Chapter 1

Universal Beginnings

1.1 The (Short) Big Story of Climate Change

The story of climate change, in particular *anthropogenic*[1] climate change, is the story of *energy*[2] in our Universe, and it is one of balance. A balance that, unlike the abstract constructions of human society and culture, is a requirement for existence. In fact, it is rigidly baked into the physics as the First Law of Thermodynamics, which states that within a closed system, energy cannot be created nor destroyed, only converted from one form to another[3]. So while we cannot remove energy from the closed system that is our Universe, we can absolutely control *how* and *when* we use it, and therefore the story of climate change is also one of competing timescales - exhausting resources faster than they are replenished can have dire results, as we will soon see.

1.1.1 The First 10 Billion Years

For some context, let us zoom out to the largest timescale we are aware of - the history of the universe itself - and start by looking at the energy we have to work with. Going back to the very beginning[4] of time itself, some astrophysicists believe that the *Big Bang* brought our Universe into existence

[1] human-caused

[2] We will define *energy* in all of its many forms in detail later, but for now, your intuitive understanding will be sufficient.

[3] For those of you hip to astrophysics, you may know something about the accelerating expansion of the Universe and *dark energy*, but we will be ignoring this topic here, as it is highly complex and not universally agreed upon by the scientific community.

[4] Physicists largely take issue with referring to the origin of the universe as a "beginning", as our conception of time and space breaks down at some point as we go farther back in time.

from nothing [1, 2, 3]. No energy, no mass, no heat - pure zero. From the nearly intractable void, all that we now know spontaneously flickered into existence. While this process is not well understood, one hypothesis attributes this flash of creation to a random quantum fluctuation, which in general allows "positive" energy to be created as long as it is paired with an equal amount of "negative" energy. Curiously, it can be shown that if we look around, the total energy does seem to equal zero roughly, though this result is still widely debated [4].

Setting aside the disputed ultimate origin story, what we do know pretty well is that just after the Big Bang, some 13.8 billion years ago [5], there existed a roughly equal balance between "positive" energy in the form of extremely hot matter and "negative" gravitational potential energy holding it together. As the Universe expanded and the dense, homogeneous matter soup began to cool, it condensed into subatomic particles called *quarks*, trading some energy for mass[5], which then coalesced further to form protons and neutrons. These composite *baryons* eventually combined to form elementary hydrogen and helium, the first *atoms* of our Universe, and shortly after, *electrons* were able to form and bind to those atoms, making them neutrally charged. Over millions of years, these single atoms were pulled into clusters under their own gravitational attraction, trading gravitational potential energy for kinetic energy and heat. As these clouds became more and more dense, their temperature and pressure eventually rose high enough to ignite *nuclear fusion*, a process in which atoms combine, losing a small amount of mass in return for a substantial amount of light and kinetic energy. With enough atoms fusing under these conditions, a chain reaction can initiate to create a massive fireball contained by the force of its own gravitational self-attraction - a *star*.

The early universe was - and still is - a constant cycle of birth and death for stars on timescales ranging from a few million years to many billions of years depending on how quickly they consume their nuclear fuel. The stars that burn hot and fast are of particular interest to our story of climate change, as they help explain the origin of the Earth itself. In general, if it were not for nuclear fusion in stars, we would be stuck with mostly hydrogen, helium, and some lithium [6], the first three elements on the periodic table containing 1, 2, and 3 protons respectively. With standard fusion, all stars are capable of turning these smaller atoms into larger ones, all the way up to nickel, containing 28 protons [7].

[5] You may have learned about the conservation of mass as being a rigid fundamental physical law; however, while this tends to hold true for fluids and solids that we can measure at the macro scale, at the atomic scale, we can actually trade mass for energy directly. According to Einstein and rigorously validated by many experiments since, this mass energy is given as the famous $E = mc^2$, where c is the speed of light.

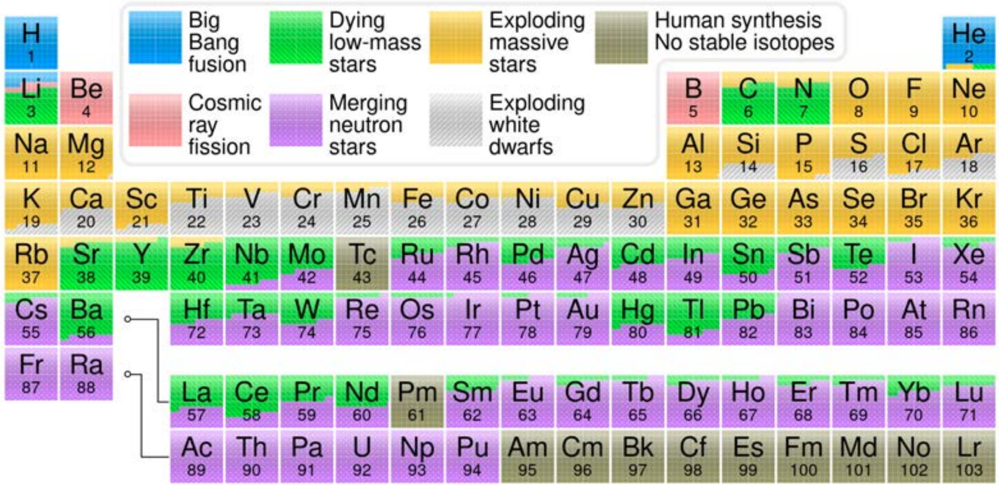

Figure 1.1: All known elements in our Universe and how they were created. Stellar nucleosynthesis is responsible for the creation of the elements Carbon through Plutonium. Image courtesy of cmglee on Wikipedia. License CC BY-SA. This content is excluded from our Creative Commons BY-NC-SA license. For more information, see https://ocw.mit.edu/help/faq-fair-use.

To create even larger atoms, however, a still more explosive approach is required. One such process can occur at the end of a star's life, depending on its initial size and energy content. Instead of simply fizzling out, under the right conditions, a star can undergo a *supernova* in which it experiences a sudden collapse of its core, causing a shock wave that generates the temper-atures and pressures required for the fusing of even more neutrons than was previously possible, creating many of the other elements we naturally find in our Universe[8]. If the remnants of that same star are not massive enough to collapse into a black hole, they can condense into an incredibly dense *neutron star*, and the subsequent colliding of neutron stars is thought to be responsible for the synthesis of the remaining elements, up through Plutonium, as shown in Fig. 1.1.

So now that the Universe has traded some gravitational potential energy to create stars, and with them all of the elements that can conceivably be produced over their lifetime, we can talk about the emergence of *planets*, which are the stellar remnants that are too heavy for *exothermic*[6] fusion. Instead the inert stellar dust collapses to form a molten ball of dense elements that stays together under the pull of its own gravity. Roughly 4.5 billion years ago,

[6]releases heat as opposed to *endothermic* which absorbs heat

one such dust cloud formed into what is now the Earth we inhabit. Given that at the same time, many other planets were forming in much the same way, this was not a tame or organized process. Indeed, for a long time, the Earth was bombarded with not just asteroids and meteors, but various other fledgling planets as well. As we can see now, only a few survived. One such collision near the end of the Earth's formation ripped enough material away from the young planet to form the Moon [9, 10]. Despite the destructive nature of this process, in a bit of dramatic irony, some of these collisions were with protoplanets rich in carbon, water, and nitrogen - the seeds of carbon-based life.

Eventually - roughly 4 Ga[7] - the "Late Heavy Bombardment", as it is referred to, slowed, giving rise to an environment in which life as we know it could spring forth and thrive. During that time, on the Earth's surface, volcanism was the norm, as the young planet was still essentially just a super hot ball of magma from its formation process. Frequent volcanic eruptions and the occasional extraterrestrial collision produced massive amounts of *greenhouse gasses* (carbon dioxide, hydrogen sulfide, methane, etc.), creating an early atmosphere that allowed the Earth to retain heat from incoming solar radiation. This development was incredibly important, because as the Earth cooled and water started coming in from collisions with icy asteroids and comets, the sun alone did not have the required power to keep that water in liquid form. Especially since in the Earth's formative years, the Sun was 30% dimmer than it is now, without this atmosphere acting like a thermally insulating blanket, all of this water would have likely been frozen in what scientists call a "Snowball Earth" scenario[8]. Instead, despite painting a hellish scene on land, the rampant volcanism actually enabled the formation of liquid water oceans, creating the necessary environmental conditions for life.

So to recap the Big History of the Universe up to this point, let us take stock of how the energy balance we started with has shifted. Ignoring the controversial exact beginning of the Universe's origin story (i.e. for $t < 10^{-11}$ seconds), we know pretty well that at some point, all measurable energy was contained as balance between hot matter in the form of subatomic particles called quarks and gravitational potential energy. As they cooled, quarks formed protons, which in turn formed various lightweight atoms that later combined with electrons to form the first several elements of the periodic table. From there, gravitational potential energy was cashed in repeatedly to form larger, hotter clumps of atoms, which eventually generated the temperatures and pressures

[7] Ga = billion years ago

[8] see *Faint Young Sun Paradox*

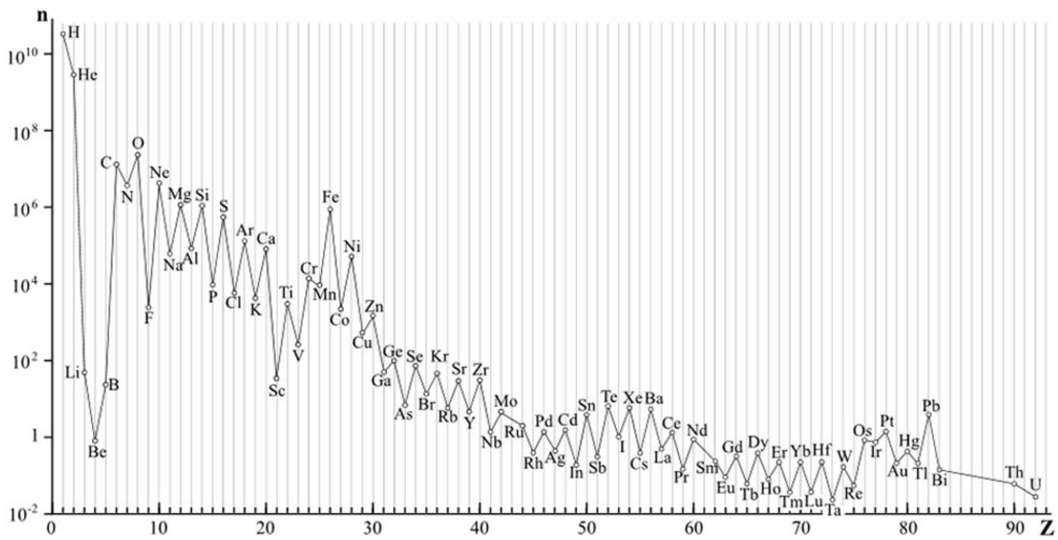

Figure 1.2: The abundance of all naturally occurring elements in the Universe [11]. This image is in the public domain.

to ignite fusion reactions that turned these dust clouds into stars. In nuclear fusion, rest mass energy (i.e. $E = mc^2$) is released as heat and light, which in turn promotes more fusion, creating a chain reaction that continually converts some rest mass of hydrogen and other lightweight elements into more heat and more light.

Depending on its size, a star can undergo a massive explosion at the end of its life that converts some thermal energy back into mass energy as most of the remaining elements that are naturally found in our universe are created, at the same time spreading them out into more massive dust clouds. Again under the pull of gravity, these clouds reform into more suns or planets now that we have some heavier elements to play with. In our solar system, this process formed the Earth, and the residual heat from the solar remnants powered the eruption of volcanoes on Earth to help create an early atmosphere. At this point, as the Earth slowly cooled, it also continued to receive an influx of energy as light from the Sun; however, this energy alone would not be sufficient for keeping the Earth's surface temperature above the freezing point of water. With an atmosphere, our planet began trapping some of this light as heat, keeping the conditions at just the right temperature and pressure for life to form - the first instance of climate change and a foreshadowing of what was to come.

1.1.2 The Inhabited Earth

Back to our story, a hasty several hundred million years into the life of planet Earth, the stage for life was set. The earliest fossilized records we have show the emergence of the first self-replicating biological structures happening somewhere between 4.3 and 3.8 Ga, with the earliest self-replicating *RNA molecules* deriving their energy for reproduction from hydrothermal vents powered by thermal energy from the Earth's core - a remnant of solar energy - and carbon monoxide. These early molecules used iron and nickel sulfides found inside the vents to catalyze the various chemical reactions required for building and sustaining proteins [12]. These free-floating *chemosynthetic* organisms eventually found homes within *liposomes*, small bubbles made from lipids that also spontaneously began to form in the primordial soup. These protocells, which from the outside very much resemble our own, could now travel somewhat farther from their sources of energy, but they still lacked most of the basic functionality our cells enjoy now. Eventually, about a hundred million years later (around 3.5 Ga), these cells evolved into the organism that would give rise to all life presently on Earth, our so-called *last universal ancestor*.

At this point, we are 10 billion years into the history of the Universe and 1 billion years into the history of Earth, and organisms have evolved another special ability - capturing the energy of sunlight directly to make their own food. To achieve this, our single-celled ancestors evolved the first "solar panels", internal structures called *chloroplasts* that enable the conversion of sunlight, water, and the highly abundant CO_2 in the atmosphere into oxygen (O_2) and sugars (e.g. glucose, $C_6H_{12}O_6$) that they could then consume for *metabolic* energy and structural material required for growth (i.e. cellulose). Very quickly the atmosphere filled with oxygen, which at first had many beneficial effects, the primary of which was that it started reacting under the intense sunlight to form *ozone* (O_3) in the upper atmosphere. This gas absorbed much of the harmful ultraviolet radiation produced by the Sun, allowing photosynthesizing organisms to be able to leave the oceans and cover the land without burning. Over the next billion or so years, however, as more and more oxygen was generated, its atmospheric concentration eventually rose to toxic levels. Additionally, more oxygen meant that more methane in the atmosphere could be converted to carbon dioxide, a much less potent greenhouse gas by comparison. Suddenly, the blanket covering the Earth became less effective, temperatures dropped to -50 °C, and the Earth was plunged into its first major ice age starting about 2.2 Ga.

Clearly, we can already see that the greenhouse effect is a) essential to maintaining conditions suitable for life, which would otherwise be impossible

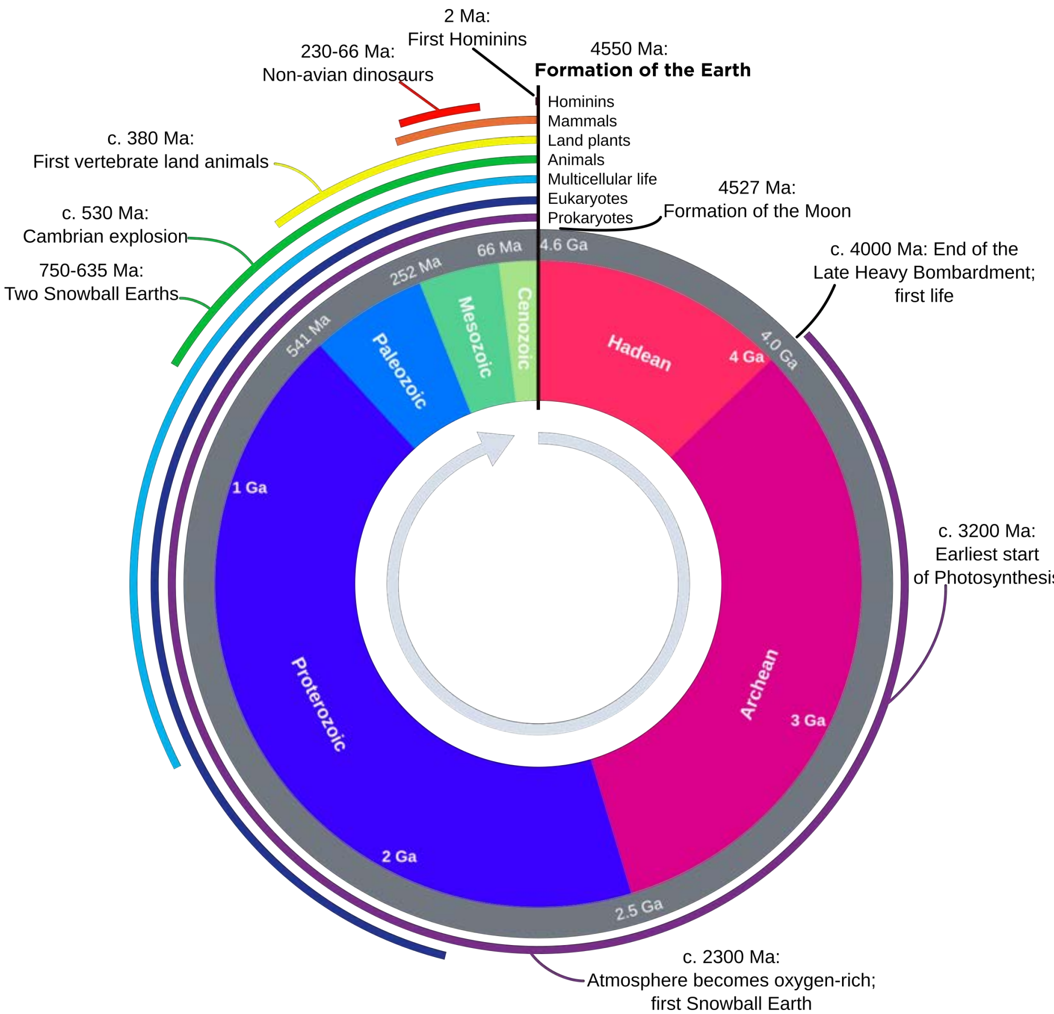

Figure 1.3: Geological history of the earth. This image is in the public domain.

given the insufficient solar power to heat the earth directly and b) highly sensitive to atmospheric compositions. When left alone, however, the climate is kept in check by the *carbon cycle*. In this process, as we have seen, carbon dioxide and other greenhouse gasses in the atmosphere trap solar energy as retained heat. Photosynthesizing organisms take carbon dioxide out of the air, and when these organisms die, their carbon is either released back into the atmosphere as methane or sinks to the bottom of the ocean, where under intense pressure it is turned into molecules made from long chains of carbon and hydrogen that we harvest today as oil. As we will see in detail later, the temperature of the atmosphere and oceans also play an important role in maintaining this balance, but at a certain point, this delicate balance can be permanently disrupted (see Venus). In the case of the Earth's first ice age, it is widely believed that volcanic activity boosted atmospheric carbon dioxide supply, once again wrapping the Earth in enough thermal insulation to bring the temperature back up above the freezing point of water[9].

Over the following 2 billion years (from 2.5 Ga to 0.5 Ga), life continued to slowly evolve, from single cell *prokaryotes* to *eukaryotes* as *DNA* migrated into a central cell *nucleus* and then to simple multicellular life. Major continents formed and moved around, and the Earth experienced several more ice ages as the carbon cycle kept getting pushed a bit too far and then recalibrated. With the end of the last major "Snowball Earth" event came the *Cambrian Explosion*, a brief 50 million year period starting around 542 Ma[10], in which the rate of evolution began to accelerate, producing molluscs, arthropods, vertebrates (including the direct ancestors of many modern fish), trilobites, and many more. With ozone now protecting land from harmful radiation, many of these species started moving farther onto land. This migration was helped by oxygen concentrations being brought down to safe levels by frequent fires and respiration, demonstrating another advantageous feedback loop within the carbon cycle. A few major extinction events occurred during this time, but soon after each, a new diversity of species would invariably spring up.

From a thermodynamics perspective, this development was also remarkable in that we began to see organisms that cannot make their own food via chemosynthesis or photosynthesis directly. Instead, these new creatures had to eat other organisms that could, in the process converting the sugars they contain into heat and metabolic energy, releasing carbon dioxide as a byproduct. Some animals start eating other animals, but as we get further from the source, it is important to remember that all life is still, and always will be, solar powered. The carbon cycle also gets more complex as a result of this development, since we now have both organisms that can remove net carbon dioxide from the air and organisms that eat this stored carbon and release it back. As before, when these organisms die, the carbon that comprises their bodies is released as methane or slowly gets compressed over millions of years as it sinks deeper into the Earth. Depending on the conditions, this carbon can turn into coal or oil stored deep in the crust, where it is effectively removed from the carbon cycle for millions of years.

[9]The climate is also affected by the procession of the Earth's axis, but it is widely believed this can still be overpowered by the carbon cycle [13].

[10]Ma = million years ago

1.1.3 Humans and the Control of Fire

At this point, we are at 500 Ma in our story, 4 billion years into the formation of the Earth, and we are just seeing life that would be familiar to us today. The 500 million years connecting then until now were a blur compared to the rate of previous development. Plants and animals soon filled the oceans and covered the land. Several smaller ice ages repeatedly froze the early continents, with their melting leaving lasting impressions on the landscape, forming lakes and other terrain that helped to diversify life further. We saw mammals, birds, and dinosaurs spring into existence around 300 Ma. The dinosaurs in particular dominated the landscape until 66 Ma when a major extinction event - the *Cretaceous-Paleogene* event - occurred in large part due to a massive asteroid hitting the Earth, resulting in the elimination of 95% of all living species at the time. Among the survivors were the mammals, however, and they seized the opportunity to take over, quickly engendering a new diversity. 10 Ma we saw the first apes[11] and roughly 8 million years later we had our first direct *human* ancestors. All the while the smaller ice ages continued to help shape the landscape and guide the movement of animals on land, breeding further diversification.

Then there was a fundamental shift in how life uses energy around 2 Ma, when the early humans discovered they could control fire. With this new ability, they could begin to extract thermal energy from solar energy stored in the carbon chains of dead plant matter. Very much like organisms that consume sugars and fats, inhale oxygen, and exhale carbon dioxide, the fires set by early humans were quite similar, though less complex, chemical reactions that combined some flammable carbon source with oxygen to produce carbon dioxide, releasing tons of heat in the process. With that, thermodynamics, though we did not know it at the time, formally began, and a world of possibilities opened up. Now humans had a new tool to protect themselves against harsher environments, which among other things, meant they no longer needed to migrate with the seasons. Staying put gave rise to permanent societies that could use agriculture to sustain more and more people. The ability to cook food and boil water meant that humans could eat a wider variety of plants and animals and better stave off disease and infection, enabling them to grow larger, stimulate larger brain development, and live longer. Control of fire also gave humans control over time in some respect, as they could now make light at will and see in the darkness. From photosynthesis to eating plants to burning plants (on purpose), this discovery truly brought us into a new era of being.

It took another 2 million years for early humans to start settling en masse

[11] *hominids*

in fertile regions, but before that, their new abilities to thrive and multiply in what were once hostile environments had a profound impact on other species. In fact, from about 130,000 BCE to 8,000 BCE, we saw the first major extinction at the hands of humans, the *Quaternary Extinction Event*, in which a significant number of animal species were wiped out due to over-hunting, in particular those in the *megafauna*[12][14] group. Their removal had long lasting repercussions that reverberated throughout the Earth's many ecosystems, fundamentally changing the makeup of life across the planet.

Conveniently in the wake of that mass extinction, which ended roughly 10,000 years ago, the first agrarian societies started cropping up. The first major civilization was established 5,000 years ago in Sumer in the Middle East, and with the advent of the first civilization also came the beginnings of anthropogenic climate change, again forewarning of the dangers of overconsumption. Studies have shown a spike in greenhouse gasses around this time, likely as a result of humans clearing forests and burning large swaths of land to make way for farms [15]. The carbon currency that kept the Earth's climate in a delicate balance (with the occasional imbalance leading to an ice age), was suddenly being expended at a rate that was greater than could be replenished by solar energy in the short term, a theme we will see persists until present day. With these early civilizations, however, this effect was minimal, as there simply were far too few humans using fire and repurposing land to make much of a difference. Early increases in carbon dioxide levels might have also been balanced by plants growing larger and more verdant during this time.

As civilizations developed, the human population began expanding both in terms of numbers and geographic area. As early as 3,500 BCE, Egyptians realized they could harness the power of the wind to propel boats to high speeds, greatly opening up the amount of territory that could be traversed, ushering in the age of rapid colonization. A quick aside, wind energy is the result of thermal gradients caused by, you guessed it, the Sun. So even wind energy is actually solar energy at its core (sensing a theme here?). The ability to now harness solar energy in three different forms, food, fire, and wind, led to the ever increasing ability of humans to manipulate their environment, other species, and later even members of their own to their own advantage, begetting more growth and more power.

[12] Think large mammals like woolly mammoths.

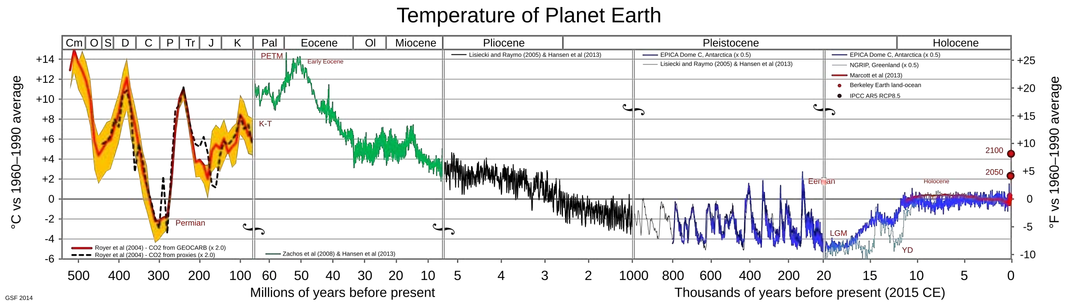

Figure 1.4: Historical global mean temperature.

1.1.4 The Origin of Thermodynamics as a Tool

In the first century CE, another incredible thermodynamics development occurred, but like with fire, it took some time to catch on - people in Ptolemaic Egypt realized that heating water inside an enclosed vessel would generate "wind", hot vapor that could be ejected in such a way that caused the vessel to spin. Thus, the first engine, called an *Aeolipile*[13] was born, though when it was discovered, it was considered to be just a simple party trick. It would not be for another 1,500 years that someone had the idea of sticking this engine in a ship to power locomotion. Fast forward another thousand years, taking us to 900 CE, when the Chinese discovered a way to harness this "wind" to make weapons. They realized that powderized charcoal[14] could be mixed with sulfur and potassium nitrate to make it burn extremely rapidly and at high temperatures. By sticking this powder mixture into a tube that is closed on one end and has a projectile blocking the other, humans had their first guns. Suddenly what was once an advantage over other species, was now an advantage over other groups of humans. The same technology that could be used to warm, cure, and liberate could now be used to threaten, destroy, and enslave.

Human development[15] continued at an accelerating rate in centuries that followed as we kept discovering how to harness available energy in new and more effective ways. In 1500 CE, which is now extremely recent compared to the timescales we have been discussing, we saw the first design of a steam-driven ship, though wind-driven vessels were still the norm. Just 200 years

[13] In Greek this translates to "ball of Aeolus", the god of air and wind.

[14] Charcoal is just wood that is heated in the absence of oxygen, leaving only the carbon behind and is itself highly flammable.

[15] from a Eurocentric perspective

later, steam engines were widely adopted for powering locomotion on land, around the same time electricity was discovered in the West. Then in the early to mid 1800's, the field of thermodynamics as we know it was starting to take shape as several key physical laws, which we will learn about in detail in later chapters, were discovered and formalized, providing engineers and technologists with powerful mathematical tools to design more efficient engines.

Around that same time, in the 1880s, humans started using coal to generate electricity, at which point we were not only burning plants that had died recently, but also now carbon from plants that died during the *Carboniferous* period - 300 Ma - that would have otherwise remained in the ground for millions of more years to come. Indeed, the adoption of coal as a widely used energy source marked a dangerous turning point in the story of climate change as our energy demands exceeded what could be readily supplied by the sun, instead causing humans to turn to stores of solar energy that had been accumulating for millions of years. Somewhat ironically, it was around this same time that scientists[16] discovered the greenhouse effect [16], with some even noting that the continued excess burning of fossil fuels would have a profound effect on the climate.

These warnings were largely overlooked, as the burning of fossil fuels also had a profound effect on technological and thus economic development via the *Industry Revolution*. Just 50 years later, in the early 1900's, vast stores of oil, which again are the liquefied carbonaceous remains of ancient sea creatures, were discovered underground, providing humanity with another energy-rich and carbon-intensive fuel source. Bolstered by numerous major wars and the rapid economic development in the West that followed, we saw the emergence of a seemingly runaway cycle of more energy consumption leading to net economic development leading to higher energy demands and so on. By the mid 1900's, now only 50 years ago and about the same time humans demonstrated their ability to escape the gravitational pull of Earth itself [17], the ever increasing carbon emissions began to leave their mark on the climate as the global mean temperature started to rise as a direct result of the pronounced greenhouse effect [17], proving many of the earliest climate scientists correct.

[16] This discovery is often wrongly attributed to John Tyndall but was actually made by Eunice Foote several years earlier in 1856.

[17] see Sputnik and the Apollo Program

1.1.5 The Anthropocene

This brings us to today, where in 2020 the Earth has warmed a deceptively substantial 1 °C above pre-industrial temperatures. Looking back, in just the past 50 years, a span of time encompassing only 0.003% of the history of humans or 0.000001% of the history of the Earth or 0.000000... - you get the idea - the culmination of human achievement in science and technological development has brought about countless advancements[18] in medicine, agriculture, transportation, communications, computation, and the list goes on. As was meticulously outlined by the most recent IPCC special report [18], we are now seeing, however, that this progress has come at cost of the stability of our climate. The rate of development and the associated energy consumption has been at direct odds with the timescale on which the Earth's carbon cycle regulates the climate, which, works over millions of years. The stress on the system from just the past 150 years is finally catching up as we begin to see measurable sea level rise, more powerful and frequent severe weather events, and beginnings of mass extinctions. What is even more concerning is that, as Solomon[19] et al showed, even if we stopped emitting carbon dioxide today, these adverse effects are "locked" into the climate response for potentially hundreds of years [19].

So where do we go from here? The IPCC report also showed a consensus among the world's leading climate experts that a 2 °C global mean temperature rise above pre-industrial levels would cause a catastrophic and irrevocable disruption to nearly all of the of the Earth's many interwoven ecosystems upon which we rely. The best climate models developed to date indicate that to avoid a safer - but still potentially devastating - 1.5 °C temperature rise, the atmosphere must absorb no more than 316 Gt of carbon dioxide if we start counting from July 2020 onward; however, at current rates of consumption, this budget is set to run out by the end of 2027 [20], just 7 years from now. Needless to say, the race is on, and just as much as the manipulation of thermodynamic principles played a central role in the development of this impending crisis, these same principles - *in responsible and conscientious hands* - may be the keys to getting us out of it.

[18] enjoyed by a small subset of humanity

[19] Susan Solomon is an MIT professor who is famous for her work that helped galvanize support around repairing the Earth's ozone layer

1.1.6 Thermodynamics - A Human History

At this point, you may be wondering just what is *thermodynamics* anyway? We have hinted in the previous section's Big Historical perspective that it has something to do with heat, engines, and carbon emissions but have left its definition intentionally vague up until now to avoid getting lost in the finer details. To start, thermodynamics is a branch of physics that investigates the relationship between energy in its various forms, in particular how *thermal* energy or *heat* interacts with matter to transform into mechanical energy and vice versa. For thousands of years, humans tried to formally understand the visceral sensation of heat, attributing it at first to mythological phenomena and eventually postulating that it was a unique physical "element" as tangible as water and earth. Ancient Greek philosophers wrote at length about the ability of heat to "flow", likening it to a fluid[20].

In fact, this fluidic theory of heat would persist for nearly another 2000 years, where by the 1700's the supposed fluid was given the name *caloric*. Around this same time, it was also postulated that all bodies had a different "volume" for this fluid, defined as the body's *heat capacity*, which despite being established using now outdated physics, is still a term we use today. It wasn't until 1798 that Count Rumford, a British physicist, undermined this theory by showing that heat could be generated via friction[21]. These observations were further supported by the research of Antoine Lavoisier and Joseph Black who concurrently were reporting that heat could be released or absorbed by chemical reactions or by freezing and thawing water, marking the end of heat being thought of as a distinct conservative quantity. This theory was instead replaced by the notion that heat is simply a different form of energy that can be traded and transformed just like kinetic or potential energy. James Joule would later show in 1843 that there was in fact an exact mechanical equivalence of heat[22].

Parallel to these developments, people were observing a peculiar relationship between heat and the motion of fluids. For example, it was also known for thousands of years that boiling water in a partially enclosed container would generate "wind" - hot gas that would exit the container with some velocity[23]. Later in the 1600's CE, scientists like Galileo were observing that a vacuum

[20] see Heraclitus, 500 BCE

[21] In line with some of the sentiment of the Big Historical context presented here, it is unsurprising perhaps that he discovered this when he noticed that boring out chunks of iron to make cannons caused the metal to heat up substantially.

[22] Interestingly, nobody believed him at first because his experiments were *too* accurate.

[23] see *aeolipile*

chamber had the ability to draw in water from the environment, and soon after, Irish chemist Robert Boyle showed in 1656 that the pressure and volume of a gas were predictably correlated. These observations, however, were not connected until French chemist Joseph Louis Gay-Lussac laid the groundwork for the famous *ideal gas law*, which accurately relates the pressure of a gas to its temperature and density.

From there, another French physicist, Sadi Carnot, the "father of thermodynamics", united the more modern framework of heat and the thermo-mechanical properties of gasses in pistons into a unified field, which was later first called *thermodynamics* by Lord Kelvin. Rudolf Clausius formalized the concept of energy that is "wasted" to the environment as being proportional to the quantity of *entropy*, which was then rigorously related to the statistical thermodynamics of large groups of particles through the work of James Clerk Maxwell[24] and Ludwig Boltzmann in the late 1800's. Finally, Willard Gibbs defined the concept of *enthalpy* and *free energy* to quantify the amount of useful mechanical energy (*work*) that could be extracted from a system, and he finally formally stated the first two laws of thermodynamics in 1873. With these contributions, and the many that followed from countless other physicists, mathematicians, and engineers, the groundwork for the subject presented in this book was laid.

There is considerable overlap between thermodynamics and the fields of chemistry, biology, magnetism, and both classical and quantum mechanics, a testament to the ubiquity and importance of thermal energy conversion in a wide array of observed phenomena. For example, combustion - and all forms of *oxidation* for that matter - is described by various chemical reactions that release thermal energy as a result of breaking and reforming covalent atomic bonds. The heat released acts as a kind of currency that can be captured and converted into mechanical energy to turn a shaft, as is done in the internal combustion engines that power a majority of the world's cars. Thermodynamics provides us with tools to examine exactly how much heat is released in these chemical reactions, how much of that heat we can expect to convert in mechanical energy, and perhaps most importantly for our future discussion about climate change, how much is "lost" to the environment. These same physics govern the operation of power plants, refrigerators, jet engines, hot air balloons, batteries, air conditioners, and the list goes on.

While thermodynamics can help explain how we came to emit enough carbon dioxide to radically change our environment, it also lays the foundation for the physics underlying the behavior of our atmosphere and climate itself.

[24] who revolutionized many fields over his career

In particular, thermodynamics dictate how clouds form from water vapor in the air and then turn into storms, as well as how thermal energy from the sun in part drives oceanic and atmospheric currents (i.e. wind)[25] and the greenhouse effect. The study of these phenomena provides an analytical basis for talking about climate change in general, and it even provides some insights into ways we might be able to manipulate certain feedback loops directly to undo some of the damage we have already done[26].

Finally, as an appeal to some sort of cosmic aesthetic beauty, it is incredible (and somewhat unsettling) to reflect on the predictive power of thermodynamics and realize that the fundamental laws, from which virtually everything we discuss here will be derived, are based solely on observation. Let that sink in. As far as we know, the three laws of thermodynamics hold true, but they have never been proven, nor is there a credible procedure for even going about proving them. Regardless, they have held up over the past two hundred or so years - through endless experimentation and theoretical development built on top of them. Even Einstein said of thermodynamics that they comprise "the only physical theory of universal content, which I am convinced...will never be overthrown". Regardless of the context of its many applications, the theories presented in this subject are truly an achievement in human imagination and is worth appreciating as we move through this content.

1.2 Summary

The history of the Universe from the Big Bang to the present day spans nearly 14 billion years, the last 4.5 billion of which saw the development of our planet Earth. Just 500 million after the Earth was formed, the first living organisms appeared. Over the next 4 billion years, what were originally strands of free-floating RNA in the depths of the oceans, evolved to create the vast diversity of life we see today, all the while shaping the climate and the Earth itself along with it. These persistent cycles of change were not only common, but *necessary* for the diversification of life and its ability to survive over the incredible stretch of time it has - now almost a third of age of the Universe itself.

Something fundamental changed, however, once humans came on the scene a comparatively short 2 million years ago. Before this time, plants and animals used energy both directly and indirectly from the sun as it was provided to

[25]In reality these phenomena are made much more complex by *coriolis* forces that arise from the fact that Earth is spinning and *tidal* forces from the moon, but thermal energy is still a major driver.

[26]see *geoengineering*

them, letting the natural rhythm of the seasons and the gradual oscillations of the climate guide their rates of consumption and therefore their evolution and development. With the emergence of humans and their ability to control fire soon after, this pace quickened, as life was no longer subject to the natural cycles of growth and decay. In the ability to liberate thermal energy stored in the bonds between carbon atoms that comprise organic matter - energy that originally came from sunlight - humans suddenly had vast stores of heat and light at their immediate disposal.

With the control of fire ultimately came the control of ecosystems, driving more development, expansion, and consumption, and once humans discovered the even more energy-dense deposits of solar energy stored in the remains of ancient plants and animals as coal and oil, this cycle accelerated. By the early 1700's CE, now just 300 years ago, the study of thermodynamics got its footing as scientists and engineers learned how to turn thermal energy into mechanical energy and then into electricity, opening the door for the invention and adoption of a seemingly limitless number of new technologies.

This progress has come at a cost, however, as the mass burning of carbon-based fuels results in the re-emission of carbon dioxide at rates greater than can be absorbed by natural means. Because carbon dioxide functions as the currency of the Carbon Cycle, its excess has put considerable strain on the climate's main feedback loop keeping temperatures within livable conditions. Coupled with the additional ecosystem destruction from over-development and pollution that further inhibits the natural uptake of carbon dioxide, the net effect of our energy consumption has been pushing the Earth towards an unprecedented warming scenario that threatens to destabilize our many necessary ecosystems.

The silver lining here is that the field of thermodynamics - which up until now has led us down this destructive path - has also provided us with many tools to work towards solutions that prevent a devastating additional 1-2 °C of warming if we so *decide* to use them in that way. The purpose of this text is to tell the story of climate change in greater detail, introducing the fundamental physics of thermodynamics and the analytical tools that use them along the way. As we continue this educational journey, be aware of the perspective you bring to this story and its impact on your motivations to learn the material. Without this greater context, we get the dangerous and unchecked push towards progress that got us here. Fortunately for all of us, the ending of this story is somewhat uncertain, and the proverbial publishers are still accepting submissions; however, we have little time to waste, as what we do in the next 10-50 years - just a veritable blip in the grand timeline - will likely seal this fate.

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Peter Godart