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CHAPTER 1

SIZE AND SCALE OF THE UNIVERSE

Neil deGrasse Tyson

We begin with the solar system. Ascend to the stars. Then reach for the galaxy, the universe, and beyond.

The universe. It's 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 numerical machinery together before we begin. Start 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. Moving onward, the number

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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 three 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."

Do you know how big a billion is? What kinds of things come in billions?

Currently we are approaching 8 billion people in the world.

How about Jeff Bezos, the founder of Amazon .com? What's his wealth up to? More than 100 billion dollars. Where have you seen 100 billion? Well, McDonald's: "Over 99 Billion Served." That's the biggest number you ever see in the street. McDonald's never displayed 100 billion, because they allocated only two numerical slots for their burger count, and so, they just stopped

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at 99 billion. After that, they pulled a Carl Sagan on us 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. Find some way to float them. This calculation uses the diameter of the bun (4 inches), so 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, the Indian Ocean, Africa, and across the Atlantic Ocean, finally arriving back in New York City. That's a lot of hamburgers. But you have some left over after you have circled Earth's circumference. So, you make the trip all over again, 215 more times. Afterward, you still have some left. You're bored circumnavigating Earth, so you stack what remains. 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. Only then will you have used your 100 billion hamburgers. That's why cows are scared of McDonald's. By

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comparison, the Milky Way galaxy has about 300 billion stars. Perhaps 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'm just geeky enough to have celebrated that moment in my life with a fast sip of champagne.

Let's keep going. What's the next step up? A trillion: 10^{12}. We have a metric prefix for that: *tera*-. You can't count to a trillion. If you counted one number every second, it would take you 1,000 times 31 years—31,000 years, which is why we 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, a spiral ramp timeline of the universe begins at the Big Bang and displays 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

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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? No. Not relative to the cosmos itself.

What's next? 10^{15}. That's a quadrillion, with the metric prefix *peta-*. Between 1 and 10 quadrillion ants live on (and in) Earth, according to Harvard biologist E. O. Wilson.

Then comes 10^{18}, a quintillion, with metric prefix *exa-*. That's the estimated number of grains of sand on ten large beaches.

Up another factor of 1,000 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: more than 10 sextillion—

the number of stars in the observable universe.

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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, how about a number much larger than 1 sextillion—10^{81}? It's the number of atoms in the observable universe. Why 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 not enough objects in the universe for a googol to count. It is just a fun number. We can write it as 10^{100}, or as is true for all out big numbers, 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*; 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

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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 declare a draw whenever one of these three things happen, then we can calculate the number of all possible chess games. Rich Gott did this (because that's just the kind of thing he does) 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). Again, you're not counting things; you are counting possible ways of doing things. In that way, numbers can get very large.

Here's a still bigger number. 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 zeroes after it. Can you even write out this number? Nope. You would need a googol zeroes, and a googol is larger than the number of atoms in the universe, then you're stuck writing it this way: 10^{googol}, or $10^{10\wedge 100}$ or 10^(10^100).

We're not just wasting your time. Here's a number bigger than a googolplex. Jacob

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Bekenstein invented a formula allowing us to estimate the maximum number of different quantum states that could have a total 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), which 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.

A mathematical theorem once contained the badass number 10^(10^(10^34)). It's called *Skewe's number*. And it dwarfs them all.

Time to get a sense of the 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 (plus 1% "other"). When we talk about density here,

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we're referencing the number of molecules, atoms, or loose particles that compose the material in question.

A density of 2.5×10^{19} molecules per cubic centimeter is likely higher than you thought. What about 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. 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 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." 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 the base of this blanket of air we call our atmosphere,

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which does indeed rush in to fill empty spaces whenever it can.

Smash a piece of chalk into smithereens against a blackboard and pick up a fragment. Let's say a smithereen is about 1 millimeter across. Imagine that's a proton. Do you know what the simplest atom is? Hydrogen. Its nucleus contains one proton, and normal hydrogen has an electron occupying a spherically shaped volume that surrounds the proton. We call these volumes orbitals. If the chalk smithereen is the proton, then how big would the full hydrogen atom be? One hundred meters across—about the size of a football field. So atoms are quite empty, though small: about 10^{-10} meters in diameter. That's one ten-billionth of a meter. Only when you get down to 10^{-14} or 10^{-15} meters are you measuring the size of the nucleus. Let's go smaller. We do not yet know the diameter of the electron. It's 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. So matter is an excellent repository of empty space.

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Now let's go the other way, climbing to higher and higher densities. How about the Sun? It's 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. Yet the Sun is undistinguished 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 the proton smithereen and the lonely, empty space that surrounds it. There are processes in the universe that collapse matter down, crushing it until there's no empty volume between the nucleus and the electrons. In this state of existence, the matter reaches the density of an atomic nucleus. Within such stars, each nucleus rubs cheek to cheek with 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.

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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 we observe pulsing, 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, then hand them to the pharmacist, who understands the cuneiform. In biochemistry, the most popular molecule has ten syllables—deoxyribonucleic acid. Yet the beginning of all space, time, matter, and energy in the cosmos is simply the *Big Bang*. We are a simple people, with a monosyllabic lexicon. The universe is hard enough, so 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 can't come out; these are called *black holes*. Once again, with single syllables, we get the whole job done.

How dense is a neutron star? Cram a herd of 100 million elephants into a Chapstick casing.

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In other words, if you put 100 million elephants on one side of a seesaw, and a single Chapstick of neutron star material on the other side, they would balance. That's some dense stuff.

How about temperature? Let's talk hot. Start with the surface of the Sun. About 6,000 kelvins—6,000 K (a temperature in kelvins is equal to its temperature in degrees centigrade + 273). 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. The Sun's core is about 15 million K.

Let's go cool. What is the temperature of the whole universe? It does indeed have a temperature—left over from the Big Bang. In the beginning, 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. (A light-year is the distance light, traveling at 300,000 kilometers a second, can travel in a year—about

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10 trillion kilometers.) The nascent universe 1 second after its birth was hot, about 10 billion K, a seething cauldron of matter and energy. Cosmic expansion since then has cooled the universe down to a mere 2.7 K.

Today we continue to expand and cool. As unsettling as it may be, all 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 will 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 (that's 0.7 million-trillion-trillionths of a degree above absolute zero) because of an effect discovered by Stephen Hawking that we will discuss in chapter 8. But that fact brings no comfort. Stars will finish fusing all their thermonuclear fuel, and one by one they will blink out, disappearing from the night 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 age, and they leave behind a corpse—the dead end-products of stellar evolu-

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tion: 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. This leaves black holes that emit only a feeble glow of light—again predicted by Stephen Hawking.

And so the cosmos ends. Not in fire, but in ice. And not with a bang, but with a whimper.

Have a nice day! And, welcome to the universe.

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