Chapter 13
Uncertainty and Risk at the Catastrophe Threshold

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13.1 Introduction

Planetary defense is the multidisciplinary and internationally coordinated effort to protect the Earth and its inhabitants from impacts by near-Earth objects (NEOs). It requires surveys to discover and track NEOs, campaigns to characterize those that are hazardous, modeling efforts to understand and predict impact effects and associated consequences, and mitigation though impact avoidance and/or civil defense. Mitigation requires the development of ways to deflect or disperse an object on a collision course with sufficient warning, as well as emergency response planning for unexpected or unpreventable impacts.

A cost/benefit analysis is required to justify the allocation of resources to any major risk-reduction enterprise. The purpose of this chapter is to make the case that a form of probabilistic risk assessment is the most appropriate method, and to provide simple but concrete examples of uncertainty and risk calculations that include catastrophic events.

This approach was originally developed to objectively quantify and compare risk associated with high-consequence failures of engineered systems like bridges, dams, aircraft, space systems, power plants, and nuclear weapons. As a method of cost/benefit analysis in the face of uncertainty, it can be used to estimate the cost of reducing a risk compared to the benefit of doing so. Others argue that this method is too restrictive when the future of the planet is at stake, and that a cost of preventive measures that exceeds the probability-weighted value of the benefit can be justified.

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N. Schmidt (ed.), *Planetary Defense*, Space and Society,
https://doi.org/10.1007/978-3-030-01000-3_13

13.2 The Cost/Benefit Risk Analysis

The cost side of the equation is relatively straightforward. The individual components and capabilities of planetary defense (astronomical surveys, follow-up observations, data maintenance, orbital dynamics calculations, asteroid characterization, impact and explosion modeling, deflection/disruption studies, emergency planning "tabletop" exercises (Boslough et al. 2015a, 2016), conferences, and publishing) all require funding and budgets that can be estimated.

The benefit side requires quantification of the losses that are to be prevented, which is a more difficult task. For impacts from NEOs of a size that falls below the threshold for global catastrophe, proximal or immediate losses can be estimated using physical models to determine the area that is subjected to various conditions such as air blast, thermal radiation, debris, and tsunami inundation. Because the possibilities span a large range of NEO properties (mass, strength, composition, etc.), impact conditions (velocity, entry angle, orientation, etc.), and geographic location, the consequences can vary greatly. The resulting risk must be based on some kind of long-term average of all possible scenarios. In practice, analysts perform probability-weighted ensemble simulations or parameterized sums over discrete NEO size bins.

Monetizing the results of these estimates requires that value be assigned to the losses. In principle, this is straightforward for estimating the replacement cost of physical assets and infrastructure that can be rebuilt. Irreplaceable losses—such as individual human lives, ecosystems, cultural sites, historical buildings and cities, religious treasures, and even pets—have wildly different values to different people and cannot be objectively quantified.

For example, British Astronomer Royal Martin Rees was quoted in the Guardian (2015) saying "The cost of an impact would be colossal, which means—if you calculate an insurance premium in the usual way by multiplying probability by consequences, it turns out to be worth spending $1 [billion] a year to reduce asteroid risk." This was only a ballpark estimate for the Guardian journalist. It assumes a rare catastrophic event every few million years, big enough to kill a billion people. The cost is based on each life being valued at several million dollars, plus a recovery cost amounting to a decade of world GDP (at about $100 trillion per year).[1]

13.3 The Price of Life

The figure of several million dollars per fatality prevention does not reflect what policymakers are actually willing to spend to save lives. Paul Weissmann, in his chapter on Impact Hazards for the 1993 Hazards volume of Gehrels (Weissman 1994), pointed out that antibiotic treatments costing only 25 cents each could be

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[1] Based on private email communication with M. J. Rees on 21st June 2015.

preventing most of the 3.6 million pneumonia deaths per year, according to the World Health Organization. The fact that resources were not available for such a vaccination program suggested that 25 cents per life was not what the world was willing to spend. More currently, the European Union reduced funding for migrant rescues in the Mediterranean. In 2014, 100,000 lives were saved with a budget of about $120 million, at a cost of about $1000 per life. This figure reflects actual lives saved, as opposed to theoretical quantification of risk reduction. However, such quantification is complicated by the complex dynamic nature of decision making under circumstances in which the cost of collective risk reduction can encourage more individual risk taking. The optimal cost for an effective rescue program must account for this behavioral feedback, which is not well understood or quantified.

Despite what we may believe is a moral truth, not all lives have equal value in the harsh judgment of economics and policy. Payouts of several million dollars per life tend only to happen in the developed world, and then only when legal liability is involved. Beyond that, only certain kinds of liability involving such things as transportation safety, food and drugs, and nuclear power that put "everyday people" involuntarily at risk (or are those that are perceived to do so) are covered. In the developed world, where people demand it, the governments have regulations that put this kind of value on life. There is also an element of irrationality that leads to a premium on what people fear (e.g. nuclear power) and a discount associated with risks they connect with optional lifestyle choices, personal responsibility, or politically favored activities. Individual tobacco and firearms victims tend not to receive large payouts, for example.

Large-scale disasters can precipitate a cascade of subsequent losses through famine, disease, mass migrations, economic recessions, geopolitical realignment, and/or violent conflict, which transcend national boundaries and are impossible to predict or quantify, even though they may ultimately dominate the bottom line. Because these two elements (irreplaceable losses and cascading losses) are not possible to objectively quantify, we must use a proxy. The planetary defense community has traditionally used the long-run average expected number of fatalities per year as such a proxy. This quantity is both flawed and confusing, as discussed below, but has the advantage of being both relatively easy to estimate and universally applicable to all locations without regard to considerations such as a person's economic value or citizenship.

As one of my colleagues put it (only partly tongue-in-cheek), the US constitutes only 5% of the world's population, so 95% of the cost of NASA's planetary defense program can be understood as "foreign aid". It is true that most of those at risk from an asteroid strike are the same desperately poor and anonymous people that our leaders fail to find the money to help now, so it is hard to argue that saving them from asteroids is more important than saving them from starvation or malaria (which are far more likely to kill them). However, because putting a dollar value on a human life is so fraught, we continue to use an individual human life itself as the basic unit of cost for purposes of objective risk assessment. This is also a matter of simple pragmatism. No matter what unit we use, it must be justified somehow. Using an individual human life as the basic quantum of value requires the minimum amount of justification. As stated in the US Declaration of Independence, “We hold these truths to be self-evident, that all men are created equal.” In other words, it is an axiom that requires no justification at all.

Even this proxy begins to break down when it is applied to highly improbable global catastrophes that could lead to the collapse of planetary-scale ecosystems, fisheries, agriculture, and even society itself, possibly ending in human extinction. Such a calculation would require determining the value of the planet, civilization, and the human race. The value of the human race, to the human race, is arguably more than the sum of the value of each individual. One could make the case that the value of our planet and our species is infinite. If the probability of losing these things to a large asteroid or comet impact is non-zero, then the product of probability and consequences is infinity. But is it worth going into debt and breaking the economy to prevent a catastrophe that almost certainly won’t ever happen in our lifetimes or the foreseeable future? This “global catastrophe singularity” beyond the threshold makes quantitative arguments difficult.

Stepping back from the catastrophe threshold, we can use methods similar to those that were developed to quantify the risk from climate change. Despite politically motivated objections and ongoing media hype, there is no scientific controversy about the fact that global warming is dominated by anthropogenic greenhouse gas pollution. Nevertheless, the scientific community acknowledges substantial uncertainty about the speed and intensity of future temperature increases. Projections related to other changes in the Earth’s climate and ecological systems, such as ocean acidification, extreme weather events, ice sheet melting, sea level rise, habitat loss, droughts, and famines, are even more uncertain. Researchers have created a parameter called climate sensitivity, which is the equilibrium rise in global mean surface temperature that would theoretically be caused by the doubling of atmospheric carbon dioxide. Climate scientists can quantify risk using the tools of probabilistic risk assessment, even when faced with uncertainty about how fast and how much the planet will warm.

Likewise, there is no longer any real scientific debate about the danger posed by near-Earth objects. Similar to climate science, the field of planetary defense is concerned with a major existential threat to the planet and to humanity, but it is dominated by uncertainty. The vast majority of asteroids in Earth-crossing orbits remain to be discovered. We know from many independent lines of evidence that an object is already on a collision course for the next deadly impact, but we don’t know where it is, how big it is, when it will hit, where it will strike, or how many people it will kill. Still, we can quantify the overall risk from impacts even when confronted with uncertainty and limitless but unquantifiable consequence, and base our policy on conservative assumptions.

At this point it is worth noting that the term “conservative assumption” has a different meaning in the context of engineering and security than it does in science. The climate change literature tends to be written from a scientific perspective that focuses on the most probable future. The most conservative scientific estimates are those that deviate the least from prior expectations (also known as erring on the side of least drama, or “ESLD” (Brysse et al. 2013)). Scientific conservatism, when applied to climate change or planetary defense, tends to downplay the risk. Safety engineering, on the other hand, is focused on high-risk occurrences. The low-probability but high-consequence set of events must be the primary focus of planning and mitigation efforts. Engineers include significant margins into their designs to account for low probability occurrences. In planetary defense, we tend to use the word "conservative" in the engineering sense.

13.4 Thought Experiment: Russian Roulette[2]

It is useful to define a thought experiment to help explain uncertainty and risk at the catastrophe threshold. An imaginary laboratory test can put these concepts into terms that are both concrete and dramatic. Suppose a professor of risk management is determined to learn how his graduate students, including you, make individual safety decisions under conditions of uncertainty. He puts his subjects in a room with three revolvers. The first gun is loaded with six rounds, one in each of its six chambers. The probability that it will fire when the trigger is pulled is 100%. The second gun has three of its chambers loaded, so the odds it will fire on the first pull is 50%. Gun 3 has only one round out of six chambers, so the probability of firing is 16.7%.

When it is your turn, the researcher informs you that you'll be strapped into a chair and allowed only to push one of three buttons controlling the triggers. The three guns will be aimed at three different objects in the room, but the decision about which button to push is all yours. You must decide whether your choice will depend only on probability, or whether you will also consider the direction in which the guns are pointed. The target for Gun 1 is your expensive smart phone. Gun 2 is pointed at your foot. Gun 3 is aimed squarely at your temple. There is a trade-off between probability and consequences. Are you willing to risk a fatal headshot to prevent damage to your prized mobile telecommunications toy? Would the possibility of a crippling injury be worth it?

What if you were given the option of removing a round from one of the guns before pulling a trigger? Would that affect your decision? Going only by stated probabilities, this would present you with a simple optimization problem. To minimize total risk, you would remove the single cartridge from Gun 3 (the one aimed at your head) and pull the trigger. Risk is defined as probability times consequences. With zero probability of firing a bullet, the objectively calculated risk is now zero, regardless of the magnitude of the consequences (certain death, in this case). Deeper reflection might lead to a different decision.

Even firearms industry groups like the National Rifle Association, not noted for prioritizing gun safety, warns its members to never point a gun at anyone—let alone pull the trigger—unless you intend to shoot them. In the real world, it is not unusual for people to be shot by guns that were thought to be unloaded. Even if you are

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[2] This idea was first published in the chapter "Defending the only home that we have ever known" by Mark Boslough in the book *Starmus: Origins of the Cosmos* (Israelian et al. 2016).

virtually certain that a gun is not loaded, the probability that it will fire a bullet is still nonzero. Your economic worth might be a thousand or several million dollars to others, but your life is arguably priceless to you and your loved ones, to whom your death would be catastrophic. The risk (probability multiplied by consequences) is impossible to quantify (nonzero times infinity) but is arguably greater than the price of a replacement iPhone. The results of this experiment would be interesting. Would people rather shoot their phone than take an ill-defined risk, even if it seems small?

In the controlled thought experiment, the statistical probability might calculate to exactly zero. But the uncertainty due to lack of knowledge might not be reducible to zero. How carefully did you watch the experimenter take the bullet out? How do you know he's not just a murderous magician attempting to make your death look like a suicide? Did you spin the cylinder and check every chamber for the presence of a round? How confident are you that you understand how revolvers function? This exemplifies the difference between "aleatory" and "epistemic" uncertainty. Risk that can be thought of as being random (dice rolls, Russian Roulette games, or asteroid impacts) are governed by aleatory uncertainty. Risk associated with lack of knowledge (whether or not dice are honest, whether or not a gun is loaded, or the nature of the size distribution of asteroids) is controlled by epistemic uncertainty.

Adding another layer to the thought experiment shows how to estimate total risk. Actual risk calculations are better demonstrated by an experiment in which the triggers of all three pistols must be simultaneously pulled. We are concurrently exposed to independent risks in the real world and they must be summed over all possibilities, so total risk is each probability multiplied by the associated consequence of all three events. The best way to minimize the risk is a cost-benefit exercise. In this experiment, trigger-pull decisions are not yours. You now have the option of selecting whatever rounds you want to take out, but there is a cost. If you only have enough money to pay for one round, the obvious choice is to remove the one from Gun 3. Eliminating that single round would avoid catastrophe by retiring all risk of death (excluding the small epistemic contribution), even though the chances were only one in six. Logic would dictate that one would choose to guarantee survival before trying to lower the risk of a disabling shot to the foot or avoiding the definite loss of a cherished electronic device.

13.5 The Threshold for Global Catastrophe

The planetary defense community came to a similar conclusion. The NEO population is analogous the numbers of rounds in the revolvers of our pretend laboratory experiment. But the expected consequences of an impact depend on the size of the asteroid. The largest asteroids have the greatest effect—including the possibility of extinction—but the quantification of consequence is also very uncertain. We simply do not know how big an asteroid must be to cause an ecological collapse, to destroy agricultural production and end civilization, or to wipe out the human race. This calculation is not possible because we do not understand all the damage mechanisms associated with an Earth system that is complex and nonlinear.

The asteroid that erased the dinosaurs altered the Earth forever, first by direct impact effects—the generation of an enormous crater and expulsion of ejecta. About 100 million megatons of energy was released in a massive explosion that changed the atmosphere, heating it up by an unknown amount. The air became opaque with dust and debris, leading to an impact winter that lasted years. The composition and radiative properties of the atmosphere were forever altered, and the climate changed. The precise mechanism for the resulting mass extinction is still debated and is unlikely to ever be completely understood. Fortunately, impacts by 10-km asteroids occur only once every 100 million years or so. The current risk is zero, because a 10-km asteroid on a collision course would be large enough to have been discovered already. The same cannot be said for long-period comets, however, the frequency of large comets entering the inner Solar System is low.

A 5-km asteroid almost certainly exceeds the global catastrophe threshold, but at half the diameter of the dinosaur killer. An asteroid's mass governs its impact energy and damage potential, so mass is a better measure of "size" for purposes of consequence estimates. A 5-km asteroid is therefore really only an eighth as big as the dinosaur killer, and its impact would deliver about one-eighth the destructive energy (for a given impact velocity). But there are more of the smaller ones, so the Earth is exposed to more frequent impacts from them (once about every 30 million years). The Earth doesn't experience mass extinctions with that high of a frequency, so it is unlikely that 5-km asteroids exceed the extinction threshold, at least not every time they hit. But if one were to hit the Earth today, the energy released (roughly 10 million megatons) and the amount of debris produced would lead to certain global catastrophe, killing billions of people.

The population of asteroids continues to increase as the size (and consequences) go down. Like the "bullets-in-guns" thought experiment, space is a shooting gallery where most of the shots are relatively harmless, but rare ones are catastrophic. There are sound arguments based on physics and backed by evidence in the geological record that more frequent and smaller impacts can have local, regional, or even continental-scale consequences without causing a major climate disruption or global catastrophe. That suggests the existence of an unknown size threshold for global catastrophe. There is no reason to think that such a threshold even corresponds to a definite size. An impact into one spot might release a large quantity of planet-warming greenhouse gases or cause soot-producing firestorms, resulting in an impact winter. On the other hand, if it landed in a deep ocean basin, there might be little if any global consequences. The threshold for catastrophe is therefore fuzzy in addition to being uncertain.

13.6 Avoiding Catastrophe by Situational Awareness

Chapman and Morrison (1994) published the first comprehensive probabilistic risk assessment for asteroids and comets. They used observations of the effects of nuclear weapons along with physics-based scaling laws to estimate the direct damage caused by an impact of a given size. However, such scaling laws only work well for impacts that are too small to cause indirect global environmental effects such as climate change. They argued that above some threshold size (which they estimated to be around 1.5 km in diameter, with large uncertainty) a comet or asteroid impact would create a global catastrophe that would kill at least a quarter of the world's population, increasing all the way up to extinction for the largest impacts. They spliced the nuclear weapons-based estimates together with the global catastrophe estimates to create a single, but crude "kill curve" that related the number of deaths to the size of an impacting body.

In our Russian Roulette illustration, our three different guns were loaded with three different integer numbers of live rounds (since bullets exist as discrete units). This is a discrete math problem with three different possible consequences, each with its own probability. For the planetary defense risk assessment, the size of the comet or asteroid is a continuous parameter, so the sum becomes an integral. We can solve it by integrating the kill curve (as a function of size) times the probability of an impact of that size, over all possible sizes. In practice, this is done by dividing the curves up into discrete size bins. One can construct a table consisting of the number of expected impacts within some size range in a specified interval of time, and the number of resulting fatalities (averaged over all possible scenarios). According to Chapman and Morrison (1994), the expected long-term number of impact fatalities per year is 3000 if the threshold asteroid diameter for a globally catastrophic impact is 1.5 km (for further discussion of the threshold for global impact effects, see (Toon et al. 1997)).

If our ability to simulate the consequences of an impact were perfect, we could improve on these estimates by running a statistically significant number of computer experiments and determining how many people would be killed, on average, from an impact of a given size. We could simulate random impacts in numbers proportional to the size distribution of the asteroid population, add up the numbers of fatalities, and divide by the number of impacts to generate a better kill curve. Unfortunately, our ability to simulate impact consequences is still far from perfect. The estimates for ocean impacts are particularly uncertain because the efficiency of impact tsunami generation is not well understood. The severity of climate-changing global catastrophes from asteroid impacts are even more uncertain because climate is a nonlinear dynamic system with unknown thresholds and feedbacks. With increased uncertainty comes greater assessed risk. Most of the uncertainty is associated with impact consequences and the "kill curve". Complex geophysical simulations will never be perfect, therefore decisions will always need to be made in the face of this uncertainty. Nevertheless, such calculations are the best way to ensure that such decisions are objective.

The estimated risk of a few thousand fatalities per year is counterintuitive, because there are no examples of unambiguous, confirmed asteroid fatalities. It depends on low-probability, high consequence events—something that only happens every million years or so but could kill hundred million people. The odds of such an event taking place in a given year are only about one in a million, but it would contribute 100 fatalities per year to the total. The expected number of fatalities per year is zero, but the long-term average is much greater. This is not the only possible way to quantify risk, and may not even be the best, yet it has become the de facto metric for the impact risk assessments, for intercomparison of contributing factors, and for performing sensitivity studies in support of cost/benefit analyses for various risk-reduction strategies.

As an example, the Chapman and Morrison (1994) analysis led to an obvious policy recommendation: catastrophe avoidance. This is analogous to removing the single live round from the gun that is pointed at your head in the Russian Roulette example. The optimal risk reduction method is to prevent large impacts. The first step toward avoidance of catastrophic impact is to find all the asteroids in Earth-crossing orbits that are above the global catastrophe threshold. This recommendation led to the establishment of a survey program and the 1998 NASA directive to discover 90% of NEOs greater than 1 km in diameter. This was also the easiest solution, because there are only about 1,000 NEOs of that size. Since they are also the biggest and brightest in the sky, they were the easiest to find. The survey was a success and led to a large reduction in assessed risk.

Using astronomical NEO surveys to eliminate catastrophic risk is based on the same philosophy as looking both ways before crossing the street. The survey is an act of situational awareness that doesn't by itself change the probability of impact. An object in a deterministic orbit will either collide with the Earth on some specified time interval or it won't. Its intrinsic impact probability is either zero or one. The situational awareness provided by looking creates the opportunity to take preventive action to mitigate the risk if something is discovered to be on a collision course. A pedestrian can change his or her own course by waiting until a potentially hazardous vehicle passes. For planetary defense, the preventive option of choice is asteroid deflection. But without a survey to discover the threat, that option is not available.

13.7 Risk "Retirement"

There has been confusion over language used to describe risk reduction attributed to surveys. It is often said that risk is "retired" when an asteroid is discovered and is found to be in a benign orbit. However, risk is (by definition) a human assessment that includes uncertainty. *Assessed* risk is a redundant term, but the adjective reinforces this notion. When uncertainty is reduced through more observation or understanding, the assessed risk can change. The act of discovering an asteroid that is not on a collision course reduces the assessed risk. For a population of NEOs in unknown orbits, the risk is aleatory, because the trajectories can be thought of as random within some range. After they are discovered (and determined to be no threat), they can be "retired" or removed from the random population for purposes of risk assessment. The assessed risk is reduced, but the intrinsic (previously unknown) probability of impact is unchanged. An asteroid is either on a collision course or it isn't, regardless of whether or not it has a name and entry in the Minor Planet Center database. A rational policy and course of action can only be based on our current risk assessment, which incorporates all we know. If our knowledge changes because something is discovered to be on a collision course, we can reduce its contribution to the risk by deflecting it.

NEO surveys have greatly succeeded in contributing to risk reduction because our assessment of impact probability has decreased. The 90% goal has been exceeded, and discovery of smaller objects continues to accelerate. The assessed risk of a global impact apocalypse has been virtually eliminated in our time. The likelihood of a continental-scale catastrophe has been greatly diminished, and the overall risk (measured in average fatalities per year) has been cut by an order of magnitude to a round-number estimate of about 100. More recent assessments (Boslough et al. 2015b; Mathias et al. 2017; Reinhardt et al. 2016; Rumpf et al. 2017; Stokes et al. 2017) make use of large-scale computer simulations and include the Earth's population distribution with better estimates of asteroid populations and physical effects over a wide range of energies and asteroid physical properties. They remain in broad agreement with one another.

Much work is required to eliminate the remaining risk. The size distribution of asteroids follows a power law. There are many more small, dim, and difficult-to-find asteroids than large bright ones that are already in the catalog. We have our work cut out for us.

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