1

THE SIZE AND SCALE OF THE UNIVERSE

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We begin with the stars, then ascend up and away out to the galaxy, the universe, and beyond. What did Buzz Lightyear say in *Toy Story*? "To Infinity and Beyond!"

It's a big universe. I want to introduce you to the size and scale of the cosmos, which is bigger than you think. It's hotter than you think. It is denser than you think. It's more rarified than you think. Everything you think about the universe is less exotic than it actually is. Let's get some machinery together before we begin. I want to take you on a tour of numbers small and large, just so we can loosen up our vocabulary, loosen up our sense of the sizes of things in the universe. Let me just start out with the number 1. You've seen this number before. There are no zeros in it. If we wrote this in exponential notation, it is ten to the zero power, 10^0. The number 1 has no zeros to the right of that 1, as indicated by the zero exponent. Of course, 10 can be written as 10 to the first power, 10^1. Let's go to a thousand—10^3. What's the metric prefix for a thousand? *Kilo*- kilogram—a thousand grams; kilometer—a thousand meters. Let's go up another 3 zeros, to a million, 10^6, whose prefix is *mega*-. Maybe this is the highest they had learned how to count at the time they invented the megaphone; perhaps if they had known about a billion, by appending three more zeroes, giving 10^9, they would have called them "gigaphones." If you study file sizes on your computer, then you're familiar with these two words, "megabytes" and "gigabytes." A gigabyte is a billion bytes.[1] I'm not convinced you know how big a billion actually is. Let's look around the world and ask what kinds of things come in billions.

First, there are 7 billion people in the world.

Bill Gates? What's he up to? Last I checked, he's up to about 80 billion dollars. He's the patron saint of geeks; for the first time, geeks actually control the world. For most of human history that was not the case. Times have changed. Where have you seen 100 billion? Well, not quite 100 billion. McDonald's. "Over 99 Billion Served." That's the biggest number you ever see in the street. I remember when they started counting. My childhood McDonald's proudly displayed "Over 8 Billion Served." The McDonald's sign never displayed 100 billion, because they allocated only two numerical slots for their burger count, and so, they just stopped at 99 billion. Then they pulled a Carl Sagan on us all and now say, "billions and billions served."

Take 100 billion hamburgers, and lay them end to end. Start at New York City, and go west. Will you get to Chicago? Of course. Will you get to California? Yes, of course. Find some way to float them. This calculation works for the diameter of the bun (4 inches), because the burger itself is somewhat smaller than the bun. So for this calculation, it's all about the bun. Now float them across the ocean, along a great circle route, and you will cross the Pacific, pass Australia, Africa, and come back across the Atlantic Ocean, finally arriving back in New York City with your 100 billion hamburgers. That's a lot of hamburgers. But in fact you have some left over after you have circled the circumference of Earth. Do you know what you do with what you have left over? You make the trip all over again, 215 more times! Now you still have some left over. You're bored going around Earth, so what do you do? You stack them. So after you've gone around Earth 216 times, then you stack them. How high do you go? You'll go to the Moon, and back, with stacked hamburgers (each 2 inches tall) after you've already been around the world 216 times, and only then will you have used your 100 billion hamburgers. That's why cows are scared of McDonald's. By comparison, the Milky Way galaxy has about 300 billion stars. So McDonald's is gearing up for the cosmos.

When you are 31 years, 7 months, 9 hours, 4 minutes, and 20 seconds old, you've lived your billionth second. I celebrated with a bottle of champagne when I reached that age. It was a tiny bottle. You don't encounter a billion very often.

Let's keep going. What's the next one up? A trillion: 10^{12}. We have a metric prefix for that: *tera*-. You can't count to a trillion. Of course you could try. But if you counted one number every second, it would take you a thousand times

31 years—31,000 years, which is why I don't recommend doing this, even at home. A trillion seconds ago, cave dwellers—troglodytes—were drawing pictures on their living room walls.

At New York City's Rose Center of Earth and Space, we display a timeline spiral of the Universe that begins at the Big Bang and unfolds 13.8 billion years. Uncurled, it's the length of a football field. Every step you take spans 50 million years. You get to the end of the ramp, and you ask, where are we? Where is the history of our human species? The entire period of time, from a trillion seconds ago to today, from graffiti-prone cave dwellers until now, occupies only the thickness of a single strand of human hair, which we have mounted at the end of that timeline. You think we live long lives, you think civilizations last a long time, but not from the view of the cosmos itself.

What's next? 10^{15}. That's a quadrillion, with the metric prefix *peta-*. It's one of my favorite numbers. Between 1 and 10 quadrillion ants live on (and in) Earth, according to ant expert E. O. Wilson.

What's next? 10^{18}, a quintillion, with metric prefix *exa-*. That's the estimated number of grains of sand on 10 large beaches. The most famous beach in the world is Copacabana Beach in Rio de Janeiro. It is 4.2 kilometers long, and was 55 meters wide before they widened it to 140 meters by dumping 3.5 million cubic meters of sand on it. The median size of grains of sand on Copacabana Beach at sea level is 1/3 of a millimeter. That's 27 grains of sand per cubic millimeter, so 3.5 million cubic meters of that kind of sand is about 10^{17} grains of sand. That's most of the sand there today. So about 10 Copacabana beaches should have about 10^{18} grains of sand on them.

Up another factor of a thousand and we arrive at 10^{21}, a sextillion. We have ascended from kilometers to megaphones to McDonald's hamburgers to Cro-Magnon artists to ants to grains of sand on beaches until finally arriving here: 10 sextillion—

the number of stars in the observable universe.

There are people, who walk around every day, asserting that we are alone in this cosmos. They simply have no concept of large numbers, no concept of the size of the cosmos. Later, we'll learn more about what we mean by the *observable universe*, the part of the universe we can see.

While we're at it, let me jump beyond this. Let's take a number much larger than 1 sextillion—how about 10^{81}? As far as I know, this number has no name.

It's the number of atoms in the observable universe. Why then would you ever need a number bigger than that? What "on Earth" could you be counting? How about 10^{100}, a nice round-looking number. This is called a *googol*. Not to be confused with Google, the internet company that misspelled "googol" on purpose.

There are no objects to count in the observable universe to apply a googol to. It is just a fun number. We can write it as 10^{100}, or if you don't have superscripts, this works too: 10^100. But you can still use such big numbers for some situations: don't count *things*, but instead count the ways things can happen. For example, how many possible chess games can be played? A game can be declared a draw by either player after a triple repetition of a position, or when each has made 50 moves in a row without a pawn move or a capture, or when there are not enough pieces left to produce a checkmate. If we say that one of the two players must take advantage of this rule in every game where it comes up, then we can calculate the number of possible chess games. Rich Gott did this and found the answer was a number less than 10^(10^4.4). That's a lot bigger than a googol, which is 10^(10^2). You're not counting things, but you are counting possible ways to do something. In that way, numbers can get very large.

I have a number still bigger than this. If a googol is 1 followed by 100 zeros, then how about 10 to the googol power? That has a name too: a *googolplex*. It is 1, with a googol of zeroes after it. Can you even write out this number? Nope. Because it has a googol of zeroes, and a googol is larger than the number of atoms in the universe. So you're stuck writing it this way: 10^{googol}, or $10^{10\text{^}100}$ or 10^(10^100). If you were so motivated, I suppose you could attempt to write 10^{19} zeros, on every atom in the universe. But you surely have better things to do.

I'm not doing this just to waste your time. I've got a number that's bigger than a googolplex. Jacob Bekenstein invented a formula allowing us to estimate the maximum number of different quantum states that could have a mass and size comparable to our observable universe. Given the quantum fuzziness we observe, that would be the maximum number of distinct observable universes like ours. It's 10^(10^124), a number that has 10^{24} times as many zeros as a googolplex. These 10^(10^124) universes range from ones that are scary, filled with mostly black holes, to ones that are exactly like ours but where your nostril is missing one oxygen molecule and some space alien's nostril has one more.

So, in fact, we do have some uses for some very large numbers. I know of no utility for numbers larger than this one, but mathematicians surely do.

A theorem once contained the badass number 10^(10^(10^34)). It's called *Skewe's number*. Mathematicians derive pleasure from thinking far beyond physical realities.

Let me give you a sense of other extremes in the universe.

How about density? You intuitively know what density is, but let's think about density in the cosmos. First, explore the air around us. You're breathing 2.5×10^{19} molecules per cubic centimeter—78% nitrogen and 21% oxygen.

A density of 2.5×10^{19} molecules per cubic centimeter is likely higher than you thought. But let's look at our best laboratory vacuums. We do pretty well today, bringing the density down to about 100 molecules per cubic centimeter. How about interplanetary space? The solar wind at Earth's distance from the Sun has about 10 protons per cubic centimeter. When I talk about density here, I'm referencing the number of molecules, atoms, or free particles that compose the gas. How about interstellar space, between the stars? Its density fluctuates, depending on where you're hanging out, but regions in which the density falls to 1 atom per cubic centimeter are not uncommon. In intergalactic space, that number is going to be much less: 1 per cubic meter.

We can't get vacuums that empty in our best laboratories. There is an old saying, "Nature abhors a vacuum." The people who said that never left Earth's surface. In fact, Nature just *loves* a vacuum, because that's what most of the universe is. When they said "Nature," they were just referring to where we are now, at the base of this blanket of air we call our atmosphere, which does indeed rush in to fill empty spaces whenever it can.

Suppose I smash a piece of chalk against a blackboard and pick up a fragment. I've smashed that chalk into smithereens. Let's say a smithereen is about 1 millimeter across. Imagine that's a proton. Do you know what the simplest atom is? Hydrogen, as you might have suspected. Its nucleus contains one proton, and normal hydrogen has an electron occupying an orbital that surrounds it. How big would that hydrogen atom be? If the chalk smithereen is the proton, would the atom be as big as a beach ball? No, much bigger. It would be 100 meters across—about the size of a 30-story building. So what's going on here? Atoms are pretty empty. There are no particles between the nucleus and that lone electron, flying around in its first orbital, which, we learn from quantum mechanics, is spherically shaped around the nucleus. Let's go smaller and smaller and smaller, to get to another limit of the cosmos, represented by the measurement of things that are so tiny that we can't even measure them. We do not yet know what the diameter of the electron is. It is smaller than we are able to measure. However, superstring theory suggests that it may be a tiny vibrating string as small as 1.6×10^{-35} meters in length.

Atoms are about 10^{-10} (one ten-billionth) of a meter. But how about 10^{-12} or 10^{-13} meters? Known objects that size include uranium with only one electron, and an exotic form of hydrogen having one proton with a heavy cousin of the electron called a *muon* in orbit around it. About 1/200 the size of a common hydrogen atom, it has a half-life of only about 2.2 microseconds due to the spontaneous decay of its muon. Only when you get down to 10^{-14} or 10^{-15} meters are you measuring the size of the atomic nucleus.

Now let's go the other way, ascending to higher and higher densities. How about the Sun? Is it very dense or not that dense? The Sun is quite dense (and crazy hot) in the center, but much less dense at its edge. The average density of the Sun is about 1.4 times that of water. And we know the density of water—1 gram per cubic centimeter. In its center, the Sun's density is 160 grams per cubic centimeter. But the Sun is quite ordinary in these matters. Stars can (mis)behave in amazing ways. Some expand to get big and bulbous with very low density, while others collapse to become small and dense. In fact, consider my proton smithereen and the lonely, empty space that surrounds it. There are processes in the universe that collapse matter down, crushing it until it reaches the density of an atomic nucleus. Within such stars, each nucleus rubs cheek to cheek with the neighboring nuclei. The objects out there with these extraordinary properties happen to be made mostly of neutrons—a super-high-density realm of the universe.

In our profession, we tend to name things exactly as we see them. Big red stars we call *red giants*. Small white stars we call *white dwarfs*. When stars are made of neutrons, we call them *neutron stars*. Stars that pulse, we call them *pulsars*. In biology they come up with big Latin words for things. MDs write prescriptions in a cuneiform that patients can't understand, hand them to the pharmacist, who understands the cuneiform. It's some long fancy chemical thing, which we ingest. In biochemistry, the most popular molecule has ten syllables—deoxyribonucleic acid! Yet the beginning of all space, time, matter, and energy in the cosmos, we can describe in two simple words, *Big Bang*. We are a monosyllabic science, because the universe is hard enough. There is no point in making big words to confuse you further.

Want more? In the universe, there are places where the gravity is so strong that light doesn't come out. You fall in, and you don't come out either: *black hole*. Once again, with single syllables, we get the whole job done. Sorry, but I had to get all that off my chest.

How dense is a neutron star? Let's take a thimbleful of neutron star material. Long ago, people would sew everything by hand. A thimble protects your fingertip from getting impaled by the needle. To get the density of a neutron star, assemble a herd of 100 million elephants, and cram them into this thimble. In other words, if you put 100 million elephants on one side of a seesaw, and one thimble of neutron star material on the other side, they would balance. That's some dense stuff. A neutron star's gravity is also very high. How high? Let's go to its surface and find out.

One way to measure how much gravity you have is to ask, how much energy does it take to lift something? If the gravity is strong, you'll need more energy to do it. I exert a certain amount of energy climbing up a flight of stairs, which sits well within the bounds of my energetic reserves. But imagine a cliff face 20,000 kilometers tall on a hypothetical giant planet with Earthlike gravity. Measure the amount of energy you exert climbing from the bottom to the top fighting against the gravitational acceleration we experience on Earth for the whole climb. That's a lot of energy. That's more energy than you've stored within you, at the bottom of that cliff. You will need to eat energy bars or some other high-calorie, easily digested food on the way up. Okay. Climbing at a rapid rate of 100 meters per hour, you would spend more than 22 years climbing 24 hours a day to get to the top. That's how much energy you would need to step onto a single sheet of paper laid on the surface of a neutron star. Neutron stars probably don't have life on them.

We have gone from 1 proton per cubic meter to 100 million elephants per thimble. What have I left out? How about temperature? Let's talk hot. Start with the surface of the Sun. About 6,000 kelvins—6,000 K. That will vaporize anything you give it. That's why the Sun is gas, because that temperature vaporizes everything. (By comparison, the average temperature of Earth's surface is a mere 287 K.)

How about the temperature at the Sun's center? As you might guess, the Sun's center is hotter than its surface—there are cogent reasons for this, as we'll see later in the book. The Sun's center is about 15 million K. Amazing things happen at 15 million K. The protons are moving fast. Really fast, in fact.

Two protons normally repel each other, because they have the same (positive) charge. But if you move fast enough, you can overcome that repulsion. You can get close enough so that a brand-new force kicks in—not the repulsive electrostatic force, but an attractive force that manifests over a very short range. If you get two protons close enough, within that short range they will stick together. This force has a name. We call it the *strong force*. Yes, that's the official name for it. This strong nuclear force can bind protons together and make new elements out of them, such as the next element after hydrogen on the periodic table, helium. Stars are in the business of making elements heavier than those they are born with. And this process happens deep in the core. We'll learn more about that in chapter 7.

Let's go cool. What is the temperature of the whole universe? It does indeed have a temperature—left over from the Big Bang. Back then, 13.8 billion years ago, all the space, time, matter, and energy you can see, out to 13.8 billion light-years, was crushed together. The nascent universe was a hot, seething cauldron of matter and energy. Cosmic expansion since then has cooled the universe down to about 2.7 K.

Today we continue to expand and cool. As unsettling as it may be, the data show that we're on a one-way trip. We were birthed by the Big Bang, and we're going to expand forever. The temperature is going to continue to drop, eventually becoming 2 K, then 1 K, then half a kelvin, asymptotically approaching absolute zero. Ultimately, its temperature may bottom out at about 7×10^{-31} K because of an effect discovered by Stephen Hawking that Rich will discuss in chapter 24. But that fact brings no comfort. The stars will finish fusing all their thermonuclear fuel, and one by one they will die out, disappearing from the sky. Interstellar gas clouds do make new stars, but of course this depletes their gas supply. You start with gas, you make stars, the stars evolve during their lives, and leave behind a corpse—the dead end-products of stellar evolution: black holes, neutron stars, and white dwarfs. This keeps going until all the lights of the galaxy turn off, one by one. The galaxy goes dark. The universe goes dark. Black holes are left, emitting only a feeble glow of light—again predicted by Stephen Hawking.

And the cosmos ends. Not with a bang, but with a whimper.

Way before that happens, the Sun, to talk about size, will grow. You don't want to be around when that happens, I promise you. When the Sun dies, complicated thermal physics happens inside, forcing the outer surface of the

Sun to expand. It will get bigger and bigger and bigger and bigger, as the Sun in the sky slowly occupies more and more and more of your field of view. The Sun eventually engulfs the orbit of Mercury, and then the orbit of Venus. In 5 billion years, the Earth will be a charred ember, orbiting just outside the Sun's surface. The oceans will have already come to a rolling boil, evaporating into the atmosphere. The atmosphere will have been heated to the point that all the atmospheric molecules escape into space. Life as we know it will cease to exist, while other forces, after about 7.6 billion years, cause the charred Earth to spiral into the Sun, vaporizing there.

Have a nice day!

What I've tried to give you is a sense of the magnitude and grandeur of what this book is about. And everything that I've just referenced here appears in much more depth and detail in subsequent chapters. Welcome to the universe.

INDEX

Italic pages refer to figures and tables