TEN EQUATIONS TO EXPLAIN THE MYSTERIES OF MODERN ASTROPHYSICS

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FROM INFORMATION AND CHAOS THEORY TO GHOST PARTICLES AND GRAVITATIONAL WAVES

Santhosh Mathew

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Ten Equations to Explain the Mysteries of Modern Astrophysics: From Information and Chaos Theory to Ghost Particles and Gravitational Waves

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Foreword

What if the reality that we see before us is only temporary? Or, perhaps it is not what we think it is. Where then do we look to grasp the essence of human existence? What if the concept of eternity is illusory? How then do we make sense of human existence? These are just a handful of the questions that Santhosh Mathew asks his readers to contemplate. These are not easy questions to answer, and when reading his book, it becomes clear that the answers to these questions are not likely to be found in many of the places where humans have typically searched for truth or have tried to garner deeper understanding. To further complicate our arrival at the truth, the noise and abundance of data that contemporary society drops on our lives diverts our ability to contemplate and understand our existence, and the world around us, with great clarity. Within Mathew's book, equations are the antidote that is suggested for the forces that stymy our understanding.

The questions posed above can be unsettling; however, Mathew acknowledges and welcomes the astonishment that accompanies the enduring quest among humans to find meaning.

As Mathew points out, humans strive to construct order from chaos in their lives through borders, systems, and tangible structures, yet all of these human ecosystems are fleeting since humans, themselves, are transient. This book, in focusing on the timeless qualities of equations, conveys both the joy of discovery and the possibilities that arise when one honors questions over answers, process over outcomes, and journeys over conclusions.

In order to thoughtfully explore such enduring questions, and to unravel select truths, Mathew suggests the importance of equations and shows readers that, due to their continual lifespans, equations offer us a link from the past to the present and into the future. Within his narrative, Mathew refers to equations as elegant, "timeless and spaceless" and can be, in the right hands, and contemplated through the right minds, a "beautiful painting hiding a message." These descriptions present equations as invitations to connect moments of our history and discern the elements that underlie our existence. Through equations, we find not only a welcoming invitation but also deeply embedded meaning that has been formed and reformed throughout history, but not always well understood, and, at times, highly misunderstood.

While the book is structured to enlighten readers on ten questions, the prevailing themes are far from linear. Mathew weaves the present with the past; science with philosophy; and the spiritual teachings of religion with the discoveries of science. To further synthesize his themes, Mathew draws upon a wide range of writers, philosophers, scientists, and sources, including Herman Hesse, Carl Sagan, Franz Kafka, Stephen Hawking, Fritjof Capra, and the Bhagavad Gita.

Mathew takes a deep dive into each of the ten equations and illuminates how all of them hold basic truths. He artfully draws our attention to how equations connect to human behavior in the past, such as cave drawings by early man, to today's newscasts that construct narratives from disparate sources and define and redefine our contemporary social worlds. Other equations within the book's chapters demonstrate how everyday concepts, such as, what goes up, must come down, are used to enlighten our understanding of our wider world, sometimes with validity, sometimes with incomplete understanding, and sometimes even leading to popular misnomers.

At the heart of Mathew's book is the concept of entropy, derived from the Greek word *entrope*, meaning to turn toward or transform. While humans crave certainty, and often seek stability and absolute truths, Mathew shows his readers that far more can be learned through disorder, decay and chaos. Through entropy, a more nuanced truth and higher meaning emerge than could ever be realized through an existence predicated on certainty. Rather, through the lens that Mathew uses, probability offers far more potential than determinism. In many ways, Mathew's book invites its readers to become blissfully lost in novel findings, unexpected directions, and conclusions that guide explorers to a boundless array of unimagined pathways.

While Mathew presents equations as gateways to human understanding, the book illustrates that, throughout history, many humans have sought absolute truth, and even a sense of justice, through philosophical and spiritual texts. While Mathew does not dismiss the quest to understand life through a wide range of sources, this book shows how these sources simply illuminate and act as metaphors for the discoveries of science rather than supplanting science or serving in any way as equivalents.

Mathew's central message is that science is a journey rather than a destination. While humans may look at other sources and crave singular explanations, or wish to place their trust in ancient texts, it becomes clear that these sources have limitations, at their best, and misguided notions at their worst, especially when used to support nationalism or other aggressive agendas. Mathew's book shows that human existence is dependent on continual discovery that only deepens and expands over time. Through this view, some of the worst enemies of the human race may very well be premature conclusions and easily arrived upon destinations since they may stifle the human quest for meaning. In essence, at the core of this book is the alluring and insatiable notion of curiosity. Through this lens, nothing is settled; therefore, everything remains possible.

Debra Leahy, Ed.D.
Chief Academic Officer, Boston, MA.

Preface

We all know transience is a part of life, but it is not just part of our life. Everything is transient, from the fundamental particles that make up every living thing to the ever-expanding universe—on a different time scale, though. We latch on to many things and ideas and assume they will remain forever, but eternity, whether on Earth or in heaven as some would like to believe, in a broader sense, is an illusion.

In his final novel, *The Glass Bead Game* for which he won the Nobel Prize for Literature in 1946, Hermann Hesse wrote:

> No permanence is ours; we are a wave
> That flows to fit whatever form it finds:
> Through night or day, cathedral or the cave
> We pass forever, craving form that binds.

The inspiration to present this work emerged from our transient human nature and the universe we inhabit. At the same time, we have a deep desire to discover the laws governing everything around us, which I consider eternal. Our ancestors gazed in wonder at the world around them, just as we do today. They thought of the big questions, as we do even now. How did the universe begin? What is it made of? Where do human beings fit in this great cosmic scheme? Finally, is there a meaning to it all?

The meek and the powerful lived on this planet; so did the rich and the poor. Kings and emperors ruled the Earth, but they have all vanished and become part of the grand universe. What did they leave behind? We know that mighty structures can crumble without a trace, that species can become extinct and even their fossils may not be found in the long run, and in the far future, our planet may be gone. So, what will remain after we disappear? Definitely not any of the material objects we have created. Today's strongest structures can become fundamental particles of nature in the far future. We call this process natural decay. Yet, we can preserve something: the secrets we have unveiled about nature using our most rational tool called science. The most elegant way we can keep this information is in the form of equations.

The equations represent our intellectual ability to explore and find the irrefutable laws of nature and our insatiable curiosity to know more. We discover universal laws from patterns of nature we observe or data we collect, and this, in my view, is the greatest achievement of humankind. This human talent supersedes any other accomplishments, and so these equations represent an eternal state—they are timeless and spaceless.

No doubt humans will leave a lasting impression on the Earth's surface, or we may terraform other planets. We will play with mass and energy and create one form or the other, or we will travel to other parts of our galaxy on light sails. We may edit the genome to design a perfect species or send radio waves millions of light-years away, but none of these will stand the ultimate test of time. Nature will be able to wipe out all signs of human existence on Earth or any other place we occupy.

As humans, we embrace specific beliefs and often imprison ourselves within the culture that we create and are proud of. We create borders and language, all with the hope of having some control over our surrounding world, and then we realize the inevitable futility of those controls. We need something in which to trust permanently, and we call it eternal. It is unimaginable for us to spend our lives in a random universe without any specific purpose and to leave things beyond our control. That will bring only despair.

I believe equations are the only way to know the universe even if we are not close to presenting a definite answer to many perplexing questions. The equations are not mere symbols with abstract meaning; rather they are like beautiful pieces of artwork that capture the essence of nature. Like a beautiful painting hiding a message, the equations unveil the mysteries of our nature and the process of knowing. That is the most wonderful experience! These equations represent absolute laws of nature, and they do not provide us with many choices. We must simply obey.

Despite all the fascination surrounding these equations, I must caution you that nature and the laws of nature are not fine-tuned for humans. We are a transient species that happened to find ourselves here on this tiny planet about a quarter million years ago. As Carl Sagan noted, "The universe is not required to be in perfect harmony with human ambition." Yet, our voyage continues.

In the coming chapters, you will see ten equations that will outlast even the most enduring signs of our civilization.

These equations have changed the way we live and view the world and will continue to do so. They have the potential to take us from planet to planet and perhaps to make us a cosmic species or to destroy the last strand of DNA. I hope that you enjoy the experience of knowing these ten equations closely (some are well known mathematically) and that you develop an appreciation for them. They are intangible but can create a tangible world; nevertheless, they remain truly eternal.

Acknowledgements

Throughout the process of writing this book, I received help from quite a number of people. This work could not have been accomplished without the help of these individuals. A great debt of gratitude is due to everyone who supported me during the course of this work.

My deepest gratitude and thanks to Jeffrey Young, editor, Universal Publishers/BrownWalker Press, who relentlessly encouraged me to complete this project. He oversaw every aspect of the publication of this work, which in fact began the day I sent out the book proposal. The prompt responses to all my queries and the valuable advice I received from him enabled me to keep to the schedule.

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I would like to thank my wife, Sumy, and son, Nathan, who have given me encouragement and support over the years. Furthermore, I wish to express my gratitude to my parents and siblings who have always supported and encouraged me in this endeavor.

Finally, I want to thank all those who provided support, talked things over, read, wrote, offered comments, and assisted in the editing, proofreading, and design of this book.

Santhosh Mathew

Introduction: the origin of equations

It has been said that humans, and all that comes of humans, fades, and so do any living things that spring from them. Nevertheless, if there were something that defied this rule, it would be those equations that humans invented and that serve as a tremendous resource to comprehend and appreciate the complex universe in which we live. Moreover, those equations have the potential to create a new world, maintain our own world, or destroy the world. They are visible everywhere—from battlefields to graveyards, from the heart of a flower to the core of a galaxy. We, the transient humans, continue to search for these eternal equations, and they provide a timeless experience in this ever-changing universe. There is no time and space in the world of equations as they transcend even the boundaries set by human imagination. Moreover, they inspire us to embark on a journey to comprehend the magnificent universe and its workings.

This book introduces ten equations that unravel the mysteries of our universe, and I hope it will take readers on a journey of self-discovery where they will learn history, science, and the significance of these equations in their lives in addition to the mathematical beauty of these equations.

What is so remarkable about equations? They have a universal beauty attached to them that transcends earthly borders. Moreover, they do not have an aspect that we associate with other things, (e.g., cultures, geographic locations, or nationalities). The equations are truly universal. It is no wonder Galileo said, "Mathematics is the language in which God has written the universe." Needless to say, it is quite natural to use mathematics to express the laws of nature in an elegant way.

Look at any product or social construct we deal with. All carry baggage associated with nationality and often relish those attachments, but the equations transcend those man-made systems. Using pictures and symbols, the ancient Babylonians and Greeks tried to explain relationships between different things. These bits and pieces set the stage for equations to appear in the human world. Essentially, the idea behind equations was the desire to connect seemingly different things with a common thread. Later on, these threads were woven into the fabric of the modern world that we live in—from electricity to the internet, from atoms to artificial intelligence, from cannonballs to rockets, and the list goes on.

This idea of interconnectedness and exploration is so fundamental to human existence that it is unlikely to vanish from the human psyche. In fact, today's world of networked systems exhibits another example of this deep-rooted desire to be connected. Long before any modern systems were even imagined, our ancestors displayed the same intention as we do now.

The equations come in myriad forms and are packed with symbols and notations that seem abstract, but they enrich our daily lives in various ways as you will see in the coming chapters that introduce ten different equations, which are also tied to various astrophysical phenomena. I have to admit that, even when some of these equations seem quite familiar, we do not fully understand their depth, although we use them in various forms—a humbling reason why we should continue to learn more about equations that connect everything in our universe.

The current form of equations, identified by the equals sign (=), appeared for the first time in the sixteenth century. That symbol, now universally accepted by mathematics as the symbol for equality, was first recorded by Welsh mathematician Robert Recorde in *The Whetstone of Witte* in 1557. In his book, Recorde explained his design of the "Gemowe lines" (meaning *twin* lines, from the Latin *gemellus*). The first-ever equation with the now common equals sign, 14x+15=71 in modern terms, was mentioned in his book. With the publication of this book, Recorde is credited with introducing algebra with a systematic notation to England.

The equations are not merely symbols and variables, as they seem to be. In fact, they combine everything we know about our universe and provide a deeper understanding about our natural world. They are the ultimate manifestation of human ingenuity rooted in the laws of nature. In light of new evidence, we will abandon old ideas and theories and humans will depart the Earth, but the equations will remain eternal.

CHAPTER 1

The equation that gave us a digital life

No theory of physics that deals only with physics will ever explain physics.

—John Wheeler, The Intellectual Digest (1973)

Abstract

On a fundamental level, what is our universe made of? Space, time, matter, and energy—those are all familiar explanations. However, some physicists propose that information is the fundamental ingredient of our universe, not force fields or space-time as generally accepted now. Therefore, if information is so fundamental and essential to this universe, the equation that launched the information revolution must be considered, not only in communications, but also in the fundamental understanding of this universe. The idea of the holographic principle makes more sense if we can link it to information theory. This chapter explores the significance of the Shannon

equation in the context of the holographic principle, a radical idea in modern astrophysics.

The idea that the information exchange among physical processes could be the foundation of this universe, though it sounds strange, is not very hard to understand. Imagine a computer, which is essentially an information-processing machine. However, without the software to run it, it is merely pieces of metal and glass. Alternatively, think about the actions that should happen in our body cells. We cannot even picture them without the information from DNA. So, we could say with a greater degree of confidence that, in the absence of information, objects are not what they seem to us. It is such simple logic.

Similarly, the universe that we live in and observe could be considered as a huge system operating with information as the underpinning factor. Proponents of the holographic principle say that we should explore this aspect to know the fundamental truth. Some theorists argue that to marry quantum mechanics with gravity requires this radical approach that put information at the core of this universe and that information is much more significant than space-time or matter and energy.

Generally, physics describes the fabric of our universe as space-time where the interplay between matter and energy embodies everything in this universe. In addition, the general theory of relativity says that, at its most basic level, this fabric should be smooth and continuous. Yet, if we examine the fabric of space-time on a fundamental level, it is not continuous, as we might imagine, but simply grainy. These grains act like dots in an image providing us with the vision of a three-dimensional universe. This idea led to the so-called holographic principle proposed by Nobel-Prize-winning Dutch theoretical physicist Gerard ’t Hooft (1993). The evidence to support this

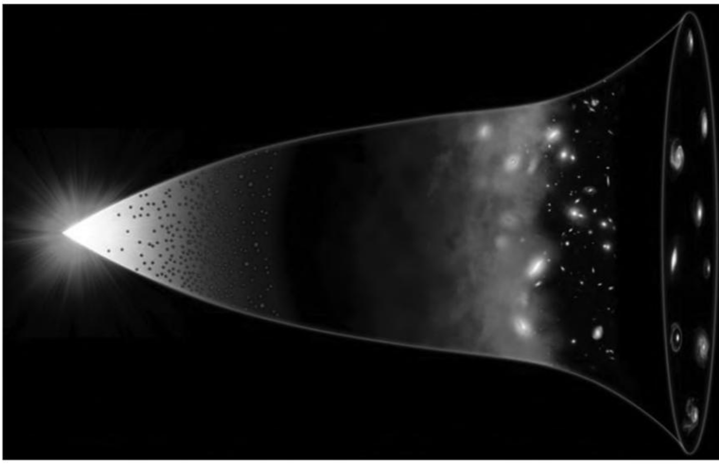

Fig. 1.1. *The universe is shaped like a giant bell lying on its side. The bell was struck nearly 14 billion years ago and emerged in oscillating waves from the singularity. Is our universe simply made of information? Image courtesy of the Perimeter Institute, Waterloo, Ontario, Canada.*

principle came from the irregularities in the cosmic microwave background, popularly known as the afterglow of the Big Bang. According to the holographic principle, our world is simply an image of the information stored on a two-dimensional projection similar to a holographic image (Fig. 1.1). The holographic principle tells us that when we look at this two-dimensional projection the right way, it gives us the view of a three-dimensional universe. In simple terms, our 3D world is a mere gift from the underlying information. Although not every physicist buys into this argument, it received considerable attention from the physics community.

In the 1980s, even before this holographic picture of our universe was presented by researchers, the legendary physicist, John Wheeler, hinted at the significance of information in understanding our cosmos. He described his evolution in physics as falling into three periods, thereby signaling the deep connection between quantum mechanics and information theory. "I think of my lifetime in physics as divided into three periods. In the first period… I was in the grip of the idea that Everything Is Particles… I call my second period Everything Is Fields… Now I am in the grip of a new vision, that Everything Is Information," that is, "It from Bit" (Wheeler, 1990).

Does this mean the fundamental reality is information? Not necessarily, and many scientists totally disagree. However, we need to recognize the fact that the descriptions of reality and information influence each other, and both are needed to account for and to paint the whole picture of our cosmos. To support his idea, Wheeler argued that an electron behaves like a particle or a wave depending on how we probe it. Information theory, similarly, postulates that all messages can be reduced to a sequence of "binary units," or bits, which are answers to yes or no questions. Essentially, Wheeler, in his 1989 essay, took the position that anything physical (it) derives its existence from information (bit) popularized by the phrase "It from Bit." So, if information is the root cause of the existence of physical objects, we can postulate theories that describe the universe in the language of information theory.

What is information theory?

In June 2016, the United Nations Human Rights Council passed a resolution making internet access a basic human right very much like the right to safe drinking water, sanitation, shelter, and basic services. The information interchange, like transportation, is so essential to the modern world that nations would be paralyzed and would collapse in the absence of the internet.

This relatively new phenomenon, a global network or internet that unfolded before our eyes, is essentially an exchange of information. It was not long ago, as many remember, that snail mail was the primary communication mode, and telegraph and telephone were not accessible to most people in the world. It has been estimated that currently more than four billion people use the internet worldwide (World Internet Users Statistics and 2018 World Population Stats, n.d.). For Generation Alpha, it would be practically impossible to imagine a time without the internet, just as it would be impossible for the previous generation to imagine a time without electric lights.

So, what caused this revolution right in front of our eyes? When did this new information age begin? Surprisingly, it is Claude Shannon's equation that really changed the way in which information, or bits, was effectively transmitted across the various systems. In fact, Shannon was addressing the fundamental problem of communication that involves the mechanism to reproduce a message exactly, or approximately, at one point that was selected at another point.

This equation was first published by Shannon as "A Mathematical Theory of Communication" in the July 1948 issue of *The Bell System Technical Journal*. In this fundamental work, he used the tools of probability theory and developed information entropy as a measure for the uncertainty in a message.

$$H = -\sum p(x) \log p(x)$$

H – Shannon entropy or information entropy
p – probability

The entropy of a message is related to the sum of the logarithm of the probabilities of each bit taking on a particular value. The

Shannon entropy equation provides a way to estimate the average minimum number of bits needed to encode a string of symbols, based on the frequency of the symbols. The physical meaning of information entropy is the absolute minimum number of storage "bits" needed to capture the information. Although Boltzmann (more about Boltzmann's equation in chapter 5) was the first person to formulate the logarithmic function to connect the average uncertainty with the probability of random variable, Shannon

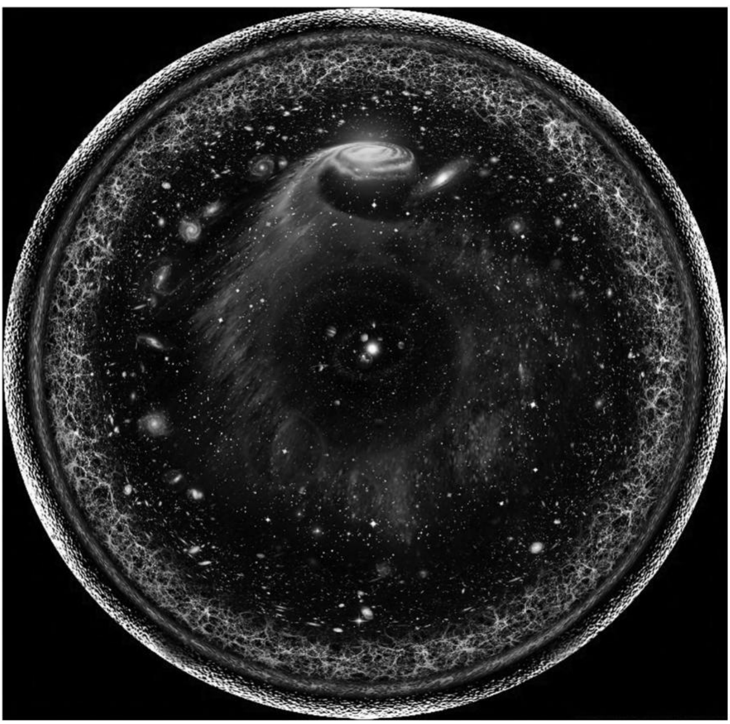

Fig. 1.2. *Artist's logarithmic scale conception of the observable universe with the solar system at the center. Can we create a universe out of information? Image courtesy of Pablo Carlos Budassi, Wikimedia Commons.*

extended this result to the communication scenario to propose two theorems—source-coding theorem and channel-coding theorem—that are the basis of modern communication technology.

We know that the earliest form of human communication was drawing pictures or creating patterns using available resources. From that, primitive stage humans evolved to encode information using zeros and ones. Now, here is an equation that tells you information is "additive"—that is, that the total information contained in two, three, four, or a billion unrelated events is equal to the sum of the information in each one (Becker, 2015). So, theoretically, if we have the means to do so, we can record all information about this universe in bits and possibly reconstruct it (Fig. 1.2). However, practically, finite resources and restrictions imposed by the laws of physics prohibit us from doing so. Therefore, we won't be able to create a cosmic computer now to run the actions of this universe, yet some real-world experiences inspire us to capture the meaning of it from bit as discussed below.

Can bit generate it?

Normally, it's hard to conceive how bit (information) alone can generate it (physical stuff) as the legendary physicist John Archibald Wheeler summarized in his 1989 essay with the catchphrase, "it from bit." However, when I think back to my childhood experiences, long before I came to know information theory or the holographic principle, one of those experiences makes much more sense in light of the phrase "it from bit."

Throughout my early school years, in a south Indian village, I remember spending a great deal of time outside the walls of my home interacting with the natural environment—obviously

I didn't have many choices. In those days, my native village had the look of a flatland that displayed a romance of many dimensions. A huge rock, seemingly indistinguishable from an asteroid belt object, occupied the heart of the village, and I always thought this stone had been transplanted from the remote corners of the solar system by some astronomical process. Every object and every piece of information was conserved in the village by the laws of nature. People believed there were no absolute realities but only descriptions of realities that existed without any knowledge of quantum mechanics or even any philosophical views that I was aware of.

The elegant movement and perfect rhythmic life cycle of people and animals obviated the need for mechanical timepieces; though a couple of villagers displayed watches on their wrists, but they never looked at them. The relative nature of time and space was fully comprehended by everyone. The village maintained a constant ratio of births and deaths, and everyone knew everything about others. Complete transparency was achieved without electronic data or documents. Sex was a taboo, yet it was performed only to maintain the population and, understandably, never discussed even between partners.

Information came to the village in the form of a local newspaper printed in a faraway town and delivered by bikes that followed rudimentary Newtonian mechanics. The other information system involved radio waves that reached the village intermittently as the countryside hills surrounding the village offered a barrier for the electromagnetic waves. Paradoxes were plentiful in the village, for example, laws were followed without laws. And when Yama (the God of death in Hindu mythology) came as a cosmic equalizer, the village people acknowledged his visit by either ringing church bells loudly, but in simple harmonic motion, or by diffusing smells of Pooja[1] materials from their homes. Unaware of any of these rituals, Yama visited the village, taking away people and animals on a regular basis. No one complained as the acts were in compliance with the cosmic law.

In 1979, the news of Skylab's apparent fall reached the village. For the next two months, the social and religious events in the village were filled with narratives of the potential destruction that could be wrought by the falling space station. The Hindu temple performed Pooja and quoted relevant texts from Ramayana and Mahabharata (ancient Hindu texts) describing how their gods and the evil-spirited asuras (demons) had floated such objects in the past. The pastor invoked biblical quotes and warned this was a punishment from God for humans venturing into stars and skies, yet he was a bit soft on the United States that owned and operated Skylab. The few leftists in the village were apparently overjoyed by the fact that an American imperialist machine was coming down and used the occasion to celebrate the bright future of the Soviet Union.

As a ten-year-old boy, my curiosity regarding Skylab was more powerful than the death it could bring. So, every night I looked at the sky with fear in my heart, but my inquisitiveness destroyed the fear. Everyone owned a subjective description of Skylab, including me, and really wanted to see the amazing machine that was falling from the sky.

A few days later, on July 11, 1979, a churchgoer brought the fall of Skylab to the attention of the collective social psyche of the village. The newspapers had not been delivered and radios had not been working for several days, creating a perfect opportunity for everyone to chime in. The Christian

[1]Ritual performed by Hindus as part of worship.

devotee described seeing the night sky littered with heavenly lights and the machine falling through the sky like a star as described in the Bible. He even claimed to have seen biblical verses from the Book of Revelations inscribed on the fireball. According to the Hindu priest's account, Skylab resembled the chariot of Arjuna piloted by Lord Krishna (a scene that looked a lot like the epic battle of Mahabharata) crushing everything on its path. These narrations were widely accepted and, by now, everyone had created an image of Skylab in his or her mind.

The following weekend my elder brother brought home some magazines from his college town, and I curiously scanned the pages. One page had a fussy picture of Skylab as it fell into part of the southeastern Indian Ocean near western Australia, about 3,000 miles away from our village. In fact, no one in the village was able to see Skylab or its apparent fall as described above, yet everyone saw it.

After several years, I realized that Newtonian physics was sufficient to explain the fall of Skylab. Yet, I wasn't sure how or why everyone had created the image of an object (it) from whatever information (bit) he or she had. When I read Wheeler's essay that explained it from bit, it made perfect sense, and I understood why everyone had seen Skylab. This radical notion is even more relevant in the contemporary era where narrative (bit) construction of reality (it) is a norm. Furthermore, I am absolutely convinced it is the same explanation I need in our contemporary political age where narratives create facts and alternate facts. Once again, it from bit.

So, if we live in an information universe and Shannon's equation provides the most effective way to transmit information, we can imagine an eternal state in which all information is recorded in bits and stored or transmitted, though in a purely theoretical sense. For now, entertaining such a thought would be a pure imagination of mind, yet I feel we must explore the power of this equation to gain some sort of eternal existence. Paradoxically, this equation rests among the dead as my journey to Mount Auburn Cemetery (Massachusetts) revealed.

The equation for eternity rests among the dead

If you mention that you are visiting a cemetery, folks will show their sympathy by asking caring questions about your lost loved ones. However, if you want to know how to achieve eternity by encoding all your information onto digital bits, you should begin by looking at an equation that rests among the dead.

In the Mount Auburn Cemetery (Massachusetts), among the gravestones of many revered men, lies the unique grave of Claude Elwood Shannon. The back of the tombstone displays Shannon's entropy formula (Figs. 1.3 and 1.4) that launched the digital information age in the 1950s. All the information that pops up in a single Google search, or compressing huge files to a few binary digits, is digitally possible because of Shannon's equation. The equation provided a way to transmit information in the form of bits as we do now. As scientists engage in finding ways to satisfy the demand to "live forever" by exploring possibilities in cryogenics or biotechnology, the future will most likely require us to find a solution for eternal existence in digital clouds. If so, Shannon's entropy equation will be the key—whether information is stored in bits or qubits.

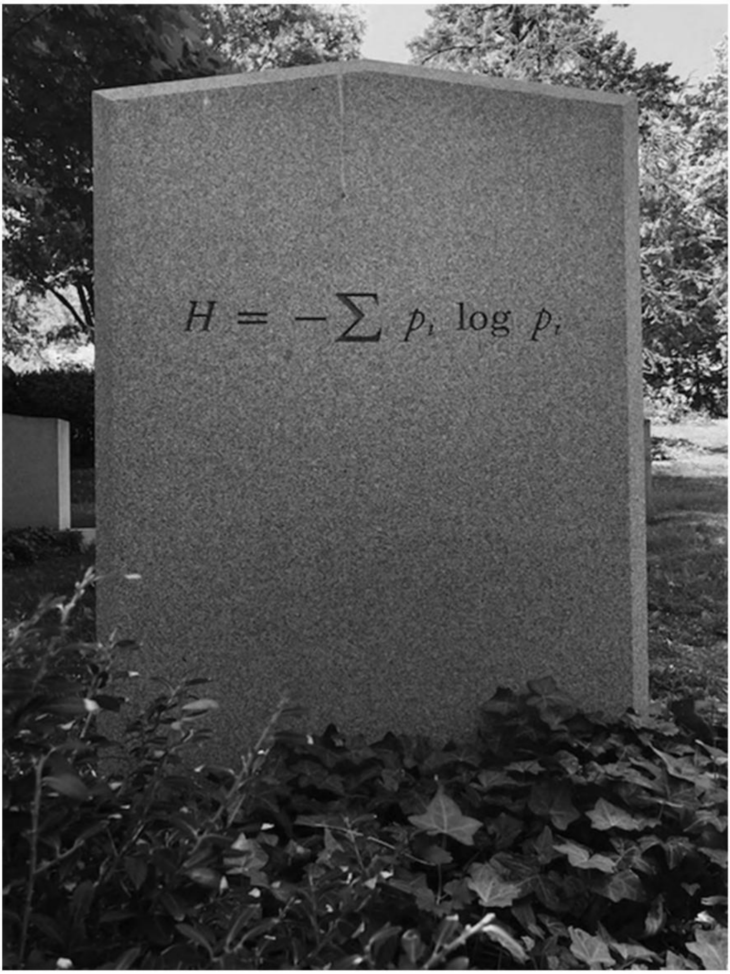

Fig. 1.3. *Shannon's entropy equation etched on his gravestone in Mount Auburn Cemetry, MA. Photo courtesy of the author.*

The Shannon equation, as discussed earlier in "What is information theory?", conveys one of the most powerful messages that physicists are exploring (i.e., that information is the fundamental building block of the universe, not space and time or matter and energy as we believe). This whole idea that everything is made up of

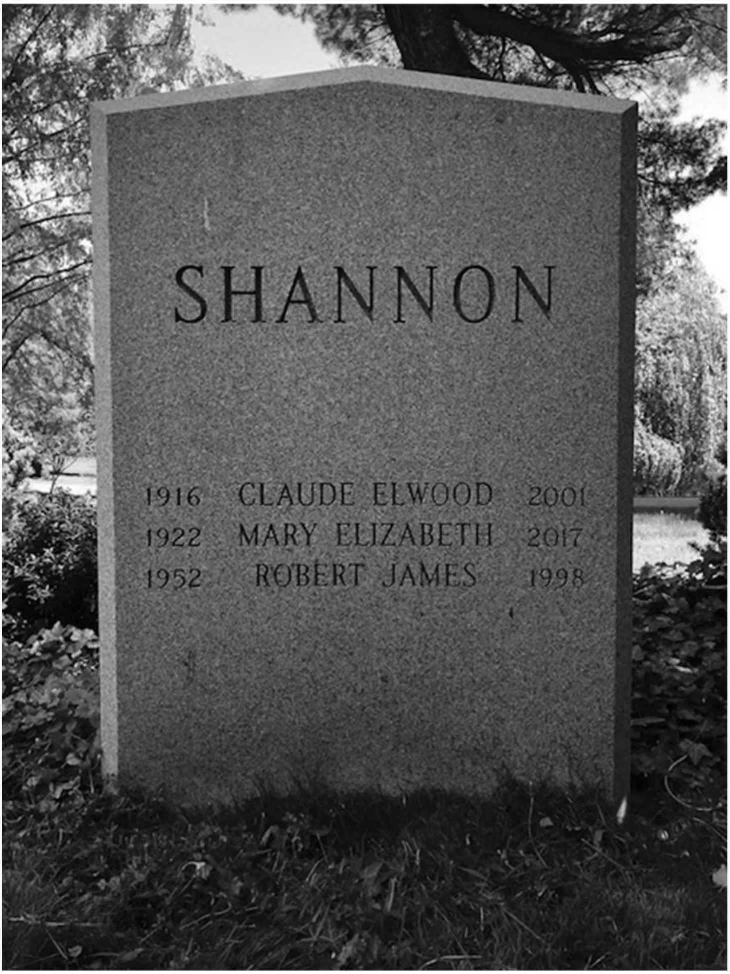

Fig. 1.4. *Shannon's gravestone in Mount Auburn Cemetery, Middlesex County, Massachusetts. Photo courtesy of the author.*

information even prompted some philosophers (Bostrom, 2003) to propose the idea that we almost certainly are living in a computer simulation. It follows that there is a significant chance that we will one day become post-humans who run ancestor-simulations. However, this is false unless we currently are living in a simulation.

The simulation argument has generated deeper debates among physicists and philosophers. If such notions were to be entertained, Shannon's formula would offer a solution to overcome human mortality that would enable us to generate and transmit every bit of information that makes us. Perhaps the same equation that created the digital information highway would help us to accomplish that goal in the future. In other words, eternity would be in digital form, not biological, as we tend to think. If information were the root cause of origin (universe and everything else that followed), then one could argue that the solution for eternal existence would be the same.

Finally, Fermat's principle, or the principle of least time, named after French mathematician Pierre de Fermat, says that the path taken between two points by a ray of light is the path that can be traversed in the least time. Some physicists extend this argument to support the holographic principle as they speculate it's a manifestation of the economical character of nature. So, the information theory, especially Shannon's equation, provides a way to describe the universe with a minimum amount of information (Correa-Borbonet, 2004).

Regrettably, we still struggle with these theories and so do the scientists. Unfortunately, we have a long time to wait for eternity. Perhaps our notion of eternity as the permanent state of existence may need to be rewritten. Eternity, according to Hermann Hesse, is a mere moment, just long enough for a joke. Either way, our quest for eternity may not be realized any time soon, but Shannon's equation remains eternal.

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CHAPTER 2

The equation that predicted ghost particles

I have done a terrible thing: I have postulated a particle
that cannot be detected.
—*Wolfgang Pauli as quoted in Physics and Beyond (1971)*

Abstract

Neutrinos are the second most abundant particles in the universe, after photons. They are often called ghost particles since they barely interact with anything. During the 1920s, scientists came to the conclusion that matter was built of only two kinds of elementary particles:, electrons and protons. Later on, neutrons were added to the list. Yet, scientists realized something was missing in the process of β-decay. In 1933, Enrico Fermi formulated his β-decay model by introducing Wolfgang Pauli's invisible particles named neutrinos. The discovery of neutrinos in 1956 inaugurated a new phase in astronomy and physics, and these particles continue to mesmerize us. Some researchers think neutrinos could answer the questions of existence, for example, "How is existence possible?"

Why are ghost particles so cool?

The world is quite familiar with the God particle (Higgs boson), the long-sought particle that was discovered in 2012. Although the existence of Higgs bosons was hypothesized in 1964, they became part of popular culture in 1993 when the physicist Leon Lederman coined the term "the God particle" in his popular science book, *The God particle: If the universe is the answer, what is the question?* Higgs Bosons were considered an important missing piece of the standard model that physicists use to describe elementary particles and their interactions. It provided an answer to a fundamental question: why objects in our universe have mass. That explains why galaxies, stars, planets, and any material objects have the form they hold. However, well before the God particle came into picture, the existence of neutrinos, popularly known as ghost particles, was revealed, and the equation that led to the prediction and eventual discovery of these particles is surprisingly simple.

While the God particle provides an explanation for *why anything has mass*, the ghost particles can potentially explain *why anything exists*. In 1930, physicist Wolfgang Pauli first predicted the neutrino in order to account for the apparent loss of energy and momentum that he observed when studying radioactive beta decays. However, Pauli himself was not confident about the detection of the particles as they were more elusive than any other known particles had been, and that made even Pauli skeptical about the existence of such a particle.

In fact, the existence of neutrinos was proposed as a solution to save one of the most fundamental laws in physics, the law of conservation of momentum and, specifically, the law of conservation of angular momentum associated with spinning objects. According to this law, the total momentum of the interacting particles before and after a reaction should remain the same. Consider the following equation formulated by Enrico Fermi to explain β-decay in which a neutron decays into a proton, an electron, and an electron antineutrino:

$$n \rightarrow p + e^{-} + \nu$$

n – neutron
p – proton
e – electron
ν – antineutrino

The law of momentum conservation requires the neutrino to be present as a particle in the above equation. In the absence of a neutrino, the total momentum before and after the decay of the neutron as shown in the equation would be different. This would lead to the violation of the law of conservation of momentum, something that is impossible for physicists to cope with (along with the law of conservation of energy). Thus, the existence of Pauli's "invisible" particle was accepted, and the name neutrino (small neutron) was coined by Enrico Fermi.

Protons and neutrons consist of fundamental particles called quarks. In the beta decay process, a neutron (made of one up quark and two down quarks) can transform into a proton (made of two up quarks and one down quark). This reaction can happen in a neutron within an atom or a free-floating neutron.

$$\underset{(udd)}{n} \longrightarrow \underset{(udu)}{p} + e + \bar{\nu}e$$

When a neutron turns into a proton, a down quark within the neutron transforms into an up quark, changing the neutron into a proton (and changing the atomic element as a result). The momentum and energy of particles must be conserved in the process and, to account for that, an electron and an electron antineutrino must be released in the process.

Neutrinos come from a variety of sources, making them the second most abundant particles (just behind photons, the particles of light). They are produced during the birth, collision, and death of stars, particularly the explosions of supernovae, and they carry invaluable information about these sources. It has been assumed that the neutrinos that originated in the early universe are still travelling and passing through all material objects without any interaction. In our Sun, neutrinos are created and pass through our planet and other materials, including the human body. The following diagrams show (Figs. 2.1 and 2.2) the proton-proton fusion reaction in the Sun and the resulting production of neutrinos.

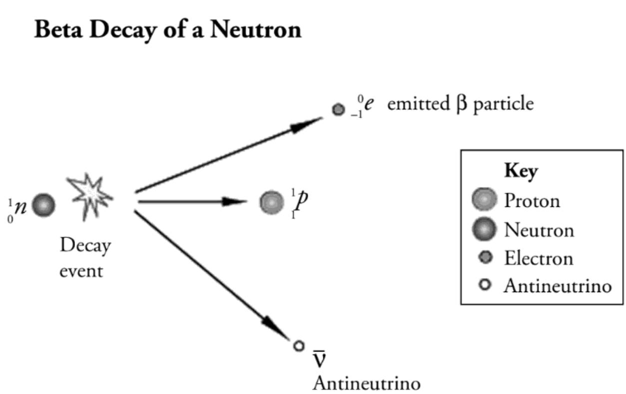

Fig. 2.1. *A neutron decays into a proton, electron, and an antineutrino.*

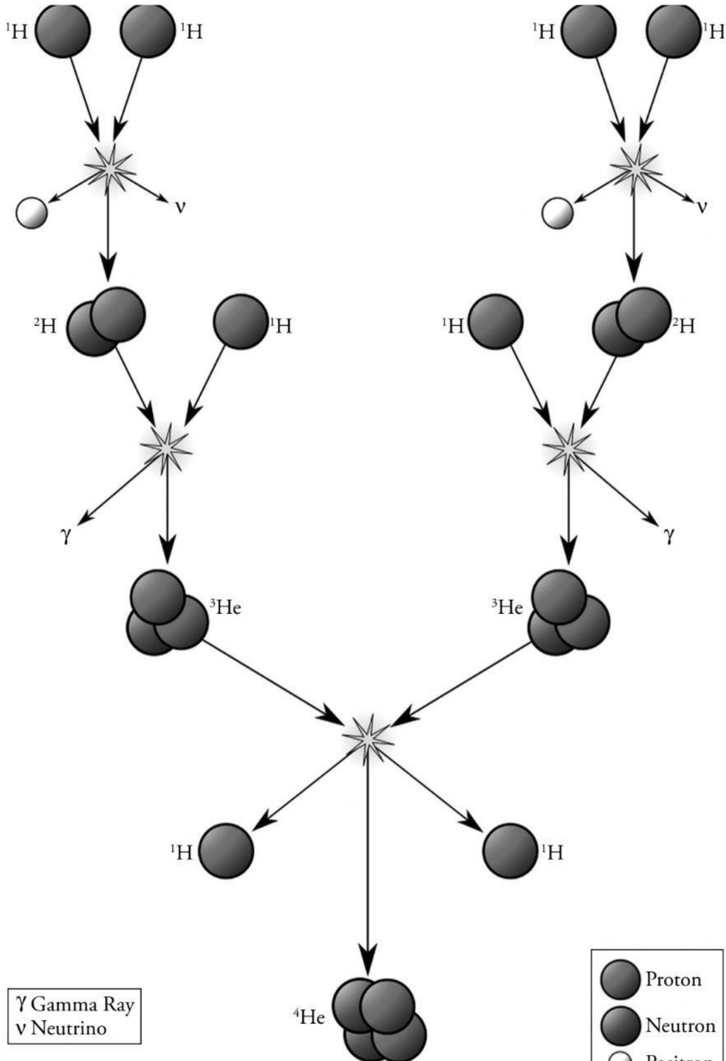

Fig. 2.2. *The proton-proton chain in the Sun. Note the production of neutrinos. Image courtesy of Wikimedia Commons.*

As the nickname ghost particle indicates, neutrinos are notoriously hard to detect as they interact very rarely with other particles, yet they pass through matter without much interaction. However, in 1956, Clyde Cowan and Frederick Reines discovered neutrinos and were awarded the Nobel Prize for their discovery in 1995. They used a nuclear reactor to produce neutrinos and detected them using photomultiplier tubes. Their experiments to detect the elusive neutrinos were originally conducted in Hanford, Washington, but they later moved the experiments to the Savannah River Plant near Augusta, Georgia where they had better shielding against cosmic rays. This shielded location was 11 m from the reactor and 12 m underground. Their discovery heralded a new era in physics, neutrino physics, that would eventually open a new field in exploring the universe. The unique ability of neutrinos to travel astronomical distances between their source origin and Earth made them ideal particles with which to learn about the unknown universe.

Cowan and Reines demonstrated that neutrino production occurred in nuclear reactors, which led to their first discovery: When particles transform into different particles, neutrinos are created in the process. Scientists identify neutrinos by detecting the fundamental particles they are associated with. There are three different types of neutrinos (electron, muon, and tau), each type relating to a charged particle as shown in the following Table 2.1.

Table 2.1. *There are three neutrino flavors (the electron neutrino, muon neutrino, and tau neutrino), which are related to the three charged particles (the electron, muon and tau). There could be additional flavors of neutrinos, but researchers are not sure about their existence.*

Neutrino	ν_e	ν_μ	ν_τ
Charged Partner	electron (e)	muon (μ)	tau (τ)

It is ironic that we don't know much about neutrinos, yet they are the second most abundant particle in the universe; they are everywhere. As mentioned earlier, their mystery is compounded by the fact that they appear in three types, or flavors, and shift among these flavors—electron, muon, and tau. As they travel, an electron neutrino can change into a muon neutrino or tau neutrino. Researchers believe that the study of neutrinos holds the key to knowing more about mysterious astrophysics sources, such as gamma-ray bursts, supernova explosions, and cataclysmic phenomena involving black holes and neutron stars. Recently, scientists have added another layer to the mystery surrounding these particles as they debate the idea of a fourth type of neutrino. Sterile neutrinos could only interact gravitationally, and that might shed light on the questions regarding neutrino mass and the role they play in understanding the existence of dark matter in the universe.

Given their ability to travel across the universe carrying momentum and energy, these ghost particles are unique and can help researchers explore the unknown. However, these particles are much stranger than scientists initially thought. To understand that, we need to know a little about antiparticles. The idea of the antiparticle came about in 1928 when British physicist Paul Dirac developed what became known as the Dirac equation. In 1932, physicist Carl Anderson discovered the antimatter partner of the electron that Dirac had theorized earlier. This particle is called the positron—a particle like an electron but with a positive charge. Since these studies and the detection of antiparticles, it has been assumed that every particle has an antiparticle, although some have yet to be discovered. Here is the strange twist with neutrinos. In 1937, Italian physicist Ettore Majorana posited another theory: Neutrinos and antineutrinos