

Assignment before next class

Read these notes. Unless otherwise noted, links to other resources are optional. If possible, read at least the Preface and Overview (pages 1-11) before the first meeting.

Watch the video [“Assault on Pelindaba.”](#) (12:43)

Optional: Read my web site’s [home page](#) and its [Build Awareness page](#). If you would like a poster to put on your door, either [download the Word file](#) and customize it, or send me your name and that of your house and I will print one for you at Kinko’s.

Preface

This seminar on “Nuclear Weapons, Risk and Hope” addresses two basic questions:

- How great is the risk that nuclear weapons will be used in anger?
- How great is the hope of reducing that risk to an acceptable level?

A story from the Talmud lays a foundation for summarizing the answers: A man comes to the famous first century Jewish sage, Hillel, and demands to be taught the whole Torah while he “stands on one foot.” Given that Hillel had spent his whole life studying the Torah, this was an insult and a joke. But, according to the story, the great sage replies, “What is hateful to you, do not do unto others.” When the man insists that there must be more, Hillel adds, “That is the essence. The rest is mere commentary.” In the same way, the following short story answers the two fundamental questions about nuclear risk while you “stand on one foot”:



Imagine that a man wearing a TNT vest were to come into the room and, before you could escape, managed to tell you that he wasn't a suicide bomber. He didn't have the button to set off the explosives. Rather, there were two buttons in very safe hands. One was in Washington with President Obama and the other in Moscow with President Medvedev, so there was nothing to worry about. You'd still get out of that room as fast as you can!

Just because we can't see the nuclear weapons controlled by those two buttons, why have we stayed here for over 50 years, complacently trusting that because Earth's explosive vest hasn't yet gone off, it never will? As if confronted by that man, we need to be plotting a rapid escape.

The process that ended slavery explains why the remainder of this course reader, although “mere commentary,” is still essential reading. Imagine that someone were to suggest reinstating human slavery in the US and you had to explain why you thought that was an appalling idea. Today, it would be perfectly adequate to say that being civilized and holding slaves are incompatible. That’s an answer you can give while the other person “stands on one foot.” That same answer should have been just as adequate back in 1800, but the combined weight of human history, conventional wisdom, and even Biblical precedent required more “commentary” to start a process that eventually led the United States to abolish slavery. While the commentary that constitutes the remainder of this course reader is important, returning every so often to the story about the man in the TNT vest will help you keep things in perspective.

Overview

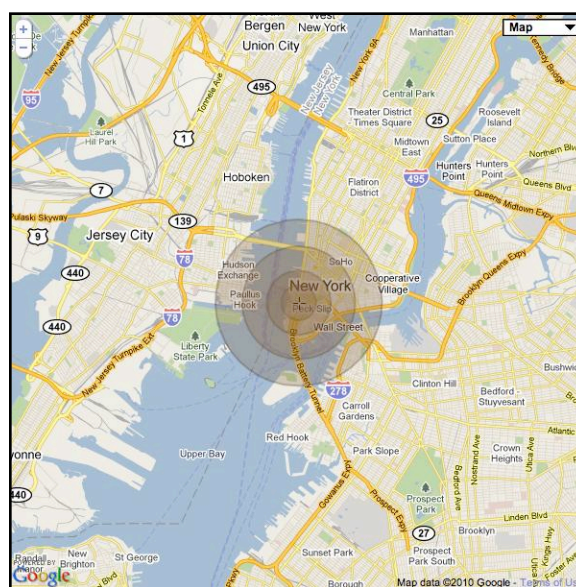
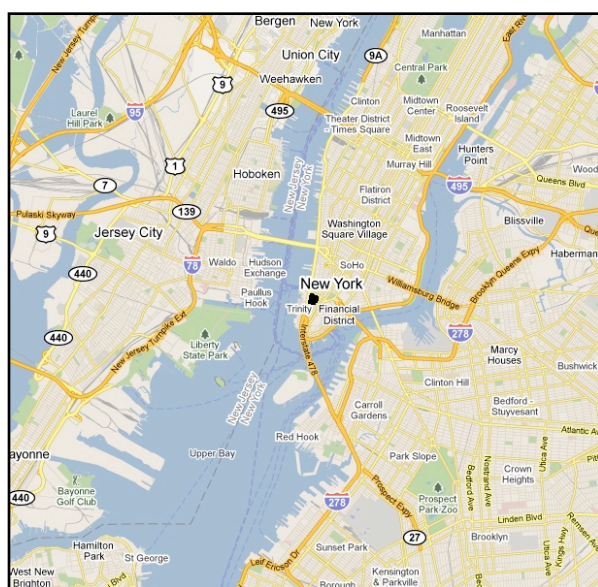
This reader breaks each of the two basic questions into several parts, resulting in the following, slightly longer list:

- How destructive are nuclear weapons?
- How likely is nuclear terrorism?
- How likely is nuclear proliferation?
- How likely is nuclear war?
- How much hope is there of reducing that risk to an acceptable level?
- What role can I play in starting a process that eventually can achieve that goal?

Each of these questions will be answered in more detail later in this reader, but summary answers are provided in this brief overview. To answer these questions, it often will be necessary to reexamine conventional wisdom and root out some fallacious assumptions, much as the arguments in favor of maintaining slavery needed to be reexamined before that institution could end. Such critical thinking is at the heart of the SLE (Structured Liberal Education) program in which many of the seminar participants are enrolled.

How destructive are nuclear weapons? Pound-for-pound, nuclear weapons can be a million times more powerful than TNT. To put this in context, the first map on the next page shows the area destroyed by the terrorist attacks of 9/11 that killed thousands of people and ravaged the US economy. It’s the small black area near the tip of Manhattan, just under the E of New York. The second map shows the area that would be devastated by a nuclear terrorist attack using a 10 kiloton nuclear device, comparable to the weapons used on Hiroshima and Nagasaki. More modern thermonuclear weapons (“H-bombs”) can be a thousand times more powerful than even that weapon. Even though the Cold War is supposed to be over, there are still over 20,000

nuclear weapons in the world's arsenal, well over 90% of which are held by the United States and Russia.



How likely is nuclear terrorism? Osama bin Laden has made no secret of his desire to obtain nuclear weapons and kill millions of Americans. Obtaining nuclear fuel is the main barrier to terrorists making a bomb, and that material is not always as well guarded as it should be. As one example, the apartheid regime in South Africa developed a small nuclear arsenal that it dismantled in the transition to majority rule. The highly enriched uranium (HEU) fuel from about a dozen bombs is stored in their Pelindaba facility, which was successfully attacked and entered by armed men in November 2007. Fortunately, the attackers did not obtain any HEU, but we should not complacently count on being so lucky every time – and all it takes is once. In another example, in August 2007, the US Air Force “lost” six nuclear weapons for well over a day, during which time they were not as well guarded as they should have been. Because of these and other lapses, numerous experts on national security have estimated that a nuclear terrorist attack might well occur within ten or twenty years – unless we start to take this threat more seriously and change course to reduce the risk. For example, in the movie *Nuclear Tipping Point*, Henry Kissinger states, “If the existing nuclear countries cannot develop some restraints among themselves – in other words, if nothing fundamental changes, then I would expect that the use of nuclear weapons in some 10-year period is very possible.”

How likely is nuclear proliferation? The United States went nuclear in 1945. Not willing to be relegated to an inferior military status (or, even worse, destroyed because it did not have a deterrent), the Soviet Union followed suit in 1949. The United Kingdom and France, both eager to regain some of their former prestige and power, joined the nuclear club in 1952 and 1960 respectively. China, feeling threatened by both the Soviet Union and the United States, conducted its first test in 1964. (China had fought the US during the Korean War, and had border disputes with the Soviets that erupted into a major crisis in 1969.) India, which had fought a border war with China in 1962, joined the club in 1974. India's nuclear status led Pakistani Prime Minister Zulfikar Ali Bhutto to declare that, if need be, Pakistanis would "eat grass" in order to acquire their own atom bomb. Pakistan conducted a successful nuclear test in 1998. North Korea, which feels threatened by both the US and China¹, conducted its first nuclear test in 2006. While Israel has never publicly admitted possessing nuclear weapons, it is an open secret that it has approximately a hundred in its arsenal.

Because nuclear weapons are the great equalizer, any nation that feels threatened by a stronger rival has a strong motivation to develop a nuclear program. Viewed in this context, North Korea's and Iran's nuclear programs, while extremely dangerous and deplorable, are the logical outcome of threats made by their adversaries, including the United States. And each new nuclear power tends to beget others which feel threatened by the new entrant. For example, if Iran becomes a nuclear power it would provide a strong incentive for other Middle Eastern nations, notably Saudi Arabia and Egypt, to follow suit.

In the current international climate, nuclear proliferation is almost certain. Paradoxically, our nations attempts to use threats to deter others from obtaining nuclear weapons actually increases their motivation to do so. As one example, President Obama's Nuclear Posture Review rules out the use of nuclear weapons against non-nuclear states with the notable [exception of Iran](#).

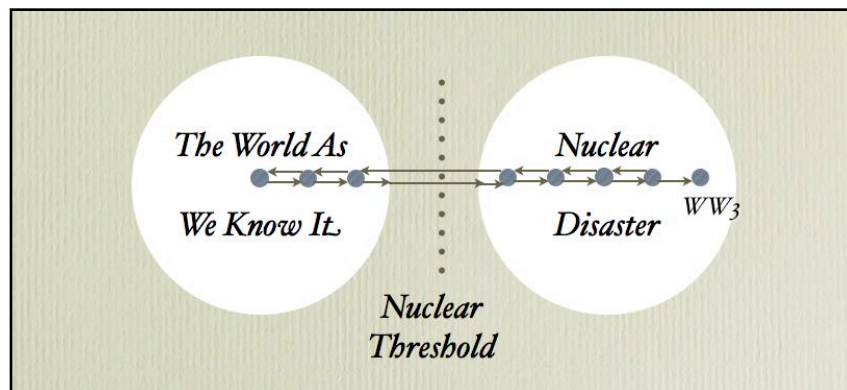
How likely is nuclear war? Post-Cold War, this threat is largely seen as a relic of the past. Unfortunately, that complacency is unwarranted. Even if the "time horizon" until we expected a

¹ Most American media refer to China as North Korea's ally. But, as we shall see, the situation is much more complex.

nuclear war were 1,000 years², there would be almost a 10% chance of it occurring during the 80-year life expectancy of a child born today.³ If the time horizon is 100 years, that child has worse than even odds.

When viewed this way, the fact that we have gone 65 years without a world war is small comfort, especially when the near misses that occurred are factored in. The 1962 Cuban Missile Crisis is the best known such event, but there are many others, including a number since the end of the Cold War. As just one example, in 1995 the Russian air defense system mistook a meteorological rocket launched from Norway for an American submarine launched ballistic missile, causing the Russian “nuclear football” – the brief case that contains the codes for authorizing a nuclear attack – to be opened in front of Boris Yeltsin. This was the first time such an event had occurred, and fortunately Yeltsin was sober enough to make the right decision.

Surviving such near misses is no reason for complacency, which is unfortunately what has occurred. Instead, we need to start seeing them as early warning signs that demand remedial action *before* a catastrophe occurs. An engineering discipline known as risk analysis does that by decomposing the process that leads to a catastrophic failure into a sequence of smaller steps and focusing attention on avoiding the precursors to disaster. Applied to nuclear war, that approach can be depicted as shown below.



² Talking of a “time horizon” until we expect a nuclear war, freezes the basic environment and asks how long we could expect civilization to survive under those conditions before a nuclear war occurred. That approach neglects the changes that would occur over an extended period of time, some of which (e.g., proliferation) would increase the risk (decrease the time horizon), and others of which would have the opposite effect. We really are trying to look at the annual probability of a nuclear war, but it is easier to think in terms of a time horizon. If nuclear war has one chance in 1,000 of occurring during the next year, that corresponds to a 1,000 year time horizon.

³ While $80/1,000 = 8\%$, using that number would suggest greater accuracy than is possible with such a rough approach. Saying “almost 10%” implies a more approximate figure.

The *World As We Know It* is a “super-state” consisting of all states (conditions of the world) short of a nuclear weapon being used in anger. That *Nuclear Threshold* can be crossed by a nuclear terrorist attack, an accident, or a miscalculation. If the violence stops there, it is still possible to recover – much as the world healed after the horror of World War II. That possibility is depicted by the arrow returning to the world as we know it. But, once the nuclear threshold is crossed, previously unimaginable states become all too possible, including the state-of-no-return labeled WW3.⁴

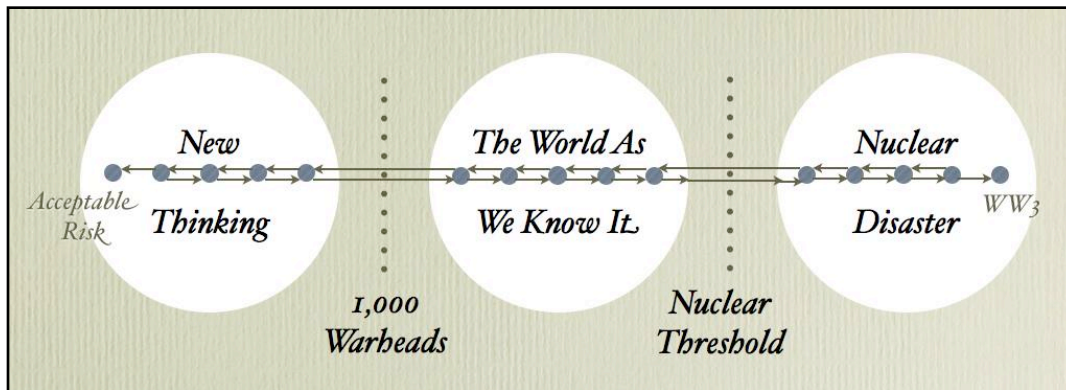
Most of the time, we are one of the less dangerous states, far from the nuclear threshold. If we stayed there forever, society’s lack of concern about nuclear war might be understandable. This is indicated in the diagram by the lack of a discontinuous jump from the safer states to WW3. What that societal complacency misses is the possibility of making a sequence of mistakes that takes us to the brink of the nuclear abyss, as happened during the Cuban Missile Crisis of 1962, and then beyond. We will revisit the above state diagram and risk analysis in more detail later in the seminar.

Nuclear war vs. nuclear terrorism: Many people discount the risk of a nuclear war because the chance of a nuclear terrorist attack is so much higher. While the danger of a nuclear war occurring in any given time period is probably one or two orders of magnitude (roughly a factor of 10 to 100) smaller than that of a nuclear terrorist incident, the consequences are orders of magnitude greater, if indeed they can be quantified at all. For those reasons, it is important to reduce the threat of nuclear terrorism *and* the threat of nuclear war. Fortunately, as we shall see, both efforts require the same first steps, making a choice largely unnecessary.

How much hope is there of reducing the risk of a nuclear disaster to an acceptable level?

While making the world safe from nuclear devastation will require changes that might seem inconceivable from our current vantage point, the same was true of past, fundamental transformations in human behavior. In 1800, ending slavery was seen as a fool’s errand, and women’s suffrage was even more difficult to envisage, but both eventually came to pass via processes that started with small, seemingly inconsequential steps – individuals questioning conventional wisdom. The state diagram used above to illuminate the negative possibility of a nuclear disaster can be extended as shown below to provide insight into the positive possibility.

⁴ We do not know for sure that World War III would be a state of no return, but prudence dictates making that assumption.



Just as the failure process does not occur in a discontinuous jump from our current state, near the middle of the diagram, to WW3, neither will the nuclear threat be eliminated in one fell swoop. Rather, as with abolishing slavery, a number of intermediate goals must be achieved before the ultimate success can become possible. Several features of this new diagram are of particular importance:

- The ultimate goal is described as a state of *Acceptable Risk*. Some have argued that this state requires nuclear abolition, world peace, or the rule of law being extended to an international level. While I personally believe that some elements of all three will be eventually be required, it is counter-productive to make that central to my arguments. Those goals seem so naive and unachievable from our current vantage point that emphasizing them would hinder early progress. If they are part of the long-range goal, it is better to discover that farther out in the process, after early steps have brought them into clearer view. As we shall see, the level of risk needs to be reduced by a factor of at least a thousand before becoming acceptable, so the goal of reducing the nuclear threat to an acceptable level is much more ambitious than it sounds.
- The new, positive threshold is crossed when the world's total nuclear arsenal, including weapons in storage, is reduced by 95% from its current level of roughly 20,000 to 1,000. A thousand weapons is more than enough for the US and Russia to maintain their current strategy of nuclear deterrence (e.g., 300 each for those two nations, and 400 to be divided among the other nuclear-armed states), but will require a fundamental change in societal thinking – hence the name for the newly introduced *New Thinking* super-state.
- The name of the new super-state is related to Einstein's observation, uttered soon after the horror of Hiroshima and Nagasaki, that "the unleashed power of the atom has changed everything, save our modes of thinking, and we thus drift toward unparalleled catastrophe." Einstein summarized both the problem (an obsolete mode of thinking about

national security) and the solution (discovering and adopting a new mode of thinking that is consistent with the realities of the nuclear age).

There is a hopeful precedent because the changes in human thinking required to defuse the nuclear threat are no greater than those that brought about the end of slavery or those that gave women the vote. Added hope comes from recognizing an additional factor that should make this shift even easier: Nuclear weapons have the potential to end civilization, while neither slavery nor the subjugation of women posed an existential threat to those in power. The thinking that causes us to cling to nuclear weapons is sometimes seen as a seemingly immovable object. But, in that analogy, the survival drive would be an irresistible force. When those two meet, I am confident that survival will win out. But, for that to happen, society must come to see that those are the stakes. Hence, the critical first step in solving this problem is creating clearer societal understanding of the nuclear threat.

Getting society to recognize that need is aided by a growing chorus of world leaders, who are sounding the alarm and calling for change. A [seminal 2007 article](#) by George Shultz, William Perry, Henry Kissinger and Sam Nunn called for a return to the vision of a world free from the nuclear threat. Because this goal was posed by Ronald Reagan and Mikhail Gorbachev during their 1986 summit at Reykjavik, this effort is sometimes called “a return to the vision of Reykjavik.” This “gang of four” effort is notable for its bipartisan nature: Shultz had been President Reagan’s Secretary of State, Perry had been President Clinton’s Secretary of Defense, Kissinger had been President Nixon’s Secretary of State and National Security Advisor, and Nunn had been the Democratic Chairman of the Senate Armed Services Committee. President Obama credits this group with laying the foundation for [his own](#) “commitment to seek the peace and security of a world without nuclear weapons.”

What role can I play?

Never doubt that a small group of thoughtful, committed citizens can change the world; indeed, it's the only thing that ever has. Margaret Mead

There go the people. I must follow them, for I am their leader. Alexandre Ledru-Rollin

While support from world leaders facilitates the task of changing societal thinking, their efforts need greater grass roots support to succeed. The [difficulty in ratifying the New START Treaty](#) shows that too few people understand this issue. If more understood the stakes, they would demand change and our elected leaders either would get on board or cease to lead.

Changing the thinking of the entire nation currently is an impossible task that far exceeds the available resources. But, if we focus our efforts, we probably can make one or two dorms on campus “nuclear aware.” If that can be accomplished, the larger number of people involved would provide a firm foundation for Stanford becoming a larger pocket of nuclear awareness. That would provide even greater resources that eventually could transform the nation as a whole, at which point significant, concrete changes that currently seem inconceivable could start to occur.

Former Supreme Court Justice Sandra Day O’Connor (Stanford ’50) wrote the letter shown on the following page, encouraging Stanford students to entertain “the audacious concept that their involvement could be the catalyst for realizing that immense and important goal.” She notes that, in entertaining that “nobler hypothesis ... there is nothing to be lost and much – potentially the whole world – to be gained.” Former Secretary of State George Shultz and former Secretary of Defense William Perry also support this effort to make Stanford nuclear aware, as does our Stanford’s President Emeritus Donald Kennedy, two of our Nobel Laureates (Prof. Kenneth Arrow in Economics and Prof. Martin Perl in Physics), and a former Dean of Engineering (Prof. William Kays).

Justice O’Connor’s letter mentions the important role that the late [Professor Harry Rathbun](#) played in both of our lives. Born in 1894, he taught business law here for many years. His last lecture of every year was more eclectic and dealt with the meaning of life. It became so popular that it had to be moved to Memorial Auditorium, and filled even that venue. The current sequence of [Rathbun lectures](#) continues that tradition. Justice O’Connor gave the inaugural Rathbun lecture in 2008, followed by Secretary Shultz in 2009 and the Dalai Lama in 2010.

My own interactions with Harry (as he preferred to be called at that point in his life) started in 1981, when my wife and I became involved with a group that he and his wife Emilia had founded. While initially our interest was in improving our marriage, the same approach required there also applied to improving international relationships: learning to look beyond my own frame of reference and trying to understand the other’s viewpoint – another way to describe critical thinking. (It is also closely related to Rabbi Hillel’s injunction, not to do unto others that which is hateful to us.) As the nuclear threat came into sharp focus during the 1980’s the group shifted its focus to that issue. As I became aware of the danger, I dropped my usual research on cryptography (codes and ciphers) and applied my efforts to help solve the nuclear dilemma. After almost 30 years, I am still at it. Short-term solutions do not appear to be in the cards!



Supreme Court of the United States
Washington, D. C. 20543

CHAMBERS OF
JUSTICE SANDRA DAY O'CONNOR (RET.)

March 2010

To Stanford's Student Body,

When I was an undergraduate at Stanford University, Professor Harry Rathbun repeatedly emphasized to me that a single caring individual could make a difference in this huge world, and might even help determine the course of events. I had not heard that before, but he put it forward so persuasively that many of us came to believe it might be true, and to take seriously the notion that we could make a difference. I can now say unequivocally that he was right.

Professor Martin Hellman, who also credits Professor Rathbun with having a major impact on his life, is currently attempting to complete "Harry's last project," whose goal was to end the threat posed by nuclear weapons. Given the Rathbun influence, it is fitting that this effort depends on Stanford students entertaining the audacious concept that their involvement could be the catalyst for realizing that immense and important goal.

Harry Rathbun died in 1987, so he cannot embolden today's students to consider that they might have that kind of impact on the world. I am pleased to encourage you, as Professor Harry Rathbun would have done, to entertain what he called "the nobler hypothesis" and take leadership roles in this effort to make society's actions consistent with the realities of the nuclear age. In doing that, there is nothing to be lost and much — potentially the whole world — to be gained.

Sincerely,

Sandra Day O'Connor

It is fitting to mention Harry Rathbun's influence from another perspective as well. He was fond of defining the scientific spirit (his earlier degrees were in Electrical Engineering) as "a zealous search for the truth, with a ruthless disregard for commonly held beliefs when they are contradicted by the observed data." That is yet another way to define the critical thinking that is at the heart of resolving the nuclear dilemma.

While applying critical thinking to root out fallacious assumptions may seem like a very small step in the long journey of defusing the nuclear threat, its importance is much larger than might first appear. In mathematics, there is a method of proof known as *reductio ad absurdum*, Latin for "reduction to the absurd." If a line of valid reasoning results in an incorrect (ridiculous) conclusion, that proves there is a false assumption. For example, this method of proof is used to prove that the [square root of 2 is irrational](#).

Our nuclear strategy has produced an absurd situation: In 1945, the United States was inviolate. Today, after spending trillions of dollars on nuclear weapons and applying some of our brightest minds to the problem of national security, we can be destroyed in under an hour. If, as appears to be the case, some false assumptions may underly our nuclear strategy, no amount of effort will fix the problem until they have been identified and eliminated from our world view. We will investigate a larger number of possibly fallacious assumptions, but for now I will list several of the most critical:

- We have gone 65 years without a major war. That's a record. Nuclear deterrence is not broken, so it would be dangerous to try and fix it.
- The thousands of nuclear weapons in our arsenal have made us more secure. Reducing our arsenal by any significant fraction would be dangerous.
- Even if change were desirable or needed, it is impossible. Look at Russia's resurgent nationalism, not to mention the nut jobs running North Korea and Iran.
- Even if change were possible, individuals like me have no role to play. Only our leaders have the power to bring about the required changes at a national and international level.

Why nuclear weapons?

The risk posed by nuclear weapons is just one among many critical problems we face, so why am I putting the bulk of my efforts into resolving just that one threat? For example, currently, there is significant momentum behind the movement to halt global warming, a modicum of concern about nuclear terrorism, and almost no public interest in the threat posed by nuclear war. It might therefore seem that we should direct our energy to global warming. But we cannot afford to neglect *any* issue with potentially catastrophic consequences, and especially ones that threaten

human survival. While addressing that many problems simultaneously may seem daunting, there is a fundamental underlying problem behind all three of those imperatives, as well as others just coming into view. For example, in the not too distant future it may be possible to create deadly pathogens that resist the body's immune system. Our experience with computer viruses shows that it takes only a small number of misdirected souls to create havoc with powerful, new technologies.

Science and engineering have given us powers that were traditionally thought of as god-like: raising the dead, creating new life forms, and destroying the world. In contrast to our awesome physical power, humanity's social progress is far from god-like. At best, our species is in its adolescent phase. This chasm between our technological powers on the one hand and our social development on the other has created a recipe for disaster that demands urgent attention if the human race is to survive. Humanity is like a 16-year-old with a new driver's license who somehow got his hands on a 500 hp Ferrari. He will either grow up fast or kill himself.

For 99.9% of our tenure on this planet, we could wait for direct evidence of our errors before correcting our actions. Sometimes the results were horrendous, as in the two World Wars and some environmental degradation. As bad as those results were, our trial and error approach did not threaten our existence as a species. But, during the last 0.1% of *homo sapiens* tenure on this planet, our physical power has become so great that we can no longer wait for direct evidence of our errors before changing our ways. Given that 99.9% of humanity's data says trial and error works, it is understandable – but terribly dangerous – that we have not recognized the obsolescence of that approach.

Because it would complicate the basic message concerning the nuclear threat, this overarching view is best left out of most discussions at this point in time. But, once society has recognized the highly unacceptable risk of our current approach to nuclear weapons, it would be natural to raise the question “How did we get into such a mess, and where else might we be neglecting catastrophic threats?” That would lead us to consider the long term consequences of our actions, and not wait for disaster to strike before taking corrective action. If we are able to do that, efforts to avert global warming, severe environmental degradation, nuclear terrorism, nuclear war, bioterrorism, and other catastrophes would be seen as part of the same underlying effort. They would reinforce one another, rather than compete for resources.

I believe that the problem with trial and error can be seen most clearly with the nuclear threat, so I put most of my effort into working on this topic, and later hope to connect it to the others. But, I have deep respect for, and often join, people who focus on other critical issues facing humanity.

The Physics of Nuclear Weapons

While the technology behind nuclear weapons is of secondary importance to this seminar, some background is helpful when dealing with issues such as nuclear proliferation. For example, the following information will put North Korea's uranium enrichment program in a less threatening context than has been portrayed in the mainstream media, while showing why Iran's program is of greater concern. Those wanting more technical details on nuclear weapons can find them online, with Wikipedia's article [Wikipedia's article](#) being a good place to start.

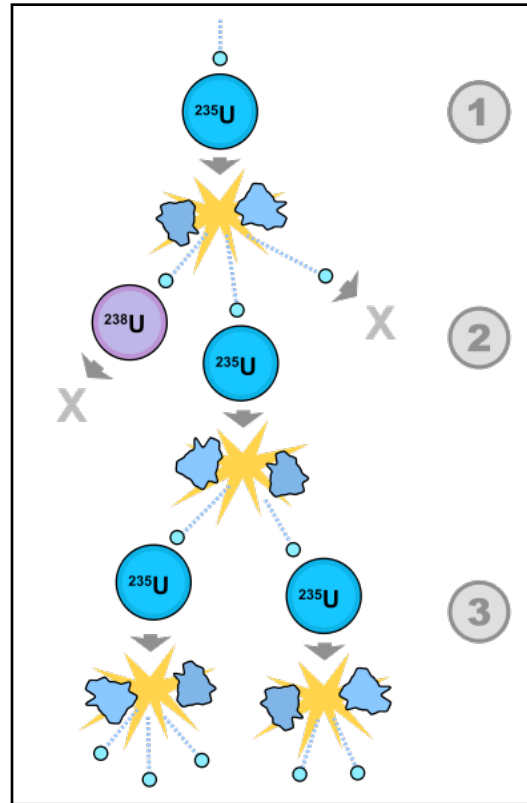
The atomic bombs used on Hiroshima and Nagasaki were fission weapons. The nuclei of atoms consist of protons and neutrons, with the number of protons determining the element (e.g., carbon has 6 protons, while uranium has 92) and the number of neutrons determining the isotope of that element. Different isotopes of the same element have the same chemical properties, but very different nuclear properties. In particular, some isotopes tend to break apart or fission into two lighter elements, with uranium (chemical symbol U) being of particular interest. All uranium atoms have 92 protons. U-238 is the most common isotope of uranium, making up 99.3% of naturally occurring uranium. The 238 refers to the atomic weight of the isotope, which equals the total number of protons plus neutrons in its nucleus. Thus U-238 has $238 - 92 = 146$ neutrons. U-235 has 143 neutrons and makes up almost all the remaining 0.7% of naturally occurring uranium. (U-234 is very rare at 0.005%, and other, even rarer isotopes exist, some of which have only been produced in the laboratory.)

U-235 is the valuable isotope from a nuclear weapons or nuclear power point of view because it can serve as the primary fuel for a weapon or power plant, while U-238 cannot. As shown in the next diagram (source: Wikimedia Commons), when a U-235 atom absorbs a neutron, it breaks into two smaller atoms plus some number of neutrons. This splitting or fission also releases "atomic energy" that can produce electricity or an explosion.⁵ On average, such a fission of a U-235 atom produces about 2.5 new neutrons. If all released neutrons are absorbed by new U-235 atoms, an exponentially growing chain reaction sets in, with the number of atoms involved growing from 1, to 2.5 (on average), to $2.5^2 = 6.25$, etc. After 10 "generations" over 10,000 atoms have fissioned, after 20 generations over 100,000,000 atoms have fissioned, etc. But, as depicted in the diagram, some neutrons escape without adding to the chain reaction (the one with an X on the right in step 2) and some are absorbed by U-238 atoms (the one with an X

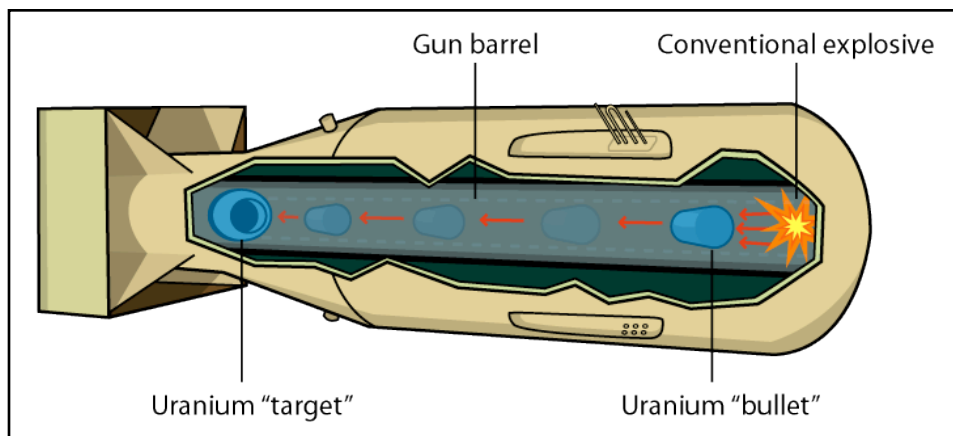
⁵ Optional reading: Technically this "atomic energy" derives from what is called the binding energy of the nucleus. Somewhat counter-intuitively, the binding energy is greater for the two atoms produced than for the U-235 atom. That is because binding energy is the energy *released* in forming the nucleus from its constituent parts. More energy is released in forming the two fission fragments than was previously lost in forming the U-235 nucleus, hence there is a net release of energy.

on the left in step 2) and do not produce additional neutrons to add to the chain reaction. (By absorbing an additional neutron, the U-238 atom becomes U-239 which we will deal with later. The important point right now is that it does not produce additional neutrons.) If, on average, each fission leads to more than one additional fission, the chain reaction grows exponentially and releases large amounts of energy.

Atomic forces within the nucleus are much stronger than chemical forces. U-235 in an atom bomb therefore liberates much more energy than exploding the same mass of TNT. The bomb used on Hiroshima contained approximately 50 kg (100 pounds) of U-235, yet packed the explosive power of 15,000 tons (30 million pounds) of TNT. If all of the U-235 fuel had fissioned, the yield would have been 500 kilotons. The actual yield was only 3% of that figure because, as the weapon exploded, most of the U-235 was dispersed before it could capture a neutron and contribute to the chain reaction.



The above discussion points out that what is usually called *critical mass* is really a critical mass density. After a bomb based on U-235 explodes, most of the U-235 is still present. It is just too thinly dispersed to maintain a chain reaction. Too few neutrons are captured by other U-235 atoms to maintain the chain reaction. That same idea is at the heart of the “gun assembly” atomic bomb depicted below (source: Wikimedia Commons). Two subcritical masses of uranium are at either end of the gun barrel. One is shaped like a bullet, while the other is a hollow cylinder



target that just fits around the bullet. Conventional explosives shoot the bullet down the gun barrel, where it mates with the target. The two subcritical masses, when brought together rapidly, form a supercritical mass, resulting in a chain reaction and an atomic explosion. Note that prior to ignition the bomb has more than a critical mass worth of uranium, but it is divided into two pieces that are too far apart for neutrons from one to cause fission in the other.

As already noted, U-238 is usually not useful as atomic fuel, but constitutes 99.3% of naturally occurring uranium, with most of the remaining 0.7% being U-235. Naturally occurring uranium therefore cannot be used in a weapon or most power plants, and must first be enriched to a higher level of U-235. The most prevalent nuclear power plants today are light water reactors (LWR's) that need uranium enriched to about 3-4% U-235, known as low-enriched uranium (LEU). Bomb-grade fuel must be enriched further, preferably to 90% U-235, which is called highly-enriched uranium (HEU).

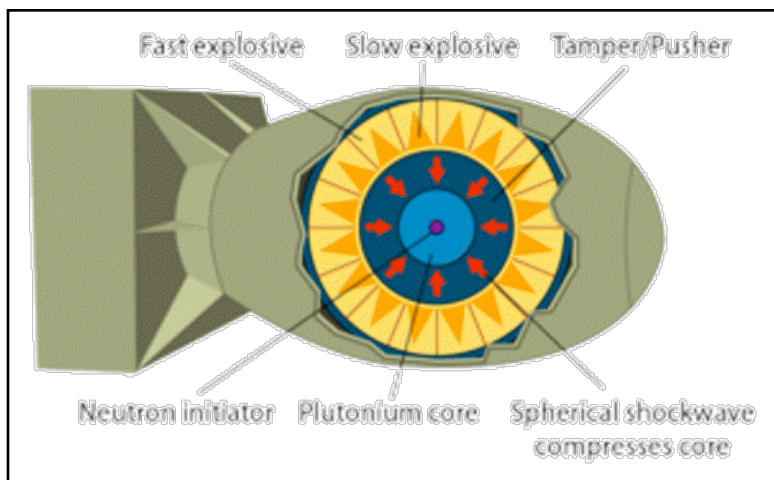
Unfortunately, the same technology used to make LEU for nuclear power (e.g., the gas centrifuges used in Iran's nuclear program) can be modified to make HEU for weapons. The Nuclear Non-Proliferation Treaty (NPT) requires signatories other than the US, Russia, the UK, France and China to forgo the development of nuclear weapons, but recognizes the "inalienable right" of all nations to develop nuclear technology for peaceful purposes.⁶ The close connections between peaceful and military applications of nuclear technology make distinguishing between those aims extremely difficult, and that is a particular problem with uranium enrichment. Mohamed ElBaradei, the former Director General of the International Atomic Energy Agency, has referred to enrichment as the Achilles' heel of non-proliferation. Iran, for example, can claim that its enrichment program is needed for its domestic nuclear power program and does not violate its NPT requirements. Yet, its ability to enrich is likely to make it a "latent nuclear power" (a nation that could build a bomb in short order, should it choose to do so) in the near future.

HEU is particularly dangerous from a proliferation point of view because weapons based on it are likely to work without any testing. The HEU weapon used on Hiroshima on August 6, 1945, was never tested before use. The nuclear test explosion on July 16, 1945, at Alamogordo, New Mexico (codenamed the Trinity test) was of the more complex plutonium design described

⁶ The five nations allowed to maintain nuclear weapons development are called the recognized nuclear weapons states. Article VI of the NPT requires them "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament." The lack of progress on nuclear disarmament since the NPT went into force in 1970 has led to arguments that these five nations, including the US, are in violation of their NPT obligations. The counter-argument is that "good faith" negotiations have in fact taken place.

below. The Manhattan Project scientists did not have enough confidence in that design to use it on Nagasaki without first running a full-scale test. North Korea's two atomic tests have been with plutonium weapons, and the low yield of the first test – on the order of 1 kiloton – is evidence of the need to test such weapons before deployment.

Plutonium (chemical symbol Pu, originally suggested as a joke by Glenn Seaborg) has 94 protons, two more than uranium. It also has several isotopes, with Pu-239 being most useful in nuclear weapons. Plutonium occurs only in trace amounts in nature, but is produced in nuclear reactors when U-238 captures a neutron and temporarily becomes U-239. U-239 has a short half-life and decays into neptunium-239 (Np-239), which decays into Pu-239. Pu-239 is much more stable, with a half-life of 24,000 years. The plutonium produced this way is an excellent bomb fuel, but harder to ignite than HEU. Rather than a simple gun assembly, plutonium-based weapons must use the complex implosion technique depicted below (source: Wikimedia Commons).



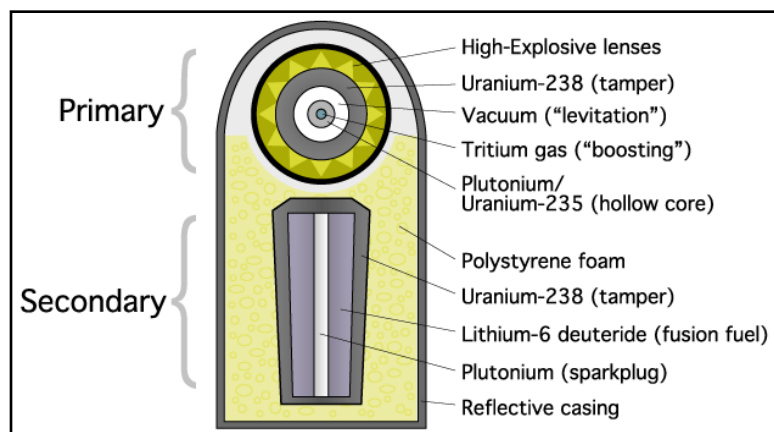
The plutonium is fashioned into a spherical core, known as a plutonium pit (as in a peach pit) that is placed at the center of a hollow shell of conventional high explosives. Known as an explosive lens, these explosives all must detonate at precise times to form a spherical shock wave that compresses the pit, reducing the critical mass. (Even metals such as plutonium will compress under extreme pressure.) In its normal, uncompressed state, the pit has less than critical mass. But once the explosive lens is detonated, the increased density results in a supercritical mass and an atomic explosion. The neutron initiator or trigger shown in the diagram is of critical importance to the functioning of the weapon, but need not concern us at this level of detail.

Although plutonium-based weapons are more complex, once a nation has mastered that design, it tends to be preferred to HEU weapons. One reason is that less than 10 kg of plutonium is needed

in a weapon, while several times that amount of HEU is needed. In a guest lecture to an earlier incarnation of this seminar, former Director of Los Alamos and now Stanford Professor Siegfried Hecker, noted that North Korea's uranium enrichment program was of less concern given its ability to make the more complex, but more militarily useful plutonium weapons. The opposite is true of Iran's enrichment program because it has not demonstrated the ability to make plutonium-based weapons.

Natural uranium, with only 0.7% U-235, is not useful as either bomb or power plant primary fuel, with an important exception. That is the Magnox reactor, which is a gas-cooled, graphite-moderated reactor. Magnox reactors can run on natural, unenriched uranium and produce bomb-grade plutonium that is relatively easy to separate out from the uranium due to their different chemical properties. (In contrast, U-235 is much more difficult to separate from the more prevalent U-238 because they have the same chemistry.) North Korea used a small Magnox research reactor to produce all of the plutonium used in its two tests and in its estimated 4-8 remaining weapons. This approach bypassed the need to master the enrichment cycle. Provided that the LEU required by a light water reactor (LWR) is provided by a supplier nation under carefully controlled conditions, LWR's are more proliferation resistant both because the fuel can be carefully monitored and because the plutonium produced by an LWR is less suitable for use in weapons. This helps explain why the 1994 Agreed Framework that sought to limit North Korea's nuclear weapons ambitions sought to trade that nation's Magnox reactors for two LWR's. We will cover those issues in more detail later.

The fission weapons described above have a theoretical limit to their yield, and the largest such weapon ever developed had a yield of 500 kilotons. Fusion weapons have no such upper limit, and the largest one ever tested yielded 50 megatons – that's 50,000 kilotons, or 100,000,000 pounds of TNT equivalent. Such enormous weapons have little practical value, and today's strategic weapons are in the 100 to 500 kiloton range, still many times more destructive than the weapons used on Hiroshima and Nagasaki. Tactical or battlefield nuclear weapons have sub-kiloton yields since too big a blast will annihilate friendly as well as enemy troops.



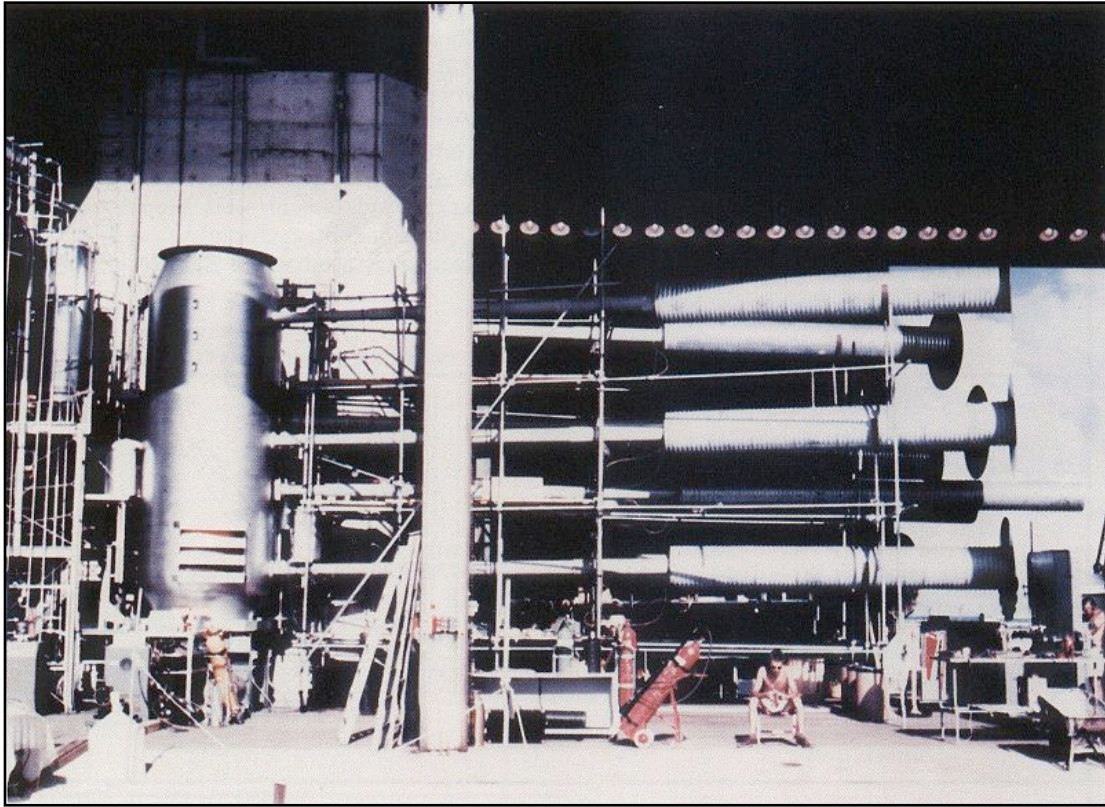
Fission weapons are sometimes called atomic bombs, while fusion weapons are also known as hydrogen bombs or thermonuclear weapons. The basic components of a fusion weapon are shown in this diagram (source: Wikimedia Commons). The “primary” is basically an implosion fission weapon that is used to ignite the

secondary, fusion reaction. Hydrogen has three isotopes:

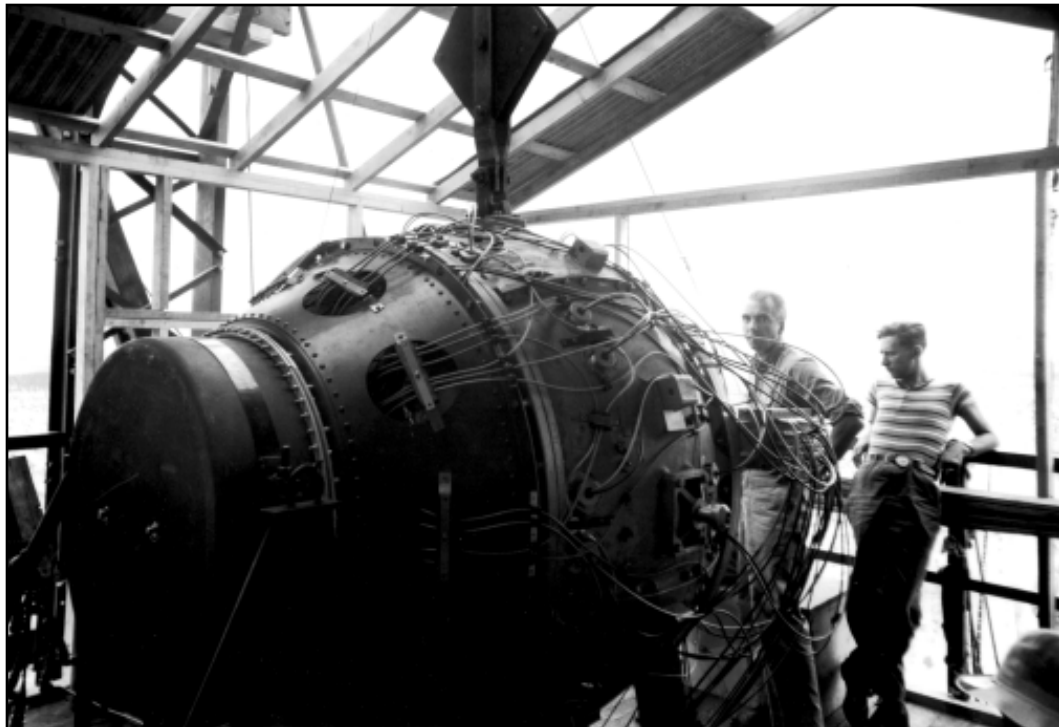
- Normal hydrogen (chemical symbol H) has a single proton in its nucleus and no neutrons. It makes up 99.985% of naturally occurring hydrogen. Light Water Reactors use normal or light water, H₂O.
- Deuterium (chemical symbol D or ²H) has one proton and one neutron and makes up almost all of the remaining 0.015% of naturally occurring hydrogen. Heavy Water Reactors use heavy water, D₂O, and are more proliferation-prone than Light Water Reactors because, like Magnox reactors, they can use naturally occurring (unenriched) uranium as their fuel.
- Tritium (chemical symbol T or ³H) has one proton and two neutrons. Tritium is radioactive with a half-life of about 12 years. Only trace amounts occur in nature and the tritium used in nuclear weapons must be man-made.

The most useful fusion reaction in a nuclear weapon is for a deuterium nucleus to fuse with a tritium nucleus. All together those two nuclei have two protons and three neutrons. When they fuse, they produce a helium nucleus with two protons and two neutrons, and an extra neutron that is ejected. (The extra neutron adds to the fission reaction and makes use of the U-238 tamper shown in the diagram. This is an exception to the general rule that U-238 is not useful as bomb fuel. U-238, by itself, cannot be used in a weapon, and requires either HEU or plutonium.) The fusion of the deuterium and tritium nuclei releases a large amount of energy, which is what makes the weapon explode.

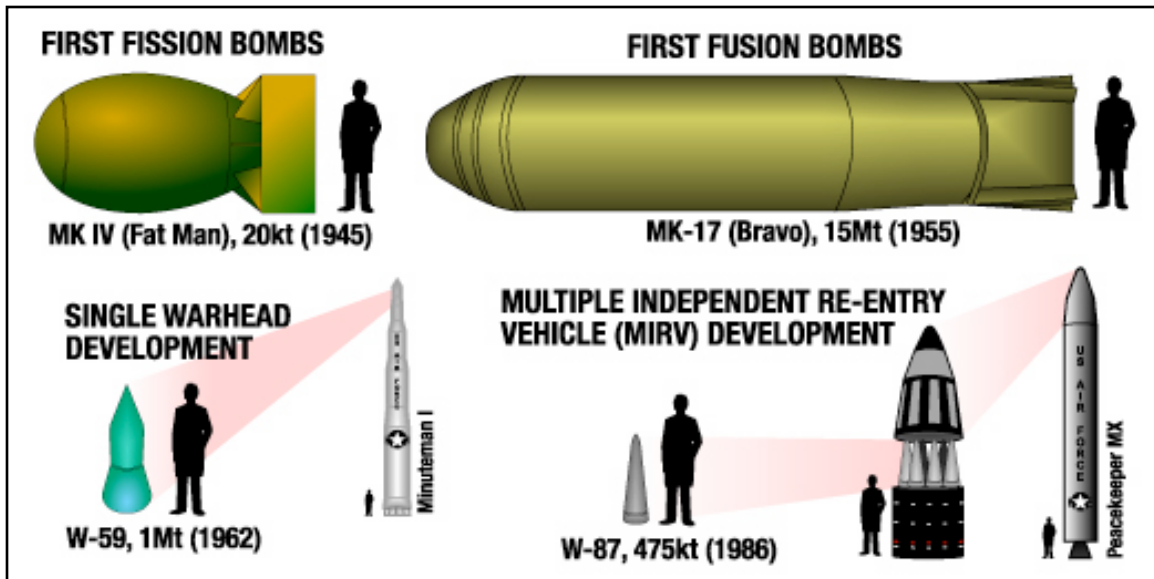
The first “hydrogen bomb,” codenamed Ivy Mike, was anything but a bomb as can be seen in the picture below (source: US Department of Energy). To get an idea of the apparatus’ size, note the men near the lower right hand corner of the picture. It was intended solely as a proof of concept, which purpose it served well with a yield of slightly over 10 megatons.



The “gadget” (as it was called) used in the July 1945 Trinity test is shown below for comparison purposes (source: US Department of Energy). While large, an airborne version was possible.

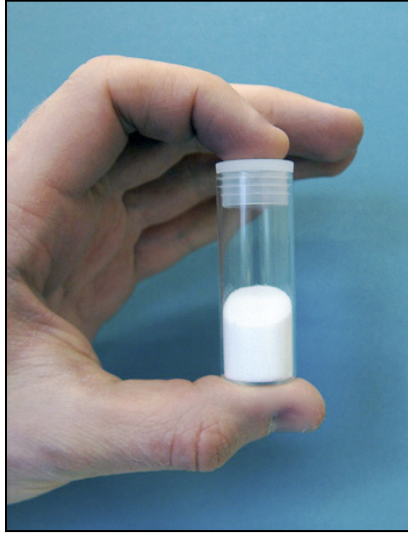


The next figure (source: Wikimedia Commons) depicts the evolution of nuclear weapons over the years, showing how they have been miniaturized. It is hard to comprehend that the 475 kiloton W87 warhead shown in the lower center of the figure is small enough to fit in a backpack, yet can destroy a city. But comprehend it, we must.



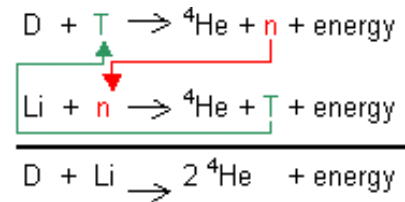
The nose cone of the MX missile (in lower right corner of the figure) can hold up to ten W87 warheads, each independently targeted, a technique is known as a MIRV'ing the missile. (MIRV stands for Multiple, Independently-targetable Reentry Vehicle.) Initially, highly MIRV'ed missiles were seen as a cost-effective way to increase an arsenal, but over time they came to be seen as dangerous and destabilizing. That is because MIRV'ed missiles make an attractive target for a first strike. It only takes one warhead (or several "to play safe") to knock out an enemy's missile with a much larger number of warheads. This leads to crisis instability, in which there is an incentive to strike first. In consequence, recent arms control agreements discourage highly MIRV'ed missiles. For example, the New START Treaty that was just ratified by the Senate limits both the US and Russia to 700 deployed launchers (missiles and bombers) and 1,550 deployed warheads, allowing only slightly more than 2:1 MIRV'ing.

There is one more aspect of nuclear weapons that I will cover in this handout, but it is optional reading since this is getting more technical than needed. I noted above that fusion uses deuterium and tritium, two isotopes of hydrogen. At normal temperatures and pressures, all hydrogen isotopes are a gas, and therefore not very dense. Ivy Mike got around this problem by using liquid deuterium and tritium, which helps explain the size of the apparatus – the cryogenic equipment all by itself was quite large. Later, it was realized that the required fuel could be stored in solid form at normal temperatures and pressures by using an innovative approach.



Lithium and hydrogen combine chemically to produce a solid compound or salt LiH, known as lithium hydride, shown in the attached photo. By using deuterium in place of normal hydrogen, the salt becomes lithium deuteride, LiD. The basic fusion equation for a nuclear weapon is the first line of the next figure: Deuterium combines with tritium to produce helium, an extra neutron and energy. The neutron can be captured by a lithium atom, which then fissions to produce helium, tritium and energy. As shown by the green arrow, the tritium thus produced can then fuse with another deuterium nucleus, allowing the reaction to continue. The third line of the figure “adds” the first two equations to show that the overall

effect is that lithium and deuterium can be the fuel for the fusion, and that is exactly what composes lithium deuteride! This approach not only solves the low density problem of hydrogen, but also the short half-life problem of tritium. As already noted, tritium has a half life of only 12 years. Hence, if tritium were used as fuel, some of it would have to be replaced every few years. The lithium deuteride is stable for long periods of time and does not require such periodic refueling.



The diagram shown below (source: Wikimedia Commons) traces the steps in the detonation of a thermonuclear weapon based on lithium deuteride, and is also optional reading. In the second step, HE stands for High Explosives.

