

An instrument group under Volney (Bill) Wilson had built a number of different detectors: air-filled ionization chambers to detect gammas, and BF_3 chambers and proportional counters to detect neutrons. The instrument group had also built a number of control rods. Some were, made of boron steel, and they could be driven remotely by motors.[8] But on 2 December, the steel rods were removed from the pile; Fermi planned to use the cadmium rod in layer 21 to control the pile by hand.

Zinn and Wilson had also installed several safety rod in the pile. Each one was attached to a

rope that ran through the pile. The ropes ran over pulleys and were hung with heavy weights. One of these safety rods was held out of the pile by being tied to the railing of the balcony where we had our electronic relay racks. The other safety rod, which we called Zip, was attached to a hook held by a solenoid magnet; if the power failed it would automatically be pulled into the pile. Zip's solenoid was also connected to an ionization chamber through a relay.

If the ionization chamber current exceeded a specified value, the safety rod would automatically be released.

Birthday Morning

The first thing Fermi did when he came in on the morning of 2 December was to have all the detectors checked. There was a great deal of redundancy in the instrumentation. Some of the physicists—including Leona Woods (later Marshall), the one woman who was present—stationed themselves to read the BF_3 counters. Several young staff members read the data from the four ionization chambers, and Dick Watts recorded them. His notebook has recently been found at the National Archives, Great Lakes region, thanks to Shirley Burton.

Wilson attached a neutron ionization chamber to a recording chart for Fermi's use. Whenever Fermi performed an experiment, he always estimated the result in advance, and he had done so in planning to use the cadmium rod in slot 21. Weil was in position to set its location by hand. Fermi had all the other rods taken out of the pile, and he told Weil to set rod 21 to a position (I think it was 13 feet) for which he had already made an estimate. With the rod in that position, Fermi had calculated, the reactor would be subcritical. Now he watched the reading on his ionization chamber rise, and then the neutron intensity leveled off. He had been right.

During the rise and saturation of the neutron flux, Fermi jotted down numbers on the back of his little slide rule. Then he told Weil to take the rod out another 12 inches. Again the intensity increased and then leveled off. Fermi did more calculations and wrote some more on the back of his slide rule. Now he told Weil to move the rod out another 6 inches, and then 6 inches more.

From the first two measurements alone Fermi could estimate the control rod setting at which the pile would go critical. It was simply a matter of applying the same equation he had used to estimate the number of layers needed in the pile. He made the additional measurements just to check that both the calculations and the instrumentation were reliable, and that the effect of the control rod was approximately linear.

Fermi then stopped to check how the various instruments were doing. Several of them were now in a nonlinear range, and adjustments were made, such as changing the resistors in the current-measuring circuits. After these adjustments, Fermi told Weil to pull rod 21 out yet another 6 inches. The intensity began to rise, and suddenly there was a loud *wh-rumpff!* It was the sound of Zip's weights falling and pulling our safety rod into the pile. The ionization chamber had turned off the restraining solenoid because the arbitrary current setting had been exceeded. Zip had acted as a safety rod should! It was now close to lunchtime. "I'm hungry," said Fermi. Let's go to lunch."

Time Dependence

I have not yet discussed the time dependence of a reactor, namely the variation of the neutron intensity with time when the multiplication constant is above or below the critical value. Fermi's lectures to us had included the time-dependent diffusion equation.[5] He showed

that the ability to control the chain reaction depends on the fact that about 1% of the neutrons are not emitted instantaneously. They have delayed emission times of the order of 10 seconds. There were at the time four known delay periods, and 10 seconds is a convenient effective average. If a control rod is pulled out to a position where the pile is still subcritical, the intensity obeys the equation

$$N(t) = (1 - e^{-t/\tau})N_{sat}$$

where N_{sat} is the saturation level at which the rising neutron flux levels off in a subcritical pile, and τ is the pile's characteristic rise time. If, on the other hand, the control rod is pulled out to a position where the pile is above critical, the intensity becomes a continuously rising exponential:

$$N(t) = N(O)e^{t/\tau}$$

If the effective multiplication constant k is very close to unity, one can approximate the rise time by

$$\tau = T_{av} \frac{1 - k(1 - f)}{|k - 1|}$$

where we can take f, the fraction of the neutrons that are delayed, to be about 1%, and T_{av}, the average delay, to be 10 seconds. The effective multiplication constant depends on the position of the control rod. When k is less than—but close to—the critical value 1, the denominator approaches 0, so that τ becomes very large and the pile's intensity changes very slowly. The table below gives a few typical values of k and τ that we confronted on 2 December 1942.

If the pile is just above critical, the rate of rise is very slow. As the pile gets further above the critical condition, the rise rate quickens. On 2 December, with all the rods out all the way, CP-1 would have had an exponential rise time of about 2.6 minutes (**table 1**), which is not very fast. Fermi never did take the last rod out all the way on that first day.

During the morning measurements Fermi had checked that the rate of exponential rise of the neutron flux was what he expected for various positions of control rod 21. He also established that the instrumentation was reliable at the intensities at which he planned to make further measurements.

'We're Cookin!'

After lunch, Fermi had all the control rods removed except for rod 21. He asked Weil to set rod 21 at one of its early morning positions. After checking that the instruments reproduced the early

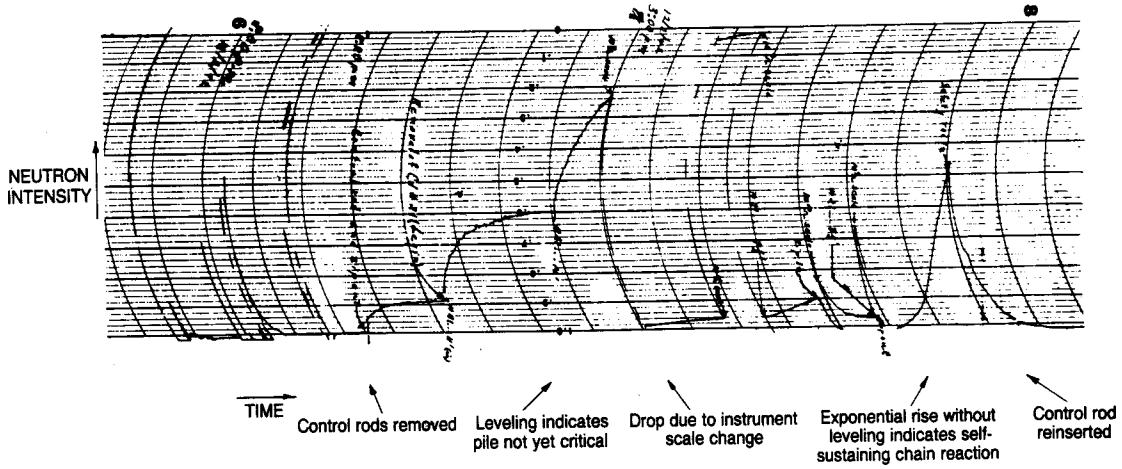
Table 1.

Rise time vs effective multiplication constant of the CP-1 pile on 2 December 1942

Below critical		Critical	
$1 - k$	τ (minutes)	$k - 1$	τ (minutes)
6×10^{-4}	2.9*	1×10^{-4}	17
3×10^{-4}	5.4	3×10^{-4}	5.4
1×10^{-4}	17	6×10^{-4}	2.6**

*Control rod 21 all the way in; all others out.
**All control rods out.

Figure 2. 'Birth certificate of the nuclear age.' This galvanometer strip-chart recording of the neutron flux in Fermi's CP-1 pile on the afternoon of 2 December 1942 records the first self-sustaining man-made nuclear chain reaction.



morning result, Fermi had the rod set to 11 feet, where it had been just before lunch. The intensity rose and leveled off. He then had Weil pull the rod out 1 more foot. Fermi measured the rate of rise and the saturation level. Then he did his little calculations and told Weil to pull the rod out another 6 inches. The neutron intensity rose linearly and very slowly, in fact painfully slowly. After a while Fermi announced that the pile was still subcritical.

He then had the Zip safety rod put into the pile to bring the intensity back down to a low level, so that his next measurements would be at a flux level where he knew that the detectors would be reliable. While the Zip rod was in, Fermi asked Weil to take control rod 21 out another 12 inches. After the control rod was set, the Zip rod was removed from the pile. Fermi then said to Arthur Compton, who was standing at his side: "This is going to do it. Now it will become self-sustaining. The trace will continue to climb; it will not level off."[9]

After a minute, Fermi computed the rate of rise; after another minute, he computed it again; after three minutes he calculated the rate of rise once more. The neutron intensity was growing at exactly the exponential rate he had expected. From those who were near him, I have heard that at this point he broke into a big, cheerful smile. He put away his slide rule and announced, "The reaction is self-sustaining."

Fermi let the activity of the pile increase and watched the pen on the recorder. The intensity continued to rise with no sign of leveling off. Watts was recording data from the ionization chambers during the afternoon in a notebook. At 3:42 pm he wrote, "We're cookin!"

At 3:53 pm Fermi told Zinn to put the Zip rod in. With that, the neutron intensity, all the radiation and the counting rates all dropped almost instantaneously, as one can see in **figure 2**, which shows the ionization chamber recording chart Fermi was watching. Some people have called this chart "the birth certificate of the nuclear age."

We had successfully built CP-1. In a thoroughly quantitative experiment, Fermi had

established that one could get a self-sustaining nuclear chain reaction and that it could be controlled in a very predictable manner. There were no fireworks, no flashing lights, no yelling or jumping up and down. We had carried out a set of successful quantitative physics measurements, which is always a great source of satisfaction to a group of physicists.

Chianti

After the neutron intensity had subsided, Eugene Wigner produced a bottle of Chianti from an unobtrusive paper bag he had brought with him and presented it to Fermi. Paper cups were liberated from the water cooler and we all drank silently, looking at Fermi. Someone asked Fermi to sign the wrapping on the Chianti flask. After he did so the bottle was passed around, and we all signed it, except for Wigner.

All the rods were put back in and padlocked in place. The power to the chambers and circuits was shut off. Some of us had been working at the machines, the presses or the pile on schedules of over a hundred hours a week. So we went home to get some sleep.[10]

Fermi's monthly report, dated 15 December 1942, is a lovely understatement of a major event of this century:[11]

The activity of the Physics Division in the past month has been devoted primarily to the experimental production of a divergent chain reaction. The chain-reacting structure has been completed on December 2 and has been in operation since then in a satisfactory way. A program of tests on the operating conditions of the chain-reacting unit and of experiments for the investigation of some of the various radiations inside and outside of the pile is in progress. The results will be reported as soon as possible.

In February 1943, I was put in charge of taking down CP-1. Four young men and I loaded the graphite blocks and uranium onto skids for shipment by truck to a new laboratory at Argone, outside Chicago. There the pile was rebuilt with many improvements and redesignated as CP-2. In the 1950s, CP-2 was uncer-emoniously buried by the Cook County Forest Preserve District.

The author is indebted to Bertram Coren for very helpful suggestions in the writing of this article.

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History and Nature of Science

Marie Curie: A Pioneer in the Study of Radioactivity

The abandoned shack did not look like a research laboratory. Tucked behind the School of Physics in Paris, the decaying wooden shed had no floor. The roof leaked, and a few discarded kitchen tables were the only furniture. Yet in this unlikely place, Marie Curie and her husband, Pierre, began their pioneering work in radioactivity.

Marie Sklodowska had left her native Poland in 1891 to study at the University of Paris. There she led the life of a poor student, skimping on coal for her stove and often having nothing to eat but bread and tea. Totally devoted to science, Marie had no time to take part in the social life of Paris. It was not surprising, then, that she met and married another scientist, Pierre Curie. They settled into a lifestyle of rigorous work. "Our life is always the same," wrote Marie. "We see nobody but my husband's parents. We hardly ever go to the theater and we give ourselves no diversions."

The Curies were inspired by the work of another Parisian, Henri Becquerel. In 1896, Becquerel found that uranium could darken a photographic plate from across a room. Fascinated by this discovery, Marie and Pierre Curie began to work with pitchblende, the rock in which uranium is found. Marie discovered that pitchblende was more radioactive than uranium alone. She concluded that there were other radioactive substances, as yet unknown, in the pitchblende.

The Curies had tons of pitchblende carted to their laboratory. During the four years of their research, they boiled over eight tons of pitchblende on their cast-iron stove.

The work was heavy and difficult. Marie wrote, "I came to treat as many as 20 kilograms (44 pounds) of matter at a time, which had the effect of filling the shed with great jars. It was killing work to carry the receivers, to pour off the liquids, and to stir, for hours at a stretch, the boiling matter in a smelting basin."

The breakthrough came in 1898. The Curies identified two new elements in the pitchblende. They named one polonium, for Marie's native Poland. The other, called radium, was a hundred times more radioactive than uranium. In 1903, the Curies and Henri Becquerel received the Nobel Prize in physics for their work on radioactivity. In 1911, Marie Curie won a second Nobel prize, this time in chemistry, for her study of the chemical properties of radium.

Science as Inquiry

The Dating Game

Four years ago archeologists Alison Brooks and John Yellen discovered what might be the earliest traces of modern human culture in the world. The only trouble is, nobody believes them. Sometimes they can't quite believe it themselves.

Their discovery came on a sun-soaked hillside called Katanda, in a remote corner of Zaire near the Ugandan border. Thirty yards below, the Semliki River runs so clear and cool the submerged hippos look like giant lumps of jade. But in the excavation itself, the heat is enough to make anyone doubt his eyes.

Katanda is a long way from the plains of Ice Age Europe, which archeologists have long believed to be the setting for the first appearance of truly modern culture: the flourish of new tool technologies, art, and body ornamentation known as the Upper Paleolithic, which began bout 40,000 years ago. For several years Brooks, an archeologist at George Washington University, had been pursuing the heretical hypothesis that humans in Africa had invented sophisticated technologies even earlier, while their European counterparts were still getting by with the same sorts of tools they'd been using for hundreds of thousands of years. If conclusive evidence hadn't turned up, it was only because nobody had really bothered to look for it.

"In France alone there must be three hundred well-excavated sites dating from the period we call the Middle Paleolithic," Brooks says. "In Africa there are barely two dozen on the whole continent."

One of those two dozen is Katanda. On an afternoon in 1988 John Yellen—archeology program director at the national Science Foundation and Brook's husband—was digging in a densely packed litter of giant catfish bones, river stones, and Middle Paleolithic stone tools. From the rubble he extricated a beautifully crafted, fossilized bone harpoon point. Eventually two more whole points and fragments of five others turned up, all of them elaborately barbed and polished. A few feet away, the scientists uncovered pieces of an equally well crafted daggerlike tool. In design and workmanship the harpoons were not unlike those at the very end of the Upper Paleolithic, some 14,000 years ago. But there was one important difference. Brooks and Yellen believe the deposits John was standing in were at least five times that old. To put this in perspective, imagine discovering a prototypical Pontiac in Leonardo da Vinci's attic.

"If the site is as old as we think it is," says Brooks, "it could clinch the argument that modern humans evolved in Africa."

Ever since the discovery the couple have devoted themselves to chopping away at that stubborn little word if. In the face of the entrenched skepticism of their colleagues, it is an uphill task. But they do have some leverage. In those same four years since the first harpoon found at Katanda, a breakthrough has revived the question of modern human origins. The breakthrough is not some new skeleton pulled out of the ground. Nor is it the highly publicized Eve hypothesis, put

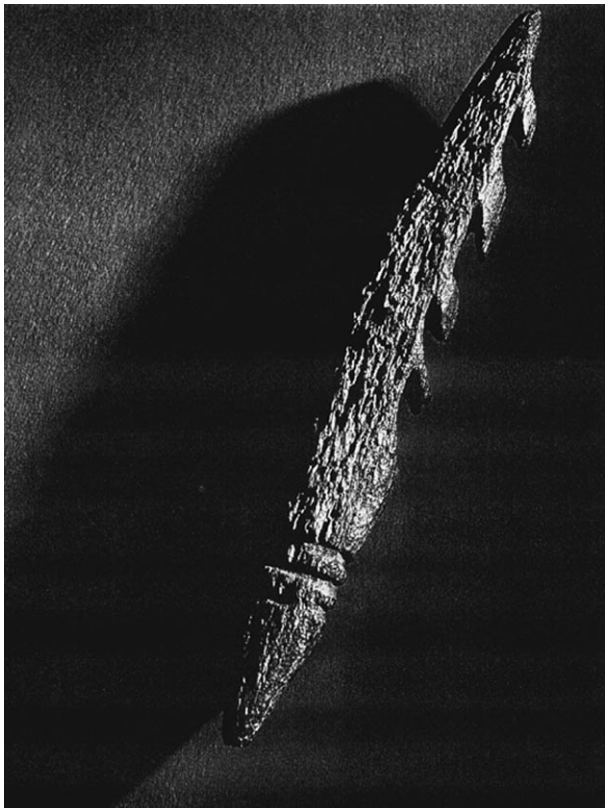
By James Shreeve. *Discover,* magazine (September 1992), pp. 76–83/" 1992, The Walt Disney Co. Reprinted with permission of Discover, magazine.

forth by geneticists, suggesting that all humans on Earth today share a common female ancestor who lived in Africa 200,000 years ago. The real advance, abiding quietly in the shadows while Eve draws the limelight, is simply a new way of telling time.

To be precise, it is a whole smorgasbord of new ways of telling time. Lately they have all converged on the same exhilarating, mortifying revelation: what little we thought we knew about he origins of our own species was hopelessly wrong. From Africa to Middle East to Australia, the new dating methods are overturning conventional wisdom with insolent abandon, leaving the anthropological community dazed amid a rubble of collapsed certitudes. It is in this shell-shocked climate that Alison Brooks's Pontiac in Leonardo's attic might actually find a hearing.

"Ten years ago I would have said it was impossible for harpoons like these to be so old," says archeologist Michael Mehlman of the Smithsonian's National Museum of Natural History. "Now I'm reserving judgment. Anything can happen."

An archeologist with a freshly uncovered skull, stone tool, or bone Pontiac in hand can take two general approaches to determine its age. The first is called relative dating. Essentially the archeologist places the find in the context of the surrounding geological deposits. If the new discovery is found in a brown sediment lying beneath a yellowish layer of sand, then, all things being equal, it is older than the yellow sand layer or any other deposit higher up. The fossilized remains of extinct animals found near the object also provide a "biostratigraphic" record that can offer clues to a new find's relative age. (If a stone tool is found alongside an extinct species of horse, then it's a fair bet the tool was made while that kind of horse was still running around.) Sometimes the tools themselves can be used as a guide, if they match up in character and style with tools from other, better-known sites. Relative dating methods like these can tell you whether a find is older or younger than something else, but they cannot pin an age on the object in calendar years.



Africans may have crafted this exquisite bone harpoon tip 40,000 years before people in Europe made anything like it.

The most celebrated absolute method of telling archeological time, radiocarbon dating, came along in the 1940s. Plants take in carbon from the atmosphere to build tissues, and other organisms take in plants, so carbon ends up in everything from wood to woodchucks. Most carbon exists in the stable form of carbon 12. But some is made up of the unstable, radioactive form carbon 14. When an organism dies, it contains about the same ratio of carbon 12 to carbon 14 that exists in the atmosphere. After death the radioactive carbon 14 atoms begin to decay, changing into stable atoms of nitrogen. The amount of carbon 12, however, stays the same. Scientists can look at the amount of carbon 12 and—based on the ratio—deduce how much carbon 14 was originally present. Since the

decay rate of carbon 14 is constant and steady (half of it disappears every 5,730 years), the difference between the amount of carbon 14 originally in a charred bit of wood or bone and the amount present now can be used as a clock to determine the age of the object.

Conventional radiocarbon dates are extremely accurate up to about 40,000 years. This is far and away the best method to date a find—as long as it is younger than this cutoff point. (In older materials, the amount of carbon 14 still left undecayed is so small that even the slightest amount of contamination in the experimental process leads to highly inaccurate results.) Another dating technique, relying on the decay of radioactive potassium rather than carbon, is available to date volcanic deposits older than half a million years. When it was discovered in the late 1950s, radiopotassium dating threw open a window on the emergence of the first members of the human family—the australopithecines, the famous Lucy, and her more advanced descendants, Homo habilis and Homo erectus. Until now, however, the period between half a million and 40,000 years—a stretch of time that just happens to embrace the origin of Homo Sapiens—was practically unknowable by absolute dating techniques. It was as if a geochronological curtain were drawn across the mystery of our species' birth. Behind that curtain the hominid lineage underwent an astonishing metamorphosis, entering the dateless, dark centuries a somewhat precocious bipedal ape and emerging into the range of radiocarbon dating as the culturally resplendent, silver-tongued piece of work we call a modern human being.

Fifteen years ago there was some general agreement about how this change took place. first, what is thought of as an anatomically modern human being—with the rounded cranium, vertical forehead, and lightly built skeleton of people today—made its presence known in Europe about 35,000 years ago. Second, along with those first modern-looking people, popularly known as the Cro-Magnons, came the first signs of complex human behavior, including tools made of bone and antler as well as of stone, and art, symbolism, social status, ethnic identity, and probably true human language too. Finally, in any one region there was no overlap in time between the appearance of modern humans and the disappearance of "archaic" humans such as the classic Neanderthals, supporting the idea that one group had evolved from the other.

"Thanks to the efforts of the new dating methods," says Fred Smith, an anthropologist at Northern Illinois University, "we now know that each of these ideas was wrong."

The technique doing the most damage to conventional wisdom is called thermoluminescence, TL for short. (Reader take heed: the terrain of geochronology is full of terms long enough to tie between two trees and trip over, so acronyms are a must.) Unlike radiocarbon dating, which works on organic matter, TL pulls time out of stone.

If you were to pick an ordinary rock up off the ground and try to describe its essential rockness, phrases like "frenetically animated" would probably not leap to mind. But in fact minerals are in a state of constant inner turmoil. Minute amounts of radioactive elements, both within the rock itself and in the surrounding soil and atmosphere, are constantly bombarding its atoms, knocking electrons out of their normal orbits. All this is perfectly normal rock behavior, and after gallivanting around for a hundredth of a second or two, most electrons dutifully return to their normal positions. A few, however, become trapped en route—physically captured within crystal impurities or electronic aberrations in the mineral structure itself. These tiny prisons hold on to their electrons until the mineral is heated, whereupon the traps spring open and the electrons return to their more stable position. As they escape, they release energy in the form of light—a photon for every homeward-bound electron.

Thermoluminescence was observed way back in 1663 by the great English physicist Robert

Boyle. One night Boyle took a borrowed diamond to bed with him, for reasons that remain obscure. Resting the diamond "upon a warm part of my naked body," Boyle noticed that it soon emitted a warm glow. So taken was he with the responsive gem that the next day he delivered a paper on the subject at the Royal Society, noting his surprise at the glow since his "constitution," he felt, was "not of the hottest."

Three hundred years later another Englishman, Martin Aitken of Oxford University, developed the methods to turn thermoluminescence into a geophysical timepiece. The clock works because the radioactivity bombarding a mineral is fairly constant, so electrons become trapped in those crystalline prisons at a steady rate through time. If you crush the mineral you want to date and heat a few grains to a high enough temperature—about 900 degrees, which is more body heat than Robert Boyle's constitution could every had produced—all the electron traps will release their captive electrons at once, creating a brilliant puff of light. In a laboratory the intensity of that burst of luminescence can easily be measured with a device called a photomultiplier. The higher the spike of light, the more trapped electrons have accumulated in the sample, and thus the more time has elapsed since it was last exposed to heat. Once a mineral is heated and all the electrons have returned "home," the clock is set back to zero.

Now, our lineage has been making flint tools for hundreds of thousands of years, and somewhere in that long stretch of prehistory we began to use fire as well. Inevitably, some of our less careful ancestors kicked discarded tools into burning hearths, setting their electron clocks back to zero and opening up a ripe opportunity to TL timekeepers in the present. After the fire went out, those flints lay in the ground, pummeled by radioactivity, and each trapped electron was another tick of the clock. Released by laboratory heat, the electrons flash out photons that reveal time gone by.

In the late 1980s Hélène Valladas, an archeologist at he Center for Low-Level Radioactivity of the French Atomic Energy Commission near Paris, along with her father, physicist Georges Valladas, stunned the anthropological community with some TL dates on burned flints taken from the two archeological sites in Israel. The first was a cave called Kebara, which had already yielded an astonishingly complete Neanderthal skeleton. Valladas dated flints from the Neanderthal's level at 60,000 years before the present.

In itself this was no surprise, since the date falls well within the known range of the Neanderthals' time on Earth. The shock came a year later, when she used the same technique to pin a date on flints from a nearby cave called Qafzeh, which contained the buried remains of early modern human beings. This time, the spikes of luminescence translated into an age of around 92,000 years. In other words, the more "advanced" human types were a full 30,000 years older than the Neanderthals they were supposed to have descended from.

If Valladas's TL dates are accurate, they completely confound the notion that modern humans evolved from Neanderthals in any neat and tidy way. Instead, these two kinds of human, equally endowed culturally but distinctly different in appearance, might have shared the same little nook of the Middle East for tens of thousands of years. To some, this simply does not make sense.

"If these dates are correct, what does this do to what else we know, to the stratigraphy, to fossil man, to the archeology?" worries Anthony Marks, an archeologist at Southern Methodist University. "It's all a mess. Not hat the dates are necessarily wrong. But you want to know more about them."

Marks's skepticism is not entirely unfounded. While simple in theory, in practice TL has to overcome some devilish complications. ("If these new techniques were easy, we would have thought of them a long time ago," says geochronologist Gifford Miller of the University of Colorado.) To convert into calendar years the burst of luminescence when a flint is heated, one has to know both the sensitivity of that particular flint to radiation

and the dose of radioactive rays it has received each year since it was "zeroed" by fire. The sensitivity of the sample can be determined by assaulting it with artificial radiation in the lab. And the annual dose of radiation received from within the sample itself can be calculated fairly easily by measuring how much uranium or other radioactive elements the sample contains. But determining the annual dose from the environment around the sample—the radioactivity in the surrounding soil, and cosmic rays form the atmosphere itself—is an iffier proposition. At some sites fluctuations in this environmental dose through the millennia can turn the "absolute" date derived from TL into an absolute nightmare.

Fortunately for Valladas and her colleagues, most of the radiation dose for the Qafzeh flints came from within the flints themselves. The date then of 92,000 years for the modern human skeletons is thus not only the most sensational number so far produced by TL, it is also one of the surest.

"The strong date at Qafzeh was just good luck," says Valladas. "It was just by chance that the internal dose was high and the environmental dose was low."

More recently Valladas and her colleague Norbert Mercier turned their TL techniques to the French site of Saint-Césaire. Last summer they confirmed that a Neanderthal found at Saint-Césaire was only 36,000 years old. This new date, combined with a fresh radiocarbon date of about 40,000 years tagged on some Cro-Magnon sites in northern Spain, strongly suggests that the two types of humans shared the same corner of Europe for several thousand years as the glaciers advanced from the north.

While Valladas has been busy in Europe and the Middle east, other TL timekeepers have produced some astonishing new dates for the first human occupation of Australia. As recently as the 1950s, it was widely believed that Australia had been colonized only some five thousand years ago. The reasoning was typically Eurocentric: since the Australian aborigines were still using stone tools when the first white settlers arrived, they must have just recently developed the capacity to make the difficult sea crossing from Indonesia in the first place. A decade later archeologists grudgingly conceded that the date of first entry might have been closer to the beginning of the Holocene period, 10,000 years ago. In the 1970s radiocarbon dates on human occupation sites pushed the date back again, as far as 32,000 years ago. And now TL studies at two sites in northern Australia drop that first human footstep on the continent—and the sea voyage that preceded it—all the way back to 60,000 years before the present. If these dates stand up, then the once-maligned ancestors of modern aborigines were building ocean-worthy craft some 20,000 years before the first signs of sophisticated culture appeared in Europe.

"Luminescence has revolutionized the whole period I work in," says Australian National University archeologist Rhys Jones, a member of the team responsible for the new TL dates. "In effect, we have at our disposal a new machine—a new time machine."

With so much at stake, however, nobody looks to TL—or to any of the other new "time machines"—as a geochronological panacea. Reputations have been too badly singed in the past by dating methods that claimed more than they could deliver. In the 1970s a flush of excitement over a technique called amino acid racemization led many workers to believe that another continent—North America—had been occupied by humans fully 70,000 years ago. Further testing at the same American sites proved that the magical new method was off my one complete goose egg. The real age of the sites was closer to 7,000 years.

"To work with wrong dates is a luxury we cannot afford," British archeologist Paul Mellars intoned ominously earlier this year, at the beginning of a London meeting of the Royal Society to showcase the new dating technologies. "A wrong date does not simply inhibit research. It could conceivably throw it into reverse."

Fear of just such a catastrophe—not to mention the risk that her own reputation could go up in a puff of light—is what keeps Alison Brooks from

declaring outright that she has found exquisitely crafted bone harpoons in Zaire that are more than 40,000 years older than such creations are supposed to be. So far the main support for her argument has been her redating of another site, called Ishango, four miles down the Semliki River from the Katanda site. In the 1950s the Belgian geologist Jean de Heinzelin excavated a harpoon-rich "aquatic civilization" at Ishango that he thought was 8,000 years old. Brooks's radiocarbon dating of the site in the mid-1980s pushed the age back to 25,000. By tracing the layers of sediment shared between Ishango and Katanda, Brooks and her colleagues are convinced that Katanda is much farther down in the stratigraphy—twice as old as Ishango, or perhaps even more. But even though Brooks and Yellen talk freely about their harpoons at meetings, they have yet to utter such unbelievable numbers in the unforgiving forum of an academic journal.

"It is precisely because no one believes us that we want to make our case airtight before we publish," says Brooks. "We want dates confirming dates confirming dates."

Soon after the harpoons were discovered, the team went to work with thermoluminescence. Unfortunately, no burned flints have been found at the site. Nevertheless, while TL works best on materials that have been completely zeroed by such extreme heat as a campfire, even a strong dose of sunlight can spring some of the electron traps. Thus even ordinary sediments surrounding an archeological find might harbor a readable clock: bleached out by sunlight when they were on the surface, their TL timers started ticking as soon as they were buried by natural processes. Brooks and Yellen have taken soil samples form Katanda for TL, and so far the results are tantalizing—but that's all.

"At this point we think the site is quite old," says geophysicist Allen Franklin of the University of Maryland, who with his Maryland colleague Bill Hornyak is conducting the work. "But we don't want to put a number on it."

As Franklin explains, the problem with dating sediments with TL is that while some of the electron traps might be quickly bleached out by sunlight, others hold on to their electrons more stubbornly. When the sample is then heated in a conventional TL apparatus, these stubborn traps release electrons that were captured perhaps millions of years before the sediments were last exposed to sunlight—teasing the date-hungry archeologists with a deceptively old age for the sample.

Brooks does have other irons in the dating fire. The most promising is called electron spin resonance—or ESR, among friends. Like TL, electron spin resonance fashions a clock out of the steadily accumulating electrons caught in traps. But whereas TL measures that accumulation by the strength of the light given off when the traps open, ESR literally counts the captive electrons themselves while they still rest undisturbed in their prisons.

All electrons "spin" in one of two opposite directions—physicists call them up and down. (Metaphors are a must here because the nature of this "spinning" is quantum mechanical and can be accurately described only in huge mathematical equations.) The spin of each electron creates a tiny magnetic force pointing one direction, something like a compass needle. Under normal circumstances, the electrons are paired so that their opposing spins and magnetic forces cancel each other out. But trapped electrons are unpaired. By manipulating an external magnetic field placed around the sample to be dated, the captive electrons can be induced to "resonate"—that is, to flip around and spin the other way. When they flip, each electron absorbs a finite amount of energy from a microwave field that is also applied to the sample. This loss of microwave energy can be measured with a detector, and it is a direct count of the number of electrons caught in the traps.

ESR work particularly well on tooth enamel, with an effective range from a thousand to 2 million years. Luckily for Brooks and Yellen, some nice fat hippo teeth have been recovered form Katanda in the layer that also held the harpoons. To

date the teeth, they have called Henry Schwarcz of McMaster University in Ontario, a ubiquitous, veteran geochronologist. In the last ten years Schwarcz has journeyed to some 50 sites throughout Europe, Africa, and western Asia, wherever his precious and arcane services are demanded.

Schwarcz also turned up at the Royal Society meeting, where he explained both the power and the problems of that ESR method. On the plus side is that teeth are hardy remains, found at nearly every archeological site in the world, and that ESR can test a tiny sample again and again—with the luminescence techniques, it's a one-shot deal. ESR can also home in on certain kinds of electron traps, offering some refinement over TL, which lumps them all together.

On the minus side, ESR is subject to the same uncertainties as TL concerning the annual soaking of radiation a sample has received from the environment. What's more, even the radiation form within a tooth cannot be relied on to be constant through time. Tooth enamel has the annoying habit of sucking up uranium from its surroundings while it sits in the ground. The more uranium the tooth contains, the more electrons are being bombarded out of their normal positions, and the faster the electron traps will fill up. Remember: you cannot know how old something is by counting filled traps unless you know the rate at which the traps were filled, year by year. If the tooth had a small amount of internal uranium for 50,000 years but took in a big gulp of the hot stuff 10,000 years ago, calculations based on the tooth's current high uranium level would indicate the electron traps were filled at a much faster rate than they really were. "The big question is, When did the uranium get there?" Schwarcz says. "Did the tooth slurp it all up in three days, or did the uranium accumulate gradually through time?"

One factor muddying the "big question" is the amount of moisture present around the sample during its centuries of burial: a wetter tooth will absorb uranium faster. For this reason, the best ESR sites are those where conditions are driest. Middle Eastern and African deserts are good bets. As far as modern human origins go, the technique has already tagged a date of about 100,000 years on some human fossils from an Israeli cave called Skhul, neatly supporting the TL date of 92,000 from Qafzeh, a few miles away. If a new ESR date from a Neanderthal cave just around the corner from Skhul is right, then Neanderthals were also in the Middle East at about the same time. Meanwhile, in South Africa, a human jawbone from the site of Border Cave—"so modern it boggles the mind," as one researcher puts it—has now been dated with ESR at 60,000 years, nearly twice as old as any fossil like it in Europe.

But what of the cultural change to modern human behavior—such as the sophisticated technological development expressed by the Katanda harpoons? Schwarcz's dating job at Katanda is not yet finished, and given how much is at stake, he too is understandably reluctant to discuss it. "The site has good potential for ESR," he says guardedly. "Let's put it this way: if the initial results had indicated that the harpoons were not very old after all, we would have said 'So what?' to them and backed off. Well, we haven't backed off."

There are other dating techniques being developed that may, in the future, add more certainty to claims of African modernity. One of them, called uranium-series dating, measures the steady decay of uranium into various daughter elements inside anything formed from carbonates (limestone and cave stalactites, for instance). The principle is very similar to radiocarbon dating—the amount of daughter elements in a stalactite, for example, indicates how long that stalactite has been around—with the advantage that uranium-series dates can stretch back half a million years. Even amino acid racemization, scorned for the last 15 years, is making a comeback, thanks to the discovery that the technique, unreliable when applied to porous bone, is quite accurate when used on hard ostrich eggshells.

In the best of all possible worlds, an archeological site will offer an opportunity for two or more of these dating techniques to be called in so they can be tested against each other. When asked

to describe the ideal site, Schwarcz gets a dreamy look on his face. “I see a beautiful human skull sandwiched between two layers of very pure flowstone,” he says, imagining uranium-series dating turning those cave limestones into time brackets. “A couple of big, chunky hippo teeth are lying next to it, and a little ways off, a bunch of burned flints.”

Even without Schwarcz’s dream site, the dating methods used separately are pointing to a common theme: the alarming antiquity of modern human events where they are not supposed to be happening in the first place. Brooks sees suggestive traces of complexity not just at Katanda but scattered all over the African continent, as early as 100,000 years before the present. A classic stone tool type called the blade, long considered a trademark of the European Upper Paleolithic, appears in abundance in some South African sites 40,000 to 50,000 years before the Upper Paleolithic begins. The continent may even harbor the earliest hints of art and a symbolic side to human society: tools designed with stylistic meaning; colorful, incandescent minerals, valueless but for their beauty, found hundreds of miles away from their source. More and more, the Cro-Magnons of Europe are beginning to look like the last modern humans to show themselves and start acting “human” rather than the first.

That’s not an easy notion for anthropologists and archeologists to swallow. “It just doesn’t fit the pattern that those harpoons of Alison’s should be so old,” says Richard Klein, a paleoanthropologist at the University of Chicago. then he shrugs. “Of course, if she’s right, she has made a remarkable discover indeed.” Only time will tell.

History and Nature of Science

Madame Curie and Radioactivity

To obtain the gram of radium—a small thimbleful—given by the women of America to Madame Curie in the spring of 1921 required six hundred tons of ore and the labor of five hundred men for six months. The process of extraction consumed ten thousand tons of distilled water, one thousand tons of coal, and five hundred tons of chemicals. The distilled water would fill a cylindrical tank twenty feet in diameter and one thousand eighteen feet tall-taller than the Eiffel Tower in Paris, and nearly twice as tall as the Washington Monument. The ore and coal would make a train of forty cars and the chemicals would require for their storage a warehouse thirty feet long, twenty-five feet wide, and twenty feet high. If these figures seem large, consider that to obtain the scant five ounces, which represent the world's total supply of this precious substance, they must be multiplied one hundred and forty times. This would mean the labor of thirty-five thousand men for a year, and a trainload of raw materials four hundred and twenty-seven miles long, and all for a product so small that it could be carried by a toddling infant.

In the early nineties of the last century there came to Paris a poor, untutored Polish girl named Marie Sklodowska. She had come to the French capital friendless and without funds, to obtain an education and in particular to devote herself to the study of science. As a little girl, she had grown up in the laboratory of her father, Dr. Sklodowski, who was a professor in the gymnasium at Warsaw. There she acquired the interest in scientific investigations which was to shape her whole life. When her association with the leaders of the revolutionary party in her native land made her stay in Warsaw unsafe, she fled to Paris, where she has since lived and worked. For many months her diet consisted of bread and milk, and she supported herself by private tutoring, and washing bottles at the Sorbonne. Her main efforts were directed toward securing a degree in Mathematics and the physical sciences from the University of Paris. The superior knowledge of this Polish girl, so eager to learn, soon attracted the notice of Dr. Lippmann, the head of the department in which she worked. Through him Miss Sklodowska formed an acquaintance with Pierre Curie, also a student of science at the Sorbonne. Stimulated by a common interest in the same field of work, this friendship deepened with the months, and in 1895 they were married. Madame Curie assisted her husband in his work and at the same time carried on her own studies. Three years later she received her degree and turned her attention to original research. She had completed her preparation at one of the most tremendous moments in the history of scientific investigation, and fate had placed her in the most auspicious spot for the róle which she was to assume.

Of course all the world knows that Madame Curie discovered radium, but, before she asked and received permission to make her systematic search for radioactive substances, three notable events had occurred. In 1879 Sir William Crookes discovered that the negative pole of a vacuum tube, when excited by a high-tension source of electricity,

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gives off a peculiar set of rays, which he named " cathode rays." Later it was shown by Sir J. J. Thomson and others that these rays consist of particles of negative electricity, to which has been given the name of electrons. Thomson also showed that these electrons, now so familiar to the general public and in particular to radio enthusiasts, weigh about two-thousandths as much each as the atom of hydrogen, the lightest of the elements.

Many workers felt that they were upon the verge of important discoveries. Still, years passed and the cathode rays promised to be little more than a scientific curiosity. Then in December, 1895, the world was startled by news from Germany that Professor William Conrad Röntgen had obtained from a vacuum tube a wonderful new light, which made visible to human eyes the interior of an opaque object. Coins in a purse, nails in a shoe, the bones of the hand stood revealed as shadowy, ghost-like silhouettes. Certain minerals such as zinc blende and willemite were caused to fluoresce brilliantly when placed in the path of these rays. Röntgen showed that heavy, black, light-proof paper was no barrier to their penetrating power, and more important still, that they would affect a photographic plate. The amusement and incredulity with which these reports were at first received quickly turned to astonishment and admiration when the abundant proof of the discovery became known. Within a month the X-Rays, as this new radiation had been named by Röntgen, became the talk of all Christendom, and radiophotography was the chief object of interest in every capital of the world. This and other discoveries soon to follow caused the last century to pass out in a blaze of scientific excitement unequaled since the time of Davy.

But what are these X-Rays, discovered, as they were, by mere chance? How do they arise and what is their nature? Röntgen learned that wherever the cathode rays strike upon an object, as the opposite walls of the tube or a screen placed in their path, an invisible radiation is produced, which has the power to penetrate opaque paper, affect a photographic plate, render a gas a conductor of electricity, and cause fluorescence in certain minerals. It is now known that these rays are short

waves in the ether, waves so short that it would take two hundred and fifty million of them to make an inch. The rate of vibration necessary to produce them is three quintillion per second.

The third discovery preliminary to the work of Madame Curie centers about Henri Becquerel, an associate of hers at the University of Paris. The discovery of X-Rays stimulated Becquerel to investigate the light-giving properties of phosphorescent substances. Is it not possible, he asked, that the radiations of these substances may also penetrate opaque matter? Becquerel selected for his experiment the metal, uranium. He exposed it to the sunlight and then placed it upon a photographic plate wrapped in black paper. Upon developing the plate, he found that it had darkened. He repeated the experiment using thin metal plates instead of black paper and obtained a like result. Here was, indeed, a radiation similar to X-Rays. But one day the sun did not shine, and Becquerel, wrapping the plate in black paper, placed the uranium upon it and thrust them into a drawer, where they remained for several weeks. Then out of curiosity he developed the plate to discover whether there had been action when the metal had not first been exposed to

sunlight. There had. The answer was clear. Uranium of itself did give off rays capable of penetrating opaque matter. Without then knowing it, Bacquerel had found the key to the anteroom of subatomic mysteries.

At this point Madame Curie, whose interest had been fired by the new discoveries, began a systematic search to discover whether any of the other elements might also possess radioactive powers. Aside from uranium, she found only one, thorium, which did. In making this search she availed herself of Becquerel's discovery that these rays are able to ionize a gas and render it a conductor, thus discharging a gold-leaf electroscope whenever a radioactive substance is brought near it. But her next step marked a turning-point in this fascinating field of study. When she examined pitchblende, the parent mineral from which uranium is obtained, she discovered a degree of activity four times as great as that produced by all of the pure uranium that could be extracted from this sample. This could have but one meaning. There must be in pitchblende some other substance more radioactive than uranium itself.

Assisted by her husband, Madame Curie began the search for this new element. The Austrian Government presented them with one ton of pitchblende from its rich mines of uranium at Joachimsthal, Bohemia. The undertaking was a prodigious one. Many of the elements, both common and rare, are found in pitchblende. To separate them and examine each part for radioactive material was a Herculean task. There was always the possibility, too, that some of the precious stuff might escape. Yet with the electroscope it is possible to trace this material wherever it may go. So delicate is this test that so minute a quantity as one fifty-billionth of a gram may be detected with ease, and Professor Soddy states that probably one-tenth of that amount would not escape discovery. This British investigator also states that were one-half of a grain of radium salt to be distributed " equally among every human being at present alive in the world, and one such portion were returned to us, it would prove sufficient for detection and identification by means of a gold-leaf electroscope with the greatest ease."

Beginning their investigations in a large building, the quantities containing radioactive material gradually became smaller and smaller until the test tubes of their laboratory were able to hold them. Their first discovery was that of a powerful radioactive substance, which proved to be a new element and was named by Madame Curie polonium in honor of her native country. But further investigation showed that, associated with the barium fraction of the separation, was a still more active element. Patiently they pushed forward their search. Gradually, by numerous processes of solution, crystallization and recrystallization they brought this element into constantly closer quarters. Finally in 1898 they separated it and named it radium. It proved to be two and a half million times as active as uranium. It would affect photographic plates, ionize the air, excite phosphorescence, liberate heat, effect chemical changes, and destroy minute organisms. That it was a new element Madame Curie proved by the distinctiveness of its bright-line spectrum from that of any other element.

In a short time she had determined its atomic weight and found it to be 226. 'This placed it in the same group in the periodic table as barium, strontium, and calcium. In 1910 she obtained it in the free state. It proved to be a pure white metal similar to calcium, melting at seven hundred degrees Centigrade and quickly tarnishing upon exposure to the air.

Thus the Curies triumphed. True, from this enormous quantity of raw material they had obtained but a few milligrams of radium. But it was the most remarkable element that men had ever seen. In the light of its astonishing properties mysteries which only a generation before had been regarded as insoluble were to disclose their secrets. In the deep insight which it has given into the structure of the atom, this discovery is without a parallel. If it in the end gives us the key to the vast reservoirs of energy locked up within the atoms of the elements, Madame Curie's discovery of radium

will be up to this point of evolution the supreme achievement of the race.

Madame Curie continued her work on radium. In 1903 as a result of these investigations she was awarded the doctor's degree by the University of Paris. In that same year the Curies received the Davy Medal of The Royal Society of London. The Nobel prize for the most notable achievement in chemistry was divided in 1900 between them and Becquerel. Again, in 1911, the Nobel prize was bestowed exclusively upon Madame Curie because of her subsequent work in the field. of radioactivity. This is the only instance in which the same individual has been twice thus honored. Upon the accidental death of her husband in 1906, Madame Curie succeeded to the professorship which he had held at the Sorbonne. There, in 1907, she delivered a lecture on polonium, which was attended by the foremost scientists of Europe and the leaders of wealth and fashion in the gay French capital. At the outbreak of the World War the University of Paris established a radium institute for research in radioactivity, and Madame Curie was placed at its head. She has since established a similar institute in her native city of Warsaw. Interesting as the discovery of radium is, the immense significance of this element lies in its activity. Radioactivity is the one process in Nature which we can neither hasten nor retard. Ceaselessly, without apparent diminution, at a definite and unalterable rate, it gives forth its supply of energy. Madame Curie showed that a gram of radium will give off sufficient heat every three-quarters of an hour to raise the temperature of an equal weight of water from the freezing point to the boiling point. In the complete disintegration of a gram of radium it is estimated that two billion nine hundred million calories of heat will be evolved. Since the complete combustion of a gram of coal gives eight thousand calories, of which only twenty-two hundred actually come from the coal, it will be seen that the energy supplied by radium is more than a million times greater than that furnished by the chief fuel of the present age.

No sooner had the announcement of the discovery of radium been made than physicists began an investigation of its properties. Chief among these scientists were Sir Ernest Rutherford, Sir William Ramsay, and Professor Frederick Soddy. To Rutherford we owe the first analysis of the complex radiations emitted by all radioactive elements. He showed that there are three distinct sets of rays, which he called alpha rays, beta rays, and gamma rays. The alpha rays are shown to be positively charged particles shot off with a velocity of about twenty thousand miles per second. They have small penetrating power, but great efficiency in rendering gases conductors. One of the most remarkable facts about them is that they have been found to be positively charged atoms of helium. Thus under our very eyes are we able to witness the transmutation of an element. The beta rays consist of streams of electrons projected with velocities ranging from sixty thousand to one hundred eighty thousand miles per second. They have been found to be identical with the cathode rays of the vacuum tube. Thus they are easily attracted by the positive pole of an electromagnet, while the alpha particles are deflected in the opposite direction, although to a much smaller extent. They also have great penetrating power. The gamma rays are waves in the ether similar to X-Rays, only shorter. Their penetrating power is about one hundred times greater than that of the beta rays, and they are wholly uninfluenced by a magnetic field. It is thought that they are produced by the impact of beta particles on matter through which these electrons pass, just as X-Rays are produced by the cathode rays.

But what is the source of this seemingly inexhaustible supply of radioactive energy? At first this was a puzzle, but experiments have shed light upon the mystery. Sir Ernest Rutherford showed that if a sample of radium salt is dissolved in water and the solution evaporated to dryness, the salt will lose the greater part of its activity. A remarkable result follows. Upon standing, the radium gradually recovers its power until at the end of thirty days it is as active as ever. Rutherford also discovered that in the solution and evaporation of the

radium salt an intensely active gas is given off. This gas he collected and named radium emanation. It causes fluorescence in the dark and possesses all the properties of radium. He found it to be a true gas and a new element, which has been called niton, and takes its place in the periodic table with the rare gases of the atmosphere. Its atomic weight is 222, just four less than that of radium. It has also been shown that helium, whose atomic weight is 4, is formed at the same time. Therefore, physicists have concluded that the radium atom disintegrates, yielding the alpha particles, which are helium atoms, and a new element, niton. These eruptions of myriads of radium atoms also liberate a ceaseless supply of energy. Thus this source of energy is subatomic. We are mere onlookers of the process. We see the birth of two elements by the transmutation of another, but it is entirely beyond our control.

Yet the most extraordinary part of this phenomenon has not been told. The life of this new element, niton, is short. The activity of the emanation, or niton, rapidly decays from day to day until at the end of thirty days it is practically zero, and the element has successively passed through a series of disintegration stages, giving rise at each stage to a new product. Just as the emanation loses its activity, the parent radium regains its lost power, there being at any moment a perfect balance between the two. The sum of the two activities is always the same. A fresh supply of emanation is always being manufactured by the radium at a definite rate, due to the disintegration of its atoms. In 1903 Sir William Ramsay and Professor Soddy demonstrated that the radium emanation in its process of change produces helium, arid that this decay gives a series of new elements each differing in its atomic weight from the preceding one by four. The end product seems to be lead, and each successive change is accomplished by the expulsion of an alpha particle, or, what is the same thing, a helium atom.

From the known rate at which radium decays it has been possible to calculate its period of average life. This is best stated as follows: In seventeen hundred and thirty years half of any given quantity of radium will have disintegrated. In another period of seventeen hundred and thirty years half of the remainder will disintegrate, and so on. From this calculation it was seen that in past geologic time there must have been prodigious quantities of radium in the earth, in order that there should be any left now. But the geology of the rocks and the fossil records of animal and plant life disproved any such conclusion. Physicists were compelled to believe, then, that radium is being produced from some other element as fast as it disappears. Such indeed seems to be the case. It has been definitely proven that radium is a disintegration product of uranium, just as niton is a product of the decay of radium. The whole series has been established from uranium to radio lead. There are no less than fourteen disintegration products, each differing from the preceding by a single helium atom. Two other elements, thorium and actinium, also give disintegration series.

The average life period of uranium has been computed as eight billion years. It will thus be seen that the geological past of the earth is much longer than had been previously supposed. The biologist, who was scraping along on a niggardly hundred million years, may now have almost infinite periods of time for his processes of evolution.

Upon the problem of solar and celestial energy the new knowledge of radioactivity throws a flood of light. What is the source of these ceaseless fires? With no other known origin than that of combustion, it had seemed certain that they must cool in the not distant future. They could not be eternal. The prodigal waste of these supplies of cosmic energy is appalling, and yet there is no apparent diminution. As far as man is able to determine they are infinite. But in 1868, Sir Norman Lockyer, by means of the spectroscope, discovered helium in large quantities in the atmosphere of the sun. Indeed, it was not until 1895 that Sir William Ramsay found this element in certain minerals and a little later identified it as one of the rare gases of the earth’s atmosphere. But there was a significant fact connected with these discoveries.

Helium always occurred in the radioactive minerals of uranium and thorium, and in no others. In the light of our new knowledge of radium is it not probable that the large quantity of helium in the sun's atmosphere is due, as it undoubtedly is on the earth, to the disintegration of radioactive elements? Is this not the explanation of the solar fires? May it not be true that just as radium here is disintegrating and being at the same time reproduced in equal and unalterable quantity, so it is on the sun? Is it too fantastical to assume that in the radioactive cycle we are observing the one majestic example of perpetual motion to be found in all the universe?

As Professor Soddy has suggested, may we not be standing at a turning point in the evolution of the race? Just as the cave man, milleniums ago, gained a mastery of fire, so may the scientist tomorrow learn to liberate and control these vast reservoirs of subatomic energy. Certain it is that present investigations are moving in that direction. When that day arrives, the material power which will pass into human hands will place the race upon a plane of development that will dwarf the mightiest achievements of the present age. The energy locked up within the atoms of a pound of uranium oxide would be equivalent to that liberated in the combustion of one hundred and sixty tons of coal. The store of energy in a ton of uranium would light the city of London for a year. Professor Le Bon has showed that the smallest French coin contains energy equal to eighty million horsepower. Every atom is a fount of energy.

The knowledge of radioactivity has given us a new meaning of the atom. There is no longer a shadow of doubt as to the existence of atoms. But they are not hard, indivisible particles of matter. We now know atoms to be systems of planetary electrons, moving at inconceivable velocities with reference to central nuclei of positive electrification. There are between these electrons and their central sun dreary wastes of space, relatively as vast as the distances between the members of our solar system. It is the disruption of these atomic systems of radioactive elements, with the evolution of electrons and alpha particles, that liberates the energy which we some day hope to control. Sir Oliver Lodge estimates that one-seventieth of a grain of radium hurls into space thirty million of these electrons per second with a velocity approaching that of light. The problem of the future is to discover means of initiating and controlling at will the liberation of this pent-up energy, whether it be from radioactive elements or those of lower rank.

But aside from its theoretical interest radium promises to be of priceless value in the saving of life. Its value is not measured in dollars and cents, but in terms of human energy, health, and happiness. For radium promises, if not absolutely to cure the most malignant cases of cancer, at least to place them under control and to banish forever this scourge in its milder forms. At the Memorial Hospital in New York, one of the most notable centers for the treatment of cancer in this country, the emanation is pumped each morning at nine o'clock from four grams of radium, securely housed in a steel safe, surrounded by thick concrete walls. The glowing gas, the active essence of radium, sealed in tiny capsules and placed in the diseased tissues soothes and heals.

So the knowledge of radioactivity has opened the way to an understanding of the underlying mysteries of energy and matter. To Madame Curie, and those who have labored before her and with her, the world will not soon forget its debt.

History and Nature of Science

Modern Alchemy

In 1901, twenty-four year-old chemist Frederick Soddy and Ernest Rutherford—a physicist barely Soddy's senior at age thirty—were attempting to identify a mysterious gas that wafted from samples of radioactive thorium oxide. They suspected that this gas—they called it an "emanation"—held a key to the recently discovered phenomenon of radioactivity.

Soddy had passed the puzzling gas over a series of powerful chemical reagents, heated white-hot. When no reactions took place, the young chemist came to a startling realization. As he told his biographer many years later.

"I remember quite well standing there transfixed as though stunned by the colossal import of the thing and blurting out—or so it seemed at the time: "Rutherford, this is transmutation: the thorium is disintegrating and transmuting itself into an argon gas.

"Rutherford shouted to me, in his breezy manner, 'For Mike's sake, Soddy, don't call it transmutation. They'll have our heads off as alchemists....' After which he went waltzing around the laboratory, his huge voice booming 'Onward Christian so-ho-ojers.'"

The emanation was not some new compound formed between thorium and the air, but a new gas being created from the transformation of the atoms of radioactive thorium itself. In the course of their scientific research. Soddy and the elated Rutherford had observed transmutation—the transformation of one element into another.

Transmutation was the pipedream of alchemists-medieval experimenters who had tried to turn lead into gold. But transmutation is also a natural process. All around us and within us, atoms are changing, disintegrating in a process called radioactive decay. As the atoms change, so do their fundamental chemical natures: atoms of one element decay into atoms of another. The atomic bomb is one consequence of this process of transformation. The origin of life and the evolution of life forms may be others.

At the Heart of the Matter The notion of transmutation seemed preposterous to turn-of-the-century scientists. Since 1803, researchers had confidently cited John Dalton's atomic theory to explain chemical reactions. In a reaction. fundamental materials called elements combined and separated. This process took place on the invisibly small scale of tiny morsels called atoms. Like tinkertoys, atoms could assemble into more complicated structures with new properties called compounds or molecules. But atoms, scientists thought, were solid, indivisible bedrock—unable to change from one type into another.

Soddy and Rutherford's finding turned that view of atoms on its head. When they announced their discovery in 1902, it "undermined the atomic theory of chemistry" and "revolutionized the foundations of physics," said Sir William Crookes, a leading chemist of the time. If atoms were transforming, it meant that something within the atom itself was changing.

Today we know that atoms are made up of simpler fragments: a central core surrounded y a

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cloud of electrons. This core, the atomic nucleus, contains protons and neutrons.

The identity of an atom—which element it is—depends on the number of protons in its nucleus. A few protons more or less can make a dramatic difference in an element's physical and chemical properties.

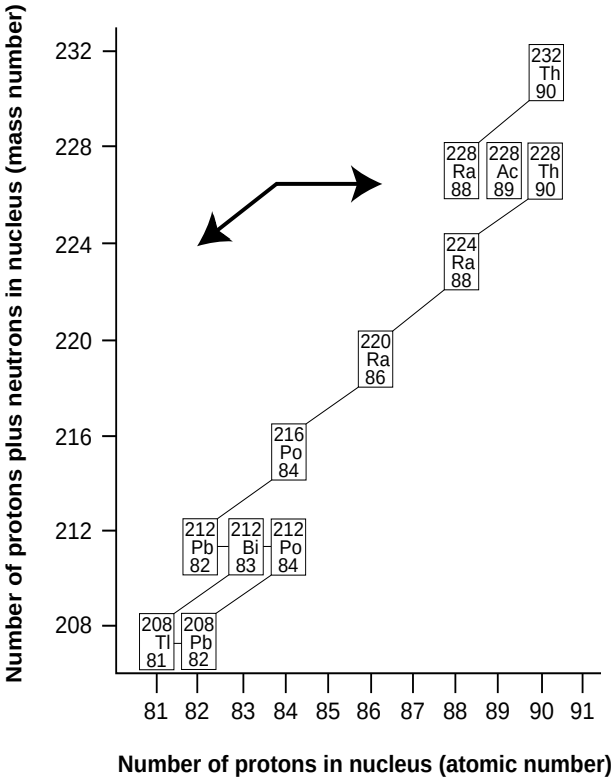
Since the number of protons tells you what element you've got, you need to add or subtract protons from the atomic nucleus to make one element into another. In their experiment, Rutherford and Soddy found that thorium, which has ninety protons in its nucleus, transformed first into radium, which as eighty-eight, and then into radon—the mysterious "emanation"—with eighty-six. In the second step, the loss of two protons converted a chemically reactive, solid, luminescent, white metal—radium—into an invisible, chemically inert gas—radon.

But how does this happen? How does one element become another?

Alpha Decay. Many radioactive atoms transform by releasing pieces of their nuclei known as alpha particles. An alpha panicle consists of two protons and two neutrons. This nuclear fragment explodes out of the disintegrating atom at speeds of up to ten thousand miles per second.

When Soddy's thorium transmuted into radium and then into radon, it did so by alpha decay. Thorium fired off an alpha particle and became radium. Radium, in turn, released another alpha particle and became radon, a gas that has been in the news lately.

Radon is a colorless, odorless, tasteless gas that has been cited as a significant cause of lung cancer. This gas seeps up through the basements and foundations of houses built over uranium mineral deposits. Technically speaking, breathing radon is not dangerous: although it is radioactive, it stays in your body too short a time to do you harm. You inhale the gas, then exhale it again. However, a radon atom will eventually shoot away an alpha particle and transform into polonium. Radon is an inert gas, but polonium isn't. It combines with dust to become a solid, and these solid panicles can lodge in your lungs. The radioactive polonium, stuck inside your body presents a cancer risk.



Radioactive thorium (Th) undergoes a series of transformations—changing from one element to another through alpha decay and beta decay—until it eventually becomes non-radioactive lead (Pb). The number below each element is the element's atomic number, the number of protons in the atom's nucleus. This number determines what element an atom is—thorium, for instance, always has 90 protons. The number just above each element is the mass number, the number of protons plus the number of neutrons. The number of neutrons makes relatively little difference to an atom's identity. A thorium atom can have as many as 146 neutrons—or as few as 122. As long as the atom has 90 protons, it's still thorium. These neutron-rich or neutron-poor forms of an element are called isotopes.

Beta Decay. You may have heard of carbon-14 dating, a technique that archeologists and paleontologists use to estimate the age of long-dead plants and animals. This dating method depends an another type of atomic transformation, known as beta decay.

Radioactive carbon is present in ail living tissue. A small fraction of the carbon dioxide that plants take in from the air contains radioactive

The Nuclear Family

Radioactive atoms often transform in a series, progressing from one radioactive form to another. Radium, for example, becomes radon by spitting out an alpha particle. Radon, in turn, becomes polonium.

Each new radioactive element in a series is called a daughter of the element that preceded it. Together, the many daughters of a radioactive element form a group called a family. Radium, radon and polonium, for example, are the fourth, fifth, and sixth of eleven daughters of thorium. Every atom in the family begins as a thorium atom and goes through eleven transformations until, after billions of years, it eventually becomes a non-radioactive form of lead, and stops changing.

Like other families, radioactive ones tend to stick together. A chunk of thorium would contain all eleven daughters—as well as the original thorium. Some of the daughters would be newborns, some in their teens, others middle-aged, some ancient. The daughters would all be present because each daughter element becomes the next at a different rate, called the element's half-life.

Half-life is a measure of time. It tells you how long it takes for half of the atoms in a chunk of a particular radioactive isotope to disintegrate into a new form. Suppose you had an ounce of radium. After one half-life, half of the radium atoms would have become radon, so you would only have half an ounce of radium left. After another half-life, only half of that half—or a quarter of an ounce—of the original radium would remain. After seven half-lives, only about one percent of the original atoms of a radioactive element are left. After ten half-lives, only a tenth of a percent.

While half-life is a reliable and precise characteristic of each radioisotope, there is no way to predict when any particular atom of a radioactive isotope will decay. You know that half of the atoms will decay in a certain time—but you don't know which atoms will make up that half.

From isotope to isotope, half-lives vary widely. The atoms at the head of the family usually. have the longest half-lives. For instance, thorium-232 has a half-life of 13.9 billion years. Thorium becomes radium, daughter number one, which has a half-life of only 5.75 years. The half-lives of other thorium daughters range from a couple of years to millionths of a second. Outside the thorium family, there are other radioactive elements that flit out of existence millions of times faster than the speediest thorium daughter. Sill others linger for millions of times longer than slow-changing thorium.

carbon. Animals accumulate radioactive carbon in their flesh by eating plants or plant-eaters. When organisms die, they stop taking in radioactive carbon. Over time, the radioactive carbon in the dead p]ant or animal undergoes a transformation. A radioactive carbon atom becomes an atom of nitrogen. As a result, the percentage of radioactive carbon in the remains declines at a steady rate. By determining the amount of radioactive carbon in fossil remains, a scientist can estimate the fossil's age.

Carbon has six protons: nitrogen has seven. Where does the radioactive carbon atom get an extra proton? Through the process of beta decay. In beta decay, a neutron suddenly shatters into three particles: a negatively charged electron, a ghost-like particle called a neutrino, and a proton. The proton remains in the nucleus, adding one to the element's number of protons. The electron and neutrino shoot off at enormous speeds, much faster than alpha particles. Early radiation researchers called electrons spewing from radioactive materials beta rays.

Unnatural Elements. By the 1930s, other researchers went Soddy and Rutherford's experiments one better. They began creating a new kind of "gold" that the alchemists could never have imagined—artificial radioactive elements.

Artificial radioisotopes are made by showing target elements with a variety of subatomic particles—electrons, neutrons, alpha particles or other, heavier, chunks of nuclei—from particle accelerators, nuclear reactors, or other radioactive sources. As of today, more than twenty-five hundred synthetic radioisotopes have been created. These radioactive materials have found wide use in medicine and industry. Once such isotope, radioactive iodine-131, was used to treat President Bush for Graves' disease, a malfunctioning of the thyroid gland. Another radioisotope, cobalt-60, is widely sued for sterilizing hospital equipment and for killing tumors. Industries use the radiation from certain isotopes to monitor the thickness of materials on production lines—if the material gets too thick, the

radiation can no longer penetrate it to reach a detector.

Artificially created radioactive elements don't exist in nature, but they can transform themselves via alpha decay or beta decay just like naturally occurring radioactive elements. Some can also change in a unique manner—by giving off positively charged electrons, or positrons. In positron decay (also called beta-plus, or positive beta decay), a proton spontaneously shatters into a neutron, a neutrino, and a positron. For instance, radioactive sodium, with eleven protons, becomes neon, which has only ten. As it does, the neutrino and positron zip away from the atom. Nuclear Fission

The most dramatic method of transmutation is nuclear fission, the transformation that gives the atomic bomb its destructive force and serves as the energy source in nuclear reactors. In 1939, German and Austrian physicists first began to understand the process of fission in uranium.

Uranium has ninety-two protons in its nucleus, more than any other naturally occurring element. Having as many or more protons than uranium makes nuclei prone to nuclear fission. In fission, the nucleus completely unzips, splitting into two medium-sized nuclei—two new elements—plus two or three free neutrons. Each of the two newly created nuclei contains roughly half as many protons as the original element. An atom of uranium, which contains ninety-two protons, can divide by fission to form the elements krypton, with thirty-six protons, and barium, with fifty-six. Or the same uranium atom can split into strontium, with thirty-eight protons, and xenon, with fifty-four. In a chunk of fissioning uranium, the atoms will break up into these and dozens of other combinations.

The positively charged protons in a nucleus repel each other, but they are held together by a strong, short-range nuclear attraction. When a nucleus fissions, the repulsion of the protons for one another pushes the two halves apart. The fragments fly away from each other with incredible energy. If alpha or beta panicles are like cannonballs blasting from a cannon, a fissioning nucleus is like the cannon itself exploding.

Biological Transformations. In living tissue, the fast-flying fragments from atomic transformations cause change and destruction. Because radioactive elements have always been a part of the earth, even the first living creatures were affected by their assaults. Speeding particles often sever strands of DNA, the cellular genetic code, killing cells or garbling their genetic messages. As a result, the damaged cells may start dividing out of control, forming cancerous tumors. If the damage is to the DNA in a sex cell, it may cause mutations in the next generation.

The subatomic bullets do their damage insidiously. We cannot see. feel. or otherwise sense them. The seeds of disease and deformity that they plant—genetically mutated cells—may lie dormant for decades or be passed on to our children. Lung cancer from exposure to radon and its byproducts, for instance, may not appear for ten to twenty-five years. Radiation damage sets the stage; smoking or some other secondary cause may trigger mutated cells to become tumors.

Ironically, atomic transformations may have also fostered life. Laboratory experiments have shown that molecules important to life can form when atoms in other, parent molecules, spontaneously decay. For example, amino acids can be created when unstable carbon atoms in certain compounds transform into nitrogen atoms via beta decay. Once life got started, atomic transformations may have also caused mutations that contributed to evolutionary change. The role they played is unknown, but alpha and beta decay, and even fission, may share some credit for the richness and variety of life today.