LOBBY SEVEN

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*"They write politics, we write government"*

# GAME THEORY AND THE NUCLEAR AGE

## The Destroyer of Worlds

*"It is a harnessing of the basic power of the universe. The force from which the sun draws its power has been loosed against those who brought war to the Far East." – Harry S. Truman*

Imagine wanting to know what is on the inside of a baseball. But you aren't allowed to cut into it or peel off the skin. You can't look for interactions with acid, fire or any other substance. Your only choice is to stand a great distance away, shoot at it with a pistol, and see what flies off. That is nuclear physics.

As late as the year 1895, there was very little evidence of any particles smaller than the atom. A mere fifty years later, the power of these sub-atomic particles had been harnessed in the most dramatic fashion possible. The unleashing of the nuclear age changed the rules of war: mankind now had the power to destroy itself. Two superpowers soon would face off in a five-decade struggle, the likes of which had never before been seen. To survive, our greatest minds had to develop a new way of thinking about the very nature of cooperation and competition.

- How do nuclear bombs work? How were they built?
- How did nuclear weapons proliferate?
- What is game theory?

**A word of caution from the author:**

Nuclear weapons are terrible things. This is true in all of the word's meanings.[1] Terrible: extremely bad, as in "a terrible movie." Terrible: formidable in nature, as in "a terrible responsibility." Terrible: extreme or great, as in "a terrible disappointment." Nuclear weapons are not to be trifled with, joked about or handled except with extreme care.

Which is all to say – this Volume will prominently feature death, destruction, fallout, nuclear winters and the end of the human race. We will flippantly talk about the gruesome deaths of millions and even billions. We will explicitly do this through the lens of a game, winning and losing, keeping score of the destruction. We will not modify our usual style of writing or the ongoing attempts at mild humor. We are not focused on the morality of these weapons, their development or their use. Except in the paragraphs immediately following.

The previous five hundred years have been a period of steady human advancement with no major steps back. It was inevitable that we would learn about the power of the atom. Every man, woman and child is innately aware of this power. It stares you in the face every day, from sunrise to sunset. We were going to learn about radioactivity, fission and fusion and chain reactions. It necessarily follows that we would try to harness this power. Even with knowledge of their destructive potential, we were eventually going to

[1] From Merriam-Webster as usual.

develop nuclear weapons capabilities. They are a by-product of these five centuries of discoveries about the Universe we live in.

Morality comes only after development: how can these weapons be controlled to prevent their use? The two decades after the Trinity Test were not just a scramble to build bigger bombs, but also to develop these controls. Game theory contains the most effective controls we've found. And we can only learn the game theory of nuclear weapons by repeatedly simulating the destruction of the world.

Only by understanding these weapons can we prevent their use.

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How do nuclear bombs work? How were they built?

The three primary sub-atomic particles were discovered by three citizens of the British Empire over a period of thirty-five years around the turn of the century.[2] All three were associated with the famed Cavendish Laboratory at Cambridge University.[3]

In 1897, J.J. Thompson found that cathode rays travel too fast for particles as large as an atom. This meant that there must be at least one smaller, more fundamental particle. He also found that these rays interact with an electrical field; this implied that the particle he discovered has a negative charge. Thompson had discovered the **electron**.

By 1908, Ernest Rutherford had already won a Nobel Prize for formalizing the nature of radioactivity. One day, he decided to shoot "alpha particles" at a sheet of gold foil. Some of the alphas bounced back. As Rutherford himself said, "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." Clearly, there were some tiny, dense parts in the atoms making up the gold foil. Because they deflected positively-charged alphas, they must themselves have positive charge. Rutherford named these particles **protons**.

Scientists theorized that something was still missing. Atoms were heavier than expected, so something else had to be there. These theoretical particles had to be uncharged, which would make them more difficult to find. James Chadwick worked tirelessly, irradiating various substances, developed new detection techniques, and found the elusive **neutrons**. The basic model of the atom was complete: a nucleus of tightly bound protons and neutrons with tiny electrons orbiting. [4]

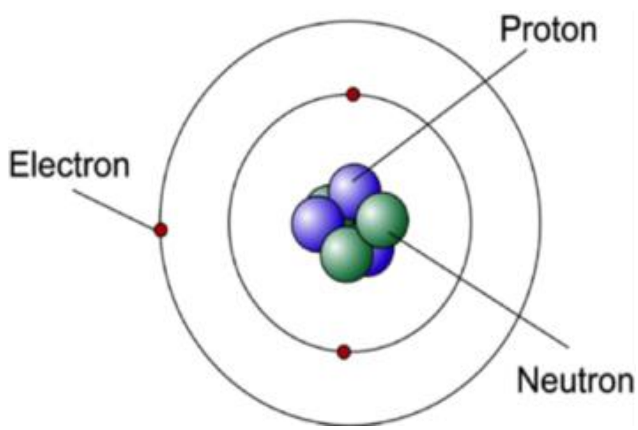


FIGURE 1 - THE BOHR MODEL OF THE ATOM

[2] OK, I've tried some ridiculous things before, but putting the history of atomic physics in a couple pages is truly nuts. You can hurt yourself doing things like this. To say this is a cursory overview is more than an understatement. If you really want to know how this happened, I suggest you read [The Making of the Atomic Bomb](), by Richard Rhodes. The paperback is 896 pages and it is not slow.

[3] Rutherford found the proton at Manchester before moving to the Cavendish.

[4] This "Bohr Model" of the atom has been significantly updated based on further discoveries but it works for our purposes. Recall that elements are defined by containing a specific number of protons. Within an element, the number of neutrons determine the isotope. For example, all Carbon atoms have six protons. Carbon-12 is an isotope of Carbon with 6 neutrons; Carbon-14 has 8 neutrons.

High school chemistry is the study of electrons; chemical reactions involve exchanging or sharing them in some manner. Radioactivity is the study of the nucleus: protons and neutrons. For instance, if you bombard an atom with neutrons, some of these will be captured by the nucleus. As the nucleus grows, the atom becomes less stable. If it gets too far, an atom may undergo **Beta decay**, where a neutron turns into proton and an electron. Your atom is now a different element, but the nucleus is the same size.[5] Depending on the isotope, an atom may also undergo **Alpha decay**, spitting out two protons and two neutrons. This will make our atom into a lighter element. Because they have no charge, neutrons are the best particle to use in nuclear reactions. With Chadwick's discovery, scientists could start to have some real fun.[6]

*An Aside: Nuclear Binding Energy Calculations*

It sounds boring, but I assure you it's quite explosive. *Nuclear binding energy* is how tightly an atom's nucleus is held together. Because energy and mass are equivalent, the binding energy of an atom is equivalent to its *mass defect*: how much less the atom weighs than the sum of its parts. The greater the mass defect, the more stable and less radioactive an atom is.

One of the most common fission reactions involves Uranium getting hit by a neutron, splitting into Rubidium and Cesium and releasing two neutrons:

$$U + n \rightarrow Rb + Cs + 2n$$

Looking up the masses of these atoms, we see that for each fission reaction, $0.323 * 10^{-27}$ kg has been converted to energy. Multiplying by $c^2$ shows this reaction creates $2.9*10^{-11}$ Joules of energy. A tiny amount – but this is for each individual atom.

There are $6.022*10^{23}$ atoms in a *mole*; a mole of Uranium-235 has a mass of 235 grams. This is about half a pound of Uranium, it would fit easily in a tablespoon.

If you could create a chain fission reaction for this amount of Uranium, it would release $1.75*10^{13}$ Joules of energy. In other words, you can fit enough Uranium in the palm of your hand to provide for your family's annual energy usage.

In 1934, Enrico Fermi bombarded the heaviest naturally occurring element, Uranium, with neutrons. He hoped to synthesize heavier elements, never before seen by man. Soon, he had created two elements that were not Uranium; he believed he had synthesized the elements that later became known as Neptunium and Plutonium. But Otto Hahn, Lise Meitner, Otto Frisch and Fritz Strassman, conducting similar experiments, soon identified one of these elements as Barium, a much smaller element. Rather than going through methods like Alpha or Beta decay, the Uranium nucleus had been cleaved in two. They had discovered **nuclear fission**.

There was a big problem with fission; it created a large amount of energy with no obvious source. It could come from only one place: the masses of the "children" of the fission reaction, added together, was less than that of the "parent". We know from Albert Einstein that $E = mc^2$. The "*m*" is mass and "*c*" is the speed of light, a very large number. The small decrease in mass during fission accounts for the enormous amount of energy created.

Leo Szilard, a Hungarian-born physicist, had already thought about the possibility of **nuclear chain reactions**. In the newly discovered fission reaction, each atom releases three neutrons when it splits.[7] If these neutrons "hit" other Uranium atoms and cause more fission, each of these atoms would in turn release three neutrons. The number of fission reactions would increase to an incredible rate. Incredible rate of reaction, enormous amount of energy. This is a bomb. Szilard, a Hungarian who emigrated to America to avoid the Nazis, explained the possibility to Einstein, who was equally concerned. Einstein added his imprimatur to

[5] Beta decay also spits out a neutrino and there are virtual particles involved too. These don't do much so we can safely ignore them.

[6] Of course, they didn't really know the risks of doing so. Marie Curie famously died of cancer caused by prolonged exposure to radiation.

[7] Usually three. Sometimes two. Or some other number.

a letter to FDR, explaining the significance of nuclear chain reactions. Intelligence showed that Nazi Germany might be developing nuclear technology. The United States soon committed its enormous industrial capacity to the development of a nuclear weapon.

The first step towards building The Bomb was to demonstrate a chain reaction. Working on a squash court under the stands of the University of Chicago football stadium, a team led by Enrico Fermi first "went critical" on December 2, 1942.[8] The biggest challenge was production of Uranium-235 and Plutonium, which would fuel the Bomb. The Army acquired enormous sites at Oak Ridge, Tennessee and Hanford, Washington to do this. In general, to create a Bomb, two smaller, sub-critical, amounts of nuclear fuel must be combined to make a **critical mass** – very quickly. To solve this and other technical problems, a group of top scientists moved to Los Alamos, high in the New Mexico Desert. The scientific work was placed under the control of Robert Oppenheimer, the Father of the Bomb. Together with many other sites, this was the Manhattan Project.

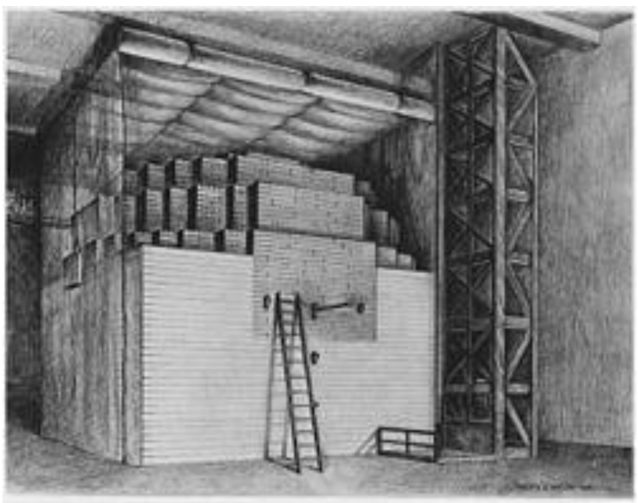

FIGURE 2 - CHICAGO PILE 1 (CP-1), NEARING CRITICAL SIZE

While work was proceeding on a fission bomb, scientists also recognized the potential for a bomb based on joining atoms together, or **fusion**. Fusion is what the sun does: Hydrogen atoms combine to form Helium. This reaction causes a much greater loss of mass than Uranium fission, with the attendant greater release of energy.[9] But, to cause a fusion reaction you need to heat your fuel to a very high temperature. The best way to do this? Set off a Fission Bomb. At the time, the Fusion Bomb was called The Super; today, we usually say H-Bomb, after Hydrogen's chemical symbol.[10]

## How did nuclear weapons proliferate?

All of the scientists who worked on the first nuclear weapons had a keen understanding that they would change the world. They understood long before the politicians exactly what it meant to unleash the power of uncontrolled nuclear chain reactions. Winston Churchill, for all of his greatness, thought The Bomb was just another weapon. Given that he had daily through The Blitz, it was not unreasonable for him to desire a bigger bomb with which to strike back. And humankind had been improving on weapons for millennia: why was this one any different? It took the scientists with their formulas and their slide rules to understand that the nature of war would never be the same.

During the period of the Manhattan Project there was a war on – a war for survival. Many fine physicists remained in Germany (and some in Japan).

[8] This was the world's first nuclear reactor. It weighed around 400 tons and produced ½ watt of energy. So, it would have taken around 100 of these to power a 50-watt lightbulb.

[9] It's hard to describe how incredibly powerful fusion is. But here goes: put your hand out in the sunlight. It gets warm, this happens quickly. That is all energy coming from the Sun's fusion reactions. Imagine a sphere around the Sun with radius equal to that of the Earth's orbit, about 90 million miles. Think of how many hands it would take to cover that sphere. Every "hand-sized" region of that sphere is receiving the amount of energy you felt, every second of every day.

[10] As an aside, I'm starting to get a bit concerned about my internet usage to write this article. Google searches include: What is the nuclear binding energy of U-235; nuclear energy calculation example; atomic bomb design; nuclear fission products.

Fission had been developed before the war cut off scientific correspondence with scientists in the Reich. Given the enormous investment to produce the first bombs, it seemed unlikely that the Axis would have one in time to affect the War's result, but there was no way to be sure. Espionage showed that at least some work continued in Germany; a heavy-water production facility in occupied Norway was especially concerning.[11] The idea of a Nazi Bomb was unacceptable, especially to the many scientist-refugees who had fled Nazi terror. The scientists working on the Manhattan Project did so despite – or because of – the full knowledge of its implications.[12]

The first real attempt by world leaders to manage the Nuclear Age was the Quebec Agreement, signed by Winston Churchill and Franklin Delano Roosevelt in August 1943. It stated that the UK and US would share resources "to bring the Tube Alloys project [UK code name for Uranium research] to fruition at the earliest moment." It also included the world's first nuclear arms control agreement:

> *"We will never use this agency against each other.*
>
> *We will not use it against third parties without each other's consent.*
>
> *We will not either of us communicate any information about Tube Alloys to third parties except by mutual consent."*

At this stage of the war, the immediate question was whether information on the Bomb should be shared with the Soviet Union. Niels Bohr[13] brought the topic to Roosevelt, suggesting that Stalin be brought in on the secret. He did not trust the Soviet leader but believed a Russian Bomb was inevitable. Building a Bomb was just not that difficult; after the war, Russia would have the means, motive and opportunity. If they were going to get it anyway, why not try to create some type of control now, before Pandora's Box was fully open? Roosevelt designated Bohr a semi-official envoy to bring this message to the British Prime Minister. Churchill, an anti-Communist of the old school, and perhaps still not understanding the Bomb's implications, thought Bohr mad.

After the war, Russia built a Bomb.[14] Like the Manhattan Project, it took about four years of concerted effort. We haven't mentioned Russian physicists in this paper, but there were many of world-class quality. Captured Germans scientists augmented their program. But the hardest work – half a century of theory and experiment – had long since been complete. The feasibility was visible in two mushroom clouds. Stalin's totalitarian regime had no trouble assigning the appropriate resources. The trickiest part was probably finding Uranium.[15] The first Russian nuclear test was in 1949.

This, of course, forced a response from the US. During the Manhattan Project period, development of the Hydrogen Bomb was not a top priority. This

[11] The destruction of the Vemork, Norway heavy-water plant was one of the most successful Allied actions of the entire War. It is a fascinating story, you can find the details in Making of the Atomic Bomb and elsewhere.

[12] Many of the scientists remaining in Nazi Germany were clearly conflicted about creating a bomb for Hitler. The most prominent nuclear scientist remaining in Germany was Werner Heisenberg, titular head of Germany's Bomb project. His internal conflict in building a Bomb for Hitler is plainly evident and it is impossible to know if he tried and failed, or if he thought it impossible, or if he intentionally stalled the research. The play "Copenhagen" is the telling of Heisenberg's meeting with Niels Bohr, and this dilemma is the key conflict.

[13] Bohr has somehow escaped mention here so far despite being a critical player in the nuclear game.

[14] More bad Google searches: History of nuclear proliferation; how did Russia build a bomb; when was the first H-bomb.

[15] Yes, they also got some useful intelligence from the Manhattan Project, most famously from the Rosenbergs and Klaus Fuchs. And they were traitors, full-stop. But in the big picture, the espionage angle was irrelevant. I am supremely confident that Russia was going to get the Bomb, no matter what.

was not due to lack of belief in its feasibility, but the relative speed of development. The fact that the fusion bomb would require a fission bomb meant that the latter would, a priori, be the first Bomb ready for use. The main proponent of developing H-Bombs was the Hungarian refugee physicist Edward Teller. President Truman responded to the Russian test by accelerating development; Teller returned to Los Alamos. The Super was tested successfully in 1952, just three years after work began in earnest.

The Hydrogen Bomb was another fundamental change in geopolitics. Fission bombs were terrible weapons. The "Fat Man" bomb dropped on Nagasaki had a yield equivalent 21,000 tons of TNT and destroyed everything within a blast radius of one mile. Around 40,000 people were killed immediately; radiation poisoning killed many more. The first H-Bomb, "Ivy Mike," had a yield of 10,000,000 tons of TNT. Even worse: fission weapons have technical limitations on their size, fusion weapons much less so. Bombs much larger than Ivy Mike were feasible. A fission bomb destroys part of a city; a fusion bomb would destroy a small state. Again, the Russians weren't far behind, detonating their first H-Bomb in 1953. By 1961, they had developed the largest weapon in history, Tsar Bomba, with the potential yield of 100 million tons of TNT.[16]

With Pandora's Box wide open, other countries wanted to join the nuclear club. When the Quebec Agreement was cancelled at the end of the War, the UK felt the need for its own nuclear deterrent. Their first test was in 1952 and by 1957 were the third state armed with fusion bombs. France, alienated from both the US and USSR after the Suez Crisis, was the fourth nuclear nation by 1960 and soon had her own Supers. China began an exchange with the Soviet Union: nuclear raw materials for nuclear know-how. This small facet of the complex, multi-decade Sino-Soviet relationship helped China become the last member of the "big five" nuclear states. India, Pakistan and North Korea acknowledge their nuclear capabilities; Israel's government is strategically vague but few doubt the capacity is there; South Africa claims to have produced nuclear weapons but has eliminated its program.[17]

While there have been many further developments in atomic weaponry, one stands out for strategic importance: Inter-Continental Ballistic Missiles, or ICBMs. In 1945, the United States dropped nuclear bombs on a Japanese homeland over which it had achieved air supremacy. In 1955, the United States and Soviet Union had many nuclear weapons, but no consistent manner to deliver them. The USSR's problem was especially acute: the US had bases near Russian soil and better long-range bombers.

ICBMs were created to address these strategic difficulties. Travelling at hypersonic speeds above the Earth's atmosphere, ICBMs can be launched from home and reach their target in a matter of minutes. They are impervious to "classical" air defense systems like anti-aircraft guns and fighter planes. Inaccuracy of the first ICBMs meant they could only be aimed at the largest targets. But this improved quickly. ICBMs were intended to give their owner a "first strike" capacity, the ability to win a nuclear war before their opponent even knew it had started. They were the first move in the chess game of the arms race.

## What is game theory?

For centuries, we have attempted to understand and systematize the way we interact with each other. Diplomacy, warfare, trade – even love and marriage: the best practitioners of each are those who understand other players' choices and motivations. Henry V slayed the French prisoners at Agincourt in full view of their commanders. His soldiers knew there would be no quarter given if they surrendered.

[16] The version tested had a yield of "only" fifty million tons.

[17] South Africa is the only country to voluntarily eliminate its atomic arsenal due to arms control agreements. The way in which this happened offers us a lot of lessons for future agreements: linkage with broader political issues, over-compliance and sufficient carrots to go along with the sticks, to name a few.

Cortez burnt his ships after landing in Mexico. His soldiers knew there was no turning back while the Aztecs feared his supreme confidence.[18]

But it was not until 1944 that a mathematical framework for these inter-personal situations began to develop. This was the year John von Neumann and Oskar Morgenstern published “Theory of Games and Economic Behavior” – a book which launched an entire mathematical discipline.[19] While many of the applications of game theory were still years or decades away, the basic structure and lexicon had been created.

Game theory is the mathematics behind the way we cooperate and compete. It is concerned with situations where your best action depends on the expected behavior of your opponent. The complexity comes because the world of game theory is not passive. All of the players are thinking, rational beings who respond based on their expectations of what you will do.

One important concept of game theory is **utility**. Utility has the same meaning in mathematics as in real life: how useful something is or how much you want it. In real life, determining utility can be tricky: I have no utility for a surfboard, but you might get a lot of use out of it. I’d love to have an apple, but 1,000 apples wouldn’t be 1,000 times better. How do define utility in a modified game of Russian Roulette where you receive a prize of $1,000,000 for playing, but there is a chance of being killed?

In game theory, we don’t worry about theses question and utility is abstracted to a number. The goal of each player is to maximize their this number. There is no extra credit for being cooperative and no penalty for causing conflict.[20] A utility of +2 is better than +1, which is itself better than -1. For simple games, utilities are often displayed in a matrix; in each cell, the first number is the utility for Player 1, the second is for Player 2. Here is our first example:

| Where will you go tonight? | | Player 2 | |
|---|---|---|---|
| | | Party | Home |
| Player 1 | Party | 10,10 | 0,0 |
| | Home | 0,0 | 5,5 |

**TABLE 1 - PURE COORDINATION GAME**

In this game, both Players have a choice between going to a Party or staying Home. Both Players want to be sure they are at the same place and both prefer if that place is the Party. Remembering that each Player is rational *and knows the other is rational*, this is a trivial game. Both will always choose to go to the Party. We can make it more complex when we have one British and one American Player and put them both behind the steering wheels of two cars.

| What side will you drive on? | | Player 2 | |
|---|---|---|---|
| | | Left Side | Right Side |
| Player 1 | Left Side | 10,10 | 0,0 |
| | Right Side | 0,0 | 10,10 |

**TABLE 2 - CHOOSING SIDES**

Here, we have a problem – if the Players have no way to communicate, they can only guess what the other will do and try to match it. There is no “winning strategy,” it’s just luck. However, if we give

[18] Both of these examples are from the Stanford Encyclopedia of Philosophy.

[19] Get your own copy at the Princeton University Press. If you don’t know him, von Neumann is one of the most brilliant and fascinating people of the 20th century. He contributed greatly to pure and applied mathematics, statistics, computer science and of course economics via game theory. He wasn’t a full-time member of the Manhattan Project team, but on one of his occasional drop-ins to Los Alamos he invented many key components of the Plutonium Bomb. Later he worked with Teller on the H-Bomb. He was an infamous eater and drinker, and a center of the Princeton social life in his impeccable 3-piece suits. Unfortunately, like too many great mathematicians, he died before his time, in 1957 at the age of 53.

[20] Or, if you like, these are already incorporated into the utility.

them the ability to communicate, the game is again easily solved. The Players are indifferent as to which side of the road they use, as long as they don't crash. They should be able to agree easily. It gets even more complex when my wife and I decide what to have for dinner.

| What shall we have for dinner tonight? | | Mrs. Lobby7 | |
|---|---|---|---|
| | | Fish | Steak |
| Lobby7 | Fish | 5, 10 | 0,0 |
| | Steak | 0,0 | 10, 5 |

**TABLE 3 - BATTLE OF THE SEXES (THAT IS THE REAL NAME)**

Because the Players now have different utilities for each result, it leads to conflict. In theory, we should be able to talk and agree on a meal; if the Players choose different options, neither gets anything to eat. However, we are now both incentivized to choose our preferred meal. If we are both obstinate, there is a chance that we end up in a situation where neither of us has any utility.[21]

The "Battle of the Sexes" game gives us an opportunity to define a new term, the **Nash Equilibrium**.[22] A Nash Equilibrium is an outcome of a game where neither player would change their decision, even with the knowledge of the other player's final decision. A game can have more than one Nash Equilibrium – or none at all. In Battle of the Sexes, {Fish, Fish} and {Steak, Steak} are Nash Equilibriums. You can easily check that both Players would lose utility if they changed their decision from these starting points. We'll play two more games, looking for Nash Equilibriums.

The most famous game theory example is the Prisoner's Dilemma. In the Prisoner's Dilemma, two criminals have been arrested after a burglary. The police have enough evidence to convict both on a lesser charge (say, trespassing), but require a confession to convict on the top count. In exchange for said confession, the police will let the confessor go free. However, if both Prisoners confess, the police will have enough evidence to lock them both up for a considerable time. Let's put this in matrix format. Think of utility as number of years in jail, perhaps; all these utilities are negative because jail is bad.

| Is there honor among thieves? | | Prisoner 2 | |
|---|---|---|---|
| | | Cooperate | Betray |
| Prisoner 1 | Cooperate | -1, -1 | -3, 0 |
| | Betray | 0, -3 | -2, -2 |

**TABLE 4 - THE PRISONER'S DILEMMA**

Considering this game from the perspective of the group, the best outcome is for both Prisoners to Cooperate; they will spend only two years in jail combined. The worst outcome is to both Betray: four years combined. However, no matter what the other Prisoner does, you are always better off Betraying. If he Cooperates, then your Betrayal will let you go free rather than spend a year in jail. If he Betrays, then Betrayal will again cut your time in jail by one year. Therefore, the only Nash Equilibrium in this game is {Betray, Betray} – the worst outcome for the group.[23]

Our final game – and the one that will tie back to Global Thermonuclear War – is Chicken. It's just like the movie Rebel Without a Cause. Two drivers are

[21] Obviously, in my household, this would never happen. Being knowledgeable of game theory, I always pre-emptively state that I will choose whichever option will result in the greatest utility for Mrs. LobbySeven. We had cod last night.

[22] Yes, this is what John Nash from *A Beautiful Mind* won his Nobel Prize for.

[23] The Prisoner's Dilemma "paradox" has led to an enormous amount of study at both the theoretical and real-life level. Despite Betray being the optimal strategy, many real-life participants choose to Cooperate. The Prisoner's Dilemma also has interesting variations. What if the Players are allowed to communicate before making their decisions? What if the game is played multiple times, allowing the Players to build up trust?

headed towards a cliff, each must decide to Swerve First or Swerve Last. If both Swerve First, the game is a draw. If both Swerve Last, both drive off the cliff and lose.

| | | Player 2 | |
|---|---|---|---|
| | | First | Last |
| Player 1 | First | 0, 0 | -1, 1 |
| | Last | 1, -1 | -10, -10 |

TABLE 5 - CHICKEN

If you squint, you can see two countries holding nuclear weapons, deciding whether to use them.

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Writing this, I was struck as I always am by how many great scientists were working in the interwar period. This wasn't the first time we created a great global salon; the period from roughly 1850-1880 featured the best work of Maxwell, Riemann, Faraday, Mendeleev and Darwin. But I don't think we are likely to ever see such a time again. The scientists of today's age are just as great, but human knowledge has advanced to the point where they are necessarily more specialized. I don't think we will see another von Neumann, contributing in so many disciplines. The engineers who build the things of the future will be different from the scientists who create the theoretical underpinnings of their use.

And for every great mind I included, three were left out. A discussion of nuclear physics is incomplete without Marie and Pierre Curie, who developed radioactivity. The great theoretical physicists who developed quantum mechanics, like Paul Dirac and Erwin Schrödinger, also get little mention here. I even missed many of those directly involved in the Manhattan Project: Ernest Lawrence, Hans Bethe, Rudolf Peierls, Emilio Segrè, George Kistiakowsky, Luis Alvarez – the more I name, the wider the circle, the more I leave out.

I suppose it isn't to me to give them what's due – they did rack up a lot of Nobel Prizes to show for the effort. Which is itself interesting. Alfred Nobel created the Prizes as a type of penance, atoning for the many deaths caused by the dynamite he had invented. Yet, the early laureates in Physics and Chemistry are littered with the key scientists in the eventual creation of the Atomic Bomb.

This ultimate irony will be further explored in our future piece, when we'll show how the scientists who gave man the ability to destroy his world also gave us the means to prevent its destruction.