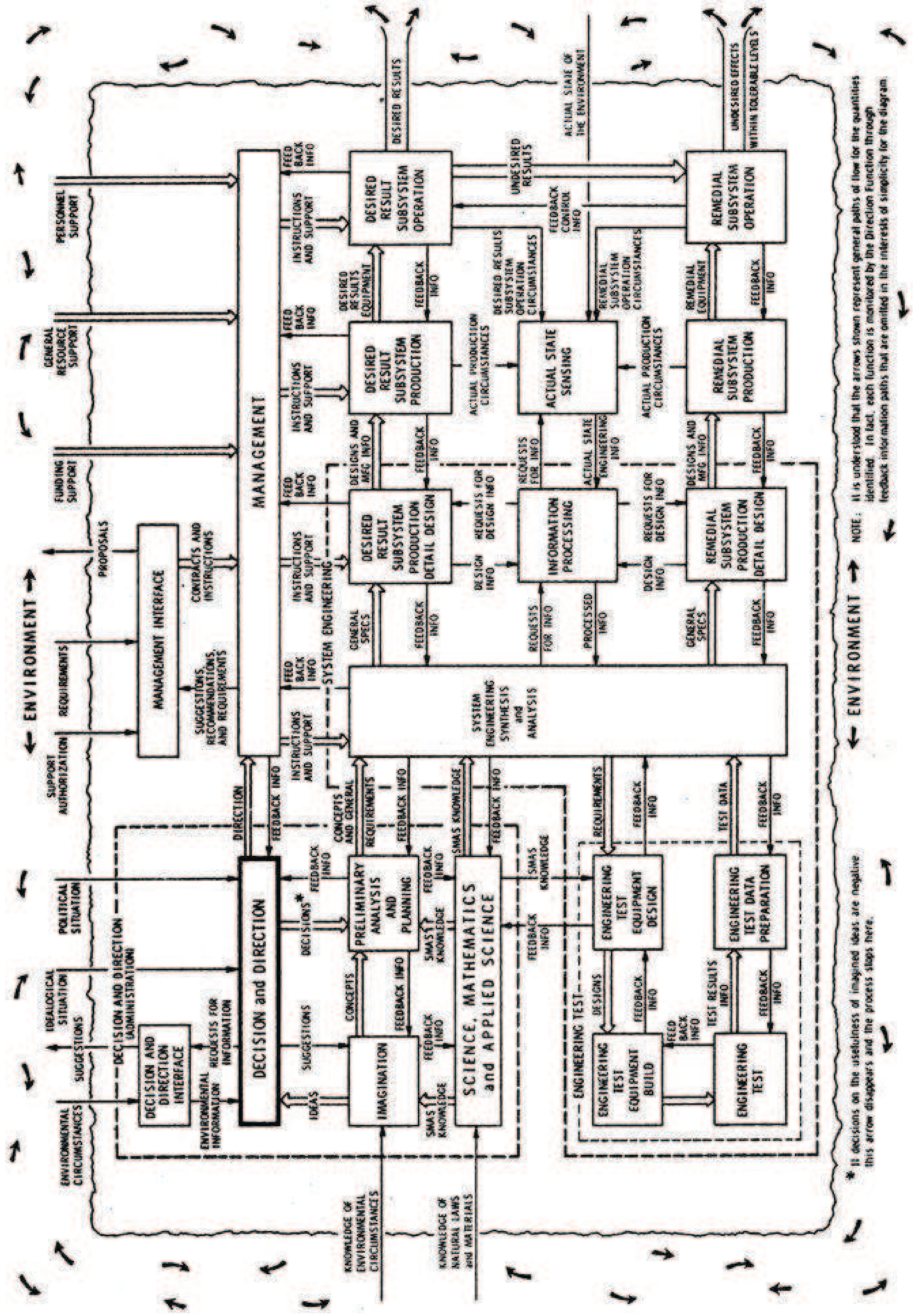

Extrait de C. Stark Draper, “Critical Systems and Technologies for the Future”, in *International Cooperation in Space Operations and Exploration*, vol. 27, Science and Technology, 1971 (American Astronautical Society).

Postface

Science, technology, arms

The text below is only a part of the postface that was announced in the preface to volume I; the full text, with references to sources, is substantially longer than the French version, already 90 pages long. It will be available to interested readers on the Internet, at the following address:

www.springer.online.com/de/3-540-20921-2

Readers who wish to understand why a mathematics textbook includes the text below will find explanations in the preface to volume I.

I have tried to be as pedagogical as possible, but since this postface deals with many topics far removed from mathematics, it will, of course, require some work and good will from the reader to understand it.

Many sources have been used, and all of them will be found in the internet version. A few have been mentioned in the printed text.

Italics have been used for verbatim quotations in the main text.

§ 1. How to fool young innocents

The H-bomb was born in September 1941 at Columbia University in New York during a conversation between Enrico Fermi and Edward Teller. The explosion of an atomic bomb based on the fission of U-235 or Pu-239 nuclei could generate the tens or hundreds of million degrees necessary for the fusion of hydrogen nuclei, which in turn would generate amounts of energy hundreds of times greater than that of the atomic bomb itself. This was nothing more than a very rough idea, but Teller and others already knew (or believed) by 1942 that, if a 30 kg mass of U-235

> is used to detonate a surrounding mass of 400 kg of liquid deuterium, the destructiveness should be equivalent to that of more than 10,000,000 tons of TNT [the standard military explosive]. This should devastate an area of more than 100 square miles.

Yet the development of the A-bombs which destroyed Hiroshima (U-235) and Nagasaki (Pu) was top priority during the war, so that nothing much happened for several years although a few people around Teller continued their theoretical studies of the problem; after a team of physicists reviewed the issues in the spring of 1946, even Teller went back to theoretical physics at

Chicago. Calculations were very difficult to carry out, they neglected physical effects that opposed the fusion reaction, the choice of which isotopes of hydrogen to fuse was not easy, and the geometrical configurations they were drawing up could not work or, if they did, could not lead to the ultimate weapon, namely something with theoretically unlimited power. Last but not least, experimental verification of the computations was impossible short of exploding an actual weapon. In addition, many influential physicists were against the development of a weapon which they viewed as being far too powerful and which would most likely be imitated by the Soviet Union sooner or later.

The situation changed dramatically after the announcement in September 1949 by President Harry Truman of a first secret (but detected) Soviet atomic test. The General Advisory Committee (GAC) of the Atomic Energy Commission (AEC, now part of the Department of Energy, DoE) was convened to deal with the new situation at the end of October. Basically for ethical reasons, the GAC members (scientists J. Robert Oppenheimer, Arthur Compton, James Conant, Enrico Fermi, Lee A. DuBridge, Isidor I. Rabi, Cyril Stanley Smith, as well as the Bell Labs president, Oliver E. Buckley, and Hartley Rowe, an engineer) were unanimous in their opposition to the development and production of the H-bomb, though they were not against further theoretical studies; they recommended the production of more fission bombs – new types under development, up to 500 kilotons (KT), were deemed powerful enough to deter the Soviets -, including "tactical" ones (for use in Europe...), and they recommended providing by example *some limitation on the totality of war*; when briefed by Oppenheimer, the tough Secretary of State, Dean Acheson, a friend and admirer, replied: *How can you persuade a paranoid adversary to disarm "by example"* ? Other scientists, like Teller and Ernest Lawrence who were not GAC members, were also strongly in favor and briefed the president of the Congressional Committee on Atomic Energy and top men in the Air Force, who began to call for it. Three of the AEC administrators (including the AEC President) were against it, and the other two for it, including Lewis Strauss, a most influential and conservative Wall Street tycoon who, like Teller, was as "paranoid" as Joe Stalin, and did not hesitate to go straight to Truman. The H-bomb supporters rejected the idea that America might come out second in the H-bomb race; and in an America again made fiercely anti- Communist by the Soviet domination of Eastern Europe, by the 1948 attempt to blockade Berlin, and by the "loss" of China to the Communists in 1949, the overwhelming majority of people also wanted supremacy over, not parity with, the Soviet Union. Furthermore, the near total American demobilization in 1945 and the rejection of Universal Military Training meant that reliance on atomic weapons was America's only means of deterring, slowing down, or resisting the onrush of a Red Army which, after demobilizing, still retained about three million men and compulsory military training, even though the said onrush was considered by people in the know to be quite improbable within five years.

As President Truman said at the time, *there was actually no decision to make on the H-bomb*: he shared these arguments and, at the end of January 1950, after three months of totally secret discussions involving about one hundred people, he publicly announced that the development of the H-bomb would continue; he also forbade people connected with the AEC, including GAC members, to discuss the subject in public.

In early February, thanks to the partial decrypting of Soviet wartime telegrams, the unfolding of the Fuchs affair in Britain a few days earlier proved that the bright ex-German Communist physicist sent by the British to Los Alamos in 1943 had transmitted to the Soviets not only essential data on the A-bomb, but also most probably what was known on the future H-bomb up to April 1946: he had even taken a patent out on it, in common with von Neumann! The Soviets thus knew America was on the H-bomb trail, and America knew that the Soviets might also be working on it, as Teller had claimed – rightly, but without proof – long before. In March 1950, on the advice of the military, who did not need this new piece of information to make up their minds, Truman, this time secretly, made H-bomb production a top priority.

The correct physical principles were not even known. Numerical calculations carried out by mathematicians John von Neumann at Princeton and Stanislas Ulam at Los Alamos, and performed partly on the new but insufficiently powerful electronic machines, confirmed that Teller's ideas could not lead to the weapon he had been dreaming of since 1942; Teller's optimistic calculations still relied on incorrect hypotheses or missing data. One (theoretical) version of the weapon under consideration in 1950, which would develop a power of the order of 1,000 megatons, *was some 30 feet long, and a stunning 162 feet wide; the fission trigger alone weighed 30,000 pounds.* Technical follies, as Freeman Dyson would later say.

Anyway, developing the weapon had to be done at the Los Alamos laboratory where the A-bomb had been developed and where a reduced team had remained or had been recruited since Hiroshima. Although the outbreak of the Korean war led many top physicists to join the project, many members were on Oppenheimer's side as Teller knew full well, and he believed they were not enthusiastic enough to succeed. Supported again by Ernest Lawrence, the Air Force, and key Congressmen, Teller asked for the creation of a rival laboratory in 1950, but his request was denied by the Atomic Energy Commission. Teller was desperate at the end of 1950 and no longer sure a true H-bomb, with arbitrary large power, could be made.

But in January 1951, Ulam devised a new geometric configuration: to separate completely the atomic triggerfrom the material to be fused. It was seized by Teller who found an entirely new way to make the fusion work before the bomb blew up: the near-solid wave of neutrons flowing from the atomic explosion was too slow; instead, his idea was to use the X-ray burst from it to generate the necessary temperature and pressure. During a meeting at the Princeton Institute for Advanced Research (which Oppenheimer now headed) in June 1951, everyone enthusiastically agreed that this was the solution, and Teller got the laboratory he had asked for in September 1952. In November 1952, a test of the principles, using liquid deuterium and a good sized refrigeration installation, produced the 10 megatons (MT) predicted in 1942; it also vaporized a small island in the Pacific ocean. In April 1954, several tests of near-operational weapons using lithium deuteride, an easily stored white powder, produced between 10 and 15 MT – two or three times more than predicted, because one of the reaction phases had been overlooked. Operational weapons (10-15 MT) went aboard giant B-36 bombers from the end of 1954 to 1957; later ones never exceeded 5 MT and most were in the hundreds of KT range. All of these successes, and the great majority of later achievements too, were the work of Los Alamos people "lacking enthusiasm". The first true Soviet H-bomb was tested in November 1955 and produced about 1.6 megatons.

Set up at Livermore, not far from Berkeley, Teller's laboratory is now called the Lawrence Livermore Laboratory (LLL) and has been managed, at least officially, by the University of California since 1952, as Los Alamos has been since 1943. All American nuclear weapons were invented at these two places; while this still remains Los Alamos' basic activity, Livermore later concentrated a large part of its work on much more innovative scientific-military projects, as will be seen below. Lawrence won a Nobel prize for his invention at Berkeley in the 1930s of the first particle accelerators (cyclotrons). To a large extent, this was made possible by philanthropists attracted by the potential medical uses of radiation or artificial radio-elements available much more cheaply and abundantly than radium. During the war, Lawrence initiated and headed a massive electromagnetic isotope-separation process inspired by his cyclotrons; you can gauge Lawrence's influence from the fact that the Treasury Department lent him over thirteen thousand tons of silver to wire his "calutrons", despite an endless series of unexpected technical problems which brought operations to a complete halt as soon as the war ended. They nevertheless performed the final enrichment, at 80% of U-235, of much of the partly enriched uranium obtained from another massive factory, where uranium hexafluoride – a very nasty gas – was blown through thousands of porous metallic "barriers"; the very primitive Hiroshima bomb used some 60 kg of the final product. Together with Oppenheimer, Fermi, Arthur Compton and Conant, as well as the Secretaries of War and State, Lawrence had participated in the June 1945 top- level discussions concerning the use of the first available bombs. They had also recommended a well-financed research program in nuclear physics, military and civilian applications, as well as weapons production.

It was to this most influential operator, whose Berkeley Rad Lab had strong connections with Los Alamos, that the Atomic Energy Commission entrusted in 1952 the task of setting up a new development center for the H-bomb. Livermore needed a director, and Lawrence chose one of his assistants, Herbert York, then 30 years old.

After Sputnik (1957), York took charge for a while of all American military research and development. Health problems forced him to cut down on his activities, and he "retired" to a California university, while still participating in negotiations and meetings on arms control. From 1970 on, he wrote articles and books about the arms race, the absurdity and danger of which he could now clearly see.

In 1976 he wrote a short book, *The Advisors*, recounting the development of the thermonuclear project and, in particular, the discussions which had taken place at the end of 1949 on the opportunity to launch a H-bomb development program. His book reproduces in full the recently declassified report in which the AEC's General Advisory Committee explains the practical and ethical reasons against it.

With a rare frankness, York discloses the reasons which led him to participate in the project after the start of the Korean War (which led some opponents of the H-bomb, like Fermi and Bethe, to change their minds). There was first *the growing seriousness of the cold war, much influenced by my very close student-teacher relationship with Lawrence*, a fierce anti-Communist like Teller, Ulam, and von Neumann. There was also *the scientific and technical challenge of the experiment itself*: it's not every day you get the opportunity to explode the equivalent of ten million tons of TNT for the first time in history (it was actually done by Los Alamos). There was also, and perhaps most importantly as every young scientist can understand,

> my discovery that Teller, Bethe, Fermi, von Neumann, Wheeler, Gamow, and others like them were at Los Alamos and involved in this project. They were among the greatest men of contemporary science, they were the legendary yet living heroes of young physicists like myself, and I was greatly attracted by the opportunity of working with them and coming to know them personally.

Moreover,

> I was not cleared to see GAC documents or deliberations, and so I knew nothing about the arguments opposing the superbomb, except for what I learned second hand from Teller and Lawrence who, of course, regarded these arguments as wrong and foolish. (I saw the GAC report for the first time in 1974, a quarter of a century later!)

In less than one page, you have something similar to the corruption of a minor taking place in the scientific milieu: you are told that the enemy is threatening your country, the scientific problem is fascinating, great men you admire set the example, other great men you don't know personally are opposed to the project but their arguments are top secret, those great men who are luring you carefully refrain from honestly telling you what these arguments are, and, anyway, you'll be able to read the official documents in 25 or 30 years if you are American, in 50 or 60 if you are French or British, and, at the earliest, after the fall of the regime if you are a Soviet citizen. If you are still alive, your delayed comments will have no impact whatsoever because the project in which you participated was completed decades before, and its justifications have perhaps changed radically in the meantime.

This had already been seen in the A-bomb project: physicists were told (or claimed) in 1941 that the A-bomb was needed before the Nazis got one, it was discovered in May 1945, if not before, that they were years behind, but the bombs were still dropped: over a thoroughly defeated Japan. Quite a number of participants felt they had been fooled, even though they did not know, as we now do, that three weeks after Hiroshima, the Air Force sent General Groves, head of the Manhattan Project, a list of two dozen Soviet cities and asked him to provide the weapons (which was not done until 1948), while Stalin was giving absolute priority to his own atomic project. And nobody then – except perhaps Groves – imagined that tens of thousands of bombs would eventually be produced.

> Main references: Herbert York, *The Advisors. Oppenheimer, Teller, and the Superbomb* (Freeman, 1976), Stanislas Ulam, *Adventures of a Mathematician* (Scribner's, 1976), Richard Rhodes, *The Making of the Atomic Bomb* (Simon & Schuster, 1988) and *Dark Sun. The Making of the Hydrogen Bomb* (Simon & Schuster, 1995), Gregg Herken, *Brotherhood of the Bomb. The Tangled Lives and Loyalties of Robert Oppenheimer, Ernest Lawrence, and Edward Teller* (Henry Holt, 2002), Peter Goodchild, *Edward Teller. The Real Dr. Strangelove* (Harvard UP, 2004), David C. Cassidy, *Oppenheimer and the American Century* (PI Press, 2005).

York may not have been alone in this kind of situation; as Gordon Dean, AEC president 1950-1954, said at the Oppenheimer security hearing in 1954:

> We were recruiting men for that laboratory [Livermore], I would say practically all of whom came immediately out of school. They were young Ph.D.'s and some not Ph.D.'s (...) Under Lawrence's administration, with Teller as the idea man, with York as the man who would pick up the ideas and a whole raft of young imaginative fellows you had a laboratory working entirely – entirely – on thermonuclear work.

Livermore's then two divisions (thermonuclear and fission) were headed by Harold Brown, then 24, and John Foster, then 29; they both were later to head Livermore, then all military R&D, and even the Department of Defense (DoD). I don't know whether, once past the age of innocence, some of these "young imaginative fellows" reflected on their past as York did.

I do know of other similar cases though. Theodore B. Taylor (1925-2004), on hearing about Hiroshima, vowed never to have anything to do with atomic weapons, but he studied physics. In 1948, believing he was working for peace, he joined Los Alamos where he developed a fascination and a gift for improving atomic weapons. He invented the best A-weapons of the time, including a 500 KT fission weapon which, in May 1951, succeeded in fusing a few grams of deuterium; he also became an expert in predicting the effects of nuclear weapons. He left in 1956 for General Atomic (founded by one of Teller's colleagues) and the design of nuclear reactors, then headed the development of a spaceship propelled by multiple small atomic explosions and able to send people to Mars and beyond – the Nuclear Test Ban treaty prohibiting atmospheric tests killed that project in 1963; in 1964 he was put in charge of the maintenance of nuclear weapons, in 1966 he resigned and worked for a while with the international Vienna agency (AIEA) responsible for controlling the civilian nuclear energy business. His initial taste for weapons turned into its very opposite, notably after a visit to Moscow when, looking at the crowd in Red Square, he remembered he had helped the Air Force select the weapons best adapted to targets around the city, the Kremlin being most probably number one on the list. He spent the rest of his life advocating the abolition of nuclear weapons and nuclear energy which, he believed, would lead to an uncontrollable proliferation of weapons and even to their use by terrorists, a prospect he predicted in 1970 by emphasizing that the World Trade Center building could easily be felled by a small atomic explosion on its ground floor.

Recruiting young imaginative fellows at Livermore and other places is still going on, of course. William Broad, a *New York Times* science journalist who spent a week there in 1984 with a very special "O group" of young physicists twenty to thirty years old, explains in *Star Warriors* the role of the Hertz Foundation, founded shortly after Sputnik by Hertz Rent-a-Car's patriotic owner in order to maintain US technological preponderance (and to show his gratitude to a country which turned a poor immigrant into a very rich man). Every year the Foundation allocates about twenty five fellowships, valid for five years, to outstanding students; some of these are invited to spend a summer (or several years) at Livermore while preparing for their Ph.D. elsewhere. Those Broad met were asked to put their energies into problems at the cutting edge of technology with a not so obvious military interest: to build an optical computer using laser lines instead of electrical connections, to design from scratch and to miniaturize a supercomputer, to devise an X-ray laser, to elaborate a credible model of an atomic bomb using only published literature, etc. The group leader, Lowell Wood (who still sits on the Foundation Board together with several other Livermore or Los Alamos people), explained that:

> The best graduate students tend to do very marvelous work because it's a win-or-die situation for them. There is no graceful second place.

> If somebody else publishes the definitive results in the area, they go back to zero and start over (...) They don't realize how extremely challenging these problems are. So they are not dismayed or demoralized at first. By the time they begin to sense how difficult the problems are, they've got their teeth into them and made sufficient progress so that they tend to keep going. Most of them win. They occasionally lose, which is very sad to see (p. 31).

One of them, Peter Hagelstein, remembers his arrival in Teller's kingdom in 1975 when he was 20 years old:

> The lab itself made quite an impression, especially the guards and barbed wire. When I got to the personnel department it dawned on me [!] that they worked on weapons here, and that's about the first I knew about it. I came pretty close to leaving. I didn't want to have anything to do with it [and his girlfriend was militantly opposed to it, which eventually destroyed their relationship]. Anyway, I met nice people, so I stayed. The people were extremely interesting. And I really didn't have anywhere else to go.

Hagelstein was asked to study the X-ray laser. He first spent four years, at the rate of 80-100 hours a week, learning the physics and doing computations with a very powerful program of his own. A senior Livermore physicist, George Chapline, had been trying for years to find a solution by using a nuclear explosion to get the energy needed to "pump" the laser (it is proportional to the cube of the frequency, which for X-rays is about 1000 times that of visible light). A first underground test in September 1978 was a failure because of a leak in a vacuum line. On Thanksgiving Day 1978, some senior physicists – including Wood, Chapline and an unwilling Hagelstein – were summoned to Teller's home to discuss the problem; Hagelstein was ordered by Teller to review the calculations done for Chapline – nothing more, but nothing less – and he had no choice but to comply. By the next day, he had to tell Wood there was a flaw in Chapline's theory, which put him in direct competition with Chapline. He found new ideas which he once dropped at a meeting in 1979, too tired after a 20-hour working day to realize what he was doing. They were seized upon at once and, he told Broad, he *had* [his] *arm twisted to do a detailed calculation* , under *political pressures like you wouldn't believe* . To his despair and with some prodding from Wood and Teller, his calculations and new ideas proved more and more promising, and in 1980 an underground test of his and Chapline's new designs proved Hagelstein's method was by far the better. He then had access to Livermore's gigantic laser lines, and his laser, though still virtual, got a name: Excalibur.

Hagelstein tells us of political pressures; no wonder. On the political side, for several years before Reagan's election, some very influential people – the Committee on the Present Danger – had been claiming that the Soviets were spending far more on defense than even the CIA said, and were re-arming to full capacity. As a matter of fact, since 1975 they had been deploying a few hundred new strategic missiles with multiple independent warheads (MIRV) (deployment of 840 American Minuteman-III MIRV missiles, and of 640 Poseidon submarine-launched similar missiles, had started in 1970 and 1971, respectively). They were also deploying very accurate middle-range SS-20s aimed at strategic targets in Western Europe and China. Their output of basic industrial goods (steel, coal, cement, etc.) was 50 to 100% higher than America's (but the American economy was converting to an "information society" far more efficient than Stalin's successors' taste for steel). They were discovering huge fields of oil and natural gas from which they got plenty of foreign currency, allowing them to buy (mostly American) grain and, much worse, advanced foreign machinery in spite of the US embargo on high-tech goods. "Marxists" were seizing power in several African states; unrest in Poland was repressed by the Polish army to avoid a Soviet intervention; the Red Army had intervened (unwillingly at first) in Afghanistan to defend the new Communist regime against its enemies, which many interpreted as a first Soviet step towards the proverbial Persian Gulf "warm waters" the Tsars had never managed to seize. The American deployment in Europe of equally dangerous American Pershing ballistic missiles and Tomahawk cruise missiles in answer to the SS-20s was opposed by strong "peace movements" that were suspected of being infiltrated by Soviet agents since, of course, ordinary German citizens were deemed too stupid to worry for themselves about these displays of atomic fire power. In short, the world had entered what became known as the *New Cold War* .

Thirty two members of the Committee on the Present Danger, including Reagan, occupied high administration offices after he came to the White House in January 1981. He immediately started to re-arm – the DoD budget, mostly financed by foreign capital attracted by high interest rates, went up from 181 BD in 1978 to 270 in 1984 in constant dollars -, and he continued to taunt the Soviets in speeches that culminated in his famous "Evil Empire" statement in 1983. However, many people in Washington, including Reagan himself, believed that in spite of its apparent strength, the USSR was under tremendous economic pressure with a grossly inflated military sector and a grossly underdeveloped civilian sector. They thought that a new round in the arms race would bankrupt the Soviets, or force them to agree to significant cuts in strategic armaments, or both.

There were already people in America trying to sell untested and wild anti-missile schemes, e.g. chemical lasers, 24 of which could supposedly destroy an entire fleet of Soviet missiles, or thousands of interceptors launched from hundreds of space stations. This led another bunch of conservative businessmen who had nothing to do with nuclear weapons, but were close to Reagan, to found a *High Frontier* committee, including Teller who wanted to sell his X-ray laser right away; they wanted to reach the White House without going through the Pentagon bureaucracy, where hard technical questions would be asked, of course. In this way, Teller was able to recommend a Los Alamos friend as Scientific Advisor, George Keyworth, who in turn appointed him to the new White House Science Council. A High Frontier report was sent to Reagan, and they got a fifteen-minute audience in January 1982; Teller apparently did not attend. They claimed that the Russians were well ahead in technology (as Teller had claimed to promote his H-bomb project), that they were close to deploying directed-energy weapons in space, thus altering the world balance of power. They recommended that America launch a major program to counter the Soviet threat in order to substitute *assured survival* for *assured destruction* , which suited Reagan quite well. Hagelstein's X-ray laser was the key to success and would be available within four years, followed by even more powerful versions. All of this rested on the secret results of a single test performed in a totally artificial underground environment.

Reagan, however, asked Keyworth to gather a team of experts from his Science Council in order to review the project before the end of 1982, if only to get an idea of the price tag. During this year, peace movements in America and Europe drew hundreds of thousands of people (and many scientists) demonstrating against the new arms race; many American Congressmen agreed. In June, a group of Livermore scientists who had the responsibility of continuing work after the first test, reported that the project would require ten more tests, six years, and 150-200 million a year to establish reliably that this laser was scientifically possible; it would then have to be transformed into an operational space weapon, which would require still more engineering, money, and years. This made Teller furious and all the more convinced that, as had been the case with the H-bomb, the project needed a lot of hype to take off. After complaining on TV that he had not yet met with President Reagan, he got an audience in September; some of those present interjected so many questions that Teller (and Keyworth) felt the meeting had been a disaster. In December, the House rejected funds for the production of a new and widely criticized generation of missiles, the MX, which could be randomly moved underground among many silos, most of them empty, in order to fool the Russian MIRV missiles. In January 1983, Teller got an audience with the Chief of Naval Operations; he was convinced by Teller's views and converted the Joint Chiefs of Staff; to them, it was at least *a way of convincing Moscow of the sheer financial power and technical superiority of the US* , as well as a new way to inflate the Defense budget since MX was becoming far too controversial. A meeting with Reagan in February 1984 ended in agreement; the military believed this would lead to an orderly development project, but Reagan did not wait. In March, to everyone's astonishment, he publicly announced his Strategic Defense Initiative (SDI, or Star Wars) project designed to protect the American people from Soviet missiles – a popular statement if ever there was one, which nevertheless did not placate the opposition.

In the meantime, in February 1983, a most famous nuclear physicist, Hans Bethe, had gone to Livermore, reviewed Hagelstein's project and found it extremely clever physics, which did not mean clever weaponry. After Reagan launched his Star Wars project, Hagelstein's laser became the most publicized – and controversial – part of it though it was still, at best, years away from any kind of operational status; a second test in March was actually inconclusive due to a recording failure. The media explained that, propelled into space by a single missile, individually oriented towards enemy missiles, and "pumped" by a nuclear explosion, fifty X-ray lasers were expected to destroy as many targets. Many physicists, foremost among them Hans Bethe and Richard Garwin, were opposed to this new exotic hardware display and said so publicly, because the chances of success were poor for many reasons – the need for fantastically fast computers and communications (laser weapons would be launched from submarines after the Soviet attack was detected, they would have to spot missiles moving at a speed of four miles per second and then orient the laser rods before firing, etc.) -, because nobody knew whether the project would cost 150 or 3,000 billion dollars (BD) if successful, and because it would only lead to one more spiral in the arms race and/or could be easily defeated (as the Soviets at once remarked). Another official panel reviewing the project came to rather pessimistic conclusions, relegating Reagan's dream to the year 2000 or so, and calling for a less ambitious goal, while at the same time recommending one billion and top priority for the laser, and 26 billion over seven years for the various other projects: SDI had already acquired an immense political power by this time. During a propaganda tour of Europe in 1985(?), SDI chief, General James Abrahamson used plenty of sexy slides to explain it all at the Paris Ecole polytechnique (I attended); this was a major contribution to the students' scientific education: they (and I) did not know a thing about X-ray lasers, but you can trust them to have "understood" everything within a week.

A few days after a successful test in December 1983, Teller sent an overly optimistic report to Keyworth, without notifying anyone, not even Roy Woodruff, a senior Livermore physicist who was deputy director for weapons design and thus oversaw the X-ray laser group; Woodruff was furious and wrote a corrective letter, which was blocked by Livermore's director. In the Spring of 1984, other objections arose. According to Los Alamos scientists, beryllium mirrors that were sending a fraction of the beam to recording instruments contained oxygen which, excited by the beam, possibly increased the recorded brightness. The dispersion of the laser beam in space, the number of space stations and the power of the explosions needed were also publicly criticized by independent scientists. But in Washington others noticed that Soviet negotiators – who had been working for years on arms reduction – were very concerned about this militarization of space and therefore might be more accommodating, others again thought SDI would be a good opportunity to wreck the 1972 ABM treaty which seriously limited the deployment of anti-ballistic missiles.

By 1984, Hagelstein had lost his initial dislike for weapons:

> My view of weapons has changed. Until 1980 or so I didn't want to have anything to do with nuclear anything. Back in those days I thought there was something fundamentally evil with weapons. Now I see it as an interesting physics problem.

He did not have any illusions:

> I'm more or less convinced that one of these days we'll have World War III or whatever. It'll be pretty ugly. A lot of cities will get busted up.

In October 1984, Hagelstein and a team of forty people realized at long last the first "laboratory" X-ray laser, using a 150-meter long laser line pumped by capacitors discharging ten billion watts; this success was still very far from the operational weapon Teller was promising Reagan.

During this time, the Livermore group had devised the theoretical means to increase the laser power by several orders of magnitude, so that now "Super-Excalibur" lasers could be placed on a stationary orbit and still be able to kill missiles 20,000 miles away! At the end of 1984, Teller wrote through Wood to Paul Nitze, since 1950 the top expert in arms-control negotiations:

> a single X-ray laser module the size of an executive desk which applied this technology could potentially shoot down the entire Soviet land-based missile force, if it were to be launched into the module's field of view.

Woodruff was again by-passed but learned of the letter; he again tried to send a corrective one, which again was blocked. However, in February 1985, he was allowed a two- hour meeting with Nitze, who said that *it's always good to get a bright skeptical mind on a problem* . The initial results of a new and very elaborate test seemed so good in March that Teller's constant lobbying did pay off: hundreds of millions were released.

That same month, Mikhail Gorbachev came to power in the USSR, with a quasi-revolutionary program to transform the Soviet Union into a near-democracy and to terminate the arms race and the Cold War, which Reagan wanted too (but by other means). Although his scientists told him that SDI could be neutralized for 10% of the price to America, he decided to focus the US-Soviet arms-control talks on removing SDI in exchange for heavy cuts in missiles. Reagan met him in Geneva in November 1985 and, although the meeting was rather friendly, Gorbachev told him he should not count on bankrupting the Soviet Union or achieving military predominance, and that SDI would render impossible the expected 50% reduction in missiles. Reagan replied by extolling the virtues of defense, as usual. They continued to correspond for months in the hope of getting some kind of agreement; many of Reagan's aides and top military (not to mention Europeans, including France's president Mitterand) were appalled by Reagan's apparent willingness to dump American missiles provided he could keep SDI.

In October, at the annual conference of Los Alamos and Livermore people on nuclear weapons, Los Alamos scientists reiterated in detail their skepticism over the test results or even the existence of the X-ray laser; this allowed most members of the X-ray laser group to understand for the first time that these objections were serious. And Los Alamos people accused Livermore managers of abdicating their prerogatives to Teller and Wood, who, of course, claimed Los Alamos were trying to sabotage their project for political reasons or out of rivalry. This was enough for Woodruff, who resigned from his position. Teller's predictions, however, became somewhat more careful, and he emphasized that defense would be efficient even if it were only 20% effective because enough US missiles would survive to deter the Soviets attacking in the first place.

In November, a new and very expensive test (30 MD) resulted mostly in failure. Some Livermore scientists, who were already exasperated by Wood's authoritarian and sarcastic manner and by Teller's constant meddling in their work, left the project; as one of them said in 1989,

> To lie to the public, because we know that the public doesn't understand all this technical stuff, brings us down to the level of hawkers of snake oil, miracle cleaners and Veg-O-Matics.

Although he dismissed Los Alamos objections, Hagelstein too was disgusted by Teller's and Wood's extravagant public claims and by the bad faith the main protagonists displayed; as he told Goodschild in 2000, *I could not believe people behaved in that way* . However, it is easy to understand why they did. These people with plenty of willpower had for decades been in charge of designing the awesome weapons on which US security was supposed to rest. They were under enormous political pressure, and billions of dollars had already been spent on or budgeted for their pet project. Their reputations and the laboratory's were at stake.

Hagelstein quit Livermore for the MIT Research Laboratory in Electronics, which had been conducting military research since 1945, and worked in quantum electronics and, later, "cold fusion". This is a very controversial and to this day unproven method of generating energy at room temperature by means of fusion reactions among metallic compounds of hydrogen and deuterium. His scientific reputation suffered greatly as a result. As to Woodruff, he was exiled to a tiny office ("Gorky West") and his salary cut for several years, a good illustration of the contradicting ethics governing open and classified research; he joined Los Alamos in 1990.

The conflict between the two laboratories surfaced in the newspapers, triggering another public but inconclusive discussion, since the relevant technical data were top secret. In 1986 several thousand scientists publicly pledged not to participate in SDI in spite of the promise of exciting problems to solve and plenty of money for their laboratories. Politically, Teller won; he was supported by the military, by influential Congressmen, and by Reagan who understood nothing but trusted the "father of the H-bomb"; Teller hesitated neither to rely on Reagan's faith, nor to use his own scientific self-confidence, reputation and authority to ruthlessly counter opponents.

As for the Star Wars project, it survived until Bill Clinton's election in 1992. In January 1986, Gorbachev proposed to get rid of all Euromissiles on both sides, and to eliminate all nuclear weapons by 2000, provided America gave up developing, testing and deploying space weapons. Reagan proposed instead to reduce strategic warheads to 6,000 on each side (this was achieved four years later under George Bush) and to redress existing conventional imbalances. In July, Reagan proposed scrapping all ballistic missiles within ten years while continuing research on SDI which, when operational, would be made available to all (!). They had a second meeting in Reykjavik in October 1986 during which extraordinary proposals were made on both sides with a view to eliminating nuclear weapons entirely and reducing conventional forces. Once more, SDI killed the agreement at the last moment. Gorbachev's advisors (who were as bewildered as their American counterparts by these proposals) told him that Congress would kill SDI for him anyway. He did not follow their advice, but they were right: Congress cut the SDI budget by one third and prohibited tests in space in December 1987. In the meantime, a Livermore friend of Teller's had found a new miracle weapon, *Brilliant Pebbles* : space stations firing thousands of sophisticated projectiles, full of electronics, which would collide with Soviet warheads. A third Reagan-Gorbachev meeting in Washington a few weeks later led to the end of Euromissiles.

The Cold War died in 1990 and with it the Soviet Union and SDI; a few years later, the French Riviera was invaded by a new brand of Bolsheviks: oligarchs. The life expectancy of ordinary Russians began to decline. The European Union eastern boundaries (and with it those of NATO, a clever way of assuaging nationalist feelings in Russia) are now the pre-1939 boundaries of the former USSR. Last but not least, it has been "proved" that socialism is a dead end (especially if confronted with savage aggression followed by a ruinous fifty-year arms race led by a far more powerful opponent).

When asked why SDI did not work, Teller recently replied with a shrug: because the technology was not ready. The X-ray laser had cost 2.2 BD, and Star Wars a total of 30 BD. America is now spending a mere ten billion a year to develop anti-missile weapons against lesser threats than the Soviet arsenal, while Livermore (as well as the French Atomic Energy Commission) is trying to achieve, among other projects, controlled nuclear fusion of hydrogen isotopes by means of convergent laser beams in the hope, going back to 1950, of transforming nuclear fusion into an inexhaustible source of energy, as was done much earlier with nuclear fission. This also allows weapons designers to gain a deeper knowledge of fusion processes so as to improve their computer programs.

> Main references: William J. Broad, *Star Warriors. The Weaponry of Space: Reagan's Young Scientists* (Simon and Schuster, 1985 or Faber and Faber, 1986), Goodchild, *Edward Teller* , Martin Walker, *The Cold War* (Vintage, 1994), John Prados, *The Soviet Estimate. US Intelligence Analysis and Soviet Strategic Forces* (Princeton UP, 1986), Stephen I. Schwartz, ed., *Atomic Audit. The Costs and Consequences of US Nuclear Weapons Since 1940* (Brookings, 1998).

Before having a look at Ken Alibek's Soviet career in biological weapons (BWs) from 1975 to the fall of the Soviet Union, let me sketch their previous development. After Pasteur, Koch, Metchnikoff and others had founded microbiology, it became possible to produce large amounts of vaccines. It also became obvious that, if required, similar techniques could be used to cultivate pathogens. That it was not pure theory was shown when the 1925 Geneva Convention prohibited it. The USA did not sign it, but the USSR and Japan did; it seems that USSR began to develop a typhus weapon in 1928, while Japan installed a very successful secret laboratory and production unit in Manchuria in the 1930s. Britain started to study vaccines after 1936 and, after the Nazis had advertized their brand of ethics at Warsaw and Rotterdam, thought it advisable to develop BWs as a hedge against similar German ones (they were not studied seriously until 1943 and came to almost nothing). British scientists worked mainly with anthrax, a bacterium which is easy to cultivate and store by transforming into spores that stay virulent for decades. Conclusive experiments on sheep were done at Gruinard Island, off Scotland; it was still contaminated and off limits fifty years later. They made anthrax cakes in sufficient quantities to be able to kill a lot of German cattle (and some people as well).

In America, studies on BWs began in 1940, and a National Academy of Sciences (NAS) committee was set up a month before Pearl Harbor. Although its February 1942 report was inconclusive in the absence of practical tests, it recommended studying all possibilities (for defense, of course) including anthrax, botulin toxin, and cholera. The program involved the Chemical Warfare Service, the Department of Agriculture for anti-crops weapons, and 28 universities. Although behind Britain until Pearl Harbor, American industry quickly developed a far bigger military potential than Britain, which, in this domain as in others (atomic bomb, radar, jet engines, etc.), contributed experts and knowledge, including penicillin which was industrialized in America during the war.

A research center was set up at Camp Detrick and, in Vigo, Indiana, a factory equipped with twelve 5,000-gallon fermenters could in principle produce 500,000 four-pound anthrax bombs a month, or 250,000 filled with botulin toxin (lethal dose: one milligram). The Americans also investigated brucellosis, a *more humane* weapon which kills few people, but is highly contagious and makes its victims ill for weeks or months, thus overwhelming the enemy's health system. Weapons for use against Japanese rice crops were also developed. But Roosevelt was not very interested in these matters about which he was very ill informed, and he never made his position clear one way or the other.

In any case, peace came before this program became operational, and Vigo was leased to a private manufacturer of penicillin. In 1945 BWs were considered potentially at least as efficient as, and much cheaper than, the atomic bomb; and since they don't destroy real estate, you don't have to compensate the enemy and allies after the victory. But atomic weapons were viewed as a sufficient deterrent, performing realistic tests of BWs was impossible, and the new German neurotoxic gases (tabun, sarin, soman) killed much faster – in a few minutes – than BWs. So, at first, work on BWs was limited to laboratory studies. During the Korean War, the Americans were accused of having experimented with BWs; it is now generally believed they had not, but the war accelerated the arms race in all domains, including BWs. In both the US and the USSR, all kinds of bacteria – anthrax, plague, tularemia, yellow fever -, and later viruses, were studied and mass produced. From 1947, the Soviets worked on smallpox which, by now eradicated, was still killing some 15 million people a year in the world in the 1960s. They built huge research centers and production units, some in cities, such as Sverdlovsk. The CIA had reason to suspect the worst as U-2 and satellite observations showed installations looking very much like the American ones, for instance a test range on an island in the Aral Sea.

During the 1950s, scientists in both countries discovered that instead of storing or spreading bacteria as liquid cultures, it was far better to dry and deep-freeze them (lyophilization); this kept them dormant for long periods, even at room temperature. The result was then milled into an ultra-fine powder which, after being carried by the wind over possibly tens of miles, became virulent again in people's lungs. This process worked particularly well with anthrax, the pulmonary form of which is normally rare and difficult to diagnose and kills 90% of its victims unless they are administered massive doses of penicillin very early.

The "top secret" American programs were actually known to plenty of people and, like the use of chemicals to destroy jungles in Vietnam, met with opposition from journalists, students, and biologists like Harvard's Matthew Meselson and Joshua Lederberg; the latter, who won a 1958 Nobel prize for his discovery of how bacteria can exchange genes in a natural setting, was in a good position to know that fast progressing molecular biology *can be bent to genocide* , as he wrote in the *Washington Post* in 1968. During the Vietnam war, opponents, particularly students, organized public demonstrations against Fort Detrick, as well as protests against military- university contracts and the National Academy of Sciences' involvement in recruiting young scientists for Fort Detrick. For their part, the military were not yet convinced of the usefulness of these weapons; proliferation was too easy and too cheap, and terrorist attacks were already being mentioned. Eventually, President Nixon unilaterally announced in November 1969 that America would limit herself to purely defensive work, and he ordered the destruction of stocks and the demilitarization of Fort Detrick, Pine Bluff and other centers; I remember a *Science* headline: *Is Fort Detrick really de-tricked* ? In 1972, an international treaty between the US, the USSR and Britain, later approved by many other countries, prohibited the production and possession of biological weapons, but not defensive laboratory work; it did not provide for inspections either.

Before 1972, and although "weaponizing" pathogens required solving difficult technical problems, only natural bacteria and viruses were used. In 1972-1973, American biologists succeeded in systematically moving a gene from an organism to a bacterium in such a way that the modified bacterium would replicate itself as usual; their first experiment yielded a variant of the normally harmless Escherichia Coli that was resistant to penicillin. Thus genetic engineering was born and, with it, the possibility of discovering, by chance or on purpose, new pathogens from which no protection was known. But in the USSR, molecular biology and Mendelian genetics had been almost destroyed by Lysenko in the 1930s, and Soviet scientists were increasingly frustrated at the thought of being left behind. According to Alibek, the situation changed when a vice president of the Akademia Nauk, Yuri Ovchinnikov, explained to the Ministry of Defense and to President Brezhnev that bioengineering could lead to new weapons.

This led to the founding in 1973 of an officially civilian pharmaceutical organization, Biopreparat, under the Ministry of Health. Biopreparat's open mission was to develop and produce standard vaccines and antibiotics, but it enclosed a supersecret "Enzyme" project whose purpose was to develop and produce for intercontinental war *genetically altered pathogens, resistant to antibiotics and vaccines* , an outright violation of the 1972 treaty. It also led, as Ovchinnikov hoped, to a reversal of the taboo against genetics and molecular biology, and to new laboratories depending on the Moscow Academy since "purely scientific" work was paramount for "defense" against biological weapons. The timing was perfect: gene splicing had just been discovered, and its practical importance would soon be proved in the USA by using engineered bacteria to produce large amounts of insulin, hormones, etc. Enzyme, which was led by military scientists and administrators with KGB men everywhere, came to employ 32,000 workers, including many of the best biologists, epidemiologists, and biochemists, in addition to thousands of people working in Army labs.

Let us now go back to Alibek. Hoping to become a military physician who could save soldiers on the battlefields, he studied medicine at a military school and became interested in research. In 1973, he was ordered by one of his teachers to investigate a very unusual outbreak of tularemia which occurred around Stalingrad in 1942 among German troops before spreading to the Soviet army. After reading old documents, Alibek reported that this incident looked as though it had been *caused intentionally* . He was at once cut short by his teacher who told him he was only supposed to *describe how we handled the outbreak* , not what had caused it, and strongly advised *never* to *mention to anyone else what you just told me. Believe me, you'll be doing yourself a favor* . The lessons he drew from this episode are worth quoting:

> The moral argument for using any available weapon against an enemy threatening us with certain annihilation seemed to me irrefutable. I came away from this assignment fascinated by the notion that disease could be used as an instrument of war. I began to read everything I could find about epidemiology and the biological sciences.

In 1975, a mysterious and well tailored visitor came to interview him and other students; he said he was working for a no less mysterious *organization attached to the Council of Ministers* which *has something to do with biological defense* , a prospect which excited Alibek. He was handed a questionnaire and told: *Don't tell your friends or teachers about this conversation. Not even your parents* . A few weeks later, he learned he was assigned to the Council of Ministers of the Soviet Union together with four other students. He was overjoyed by the prospect of working in Moscow, but he was actually sent to a "post office box" hundreds of miles from Moscow. Like Hagelstein, he was impressed by the concrete wall and barbed wire surrounding the place and by the armed guards at the entrance. The huge Omutninsk Base where he arrived already employed some 10,000 people; it was part of the Enzyme project.

On arrival at Omutninsk, Alibek and his friends were not given any information about their research program. A KGB instructor however informed them that although an international treaty banning biological weapons had been signed in 1972, it was obviously *one more American hoax* , which they were quite prepared to believe; the Soviet Union therefore had to be ready to reply.

When Alibek began to discover Omutninsk's true mission – mass production of pathogens and not merely laboratory research -, he tried to get another job but was told he could not be spared. He thus remained and, after this classic early conscience crisis, adapted to the situation with enough success and enthusiasm to become Biopreparat's deputy director fifteen years later. The science and technique were fascinating and the career very rewarding provided you were bright, which he was, and made no big mistakes (such as inoculating yourself or being too talkative...).

The new recruits were trained in the culture of bacteria, the techniques being the same *whether they are intended for industrial applications, weaponization, or vaccination* . This is a difficult art which is first learned on harmless bacteria; one then has to learn how to infect lab animals with mildly pathogenic agents and conduct autopsies, until one may perhaps be allowed to work in "hot zones" with infected animals and where wearing the equivalent of a space suit is compulsory: half a dozen Ebola viruses will kill you in a month by destroying your blood vessels. A very competent colleague of Alibek once made a false move while inoculating an animal; after his death, they noticed the viruses in his body were particularly virulent, and therefore they weaponized this “Ustinov strain”. One also has to learn industrial production processes.

Smallpox was modified to render all known vaccines useless. Diphtheria was grafted on plague. Sergei Popov, a bright colleague, improved Legionnella with fragments of myelin DNA to trigger metabolic reactions that devastate the brain and nervous system. The invention of a form of tularemia resistant to three of the main antibiotics, as well as studies on Ebola-like viruses took years of work. All in all, little produced by the genetic engineering programs was turned into weapons before the Soviet Union collapsed, according to Popov who has been living in the USA since 1992; Alibek also remains somewhat skeptical, though more pessimistic.

Incidents happened during this period. In April 1979, about sixty people died within a few weeks in the city of Sverdlovsk, an extremely unusual event. There was a Biopreparat branch located in the city, working round the clock on anthrax. A Russian magazine in West Germany broke the news of the outbreak in November, from which US intelligence agents again drew conclusions, despite claims that the deaths were due to contaminated meat. It is now known that a clogged air filter had been removed but not replaced for several hours...

In October 1989, Vladimir Pasechnik, a very bright scientist at the head of a civilian institute in Leningrad, went to France at the invitation of a pharmaceutical equipment manufacturer, and never came back. Since his institute had worked very efficiently for Biopreparat, he knew quite a lot. He was brought to Britain and debriefed.

Pasechnik’s defection had serious consequences. In a memo to Gorbachev, KGB chairman Vladimir Kryuchkov recommended *the liquidation of our biological weapons production lines* , a stunning move which Alibek approved since, after all, *so long as we had the strains in our vaults, we were only three to four months away from full capacity* . Although many powerful people disapproved of Kryuchkov’s initiative, Gorbachev issued a few weeks later a secret decree, prepared by Alibek and another fellow, ordering Biopreparat to *cease to function as an offensive warfare agency* ; but in transmitting Alibek’s text to the Kremlin, his chief added a paragraph instructing the organization *to keep all of its facilities prepared for further manufacture and development* , which resurrected Biopreparat as a war organization, as Alibek says. He was furious but this, at any rate, allowed him to order an end to military development at some of the most important installations.

A second consequence was an agreement between the USA, UK and the USSR to organize inspections of suspected BW facilities. The first inspection of a few Biopreparat installations took place in January 1991; Alibek and the Russian side were very successful in showing as little as possible, but the visitors, who were aware of Pasechnik's disclosures, were not fooled.

In December 1991, during the week the Soviet Union collapsed, a visit to four American installations chosen by the Russians took place; they were known to anybody who had read *Science* magazine around 1970 (as I did). The Russian team included Alibek who could verify that these installations were in a dilapidated condition that precluded military work, or had been converted to medical research – work on the rejection of organ transplants fascinated the Russians -, or, in one case, had never done any military research. The Soviet delegation nevertheless reported to the contrary, and this convinced Alibek that official justifications for his work had been a KGB hoax rather than an American one.

He resigned from the Army, then from Biopreparat, got a job at once in a bank – *I had no aptitude for finance, but I was soon making deals like everyone else* -, and went on business trips abroad. His telephone was tapped, police watched him around Moscow, and some associates warned him that he had better not leave Russia for good and that in any case his family would never get permission to leave. In the meantime, a Yeltsin decree banned all offensive research and cut defense funding.

Alibek then went back to his native Kazakhstan, a newly independent country where a huge Biopreparat production center had been built years before. Local officials asked him to head a "medical-biological directorate" obviously intended for weapons research. He flatly rejected the offer, thus burning his bridges to both Russia and Kazakhstan, he tells us. Since he could still travel abroad for business, he was able to get in touch with Americans who were highly interested in his past and, with the help of a few Russians, managed to get himself and his family out in circumstances he obviously does not disclose.

While being debriefed in Washington, Alibek struck a friendship with his American counterpart, Bill Patrick, who had been at Fort Detrick for forty years and was then its chief scientist. Comparing the nature and timing of American and Soviet programs since the war, they came to the conclusion that at least one disciple of Klaus Fuchs must have been near the top of the US organization. After being kept under wraps for several years, Alibek went public and told his story in *Biohazard* (Delta Books, 1999). He is now the president of a new company, Advanced Biosystems, working on defense against biological weapons and employing, among other people, ex-Soviet scientists, e.g. Popov. And a good deal of cooperation with the US is helping former weaponeers in Russia to convert to peaceful research and to survive the rise in Lenin's country of the Robber Barons' variant of American capitalism.

Pyromaniacs, let us hope, are thus being transformed into firemen; a classic process. Nevertheless, the work is going on everywhere now, not only for "defensive" purposes in military laboratories, but also and mainly in perfectly harmless civilian labs by scientists who publish their findings in standard journals. Although many biologists have tried for decades to devise "ethical rules", knowledge is spreading, the techniques are becoming increasingly easier to learn, and weapons of mass destruction are now threatening their initiators in this domain, as atomic and chemical weapons did long ago.

> References: Ken Alibek with Stephen Handelman, *Biohazard* (Delta Books edition, 2000), Judith Miller, Stephen Engelberg, and William Broad, *Germs. The Ultimate Weapon* (Simon & Schuster, 2001), Robert Harris and Jeremy Paxman, *A Higher Form of Killing. The Secret Story of Gas and Germ Warfare* (Granada Publishing edition, 1983). The potential of some of these weapons can be judged from Richard Preston's (real life) thriller, *The Hot Zone* (Random House, 1994, or Anchor, 1995).

The adventures of these weapons designers are, of course, extreme cases; I relate them here because extreme cases are extremely clear. In normal practice, a scientist and particularly a mathematician can only bring a small contribution to a complex weapons system. This does not raise such enormous and visible ethical problems as the development of H-bombs or biological weapons. But it only makes it easier for confusionists, mystifiers or corruptors to neutralize your objections.

More simply, one may be asked to solve a limited problem without being told of its military end. Although headed by the Department of Defense (DoD)*Advanced Research Projects Agency* (ARPA or DARPA), the Internet project – more accurately Arpanet, its predecessor – was to a large extent developed in a few university centers by many graduate students who were fascinated by it; many innovations are due to them. Contract holders ("Principal Investigators") had, of course, to provide ARPA with (sometimes vague or long term) military justifications, and some of the top people went from ARPA to universities or back. But, as Janet Abbate tells us in *Inventing the Internet* ,

> although Principal Investigators at universities acted as buffers between their graduate students and the Department of Defense, thus allowing students to focus on the research without necessarily having to confront its military implications, this only disguised and did not negate the fact that military imperatives drove the research (...) During the period during which the Arpanet was built, computer scientists *perceived* ARPA as able to provide research funding with few strings attached, and this perception made them more willing to participate in ARPA projects. The ARPA managers' skill at constructing an acceptable image of the ARPANET and similar projects for Congress ensured a continuation of liberal funding for the project and minimized outside scrutiny.

Military secrecy can only lead to similar situations.

That said, not everyone was fooled or seduced, as the case of Pierre Cartier shows. While a student at the Ecole normale supérieure in Paris around 1950, he was attracted by both mathematics and physics without at first being able to choose. He once told Yves Rocard – a physicist with strong industrial and military connections, who headed the physics lab at the school – that he wanted to work for a doctorate. Rocard then handed him a thick bundle of photographs; Cartier understood at once that these were a series of very close steps in an atomic explosion. Rocard proposed that he find a way of computing its power from these pictures, for instance from the propagation of the shock wave, or something similar. Cartier did not like the idea, still less Rocard's conditions: Rocard would help Cartier to get a good university position, but his thesis would remain secret, and he would have to sever his relations with his Communist friends, as well as with Rocard's son Michel, who was embarking on a political career (he became a Socialist Prime Minister thirty years later) and, at the time, had rather leftist opinions which were out of phase with Rocard's.

This decided Cartier to choose mathematics. He soon became a Bourbaki member and one of the best French mathematicians of his generation, still with a taste for mathematical physics, though not Rocard's brand. Of course, one can explain Cartier's reaction by the fact that, beside having strong religious beliefs, he was exposed to a much wider spectrum of political and philosophical opinions at the Ecole normale – where there are as many students in humanities as in science, all living together – than at Livermore or at a Soviet military school of medicine. Still, not everyone reacted the way he did. Thousands of scientists (and many more engineers) worked, and are still working, on military projects with no qualms.

§ 2. The evolution of R&D funding in America

All scientists of my generation know, if only vaguely and without proclaiming it too loudly, that WW II and the Cold War *did wonderful things* (I.I. Rabi) for science and technology; Rabi spent his whole career at Columbia University from 1928 to his death, was already a physics star by WW II, later a Nobel Prize winner, and a top government advisor for decades. I have sometimes been told by colleagues that a statement as "obvious" as Rabi's requires no proof, cafeteria gossip presumably being enough. If this is the case, then professional historians of science and technology might as well retire.

In this section, I'll first summarize the evolution of R&D in the USA since the war, since this country has clearly been the leader and even the model for half a century; Britain and France, as well as the Soviet Union, have always tried to follow America and to adopt its priorities, more or less, with differing results. R&D, for "Research and Development", means basic research (without any practical purpose in sight), applied research (with a more or less well defined practical purpose), and development, during which scientific results are used to design prototypes ready for production. These distinctions are not always very definite, and development usually requires solving many engineering problems, sometimes unexpected scientific ones, as well as extensive (and expensive) tests. Roughly speaking, basic and applied research cost 10 to 15% of R&D budgets each and development requires some 70% of it, but the proportions very much depend on the field.

The roughest measure of a country's R&D activities consists in comparing their total cost to the Gross National Product (GNP). In the USA, the proportion increased from 0.2% in 1930 and 0.3% in 1940 to 0.7% in 1945, 1.0% in 1950, 1.6% in 1954, 2.4% in 1958, and to a peak of 3.0% in 1964; at that time, US funds represented about 60% of all that was spent on R&D in OECD countries (North America, Western Europe, Japan, etc). As many articles, reports on "technological gaps", and books attested at the time, all other countries, and especially de Gaulle's France, looked at this 3% figure with an awe bordering on the mystical; someone joked that the optimal rate might be 3.14159...%. Since, moreover, the US GNP had climbed, in constant currency, from 100 BD in 1940 to about 300 MD in 1964, you can see that in this decisive quarter of a century, R&D expenses multiplied by ten in proportion with the GNP and by thirty in constant dollars! Such a miraculous growth rate could not, of course, be sustained: the R&D/GNP ratio began to fall as soon as it reached 3%, went down to 2.2% in 1978 and wavered between 2.6 and 2.8% between 1983 and 2000. The current and very optimistic goal of the European Community is to reach 3% by 2010.

In America as everywhere else, the two main sources of R&D funds are the Federal Government and private industry. Universities and not-for-profit private organizations also contribute, but on a much smaller scale, though their contributions to basic research may be important in some sectors. For instance, after having made a huge fortune at Hollywood, on the TWA airline, in buying hotels and casinos in Las Vegas and in selling planes to the Pentagon, Howard Hughes, like John D. Rockefeller long before him, set up a foundation whose trustees manage his little hoard, by now worth some 11 billion; the dividends support selected projects in medical research, by far the most popular field in America for a long time.

The relative importance of these two main sources of R&D funding has changed considerably since 1940. This is basically due to the nearly linear or weakly exponential growth of private industrial funds, while the fluctuations in federal funding were much larger, as will be shown.

In 1940, the figures (in current MD) for national total and for federal and industrial contributions were 345, 67 and 234, respectively. In 1945, they were 1520, 1070 and 430, respectively. In 1950, they were 2870, 1610 and 1180. Although data for these years are not entirely reliable, the trend is clear.

For each year between 1953 and 2000, data in *constant* (1996) MD are available in *Science and Engineering Indicators 2002* , an NSF publication easily available at nsf.gov/srs. It provides some significant figures:

	Total	Federal	Industry	Universities	Nonprofit
1953	26805	14455	11670	190	286
1958	50439	32228	17130	256	492
1966	90236	57910	29971	673	1028
1975	89112	46289	39531	1078	1335
1982	122034	56200	61422	1821	1653
1987	162798	75468	80660	2916	2383
1994	176246	63316	103326	4100	3816
2000	247519	65127	169339	5583	5415

From less than 20% in 1940, federal contributions to the *total* R&D reached almost 62% in 1966, stayed over 50% until 1975, remained at 46% during the Reagan years (1980-1988) in spite of a sharp increase in federal (actually, military) funds, then decreased to 26% in 2000. It is only since 1980 that industry has been spending more than Washington. To a large extent, the proverbial "innovative capacity" of US private enterprise has been propelled by federal dollars for almost 40 years, and mainly by defense as shown below.

All federal agencies contribute to the funding of R&D. The Department of Defense (DoD) has been the most significant since 1941, followed by the Department of Energy (DoE, founded at the beginning of the 1970s, dealing with all kinds of energy, including the former Atomic Energy Commission, AEC, founded in 1946), NASA (or NACA, aeronautics, until 1958), the National Institutes of Health (NIH), and the National Science Foundation (NSF). Other federal departments together account for no more than 6% of the federal total, although their role, here too, is substantial in some fields. NSF annual statistics (*Federal Funds for Research and Development*) provide a good, if probably not 100% accurate, view of their evolution.

In 1940, the government allocated 26 MD (current money) to defense R&D, 29 to agriculture and some to geology and mining; there was also a National Bureau of Standards which had been created in 1901 on the model of a German laboratory where much important research was conducted to determine accurate values for physical constants, weights, measures, etc. During WW I, the Washington Academy had created a National Research Council which did a lot of military research and was officially recognized after the war, but it got most of its small budget from private sources and spent it mostly on fellowships for young scientists. Otherwise, practically nothing went to research proper except for the creation in 1937 of a National Cancer Institute.

The picture had changed by 1945. Out of the 1590 MD in federal funds for R&D, agriculture still got 34, defense (atomic excluded) 513, the Manhattan Project (atomic) 859, and 114 went to the Office of Scientific Research and

Development (OSRD) created during the war to organize military research in all sectors. Not surprisingly, defense justified 90% of the total. During the war, industry spent less of its own funds on R&D than in 1940 in constant dollars, but, of course, received a flood of military contracts. Many universities received undreamed of amounts of money for military research: MIT 117 MD, CalTech 83 MD, Harvard 31 MD, Columbia 28 MD, to name but a few; new off-campus installations had to be set up for the most expensive projects. In 1950, out of 1083 MD in federal funds, agriculture got 53, DoD 652, AEC (essentially military at the time) 221, and NACA (similarly) 54 instead of 2 in 1940. Although Truman had considerably "restricted" the total defense budget after 1945 (13-14 BD until 1950, as against one in 1940), it remained large enough to finance a few large-scale technological projects, such as the development of the big jet bombers (B-47 and B-52) and supersonic jet fighters, progress in rockets and missiles, and the beginning of the development of nuclear submarines. The contributions of the main agencies are as follows for selected subsequent years, in *current* money:

	Total	DoD	AEC/DoE	NASA	NIH	NSF
1953	1851	1275	278	84	59	0.151
1958	4774	3480	828	97	218	41
1966	16178	7099	1441	5327	1142	323
1975	19859	9179	2439	3207	2436	618
1982	37822	16786	5896	3708	3950	976
1987	57099	35708	5529	4096	6643	1531
1994	69450	34818	6959	8811	11141	2212
2000	77356	33215	6873	9754	18645	2942

These figures show the relative importance of the main federal sources of R&D money. DoD's contribution has always been, by far, the most important one, but to gauge the real size of defense-related funds, one should also take into account the AEC/DoE budget. In 1968, for example, out of a total of about 1600 MD, AEC's R&D budget included 400 for research proper (48 for weapons, 265 for physics, 86 for biology and medicine); 425 went to the development of weapons, 491 to the development of nuclear reactors, much of it for the Navy and Space, and 224 to construction work. It may also be assumed that NASA's R&D was not totally disconnected from defense even though the DoD itself spent between 500 and 1100 MD yearly on R&D for military astronautics between 1961 and 1965, and between 2 and 3 billion for the development of missiles. It may also be assumed that the CIA and the National Security Agency (NSA, cryptology, reconnaissance satellites, etc.), whose contributions are not reported, had sizable amounts to spend on R&D. And although much R&D for military industrial projects was to a large extent financed by the government even prior to any production, still some of it was private money.

On the other hand, the prospect of a federal budget surplus under Clinton prompted Congress to adopt a bill in 1998 to double the non-defense part of the federal R&D budget over ten years. This target was reached for the NIH by 2003, at least in current dollars, to the displeasure of specialists in other domains left behind.

The above table shows a substantial decrease of DoD funds after the Reagan years, but the trend was later reversed, courtesy of Mr Ben Laden. According to a recent analysis by the American Association for the Advancement of Science (www.aaas.org/spp/rd), out of the projected federal budget for R&D in the year 2005, the defense-related part, including 4.5 BD from the DoE, should amount to well over 74 billion, and the non-defense portion to over 57, of which NIH will get almost 30, Space over 10 and NSF 3.8. A new domain, antiterrorism R&D, will absorb 3 BD, of which 1.7 will go to NIH to fight bioterrorism, e.g. anthrax pocket weapons which are seen as a serious threat. Although the 2004 budget is the biggest ever since 1945, even in constant dollars, and far bigger than any other country's, America is able to afford it by devoting less than 4% of her GNP to total defense, as against at least 12% at the height of the Cold War. This is because GNP has grown at least five times in constant dollars since 1945.

The tables above make it possible to estimate the percentage of Defense money over total R&D, by converting current dollars into 1996 dollars. In 1958, defense-related federal funds for R&D accounted for 82% of all federal funds and 53.1% of national R&D expenses, hence more than industry's own contribution. In 1987 defense still accounted for almost one third of total R&D and 68% of federal R&D; it later decreased to a low of 13.6% in 2000 because of the growth of industry's own funding; Microsoft for instance is currently spending about 5 BD a year on R&D and presumably does not use the Pentagon's money to develop Windows, which may explain its quality... R&D is mostly development, but the importance of development in Defense is particularly striking: 2.9 BD out of 3.5 BD in 1958 and 28 BD out of 33 BD in 2000, with similar proportions in the interval. Industrial firms always get at least 60% of the DoD funds for R&D, while about 30% of the money is spent in DoD's own technical centers. According to the AAAS, only 5.18 BD should go to basic and applied research in 2005.

Some federal funds go to so-called Federally Funded Research and Development Centers (FFRDC). These were organized during or after WW II and are administered by industrial firms, universities, or nonprofit institutions. The first category includes huge centers such as Idaho, Oak Ridge, Sandia and Savanna River producing nuclear material or weapons, though on a very reduced scale now. The second includes the MIT Lincoln Lab (electronics, radar, SAGE, anti- missiles, etc.), the Jet Propulsion Lab (Cal Tech), Argonne (Chicago U.), Brookhaven (several universities) and huge installations for particle physics at Berkeley, Princeton, Stanford, etc.; last but not least, it also includes Los Alamos and Livermore labs initially founded for the development of nuclear weapons and administered by UC Berkeley, which didn't always relish it although it earned money from it. In the third category, there is the Rand Corporation which was organized in 1946 by Douglas aeronautics and the Air Force and soon became a research center financed by the Pentagon; it became famous in the 1950s for its development of operational research, game theory and mathematical programming, and for its slightly pathological strategic studies, particularly when Herman Kahn, in *Thinking the Unthinkable* and other books, made them popular by explaining nuclear war "escalation" theory (up to what he called a "nuclear spasm" or, as some said, "orgasm") as if it were a very funny poker game.

These cold figures should be supplemented with some more concrete information. As mentioned above, academic research got very little from Washington before the war; it was financed by university funds, philanthropic organizations and, in many engineering departments, by industry, enough to increase significantly the number of scientists during the inter-war period. The Rockefeller Foundation, which up to 1932 spent 19 million on academic research, spent a lot more on medicine than Washington. It also financed physics during the 1920s: thanks to its fellowships, many scientists, including future American designers of atomic bombs, learned their trade in Europe; European physicists were invited to America, some permanently; and the Foundation financed new laboratories in Copenhagen and Göttingen as well as the Poincaré, Institute in Paris. By 1930, and like many social scientists, it was having doubts over the value of physical sciences and technology: gas warfare in WWI had been rather bad publicity, as had the disruption of the American way of life and traditional values by technological advances. It therefore decided in 1932 to concentrate on applications of physics and chemistry to biology, which made it a prime sponsor for many of the future creators of molecular biology. Ernest Lawrence, and he alone, succeeded in attracting big money for his Berkeley cyclotrons: as much as one million in 1940 – a staggering sum at the time for physics – from the Foundation which betted on the prospect of cheap artificial radio-elements to fight cancer; otherwise, almost all of his money came from other philanthropists and the university. America had a good number of first class physicists by the 1930s; three dozen generally small particle accelerators were built in universities (Germany had none in 1940, France had one). In these depression years, particularly 1932-1934, attempts to get federal money were unsuccessful – almost all the New Deal relief money went to jobless people. Although senior scientists were generally comfortable, many younger ones were badly paid, and some unpaid ones spent part of their time making money to survive while continuing laboratory work. It is remarkable that the production of PhD's between 1930 and 1939, namely 980 in mathematics and 1924 in physics, was almost triple that in the preceding decade; this was mainly due to the strong growth of higher education in all domains. Without federal help to speak of, America was thus already the new dominant country in physics.

There were Jewish refugees in all intellectual domains after Hitler's seizure of power; though they were generally much younger, less well known than Albert Einstein, and not always welcome as Jews at the time, many American scientists helped them. After having a hard time until the war, most of the refugee scientists – almost 200 in mathematics and physics – were to find permanent university positions after 1945, and several dozen became leading scientists, or even stars. This also contributed to America's standing in these two domains, as in many others.

MIT, where many top American industrialists and engineers had been educated since the 1880s, already had the biggest electrical engineering department in the world, thanks to industrial contracts, gifts from alumni, and tuition fees. Private industry spent about 250 MD on R&D in 1940, partly in laboratories created fifteen or thirty years earlier by big companies like General Electric, AT&T, Westinghouse, or DuPont; they started doing some basic research in the 1920s. In 1925, AT&T, the private telephone monopoly, founded its Bell Labs, which soon became the largest industrial research laboratory in the world, with a 20 MD budget and some 2,000 employees by 1940; a physicist there won a Nobel prize for experiments on electron diffraction which confirmed the dual nature of elementary particles. Another Nobel Prize went to General Electric's physical chemist Irving Langmuir (who had its first success in 1913 in discovering that filling incandescent lamps with nitrogen greatly increased their life). At DuPont, a basic research program on polymers began in 1927, with initial funding of 250,000 dollars (to be compared with Columbia University physics department's budget of 15,000 dollars in 1939); from there came nylon in 1938, for the development of nylon in 1938; it cost about 2 MD and generated a 600 MD business twenty years later. There was also much R&D in the petroleum industry, with projects costing from a few hundred thousand to 15 MD. This figure looked enormous at the time.

> References: David Noble, *America by Design. Science, Technology and the Rise of Corporate Capitalism* (Knopf, 1977), Daniel J. Kevles, *The Physicists. The History of a Scientific Community in Modern America* (Vintage Books, 1979), L.S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge UP, 1985), Pap Ndiaye, *Du nylon et des bombes. DuPont de Nemours, le marché et l'Etat américain, 1900-1970*, (Paris, Belin, 2001), Thomas P. Hughes, *American Genesis. A Century of Invention and Technological Enthusiasm, 1870-1970* (Chicago UP, 2004).

As previously mentioned, the war changed the picture. At MIT, a Radiation Lab was founded in order to develop radar; scientists of all levels worked there, including Hans Bethe (until 1943), Isidor I. Rabi and Lee A. DuBridge who headed the lab; Louis Alvarez and other young collaborators of Lawrence brought the expertise in electronics and high frequencies they had acquired in Berkeley; many of these people became very influential science advisors to the government after the war. At MIT and elsewhere, the work on radar required many advances in all domains of electronics, e.g. in high frequencies, or in semi-conductors because glass valves could not detect centimetric radar waves. Methods for purifying germanium were found at Purdue and were crucial to the invention of transistors a few years later, while Bell Labs did the same, with less success, for silicon. The size of the radar business can be gauged from the fact that the Rad Lab employed up to 4,000 people, while the industrial production proper cost almost 3 BD – more than the atomic bomb project.

Headed by General Groves, the Manhattan Project – that most spectacular success story, though less useful for winning the war – employed hundreds of scientists in Los Alamos and elsewhere; these included Fermi, Bethe, James Franck, Harold Urey, Arthur Compton, Lawrence, von Neumann, Alvarez, and even Niels Bohr, all of them (except von Neumann) past or future Nobel prizewinners. Oppenheimer, a former Rockefeller fellow and the best native theoretician, headed Los Alamos with fantastic brio; he understood everything and made the whole enterprise succeed. He was under permanent surveillance by the FBI who were well aware of his pre-war leftist leanings and connections; this did not prevent the bombs' blueprints from quietly leaving Los Alamos for Moscow in a Plymouth driven by Klaus Fuchs in the summer of 1945. The project cost two billion, 70% of which was spent on the production elsewhere of U-235 in a gigantic isotopic separation factory or in Lawrence's calutrons, and of Pu in huge atomic piles. Most of the basic techniques later used in civilian nuclear energy were invented between 1942 and 1945, and this allowed General Electric, Westinghouse, DuPont and other companies to learn them and to become world leaders after the war in using nuclear power for electricity production, and first of all for the propulsion of submarines or aircraft carriers. More about this in the Internet file.

In 1945-1946, nuclear physicists were rewarded with millions left over from the Manhattan Project, which allowed them, among other consequences, to build new particle accelerators whose cost eventually came to billions (not millions). Before 1940, this prospect would have been dismissed as utterly insane. The AEC/DoE has funded this domain in America from 1947 to this day, while the Rockefeller Foundation withdrew its support after 1945 since the government could provide far more; in addition, since 1941 Lawrence and others had been hinting at spreading radioactive waste over or in front of enemy troops in case of war, which was not quite as glamorous as fighting cancer.

In a famous 1945 report, *Science, the Endless Frontier* , the chief of military R&D (OSRD) during the war, Vannevar Bush, advocated the establishment of a National Science Foundation funded by the government and whose president and programs would be chosen by scientists; the project was rejected by the President. It came into being in 1950 as a federal agency funded and governed by the government and controlled by Congress like other agencies, with, of course, plenty of scientific advisory committees; but it got very little money before Sputnik, as the table above shows. In the bio-medical sector, where a first National Cancer Institute had been founded in 1937, new National Institutes of Health were established; with strong backing from Congress and voters, they continued to grow and multiply and are now by far the most important non- defense source of federal money. Meanwhile, the Office of Naval Research founded in 1946 spent some 20 MD per year to help research in all domains, mainly to keep in touch -"in case" – with scientists and research; mathematics got about 10%, but a threateningly increasing part of it (up to 80% in 1950) was – already! – funding the development at MIT of a futuristic Whirlwind computer working in real time; a riot ensued, and Whirlwind would have died but for the birth of a far better sponsor in 1950, namely the air-defense system of the American continent, as we shall see later.

Private universities, where government interference was anathema before 1940, reversed their principles: ONR was very liberal and people got used to this new kind of "tainted money"; after all, nobody had ever asked trustees or benefactors of the rich universities how they became so wealthy; but it sometimes took several years before federal money (and possibly classified military contracts) were accepted. CalTech was still a small university in 1945; with a board of trustees made up of very conservative bankers and industrialists who approved the policy of basic research presided over by physicist and Nobel Prize winner Robert Millikan, it was several years before it bowed to the inevitable; meanwhile, the off-campus Jet Propulsion Laboratory founded by von Kármán prospered on guided missiles and DoD money, as was the case at Johns Hopkins with the Applied Physics Laboratory founded during the war. Julius Stratton, a future president of MIT who during the war had close ties with the higher echelons of the Pentagon – he was one of the stars of the MIT Radiation Lab -, wrote in October 1944 to MIT president:

> Twenty-five years ago everyone talked about the end of war; today we talk about World War III, and the Navy and Air Force, at least, are making serious plans to prepare for it. Inevitably this national spirit will react upon the policies of our educational and research institutions. It always has, and we might just as well face it (...) We shall have to deal with the Army and Navy and make certain concessions in order to meet their needs.

This means that by 1950, 85% of the MIT total research budget came from the military and AEC, with a still higher proportion for physical sciences in other elite universities. John Terman, another star in electronics, wrote in 1947 to his university's president that

> Government-sponsored research presents Stanford, and our School of Engineering, with a wonderful opportunity if we are prepared to exploit it,

which of course they were. The importance to the military of these university departments was due not only to their research work, but also to their educating thousands of scientists and engineers for defense work in particular.

> References: Everett Mendelsohn, Merritt Roe Smith and Peter Weingart, eds., *Science, Technology and the Military* (Kluwer, 1988), Paul Forman & J.M. Sanchez- Ron, eds, *National Establishments and the Advancement of Science and Technology* (Kluwer, 1996), Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (Columbia UP, 1993).

Various more or less successful attempts were made after 1950 to bring scientific advice to the highest levels of government, particularly the DoD; it was Sputnik which brought scientists to the White House. Meanwhile, the Korean War was an opportunity to organize "summer studies" during which scientists, engineers and military men would gather for several weeks in order to study such (classified, i.e. secret) defense problems as anti-submarine warfare, tactical nuclear weapons, air defense, etc.

The size of American defense activities in the 1950s and 1960s can easily be explained by political factors and by reactions to perceived Soviet threats (or counter-threats to perceived American threats: bombs, bombers to deliver them, and the "encirclement" of the USSR by US air bases). As we have seen, the first Soviet atomic test launched America into the race for the H-bomb. In the spring of 1950, the celebrated NSC-68 report of the White House National Security Council, vastly exaggerating the Soviet military threat and supposed plans for world domination, recommended (among other things, e.g. much stronger West European forces) a huge increase of the Defense budget; the figures which were known but remained unwritten, namely 40- 50 billion instead of 13-14, were judged excessive even by the military, who did not know how to spend so much money. Truman did not agree either, but the "Socialist camp" forced it on by sparking the Korean War. In particular, the production capacity for U-235 and Pu was increased in a staggering way: five new piles for the production of Pu, one for the production of tritium, and two more huge isotopic separation units, with sixteen times the capacity of the 1945 factory, which had already been enlarged; up to 85 tons of U-235 could be produced per year, which needed 6,000 megawatts of electricity, or 12% of total US production. Nuclear weapons of all types grew in America at a rate of several thousand per year, to reach 32,000 in 1964, with powers ranging from a few tens of tons up to several megatons in TNT equivalence. This was about fifteen times the Soviet arsenal at the time and could be delivered by 800 intercontinental ballistic missiles (ICBM), 200 submarine-launched missiles (SLBM), a thousand fighter- bombers based in Europe, the Middle East, Japan or on aircraft carriers, and strategic bombers (about 2,000 B-47 and 700 B-52 were built before 1962).

A gigantic system to defend America against Soviet bombers was built, as we are now going to see. The first Soviet atomic bomb led people at MIT to take the first steps to protect the USA from future Soviet bombers in 1950 (this threat was dismissed by Curtis LeMay, the Strategic Air Command (SAC) chief during the 1950s: his personal strategy was to wipe out Soviet planes, copies of the US B-29 bombers of 1944 vintage, before they could take off, but bypassing the President was slightly illegal...). This originally small Project Lincoln based on the Whirlwind computer led to the founding of a Lincoln Lab at MIT, and to the gigantic SAGE system of continental defense – a precursor to SDI -, at a cost of 30 billion (or 200 billion in 1996 money, and much more if personnel and other costs are included). Thousands of Bell Labs Nike-Hercules missiles, each carrying a 2 to 30 KT atomic warhead, could destroy *entire fleets of incoming aircraft* , assuming the Soviets were clever enough and able to send such fleets over the North Pole in suicide raids since, in any case, they could not make the round trip until big jets – never more than 200 – began to appear in 1955. Bell Labs, which had developed anti-aircraft rockets since 1945, managed everything while hundreds of subcontractors in practically all domains of technology helped develop the hardware and software needed in SAGE. SAGE was obsolete as soon as it became operational in 1960- 1962: bombers were replaced by unstoppable missiles after 1962, which led to the first and useless anti-missile systems, including the highly controversial Nike-Zeus missiles with 60 to 400 KT warheads, based around big cities and never deployed. The USSR's program evolved in similar fashion, but was even more expensive since missiles and bombers could come from many directions.

The SAGE project however played a major role in all kinds of technical advances, particularly long-range "over- the-horizon" radars, guided anti-aircraft weapons, and computers. In this last field, it led to magnetic core memories, video displays, light pens, graphics, simulation, synchronous parallel logic, analog-to-digital conversion and transmission of radar data over telephone lines via the first transistorized modems made by Bell, multiprocessing, automatic data exchange between different computers, etc. With its hundreds of thousand lines of code and hundreds of computer screens, SAGE provided the first opportunity to train several thousand programmers (most of whom later went to industry); this was done by the SDC branch of the Rand Corporation, which was founded in 1957 to that effect. Among many other machines, SAGE needed fifty six IBM AN/FSQ-7 and -8 (or "Whirlwind II") computers; there were twenty-four SAGE main command centers connected to a pharaonic installation under the Colorado mountains, itself connected to the White House and Pentagon; each of the centers used two of these IBM computers working in tandem to increase reliability. Made to order at a cost, in current money, of 30 million a piece, each of these machines weighed 275 tons, had some 60,000 valves, used 32-bit words, had a magnetic core memory – one of the great innovations from Whirlwind – of about 270 kilobits, twelve magnetic drums each storing 12,288 words of program, and was connected to about one hundred screens displaying enemy planes' trajectories and enabling operators to vector fighter planes graphically. It needed 750 kw of electric power to run and a hurricane to evacuate the heat it generated. These performances may look puny by 2005, but there was nothing more powerful at the time and, of course, the new techniques were put to good use in IBM's future commercial computers. All of the latter were transistorized after 1960, the first large ones (series 7090) being delivered to the three gigantic radars of the Ballistic Missiles Early Warning System in Alaska, Greenland and Scotland.

> References on SAGE: chap. 4 of *Atomic Audit* , Edwards' chap. 3, Kent C. Redmond and Thomas M. Smith, *From Whirlwind to Mitre. The R&D Story of the SAGE Air Defense Computer* (MIT Press, 2000), very weak on technology, and Thomas P. Hughes, *Rescuing Prometheus* (Random House, 1998).

Then came Sputnik in October 1957, which scientists used very successfully to clamor for increased research funds. NACA was transformed into NASA, with very soon a budget in billions of dollars, while the Defense budget proper decreased. A scientific committee (PSAC) was instituted at the White House. The Advanced Research Projects Agency, ARPA, was founded by the DoD in order to fund and organize the most sophisticated research projects with military implications. Americans reacted to the "missile gap" with wild and shifting predictions on the size of the Soviet arsenal (100 in 1959, 500 by 1960 and 1,000 by 1961-1962) from the CIA, the Air Force, journalists, and democrat politicians, including Kennedy and especially Johnson, wishing to destroy the 1952-1960 Eisenhower republican administration. But radars from Turkey and Iran had detected Soviet missile tests in 1953-1954, and, from 1955 on, absolute priority was given to similar American programs, Atlas and Titan, soon followed by the silo protected Minuteman series of ICBMs, the Polaris missiles for nuclear submarines, and the first satellites for reconnaissance, infrared detection of missile firings, meteorology, communications, etc (1959-1961). Extended flights over Soviet territory first by U-2 spy planes, then satellites, proved in 1960 that there was indeed a big "missile gap": perhaps four Soviet operational missiles, to dozens of American ones.

Like the Korean War, Sputnik and Khrushchev's boasts proved to be a self-defeating move and another wonderful opportunity for the American and Soviet "scientific-military- industrial complexes". The Soviet arsenal, vastly outnumbered by the American arsenal until the 1970s, was nevertheless big enough to make an American attack unlikely, and in any case America's top political rulers found the Air Force's apocalyptic war plans quite repellent, although they knew they might have to "push the button" as a last resort (see my vol. I, p. 122; in 1960, over 150 weapons were reserved for the Moscow area alone, and quite a number of them would have destroyed each other). To paraphrase a journalist writing in *Science* , September 27, 1974, these huge defense systems were *the cathedrals of a century that future historians will characterize by its extraordinary technical capacities and its permanent devotion to the mortuary arts.* And so on, with ups and downs, until the fall of the Soviet Union. The most exotic parts of Reagan's Star Wars project were terminated, but a less ambitious anti-missile program is still going on, at the rate of several BD per year, with a first deployment in Alaska of weapons guided on a collision course with enemy missiles (a fascinating problem in Control Theory) although no one can guess who would be foolish enough to launch them. America's military doctrine is now undergoing a "Revolution in Military Affairs" based on "Space Dominance", which aims at fully integrating every weapon and everyone – from the President and the Pentagon warlords down to the GI on the battlefield – through all kinds of satellites, drones, telecommunications, information networks, etc. You will find an impressive survey of it in *Introduction au siècle des menaces* (Paris, Odile Jacob, 2004), by Jacques Blamont, a French specialist in Space Sciences with long and strong ties to the Jet Propulsion Lab (and, more recently, Soviet astronautics), and a member of the US Academy of Sciences. Another "revolution" has been under way since the Strategic Computing Initiative of the 1980s: substituting all kinds of "intelligent" robots for weak mortals on the battlefields of 2030, according to the New York Times (02/16/2005). Contracts worth 127 BD have already been issued for this Future Combat Systems project, which will contribute to boosting weapons acquisition costs from 78 BD now to 118 by 2010. Those who believed the end of the Cold War would slow down the technical progress of armaments were badly mistaken...

The development of nuclear weapons, fighter planes, bombers, missiles, nuclear submarines, aircraft carriers, SAGE, satellites for C$\underline{4}$ RI (command, control of operations, communications, computers, reconnaissance and intelligence), etc. relied on and greatly encouraged technical progress in dozens of less spectacular domains: electronic components (from glass valves to transistors to printed circuits to integrated circuits to VLSI...), computer hardware and software, navigation and guidance systems, infrared detection, fire control devices, radar and sonar, microwave propagation, space telecommunications, materials, etc. The list is endless.

The development of transistors and integrated circuits is a good example. Semi-conductors had been known for a long time and were the first detectors used in wireless in the 1900s. Systematic experimental studies in the 1930s and during WW II, as well as the development of a solid-state theory using quantum mechanics, had led to a good understanding of the phenomena by 1945, and, at Purdue university, to methods of obtaining highly purified germanium (so named by its German discoverer), from which rectifying diodes were mass produced for radar detection. The Bell Labs did the same with silicon with less success at the time. After 1945, they tried to discover solid-state amplifiers, and the first very primitive point-contact transistors were made there in 1947 by two physicists, John Bardeen and Walter Brattain, headed by William Shockley who a few years later found a way to make industrialization far easier; all three shared a Nobel Prize. Transistors, patented by Bell in 1948, were expected to replace electronic valves and electro-mechanical switches in a myriad of devices used by the AT&T telephone system. But there was nothing urgent here – the capital invested in standard equipment was far too high to be scrapped – and, anyway, replacement would require years of further development and industrialization. AT&T, however, was under an anti-trust suit at the time and the military watched the development of transistors with great interest. Bell therefore organized a first information meeting at the beginning of 1951 for military and government officials only, then a symposium in September for some three hundred American and European engineers to whom the characteristics of a dozen transistors were disclosed. In 1952, Bell decided to sell its patents to 36 companies and, in April, to divulge the know-how to licensed companies. A first production unit for military transistors was built by Western Electric, the manufacturing branch of AT&T. The anti-trust suit ended in 1956 and, among other clauses, AT&T was ordered to limit its production to its own needs and to the government market, for which many Bell innovations were made; this favored other manufacturers. The Army Signal Corps had already issued production contracts to twelve makers for use in the forthcoming strategic missiles, and demanded 3,000 units of thirty different types per month. Since at that time only 5 to 15% of the production was free of defects, this required much higher production capacities, with very high unit costs. But the rate of rejects, and hence prices, soon dropped, and sales to less demanding buyers went from 14 million in 1956 to 28 million in 1958. The military were interested in transistors because they were small and light, consumed very little power, and were much less sensitive to shocks, vibrations and wear than valves. First models of transistorized computers were built at Bell Labs and Lincoln Lab (MIT) in the 1950s, for the military, of course.

The first civilian commercial uses of transistors were for hearing aids (Raytheon, 1954) costing 150-200 dollars; transistor portable radios came a few years later. It took at least ten years before a large commercial market developed because classical valves were far cheaper – one dollar instead of eight around 1953 -, had much better characteristics than early transistors, were much easier to make, and were much more familiar to most electronics engineers; the main advantages of transistors were not needed in most applications, though they attracted the military. Between 1954 and 1956, the markets for transistors and valves were $55 and over 1000 million respectively. And though several established valve manufacturers (General Electric, RCA, etc.) had 31% of the market in 1957, new and much smaller firms (Texas

Instruments, formerly a geophysical services company, Transistron, Hughes, etc.) had 64%.

Integrated circuits were invented in 1958 by Texas Instruments without military funding (military projects for miniaturizing electronic circuits all failed or came too late in the 1950s), but their mass production was made possible by the invention of the so-called planar process for silicon transistors by a group of eight physicists and engineers who left a company the insufferable Shockley had founded in 1954. The Fairchild Company which, since the 1920s, made aerial cameras and later components of analog computers (all mostly for the military), set up for them the Fairchild Semiconductor Corporation in 1957. Since they had their eye on the commercial market – some of them founded Intel a few years later -, they rejected military R&D contracts to remain free of having to develop products which, although militarily important, would be of little commercial interest. They nevertheless decided to concentrate first on the improvement and manufacture of high performance silicon transistors for the military market. This was the time the military was beginning to replace analog computers with digital ones in avionics and missiles because only silicon – and neither very expensive germanium, nor electronic valves – could stand the high temperatures, shocks and vibrations prevalent in many military systems. Their first customer was IBM which bought one hundred Fairchild “mesa” transistors at 150 dollars a piece for use in the navigational computer for the prototype of the B-70 supersonic bomber they had already made the analog computers for the B-52s, a much bigger market). They had no competitor other than Bell Labs, their mesa transistors immediately found many other avionics uses, and their sales jumped from 65,000 dollars in September 1958 to 2.8 MD for the first eight months of 1959. Their most important customer was Autonetics, in charge of developing the digital computer guidance system for the Minuteman missile. Other early uses included an air-to-air missile, a torpedo, and the Apollo space station. Problems of reliability led to the “planar process” to make much better transistors; the rate of defect-free components was 5% at first, but they were under such pressure from Autonetics, which demanded one year without failure, not to mention the now growing competition in mesa transistors, that they persisted, then developed ultra-reliable planar diodes for computers and eventually integrated circuits. The planar process made it possible to fabricate many components on the same silicon wafer and to connect them, again with a very low initial proportion of defect-free circuits. All of this looks very simple, but required extraordinary standards of cleanliness, manufacturing skills, and *an unprecedented level of discipline on the workforce* , as one of my sources said.

Total sales of ICs amounted to 4 MD in 1962, 41 in 1964, 148 in 1966 and 312 in 1968, while the average unit price dropped from 50 dollars to 2.33; in those same years the military bought 100%, 85%, 53% and 37% of the total sales. More generally, the military part of the electronics industry’s total sales, which was 24% in 1950, climbed to 53-60% during the years 1952-1968. The general pattern in electronics at the time was that the first customers, namely the military and their industrial contractors, bought the initial product at prices which included most of the R&D and at least part of the tooling; prices then went down to a level which civilian industry and business could afford for their own uses, which in time lowered the prices again until the general public could buy solid-state gadgets like radios, TV sets or PCs. With a huge civilian market after 1980, chip makers like Intel could continue to improve their products with little help from the military; Intel even refused to work on highly sophisticated very high speed circuits (VHSIC) with no civilian uses.

The military actually benefited from this civilian market as they too needed a lot of standard electronics that could be purchased off-the-shelf at low prices. For this reason and to help American industry against Japanese competition, they became interested in "dual" technologies with military and civilian uses. The DoD still spends about 25% of its R&D budget on electronics and communications, but for more sophisticated products than personal computers...

The early development of computers was still more influenced by the military. Explaining it here would take too much space; see the Internet file. I'll merely point out that the 35 computers made between 1945 and 1955 were entirely financed by the DoD, with the exception of two in universities which my source does not know, and of the von Neumann Princeton computer which was financed by the Army, Navy, AEC and RCA (but its five copies were financed by AEC or, at Rand, by the Air Force). Almost all of these machines were one of a kind; only three companies made several production units: UNIVAC, the company Eckert-Mauchly had founded in 1947 in order to make huge data-processing machines with the commercial market (banking, insurance, etc.) in mind, although it also had military customers; ERA, founded by a team of former cryptologists from the Navy who made very advanced computers for the National Security Agency; and IBM which, at the start of the Korean War, decided to make digital machines. They looked for customers and found seventeen, either military or in the military industry. Of course a huge civilian market developed later – mainly after 1960 -, but the influence of military research contracts and procurement always was extremely powerful, and still is.,

References: Herman H. Goldstine, *The Computer: From Pascal to von Neumann* (Princeton UP, 1972), Kenneth Flamm, *Targeting the Computer* (1987, Brookings Inst. Press) and *Creating the Computer: Government, Industry, and High Technology* (1988, Brookings), Arthur L. Norberg and Judy E. O'Neill, *Transforming Computer Technology. Information Processing for the Pentagon, 1962-1986* (1996, Johns Hopkins UP), Donald MacKenzie, *Knowing Machines* (MIT Press, 1998), Janet Abbate, *Inventing the Internet*

> (1999, MIT Press). National Academy of Sciences, *Funding a Revolution. Government Support for Computing Research* (NAS Press, 1999), very explicit and thankful to the DoD, Alex Rolland & Philip Shiman,*Strategic Computing: DARPA and the Quest for Machine Intelligence* (MIT Press, 2002).

Below industry level, all domains of science, from mathematics and computer science to nuclear physics, electronics, optronics,..., oceanography, geology (used e.g. for monitoring underground nuclear tests) and even to some extent biology and medicine, expanded tremendously since much of their results and many experts were needed in all domains of high technology and defense.

§ 3. Applied mathematics in America

In the entertaining chapter of his autobiography, *Un mathématicien aux prises avec le siècle* (Paris, Odile Jacob, 1997, trad. Birkhaser), which he devotes to his teaching at the Ecole polytechnique, Laurent Schwartz accuses (p. 355) the French *pure mathematicians* , and especially the Bourbaki group, of having *ostracized* their applied colleagues. As a matter of fact, for at least ten years there was nearly nobody to be "ostracized" before the rise of Jacques-Louis Lions (1928-2001), a very bright student of Schwartz who first worked on distributions and partial differential equations (PDEs) in the modern way made possible by the development of functional analysis. He discovered applied mathematics and computers in America in 1956 in circumstances that will be explained below, and later founded the very brilliant French School of Applied Mathematics; he himself was appointed a professor at Nancy in 1954, in Paris in 1963, at the Polytechnique (1965-1986), and at the Collège de France in 1973.

From 1980 to 1984, he headed the French government National Institute for Research in Informatics and Automatics (INRIA) with which he had been connected for ten years, the French NASA (CNES) from 1984 to 1992, and he won some of the highest international prizes; quite a victim of our ostracism, and otherwise a great mathematician with some 50 doctoral students and hundreds of "descendants" in the world. See a substantial biography by Roger Temam, one of his principal students, at www.siam.org/siamnews/07-01/lions.htm.

Schwartz decrees that *every mathematician must concern himself with the applications of what he is doing* without, it seems, being aware of the fact that "to concern oneself with" may have quite a number of different meanings, whether in French or in English. He provides neither a justification for his categorical imperative nor the slightest account of the very diverse applications of mathematics. The fact that applied mathematics *were undergoing a powerful expansion in the United States and USSR among others* seems to justify everything, without it being necessary to explain this strange and very new development in the two countries which led the arms race until 1990.

The development of applied mathematics in the USA which so inspired Schwartz is not too difficult to explain, even though much remains to be done since physics and technology, being far more spectacular, have almost monopolized historians until now. The Soviet situation, although less well known, was certainly no better.

Before the war, "pure" mathematics prevailed in universities everywhere (except in the USSR, since this "bourgeois" concept was anathema to Marxism); engineers and physicists almost always solved their mathematical problems by themselves, even when the new quantum mechanics obliged physicists everywhere to rediscover strange mathematics. By the 1930s, the situation began to change in a few places, partly due to the arrival of European Jewish refugees. Richard Courant, Kurt Friedrichs, Fritz John and Hans Lewy brought to New York university some of the Göttingen tradition founded by Felix Klein forty years before. They dealt less with applied mathematics as we know them – computers had yet to come – than with often "modern" mathematics such as found in Courant and Hilbert's celebrated *Methoden der Mathematischen Physik*. In 1937, the Army Ballistic Research Laboratory at Aberdeen set up a scientific committee including von Neumann and von Kŕmń besides other luminaries. Von Kármán, formerly a student and later a competitor of Ludwig Prandtl, the foremost German aerodynamicist in Göttingen, had been at CalTech since 1934 (and part-time since 1926), where he founded the future Jet Propulsion Laboratory. In 1945 he became the Air Force's main scientific advisor and, in this capacity, one of the first promoters of atomic missiles. Classical Calculus being often sufficient, the WW II military R&D organization did not at first enlist mathematicians. Mainly at the request of mathematicians themselves, an Applied Mathematics Panel was set up in 1942 with teams in several universities put at everyone's disposal; they were, so to speak, the coalers of the R&D Dreadnoughts of which the officers were physicists. Stanislas Ulam, who later became chief mathematician at Los Alamos, had to ask his friend von Neumann for his help in getting war work in 1943. Applied (or, as Saunders McLane said, applicable) mathematics, much of it boring, blossomed in all kinds of fields, and some people converted to it for life. Shock waves propagation, surface waves in water of variable depth, "hydrodynamics computations" for the Nagasaki bomb, gas dynamics, statistical optimization of air bombings and anti-aircraft defense, operational research, statistical quality control for the mass production of weapons, etc. For anti-aircraft defense, Norbert Wiener invented statistical prediction methods based on harmonic analysis and analytical functions, but they were too sophisticated: he had been lured into the mathematics of the problem. Transmitting orders or conversations in a secure way, that is to say unintelligible to non-authorized people, was very difficult, particularly communications between such high level persons as Roosevelt, Churchill or Eisenhower. This was intensively studied at Bell Labs, where digitalization of continuous speech was apparently invented, while separate frequency bands were encoded by adding random numbers and reduction modulo 6 (it took quite a while for Bell's engineers to discover it, although they were familiar with mod 2 arithmetic); each encoding system was used only once, and recorded on two highly precise phonograph records, one of which was used at the sending end and the other sent in advance to the receiving end; this involved a lot of very complex electronics using kilowatts of power to transmit milliwatts of speech, and the help of some people with mathematical abilities which the electronics engineers lacked. One of them was Claude Shannon, until 1941 at MIT and Princeton where he had studied applications of "Boolean algebra", i.e. set theory, to the analysis of electronic circuits; he derived from his work at Bell Labs the Information Theory that made him famous after the war. If you understand electrical engineering, see *A History of Engineering and Science in the Bell System. National Service in War and Peace (1925-1975)* (Bell Telephone Laboratories, 1978), pp. 291-316.

Most postwar standard mathematical publications, written by mathematicians who are too busy or too discreet to consult sources, contain only rather abstract and summary generalities about the relevant mathematics. But luck may help those who read books that mathematicians generally do not open, or know of, since they don't deal with mathematics.

The 1945 bombings on Japanese cities (and earlier ones on Germany) led to a fascinating problem: to determine the right proportion of explosive and incendiary bombs for maximum damage. A Berkeley statistician, Jerzy Neymann, was then called to help; he used methods which, after the war, made him a celebrity. Mathematical details are not to be found in my source, and it is likely that Neymann's contribution was less useful than those of scientists, led by Harvard chemist Louis Fieser, who in 1942 invented napalm, among other incendiaries, though it was not widely used until the war in Korea. During a bombing raid, planes were supposed to drop bomb clusters at 50-foot intervals, which would open at 2,000 feet and disperse 38 smaller bombs, starting a dozen fires; thus a B-29 was able to set fire to a 350x2,000-foot area. Relying on statistical computations to get the best results would thus have been a good idea (or a bad one, depending on your point of view). But recent books suggest that the method was discovered experimentally.

On the other hand, the task of choosing targets, based at first on their contributions to Japanese armaments, and of evaluating the weight of bombs needed, was conferred on a Committee of Operations Analysts which relied on methods developed in Britain, mostly by physicists like P.M.S. Blackett, initially for anti-submarine warfare, then for bombing operations. These problems involved fairly simple mathematics but gave rise soon after the war (first of all at the Rand Corporation) to an extravagant amount of hype in favor of game theory, Operations Research, and linear or dynamic programming; it was claimed they were the truly "modern" mathematics that could be applied to "solve the problems of society" – logistics, bombers basing, optimizing a massive nuclear strike in case of war, dispatching packs of Coca-Cola to troops in the field or grocery stores, etc. No wonder these disciplines, which were still rather primitive mathematics assisted by the first computers, did not attract everyone after the war even if they found harmless applications later:

> What are we to think of a civilization which has not been able to talk about killing almost everybody, except in prudential and game-theoretical terms,

a good question Oppenheimer asked on TV in February 1950 or perhaps in 1959 – my sources do not agree.

In the atomic sector, where the most difficult problems were to be found, the development of the implosion bomb (Nagasaki, plutonium) forced theoreticians, headed by Hans Bethe, to solve numerically the PDEs governing the propagation of the convergent shock wave produced by classical explosives surrounding a sub-critical ball of plutonium. At hundreds of thousands of bars of pressure, plutonium behaves like a viscous fluid which you have to keep perfectly spherical, whence a "hydrodynamics" problem as they called it. To get the needed spherical shock wave required an assembly of 32 pentagonal pyramids of fast explosives, with a half-sphere ("lens") of slow explosives in the middle of each one. Ready in the Spring of 1945 after thousands of tests, this device required solving countless problems by American and British experts in explosives, many of them academics. Von Neumann contributed significantly to this effort in recommending that much larger amounts of conventional explosives be used than was projected, as well as in the design of the explosive lenses; after having learned chemical engineering at Zürich Polytechnicum in his youth, he had participated at Aberdeen in the development of "shaped charges" for anti-tank projectiles. Hans Bethe, a nuclear physicist who knew a lot of mathematics, wrote a 500- page report on shock waves at Los Alamos.

To solve the two-dimensional PDE (three-dimensional computations were beyond them until the 1980s), they first used the same classical finite difference method as for one-dimensional problems. It turned out that small variations in the dimensions of time and space steps led to large variations in the results: instability. Richard Courant was then called to the rescue. He explained to Bethe the successive approximations method that Friedrichs, Lewy and himself had used (Math. Annalen, 1928) to prove the existence of solutions: it prescribes non-obvious restrictions on the relative dimensions of the time and space steps used. It is at Los Alamos, it seems, that the first opportunities to use the method arose. Thanks to that,

> very soon problems involving fluid dynamics, neutron diffusion and transport, radiation flow, thermonuclear reactions and the like were being solved on various machines all over the United States

writes Bethe's first successor as chief of theoretical physics at Los Alamos, D. Richtmyer, in a 1957 book explaining, among other things, advances made after the war by von Neumann and Peter Lax concerning the convergence and stability of approximations; Banach spaces could now be used indirectly to understand what went on inside a bomb, for obviously this is what everybody was interested in at the time in Los Alamos. Lax, who spent his summers at Los Alamos during the 1950s, was one of applied mathematics' rising stars and, later, a strong opponent of Bourbaki's mathematics. He once wrote of Vietnam war opponents who wanted to enlist the AMS that most of them *specialize in branches of mathematics that are abstract, often esoteric, and completely unmotivated by problems of the real world* , thus implying that, had they instead busied themselves with, say, the mathematics of shock waves, they would have had no qualms over B-52s flattening Laos...

J-L. Lions, mentioned above, said much later in an interview (Le Monde, May 8, 1991) that he discovered applied mathematics and computers in America in 1956 thanks to Lax, who told him of von Neumann's ideas; after mentioning a few current civilian applications, Lions treats us to an eulogy of von Neumann,

> the father of the discipline who, at the end of the 1940s, was so able to guess all the benefits that would result from the use of the first computers to describe such complex systems as meteorological phenomena,

and that he himself only *added one chapter which von Neumann had not entered: the industrial chapter* (with enough success to be a member of the board of several big French industrial companies during his last years). Von Neumann's (and the Air Force's) interest in meteorology is well known but, as the reader already knows, he was interested in other uses of computers. By 1956,

> [his] combination of scientific ability and practicality gave him a credibility with military officers, engineers, industrialists, and scientists that no one else could match. He was the clearly dominant figure in nuclear missilery.

This other eulogy is from Herbert York *Race to Oblivion* (Simon & Schuster, 1970, p. 85); the was a member of the *Teapot Committee* which, chaired by von Neumann, chose in 1954-1955 the characteristics of ATLAS, the first intercontinental missile. Lions may not have been told in 1956 of von Neumann's taste for military projects, but in 1960, the year he started a seminar on numerical analysis in Paris, his first "really applied" paper was on nuclear reactors. That he did not even hint in a 1991 interview at the huge military influence on the development of his discipline may be explained by the Russian principle: *show the best, hide the rest* . One of his best students, Roland Glowinski, tells us on the web that the A (for Automatics, i.e. Control) of the IRIA Institute of Research in Informatics and Automatics that Lions headed had been suggested by Pierre Faurre. A bright Polytechni cien well known among applied mathematicians, Faurre published a book on the mathematics of inertial guidance (1971) in a collection directed by Lions. In America, this technique made Charles Stark Draper and his Instrumentation Laboratory famous (it was the focus of student riots at MIT in 1969) and was developed first for strategic bombers, later missiles, and still later commercial planes; Faurre soon became the general secretary of SAGEM, a well-known company he eventually headed and which was making (among other things, e.g. telecommunication hardware and fire-control systems) inertial guidance systems for planes and missiles, whether civilian or military. One should not forget the multi-volume and multi-author treatise of *Analyse mathématique et calcul numérique pour les sciences et les techniques* (English trad. Springer) which Lions edited together with Robert Dautray, a Polytechnicien who, from 1955 to 1998, followed a bright career at the French AEC (CEA) up to the highest position. Dautray was appointed scientific director of its Military Applications Division (DAM) in 1967 in order to help its engineers extricate themselves from the complexities of H-bomb design; it seems he did this by asking questions to a well-known British expert who told him they had found, but not recognized, the solution. To be sure, none of these connections proves that Lions did actual military work, and it may well be that he was mainly interested in applications to astronautics, meteorology, the environment, industrial processes, etc. Let me say simply that I have read too many biographies by scientists to trust them automatically to tell the whole truth.

Richtmyer mentions “machines”. At Los Alamos in 1943, numerical computations were first carried out on mechanical desk computers – distant descendants of Pascal’s and Leibniz’s machines -, as everywhere else. The enormity of the task led physicists to order commercial IBM punch card machines, improved to perform multiplications (!) and not merely additions. For months, Richard Feynmann headed dozens of (human) computers who had to push millions of punch cards into the machines.

Von Neumann devoted two weeks to learning how to use them, which explains the shock that was his chance discovery, in 1944, of the Eckert-Mauchly team who, at the University of Pennsylvania, were designing the first electronic computing machine, ENIAC, to help the Aberdeen Proving Ground accelerate its firing-tables business; though not yet automatically programmable, ENIAC was far faster than IBM’s primitive machines were; it was not fully operational before the Fall of 1945 and was at once used for the H-bomb program, as was von Neumann’s own machine when operational in 1952. Drawing in part on Eckert-Mauchly’s ideas, von Neumann formalized in 1945-1946 what is now called the “von Neumann architecture”, thus creating true computers, and (slowly) built one at Princeton; Maurice Wilkes built one in Britain in 1948, Eckert-Mauchly delivered their first commercial UNIVAC in 1950, while another small company, ERA, delivered very advanced machines for cryptological work to the National Security Agency (NSA) also before 1950, as already said, all on von Neumann’s architecture. The Los Alamos and Livermore laboratories were first served with almost all the new “scientific” computers available, from copies of von Neumann’s machine to the present teraflop supercomputers, of which they were always the most demanding users and often the promoters.

And while we are celebrating WW II applied mathematics in the United States, we might as well inquire about a country that is so often “forgotten” by most apostles of applied mathematics: Germany, which in some scientific and technical domains was well ahead of her enemies. At Göttingen, Prandtl’s lab had been transformed during WW I into an Aerodynamischen Versuchanstalt (AVA) which, in 1925, became associated with the newly founded and more theory- oriented Kaiser-Wilhelm Institut (KWI) fr Strömungsforschung. The arrival of the Nazis opened the way to the new Luftwaffe, which was good for aerodynamics, and AVA expanded. Prandtl, who was much more an innocent than a Nazi, congratulated them publicly for it while trying, without success, to protect valuable scientists who were not 100% Jewish. Now running under the Luftwaffe ministry and almost entirely devoted to the needs of the aeronautical industry, AVA was separated from the KWI in 1937. Work at KWI, under Prandtl, while more “fundamental” than at AVA, was nevertheless increasingly devoted to studies for the Luftwaffe (high speed aerodynamics), or von Braun (supersonic aerodynamics), or the Navy (cavitation studies for fast torpedoes), as well as for meteorology. A young mathematician, Harry Görtler, took charge of numerical computations and devised simple ways of programming them for KWI’s biological “computers”, young girls with a high school degree and desk machines.

Outside fluid mechanics and ballistics, military research did not really start before 1942, when the *Blitzkrieg* myth was dispelled; as in 1914, most scientists had been mobilized like everyone else in 1939. Furthermore, Nazi Germany, a conglomerate of administrative feodalities fighting each other for power, lacked the centralized coordination of R&D that America set up even before Pearl Harbor. Most Nazi leaders, Hitler to begin with, could hardly understand the importance of revolutionary weapons, except for their psychological impact. The development of jet fighters was delayed by two years (fortunately for Allied bombers) and von Braun’s V-2s production, though not development, longer still. In 1943, they changed their mind and tried to develop “miracle weapons” in earnest; engineers had plenty of these on their drawing boards, but it was too late for most of them.

Student numbers enrolling in aerodynamics and the like grew from a mere 80 in 1933 to reach 700 by 1939, while the Nazi policy had the opposite effect on mathematics – student enrolment fell by 90% at Göttingen – and physics, not only as a result of dismissing Jewish scientists, but also because the official ideology favored more virile prospects. In physics, mentioning “Jewish” Relativity theory was anathema, but most atomic physicists were not foolish enough to fall into this trap. There was also a “Deutsche Mathematik” gang trying to discredit some parts of mathematics and the mathematicians connected with it. Jewish- made transfinite numbers were fortunately not really needed to compute rocket trajectories.

Often at their own request mathematicians were eventually mobilized for military research. In Germany as in Allied countries, it was thus possible to protect scientists from the *chances of a Turkish bullet* , a fate which had so incensed Ernest Rutherford when one of British physics’ rising stars, Philip Moseley, was killed in the Dardanelles in 1915 – a fate that should obviously be reserved for scientifically uneducated people. Some mathematical work remained rather theoretical, like Wilhelm Magnus’ first version of the Magnus and Oberhettinger book on special functions, Erich Kamke’s on differential equations, or Lothar Collatz’s on eigenvalue calculations. Other studies were more directly applied to supersonic aerodynamics of shells and missiles, wing flutter, pursuit curves for self guided projectiles, cryptology, etc. Some well known “pure” mathematicians, like Helmut Hasse, Helmut Wielandt, Hans Rohrbach, even converted to it temporarily. Alwin Walther, Courant’s former assistant, who before the war had founded a Practical Mathematics Institute (IPM) at the Darmstadt Teknische Hochschule, already worked for von Braun in 1939, and IPM became the main computing center for military research during the war. Walther’s first task after the war was to direct the writing for the Allies of five reports on mathematics; he pointed out the similarity of German and American areas of work, *miraculously bearing witness to the autonomous life and power of mathematical ideas across all borders* . Courant agreed and invited Walther to emigrate to the US; to this moving reunion – applied mathematicians of all countries, unite! – Walther, now a “pacifist”, preferred working for the reconstruction of his country.

In Germany also, a remarkably clever engineer, Konrad Zuse, who had attended Hilbert’s lectures in mathematical logic, started in 1936, without any government help and ahead of the Americans, to build three computing machines using telephone relays. The last one, Z3, became operational during the last months of the war and was used to control the shape of mass-produced rocket wings. All these machines were damaged during the war. Components of an electronic machine (which would have used 2,000 tubes instead of ENIAC’s 18,000) were built by his friend Wilhelm Schreyer; this aroused even less interest, and Schreyer later emigrated to Brazil to teach. At the end of the war, Zuse went to the Zürich Poly where he built a Z4, much more reliable than the first electronic machines, then enjoyed a successful technical and business career in computers, later at Siemens. He also invented a Plan Kalkül in 1945, i.e. a logical architecture for computers; but he was not in a position to compete with von Neumann, if not in software, at any rate in prestige and support.

> References: Amy Dahan-Delmedico, *L'essor des mathématiques appliquées aux Etats-Unis: l'impact de la seconde guerre mondiale* (Revue d'histoire des mathématiques, 2 (1996), pp. 149-213) and two papers by the same author and Peter Galison in Amy Dahan et Dominique Pestre, eds, *Les sciences pour la guerre, 1940- 1960* (Paris, EHESS, 2004), the first one dealing in detail with a Soviet team at Gorky. On Germany, see H. Mehrtens, "Mathematics and War: Germany, 1900-1945", in Forman, *National Military Establishments* , Sanford L. Segal, *Mathematicians under the Nazis* (Princeton UP, 2003), Konrad Zuse, *The Computer. My Life* (Springer, 1993).

Going back to America, a long report on applied mathematics stated in 1956:

> Let it also be said at the outset that, with very few exceptions, their organization does not antedate World War II and their continued existence is due to the intervention of the Federal Government. *Without the demands resulting from considerations of national security, applied mathematics in this country might be as dead as a door nail* .

According to the report, government administrations – i.e., in those times, military de jure or, like AEC or NACA, de facto – and connected industries were practically alone in employing professional applied mathematicians. A 1962 report claimed that in 1960, out of 9,249 "professional mathemati cians" employed in government or industry, about 2,000 were in federal military centers, 1,000 at the AEC, while aeronautics and electronics employed 1,961 and 1,226 respectively in the private sector. These two fields consistently got about 60% and 25% of the federal R&D money going to industry.

In 1968, another report – this one about mathematics in general – recommended that the so-called mission-oriented agencies, namely Defense, AEC, NASA and NIH in that order, should continue to fund research in those domains most useful to their missions, and to propose their problems to the mathematical community. This report was edited during the Vietnam War by Lipman Bers, one of the main opponents to the war among mathematicians. He explained in the 1976 *Notices* of the AMS that he had agreed to do it only after being assured that the war would end before the report's publication; it ended five years later. A 1970 report finds 876 mathematicians (166 with PhDs) at AT&T, 170 at Boeing, 239 at McDonnellDouglas, 147 at Raytheon, 68 at Sperry Rand, 287 at TRW, 137 at Westinghouse, etc. All of these high-tech companies had large military markets.

In 1971, the DoD employed 81% of all mathematicians and statisticians employed by the government, 67% of all engineers, 41% of all physicists (but there was also the AEC), and 10% of all biologists and physicians. Serious work needing e.g. harmonic analysis, stochastic processes, information theory, differential equations and PDEs, etc., was performed most of the time via university contracts. This is where historians should look to get a more precise idea of the importance of “higher” mathematics in military or industrial applications, a huge program.

Applied mathematics and numerical analysis have many civilian applications nowadays, but their degree of militarization always remained very high in the USA if we are to judge from the amount of federal funds attributed to them. The same is true a fortiori for what is now called computer science or informatics (logical architecture of machines, programming, networks structure, etc., hardware excluded). Here is a simplified table, taken from NSF statistics, on the main sources of federal funds (in current MD) for basic and applied research (no development) in mathematics and computer science attributed to all public or private organizations concerned with these fields: Since one 1958 dollar is worth about six 2001 dollars, this means that our field got about twelve times as much money in 2001 as in 1958, while between 1945 and 1950, it got about two million per year from ONR, a large part of it going to the Whirlwind computer. Here too the change of scale is stunning. The more recent increase in DoE funding is largely due to the development of 3D simulation methods for nuclear weapons, as well as to controlled fusion experiments designed to check the computations: 751 MD were allocated to it in 2004. The DoD was planning in 1998 to spend some 2.5 BD over several years on simulation and modelization.

	1958	1964	1968	1974	1980	1987	1994	2001
Total	40.4	98	119	127	241	759	1,242	2,810
DoD	36.4	69	79	70	137	453	593	947
NSF	1.4	11.4	18.6	24	53	124	238	569
NASA	0	6.3	3.7	1.9	3.7	70	26	85
AEC/DoE	1.9	5.1	5.8	5.6	11.6	38	201.8	824

Separating mathematics and computer science yields interesting results. The funding of informatics was still comparatively low in 1958; in 1980, out of a total 241 MD, computer science got 128 MD and mathematics 90, the remainder being a mixture of both. In 2001, mathematics got 396 MD and computer science 2,022. The difference is, of course, still more striking in applied research, for which maths (resp. computer science) got 23.8 (resp. 82) MD in 1980, then 95 (resp. 566) in 1994, then 105 (resp. 1,438) in 2001. The same year, Defense ARPA’s funding was 8.7 MD for mathematics and 424 for informatics. All of these figures are from the NSF statistical series. A striking feature of this growth since the 1970s is the fact that basic research in computer science has been increasingly financed by the NSF and decreasingly by DoD, in part a consequence of Mansfield’s amendment (1970) prohibiting DoD from funding research without explicit military relevance, in part the result of an increasing number of relatively small standard contracts with many new computer science departments which were then on the rise, while ARPA limited its grants to a few "centers of excellence". It was also due to the financing of specialized and costly equipment in universities, e.g. supercomputing centers connected to other places. The end result was that in 2001, the NSF spent 119 MD for basic research in mathematics and 450 in computer science.

Obviously, not all funding goes to universi ties. The following table gives some idea of recent trends in the federal funding of research in universities (in current MD).

	1976	1984	1992	1999
Total	57	182	478	662
Mathematics	30	76	150	131
Computer Sci.	26	74	320	506

These data concern basic and applied research and represent a large part of the total, which also includes a small portion involving both sectors. For instance, in 1994, according to another NSF report which does not quite agree with the above data, the federal government attributed 196 MD to mathematics and 453 to computer science, while total expenses – funds specifically attributed to research by all sources – were 278 and 659 MD; this means that federal funds accounted for about two thirds of university research support in mathematics and computer science, the remainder being universities' own funds and, presumably, industrial contracts at least in computer science. In 2000, out of the total federal funding of university research in mathematics (resp. computer science) of 211.5 (resp. 568) MD, these fields got 29.5 (resp. 209.8) from DoD, 8.9 (resp. 6.1) from DoE, 75.2 (resp. 0.5) from NIH (as against at most 12 MD before 2000), 0.7 (resp. 18.3) from NASA, and 99.6 (resp. 336.6) from NSF. This is no longer the 1958 situation, when nearly all federal funds were military, and over 80% of military funding now goes to computer science.

These statistics, mainly for the early years, do not accurately reflect the importance of activities specifically devoted to direct military work. Before the 1960s, when NSF hardly existed, military contracts went to many people who specialized in "useless" and "abstract" maths. These contracts allowed the universities to recruit more people, to help graduate and post-graduate students, to invite foreign colleagues, including perhaps the present author, and, last but not least, to secure America's *preponderance of power* in mathematics as in everything else. However, it is not the bystander's duty to prove that a military contract commits its beneficiary; it is up to the beneficiary who disputes it to prove that it does not.

And how are we to explain that the life sciences sector, on the other hand, never benefited from proportionally equivalent DoD favors? In 1968, federal funding of life sciences totalled 1,534 MD, of which 105 came from the DoD;

in 1994, 9.3 BD, of which 265 MD; and in 2001, 23.057 billion in federal money, of which 1.052 billion from the DoD. Life sciences have been financed for fifty years essentially by the NIH (and, to a much lesser extent, by the NSF), and very strongly encouraged by Congress and the voters. As for the drug industry, it devotes billions to R&D without ever having received more than a few percentage points from the federal government, less than 4% in 1993 for instance. In 2001, the industry spent a total of 12.2 BD, and since it belongs to the chemical industry sector, and the NSF tells us elsewhere that it got 150 MD in federal funds, an upper limit of 1.4% in federal funding for the drug industry follows. To be sure, drug companies indirectly benefit from their university contracts, but their main source of R&D money is obviously the countless products which are sold around the world to all who can afford them.

After students rioted against the Vietnam War and military work in universities, a Congressional Mansfield's amendment forbade the DoD from financing research without a clear military interest, as already said. It was somewhat softened later, but its spirit remained, and military support of "pure" mathematics nearly vanished, except in cryptology. The main threat to "pure" mathematics now comes from the enormous development of applied mathematics, even though their applications may be mostly civilian. As we shall see in the next section, this is the most striking difference between post-WW II applied mathematics and Jacobi's mathematics *pour l'honneur de l'esprit humain* (or for mathematicians' entertainment...) which, to a very large extent, were preponderant from the 1820s to the eve of WW II.