What You Always Wanted To Know About Nuclear Weapons
But Were Afraid To Ask

by Jeremy Bernstein

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The first nuclear weapon to be tested was known as the "gadget." It was exploded at 5:29 am July 16, 1945 in a scrub desert which was part of the Jornada del Muerto--a wagon trail across New Mexico where many travelers had died.

Robert Oppenheimer had called the test "Trinity." When, many years later, General Leslie Groves, who headed the Manhattan Project of which Los Alamos was part, asked him why the name, he said that he thought that he had been reading Donne's devotional poem, the Holy Sonnet XIV, which begins "Batter my heart, three person'd God." Then he added, "Beyond this, I have no clues whatever."

Kenneth Bainbridge, my department chairman at Harvard, went over to Oppenheimer after the explosion and said, "Now we are all sons of bitches." Frank Oppenheimer, Robert's brother, who was standing next to him when the bomb went off, told me that Robert simply said "It worked."

The Sanskrit came later. Rabi gave his impressions: "Suddenly there was an enormous flash of light, the brightest light that I have ever seen or that I think anyone else has ever seen." He is overlooking the residents of Hiroshima and Nagasaki. It blasted; it pounced; it bored its way into you. It was a vision which was seen with more than the eye. You would wish it would stop; altogether it lasted about two seconds. Finally it was over, diminishing, and we looked toward the place where the bomb had been; there was an enormous ball of fire which grew and grew and it rolled as it grew; it went up into the air, in yellow flashes and into scarlet and green. It looked menacing. It seemed to come toward one.

A new thing had just been born; a new control, a new understanding of man, which man had acquired over nature."

On August 6, 1945, Little Boy was dropped on Hiroshima. It was a uranium fission bomb of a design that had not been tested. Hiroshima was the test. On August 9 Fat Man was dropped on Nagasaki. It was a plutonium fission bomb, essentially a clone of the gadget. These were the only two nuclear weapons to have been used, so far, in combat. But testing of new and improved designs of nuclear weapons began very soon after the end of the war. These tests were above ground. The fission bomb tests were done at a site at Mercury, Nevada, not far from Las Vegas.

The fusion bomb tests--the hydrogen bombs--were tested in the South Pacific. We tested above ground until 1962, as did the Russians. The British stopped in 1958 and the French in 1974. The Chinese were the last to stop, in 1980. Since then several countries have tested underground. While the fact that above-ground testing stopped a quarter of a century ago worldwide and here four decades ago is certainly a good thing, there is I think a downside. The number of people who have actually seen a nuclear explosion is dwindling away. Two of my Harvard professors who were at Trinity are still around--both Nobel Prize winners. Norman Ramsey (b. 1915), who won his in 1989, helped assemble Fat Man on Tinian Island. Roy Glauber (b. 1925), won his in 2005. He was the second youngest member of the technical staff at Los Alamos. The youngest was Theodore Hall, who had been Glauber's roommate in their senior year at Harvard. It later turned out that Hall was a Russian spy. But each year there are fewer and fewer.

It has been a half century since March 1, 1954, when the "Bravo" test of hydrogen bomb performed on the island of Bikini. The designers claimed that a certain nuclear reaction involving an isotope of lithium would not be important. They were wrong. The bomb was three times more powerful than they had predicted--about a thousand times more powerful than the Hiroshima bomb. It produced a fireball that, within seconds, was three miles wide. It was visible for almost a minute on the island of Rongerik, 135 miles away. It pulverized corral, producing a grey radioactive ash. The Japanese fishing boat unluckily named the Lucky Dragon was fishing for tuna about 80 miles away from Bikini in what was thought to be a safe area. White ash began falling on the ship. The crew of 23 had no idea what it was, but when the ship returned to port two weeks later, they were all suffering from radiation sickness and the radio operator later died. This incident caused a worldwide protest against these atmospheric tests, but we and the Russians continued for another eight years, partly because people like Edward Teller brought one specious argument after another about the risks of the Russians cheating. If there was any residual doubt about our ability to detect underground nuclear tests, it should have been put to rest by the October 9, 2006, North Korean test. Within days it had been determined that, even though it was hidden underground, it was a plutonium fission device with an explosive power of a small fraction of the Hiroshima bomb.

In August 1941,Churchill received a recommendation from Lord Cherwell (who, when the war began, was plain professor Lindemann) that the work the British had started on the bomb should be supported. Churchill responded with "Although personally I am quite content with the existing explosives, I feel we must not stand in the path of improvement." Since nuclear testing has become "sanitized," hidden from view, many people seem to have acquired the idea that nuclear weapons are a mere "improvement"--somewhere on the continuum that begins with a firecracker, then a stick of dynamite, then the 5,000 pounds of high explosives packed in the rented Ryder truck that Timothy McVeigh used on April 17, 1995 to partially blow up the Murrah building in Oklahoma City, then a few notches over, Little Boy or Fat Man.

But it is not a few notches over. It is instructive to compare Oklahoma City with Hiroshima. Little Boy would have fitted into Timothy McVeigh's Ryder truck. In addition to the damage that McVeigh's device caused to the building, it killed 168 people. Little Boy was equivalent in its explosive power to about 32 million pounds of TNT**!** It would take 6,000 Ryder trucks to produce an equivalent explosion. The Hiroshima bomb destroyed the infrastructure of an entire city. By December 1945, at least 90,000 people had died. Near the epicenter of the explosion a wind was produced that was stronger than any known typhoon. Houses were turned into kindling and a firestorm resulted.

The only comparable bombing damage on Japan was done in March 1945, when 334 B-29 bombers dropped 2 million pounds--a kiloton--of incendiary bombs on Tokyo, killing perhaps 100,000 people. The one Ryder truck-sized Hiroshima bomb produced an explosion that was sixteen times greater. We are clearly dealing with very something different here. What is the science of these weapons?

Fission Weapons

All fusion—i.e., hydrogen bombs--require a fission primary. Without a fission bomb you cannot make a hydrogen bomb, and most of the energy in a hydrogen bomb comes from fission. The fusion reactions, while they do produce energy, have mainly the function here of enhancing fission. So why is the explosion of fission bombs so large?

My paradoxical answer, which will need a good deal of adumbration, is because the atomic nucleus is so small. The nucleus is a roughly spherical chunk of very dense matter. The sphere is so small by everyday standards that a special unit of length has been introduced--the Fermi, after the late Italian-American physicist Enrico Fermi. The Fermi is a millionth of a millionth of a tenth of a centimeter. The radii of nuclei are of this general order of magnitude. The uranium nucleus, for example, has a radius of about 7.5 Fermis. How many of these tiny nuclei fit into a cubic centimeter of uranium? To get a grip on this huge number, take a billion, square it, and then multiply that number by ten thousand. Now you have a number that can be represented by 10 followed by twenty-one zeros--10^{22}. That is about the number of uranium nuclei in a cubic centimeter.[1] If we can find a nuclear reaction that generates even a miniscule amount of energy by household standards, and if that reaction can be made to propagate, then because of the incredible number of nuclei in, say, a cubic centimeter, there will be an enormous amplification factor. Enter fission.

To understand fission we need a model of the nucleus. I have said that it is a very dense bit of matter of roughly spherical shape but of miniscule size. Nuclear matter is made up of two kinds of particles--neutrons and protons. Protons carry a positive electric charge. Neutrons, which have no electric charge, have about the same mass as the protons. In an atom, a cloud of negatively charged electrons which have masses about a 2,000th of a neutron or proton mass circulates at great distance from the nucleus. If we were to blow up the nucleus to be about the size of the earth, then the electrons would be nearly half way to the sun. The electrons can go about their business without interference from the nucleus and vice versa. Atoms are electrically neutral which means that the number of electrons is determined by the number of protons so as to

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[1] No/cc=no/molexmole/cc=no/molexgrams/ccxmole/gram=19 grams/ccx6.023x10^{23}/molex1/238 moles.gtram=19x6.023/238x 10^{23}=.5x10^{23}

balance the charge. To take two examples, the hydrogen nucleus consists of 1 proton, so the atom has one electron. The uranium nucleus consists of 92 protons, so the atom has 92 electrons. The business of these electrons is chemistry. In chemical reactions the atomic electrons of neighboring atoms interact with each other. For a given number of protons, there can be variants of the nuclei with different numbers of neutrons. These variants are called “isotopes” and they all have sensibly the same chemical properties since they have the same number of atomic electrons. I will give two relevant examples; hydrogen and uranium.

The nucleus of ordinary hydrogen, as noted, consists of one proton. The nucleus of “heavy hydrogen”--the so-called “deuteron”--consists of one proton and one neutron. But there is “super-heavy” hydrogen whose nucleus--the triton--consists of one proton and two neutrons. All three of these isotopes can combine with oxygen to produce water. There are sixteen known uranium isotopes. We will be concerned with two--uranium-238 and uranium-235. Both of these isotopes contain 92 protons, but the uranium-238 nucleus contains 146 neutrons while the uranium-235 contains 143 neutrons.

For the lighter nuclei such as the deuteron we can describe the behavior of the individual neutrons and protons. But when it comes to the heavy nuclei, there are so many particles that tracing them individually becomes a practical impossibility. We must resort to models of their collective behavior. One of the most successful, which was exploited by Niels Bohr in his analysis of fission, was what is called the “liquid drop” model. What characterizes a liquid drop is that it has a definite shape that is maintained by the electrical forces that produce a surface tension. If we agitate the drop we can succeed in breaking it up into droplets. In this nuclear model, the nucleus has a definite shape that is maintained by a surface tension. But this surface tension is caused by a strong nuclear force. It is so strong that it keeps the protons, which electrically repel each other, from flying apart. If this “liquid drop” is agitated it becomes deformed. The spherical shape becomes elongated and begins to resemble a cigar. If it is elongated enough, it splits apart into droplets and we have fission.

Put this way you might think that physicists like Bohr and Hans Bethe, who were completely familiar with the liquid drop model, would have predicted fission. But this is not at all what happened. After the neutron was discovered by the British physicist James Chadwick in 1932, it was clear to a number of people, especially Fermi, that since it had no electric charge and would not be repelled by the protons, it would make an ideal nuclear probe. Fermi had a group of brilliant physicists in Rome who began a systematic investigation involving the bombardment of elements with neutrons. Fermi had discovered that, paradoxically, the slower the neutron was, the more readily it interacted. He invented a wholly new discipline of slow neutron physics. In 1938 he was awarded the Nobel Prize, partly for this and partly for something he thought he had discovered but hadn’t.

Using slow neutrons one performs alchemy. After the neutron is absorbed by the target nucleus, new isotopes are produced of different elements. Fermi was sure that when a uranium nucleus absorbed a neutron it would be transmuted into new elements heavier than uranium. Indeed, he was so sure he had discovered them that he gave them names--Ausenium and Hesperium. We now call them neptunium and plutonium, and Fermi did not discover them. What he had discovered, without realizing it, was fission.

This was 1934, and several other laboratories took up the study. The one that interests us is the Kaiser Wilhelm Institute in Berlin; its two radio chemists, Otto Hahn and Fritz Strassmann; and its physicist Lise Meitner. They repeated Fermi's experiment and also claimed to have discovered transuranic elements. This was 1938, and the roof collapsed on Meitner. Although she had converted to Christianity, as far as the Nazis were concerned, she was a Jew. She was Austrian, which immunized her until the Anschluss, when Austria and Germany were united. She was forced to leave Germany in a great hurry and ultimately ended up in Sweden. But she was able to keep some contact with Hahn.

In December 1938, Hahn informed her of something he and Strassmann had observed which they did not understand at all. They had been bombarding uranium with slow neutrons and one of the products was something that they could not distinguish from barium. Barium is an element more or less in the middle of the periodic table with 56 protons in its nucleus. Where did it come from?

It was now Christmas vacation and Meitner's nephew Otto Frisch came to visit her. He was a physicist who also was driven out of Germany and had sought refuge in Bohr's institute in Copenhagen. They met in the Swedish village of Kungälv near Göteborg. Frisch had brought his cross-country skis and she had brought Hahn's letter. They went for a walk in the woods with Meitner trotting alongside her nephew. Frisch wrote a charming account. They sat down on a tree trunk and discovered fission. More exactly they realized that the liquid drop model of the nucleus explained what Frisch later named fission. The important question was the energetics. You must have energy conserved in the process. How did this come about? The key lay in the masses of the nuclei--the uranium and the fission fragments. They knew that boron was one of the fragments and, by adding up the proton charges, they could deduce that the other was the inert gas krypton, which has 36 protons in its nucleus. Thirty-six and 56 add up to 92--the number of protons in the uranium nucleus. I have always found it quite wonderful that the name of the planet on which superman was born and the name of the element produced in the first fission experiment was the same. Frisch says that his aunt knew the masses of these isotopes. Why does that matter? Here we invoke Einstein's equation $E=mc^2$.

What you do is to add up the masses of the barium and krypton nuclei and subtract the sum from the mass of the uranium nucleus. Then you take the difference and multiply it by the square of the speed of light. This is the energy released in the fission. When you do this you get an answer that may surprise you. To understand this we must understand units of energy. I begin with something familiar--an electric light bulb. Light bulbs are graded in watts, but a watt is not a unit of energy. It is a unit of power--an amount of energy per second you take from the electric grid to illuminate the light bulb. If we take a watt and multiply it by a second, we have a watt-second, which is a unit of energy. Your electric bill usually is measured in kilowatt hours, which is also a unit of energy. Physicists have a name for a watt-second: a joule.

James Joule was a nineteenth-century British physicist who did important work on the conservation of energy. If you have a hundred watt bulb and keep it on for an hour then you will have used 360,000 joules of energy. Then how many joules are created in one act of uranium fission producing barium and krypton?

The answer is a tenth of a millionth of a millionth of a joule--one divided by 10 followed by twelve zeros. This is an absurdly small amount of energy. If this was all there was to it there would be no bomb and no reactors. But there is more.

Frisch returned to Copenhagen to find Bohr about to leave for the United States, where he was going to spend the spring semester in Princeton. He told Bohr what he and his aunt had done and Bohr's reaction was to say "What idiots we have been." How was it possible not to have thought of fission? The news of fission spread like wildfire in the U.S. physics community, and many people began working on it. Bohr and the Princeton physics professor John Wheeler wrote a monumental paper on the liquid drop model of fission. In the course of this Bohr had an epiphany. He discovered the difference between an isotope that is "fissionable" and one that is "fissile," to use the modern terminology.

Take the case of uranium. If you take a sample of uranium from a mine, it will consist of over 99 percent of the isotope uranium-238, Less than 1 percent will be uranium-235, which has three neutrons fewer in its nucleus. What Bohr realized was that, due to a quirk in the nuclear physics, while uranium-238 was fissionable, uranium-235 was fissile. To fission uranium-238 the neutrons incident on it must have a minimum or threshold energy. A neutron with less energy will not fission the nucleus. On the other hand, uranium-235 is fissile--neutrons of any energy will fission it. Bohr understood at once that any application of fission energy would require the separation of isotopes. Because these isotopes have the same chemistry he decided that this was hopelessly difficult. So until the fall of 1943, when he escaped to England and learned about the Manhattan Project, he assumed that nuclear weapons were impossible. Henceforth when I discuss the fission of uranium I will mean the fission of uranium-235.

Bohr's epiphany by itself does not solve the problem of how to amplify the tiny energy produced in a single fission of uranium. I left something out. The heavy fission fragments are accompanied by neutrons emitted in the fission process. Sometimes one neutron is emitted, sometimes two, sometimes three, and so on. For uranium-235 the average is a little more than two, so to keep things simple I will round it off to two. I will also assume that each of these neutrons will in turn fission another uranium nucleus. In fact, the most probable thing is that the neutron will bounce off the next nucleus, but if the uranium sample is large enough, so the neutron does not escape through the surface, it will sooner or later fission a nucleus. Thus the first generation produces two neutrons, the second four, the third eight and so on--a chain reaction.

For reasons that I will now explain, I am interested in the 80^{th} generation. This produces 2^{80} neutrons. But this is about equal to 10^{24} neutrons. Why am I interested in this number? Because it is about the number of uranium nuclei in a kilogram of uranium. Thus eighty generations of fissions will produce enough neutrons to fission a kilogram of uranium-235. This is the amplification mechanism we have been looking for.

Uranium is very dense--about nineteen times as dense as water. A kilogram is a little over two pounds. If this amount of uranium were made into a sphere, it would be about the size of a squash ball. If we fissioned all the nuclei in it, how much energy would be generated? If we multiply the number of nuclei in the kilogram by the fission energy generated by each nucleus, we arrive at the remarkable result that the total energy generated is equivalent to about 19,000

tons of TNT! Think about that. The fission energy potentially available in a squash ball-sized lump of uranium is enough to flatten a city. However, the existence of this energy by itself does not guarantee an explosion. By definition an explosion is the production of energy in a very short time. We must investigate how long it would take to fission a kilogram of uranium. The key here is the speed of the neutrons produced.

In fission, the heavy fission fragments take away most of the energy of motion--the kinetic energy--but the neutrons take away enough so that they are moving very fast--about a tenth of the speed of light. How far does a neutron have to go on average before it produces another fission? In uranium-235 it turns out that this is about 13.5cm. The neutron can cover this distance in about ten nanoseconds--ten billionths of a second. This is such an important unit of time in this business that the practitioners have given it a name--a "shake"--one shake of a lamb's tail. To fission a kilogram we need eighty generations, which takes eighty shakes--about a microsecond. In a nuclear explosion all the action takes place in thousandths of a second. Unless you have a very high speed camera you cannot record what happens.

A reader may object that the mean free path for fission is about 13.5cm, but the diameter of a squash ball is only about 4cm. Don't many of the neutrons leak out of the surface of the spherical kilogram, taking them out of the chain reaction? Yes, which brings us to the matter of the critical size needed to just sustain the chain reaction. If we know the size, then we can find the mass by multiplying the volume by the density. This was a major focus of the work at Los Alamos. If you are discussing a spherical shape, then the geometry is simple enough so that you can make good theoretical predictions. But Los Alamos needed odd shapes and the critical masses had to be determined empirically. This is something that Feynman called "tickling the tail of the sleeping dragon." It was a very dangerous operation adding bits of fissile material a little at a time until the configuration went critical. For uranium-235 the critical mass of a sphere is about 50 kg--a bit over 100 pounds.

A sphere of uranium with this mass is about the size of a baseball. This volume will have more nuclei in it than the squash ball. It might take another shake or two to fission them all, but that is not going to add much to the time. Incidentally this brings up something about the German wartime nuclear program. In 1942, the official program was led by Werner Heisenberg. In June 1942 he went to see Albert Speer, the newly appointed Minister of Armaments and Munitions. Speer wanted to know how big a uranium bomb would be, by which I think he meant how much uranium would it require. Heisenberg told him it would be about the size of a pineapple. I have discussed this with German colleagues and pointed out to them that this must mean that Heisenberg never correctly calculated the critical mass of uranium. The Germans never produced any uranium-235, so they could not have measured it. One of my German colleagues noted that, in wartime, pineapples were unknown in Germany. I am sure that Heisenberg was enough of a man of the world to know that a pineapple is larger than a baseball.

Thus we see that a necessary condition for making a Hiroshima-type nuclear weapon is to acquire about 100 pounds of uranium-235 in metallic form. We want it to be metallic so that we can shape it. We don't, it turns out, need absolutely pure uranium-235. If we can enrich a sample of natural uranium so that it becomes something like 90% uranium-235, that will work. But how to do this? I am not going to describe the methods employed, after a certain amount of trial and error, at Oak Ridge in Tennessee to produce the enriched uranium that was used in Little Boy. Rather I am going to focus on a method that was tried and abandoned because it was too complicated and unreliable. This was the use of the centrifuge, which has become so important recently. The people at Oak Ridge did not have available to them what is known as the "Zippe centrifuge."

First let me explain how a centrifuge works. It is basically a device with a container that can be made to spin around an axis. When it is spinning, a centrifugal force acts on the molecules in the container. This force acts outwards and tends to push the molecules towards the outer surface of the container. The magnitude of the force depends on three things. It is proportional to (1) the distance of the molecule from the axis of spin; (2) the rate of spin--the number of revolutions per minute; and (3) finally, and crucially, the masses of whatever the mixture of spinning particles is made up of. Thus, if you have a lighter and heavier component, the heavier component will have more force on it and will move out to the sides leaving the lighter component close to the middle. When I was preparing this lecture I decided to Google "centrifuge" to see what was on offer. I came across one called "Valcon QM-100 Quantum Large Capacity Benchtop Centrifuge." I liked the name. Anything with "quantum" in it can't be all bad. It goes for $1,366. The manufacturers claim it can rotate at 2,800 revolutions per minute. This sounds impressive until one learns that the Zippe centrifuge can rotate at 90,000 revolutions per minute. What is its origin, including its name?

When, in the spring of 1945, the Russians occupied Berlin, they knew a good deal about the atomic bomb program--both ours and the Germans'. Los Alamos spies like Harry Gold, Ted Hall and, above all, Klaus Fuchs had turned over a lot of material, including the fact that the "gadget" was going to be tested and that it was a plutonium device. The Russians also knew which German scientists were working on nuclear energy and where they could be found. They got a hold of as many as they could and shipped them East along with their equipment. Among them was the 1925 Nobel Prize winner in physics, Gustav Hertz. Less known, but very important, was a physicist named Max Steenbeck, who had headed the research department in an aircraft company. He, and the rest, ended up in a sort of gilded cage in the resort town of Sochumi and the Black Sea in Georgia. The task that the Sochumi inmates were given was the separation of uranium isotopes. Steenbeck's group, some sixty, explored separation by centrifuge. He made great improvements in the centrifuges that were being used. In 1946, he was joined by an Austrian physicist named Gernot Zippe. Zippe had been in a POW camp from which he was fished out. Zippe then took over the experimental side of the centrifuge development while Steenbeck focused on the theory. It is quite unclear who did what when it came to the final product, and there was some contention when, in 1956, Zippe left Russia with the plans and his name attached to the device It was not until he attended a scientific meeting in Amsterdam the next year that he realized that his centrifuge design was better than anyone else's.

The Zippe centrifuge is what is known as a "gas centrifuge", meaning that the material that is being separated is in gaseous form. A Zippe centrifuge is a thin tube which, in the original version, was made out of aluminum. "Aluminum tubes," that sounds familiar. An improved version uses carbon fiber tubes. The velocity of a spot on the perimeter is about 600 meters a second, much faster than the speed of sound!. One of the innovations in the Zippe centrifuge is to introduce heating elements at the bottom of the cylinder which drives the gas up and increases the efficiency of the separation. In the case of uranium, natural uranium is converted into a gas by combining it with fluorine. One uranium atom combines with six fluorine atoms to make a molecule of uranium hexafluoride. This is a difficult gas to make and a dangerous one to use. A country that has manufactured sizeable amounts of uranium hexafluoride already demonstrates technological sophistication. As I have already mentioned, natural uranium is over ninety nine percent uranium-238. These nuclei differ in mass from those of uranium-235 by something like a percent. Hence the separation is not easy. The centrifuges are configured in a cascade in which each partial separation is fed into the next step. A cascade of, say, three thousand, running for a year, will produce enough highly enriched uranium to make at least one bomb. I will shortly explain how this material is used to make a bomb, but first I want to tell you what happened to the Zippe centrifuge.

Upon his return to Germany, Zippe went to work for the Degussa Corporation, one of the largest chemical companies in Germany. Many German companies behaved disgracefully during the Nazi period, but Degussa was one of the worst. Their subsidiary, Auer, made, and sold, uranium metal to the German nuclear energy program. The most dangerous part of making this was done by slave laborers from concentration camps. One of its subsidiaries, Degesch, produced and sold the Zyklon B gas that was used in the German extermination camps. And, to complete the cycle, between 1939-45 they received at least five metric tons of gold, much of it extracted from the teeth of concentration camp victims who had been murdered with Zyklon B. This was the company that Zippe joined. In 1958, Zippe went to the University of Virginia to work with Jesse Beams, who was the fist person to separate isotopes with a gas centrifuge. In 1934 he had separated isotopes of chlorine. There was now a four-way cooperation between Degussa, the University of Virginia, our Atomic Energy Commission and the German Ministry for Atomic Energy. A German state owned corporation was formed which was privatized in 1970. In 1971, this company was merged with a British and a Dutch company. The merged company was known as URENCO. Their goal was to produce industrialized Zippe centrifuges. It is the Dutch company that interests us. It had a subcontractor located in Almelo in Holland. In May 1972, it acquired a new employee, a young Pakistani metallurgist named Abdul Qadeer Khan.

Khan was born in 1936 in Bophal, which was then in British India. After partition he made a very traumatic move to Pakistan. He did his undergraduate work in Karachi and then went to West Germany to continue his studies, then to Delft in Holland and, finally Belgium, where he got his Ph.D. His thesis advisor got him his job in Almelo. Along the way, he had acquired Dutch and German and a South African-born Dutch wife. In 1971, the Indians supported a successful rebellion in East Pakistan creating Bangladesh. That year the western-educated Zulifkar Ali Bhutto became president of Pakistan and was able to implement his long-standing idea of creating a nuclear deterrent. When the Indians successfully tested in 1974 he famously said that the Pakistanis would have a nuclear weapon even if it meant that they had to eat grass. He called for scientists in the diaspora to return and help. Khan wrote a letter directly to Bhutto offering his services, which were accepted. He decamped from Holland with his wife and the plans for the Zippe centrifuge. At first, he was content to work within the official program, but when he decided it was moving too slowly, he was able to persuade Bhutto to set him up in his own enterprise near Islamabad, which eventually became the Khan Research Laboratories. It was so closely held that even government officials were not allowed to enter it. It became the perfect cover for Khan's activities. I will just sketch these. He began by trading the centrifuge design to the Chinese for plans for a fission bomb--successfully tested by Pakistan in 1998--which the Chinese had gotten from the Russians, who had in turn gotten them from Los Alamos via Fuchs. He traded centrifuges to North Korea for missiles. At the same time Degussa was trying to sell centrifuges to Iraq, he sold them to Iran, where they formed the basis for the Iranian enrichment program. He sold the whole package, centrifuge parts, bomb plans and all, to Gadafi in Libya, but the ship bringing some of it from Malaysia in October 2003 was intercepted and Gadafi turned everything over to the CIA. In February 2004, Khan confessed all of this to Pervez Musharraf, then president of Pakistan, and was put under house arrest in Rawalpindi, where hh was until this year--all of this thanks to the Zippe centrifuge. Zippe himself died in 2008.

Now, imagine that we have acquired a hundred pounds or so of highly enriched uranium, how would we make a bomb? The first thing that might occur to you is to make two hemispheres, each of which has less than the critical mass, and then bang them together. This brings up an important point. The critical size of a sphere of uranium is just that size at which the number of neutrons escaping through the surface is equal to the number being created by fissions in the interior. This equilibrium is not going to produce an explosion, We need a super-critical mass so that more neutrons are being produced than are escaping. Banging two sub-critical hemispheres together will do this, but we can actually do better. This involves something that is essential to understand for the plutonium bomb.

The figure we gave for the critical size supposed that the uranium is at its normal density. Suppose, however, we take our sphere and squeeze it so that it remains a sphere of reduced volume but with the same amount of material. This will increase the density. At this increased density the distance between the nuclei is less and therefore the distance between fissions is less. This means the critical size and hence the critical mass is less. In fact the critical mass falls of as the square of the density. If we double the density the critical mass is reduced by a factor of four. Conversely if we reduce the density by a factor of two the critical mass increases by a factor of four. This is what shuts the chain reaction off in the bomb. The immense heat very rapidly expands the uranium, which has become a gas. Neutrons can no longer find other uranium nuclei to fission and the chain reaction stops. This happens so fast that most of the uranium in the bomb is never fissioned. In Little Boy only 2 percent was fissioned. The rest wafted off into space.

In designing Little Boy the observation about the density was used in the following clever way. Suppose we start with a solid sphere of uranium and drill out a sizeable cylindrical hole-one into which we can fire an artillery shell. This way we have lowered the density of the remaining object because part of it has no mass and therefore zero density. Thus we have increased the critical mass of this structure and we can build it with additional uranium without the thing going critical. If it was at the original density it would actually be super-critical. Then, if we make the artillery shell out of uranium at the normal density, but sub-critical, we can fire it into the hole and produce a super-critical assembly. This is called the “gun assembly” design and, with a somewhat different geometry, became the Hiroshima bomb. As I have mentioned, it was considered simple enough so that it was never tested before it was used. An entity that managed to get a hold of this much highly enriched uranium, but had limited technical capacity, would probably try to design a nuclear device this way. Starting with a sub-critical sphere and imploding it to produce a sphere with a smaller volume and therefore a higher density and a smaller critical mass it technically much more difficult. But if you can do it, since you do not lose any of the uranium in the implosion, what was sub-critical before the implosion is now super-critical after it. However, the technical problems in making the implosion are very substantial. In the gadget, one began with a solid sphere of plutonium--the “pit”; wrapped carefully machined explosive lenses around it; and then set off the explosives simultaneously--within nanoseconds of each other--at several points on the sphere. Getting this to work was one of the hardest jobs done at Los Alamos. Fuchs gave most of the details to the Russians who, as I have said, gave it to the Chinese. But the Chinese surprised everyone when, on October 16, 1964, in the desert at Lop Nor in the Uygur Autonomous Region in northwestern China, they successfully tested what turned out to be a **uranium** implosion device, demonstrating that they had a very sophisticated weapons program which included the separation of the uranium isotopes. We thought that they would use plutonium.

On plutonium, I am not going to go into great detail, but here are a few highlights. All of the twenty-one known plutonium isotopes are unstable and, assuming they were about as plentiful as uranium at the time of the earth’s formation, in the 4.5 billion years since, have decayed away. The uranium isotopes are also unstable but uranium-238 has a lifetime comparable to the age of the earth. Uranium-235 has a much shorter life time, which is why there is so much less of it now. Plutonium has to be manufactured. It was first identified for sure in February 1941 by the chemist Glen Seaborg and his collaborators. They used a cyclotron at Berkeley to create a beam of neutrons to bombard uranium. This was a version of the experiment that had been tried since Fermi, but Seaborg had a more powerful neutron source. He also knew about fission so he could weed out fission events from the nuclear transformations of uranium that lead to plutonium. It was immediately realized that Bohr’s argument that showed that uranium-235 was fissile applied, *mutatis mutandis*, to plutonium-239. In fact, plutonium-239 is more fissile that uranium-235. The critical mass situation for plutonium is a little tricky, because it exists in different phases, called allotropes, with different densities. For the so-called delta phase that is used for making nuclear weapons, the critical mass of a bare sphere of plutonium is about 16 kilograms, a lot less than uranium-235. Plutonium is manufactured in nuclear reactors. The plutonium for the gadget and for Fat Man, the Nagasaki bomb, was manufactured in the specially built reactors in Hanford, Washington on the Columbia River. The cleaning up of this site, which goes on to the present day, is a nightmare.

When the first significant quantities of reactor plutonium arrived at Los Alamos in the spring of 1944, it was clear there was a serious and perhaps fatal problem. Heavy elements like plutonium and uranium have so many protons that repel each other electrically that they are on a knife edge for fissioning. We have seen that colliding neutrons can fission them. But these elements also fission spontaneously, with no outside help. This is a potential disaster in weapons design, because if there is a substantial amount of spontaneous fission before a supercritical mass is assembled, the chain reaction will be started prematurely and one will produce what the weapons designers call a “fizzle.” These fizzles can involve explosions of hundreds of tons of TNT equivalent but they are not a full-scale nuclear explosion. Spontaneous fission of uranium is manageable, but in the production of plutonium in a reactor, both plutonium-239 and plutonium-240 are produced. Plutonium-240 has a high spontaneous fission rate. It is so high that the gun-assembly design is ruled out. The assembly is too slow and such a device would almost surely pre-detonate. At Los Alamos some thought was given to try to separate these isotopes. But this would be even harder than separating the uranium isotopes since the masses are even closer together. Thus Oppenheimer turned the whole laboratory around to work on implosion. This is technically very complex so it was decided that a test was needed and hence Trinity--and then Nagasaki with the same design.

In discussing the hydrogen bomb there is a serious limitation of classification. Most of the details of fission bombs like the gadget are available in the open literature. You can, for example, find on the web what Fuchs gave the Russians, who have declassified it. On the other hand, you cannot find the details of the hydrogen bomb--at least details that are correct--anywhere. That is a good thing. We do not want to make it any easier for countries like Iran or North Korea to make a hydrogen bomb. But I can tell you a few general principles.

Hydrogen bombs, more correctly described as thermonuclear weapons since they don't involve ordinary hydrogen, make use of nuclear fusion instead of fission. In fission, energy was obtained because a heavy nucleus was split and the products were less massive than the original nucleus-the mass difference producing an energy because of Einstein's equation $E=mc^2$. Fusion is the exact opposite. Two light nuclei fuse into a new nucleus or nuclei. What is paradoxical here is that while the nuclei that are the products of the fusion have the same numbers of neutrons and protons as the fusing nuclei, they are less massive. This is what produces the energy.

Let's begin with the simplest example--one neutron and one proton. When the neutron gets close enough to the proton it can capture it, producing a nucleus of heavy hydrogen--the deuteron. Suppose we want to get the free neutron and proton back again. We can do this by allowing a very energetic radiation quantum to interact with the deuteron. This is called the photo-disintegration of the deuteron. There is a minimum energy the quantum needs to make this process work. That is because the free neutron and proton are more massive than the deuteron. In the reverse capture process a radiation quantum of the same energy is produced. This energy is given by Einstein's relation using the mass difference between the free neutron and proton and the deuteron. This is where fusion energy comes from.

We might think that all we have to do to exploit fusion energy is to collect neutrons and protons in a container and let them fuse into deuterons. Were it that simple our energy problems would have been solved long ago. The difficulty is that the free neutron is unstable. It decays into a proton with a lifetime of about fifteen minutes. Neutrons can't be stored. We have to do the next best thing and go to isotopes of hydrogen where the neutron is bound and can't decay in the same way. We could take two deuterons or, as it turns out, even better, one deuteron and one triton--the nucleus of super-heavy hydrogen with one proton and two neutrons. These two objects can fuse into a helium nucleus and an energetic neutron. The total energy released in this reaction is less than the energy released in a typical fission reaction. But the fusing elements are so much lighter that we make up for this since so much less mass is used in each fusion. There is no critical mass for this reaction and no theoretical limit to how much of the stuff we can use.

But there is a catch. There is always a catch. Both of these nuclei have a net positive charge. Like charges repel, so these nuclei have a difficult time getting close enough to each other to fuse. In fact in the world of classical physics they would essentially never got close enough and that would be the end of the story. But in the quantum world there is a new possibility. The nuclei can tunnel through the repulsive barrier. For this to happen frequently enough the nuclei must be very energetic, which means they must be in a very high temperature environment. There is one place we know that this works and that is the sun--and indeed all the stars. The central temperature of the sun is about 13.5 million degrees. To reach a temperature at which the thermonuclear reactions could start, the force of gravity compressed the Sun. Then the reactions can proceed until the nuclear fuel is used up, whence the gravitational contraction begins again.

On earth, we know one device that can produce temperatures like this--a fission bomb. This was understood by people like Hans Bethe and Teller. Even before there was a Los Alamos they began thinking about a “super-bomb.” The first thought that might occur to you is to take a container of fusible elements and put a bomb in the middle of it and let it go off--something like dropping a match into a container of gasoline. This configuration, with all its innumerable adumbrations, is known as the “classical super.” None of the proposed designs seemed to work. While there was enough energy to ignite the fission reactions, they would not propagate. The fusible elements cooled down too quickly. It was like trying to light a log with a match. Here is where things stood until 1951.

At that time, the Polish-American mathematician Stanislaw Ulam made a breakthrough. Ulam had been at Los Alamos during the war, fell in love with New Mexico, and decided to stay. He was a pure mathematician by training and temperament but, when the occasion arose, he could do very significant physics. He was one of the people who kept killing Teller’s classical Super designs. Ulam’s idea was to use a staged device. The first stage would be the fission bomb. The fusible material would be kept in a capsule separated from the fission bomb. His first idea was to use the material from the fission bomb to violently implode the capsule. The material in the interior would then be heated throughout by the compression. Teller made the important observation that the same effect was possible if one used the x-ray radiation from the bomb, which actually carries off most of the energy. These x-rays move with the speed of light, which accelerates the process. It is the details of how this is done that are classified. But it is known that inside the capsule of fusible elements a hollow rod of plutonium is placed. The heated gas now implodes the plutonium rod and fission is initiated. The energy from this fission ignites the fusion reactions. The fusion reactions produce energy but, more importantly, they produce neutrons. If one makes the capsule out of uranium, then these neutrons cause intense fission. It is the fission that provides most of the energy produced by the device. I never cease to marvel at the ingenuity that went into creating a device for killing people.

The yield of hydrogen bombs is about a thousand times greater than that of the Hiroshima or Nagasaki bombs. We are talking yields of **millions** of tons of TNT equivalent, megatons, 600,000 of Timothy McVeigh’s Ryder trucks. Before President Truman, on January 31, 1950, ordered a crash program to make a hydrogen bomb, and before anyone knew how to make one, there were debates among the physicists as to whether such a device should even be made at all. Oppenheimer was opposed. One of his arguments was that the targets were too small. The Hiroshima and Nagasaki bombs brought two cities-and a country--Japan surrendered four days after Nagasaki--to their knees. What would a hydrogen bomb have done? As horrible as they were, the atomic bombs still left a semblance of cities and their populations--something to build on. Hydrogen bombs would have left a waste land. Once the Ulam-Teller idea was known, the hydrogen bomb, in Oppenheimer’s memorable and unfortunate phrase, became “technically sweet.” It could not be stopped. While I think that an argument can be made for the making and use of atomic bombs during the war, I do not see any argument for making the hydrogen bomb. As far as I am concerned, it was a terrible mistake.

My own brief encounter with nuclear weapons took place in the summer of 1957. From the time I got my PhD in 1955 to the spring of 1957 I was employed as the “house theorist” for the Harvard Cyclotron. The job was temporary and that after two years I was expected to move on. Therefore I applied to the Institute for Advanced Study in Princeton, a place that I always wanted to go to. Einstein had died two years earlier, but there were people there such as Freeman Dyson and the Chinese American physicists T.D. Lee and C.N. Yang whose work I admired enormously. And, of course, Oppenheimer was the director. Much to my surprise and joy I was accepted for the fall of 1957. This left the summer.

I cannot remember how it was that I was recruited to go to Los Alamos as a summer intern. I mentioned earlier that I was practically surrounded by people from Harvard and MIT who had been at Los Alamos during the war. In addition to Bainbridge, Ramsey and Glauber, George Kistakowski, the Harvard chemist, had done much of the basic work on implosion. Viki Weisskopf at MIT had been second in command behind Bethe of the Theoretical Division, and there were several others. What strikes me as odd now is that none of these people, at least in my presence, ever said anything about what they had done at Los Alamos. Perhaps the experience was too raw or perhaps everything was still so secret that there was nothing they could say. I had absolutely no idea of how an atomic bomb worked. But someone must have given my name as a possible recruit and I was offered a summer job in the Theoretical Division.

The first obstacle was to get what was known as a “Q-clearance.” This was the most rigorous kind of clearance, which required you to give all your addresses since conception. Your friends and neighbors and family were interviewed. I had a great aunt May, who subscribed to the *Daily Worker* and spoke darkly about the “bosses.” I have often said that I hoped for their sake that she was not a member of the Party. I would imagine the FBI learned about this but it was not enough to keep me from getting my clearance. I have no recollection of how I actually got to Los Alamos. Perhaps I took a train-the Topeka-Santa Fe-to Lamy, New Mexico as they did during the war. When Ulam found that he was going to New Mexico, a place about which he knew nothing, he had his wife check out an Atlas from the library. He had previously noted that a number of physicists had disappeared from the university. When he looked at the list of previous borrowers he found the names of these physicists. Even an incompetent spy could have put 2+2 together. I do not remember how I got from Santa Fe up to the Los Alamos mesa. During the war there was a nondescript house at 109 East Palace Avenue where new arrivals would meet Dorothy McKibben, who would make the arrangements for them to get to the laboratory. I wonder what I did when I arrived. Los Alamos was a closed city then, with barbed wire and armed guards. Somehow I was let in and shown to my dormitory room in one of the wooden dormitories left over from the war used then and in 1957 to house single people. I do remember that when I found out how far it was from the dormitory to the Theory Division headquarters I acquired a bicycle.

I had no assignment, but there was a Harvard colleague who was also there as a summer intern and we decided to collaborate on a problem in elementary particle physics. This had nothing to do with anything involving weapons, but no one seemed to mind. Ultimately we wrote a paper which gave Los Alamos as our address. I was on my way to Princeton and he to Copenhagen. During the war Oppenheimer had introduced a policy of “need to know.” If you had the right clearance and needed to know you could be told. I had the right clearance, but did not need to know, so no one told me anything. I might as well have been on a college campus and not at a laboratory at the height of the Cold War whose primary mission was the design and testing of nuclear weapons. Once the summer started a very distinguished group of somewhat senior theoretical physicists arrived for consulting visits. The thing that most of them were working on was how to use fusion in a controlled way to produce energy. At the time it was also a classified project. Now it is declassified but, as far as I know, all the problems have not been solved.

One of these newly arrived physicists was a man named Francis Low. He had done some exceedingly brilliant work that I admired and was on his way to taking up a professorship at MIT. It turned out that we also shared a passion for tennis which we played on the Los Alamos concrete courts with their steel nets almost every day. Toward the end of August Francis announced that he would not be able to play tennis with me because he was going to Mercury, Nevada to watch some above-ground nuclear tests. This really surprised me because I had no idea that Francis was working on weapons. He said that he wasn’t but that the head of the Theory Division, a Canadian named Carson Mark, had invited him to come and he had accepted out of curiosity. When I asked if I could go as well, Francis told me to speak to Carson. Carson was agreeable on the condition I pay my own expenses such as air fare, to which I readily agreed. So it was on the afternoon of August 30 the three of us left Los Alamos for Albuquerque in a light plane from a landing strip at Los Alamos, then by commercial airline to Las Vegas which is about 65 miles from Mercury. I had no idea of what our schedule would be, but in fact we went directly from the airport to a casino. I was aware that some time earlier a mathematician had published a paper showing that if you played an optimum strategy you could beat the house at casino blackjack. In fact it had been tested by playing hundreds of thousands of games on one of the Los Alamos main frame computers when it was not engaged in matters of national security. Indeed the people from Los Alamos who went to Mercury, often for weeks at a time, were given a little card that summarized the strategy.

This casino must have done a brisk business with people from Mercury because that had a blue light that could be lit if a test that had been scheduled was actually going ahead. There were very frequent postponements because of the weather. I guess we must have left the casino around midnight to get a few hours of sleep. The tests were always at dawn to optimize the lighting for the photography. This test had been scheduled for 5 am. About 4:00 Carson got us up and we went to a building which housed the local meteorologist. He did not like the look of things so the test was postponed for half an hour. Carson told us that it was being fired from a 700-foot tower, which turned out to be the tallest tower ever built for one of these tests. He also told us that it was a Livermore test, Teller’s lab, and was therefore named after a mountain or mountain range--the Los Alamos tests were named after scientists. This one was called “Smoky.” I guess we were at least five miles away. Carson told us that after the countdown we were to look away and count to ten otherwise the light would blind us. He did not otherwise explain what we were going to experience. There was someone talking on a loudspeaker who counted backwards from ten. I had turned my back, but at “zero” there was a blinding blue and white reflected light. This is the first thing someone from Hiroshima or Nagsaki would have seen. I counted to ten and then turned around. I was not prepared for what I saw. A fireball with livid reds, oranges and above all, incandescent yellows filled the horizon. It was as if a malignant genie had been unleashed from the earth. And surrounding the fireball in a circle like worshippers at a pagan rite were odd formations of debris that had been lifted from the scrub desert. To add to the effect, an entire hillside of yucca plants had been set on fire. I understood how the people at Trinity must have felt. I also understood Oppenheimer's quotation from the Bhagavad-Gita

If the radiance of a thousand suns
Were to burst at once into the sky,
That would be like the splendor of the Mighty One...
I am become Death,
The shatterer of Worlds.

There is discussion about doing research on nuclear weapons. It is a pity that people who suggest this have never seen one explode.

I was so overwhelmed by this impression that what happened next did not fully register with me for many years. After some seconds I felt a sharp crack in my ears. Not a sound but just a crack. This was followed by a rush of wind. At Trinity this wind knocked Kistiakowski over. It is what produce the firestorm at Hiroshima. Then, there came the sound--rolling thunder. It did not occur to me to ask Carson why things happened in that order. The shockwave must have been moving at supersonic speeds. Why? All during our visit I observed things that I didn't understand. But since I did not need to know, I didn't ask. I think that was part of our unspoken understanding. All of this was classified then and most of it is no longer.

At Trinity the electrical engineer, Harold Eugene Edgerton, who had invented strobe photography, had been engaged to take strobe films of the explosion. He had a camera at about 3500 feet that shot sequences separated by less than a millisecond. One can see the whole sequence on the web. The camera was going so fast that after shooting about two-thirds of a mile of film it exploded. A millisecond is too slow to record the actual fission which takes place in a microsecond. At this point the fireball--a small incredibly hot blob, with a temperature of something like 60-100 million degrees. By comparison, the surface temperature of the sun is about 6,000 degrees. "Radiance of a thousand suns" is about right. Although 60 million degrees, most of the radiation is in the x-ray regime and not in the visible.

Up to this point in the time sequence, all the effects are intrinsic to the bomb and do not depend on the environment. The same effects would occur in the vacuum of outer space. But what happens in the next fractions of a millisecond does depend on the environment. I am going to focus on the kind of ground-level burst that I saw. These take place in the earth's atmosphere, where the composition of gasses is mostly nitrogen and oxygen. These gasses absorb the x-rays from the blast within a few feet of the epicenter of the explosion. This heats up the air which now has a temperature of some 300,000 degrees. The temperature falls rapidly with the expansion of the fireball. But even at this reduced temperature the pressure inside the fireball is a few thousand times the ambient air pressure. The air near the surface of the fireball is sharply compressed and this produces the shock wave. It moves much faster than the speed of sound in air and heats up the air it comes in contact with which becomes incandescent. This incandescent air absorbs the much hotter radiation coming from the interior of the fireball, which now becomes invisible to an outside observer. At this stage Edgerton's photographs show the incandescent air external to the fireball. At about 15 milliseconds for a bomb the size of the gadget, the temperature of the air drops to where it is no longer opaque to the radiation from the fire ball and at this stage Edgerton's photographs show the interior of the fireball with all its complexity. This is what I saw when I first turned around to face the blast. The mushroom cloud also begins to form. The fireball rises like a hot air balloon sucking up the cooler air below with the debris from the ground. In Smoky this produced a dark, ominous, radioactive cloud that hung over us like a guillotine. As you can see, the physics of this is very complicated.

After the explosion we did not have much to say to each other. We went back to the bunkhouse for a nap. A few hours later I heard the sound of helicopters. I had no idea what this meant and did not learn until years later. This test was part of the most extensive series ever done at Mercury. It was called "Operation Plumbob." It consisted of 29 explosions beginning on May 29 and lasting until October 7. It was later estimated that the cumulative fallout radioactivity from these tests would cause an additional 38,000 cases of thyroid cancer, leading to some 2,000 deaths. The fallout was deposited throughout the U.S. But this was not all. The Department of Defense had decided that these tests would be a good opportunity to train troops for battlefield atomic war. During the series some 18,000 servicemen participated, often being marched or helicoptered into Ground Zero not long after an explosion. At Smoky, some 3,000 troops participated in this folly. Their health was followed for several decades and a 1980 survey showed that their leukemia rates were more than double that of the general population. That was the noise of helicopters I heard.

When we got up Carson took us on a tour of the site. Much of the ground where previous explosions had been was like fused glass. There were signs that indicated where the level of radioactivity was high. We stopped at a 500-foot tower with an exposed lift on the outside. On the platform on top the bomb for the next morning was being prepared--"Galileo," a Los Alamos test. To get to the platform we had to climb a somewhat makeshift ladder from where the elevator let us off. There were several men working on the bomb. There was the clicking sound of a pump. I had been around laboratories enough to suspect that this had something to do with cryogenics but I had no idea what and didn't ask. Our last stop was a concrete block house. Carson had not warned us. When he opened the door I could see shelves with "pits" on them--the plutonium spheres--enough to blow up a continent. Instinctively I stepped back and Francis said laconically that if one of them went off my retreat would not make much difference to my outcome. Carson handed me one to hold, suggesting that I should probably not drop it. It was about the size and the weight of a bowling ball. It did not occur to me that this needed an explanation. I didn't know enough even to ask the right question. I did not know that the gadget and Fat Man had been solid spheres of plutonium. A solid sphere of plutonium the size of a bowling ball would weigh well over 200 pounds. These spheres were, I later realized, hollow. I came to realize much later that Smoky and the other bombs being tested then were not pure fission bombs. They were what are called "boosted" bombs. That hollow was going to contain fusible elements, perhaps in liquid form--hence the cryogenics. These mixed weapons were much more powerful than a pure fission bomb like the gadget. Indeed Smoky had more than twice the yield. All the fission bombs in our arsenal are boosted weapons. This one would imagine is true for the other countries. There are thousands of these weapons and it is time to get rid of a great many of them.