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The Economics of Humanity-Ending Catastrophes, Natural and Man-made: Introduction

1.1 Fables of Catastrophes in Three Worlds

Since the beginning of human civilizations, humanity has feared catastrophes and has endeavored to prevent them, or cope with them if not stoppable. It is not an exaggeration to say that fears and horrors of catastrophes are deeply inscribed in the consciousness of human beings. As such, an enduring literature of catastrophes, natural and man-made, is easily found in a rich form in virtually all fields of mental endeavors including science, economics, philosophy, religion, policy, novels, poetry, music, and paintings.

The author has grown up listening to many fables and myths of catastrophes, some of which will be told presently, and is convinced that the readers of this book have heard similar, perhaps the same, stories growing up. Many stories of catastrophes may have been culturally passed on from generation to generation, some of which are a local event while others are larger-scale events.

Of the three fables, let me start with a fearful tale of a catastrophe that has been transmitted in the Mesopotamian flood tradition and the biblical flood tradition (Chen 2013). The great deluge myth goes that there was a great flood catastrophe a long time ago, which was caused by the fury of a heavenly being. All humans, animals, and plants were swept away to death by the deluge.

An old man, however, was informed of the catastrophic flooding days ahead, owing to the services he had rendered during his lifetime, and was instructed to build an ark. He built and entered the ark with his household members, essential goods, and animals. His family would be the only ones to survive the catastrophe, being afloat for 150 days in the deluge.

This myth of flood catastrophe has been passed down millennia as an early-warning fable for an imminent catastrophe on Earth, called popularly a judgment day. In that fateful day, only a handful of people will be permitted to escape the doomed fate. This fable or myth has left enduring imprints on many cultures and civilizations, including academics (Weitzman 1998).

When it comes to the tales of catastrophes, not all of them are loaded with fear and invoke imminence of a judgment day. Some tales are rather humorous and even make fun of the doomsday foretellers.

In the Chinese literature Lieh-Tzu, there was a man in the nation of Gi who was worried greatly that there was no place to escape if the sky fell. His panic was so much that he could neither eat nor sleep. On hearing his anxiety, a person who pitied his situation

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told him, “Since the sky is full of energy, how could it fall?” The man from the Gi nation replied, “If the sky is full of energy, shouldn’t the Sun, Moon, and Stars drop because they are too heavy?” The concerned neighbor told him again, “Since the Sun, Moon, and Stars are burning with light, in addition to being full of energy, they will remain unbroken even if they should fall to the ground.” The man from the Gi nation responded, “Shouldn’t the Earth be collapsed then?” (Wong 2001).

In the East Asian culture, there is a popular word “Gi-Woo” which comes from the “Gi” nation and “Woo” which means worry and anxiety. The word is used in a situation in which someone is worried about something too much without a sound basis. The fable of Gi-Woo is a humorous depiction of a human tendency to worry too much beyond what is reasonably needed.

In the third type of fable of catastrophes, tellers of the fable take a different approach from the two aforementioned fables – that is, a rational and intelligent approach on the catastrophic risk. Recorded in the Jataka tales, the Buddha’s birth stories, there was a rabbit who always worried about the end of the world. One day, a coconut fell from a palm-tree and hit the rabbit who, startled, started to run, screaming the world is breaking up. This intriguing tale goes as follows (Cowell et al. 1895):

> Once upon a time, a rabbit was asleep under a palm-tree. All at once he woke up, and thought: “What if the world should break up! What then would become of me?”
> At that moment, some monkeys dropped a cocoanut. It fell down on the ground just back of the rabbit. Hearing the noise, the rabbit said to himself: “The earth is all breaking up!” And he jumped up and ran just as fast as he could, without even looking back to see what made the noise.
> Another rabbit saw him running, and called after him, “What are you running so fast for?” “Don’t ask me!” he cried. But the other rabbit ran after him, begging to know what was the matter. Then the first rabbit said: “Don’t you know? The earth is all breaking up!” And on he ran, and the second rabbit ran with him.
> The next rabbit they met ran with them when he heard that the earth was all breaking up. One rabbit after another joined them, until there were hundreds of rabbits running as fast as they could go.
> They passed a deer, calling out to him that the earth was all breaking up. The deer then ran with them.
> The deer called to a fox to come along because the earth was all breaking up. On and on they ran, and an elephant joined them.

This tale of a frightened rabbit does not end here: there is a remarkable turnaround in the tale, which the author has saved, along with the rest of the story, for the final chapter of this book. It is quite sufficient to point out that we all – that is, the author and the readers who picked up this book on humanity-scale and universal catastrophes – are frightened rabbits. We are much scared about the possibility of the world’s break-up owing to numerous uncontrollable mishaps, including nuclear wars, a gigantic asteroid collision, strangelets, singularity, killer robots, and global warming (Dar et al. 1999; Hawking et al. 2014).

1.2 Feared Catastrophic Events

The list of catastrophic events that are feared by people and societies is hardly short (Posner 2004). Some of these events have received extensive attention from researchers and policy-makers in the past, while others are emerging threats, therefore not-well-understood phenomena (for example, refer to the survey of American fears by Chapman University 2017). Some events have inflicted great harm on humanity over and over again historically, while other events are only a threat with a remote possibility. Some catastrophes are caused primarily by the force of nature, while others are primarily manmade.

Historically, catastrophic events are locally interpreted (Sanghi et al. 2010). A catastrophic event is one that wreaks havoc on a local community. The local community can be as small as a rural village, a town, or a city. A local catastrophe is most often a natural disaster, such as earthquakes, droughts, floods, heat waves, cold waves, tornadoes, and hurricanes.

Examples of a local catastrophe include an earthquake that strikes a city. Among the strongest earthquakes recorded are the 1960 Valdivia earthquake that hit the city of Valdivia in southern Chile, the 1906 San Francisco earthquake, the Great Kobe earthquake in 1995 in Japan, the 1950 Assam–Tibet earthquake, the 2004 Indian Ocean earthquake, and the 2011 earthquake off the Pacific coast of Tohoku in Japan.

The numbers of fatalities that resulted from the deadliest earthquakes in history make it obvious to the reader why these events are catastrophic events. The Shaanxi earthquake in China in 1556 killed 830 000 people; the Indian Ocean earthquake in 2004 resulted in the deaths of 280 000 people in South Asia; the 2010 Haiti earthquake was reported to have killed about 220 000 people; the Great Kanto earthquake in 1923 in Japan killed about 105 000; and the Kobe earthquake in Japan in 1995 killed 6434 people (Utsu 2013; EM-DAT 2017).

The deadliest earthquakes recorded in history are shown in Figure 1.1. Labels are attached to the vertical bars with more than 100 000 deaths. It is noticeable that the high-fatality earthquakes occurred most often at the centers of civilizations: Mongolian earthquakes at the time of the Mongol empire, Roman earthquakes during the time of the Roman empire. Also, high-fatality earthquakes occurred in high population centers: the Indian Ocean earthquake, Kashmir, and Chinese cities such as Shaanxi and Tangshan.

As is clear in Figure 1.1, the high casualty events have not let up in recent decades despite progresses in technological and information capabilities. The 2011 Tohokhu earthquake in Japan claimed about 16 000 lives; the 2010 Haiti earthquake was reported to have killed about 220 000 people (according to the Haitian government); the 2008 Sichuan earthquake claimed about 88 000 lives; the 2005 Kashmir earthquake 100 000 lives; and the 2005 Indian Ocean earthquake 280 000 lives. As such, earthquakes remain one of the most catastrophic events that people are concerned about today.

An earthquake occurs as a result of the movements and collisions of the lithosphere's tectonic plates (Kiger and Russell 1996). The Earth's lithosphere, i.e. a rigid layer of rock on the uppermost cover of the planet, comprises eight major tectonic plates and many more smaller plates. By connected plates, an earthquake in Japan can induce

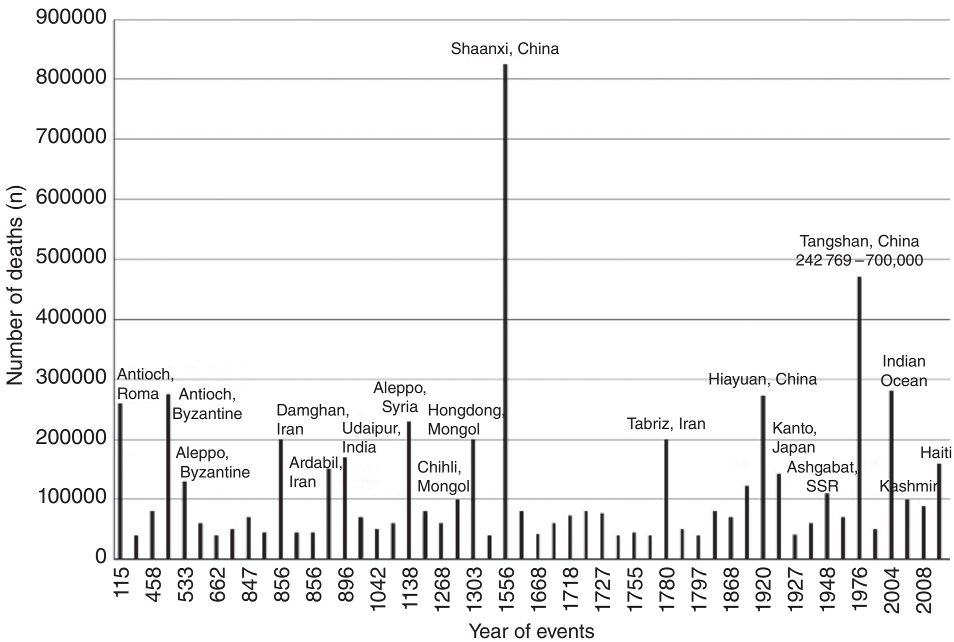

Figure 1.1 Deadliest earthquakes during the past 2000 years. *Source*: Utsu (2013), EM-DAT (2017).

another earthquake in New Zealand. Therefore, an earthquake catastrophe can occur at a regional or subglobal scale.

A hurricane is another catastrophic natural event that is feared and has received much policy attention (Emanuel 2008). It is another example of a local catastrophe. A hurricane, or a tropical cyclone as it is called in South Asia and the southern hemisphere and a typhoon in East Asia, is generated in an ocean, moves toward a landmass, and makes landfall on a coastal zone; many also dissipate in the ocean. As soon as it reaches the land, a cyclone weakens and quickly dissipates.

A hurricane's catastrophic potential is often characterized by wind speeds (McAdie et al. 2009). A category 1 tropical cyclone moves at the speed of over 74 mph (119 km h^{-1}) measured as the maximum sustained wind speeds (MSWSs); a category 2 tropical cyclone moves at the speed of over 96 mph; and a category 3 tropical cyclone moves at the speed of over 111 mph. A category 3 tropical cyclone is classified as a severe tropical cyclone, along with category 4 and 5 tropical cyclones.

The destructive potential of a hurricane is approximated by the rate of spinning of the cone of the storm, as well as the size of the cone of winds. Both variables are determined by the minimum central pressure of the hurricane. At sea-level altitude, the pressure stands at 1000 hPa (hectopascals or millibars). The lower the pressure at the center of a tropical cyclone, the faster the rate of spin motion of the cyclone. The lower the minimum central pressure, the more destructive a tropical cyclone becomes.

A catastrophic hurricane event is measured by the number of human deaths as well as the magnitude of economic damages (Seo 2014, 2015a). Economic damages occur most often in the form of destruction of houses and buildings or structural damages to them.

As such, damages are larger in low-income coastal zones with structurally weak houses (Nordhaus 2010; Mendelsohn et al. 2012).

The strongest hurricanes resulted in the number of deaths as large as those from the deadliest earthquakes shown in Figure 1.1. Cyclone Bhola that made landfall along the Bangladesh coast in 1970 incurred 280 000 human fatalities; the 1991 Bangladesh tropical cyclone killed 138 000 people; the 2008 Cyclone Nargis that hit the southwestern coast of Myanmar killed 84 000 people (Seo and Bakkensen 2017).

Cyclone fatalities are relatively much smaller in advanced economies such as the US, Japan, and Australia (see Figure 5.3). Since 1973, there has been no hurricane event in the US that has resulted in the deaths of over 100 people, with the exception of hurricane Katrina which killed more than 1225 people (Blake et al. 2011; Seo 2015a; NOAA 2016; Bakkensen and Mendelsohn 2016).

Another local-scale catastrophic event that is cyclically occurring and is a major concern for countries in the Asian monsoon climate zone is flooding. A monsoon climate is a climate system characterized by an exceptionally high rainfall during the monsoon season and an exceptionally low rainfall during a nonmonsoon season (Meehl and Hu 2006; Goswami et al. 2006; Chung and Ramanathan 2006; Seo 2016d). Overcoming this cycle of heavy rain and drought is an important policy endeavor in the monsoon climate-zone countries such as Thailand and India (Maxwell 2016).

In Thailand, flooding is a regularly occurring natural disaster attributed to the monsoon climate system. A severe flooding event occurs once every few years and often results in a large number of human deaths. The 2017 southern Thailand flooding resulted in over 85 deaths; the 2011 flooding caused 815 deaths; the 2010 floods killed 232 people; the 2013 South Asian floods killed 51 people; and the 2015 South Asian floods killed 15 people in Thailand (EM-DAT 2017).

The total number of deaths caused by floods in 2004 amounted to 7366 globally, 5754 in 2005, 8571 in 2010, 3582 in 2012, and 9819 in 2013. During the 2004–2013 period, the total number of deaths globally caused by floods amounted to 63 207, of which 71% occurred in the Asian continent (IFRC 2014).

Other catastrophic events have a scale of consequences at the national level as well as at the global level. A national-scale catastrophe would affect the population of an entire nation in a direct way. A severe drought event that befalls an entire nation over a sustained period, for example, a year or several years, is one example of such a national catastrophe. All communities across the nation will experience the consequences of the severe drought in a direct way.

The Dust Bowl of the 1930s in the US is one example of a national catastrophic event caused by a severe drought coupled with other factors such as farming practices and storms (Warrick et al. 1975; NDMC 2017). An exceptionally long period of severe and extreme droughts in Ireland during the 1854–1860 period resulted in a nationwide famine and the great Irish migration period to the US (Noone et al. 2017).

Catastrophes caused by earthquakes, hurricanes, flooding, and severe drought are primarily naturally occurring. Another type of catastrophe is primarily caused by humankind's activities – examples include toxic substances and chemicals, criteria pollutants, nuclear accidents, and ozone depletion.

Toxic chemicals and substances are a national health issue, the productions and uses of which can lead to a serious public health crisis as well as a damaged ecosystem (Vogel and Roberts 2011; Carson 1962). Toxic substances are chemical substances and mixtures whose manufacture, processing, distribution in commerce, use, or disposal may present an unreasonable risk of injury to health or the environment (US Congress 1978).

The US Environmental Protection Agency (EPA) created an inventory of existing chemicals, relying on the authority given by Congress through the passage of the Toxic Substances Control Act (TSCA) (Noone et al. 2017). The inventory listed 62 000 chemicals in the first version and has grown to more than 83 000 chemicals to date.

Relying on the authority specified by Section 1.6 on the Regulation of Hazardous Chemical Substances and Mixtures of the TSCA, the EPA attempted to restrict toxic chemicals such as asbestos, polychlorinated biphenyls (PCBs), chlorofluorocarbons (CFCs), dioxin, mercury, radon, and lead-based paint.

However, the US federal agency failed to regulate these toxic chemicals, halted by a series of lawsuits filed by chemical companies as well as a high burden of proof placed on the EPA by Section 1.6 for demonstrating substantial evidence of unreasonable risk (Vogel and Roberts 2011).

Notwithstanding the failures of the federal agency, US state-level regulations on toxic chemicals have increased. Since 2003, state legislatures passed more than 70 chemical safety laws for limiting the use of specific chemicals such as lead in toys, polybrominated diphenylethers (PBDEs) in flame retardants, and bisphenol A (BPA) in baby bottles (NCSL 2017).

Another category of manmade catastrophes could occur through numerous air and water pollutants. Through repeated exposures to smog, acid rain, particulate matter, lead, and other pollutants, an individual may suffer from various chronic diseases for a sustained period, and even face death. Particularly vulnerable to pollutants are those with existing health conditions, the elderly, children, and pregnant women (Tietenberg and Lewis 2014).

According to the World Health Organization (WHO), around seven million people die annually as a result of air pollution exposure, of which three million are due to exposure to outdoor pollution and four million due to exposure to indoor pollution. Of the seven million deaths, about six million deaths occur in South-East Asia and West Pacific regions (WHO 2014, 2016).

The US Clean Air Act (CAA), the signature legislation for regulating air pollutants, which was passed in 1970 and has been revised since then, defines the six most common pollutants as criteria pollutants. These are ground-level ozone, particulate matter, sulfur dioxide, nitrogen oxides, lead, and carbon monoxide (US EPA 1977, 1990). The CAA defines and enforces the ambient air quality standards for the six criteria pollutants, which are explained in depth in Chapter 6.

The sources of emissions vary across the pollutants. Coal-fired, oil-fired, and gas-fired power plants which generate electricity for numerous economic activities are primary sources of air pollutants such as sulfur dioxide, nitrogen oxides, particulate matter, volatile organic compounds, and ammonia (Mendelsohn 1980). A variety of vehicle uses is another primary source of air pollutants such as nitrogen oxides, volatile organic compounds, and particulate matter. Agriculture and forestry as well as manufacturing are also major sources of air pollution (Muller et al. 2011).

A nuclear power plant is another way to produce electricity and energy (MIT 2003). Through human mistakes or an unforeseen series of events, accidents at nuclear power plants have occurred, which led to one of the most catastrophic outcomes in human history. Leaks of nuclear radiation or contacts with radioactive materials led to a large number of immediate deaths or prolonged deaths through cancer.

There have been two catastrophic nuclear accidents categorized as an International Nuclear Events Scale (INES) level 7 event: the Chernobyl disaster and the Fukushima Daiichi accident (NEI 2016). The Chernobyl disaster in Ukrainian SSR in 1986 caused 56 direct deaths and cancer patients estimated as ranging from 4000 to 985 000.

The Fukushima Daiichi nuclear accident in Japan in 2011 was caused by the above-mentioned 2011 Tohoku earthquake and the subsequent tsunami. The earthquake was itself once-in-a century magnitude. The earthquake–tsunami–nuclear disaster event destroyed more than one-million buildings. The government of Japan declared a 20-km evacuation and exclusion zone, from which 470 000 people were evacuated.

Nonetheless, the reality of producing enough energy to support the national economies is that a large number of countries rely heavily on nuclear power plants for energy production. Countries that supply at least a quarter of national energy consumption through nuclear energy are France (76.9%), Slovakia (56.8%), Hungary (53.6%), Ukraine (49.4%), Belgium (47.5%), Sweden (41.5%), Switzerland (37.9%), Slovenia (37.2%), the Czech Republic (35.8%), Finland (34.6%), Bulgaria (31.8%), Armenia (30.7%), and South Korea (30.4%) (NEI 2016).

The permanent members of the United Nations (UN) Security Council and other major countries rely on nuclear energy significantly: the US (19.5%), China (2.4%), Germany (15.8%), Spain (20%), Russia (18%), and the UK (17%).

1.3 Global or Universal Catastrophes

The categories of catastrophic events introduced in Section 1.2 may wreak havoc on the communities that these events befall, but the scale of impacts is limited to a local area or to an entire nation even in a larger-scale shock. It does not mean, however, there would be no indirect effects on neighboring nations or trade partners.

Having said that, concerned scientists have often noticed that the possibility of an even larger-scale catastrophe may be increasing since the middle of the twentieth century. Notably, the ending of World War II through the first use of nuclear bombs in Hiroshima may have signaled at the same time both rapid scientific and technological advances and the possibility of potentially global-scale catastrophic events.

Many observers also noted that truly catastrophic events that can challenge human survival on Earth or even end the survival of the universe itself may be becoming more likely in tandem with the increase in scientific and technological capacities of humanity (Posner 2004; Kurzweil 2005; Hawking et al. 2014).

A catastrophic event that could end life on Earth is a global-scale catastrophe, while a catastrophic event that could end the existence of the universe as we know it now is a universal catastrophe. A global or a universal catastrophe is what humanity is most concerned about when it comes to a probable future catastrophe.

What are global or universal catastrophes? Is a global catastrophe likely at all? As a matter of fact, several such events have been proposed by concerned scientists. Nuclear warfare, a large-size asteroid colliding with the Earth, a high-risk physics or biological experiment for scientific purposes, and artificial intelligence (AI) and killer robots are recognized as causes for a likely global-scale or universal catastrophe.

An asteroid collision with the planet is a probable global catastrophe event (Chapman and Morrison 1994; NRC 2010). It is widely supported that a single asteroid led to the extinction of dinosaurs on Earth 66 million years ago by hitting “the right spot” with oil-rich sedimentary rocks (Kaiho and Oshima 2017).

An asteroid is a small planet that orbits the Sun, most of which is located in the Asteroid Belt between Mars and Jupiter. Asteroids, meteorites (fragments of asteroids), and comets (an icy outer solar system body) refer to different near-Earth objects (NEOs) against which the US’ planetary defense activities are directed to prevent a possible collision with the Earth (NASA 2014).

When asteroids, meteorites, or comets are within 30 million miles (50 million kilometers) of the Earth’s orbit, they are called NEOs. According to the US National Aeronautics and Space Administration (NASA), a 0.6-mile (1-km)-wide NEO could have a global-scale impact and a 980-ft (300-m)-wide NEO could have a subglobal impact (NASA 2014). The dinosaur-extinction asteroid was 7.5 miles wide (Kaiho and Oshima 2017).

According to NASA, as of 2016, about 50 000 NEOs have been discovered, but it is estimated that three-quarters of the NEOs existent in the solar system are still undiscovered. The discovery of an asteroid is the first and critical step in planetary defense against it, which is done mostly by ground-based telescopes. Deflecting or destroying an asteroid is another stage of the planetary defense mission, the possibility of which increases dramatically when it is discovered early (NRC 2010).

Reflecting the rising concern on possible asteroid collisions, the US government established the Planetary Defense Coordinating Office (PDCO) in 2016 under the leadership of NASA (NASA 2014). Of the total NEOs discovered globally, about 95% of them are discovered by NASA.

Nuclear warfare is cited as another probable global-scale catastrophe (Turco et al. 1983; Mills et al. 2008). A nuclear war between two nuclear powers, e.g. between the US and Russia or between India and Pakistan, has the potential to devastate entire civilizations on Earth.

A series of nuclear explosions will destroy living beings and built structures on the local area of explosions, which itself would not lead to a global-scale catastrophe. However, such nuclear explosions can alter the global atmosphere to cause global-scale freezing, which results in a global catastrophe (Turco et al. 1983). Alternatively, it is projected that nuclear explosions could destroy the ozone layer in the stratosphere, which possibly could result in a global-scale catastrophe (Mills et al. 2008; UNEP 2016).

A handful of countries in the world may have the capability to stage a nuclear war against their foes. As of 2018, nine countries are recognized, at different levels, to have the capabilities to own or build nuclear weapons. Among them are five permanent members of the UN Security Council: the US, Russia, the UK, France, and China. Additionally, four countries are known or believed to have nuclear weapons or have the capacity to make them: India, Pakistan, North Korea, and Israel (UNODA 2017a,b,c,d).

However, many other countries are reported to have the scientific and technological capacities to build nuclear arms, but have complied with the international nuclear treaty (explained below) and withheld their ambitions for developing them (Campbell et al. 2004). The international treaty refers to the Treaty on the Non-Proliferation of Nuclear

Weapons, commonly known as the Non-Proliferation Treaty (NPT), at the UN which aims to contain the competitive buildup of nuclear weapons and prevent a nuclear war.

The NPT entered into force in 1970 and was extended indefinitely in 1995. As of 2018, the NPT has been signed by 191 nations, which is an over 99% participation rate (UNODA 2017a,b,c,d). The NPT has established a safeguards system with responsibility given to the International Atomic Energy Agency (IAEA). The IAEA verifies compliance of member nations with the treaty through nuclear inspections.

However, the threat of a probable nuclear war has not been eliminated. It is notable that many nuclear-weapon regimes have not joined or not complied with the NPT, e.g. India, Pakistan, Israel, and North Korea, while other nations are on their way to developing them, e.g. Iran.

Further, whether the nuclear-weapons regimes including the US and Russia will commit to the NPT's grand bargain for a complete and full disarmament of nuclear weapons has yet to be confirmed, that is, by ratifying the treaty of a complete ban of further nuclear tests (Graham 2004).

Many researchers, but not all, have also cited global warming and climate change as a probable global catastrophe. The observed trend of a globally warming Earth may continue in the centuries to come, and if some of the worst projections of future climate by some scientists were to be materialized, a global-scale climate catastrophe should be unavoidable (IPCC 1990, 2014). However, these worst case scenario projections are treated by the Intergovernmental Panel on Climate Change (IPCC) as statistically insignificant (Le Treut et al. 2007).

The most dismal outlook with regard to the phenomenon of a globally warming planet is that global average temperature would rise by more than 10° C or even up to 20° C by the end of this century (Weitzman 2009). Such levels of global climate change would certainly force the end of human civilizations on Earth, as we know them (Nordhaus 2013).

However, this dismal outlook is in sharp contrast to the best-guess prediction or mean climate sensitivity presented by the IPCC, which has been in the range of 2 to 3° C by about the end of this century (Nordhaus 2008; IPCC 2014; Seo 2017a).

Also, several scientific hypotheses exist on catastrophic climatic warming, of which the author introduces several here. A hockey-stick hypothesis states that global average climate temperatures will run away in the twenty-first century as in the blade of a hockey-stick (Mann et al. 1999; IPCC 2001). The second hypothesis is that an abrupt switch in the global climate system may occur, shocking everyone on Earth, including scientists (NRC 2010). The third hypothesis is that a global catastrophe may occur by way of crossing the threshold or reaching the tipping point of various climate system variables, e.g. a reversal of the global thermohaline circulation in the ocean (Broecker 1997; Lenton et al. 2008).

However, projections of the future climate system by climate scientists are highly uncertain, and are expressed as a wide range of divergent outcomes from a large array of future storylines or scenarios (Nakicenovic et al. 2000; Weitzman 2009). Further, many scientific issues remain unresolved in the climate prediction models called in the literature Atmospheric Oceanic General Circulation Models (AOGCMs) (Le Treut et al. 2007; Taylor et al. 2012).

Notwithstanding the range of uncertainties and scientific gaps that exist even with more than four decades of admirable scientific pursuits, there is a silver lining with regard to the future of global climate shifts. If the Earth were to warm according to the IPCC's middle-of-the range predictions or the most likely projections, people and societies will find ways to adapt to and make the best of changed climate conditions (Mendelsohn 2000; Seo and Mendelsohn 2008; Seo 2010, 2012a, 2015c, 2017a).

The magnitude of damage from global warming and climatic shifts will critically hinge on how the future climate system unfolds and how effectively and sensibly individuals and societies adapt (Mendelsohn et al. 2006; Tol 2009; Seo 2016a,b,c).

Existing technologies as well as those developed in the future will greatly enhance the capacities of individuals and societies (Seo 2017a). Some of these technologies are breakthrough technologies that can replace fossil fuels entirely or remove carbon dioxide in the atmosphere or engineer the Earth's climate system, which include, inter alia, nuclear fusion power generations, solar energy, carbon capture–storage–reuse technology, and solar reflectors (ITER 2015; MIT 2015; Lackner et al. 2012; NRC 2015).

These mega technologies are broadly defined as a backstop technology in the resource economics literature. Although many of these breakthrough technologies can be employed to tackle climate change for the present period, the cost of relying on any of these technologies is more than an order of magnitude higher than the least-cost options available now to achieve the reduction of the same unit of carbon dioxide (Nordhaus 2008).

A catastrophe whose scale of destruction goes beyond the planet has been suggested by scientists (Dar et al. 1999; Jaffe et al. 2000). A salient example is a probable accident in the Large Hadron Collider (LHC), built by the European Organization for Nuclear Research (CERN) for the purposes of testing various predictions or theories of particle physics. It is a 27-km-long (in circumference) tunnel built under the France–Switzerland border at a depth of 175 m (CERN 2017).

The LHC is a particle accelerator built to test theories on the states of the universe during the short moments in the origin of the universe. More specifically, it tests the initial states of the universe right after the Big Bang (Overbye 2013). It was suggested by scientists that the experimental process may create a strangelet or a black matter unintentionally, through which a black hole is created. The entire universe would be drawn to the black hole, if it were to be stable, bringing an end to the universe (Plaga 2009; Ellis et al. 2008).

Scientists overwhelmingly reject the possibility of such a universal catastrophe. A group of researchers called the probability of it absurdly small (Jaffe et al. 2000). An impact analysis group of the CERN experiments reported that there is no possibility at all of the universe-ending catastrophe (Ellis et al. 2008). Many groups of scientists argue that such collisions of particles occur naturally in the universe, leaving no impacts on the universal environment (Dar et al. 1999; Jaffe et al. 2000; Ellis et al. 2008).

Although no actions have been taken to reduce the risk of this universe-ending catastrophe, the forecast of it has not materialized yet. The experiments at CERN led to the award of the Nobel Prize in Physics in 2013 "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS [A Toroidal LHC ApparatuS] and CMS [Compact Muon Solenoid] experiments at CERN's LHC" (Nobel Prize 2013).

The list of catastrophes presented up to this point paints quite a dismal picture for the survival of humanity and even the universe. Nonetheless, there seems to be a more feared and more likely catastrophe in the minds of many concerned scientists, that is, AI.

AI, i.e. intelligent robots and machines, may become more intelligent and powerful at some point and kill all the living beings, i.e. beings with life, including humans (Hawking et al. 2014).

The all-life-ending catastrophe may be brought on by the lifeless machines and robots. In some areas of human activities and dimensions, robots are already more efficient and intelligent than humans and have replaced human laborers. The day may come quite quickly according to many experts when the brain capacity of robots, measured by such indicators as IQ, surpasses that of humanity. This would be the moment of singularity (Kurzweil 2005).

When the singularity arrives, it would be the greatest marvelous achievement of humanity, but the last one, according to the physicist Hawking (Hawking et al. 2014). The AIs will control humans and may end up killing all humans and even all living beings in the universe, intentionally or unintentionally.

Not all the experts on AI share this perspective. Optimists would argue that robots who are lifeless beings or insentient beings may become friendly neighbors to humanity, all-smiling and supportive as they are at present.

The world's notable entrepreneurs have been pursuing competitively advanced AI machines and robots and their applications to various business fields, examples of which include a self-driving automobile by Tesla motors, an AI healthcare software system by Softbank, and an intelligent personal assistant Siri by Apple.

In many ways, many nations are investing competitively in the development of AI based on the conviction that gaining superiority in AI would make the nation a military superpower in the world. The downside of this competition lies in the fear that the killer robots may become uncontrollable, or even the war robots could start a war without a human order.

In fact, war robots already play a pivotal role in war army combats as well as local police battles. Ethical issues and banning the use of such robots were taken up for discussion at the UN experts meeting on Lethal Autonomous Weapon Systems (LAWSs) (UNODA 2017b).

1.4 A Multidisciplinary Review of Catastrophe Studies

Having presented the first impressions of the range of catastrophic events that this book is concerned with in establishing the economic perspectives, the author, perhaps the reader as well, needs to consider how the book should proceed and what approach should be taken to achieve the goals of the book.

Of the many possible ways that the book can be written, the author has determined to emphasize the generality of the concept of catastrophe across many academic fields of catastrophe studies. This book, consequently, takes a multidisciplinary approach, which should also be appealing to a wide range of academic disciplines and in a wide range of policy circles.

On the other hand, the book is also positioned to make the clearest and the most direct presentation of the economic issues and analyses with regard to catastrophic events. This means that the background of the economic analyses presented in the book will be market places in which an economic agent, whether an individual or a community, weighs the benefit against the cost incurred over a long period of time of a decision for the purposes of achieving an optimal outcome resulting from the decision (von Neumann and Morgenstern 1947; Koopmans 1965).

Studies of and stories about catastrophic events are perhaps as old as the birth of human civilization or humanity's invention of letters. The three tales and fables introduced above were recorded in some of the oldest books that human civilization compiled and transmitted through time until today. Further, catastrophe concepts and studies are quite pervasive across the sciences, mathematics, philosophy, economics, psychology, policy sciences, and even literary works, which will be made clearer in this book.

Scientific descriptions and mathematical formulations of catastrophe and chaos emerged during the latter half of the twentieth century. Taking advantage of his predecessor's works on structural stability, catastrophe theory was presented during the 1960s and 1970s by French mathematician René Thom who formulated it in the context of structural stability of a biological system (Poincaré 1880–1890; Thom 1975). Catastrophe was defined as a sudden dramatic shift of a biological system in response to a miniscule change in a certain state variable (Zeeman 1977).

Thom's works became known as the catastrophe theory because he presented a list of seven elementary catastrophes that would become widely appropriated by applied scientists and economists of catastrophes. Seven generic structures of catastrophe, each of which is expressed as a form of a potential function, were fold catastrophe, cusp catastrophe, swallowtail catastrophe, butterfly catastrophe, hyperbolic umbilic catastrophe, elliptic umbilic catastrophe, and parabolic umbilic catastrophe (Thom 1975).

In another literature, the chaos theory surfaced by a stroke of serendipity and was developed to depict the systems that are in chaos or disorder, in which chaos was defined as the absence of an order in the system, or a disorderly system, or an unpredictable system (Lorenz 1963; Strogatz 1994).

As it has turned out over the course of its development, the literature of the chaos theory has become as much about the scientific endeavors to find an order in a chaotic, disorderly system as it was about the absence of order, disorder, or unpredictability of a certain system (Tziperman 2017).

Edward Lorenz is generally credited with the pioneering experimental works that led to the establishment of the field of chaos theory. As a meteorologist at the Massachusetts Institute of Technology, he was working to develop a system of equations that can predict the weather of, say, Cambridge, Massachusetts a week ahead of time (Lorenz 1963). Through his experiments with the computer simulation of the weather system, he came across the finding that a miniscule change in an initial point or any point in the system leads to a widely strange outcome in the predicted weather, a phenomenon that he later called "butterfly effects" (Lorenz 1969).

Continuing to work on his weather system, Lorenz presented a simplified system, that is, a system of three ordinary differential equations, the set of outcomes of which has been known to represent the chaos theory. The Lorenz attractor, i.e. the solutions to the Lorenz system, is deceptively simple mathematically; however, it so richly expresses a disorderly system or an unpredictable system (Gleick 1987; Strogatz 1994). The Lorenz attractor is the system with the absence of order in that it shows neither a steady state nor a periodic behavior, i.e. two known types of order in a system (Tziperman 2017).

Another important contribution to the theory of catastrophe or chaos came from the theory of a fractal developed separately by Benoit Mandelbrot (Mandelbrot 1963, 1967, 1983, 1997). From the studies of crop prices, coastal lines, financial prices, and others, Mandelbrot defined a fractal to be a figure that has a self-similar figure infinitely as its component or at a larger scale and in which this self-similarity is repeated in ever-larger scales of the figure (Frame et al. 2017).

In the fractal image, you can zoom in on the figure over and over again and find the same figure at a smaller scale forever. It is interpreted that a fractal is an image of an infinitely complex system and a fractal is often described as a "picture of chaos" (Fractal Foundation 2009). For instance, it would be impossible in a fractal world to measure the length of the British coastline correctly (Mandelbrot 1967).

The self-similarity, also referred to as self-affinity, is the central concept of the fractal theory, which manifests as scale invariance in the statistical literature that defines a power law tail distribution, also called the Pareto–Levy–Mandelbrot distribution, as well as a fat-tail distribution (Pareto 1896; Mandelbrot 1963, 1997; Gabaix 2009). The power law distribution arises in many economic and noneconomic processes and has been relied upon in the study of a highly volatile system such as financial market crashes or a highly uncertain catastrophe event such as the end of human civilization caused by global warming (Mandelbrot 1997; Taleb 2005; Weitzman 2009).

Fractal theorists argue that a fractal is very common or "everywhere" in nature; that is, one can encounter a fractal easily in such things as trees, rivers, cauliflowers, coastlines, mountains, clouds, seashells, and hurricanes. The fractal theorists strived to formulate a fractal image as a set of simple equations, the best known of which are the Mandelbrot set and the Julia set (Mandelbrot 1983; Douady 1986).

At this point, one may wonder: Is chaos the world as it is or is there an order that is simply elusive to untrained observers? As noted above, scientists had the same curiosity very early in the literature and the search for an order in a chaotic system, say, a disorderly order, has increased over the course of the literature with as much prominence as chaos itself.

The Feigenbaum constant is broadly thought to be a ground-breaking discovery in the chaos theory in that it unveils a hidden order in a chaotic or disorderly system (Feigenbaum 1978). Feigenbaum was examining a population bifurcation diagram, that is, a diagram of successive bifurcations of a biological population in which bifurcation points hinge on the rate of population growth. Feigenbaum made a major discovery in the field of the chaos theory that the population bifurcations in the diagram occur in an orderly way at a constant rate of 4.669.

To put it more precisely, he discovered the exact scale at which the population diagram is self-similar, which is the scale in the fractal image. In other words, if we make the population bifurcation diagram 4.669 times smaller at the point of a bifurcation point, then it will look exactly the same as the next point of bifurcation (Tziperman 2017).

Long before these catastrophe sciences and models ever existed, there had been already voluminous works on conceptualizations of a catastrophe. In the philosophical and theological traditions, inquiries on catastrophic events had been framed with reference to the end of the world or the beginning of the world as we know it presently. Numerous theories or even haphazard forecasts of an ultimate doomsday had been proposed in association with human activities.

In Chapter 3, the author provides a wide-ranging review of selected theories and works in the ancient and contemporary philosophical, broadly defined, traditions. The chapter starts with environmental and ecological classics by Rachel Carson and Aldo Leopold.

This is followed by the review of climate doomsday modeling works and the archaeology of civilizational collapses, so-called collapsiology.

An environmental classic by Rachel Carson entitled *Silent Spring* is filled with the sentiments of doom and death caused by humanity's environmental and ecological degradations through unregulated chemical uses (Carson 1962). In her book, Carson laments that "Everywhere was a shadow of death," "the haunting fear that something may corrupt the environment to the point where man joins the dinosaurs as an obsolete form of life," and "It was a spring without voices." *Silent Spring*, one of the most influential environmental books in history, does not, however, rely on a formal theory or conceptualization of a catastrophe.

Quite a different perspective on human civilizations and their existence was put forth by Aldo Leopold, which is ecocentric (Leopold 1949). In his much-acclaimed and influential book *Sand County Almanac*, Leopold proposes a new ethical perspective in which the ultimate value lies in the wilderness or wildness of things.

Leopold writes that "the ultimate value … is wildness. But all conservation of wildness is self-defeating, for to cherish we must see and fondle, and when enough have seen and fondled, there is no wilderness left to cherish." And in another chapter, he declares that "In wildness is the salvation of the world" (Leopold 1949).

Leopold wields a double-edged sword: on the one side, he sees little value in mankind's works and establishments; on the other side, he sees no danger in destructions of mankind's works and establishments by the ineluctable forces of nature. In his unique perspectives, it seems as if a true catastrophe lies only in humanity's excessive interventions in the holistic existence of natural worlds.

Recently, renewed enthusiasm in catastrophes has emerged among archaeologists and scientists. A group of researchers have re-examined past collapses of once-glorious civilizations, including the Maya civilization in Mesoamerica, the Mycenaean civilization in ancient Greece, the Moche civilization in northern Peru, and the Western Roman Empire (Diamond 2005; Gill et al. 2007; Kenneth et al. 2012; Drake 2012).

The common feature in this emerging literature is that the past civilizations' collapses are attributed to abrupt climatic shifts at the times of those collapses (*New Scientist* 2012). These archaeologists and scientists rely on newly available archaeological data thanks to climate change and global warming research, such as ice-core temperature data, cave stalagmites, carbon isotopes, and sea-surface temperatures (Le Treut et al. 2007).

However, the archaeological literature of civilizational collapses by and large refutes the climate doomsday assertions by the aforementioned researchers based on unmodified associations between societal collapses and changes in climate conditions. In the collapsiology or the archaeology of collapses, the fall of a civilization is explained as "a highly complex operation" which is certain to be "distorted by oversimplification" (Wheeler 1966).

Collapsiologists offer intelligent discussions on past societal, civilizational collapses that take into account complexities in social, economic, and cultural systems (Middleton 2017). One of the definitions widely adopted by them of a societal collapse is a rapid political change and a reduction in social complexity. Society's collapses are identified through various empirical measures, including fragmentation of a state into smaller entities, desertion of urban centers, breakdown in regional economic systems, and abandoning prevalent ideologies (Schwartz and Nichols 2006).

An insightful conclusion from the archaeologists is that a civilization does not collapse. The Mayan civilization, for example, underwent many periods of states' collapses through outsiders, internal conflicts, Spanish armies, and Christianity, but the Mayan civilization itself has survived. Millions of Mayan descendants live in Central America today. What collapsed are the Mayan states, not the civilization (Middleton 2017).

Leaving aside a collapse archaeology, Chapter 3 takes up ancient philosophical and theological traditions on catastrophes for discussion. A conceptual formulation of a catastrophe is abundantly found in the ancient philosophical traditions that delved into the question of the end and beginning of the universe. In the chapter, the author sketches two such traditions that have had enduring influences.

An Indian school formulated that things occur randomly, that is, things and beings arise without a cause. In the same way, things and beings perish without a cause, at random. The philosophical arguments of this school are expounded in detail in the Buddha's sutra entitled "The all-embracing net of views" (Tipitaka 2010). This school was called a "fortuitous originationist" as the sages of this school proclaimed that self and the world originate fortuitously, by chance.

In the world of fortuitous originationists, as beings come into being randomly, i.e. without a cause, they decease randomly, i.e. without a particular cause. Stated another way, according to this school, life begins catastrophically and it ends catastrophically, with neither a cause nor a warning.

The aforementioned sutra, told by the Buddha, elaborates other philosophical views, which were prevalent in ancient India, that are pertinent to the literature of philosophical traditions on catastrophic events. These include the views of eternalists as well as the views of annihilationists (Tipitaka 2010).

Directing our attention to the western philosophy, a prominent tradition that explicates conceptualizations of a catastrophe is Blaise Pascal's probability theory or probabilistic thinking on eternity (Pascal 1670). In formulating his probability theory, Pascal refers to an extreme case in a probability distribution: an extremely low probability event which, nonetheless, is rewarded with infinity of welfare or wealth, if it were to turn out to be true.

In Pascal's so-called wager argument, this extreme event is a belief in God. In Pascal's wager, it is argued that the existence of God is an extremely low probability event, a highly unlikely event. But, the belief in the existence of God is worthwhile, *at all costs*, because it safeguards or salvages one from the catastrophic event in which God does exist and shall send nonbelievers to an eternal hell. According to the wager, it would be a winning gamble even if one were to lose all things in this life and perhaps in the next lives eternally.

Pascal's world is one in which the concern of a truly catastrophic event dominates all worldly decisions. Applied to a policy decision on a probable catastrophe, the wager theory would imply that all available resources are directed to prevent a catastrophic event whose damage is in infinity. This infinity of a catastrophe's destruction would include "a catastrophic end of human civilizations as we know it or the catastrophic end of all life on the Planet," an expression popularized in the global warming policy literature (Weitzman 2009).

In theory as well as reality, there are a whole range of options one can take to avoid such a catastrophic end of human civilizations, and most often there are alternatives that demand much less sacrifice to achieve whatever goals an individual or society hopes to achieve (Nordhaus 2011). From another perspective, even the truly catastrophic event such as the one Pascal put forward can be prevented by wisely employing the alternatives available and is not expensive (Seo 2017a).

1.5 Economics of Catastrophic Events

Economists have long been interested in the characteristics of catastrophes, differences among catastrophic events, and effective ways to hedge against or prevent such events. What distinguishes the economics of catastrophes from other fields of studies is its exposition and utilization of individuals' incentives in the face of catastrophic challenges which are translated into market systems and securities bought and sold among individuals. In Chapters 4 and 5, the author explains the theoretical aspects of catastrophe economics in the former and empirical models of catastrophe economics in the latter.

A catastrophe is often defined by a threshold, also called a critical value, which is also sometimes called a tipping point with an implication of a catastrophe theory. A threshold approach is applied to various pollution control policies (US EPA 1990). For example, the US CAA regulates air pollutants using the National Ambient Air Quality Standards (NAAQS), in which the ozone's NAAQS is set at the threshold of 0.070 ppm in 8-hour average concentration and the primary threshold for particulate matter (PM10) is 150 $\mu g\ m^{-3}$ in 24-hour average (US EPA 2017).

Another way to define a catastrophe is through the characteristic of a tail in a statistical distribution. Take climate change predictions for the year 2100 by numerous climate centers. The predictions would report a range of outcomes whose distribution can be statistically derived nonparametrically. A long-tail event is an unlikely event, but when it is also fat it can dominate any rational decision-making (Schuster 1984; Weitzman 2009).

A long-and-fat-tail distribution is relevant to catastrophe economics in that it can arise from a high degree of uncertainty about the future. The author explains a classification of statistical distributions by tail properties. An event, or a random variable, can be classified into one of three types according to the tail behavior: a thin tail distribution, a medium tail distribution, and a fat tail distribution (Schuster 1984).

The author then examines the broader economics literature of risk and catastrophes which have a large uncertainty or occur with a very low probability. A large volume of economics literature is available on behaviors of investors who manage a high-risk asset or a high-risk portfolio (Markowitz 1952). A rich economics literature is also available on market securities that are contingent on occurrences of catastrophic events such as fires, hurricanes, earthquakes, and droughts.

An insurance is the earliest financial instrument that was devised to help individuals hedge against a catastrophic event which is largely uncontrollable (Shiller 2004). By pooling the same risk across a large number of individuals, an insurance company can pay for the catastrophic damage in return for insurance premiums paid by the insured.

Of the weather-related catastrophic losses, insured losses accounted for about 30% in 2016 of total economic losses of US$175 billion. In North America and Europe, insured losses accounted for about 50%, while they accounted for only 10% in Asia (Swiss Re Capital Markets 2017). The author explains the catastrophic coverage in the US crop insurance and subsidy program in detail in Chapter 4 (Sumner and Zulauf 2012).

An options contract and a futures contract are other financial instruments that are widely used in respective markets for managing specific risks or catastrophes. An option contract specifies the rights of the purchaser to sell or buy at a written price an underlying asset at a future date, which may or may not be exercised by her/him (Black and Scholes 1973; Fabozzi et al. 2009). The investor will consider the possibility of a catastrophic event in deciding whether or not to exercise the option contract.

An investor who owns a financial or commodity asset, e.g. a residential property, can purchase a relevant option contract for the asset in order to minimize the risk from a precipitous price fall, as was experienced in the subprime mortgage crisis in the late 2000s (Shiller 2009). A large number of different types of options are traded in the commodity and financial markets, including crude oil options, natural gas options, corn options, gold options, and S&P 500 options (CME Group 2017).

Catastrophe bonds (more commonly called CAT bonds) are a new financial derivative that was devised specifically to deal with very rare or unprecedented catastrophe events for which traditional insurance products are inadequately developed. The CAT bond is based on the concept of reinsurance, i.e. the insurance of an insurance product (Edesess 2014). An insurance company purchases a reinsurance from a reinsurance company, which is contingent on an occurrence of an exceptionally catastrophic event and an exceptionally large amount of insurance claims.

The concept of a CAT bond was developed during the 1990s after Hurricane Andrew that hit the US in 1992, from which multiple insurance companies went bankrupt. Since then, outstanding CAT bonds have increased steeply, from US$20 billion in 2007 to US$70 billion in 2015 (Swiss Re Institute 2017). Besides the reinsurance companies, issuers of CAT bonds have expanded to an insurance company, a government entity, pension funds, a corporation, and a nongovernmental organization. Mexico issued CAT bonds in 2006 for earthquakes, the first national sovereign to do so. In 2014, the World Bank issued the first CAT bonds for natural disaster risks in 16 Caribbean countries (World Bank 2014).

With the background of the range of market securities that are designed to deal with the catastrophe risks, how should a government intervene and design a policy for a specific catastrophic event of public concern? In the economic policy literature, a rational decision-making framework has long been the foundation of policy interventions (von Neumann and Mrogentern 1947). In this approach, the government should intervene in a way that the benefit of a policy remedy over the cost is maximized over a long-term timeframe (Ramsey 1928; Koopmans 1965).

In the rational expectation approach on policy interventions, the tail distribution of a catastrophe event is captured by the variance of a random event (Nordhaus 2011). Let's take for consideration the degree of global warming by the year 2100. The higher the uncertainty, the larger the variance of the distribution. The lower the uncertainty, the smaller the variance of the distribution. The probability density function of the random event contains the full information on whether the tail is long and fat or short and thin (Nordhaus 2008).

A policy decision is made on such variables as the penalty imposed on the emissions of carbon dioxide, a primary Earth-heating molecule. The levels of the carbon dioxide penalty are determined from the range of outcomes based on the estimation of variance in the random variable. The carbon penalty, in the form of carbon tax or carbon price, is determined in the matter to achieve an optimal social welfare, with the policy measure permeating through the economy (Nordhaus 1994).

Is this rational social welfare optimization approach adequate for addressing catastrophic events? Since the late 2000s, it has been one of the most debated questions, especially in the context of global warming policy. Arguing that the approach is a misleading policy principle, critics suggested a generalized precautionary principle as an alternative (Weitzman 2009).

The critics' arguments are based on the concept of a fat-tail distribution and formalized as the dismal theorem. The crux of the arguments is that an individual is willing to sacrifice an infinity of resources in order to prevent a truly catastrophic event such as future global warming because the tail distribution of a global warming prediction is fat (Wagoner and Weitzman 2015).

The author elaborates a general structure of the integrated assessment model (IAM) which is an empirical policy model for the social welfare optimization policy approach. The first and most well defined of the IAMs, the Dynamic Integrated model of Climate and Economy (DICE), is explained with major policy results. These results are compared with the results from the generalized precautionary principle.

The author then critically examines the dismal theorem's model structure, critical assumptions, model parameters, and missing components, which shows that a modification of each of these aspects in the model leads to a different conclusion contradictory to the precautionary principle (Nordhaus 2011; Pindyck 2011; Yohe and Tol 2012; Seo 2017a).

The highlight of the critique is a great number of adaptation strategies and technological changes that are available for a long-term policy issue such as global warming (Seo 2015b, 2017a). Incorporating these aspects into the dismal model structure, the author offers an enhanced richer climate policy model, whose implications in the context of catastrophe management cannot be understated.

1.6 Empirical Studies of Behaviors Under Catastrophes

Catastrophic events are in most cases unexpected. That is, they occur with an element of surprise. They are referred to as a once-in-a-century event, or a once-in-a-millennium event, and so on. As such, it is often very difficult to avoid catastrophic consequences once the event is set in motion. For example, once an earthquake hits a high-rise building in a city, it is very difficult for the dwellers to escape from the collapsing building. For another, if a large asteroid were about to hit a city, it would be nearly impossible for the residents to escape in time from horrendous disasters.

Notwithstanding, an examination of the historical damages and fatalities caused by deadliest natural events such as earthquakes and tropical cyclones reveals that they have fallen substantially over time. Figure 1.2 shows the number of deaths annually caused by tropical cyclones in the North Atlantic Ocean from 1900 to 2016 (Blake et al. 2011; NOAA 2016). As revealed, the number of fatalities has fallen markedly during the twentieth century. With the exception of 2005 when Hurricane Katrina hit, the number of fatalities rarely exceeded 10 annually.

How has the reduction in the number of fatalities from natural catastrophes occurred? Although it varies across different natural or man-made events in the degree of difficulty,

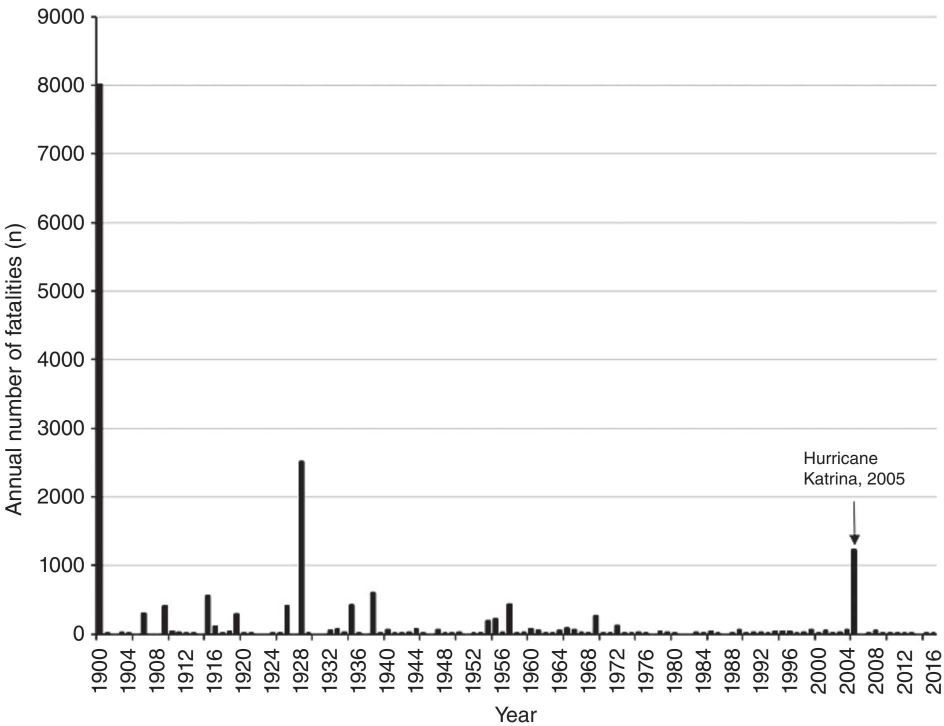

Figure 1.2 Annual number of cyclone fatalities in the North Atlantic Ocean since 1900. *Source*: Blake et al. (2011), NOAA (2016).

it is generally difficult to take reactive actions to a catastrophic event, that is, *post* the event. However, it does not mean that individuals and societies cannot be prepared for a catastrophic accident, that is, *ante* the event.

Among the preparatory actions and strategies that can be taken, some actions are taken well before the event in time, while others are taken just before the event. Adaptation can take place long before the event, just before the event, at the time of the event, and even without any direct association with the event (Seo 2017a).

Chapter 5 is devoted to the review of empirical economic studies on catastrophic events, as a continuation of the economics of catastrophes. The chapter utilizes the historical data of the two deadliest natural events in the past century in terms of the number of human fatalities: tropical cyclones and earthquakes (EM-DAT 2017; Swiss Re Capital Markets 2017).

The empirical data, empirical economic models, and questions raised and addressed through these models in Chapter 5 are without doubt fundamental inputs or aspects of the economics of catastrophes presented in Chapter 4. Empirical results in Chapter 5 augment or lessen various arguments and theories offered in the previous chapter.

With reference to the tropical cyclone literature and that of earthquakes, the author illustrates the fascinating complexity in the sciences of these natural events: How is a hurricane generated? What are the indicators of destruction and deaths? Is it possible to predict hurricanes in the year 2100? What are the best indicators of earthquake size, magnitude, and destructiveness? (Richter 1958; Emanuel 2008; McAdie et al. 2009; Knutson et al. 2010).

The complex science questions can be put in the economics context: What are the primary causes of human deaths through hurricane events? The traditional measures of hurricane intensity are expressed by way of hurricane wind speeds. The Saffir–Simpson scale of hurricane intensity distinguishes five categories of hurricanes based on MSWSs (NOAA 2009). Other measures that are based on maximum wind speeds are accumulated cyclone energy (ACE) and the Power Dissipation Index (PDI) (Emanuel 2005).

However, it has been reported that central minimum pressure of a cyclone better explains the destructiveness of hurricanes than maximum wind speeds (Mendelsohn et al. 2012). A further study in cyclone-prone zones of South Asia shows that it is neither wind speeds nor central pressure that is a primary killer of people there, but the surge of seas during cyclone events (Seo and Bakkensen 2017).

Economists have asked how sensitive the total economic damage is to an increase in hurricane intensity (Pielke et al. 2008). In the US, a very large elasticity of hurricane damages was reported with an increase in the maximum wind speeds or a decrease in minimum central pressure (Nordhaus 2010; Mendelsohn et al. 2012; Seo 2014).

Simultaneously, hurricane studies have found a large income elasticity of hurricane economic damages as well as of hurricane fatalities. That is, the higher the income of the region of a hurricane landfall, the lower the number of fatalities and the smaller the magnitude of economic damages. In the southern hemisphere ocean, a one-unit increase in income decreases the number of fatalities from a cyclone by 4.85% (Seo 2015a). In South Asia, a one-unit increase in income decreases the number of human fatalities by 3% (Seo and Bakkensen 2017; Seo 2017b).

The large income effect is ascribed to behavioral factors, exogenous technological changes, and induced technological changes. Behavioral factors include better awareness of hurricane threats, better knowledge of effective evacuation strategies, and moving out of hurricane-prone zones. Exogenous technological changes are economy-wide technological advances that help effective responses, which include resilient houses and buildings, ownership of automobiles, and communication technologies.

Recent studies have highlighted the important role that induced technologies have played in reducing the number of fatalities to cyclones. Induced cyclone technologies include satellite monitoring of cyclones, early warning systems, and cyclone trajectory projection technologies. The higher the income, the higher the adoption of these technologies. The higher the adoption of induced technologies, the lower the number of fatalities (Seo 2015a; Seo and Bakkensen 2017).

One of the salient findings of the behavioral economics of cyclones was its analysis of the effect of a long-term policy intervention in Bangladesh. A recent study of tropical cyclones in South Asian countries that included Bangladesh, India, Myanmar, and Sri Lanka showed that the cyclone shelter program run by the government of Bangladesh since the 1970s has become highly effective in reducing the number of fatalities in the event of severe tropical cyclones. It showed that the number of fatalities fell by 75% due to the cyclone shelter program, given the same degree of severity of a cyclone (Seo 2017b).

The cyclone shelter program was initiated by the government of Bangladesh in order to reduce the extremely large number of cyclone fatalities in the country (Khan and Rahman 2007). Cyclone Bhola in 1970 killed 280 000 people, while the 1991

Table 1.1 Deadliest cyclones, globally.

Rank	Year	Cyclone ocean basin	Country most affected	Name	Number of fatalities
1	1970	Indian Ocean	Bangladesh	Cyclone Bhola	Up to 500 000
2	1975	Western North Pacific	Philippines	Typhoon Nina	229 000
3	1991	Indian Ocean	Bangladesh	1991 Bangladesh Cyclone	138 866
4	2005	Indian Ocean	Myanmar	Cyclone Nargis	138 366
5	1975	Indian Ocean	India	Andhra Pradesh Cyclone	Up to 14 204
6	1963	Indian Ocean	Pakistan	Severe Cyclonic Storm Three	11 520
7	1998	North Atlantic	Atlantic	Hurricane Mitch	11 374
8	1999	Indian Ocean	India	Odhisha Cyclone	At least 10 000
9	2013	Western North Pacific	Philippines	Typhoon Haiyan	6329
10	2005	North Atlantic	US	Hurricane Katrina	1833
11	1959	East Pacific	Mexico	1959 M Hurricane	1800
12	1982	East Pacific	Mexico	Hurricane Paul	1696
13	1976	East Pacific	Mexico	Hurricane Liza	1263

Source: Fatality data are from various sources including the Joint Typhoon Warning Center (2017), Indian Meteorological Department (2015), National Disaster Risk Reduction and Management Council, the Philippines (NDRRMC 2017), and Bakkensen and Mendelsohn (2016).

Bangladesh tropical cyclone killed 138 000 people (Seo and Bakkensen 2017). The program subsequently received international support from the World Bank to restore existing shelter and build new shelters (World Bank 2007; Paul 2009).

It should be emphasized that cyclones, also called hurricanes in North America and typhoons in East Asia, are the most catastrophic natural events, measured by the number of human deaths, that humanity has experienced since the beginning of the twentieth century, with earthquakes being another deadliest catastrophe. In the twentieth century, many earthquakes killed more than 100 000 people (see Figure 1.1) and four tropical cyclones resulted in more than 100 000 human fatalities (see Table 1.1).

Therefore, empirical studies of these deadliest events reveal ample insights for the analyses of other catastrophes that neither are well described nor have quality empirical data, but are of much public concern, e.g. nuclear explosions, destruction of the ozone layer, asteroid collisions, a catastrophic failure in physics experiments, and AI. These are elaborated and then integrated into the economic models of catastrophic events presented in Chapters 4 and 5 and policy analyses in Chapter 6.

1.7 Designing Policies on Catastrophic Events

As made clear in Figure 1.1 on earthquake fatalities, Table 1.1 on cyclone fatalities, and many other empirical catastrophe data, catastrophic shocks, both natural and man-made, have long been one of the fundamental, perhaps ineluctable, aspects of human existence. As such, mankind's efforts to deal with and reduce the risk and fatal consequences from catastrophe events have long been as much an essential aspect of human societies. A large array of policies undertaken historically to deal with catastrophic events, failed or successful, is also available for those who are concerned about future catastrophes.

In Chapter 6, the author provides a wide-ranging review of policy principles and measures that were adopted and implemented to address catastrophic risks, which include asteroids, earthquakes, cyclones, nuclear wars, criteria pollutants, toxic and hazardous chemicals, destruction of the ozone layer, global warming, high-risk physics experiments, and AI.

The US government's policy interventions for protecting the Earth from NEOs such as asteroids, meteorites, and comets are very recent and centered on the programs run by the PDCO under NASA (NRC 2010; NASA 2014). The PDCO was established in 2016 and coordinates all the efforts related to protection against NEOs, the government budget for which has increased sharply in the past few years.

Policy concerns on asteroid collisions with the Earth are rather novel, even though multiple impacts of large asteroids are recorded in history. Up until now, the issue is discussed and addressed at a national level, despite a global-scale threat posed by a large asteroid, with more than 95% of all NEOs discovered by NASA.

The protection problem from asteroids is unique because asteroid protection has a best-shot technology production function (Hirshleifer 1983; Nordhaus 2006). This means that not all countries need to mobilize resources to protect the Earth from asteroids.

By contrast, another global environmental challenge has been tackled by extensive global cooperation: the ozone layer depletion. The global policy efforts to address the problem of the ozone layer depletion are encased in the Montreal Protocol on Substances that Deplete the Ozone Layer, a global environmental treaty signed in 1987.

The ozone layer in the stratosphere plays a vital role in protecting the Earth from the ultraviolet A (UVA) radiation from the Sun, the depletion of which is found to cause skin cancer and is related to other health effects such as cataracts. Scientists reported during the 1970s that a widely applied coolant for refrigerators and air-conditioners, i.e. CFCs, was destroying the ozone layer in the stratosphere (Molina and Rowland 1974). In Montreal in 1987, countries agreed to phase out CFCs, and this was updated multiple times, most recently in Kigali, Rwanda in 2016 (UNEP 2016).

The success of the Montreal Protocol as a global treaty is widely recognized. Remarkably, the participation rate is 100% of all UN members. Under the Montreal Protocol, the nations have phased out nearly all Ozone Depleting Substances (ODSs), and the total column ozone is projected to recover to the benchmark 1980 levels by the middle of the twenty-first century over most of the globe with the full compliance of the Protocol (WMO 2014). However, it remains unclear whether the recent Kigali Amendment would be ratified by as many nations and be as successful as the previous Amendments, owing to its non-UVA emphasis (White House 2013).

The international policy roundtable on nuclear weapons and wars is where global-scale catastrophic consequences are explicitly elaborated (Turco et al. 1983; Sandler 1997). In addition, it is an international policy area where an international treaty is clearly established. The NPT entered into force in 1970 and was extended indefinitely in 1995. As of 2018, the NPT is signed by 191 nations, but with notable nonmembers such as India, Pakistan, and Israel (UNODA 2017a).

Unlike other global-scale challenges, there are only a handful of countries, nine countries more precisely, that are known to have the capacity to build nuclear weapons or own them. However, there are many other countries that have the technologies but are restrained from developing nuclear weapons by reliance on a grand bargain in which nuclear weapon states provide a nuclear umbrella and commitment to a full and complete disarmament of nuclear arms. The stability of this grand bargain in the future remains to be seen (Campbell et al. 2004).

Chapter 6 describes the details of the NPT, including the safeguards system, and the implementations of the treaty by the IAEA. Other than the NPT, other treaties and agreements on other weapons of mass destruction at the UN level are discussed, such as the Biological Weapons Convention (BWC) and the Chemical Weapons Convention (CWC) (UNODA 2017b,c).

Local-scale and national-scale catastrophic events are addressed by local/national laws and regulations, calling for no international cooperation through a global treaty or agreement. Earthquakes, hurricanes, flooding, severe droughts, toxic substances, and air pollutants are such events whose policies and experiences are detailed in Chapter 6.

The US earthquake policy responses are anchored by the National Earthquake Hazards Reduction Program (NEHRP) authorized by the US Congress in 1977, which was amended in 2004 (US Congress 2004). The objective of the NEHRP is to "reduce the risks to life and property from future earthquakes in the United States."

The NEHRP is run by the National Institute of Standards and Technology (NIST) as the lead agency for the program, in collaboration with other federal agencies such as the Federal Emergency Management Agency (FEMA), the National Science Foundation (NSF), and the United States Geological Survey (USGS) (FEMA 2016).

Each of these agencies plays a distinct role. The NIST is charged primarily with the responsibilities of developing earthquake-resistant design and construction practices; NSF with supporting basic research programs; USGS with monitoring and analysis of earthquakes; and FEMA with implementing effective earthquake risk reduction tools.

Governmental responses to hurricane disasters in the US are anchored at the National Flood Insurance Program (NFIP) that was established by the National Flood Insurance Act of 1968. As declared in the name of the program, the NFIP is a federally subsidized insurance program for residents in hurricane-prone zones (Knowles and Kunreuther 2014).

Like other federal subsidies, the cost of the NFIP has increased drastically since its introduction in the 1970s for several reasons, one of which was a remarkable population shift to hurricane-afflicted zones and coastal counties. The astounding shift of population meant that more people and property are placed in vulnerable zones to hurricanes, which eventually resulted in a drastic increase in the NFIP's borrowing authority. As of 2012, the NFIP was in debt by US$17.7 billion (King 2013).

For the purposes of addressing the financial burden of the NFIP, the US Congress passed in July 2012 the Biggert Waters Flood Insurance Reform Act (BW12) as a comprehensive reform of the NFIP. The BW12 introduced a major reform of the NFIP by phasing out insurance subsidies and discounts and forcing a system of insurance premiums that reflect the flood risk, but these transformational provisions were rolled back subsequently (FEMA 2012).

The laws and regulations that regulate toxic chemicals and hazardous substances in the US include the TSCA of 1978, the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) of 1948, and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (US Congress 1978, 1980, 2012).

The US EPA, entrusted with the authority under the TSCA, made numerous attempts to restrict or ban toxic chemicals such as PCBs, CFCs, dioxin, asbestos, hexavalent chromium, mercury, radon, and lead-based paint.

But, the EPA's interventions were largely unsuccessful, faced with legal challenges from chemical companies. In the case of asbestos, the EPA issued a regulation that would have banned almost all uses of asbestos, based on an extensive risk assessment over 10 years as a carcinogen. Asbestos producers immediately challenged the regulation in the court which ruled against the regulation and the EPA, citing a lack of "substantial evidence" for both unreasonable risk and the least burdensome approach to remove the risk (Vogel and Roberts 2011).

Other laws and regulations that aim to limit or remove harmful chemicals include the CAA and the Clean Water Act. Atmospheric concentrations of six criteria pollutants are regulated by these laws: ground-level ozone, particulate matter, sulfur dioxide, nitrogen oxides, lead, and carbon monoxide. For these so-called criteria air pollutants, the US EPA has established the NAAQS, a set of thresholds for the concentrations of each of these pollutants (US EPA 1977, 1990, 2014).

With a view to achieving the pollution thresholds/targets at the least cost to the society, market-based policy instruments to control emissions of these gases were subsequently devised, which include the sulfur dioxide allowance trading program in the US (Stavins 1998; Burtraw and Szambelan 2009). The market price of the sulfur dioxide allowance, a measure of cost of the pollutant to society, fell to zero by the early 2010s, after peaking at US$1200 per ton in 2005 (Schmalensee and Stavins 2013).

In a global environmental-policy setting, the Kyoto Protocol and the Paris Agreements purport to limit the emissions of planet-warming gases such as carbon dioxide, methane, nitrous oxides, and fluorinated gases such as hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), and sulfur hexafluoride (SF6) (UNFCCC 1997, 2015).

International negotiators have pushed for meeting various targets/thresholds: the 1990 level of carbon dioxide emissions in the Kyoto Protocol, the 2° C threshold for global temperature increase, and the carbon budget for attaining the temperature threshold. These targets were adopted by the negotiators to avoid a dangerous anthropogenic interference with the climate system, which was the declared goal of the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro in 1992 (UNFCCC 1992).

The negotiations of almost three decades on global warming tell the important lesson in addressing a truly global problem: it is extremely difficult to agree on an international treaty with a near-universal participation. This is due, inter alia, to disparate impacts of global warming across countries, unequal policy effects, accounting for historical emissions, and rich countries' climate aids (Seo 2012b, 2015c, 2017a). A recent announcement by the Trump administration to pull out from the Paris Agreements signals that the Paris Agreements may not be a forceful international treaty to achieve its proclaimed goal, although it was hailed as a turning point in climate policy by negotiators (White House 2017).

The most catastrophic outcome may occur through AI or high-risk physics experiments. The former would be life-ending, while the latter would be universe-ending, if the worst-case scenario of each event should materialize. Given the extreme nature of the worst-case scenarios, it is not very surprising that there is not much to discuss when it comes to policy experiences of these events.

Nonetheless, the concern of experts regarding these events has increased quite sharply since the 2010s and some have even suggested a specific policy measure to address certain aspects of the problem (Marchant et al. 2011). The UN experts meetings on LAWS are being organized (UNODA 2017e).

How the global community should deal with singularity in AI or strangelets that can create a stable black-hole is the question at the heart of this book. These are extremely unlikely events, but their consequences, if realized, would be truly catastrophic. The book provides an answer to this important question through a multidisciplinary review of the literatures and examinations of mathematical and probabilistic models. In Chapter 7, the final chapter, a policy framework for dealing with these catastrophes is summarized.

1.8 Economics of Catastrophes Versus Economics of Sustainability

Learning from the wide-ranging review of literature on catastrophic events including life-ending and universe-ending catastrophes, this book elucidates the economics of truly catastrophic events. It offers an ensemble of ideas and quantitative models that can be utilized to support rational decisions on global-scale random catastrophes.

In the economics literature, this field, i.e. the economics of catastrophes, has received little attention in the past (see, for example, Stavins 2012; Tietenberg and Lewis 2014; Mankiw 2014). In the simplest terms, the economics fields of environmental and natural resources where environmental and natural catastrophes are researched are concerned with an optimal allocation of environmental or natural resources in which markets play a central role. In certain situations of externalities, mutual bargaining among concerned parties may arise to settle the externality cost (Pigou 1920; Coase 1960). Governmental policy interventions are called for when such bargaining incurs too high transaction costs or the goods that are in dispute are publicly consumed goods (Samuelson 1954; Nordhaus 1994). A policy instrument is to be chosen from the gamut of policy options in a way to minimize the cost of policy actions given the targeted benefits of regulations (Montgomery 1972; Hartwick and Olewiler 1997). The benefits, and sometimes costs, of a regulation must be measured through the empirical methods that account for a large pool of market behaviors that can be observed (Mendelsohn and Olmstead 2009; Freeman et al. 2014).

In the broader literature of environmental, ecological, and natural resources, there is a group of researchers who are primarily concerned about whether an optimal decision-making can lead to an unsustainable economy or whether sustainability itself should be given priority over optimal uses of resources (World Commission on Environment and Development 1987). This field is recognized as sustainability science (Solow 1993; Hartwick and Olewiler 1997).

The literature of sustainability economics or sustainability in general emphasizes the collapse of a concerned system due to unsustainable practices in which the concerned system may be a society, or an economic system, an ecological system, or a particular ecological population (Ehrlich 1968; Meadows et al. 1972; Costanza 1991; Daly 1996).

What is the difference between the economics of sustainability and the economics of catastrophes that this book describes? The two fields are mostly nonoverlapping. The economics of catastrophes is distinct in that it addresses the decision problems with regard to a very low probability event with a truly shocking consequence in terms of both human deaths and destructions. Put differently, it is concerned about catastrophes that seem to strike randomly, utterly shocking the society.

By contrast, the economics of sustainability is concerned with unsustainable practices or systems. These practices and systems are common and pervasive in the society or industries. Further, the concept of "unsustainability" is loosely defined and utilized in the literature of sustainability. In particular, the concept of unsustainability does not cover truly catastrophic outcomes such as life-ending catastrophes, universe-ending catastrophes, fat-tails, chaos, singularity, and fractals.

More concretely, the threat of an asteroid collision does not result from unsustainable practices or systems, and neither does the threat of AI or black-hole-generating strangelets created from high-risk physics experiments. These catastrophic challenges and others described throughout this book cannot be addressed adequately through the concepts of sustainability.

1.9 Road Ahead

This concludes the introduction to the book. Intriguing theories and models of catastrophe, chaos, fractals, and order await you on the road ahead in the upcoming chapter.

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