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Mysteries of Modern Physics: Time

Course Guidebook

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Prior to arriving at Caltech, Professor Carroll taught and did research at the Massachusetts Institute of Technology; the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara; and the University of Chicago. His major contributions have included models of interactions among dark matter, dark energy, and ordinary matter; alternative theories of gravity; and violations of fundamental symmetries. His current research involves the foundations of quantum mechanics, the physics of inflationary cosmology, and the origin of time asymmetry.

While at MIT, Professor Carroll won the Graduate Student Council Teaching Award for his course on general relativity, the lecture notes of which were expanded into the textbook *Spacetime and Geometry: An Introduction to General Relativity*, published in 2003. In 2006, he received the College of Liberal Arts and Sciences Alumni Medallion from Villanova University, and in 2010, he was elected a Fellow of the American Physical Society.

Professor Carroll is the author of *From Eternity to Here: The Quest for the Ultimate Theory of Time*, a popular book on cosmology and time. His next book is *The Particle at the End of the Universe*, about the Higgs boson and the Large Hadron Collider. He is active in education and outreach, having taught more than 200 scientific seminars and colloquia and given more than 50 educational and popular talks. Professor Carroll has written for *Scientific*

American, *New Scientist*, *The Wall Street Journal*, and *Discover* magazine. His blog, *Cosmic Variance*, is hosted by *Discover*. He has been featured on such television shows as *The Colbert Report*, PBS's *NOVA*, and *Through the Wormhole with Morgan Freeman* and has acted as an informal science consultant for such movies as *Thor* and *TRON: Legacy*.

The first of Professor Carroll's Great Courses was *Dark Matter, Dark Energy: The Dark Side of the Universe.* ■

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Mysteries of Modern Physics: Time

Scope:

This course addresses one of the most profound questions of modern physics: Why does time work the way it does? Time is as mysterious as it is familiar, and over the course of these lectures, we will explore where those mysteries come from and how they are addressed by physics, philosophy, biology, neuroscience, and cosmology.

We will start by exploring how time works at a basic level: what time is and how we measure it using clocks and calendars. But we will quickly come up against a central mystery: Why does time have a direction? The difference between past and future will be a primary concern throughout the course.

We will see that the fundamental laws, ever since Isaac Newton, have a profound feature: They do not distinguish between past and future. They are reversible; if we make a movie of the motion of a planet around the Sun or the back-and-forth rocking of a pendulum, we can play it backward and it seems perfectly sensible. But for systems with many moving pieces, there is a pronounced directionality to time. Many familiar processes are irreversible: scent dispersing into a room, cream mixing into coffee, the act of scrambling an egg. In the real world, these happen in one direction in time, never backward. That difference is the arrow of time.

Explaining why time has an arrow is a primary concern of modern physics. We will see that it does not arise from quantum mechanics or particle physics. Rather, it is due to the increase of entropy—a way of measuring how messy or disorderly a system is—as time passes. The increase of entropy is responsible for many deeply ingrained features of time, such as our ability to remember the past or make decisions that affect the future.

The question then becomes: Why does entropy increase? The increase of entropy toward the future is known as the second law of thermodynamics and was explained in modern terms by Ludwig Boltzmann in the 19th century. Boltzmann's insight is that entropy increases because there are more ways for a system to have high entropy than low entropy; thus, high entropy is a natural condition.

This raises a new question: Why was entropy lower in the past? That turns out to be a much harder problem, one that traces back to the very beginning of time. The low entropy of the past is ultimately due to the fact that our universe had low entropy 13.7 billion years ago, at the time of the Big Bang.

Cosmology would like to explain why the Big Bang had low entropy, but our best current models aren't up to the task. It's possible that the ultimate explanation might lie beyond our observable cosmos, in a larger multiverse. Even without knowing what that explanation will be, we can marvel at the deep connections between time in our everyday lives and the larger universe in which we live. ■

Why Time Is a Mystery

Lecture 1

Time is something we're all familiar with, but what's less clear is what science has to say about time. You probably know that the idea of time is important to physics; it's also important to biology, medicine, neuroscience, psychology, and the human sciences, such as history, politics, and economics. Time is absolutely central to every endeavor of humankind, and physics is a kind of bedrock for time. If we come to understand how time works from the point of view of physics, we can better understand how it works elsewhere in science and in our everyday lives.

Penetrating the Mysteries of Time

- Although we think about and use it every day, time has a reputation for being mysterious. As Saint Augustine wrote, "What is time? If no one asks me, I know. But if I wish to explain it to someone who asks, I know not."

- The difference between our everyday dealings with time and the attempt to understand time on a deeper level is similar to the difference between operating a microwave oven and understanding how one works. As with the microwave oven, even though time may appear to be mysterious and incomprehensible, it can be understood.

- Our goals in this course will be to understand time as physicists and then to connect that physical understanding to other ways that time manifests itself in science and in our everyday lives. Along the way, we'll discover that time has a manifestation both in our everyday lives and in a more cosmic perception and that there is a direct connection between how time works in the two realms.
    - The reason that time works the way it does in our everyday lives is ultimately because of how the universe works.

- Once we penetrate the mysteries of time, we'll find that the secret to those mysteries isn't in our everyday experience but in the creation of the universe itself.

Telling Time

- We have time-measuring devices—clocks—in almost everything around us—our phones, our computers, and so on. At a basic level, a clock is something that repeats itself in a predictable way. Both elements of that definition are important: repeatability and predictability.

- The classic idea of a clock is the Sun moving across the sky, rising in the east in the morning and setting in the west in the evening. That's the simplest possible timekeeper we have. Other clocks are based on that same basic principle: doing the same thing over and over again in a repeatable, predictable way.

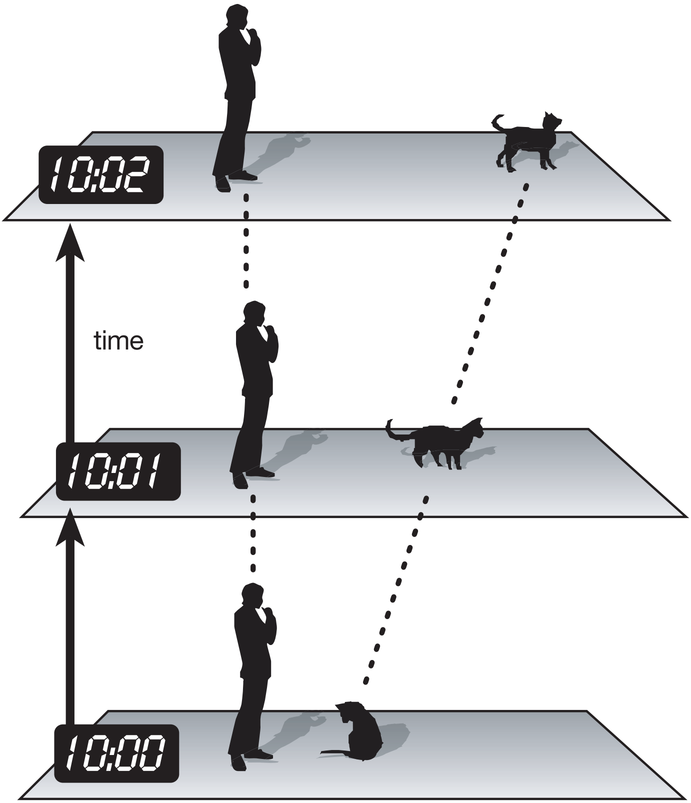
- As we'll learn in this course, it's not easy to make a clock, and even though clocks are all around us, they're not very accurate. There is a great deal of challenge in building a clock that's as accurate as the modern world demands.

Time within Ourselves

- A clock measures the passage of time, but we also feel time within ourselves, at least partly because clocks—mechanisms that repeat themselves in predictable ways—exist within us, such as our breathing and the beating of our hearts.

- There are also things about us that don't repeat themselves but that progress as time passes: We age; we think; we make choices; we plan for the future; we remember the past. These different aspects of time are crucial to what it means to live our lives, to be human beings.

- Perhaps the most important aspect of the passage of time for our lives as human beings is the accumulation of experiences.



Both individual frames and the whole series of frames define what we think of as the universe; it's a four-dimensional thing—both space and time.

- It's not just that we experience something today, and then tomorrow, and then the next day, but we experience something today and we remember it tomorrow. As time passes, we have more life experience to draw on. There's a gradual buildup of our life spans through time.

- The past that we have experienced is important to who we are today. Even in the process of watching these 24 lectures, you'll learn things, you'll change, and you'll come out of this course a different person than you were when you came in. That's a central aspect of how time works.

Moving through Time

- When we look closely, the idea that time passes or that we move through time is not entirely clear. What does it mean to say that time passes?

- The notion of time passing has two different aspects: continuity and progress.
  - The passage of time isn't a story of complete rearrangement of reality; it's more like an uncut movie reel. We see moments in the history of the universe one after another, but the moments have the same basic "stuff." Things evolve, but everything is not different at every moment.

  - Time isn't only a label that we apply to different moments, but it's an ordered list of moments, moving in a direction. Just as a movie isn't a set of frames scattered randomly on the floor, likewise, the progress of time from past, to present, to future is crucial.

  - The fact that we all agree on the directions of the past and the future is the basis of a concept known as the arrow of time.

- How fast are we moving through time? What else could the speed of time be other than something like 1 second per second?
  - When we move through space and we have a velocity, what we're talking about is how much space we travel through per unit of time, such as how many miles per hour.

  - But if we're talking about the speed of time, that kind of measurement doesn't quite make sense. If there were something called the speed of time, it could only be 1 minute per minute, 1 year per year, and so on. Time moves at the rate time moves, or time doesn't move at all; it simply is.

- Time happens, whether we like it or not. Space is something that we can choose to move through, but time is inevitable. There is no velocity at which we move through time; we just experience time moment after moment.

The Direction of Time

- The fundamental distinction between time and space is the division of time into past, present, and future. The progression of time from the past, to the present, to the future only happens in one way, and as it happens, things occur always in the same sense.
  - Memory, for example, is something we have about the past; we don't have a memory of the future. When we age, we always are born young, we grow older, and then we die; that's how time works.

  - This is the arrow of time; the arrow points from the past, into the present, and toward the future. Time is absolutely, fundamentally directed in that way.

- Einstein taught us that time is related to space, but space doesn't have any fundamental directionality; it has a sort of nonfundamental directionality.
  - If you drop something in a room, it will always go down as opposed to up, but the difference between up and down in a room doesn't reflect any deep feature of reality. If you were in Australia instead of the United States, the downward direction would be something different; the "arrow of space" depends on where you are.

  - We don't even really think about an arrow of space because it's obviously a feature of our environment. There's an arrow of space because we live in the vicinity of an influential object called Earth.

  - The arrow of time, in contrast, seems to be a deep feature of reality; it seems to be the same everywhere.

- The ultimate explanation for the arrow of time is similar to the ultimate explanation for the arrow of space.
    - Just as the arrow of space is explained by the fact that we live in the vicinity of an influential object—the Earth—the arrow of time is explained by the fact that we live in the vicinity of an influential event—the Big Bang, the beginning of the universe.
    - At a deep level of reality, there is no arrow of time; there's no difference between the past and the future as far as the ultimate laws of physics are concerned.
    - The arrow of time has something to do with the macroscopic behavior of objects in the world, but it doesn't appear at the level of two particles bumping into each other and scattering off; that's something that treats the past and the future absolutely identically.
    - The arrow of time arises only when there are many, many particles—when we have a person or a cloud of gas in the solar system forming a new planet.

Entropy

- Entropy is a way of talking about the disorderliness of "stuff" in the universe. An egg is very orderly, but if we break the egg, it becomes disorderly; if we scramble the egg, it becomes even more disorderly. A scientist would say that the entropy of the egg is increasing.

- Left to their own devices, objects in the universe experience an increase of entropy; they become more disorderly as time passes. That, in fact, is the important distinction between the past and the future.

- There are many ways in which the arrow of time manifests itself, but there's one underlying feature that explains all those different manifestations: In a system left to itself, entropy increases. This is so important that it's literally a law of nature: the second law of thermodynamics.

- In the 19th century, scientists made great strides toward understanding how entropy works, why it tends to go up toward the future, and how it underlies the arrow of time in all of its manifestations. But that understanding left us with one unanswered question: Why was entropy lower in the past?
  - This question brings us all the way back to the Big Bang. Our universe started 13.7 billion years ago in a condition of very low entropy and very high organization. That's what got time started in the way we experience it in our everyday lives.
  - Ever since the Big Bang, we've been living out the process by which the universe increases in entropy. That's the influential event in the aftermath of which we live.
- In this course, we will come to understand what entropy is and why it tends to increase. Once we understand how entropy is responsible for the arrow of time and all of its forms, we will go back and explain why it's there; that's a matter of understanding relativity, spacetime, cosmology, the Big Bang, and how all these ideas fit together.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 1.

Falk, *In Search of Time*.

Frank, *About Time*.

Greene, *Fabric of the Cosmos*, part II.

Questions to Consider

1. How would you define "time"? How do you use it in your everyday life? Do you think of yourself as moving through time or time passing through you?

2. In what ways is the past different from the future? Do those differences seem fundamentally important? How do they relate to each other?

What Is Time?

Lecture 2

Science and philosophy have a longstanding relationship, a sort of friendly rivalry. The two disciplines have different aims, but their subject matters often overlap, and the study of time is one area where the philosophical perspective is extremely helpful, even to physicists. Philosophers try to understand the logical inner workings of something, while physicists are often happy just to get a theory that works, not necessarily one that makes sense. We have an understanding of how time works in a physical way in certain well-defined circumstances, but philosophical questions remain. In this lecture, we'll look at some of those questions to help us understand the scientific aspects that we'll uncover in the rest of the course.

Time and Space in the Universe

- When we think of the universe, we generally think of space—not just outer space but the space around us, the location of things in the world. We also think of the universe as happening over and over again. Right from the start, we treat time and space differently.
  - Space seems to be somehow more important or relevant to what the universe is, whereas time is just a label that tells us which moment of the universe we're talking about.
  - In Lecture 1, we discussed the analogy of the universe as a movie reel. It's important to note that both each frame and the whole series of frames—the movie—define what we think of as the universe; it's a four-dimensional thing, with both space and time.
- Unlike space, the universe doesn't rearrange itself.
  - In space, what happens at one point seems more or less completely disconnected from what happens at another point. Space doesn't have any rules about what comes next to everything else.

- Time, on the other hand, has rules about what comes one moment after the other. That's how the laws of physics work: If you know everything that the world is doing at one moment in time, the laws of physics will tell you what happens next. And from that moment, the laws of physics will tell you what happens next, and so on.

- The laws of physics start from a moment—a state of the universe at one instance in time—and they tell you, using the equations that are the laws of physics, what happens at each subsequent moment.

The Difference between Time and Space

- Later in the course, we'll talk about relativity and the relationship between time and space, but for right now, let's examine the notion that time and space are completely different.

- We can choose to go to some other location in space, but we can't choose to go to some other location in time. Time is relentless, whereas how we move in space is up to us.

- This fact gives us a certain perspective on reality. We think of reality as one moment in time; however, we don't think of a distant location that may be inaccessible to us as not real.
  - Different locations in space are absolutely real, whether or not we're there, but what about the past and the future? Are they real?

  - We think of the universe right now as existing, but we think of the past as over with; we don't think of the past as real in the same way that the present is, and we certainly don't think of the future as just as real.

  - Why do we treat the past and future so differently? Why are we thinking of them in such a different way than we think of the different parts of space?

- To answer that question, let's consider how we go about describing space and time.
  - If you propose to meet a friend at a coffee shop at a certain time, what you're really doing is giving your friend coordinates in the universe—what a physicist would call an "event."

  - You need to specify space (where you're going to meet) and time (when you're going to meet). On Earth, to specify location, you need to give only two numbers—the street that you're on and the address on that street—but in space, you would need to give three numbers, because space is three-dimensional.

  - Time is another dimension in the universe; we can marry the three dimensions of space to the one dimension of time to get four-dimensional spacetime.

Presentism and Eternalism

- Philosophers would call our everyday way of thinking about the world "presentism." This is the idea that what exists and what is real is the three-dimensional universe at some moment in time and everything in that universe. The past and the future are not real.

- But physics suggests a different point of view: If we know the universe exactly right now, we can predict what the future will be and can reconstruct what the past was. The laws of physics connect the present moment to the future moment and the past moment.

- From that perspective, we begin to think that the past, present, and future are perhaps all equally real. This point of view is called "eternalism."
  - As opposed to presentism—which says that the present is real, the past is a memory, and the future is a prediction—eternalism says that all the moments in the history of the universe are equally real. There's nothing special about the present moment except that you're experiencing it right now.

- Eternalism is sometimes called the “block universe perspective” because it’s like stepping outside the universe and seeing all four dimensions as one block of both space and time. Another term for it is the “view from nowhen,” the view not from any one moment in time but outside the whole thing.

- The current laws of physics suggest that eternalism—this idea of treating the past, present, and future on an equal footing—is the correct view of the universe.

The Arrow of Time

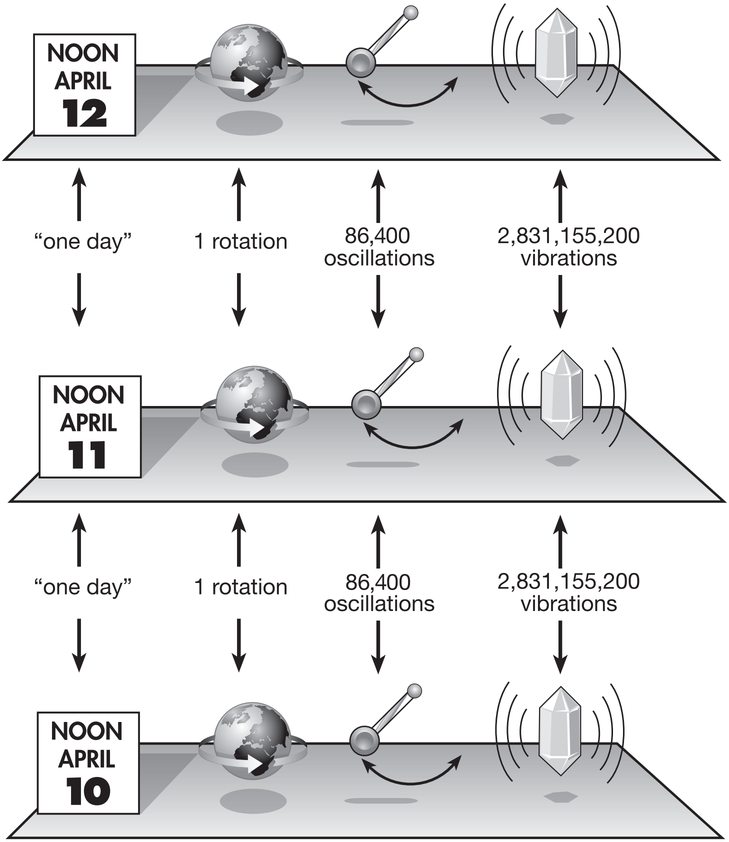
- As we said, presentism views the present moment as real, but not the past or the future. A slight twist on presentism treats the present and the past as real, but not the future. The past is fixed—we might not be living there, but it happened—whereas the future is unsettled. This way of thinking seems natural to us as human beings, but it has no reflection in the laws of physics.

- A better way to understand the reason we treat the past and the future so differently is the arrow of time. It’s not time itself that treats the past, present, and future differently; it’s the arrow of time, which is ultimately dependent on the “stuff” in the universe, our macroscopic matter and the configurations that it is in.

- The arrow of time gives us the impression that time passes, that we progress through different moments. From that perspective, we understand that it’s not that the past is more real than the future; it’s that we know more about the past. We have different access to it than we have to the future.

Clocks

- One way of thinking about time is that it is what clocks measure. With a clock, we can say not only that time has passed but that a certain amount of time has passed. As we said earlier, a clock is a device that does the same thing over and over in a repeatable way.



The "good clocks" in our universe include the rotation and revolution of the Earth, the rocking of a pendulum, and the vibration of a quartz crystal.

- Are we dealing in circular definitions here? We seem to be defining time as what clocks measure and defining clocks as devices that do the same thing over and over again as time passes.

- In fact, this is not a circular definition; there is some substance to the claim that time is what clocks measure. Further, the existence of things that do the same thing over and over again in a predictable way—like clocks—isn't something we can take for granted. We might have lived in a universe where everything that repeated itself did so unpredictably.

- An important feature of clocks is that there's more than one clock in our universe. Of course, "clocks" here means anything by which we can measure the passage of time.
    - The Earth rotates around its axis; it also revolves around the Sun. These are two different things that the Earth does, and it does them in a predictable way.

    - These two things are comparable to each other: Roughly speaking, the Earth rotates 365¼ times every time it revolves around the Sun. It's not a different number of days per year; it's the same number year after year. That's what makes the motion of the Earth give us reliable clocks.

- The rotation and revolution of the Earth make it an obvious choice for a good clock. These days, in wristwatches, the best clocks come in the form of quartz crystals, which can be made to vibrate at a precise rate. The motion of a pendulum is also a good clock.

- In a world in which there were no regularities, there would be no good clocks anywhere in the universe. Things would happen over and over again, but they would happen at unpredictable rates compared to each other. Time would still exist, but we could never say how much time had passed from one moment to another.

- Clocks give us an operational way of thinking about time; they refer to things that really happen, not just to abstract concepts.
    - What if time were to simply stop? Or what if time slowed down everywhere in the universe?

    - Actually, the answer is that it would mean absolutely nothing. If time stops everywhere for everything in the universe, there would be no way of knowing.

- What would happen if you could stop time for everything in the universe that was a distance of about 3 feet from you?
    - Suddenly, you wouldn't be able to see anything more than 3 feet away from you because there would be no light coming to you from anything in your time-stopping zone.
    - If you started to move through the air and the molecules 3 feet from you were absolutely stationary, they would be like a brick wall to you.
- The idea of stopping time or even that times moves at different rates for different people is a very slippery notion. When we talk about relativity, we'll see that there's a well-defined scientific sense in which different people can measure time moving at different speeds, but the only way they can do that is by being in different places in the universe or moving through the universe at different velocities.

Suggested Reading

Callender, *Introducing Time*.

Carroll, *From Eternity to Here*, chapter 1.

Klein, *Chronos*.

Questions to Consider

1. Do you think the past, present, and future are equally real? How would you try to convince someone who didn't agree with your viewpoint?

2. What processes around you would qualify as "good clocks"?

3. Can you imagine time speeding up, slowing down, or stopping altogether?

Keeping Time

Lecture 3

In our last lecture, we got a little philosophical, but in this lecture, we want to be practical. If time passes and we experience the passage of time, the obvious practical question is: How do we measure the passage of time? Clearly, this is a question about building clocks. But as we become more technologically advanced—as society moves through the arrow of time—the demands for measuring time precisely become greater. We want to know: What are the best clocks? To answer that question, we'll look at how the notion of keeping time has developed through history.

Units and Measurement of Time

- A solar day is the amount of time it takes the Sun to go from one position, such as noon, to the same position the next day. A solar year is the amount of time it takes for the Earth to go around the Sun. The lunar month is the amount of time it takes the Moon to go from one phase—new moon or full moon—back to the same phase again.

- Our task is to build a device to measure those time periods—the day, year, and month—as precisely as possible.
  - The simplest such device would be a sundial. We could put a stick in the ground and watch the progress of the shadow of the stick over time as the Sun moves through the sky.

  - Even this, however, is not as simple as it seems. If we put the stick exactly vertically, the time of day it measures would be different in the spring, summer, fall, and winter. The key is to align the stick with the axis of the Earth's rotation.

  - The sundial represents a small version of a bigger problem we have: What is the best way to tell time that is not subject to the vagaries of astronomical whims?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Stonehenge performs the most basic function of an astronomical observatory; it tells us the time of year.

- We can tell what time of year it is using an observatory. We know—and ancient people knew, as well—that the Sun is more northerly in summer and more southerly in winter. Stonehenge is a classic example of a simple astronomical observatory. The stones at Stonehenge are aligned so that at sunrise on the summer solstice—the longest day of the year—the Sun bisects the design.

Building a Calendar

- Ancient people would have found it useful to know when summer begins, but more generally, we would like to build a calendar, a system of units that lets us tell, in a uniform way, where we are in the year. That means taking a long period of time, such as a year or a month, and dividing it into shorter periods of time.

- A year, a lunar month, and a day are all specific time periods that we can compare to each other, but the problem is that they don't match up in easy ways.

- A year is 365¼ days, but even that is not precise. At a more accurate level, a year is 365.2422 days, a very awkward number.

- Even worse is the lunar month. It is 29.5306 days, another completely awkward number, and a year is 12.3683 lunar months.

- The universe has given us no relationship between a month, a year, and a day. For thousands of years, humans have struggled to find clever ways to reconcile these astronomical timekeepers.

- This struggle resulted in different notions of a calendar in different cultures. The Islamic calendar, for example, based on a lunar month (29.5 days), alternates months of 29 days and 30 days. The problem is that when we add all the lunar months, we get 354 days, not quite a year.

- The desire to reconcile months with years resulted in the clever notion of the leap month, which can be traced back to ancient Babylon.
  - The Babylonians hit on the curious fact that 19 solar years is very close to 235 lunar months.

  - They further realized that if they let 12 months per year be the rule for 12 years in a row, and then 13 months per year be true for the next 7 years, they would have a 19-year cycle that synchronized the lunar calendar with the solar calendar.

The Gregorian Calendar

- The Gregorian calendar that we use today has given up on the notion of the lunar month, which is why some months have 30 days; some, 31; and February, 28 or 29.

- The idea of the months having different numbers of days unsynchronized with the Moon comes from the Julian calendar. The Julian calendar basically had the same months that we have except it had a leap year every 4 years. This seems close to our current system, but if we had a leap year every 4 years, we would go out of synchrony with the Sun by about 11 minutes per year.

- The system embedded in the Gregorian calendar is as follows: Every 4 years, we have a leap year, but then we skip leap year every 100 years.
    - The last time we had a year divisible by 100 was the year 2000, and the fine print in the Gregorian calendar says that we do have a leap year every 400 years.
    - Thus, 1700, 1800, and 1900 were not leap years; 2000 was; 2100, 2200, and 2300 will not be leap years; 2400 will be; and so on.

- The Gregorian calendar was developed and implemented in 1582, based on the realization that the Julian calendar was getting out of sync with the solar cycle.

- The Julian calendar was wrong by 11 minutes every year, but the Gregorian calendar is accurate to 2.6 seconds per year. In the year 4000, we might need another leap day to realign the Gregorian calendar with the Sun.

The Leap Second

- The leap second is completely different conceptually than the leap month or the leap year. The leap day and the leap month exist to fix the fact that one cycle—the rotation of the Earth or the orbit of the Moon—gets out of sync with another cycle—the Earth going around the Sun. Leap seconds exist to fix the fact that the Earth does not rotate at a completely constant rate.

- As we've said, the whole point of an accurate clock is to get something that repeats itself over and over again in a predictable way, but now that we have much more accurate clocks, we realize that the rotation of the Earth is not perfect, and it is not perfect in an unpredictable way. Things like earthquakes and hurricanes change the rate at which the Earth rotates.

- Rather than fixing that unpredictability once and for all, we have to wait for the Earth to get out of sync and then add a leap second to the calendar. You do not even notice it, but occasionally, New Year's Eve is 1 second longer than it was the day before. This is a controversial issue because it presents problems for computers.

More Accurate Timekeeping

- As technology evolves, it is not good enough to look at the sky to measure what time it is. In crossing the ocean, for example, it's necessary to know the time to know where you are. You can figure out your longitude by looking at the stars but only if you know what time it is.

- This puzzle—how do you know what time it is when you are on a boat far away from any land-based clocks—was so important that in the 18th century, the British Parliament offered a prize of ₤20,000 for figuring out how to measure time accurately, even at sea. The motion of the boat meant that a pendulum couldn't be used, and changes in temperature and humidity meant that metal springs couldn't be used.

- The problem was ultimately solved in 1761 by a man named John Harrison, who invented the marine chronometer.

Personal Timepieces

- These days, of course, we live in a world where keeping time is something that everyone wants to do, whether or not you are a navigator on a ship.

- In the 19th century, what that meant was a pocket watch, but the early pocket watches were maybe accurate to 15 minutes a day.

- In World War I, military personnel started wearing wristwatches to keep their hands free to carry weapons, and the fad eventually spread to people outside the military. Building mechanical wristwatches became a major industry, especially in Switzerland.

- In the 1960s, Japanese manufacturers realized that they could base a wristwatch on a vibrating quartz crystal. A watch based on quartz is much more accurate than any mechanical timepiece and much cheaper.

Atomic Clocks

- Today, we use atomic clocks, not quartz crystals, for maximum accuracy. A quartz crystal can be very accurate, but we want increasingly more accurate clocks because we are putting more and more demands on them.

- We can increase accuracy by looking at the transitions of electrons in individual atoms. In practice, we use cesium or rubidium, specific atomic elements that give up very precisely defined frequencies.

- The best atomic clocks are more accurate than 1 billionth of a second per day. Such accuracy is needed for a global positioning system (GPS).
    - By comparing how much time it takes for the signals from at least four satellites to reach your GPS, the system can determine your exact location on Earth.

    - A GPS can tell you exactly where you are to within a few feet, but that depends on the fact that the clocks onboard the satellites are incredibly accurate.

    - If the satellite clock were off by 1 microsecond, your location would be off by 1000 feet. Given that the speed of light is so fast, to triangulate correctly, it's necessary to know exactly when that signal left the satellite. That's what a good atomic clock can do.

Clocks and the Arrow of Time

- As we've said a good, accurate timepiece always does exactly the same thing, which means that it doesn't have an arrow of time in the sense that many things in the universe do.

- If we took the hands off a clock and made a movie of it, it would be impossible to know whether the movie was playing backward or forward.

- The arrow of time is a feature of things that do not always do exactly the same thing. We can turn an egg into scrambled eggs, but that process goes only in one direction.

- That is the difference between pristine accurate timepieces and the universe. Understanding where that difference comes from will be our goal for the rest of the course.

Suggested Reading

Barnett, *Time's Pendulum*.

Falk, *In Search of Time*.

Questions to Consider

1. If you didn't have any clocks or calendars, how would you personally keep time? Would you be able to fashion (or at least design) a sundial or astronomical calendar?

2. Do you wear a watch? Have your watch-wearing habits changed over the years? What kind of clocks do you usually use to tell the time?

3. Do you usually know what time it is?

Time's Arrow
Lecture 4

In the past few lectures, we have talked about the philosophy of time; the reality of the past, present, and future; and the down-to-earth aspects of how we measure time. Now, we are free to concentrate on the important issue that will motivate the rest of the course: why there is an arrow of time—why the past is different from the future. In this lecture, we'll try to understand what is meant by the arrow of time and why its existence in our world is so startling.

How Is the Past Different from the Future?

- All aspects of memory (meaning any form of historical knowledge) refer to things that already happened. Memory is a correlation between some artifact here and something that happened in the past.
    - There are no memories of the future; there are predictions, but they are different than memories. They are not artifacts; they are not connected in some recordkeeping way with what happens in the future.
    - Our difference of "epistemic access"—what we know about the past versus what we know about the future—is probably the most obvious and the most important difference that the arrow of time gives to our everyday lives.
- Another obvious difference between the past and the future is, of course, aging. We are all born young and grow older with time. Aging applies not only to people and to other animals but to physical objects, as well.
- Of course, we all know that art, politics, literature, and music are all things that evolve in time. Although cultural changes are not as closely tied to the arrow of time as physical changes are, they still represent one-way evolutions. There is a past, a present, and a future, and all of them are different from each other.

- The same thing is even true for society, in what we might call social progress. Societies change through time in interesting ways.
    - We would like to believe that social changes through time represent true progress.

    - That statement is arguable from a historical point of view, but it is unarguable that there is an evolution in society that points in a certain direction.

- Such evolution is also reflected in the physical universe. The past of the universe is very different from what we think the future will be like.
    - The universe at early times was hot, dense, and smooth. Currently, it is more or less empty, and the matter that is present is lumpy. It is very different in one place, where there is a galaxy, than in another place, where there is interstellar space. In the future, the universe will continue to empty out.

    - The universe has a very strong arrow of time, which is reflected in the life cycles of stars and planets.

- That physical change in the universe is reflected in biological change here on Earth. The Earth is only about 4.5 billion years old, so it is a substantial fraction of the age of the universe.
    - Life formed fairly quickly after the Earth formed, but there is a clear evolution. This is not just a Darwinian evolution, but evolution in the sense of change over time in a certain direction.

    - The first life forms were simple single-celled organisms. The fact that individual species became more complicated as time progressed is not a requirement of evolution.

    - Because there is room for differentiation and change, our biosphere supports increasingly complicated systems of species.

- Besides physical and biological change, there are some features of the arrow of time that seem ingrained or logically necessary.

- For example, we have the idea that a cause will always precede an effect. If the laws of physics do not account for what happens first and what happens after, we will clearly have to think harder about what causality means.

- We also have to think harder about free will. We do not have the ability to make choices about the past.

- All of these different areas—from biology and sociology, to the universe and physics, to logical issues of causality and free will—reflect the arrow of time. A universe without the arrow of time would not have progress or differentiation from the past to the future.

Storytelling

- The arrow of time plays a crucial role in storytelling. As you know, most novels are chronological narratives, but novels can be made more interesting by playing with the conventional way time works—incorporating flashbacks or reverse narration. The idea behind these literary devices is that the information we have changes the way we perceive events.

- If we are given a certain scene happening right now, the meaningfulness of that scene depends on things that happened in the past; those past occurrences may change our perception in the future. The notion of information and what it means to us is absolutely central to the arrow of time.

- Many attempts to use time in clever ways in storytelling actually miss the impact of the arrow of time. It is almost impossible for us to imagine two characters talking to each other from two different directions of time. One feature of the arrow of time is it must be the same arrow for everyone.

- As scientists or philosophers, the imaginative storytelling aspects of the arrow of time help us think of different ways that it could work and compare them to our world.

The Universe without the Arrow of Time

- We have basically two choices for what the universe would look like without an arrow of time. One is a world in which nothing changes over time. In this world, there would be no arrow of time because time would not do anything.

- Another possibility is a random world. Things would happen one way sometimes and another way at other times. In this world, you could not make plans. You would remember tomorrow just as much as you remembered yesterday, which means you probably wouldn't remember anything at all.

- The need for an arrow of time is something about being human. We cannot imagine a life in which the past and future were truly built on symmetric principles.

Irreversibility

- Breaking an egg and scrambling it (increasing its entropy) is an example of the arrow of time in action. Other examples include putting an ice cube in a glass of water and waiting for it to melt, releasing the scent of perfume in a room, or breaking a glass.

- The common thread in these examples is irreversibility: Something happens in one direction, and it is easy to make it happen, but it does not happen in the other direction, or if it does, it is because we put effort into it. It does not spontaneously happen. Things go in one direction of time. They do not go back all by themselves.

- That difference between going from the past to the future is consistent throughout the universe as far as we know. This is clearly not a feature of our biology but a feature of the way the universe works.

- We actually define the past versus the future using the arrow of time. The fact that we remember the past and not the future is so obvious to us, so inherent in how we think about the world, that we automatically assign an intrinsic difference to the past versus the future.

- Time could exist in a universe without an arrow, and time is not the arrow itself. The arrow is a feature of the stuff in the universe—the eggs, the glasses, the scent of perfume in a bottle. It is these things that evolve in certain ways always in the same direction, from the past to the future.

- The arrow of time is the arrow of stuff evolving in time. Thus, it is not time that we need to understand but matter. It is the motion of particles and objects in the universe.

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The egg is a classic example of a physical system in which the arrow of time is obvious; we can scramble an egg, but we cannot unscramble it.

The Second Law of Thermodynamics

- As we have said, the feature of matter that changes with time is called entropy. The feature of the universe that we are trying to understand is that the increase of entropy is associated with the passage of time.

- The second law of thermodynamics—entropy of the universe increases—underlies all the ways in which the past is different from the future. That is a very surprising claim.
  - The claim makes sense when you say that the reason you can scramble an egg but not unscramble it is ultimately that entropy increases.

  - But we're saying that the fact that entropy increases is the reason you remember the past and not the future, the reason you are born young and grow older, the reason you can make a choice about what to have for dinner tomorrow but not about what to have for dinner yesterday.

- It's important to note that the second law of thermodynamics does not imply that every single object in the universe needs to experience increased entropy.
    - Here on Earth, the biosphere is more organized now than it used to be. The existence of complicated multicellular organisms is a low-entropy phenomenon. Through the course of evolution, however, the Sun shining on the Earth increased the entropy of the universe enormously.

    - We usually find that when entropy decreases in one small system, it is because the universe was increasing its entropy greatly in the wider system.

- The more we understand nature at a fundamental level, the more mysterious the arrow of time becomes. Deep down, time is just like space; it is a label on events in the universe. There is no arrow of space—no preferred directionality—but there is an arrow of time.

- The same kind of reasoning that tells us why entropy will be greater tomorrow would seem to tell us why it should be greater yesterday.
    - That is a reflection of the fact that the fundamental laws of physics do not distinguish between the past and the future, and if we think we can prove that entropy will be greater tomorrow, then we should be able to prove that it was greater yesterday.

    - Nobody believes that the entropy of the universe was greater yesterday than it is today, but we cannot prove that using just the laws of physics.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 2.

Greene, *The Fabric of the Cosmos*.

Price, *Time's Arrow and Archimedes' Point*.

Questions to Consider

1. How many different aspects of the arrow of time can you think of?

2. What is your favorite story involving flashbacks, reverse chronology, or time travel? Is the passage of time portrayed realistically?

3. Can you imagine a world in which time existed, but there was no arrow to it?

The Second Law of Thermodynamics

Lecture 5

The central theme of this course is that entropy is the reason for the existence of the arrow of time, the fact that the past is different from the future. In the past, because of initial conditions near the Big Bang, the entropy of the universe was lower. In this lecture, we begin to put together the pieces of our picture of time with an exploration of the second law of thermodynamics: In an isolated system, entropy either increases or stays constant; it never decreases. Things happen in one direction of time—not the other.

The Laws of Thermodynamics

- There are actually four laws of thermodynamics, but we are primarily concerned only with the first and second ones.
    - According to the first law, energy is conserved; according to the second, as we know, entropy increases or remains constant in isolated systems.

    - The second law is crucial to these lectures. It says that there is an irreversibility—a direction—of time. Entropy increases in one direction and decreases as we go to the past.

- Although it is one of the most rock-solid laws of physics, when we look at the second law carefully, we realize that the statement of it is actually only an approximation. It is not absolutely impossible for entropy to decrease spontaneously; it is, however, extremely unlikely.

- The reason the second law seems to be immutable is that it is not a specific model of some fundamental interaction, like Maxwell's theory of electricity and magnetism. The second law is a metalaw; it refers to how different kinds of laws of physics can possibly work.

Development of the Second Law

- The second law of thermodynamics was first formulated in 1824 by a French military engineer named Sadi Carnot. It was Carnot who came up with the idea that entropy increases, although he didn't know about the idea of entropy itself.

- Motivated by a desire to catch up to the British in the science and technology of steam engines, Carnot set himself the task of formulating a concept for the most efficient possible steam engine. In the process, he discovered that there is a maximum efficiency that a steam engine can achieve.
  - Carnot further realized that this maximally efficient steam engine had an interesting property, namely, that it could be run backward.

  - We have already hinted at the idea that reversibility is at the heart of the arrow of time. A process that goes forward and backward equally well is a reversible process, and it does not have a direction of time.

- Most real-world steam engines are very inefficient and are not reversible. Today, we would say that they generate entropy. But Carnot's formulation of the second law is that it's possible to have either a perfectly reversible engine, which means that entropy stays constant, or any other engine, which means that entropy is increasing.

- About 40 years later, a German physicist, Rudolf Clausius, realized that Carnot's idea was a law of nature. Clausius was interested in thermodynamics—the science of heat; at the time, heat was considered a substance, called caloric. Clausius's discovery was that heat flows in only one direction.
  - If we put a box of hot gas next to a box of cold gas, the hot box heats up the cold one, and they equilibrate. We go from one hot box and one cold box to two warm boxes. Once we have two boxes at the same temperature, the heat can no longer travel.

- Notice that this is a one-way process; it is an arrow of time. We go from a difference in temperature to a sameness in temperature.

- Clausius's version of the second law can be thought of as the statement that heat gradients tend to even themselves out. Boxes of gas at different temperatures or other things, solids or liquids, tend toward equilibrium.

- Clausius invented the word "entropy" to quantify exactly what was happening, and his formula for the second law says that entropy is the change in heat divided by the temperature. The result will always be a positive number.

Our Intuition about the Second Law

- It might seem that Clausius's version of the second law is not compatible with how we know the world works. It seems to be saying that temperature gradients always smooth out, that different objects always come to the same temperature, no matter what we do.

- Such a statement seems to be at odds with our experience that we can heat things up. We can start with a room-temperature situation, such as a stove and some eggs we want to scramble, and we can turn on the stove and heat up the eggs. How is that possible if temperatures only even out? How is it possible to cool something down from room temperature by putting it in a refrigerator?

- The first law of thermodynamics says that energy is conserved, but we can change energy between different forms.
  - When you turn on the gas burner of a stove, you are not creating new energy. You are taking energy that was stored in natural gas, and you are combusting that natural gas to release its energy in the form of heat. The energy was always there; you are changing its form from unconsumed natural gas into heat.

- That is easy to do, and it does not violate the second law. Clausius's version of the second law tells us how heat moves around. It doesn't say that we cannot create heat by burning something.

- Decreasing the amount of heat in an object is more difficult than increasing it because the process does not involve just releasing energy. If we release energy, we increase heat, so how can we ever cool things down?
  - Again, the answer can be found in thermodynamics. Instead of applying heat to a box of gas, we expand the size of the box. The energy inside the box is the same, but because we are moving things apart, the molecules slow down and become colder.

  - That is the principle behind a refrigerator. We take Freon or some other appropriate gas, expand it, and it cools down.

  - Both freezers and refrigerators work in this way, but note that you cannot cool off your living room by opening the door of your refrigerator. Why not? The answer is that you are not actually destroying the heat that was in the Freon in your refrigerator; you are moving it around.

  - When we expand Freon, we cool it off, but at some point, we have to recompress it to make it go through the cycle again and again. That is why the backside of your refrigerator is hot.

The Uselessness of Energy

- This way of thinking about heat suggests another way of thinking about entropy. We said that entropy measures disorderliness, and we also said that Clausius gave us a formula for it, the change in heat divided by temperature. Yet another way to think about entropy is as a measure of the uselessness of a certain amount of energy.

- Energy is conserved, but it can change forms. If you have energy in a low-entropy form, you can do useful work with it. You can lift something up, drive a car, or fly an airplane. If you convert that energy into a high-entropy form, it becomes useless.

- A low-entropy concentration of energy is called fuel. We have fossil fuels sitting in the ground with energy in them in a concentrated form. We can extract the energy because the entropy of the fuel is low. Once we burn the fuel, we cannot go back. You can heat a room in your house by burning wood, but you cannot cool off a room in your house by unburning fuel and turning it into wood.

Does Clausius's Law Always Work?

- Clausius's version of the second law says that if we have two boxes at different temperatures and we put them next to each other, the temperature smoothes out; the gradient decreases.
  - If the system we are looking at is two fixed-sized boxes of gasses, that is a perfectly good formulation of the second law, but it would be a mistake to think that everything always smoothes out under all circumstances.

  - Think, for example, of a cloud of gas—not a box. If you went out into empty space and released a small amount of gas, what would happen? It would fly out in different directions. That is what you might expect according to the second law. It would become smoother and smoother, spreading throughout the universe.

  - Now imagine that you have a giant cloud of gas, an amount equivalent to billions of solar masses. Then, gravity kicks in. Of course, there is gravity even for a small box of gas, but it is not that important because the mass is very tiny. Once you have enough gas to make a galaxy, gravity becomes very important. The galaxy contracts, stars and planets form, and so on. That's how our galaxy started.

   - It's important to realize that the process of forming a galaxy increases the entropy of the universe. The formation of a galaxy makes the universe lumpier, not smoother, so increasing entropy does not mean increasing smoothness.

- A more widely applicable definition of entropy was given to us by Ludwig Boltzmann in the 1870s, based on his understanding of the existence of atoms.
   - In this definition, heat is actually thermal energy—the random motions of atoms. This understanding based on atoms led from thermodynamics to statistical mechanics, the study of the probabilities of atoms being in different arrangements.

   - Boltzmann realized that arrangements of atoms are macroscopically indistinguishable, and his insight was that entropy is simply a way of counting the number of arrangements of atoms inside a certain system.

   - In other words, the reason entropy increases, according to Boltzmann, is simply that there are more ways to be high entropy than to be low entropy. That is a rigorous definition that corresponds to our intuitive feeling that entropy measures disorderliness.

   - When entropy is low, the macroscopic configuration is very precisely arranged. There are only a few such configurations that look the same. When entropy is high, the configuration is spread out. There are many different ways to arrange the atoms, and all of them look alike.

   - Boltzmann's definition of entropy is the one that makes the arrow of time go. Once we understand it, we can ask why entropy was so low in the early universe.

Suggested Reading

Albert, *Time and Chance*.

Carroll, *From Eternity to Here*, chapter 2.

Von Baeyer, *Warmth Disperses and Time Passes*.

Questions to Consider

1. How does the second law play out in common household appliances, such as an oven or a refrigerator?

2. How does the second law play out in the evolution of the Earth? The universe? The biosphere?

Reversibility and the Laws of Physics

Lecture 6

We have seen that the arrow of time is fundamentally connected to the notion of irreversibility, but our best understanding of physics does not include this notion. For this reason, it's useful to think about the idea of reversibility and where it came from. In this lecture, we'll trace the development of the reversible laws of nature from Aristotle to Avincenna and Galileo and to Newton and Laplace. This exploration leads us to the question of why reversibility on the microscopic level is not reflected in our macroscopic world.

Newton's Insight

- Isaac Newton put the earlier ideas of Avincenna, Galileo, and others into a mathematical framework that allowed for the development of physics. His laws of motion and gravity suddenly made the world make sense.
  - Perhaps Newton's most famous law is the law of universal gravitation: the idea that what makes an apple fall from a tree and what explains the motion of the planets in the solar system is the same.

  - Newton realized that the force pulling the apple down from the tree could be the same force that explained the motion of the Moon around the Earth or the planets around the Sun. It was the universality of gravity that was new for Newton, and the reason that was a breakthrough is that the motion of the planets does not look like the fall of an apple.

- The motion of the planets is reversible, whereas the motion of the falling apple seems irreversible. It required the genius of Newton to realize that the laws governing the motion of the apple are reversible.
  - If you filmed the Moon going around the Earth with a movie camera and then you played that movie to an audience, no one

in the audience would be able to tell whether the movie was playing backward or forward.

- A solution to the equations of motion that is played backward in time is still a solution. That means that if we know the state of a system right now, we can figure out what the state was in the past. There is a match between where we are today and where we were.

- Since Newton's time, every attempt we have made to understand the laws of physics works in that way. In other words, we think that there is a state of the system right now, and if we know that state, we can evolve it forward or backward in time. It is perfectly reversible. How does that accord with the apple falling from the tree?
  - The motion of the apple does not look reversible. It starts at the top and ends at the bottom, never the other way around.

  - The key is that the initial state—when the apple was tied to the tree by its stem—and the final state—when it lands on the ground—are irreversible processes because entropy is involved. The trajectory of the apple from the tree to the ground is one where air resistance is not that important—the trajectory is caused by the influence of gravity on the apple, and that trajectory is perfectly reversible.

  - If you try to throw an apple into the air and catch it using the same motion for both actions, you will find that the trajectory of the apple is the same played forward and backward.

  - This was part of Newton's great insight: that the fundamental laws of nature do not pick out a direction of time. It is only the interaction of the apple with the tree or the ground that gives us the impression of irreversibility.

- The same thing is true for many other simple systems in nature. Newton applied it to planets and moons. Physicists apply it to billiard balls on a frictionless surface.

- The lesson we derive from this is that when we have simple systems, the Newtonian laws of physics apply, and the rules are reversible.
  - You may guess that the difference between Newton's laws of physics and the complex, irreversible processes we see around us is simply a matter of how many moving parts there are.

  - Note, however, that complicated systems are made out of individual simple systems. If the rules of physics govern what simple systems do, then complicated systems should obey similar rules. The challenge of reconciling those two facts will be the challenge of understanding how entropy works in the real world.

Determinism

- Newtonian physics is self-contained. If we know the state of a system at any one moment in time, Newton's laws of physics let us figure out what the state of the system will be at any moment in the future and what it was at any moment in the past.

- We can build up the entire history of the system starting from the information at any one moment. The present completely determines every other picture of the universe in the past and the future.

- This is a particular way of thinking about physics that is not at all obvious. It was not, for example, a property of Aristotelian physics.
  - According to Aristotle, if you see something that is not moving, you do not know whether a little while ago it was moving—someone was pushing it—or whether it had been sitting still forever. There would be no way, in Aristotle's physics, to figure out the past given the present.

  - Newton said that if an object was not moving, the cause was friction; the object was interacting with the environment. If we could recover all the information about the object and the environment and work backward, we could figure out exactly the state of the system arbitrarily far into the past.

- The French scientist Pierre-Simon Laplace realized that Newton's laws contained within them a feature called determinism. Knowing the state of the universe now, we can determine its state with 100% accuracy arbitrarily far into the future or the past.
    - Laplace further posited a vast intelligence—now called Laplace's demon—that knows everything possible about the world at one moment of time, knows all the laws of physics to arbitrary accuracy, and has infinite computational capacity.

    - To this demon, there is no difference between the present, past, and future. If the demon knows the state of the universe at one moment in time, it knows it at all moments of time.

- We can imagine other kinds of laws of physics that are not deterministic. In an Aristotelian world, for example, the laws of matter and motion are teleological, that is, oriented toward a goal.
    - We can also imagine laws that are past-dependent. In fact, we generally think of the laws of nature as past-dependent; we think that what will happen to us in the future depends on where we are now and where we came from.

    - However, if we have *complete* information, we do not need to also remember the past in order to predict the future. The past is embedded in the current situation.

Conservation of Information

- If we have an object moving in some direction, what do we need to know to predict what it will do next? According to Newtonian mechanics, what we need to know to figure out the future and past of a moving object is its position and momentum (velocity).
    - But we need to know the position and velocity of every single part of that object.

    - With a human being, we would need to know the position and velocity of every single atom in the body to be able to predict what the human will do next.

- One implication of Newton's laws is that information is conserved, meaning that the total amount of knowledge that we could possibly have about a system is the same at every different moment of time. The position and velocity of every particle in some collection of particles is the total amount of information we can possibly have, and that amount of information is the same at every moment. Information is neither created nor destroyed.
  - Of course, particles can be created or destroyed. An electron and a positron can come together and be destroyed, but they do not disappear into nothingness. They create photons that carry off both their energy and their information.

  - Not only energy but information is conserved in the universe. That is why we can predict the future and retrodict the past. That is why the laws of physics are reversible—because the total amount of information does not change.

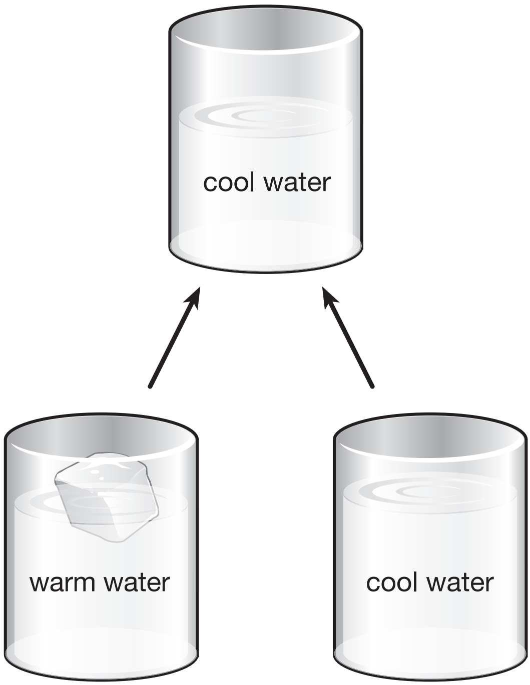
  - That is also why time has continuity, why the universe does not rearrange itself fully from moment to moment in time. The information contained in the universe is present at any one moment of time and is preserved from one moment to the next.

The Irreversibility of the Real World

- The tiny particles of which the world is made—quarks, electrons, neutrinos, and so on—basically obey Newtonian mechanics; their motion seems to be reversible. But when we get large collections of many, many particles, the real world is not reversible. Why not?

- Another way of stating this is to say that macroscopically, information does not seem to be conserved. If you believe that a glass of water with an ice cube in it is made of atoms, and those atoms have positions and velocities, then you believe that if you were Laplace's demon, you could tell the future and the past of that glass of water.

- But you are not Laplace's demon. You do not know the position and velocity of every molecule of water inside the glass. Instead,



Consider the apparent loss of information with a glass of water: A glass of warm water with an ice cube in it and a glass of cool water can evolve into what appears to be the same state—a glass of cool water.

you have macroscopic information, and from that, you cannot reconstruct the past. In the evolution from the glass of water with or without an ice cube to the glass of water in the future, information is lost.

- Clearly, there is something going on when we change our perspective from the microscopic to the macroscopic laws of physics. This is a complex topic, but in the next lecture, we will sketch out a few simple assumptions that will enable us to match the irreversibility of the real world to the reversibility of Newton's laws of physics.

Suggested Reading

Albert, *Time and Chance*.

Carroll, *From Eternity to Here*, chapter 7.

Price, *Time's Arrow and Archimedes' Point*.

Questions to Consider

1. Think about everyday events, such as writing, watching TV, or reading. How is information conserved? How is it lost at a macroscopic level?

2. What are the implications of Laplace's demon for human history? Do you think we could ever have enough information about human beings to accurately predict the future?

Time Reversal in Particle Physics

Lecture 7

The reversibility of the fundamental laws of physics raises a puzzle for our understanding of the arrow of time: How can it be true that the deep laws of physics are perfectly reversible, yet the macroscopic laws strongly pick out a direction of time? The fundamental laws of physics on which that tension is based came from Newton's classical mechanics, but today, quantum mechanics and particle physics have affected our notion of reversibility. In this lecture, we'll begin to understand exactly why quantum mechanics and particle physics are not fully reversible yet still do not help us explain the arrow of time.

The Four Forces of Nature

- Particle physicists tell us that there are four forces of nature, two that are long range and two that are short range. To a particle physicist, a force is not like friction or centrifugal force; it is one of the fundamental interactions that allows different particles to bump into each other and go their own separate ways or pull together.

- The long-range forces are the ones we know about in our everyday lives: gravity and electromagnetism. Of course, gravity pulls us to the Earth and keeps the planets moving around the Sun. Light, X-rays, and radio waves are waves in the electromagnetic field.

- The short-range forces, or nuclear forces, are known as the strong force and the weak force. The strong force is what holds the nuclei of atoms together. An atom is an electron or a set of electrons orbiting a nucleus. The nucleus is a set of protons and neutrons, which are, in turn, made of quarks. That collection of quarks that makes up protons and neutrons in the atomic nucleus is held together by the strong nuclear force.

- The weak nuclear force has almost no effect on our everyday lives. What we need to know about it is that weak interactions are not invariant under time reversal.

Varying Degrees of the Arrow of Time

- We need to recognize that there are different degrees of having an arrow of time. There are different ways in which you could be different from the past going to the future.
    - The weakest, most trivial kind of arrow of time is represented by something in the world that goes one way and not the other—a car going one way down a road. In some sense, that's an arrow of time, but it's not a deep, fundamental insight about nature.

    - The next level of an arrow of time is represented by fundamental processes going one way and another way but perhaps at a different rate or in a different way. Note that this is not the same as entropy.

    - The third level of an arrow of time is that things can only go one way. That is true irreversibility, and that is the arrow of time that we care about.

- Even Newtonian mechanics includes the weak first-level arrow of time; things happen in one direction but not the other.
    - For example, the Sun always rises in the east and sets in the west. That is, in some sense, an arrow of time. We can tell which was morning and which was evening from where the Sun is, but it's clearly an accident of nature.

    - If we made a movie of the Sun and played it backward, an audience would be able to tell that we were playing the movie backward because the Sun would be setting in the east, but we could easily imagine a universe in which the Sun really did set in the east still obeying the same laws of nature.

- Likewise, the hands of a clock move in the direction we call clockwise, but there's no difficulty in building a clock that goes counterclockwise. Even the expansion of the universe is something that just happens to be the case in our actual world. We can invent hypothetical universes that obey the same laws in which the universe is contracting.

- All these are just accidents of nature in our world. They are different from the past to the future, but they are not fundamental arrows of time.

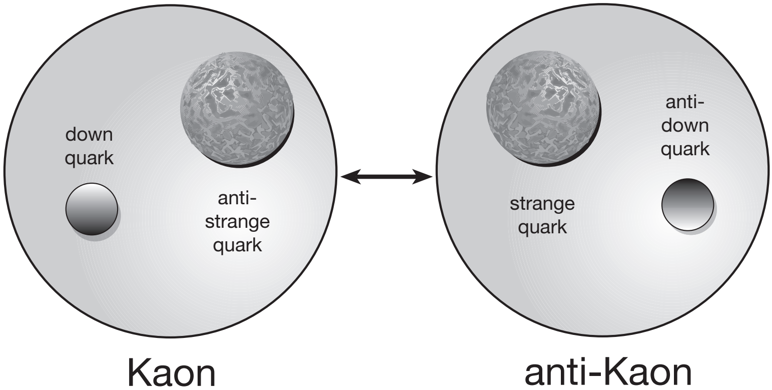
- The weak interactions of particle physics are in the second level. They are not irreversible, but one way they happen in time is different or at a different rate than when they happen another way in time.
    - In the language of Laplace, if you know the state of the universe at one time, you can evolve it forward using the laws of physics, including the weak interactions, and from wherever it gets to, you can know where you came from.

    - You can unevolve the universe—you can go backward—but you need to know that you are going backward in time because the weak interactions work differently going in one direction than the other direction.

Weak Interactions

- In particle physics, a paradigmatic experiment is to smash two particles together and watch what comes out. For a weak interaction, we could smash a proton and an electron together, and they could interact through the weak nuclear force and turn into a neutron and a neutrino.

- What about the time reverse of that interaction? Can we smash a neutron and a neutrino together and create a proton and an electron? The answers is yes; that is allowed by the weak nuclear force, but remember the force is weak, so the probability of that happening is very small.



Nature gives us a perfect candidate for experiments in particle oscillation: the neutral kaon.

- It makes sense to us that the interaction of two particles can generate two different particles, but the phenomenon of particle oscillation involves only one particle turning into another kind of particle and then turning back.

- Particle oscillation illustrates a distinction in the concept of reversibility.
  - In previous lectures, we've said that reversibility means you can play the movie backward or you can recover where you evolved from. In the weak interactions, these are not quite the same.

  - You can recover where you evolved from, but if you really understood the weak interactions and you saw one particle oscillating into another one, you could figure out whether you were playing the movie backward or forward.

- A particle called the neutral kaon exhibits particle oscillation. The neutral kaon has an antiparticle that has the same mass and is also neutral. The fact that the kaon has no charge means that it has no conserved quantities. It can oscillate into an antikaon and back into a kaon.

- We know this oscillation occurs because neither the kaon nor the antikaon is stable. They both decay into different particles. A kaon decays into a negatively charged pion, a positron, and a neutrino. An antikaon decays into a positively charged pion, a regular electron, and an antineutrino.

- The important point for us is that if time reversal is violated in weak interactions—if the weak interactions treat going forward in time differently than they treat coming backward in time—then kaons and antikaons will decay at slightly different rates.

The CPLEAR Experiment

- In 1998, an experiment was conducted at CERN to test whether time reversal invariants were a good symmetry of nature.

- The researchers started with a 50/50 beam of kaons and antikaons. If the weak interactions respected going forward in time and going backward in time equally, then an equal amount of decay products from kaons and from antikaons would be expected.

- But the results showed more kaons decaying than antikaons. In other words, it takes more time for a kaon to turn into an antikaon than for an antikaon to go back to a kaon. The time it takes to go in one direction is different than the time it takes to go in the other direction.

- Time reversal is not a symmetry of the weak interactions. Unlike the other forces, the weak force does not respect time reversal invariant.
    - Laplace seems to give us an implication of reversibility, and because the world is reversible, there must be something symmetric about the past and the future. What is the symmetry between past and future that is a reflection of the underlying reversibility?

    - The answer is found in a symmetry called CPT; the different letters here stand for different hoped-for symmetries of nature that are all violated, but the combination of all three yields a good symmetry of nature.

CPT

- The C in CPT stands for charge reversal. Basically, the C operation changes a particle for its antiparticle. You might think that if we had a collection of particles in a box and we changed all of them for antiparticles and did not let the box interact with the outside world, it would be the same—it would weigh the same, act the same, and so on. It turns out that is not true.

- P stands for parity. This literally means that we flip the orientation—we flip clockwise for counterclockwise. In other words, we hold the experiment up to a mirror. Again, you might think that if we did an experiment and then a mirror-image of that experiment, we would get the same answer, but that's not true either. Nature violates parity.

- T stands for time reversal. Here, you would expect that if we did an experiment forward in time and then did it backward in time, we would get the same answer, but we have just seen from the CPLEAR experiment that this is violated.

- All of these transformations, C, P, and T, are things that you might guess are symmetries, but all three are individually violated by the laws of physics.

- The violation of parity in weak interactions was a tremendous discovery, made in the 1950s by three Chinese-American physicists. In 1964, researchers showed that the combination of parity and charge conjugation (CP) also violated symmetry. However, CPT seems to be a perfectly good symmetry of nature.

- The fact that the weak interactions violate time reversal invariance still does not explain the arrow of time.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 7.

Greene, *The Fabric of the Cosmos*.

Questions to Consider

1. How are violation of time-reversal invariance and the arrow of time different, as defined by the second law?

2. Can you think of other experiments that would test time-reversal invariance in particle physics? Can you think of another test of parity invariance? What about CPT?

Time in Quantum Mechanics

Lecture 8

Quantum mechanics is a model of physics that was developed in the first half of the 20th century and came to replace the classical Newtonian view. It describes the world on both very small and very large scales, although on those very large scales, Newtonian mechanics also works. When we look at things that are very small, however, the predictions of quantum mechanics deviate from the expectations of Newtonian mechanics. Quantum mechanics is the correct theory of reality as far as everything we know about the universe is concerned, so we need to understand what the implications of this theory are for our understanding of the arrow of time.

Folktales about Quantum Mechanics

- Quantum mechanics is more complicated that just a theory of quanta—discrete packets. Quantum mechanics says that some things come in discrete packets, such as individual photons in an electromagnetic wave, but other things do not, such as time.

- In quantum mechanics, it's also true that we can predict only the probability of outcomes; we cannot predict with 100% certainty that any particular outcome will ever attain.

Quantum v. Classical Mechanics

- The laws of physics in classical mechanics are deterministic. They tell us what will happen and what did happen, and information is conserved along the way. Quantum mechanics is a much richer theory.

- The way quantum mechanics differs from classical mechanics is in what can be observed. In classical mechanics, we don't worry much about what we can observe. The state of the system is defined by its position and velocity.

- In quantum mechanics, we don't define a system by giving positions and velocities. In fact, there are no such things as positions and velocities. Instead, the world is described by something called a wave function.
    - This is basically a set of pieces of information that answers the following question: If we were to observe a certain thing, what is the probability that we would get a certain answer?

    - For example, I know that I have an orange, but I don't know exactly what state the orange is in. The orange has a wave function. If I look for where the orange is, the wave function can tell me the probability that I see it in one place or that I see it in some other place.

    - It is not just that quantum mechanics doesn't let us know where the orange is; quantum mechanics says there is no such thing as where the orange is. It's not that our measurements aren't good enough; it's that quantum mechanics doesn't let us go from the state of the universe to a prediction with a perfect match. There are always probabilities that get in the way.

- In quantum mechanics, we say that objects exist in superpositions of classical properties. In other words, there really is no position of the orange. It's not in one position or the other; it's in both. The wave function tells us how much of the superposition is here and how much is there and, therefore, the probability we have of seeing it in one position versus the other.

- The wave function can be a positive or a negative number. This means that we can contribute to the wave function in different ways, and they can interfere with each other. A positive contribution can cancel a negative contribution.

- There is no connection between this way of thinking and classical mechanics. There are no negative numbers for the probability of seeing something in classical mechanics. There are no negative numbers for probability in quantum mechanics either, but the "machine" we use to make the probability—the wave function—can be negative.

The Remarkable Consequences of Quantum Mechanics

- When we think about reality in this way—that it's made of wave functions, not positions and velocities—remarkable consequences follow.

- Some of those consequences are as simple as the fact that certain things are quantized. For example, in an atom, the energy levels that an electron can be in come only in discrete, quantized pieces. You cannot get any possible energy for the electron around an atom; you can get only certain possibilities.

- The major difference between quantum mechanics and classical mechanics is in the relationship between what exists and what you can see.
  - In classical mechanics, you can see everything there is. If you look hard enough, you can measure the position and velocity of every particle. Quantum mechanics embodies the wave function, but you don't see the wave function.

  - For example, the orange could have one position or another, but it doesn't have either one until I look at it. The orange has a wave function that describes the probability that I will see it.

  - When I look at the orange, that is when reality collapses. Before I looked at it, it was really in both positions—that's what the wave function is—but when I look at it, I will only ever see the orange in one position.

  - This is a bizarre feature of quantum mechanics: that reality seems to change when you look at it. But it's not true that our interactions with the world bring reality into existence. The laws of physics are still being obeyed, but the laws themselves are disturbing to us. They say that the rules by which physical objects evolve are different when we are looking at them and when we are not looking at them.

The Measurement Problem

- The rules of quantum mechanics tell us that things evolve in one way when we are not looking at them and another way when we look at them. This prompts us to ask: What counts as an observation? When does it become the case that reality collapses into one configuration?

- One of the puzzles here is the fact that wave function collapse seems to be irreversible, which means that information seems to be lost. If I look at the orange and I see it in one position, I don't know where it came from; I don't know what the wave function of the orange was before I looked.
    - There is a huge number of possible wave functions, all of which have some probability that I will see the orange in one position, and once I see it, that's where it is. I cannot reconstruct what the wave function was before I did my measurement.

    - That sounds like true irreversibility, an arrow of time, and this is why when we say that the fundamental laws of physics are reversible, we have to add a footnote saying, "except for quantum mechanics."

- In the 1960s, three physicists, Yakir Aharonov, Peter Bergmann, and Joel Lebowitz, argued that the reason we think there is time-asymmetry in wave function collapse is that we're asking a time-asymmetric question.
    - If we asked a symmetric question, we would get a symmetric answer, even in quantum mechanics. In other words, quantum mechanics doesn't impose time-asymmetry on the world; the world imposes time-asymmetry on quantum mechanics.

    - The lesson for us is that the arrow of time is not explained by the time-asymmetry of quantum mechanics. The time-asymmetry of quantum mechanics is explained by the arrow of time.

Interpretations of Quantum Mechanics

- The fact that information doesn't seem to be conserved in quantum mechanics has driven a philosophical field of interpretation.

- The leading interpretation, known as the Copenhagen interpretation, was developed by the founders of quantum mechanics in the 1920s and 1930s. This interpretation simply says that there are two different ways for a quantum mechanical system to evolve: what happens when you're not looking at it and what happens when you look at it.
  - According to the Copenhagen interpretation, the collapse of the wave function is real and it is irreversible. The collapse occurs when a macroscopic classical system, such as a person or a cat, interacts with a small-scale quantum mechanical system.

  - For a number of physicists, the Copenhagen interpretation is basically a stopgap measure; it's good enough as long as we don't do sufficiently careful experiments to distinguish between what happens on small scales and what happens on large scales.

- The leading alternative to the Copenhagen interpretation is the many-worlds interpretation, according to which there is no separate way of evolving when you are looking at a system versus when you are not looking at a system. The world evolves in only one way, and that is in accordance with the rules of quantum mechanics.
  - The many-worlds interpretation takes seriously the fact that the observer is a quantum mechanical system. Not only does an orange have multiple positions it could be in, but the observer has different possibilities, and they are also described by a quantum mechanical superposition.

  - When I look at the orange, my wave function interacts with the wave function of the orange, and I evolve into a superposition myself. There is a version of me that sees the orange in one place and another version of me that sees the orange in another place, and these two versions exist in separate worlds.

- Every time two quantum mechanical systems interact with each other, the wave function splits rather than collapsing. It splits into alternative versions of reality, all of which are equally real.

- According to the many-worlds interpretation, there is one wave function for the whole universe, and it evolves according to one equation. It is true that that wave function describes many universes, but it is still the same amount of information contained in the same wave function.

- The evolution of the wave function is completely deterministic. In fact, Erwin Schrödinger wrote the equation that tells us how the wave function evolves. The reason information seems to be lost when wave functions collapse is that we don't know where we are in the wave function.

- The application of this story to reality seems outlandish at first, but the more we look at it, the more logical it becomes and the better it fits with other things we think are true about the universe.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 11.

Greene, *The Fabric of the Cosmos*.

Questions to Consider

1. What is a quantum state? What are the different ways it can evolve?

2. Why does the process of observing a quantum system seem to pick out a direction of time? How does this relate to the second law?

Entropy and Counting

Lecture 9

Thus far in the course, we have talked about time and measuring time, and we've said that the real mystery of time is the arrow of time, the fact that the past is different from the future. We have also claimed that the reason the past is different from the future is that entropy increases. In this lecture, we will dive into what entropy really is—give the rigorous modern definition of it—and explain what we do and do not understand about how entropy works.

Boltzmann's Introduction of Atoms

- Our modern understanding of entropy comes from the Austrian physicist Ludwig Boltzmann in the 1870s. What Boltzmann added to the previous work of Carnot and Clausius was the idea that matter is made of atoms. This is a tremendously powerful idea. It means that ice, water, and water vapor are not different things but different arrangements of the same fundamental set of things.

- Of course, even in a very small collection of macroscopic material, there is a large number of atoms. The number that scientists use to indicate a macroscopic amount is Avogadro's number, which is the number of carbon atoms in 12 grams of carbon ($\sim 6 \times 10^{23}$).

- Avogadro's number is an indication that we can throw away information. That is the key to going from the world of atoms to the macroscopic world. It's called "coarse graining."
    - This is basically the idea that we can't possibly keep track of what every atom is doing in any tiny macroscopic object, so we need to keep track of less-than-perfect information.

    - Laplace taught us that if we wanted to know exactly what was going to happen, we would have to know the position and velocity of every atom, but that is completely impractical in the real world. Instead, we average; we take typical features of the whole collection of atoms in some macroscopic object.

  - These typical features include the density of the material (the number of atoms in any one volume), the pressure, the temperature (the average kinetic energy), and heat (the total thermal energy). Boltzmann realized that entropy, like these other thermodynamic properties, could be thought of as a property of the arrangement of atoms.

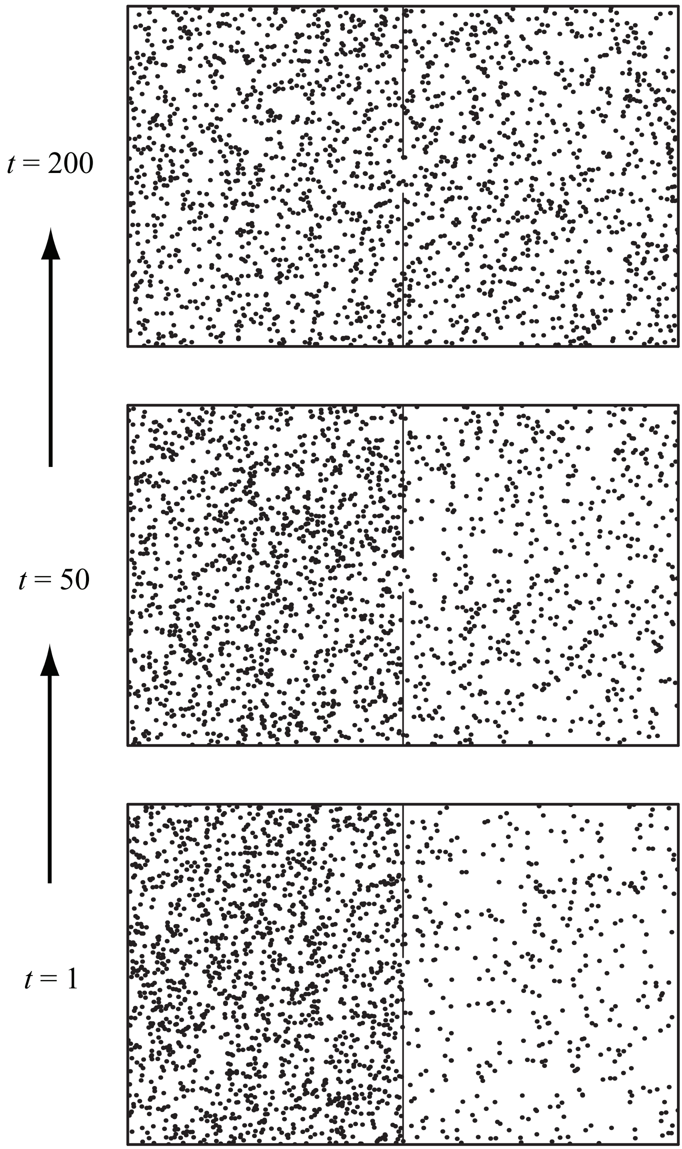
Boltzmann's Formula for Entropy

- Consider a box of gas with a partition in the middle of it that has a tiny hole. Most of the time, the atoms in the gas bounce around inside the box on either the right side or the left, but occasionally, an atom will pass from one side to the other through the hole.

- If we start with all the atoms on the left and we wait long enough, the box of gas will equilibrate, just as heat equilibrates when we bring a hot object close to a cold object. Intuitively, it's clear to us that entropy increases during this process.
  - Now imagine that we have 2000 particles of gas, all on the left side of the box. Every atom has a 1% chance per second of going through the hole; it doesn't matter whether the atom is on the left or the right. What happens in this circumstance?

  - Obviously, if all the atoms start on the left, they will gradually diffuse to the right until they even out. After only about 200 seconds, we can't tell the difference between the left and right sides of the box. Clearly, entropy has increased, and clearly, this is an irreversible process.

- Boltzmann tried to describe this process quantitatively. He tried to figure out how many combinations there would be of atoms in one configuration versus another and show that our intuitive notion of high entropy corresponds to many different arrangements of a particular configuration.



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Entropy increases over time as the distribution of particles equilibrates.

- If we try to count the number of arrangements of atoms, we see that it quickly becomes astronomical. The maximum number of arrangements with 1000 atoms on the right and 1000 on the left is greater than 2×10^{600}.

- The number of arrangements is small when there is an imbalance between left and right and large when there is a balance. Our intuitive notion is that entropy is higher when things are balanced and lower when it is unbalanced.

- Boltzmann developed the idea that entropy is really just counting the number of arrangements. In other words, entropy tells us the number of microscopic arrangements of a set of atoms that look indistinguishable to our macroscopic perception.

- Boltzmann's formula is that entropy is proportional to the logarithm of the number of indistinguishable states. This formula is $S = k \log W$, where S is entropy; k is Boltzmann's constant, a proportionality constant; and W is the number of ways we can rearrange things.

Understanding Logarithms

- A logarithm is basically the power to which you would raise the number 10 to get the number you want. The logarithm of 10 = 1. Why? Because in order to get 10, you raise 10 to the power 1, $10^1 = 10$. The logarithm of 100 is 2 because $10^2 = 100$. The logarithm of 1000 is 3 because $10^3 = 1000$ and so forth. The logarithm of 1 is 0 because $10^0 = 1$.

- Taking the logarithm of a power of 10 is easy, but we can also define the logarithm for every number in between. Basically, the logarithm is a function. It's small when the number you're taking the logarithm of is small, and it's negative when the number is less than 1.

- Notice that the logarithm grows slowly. The logarithm goes from 0 to 1 to 2 as the number we are taking the logarithm of goes from 1 to 10 to 100. The logarithm tells us the number of ways we can rearrange something, but it tells us in a more compact and manageable form.

- Recall that in our box of gas, the lowest-entropy configuration had 2000 particles on the left and 0 on the right. The number of combinations that looked like that was 1 and the logarithm of 1 = 0, so the entropy of that configuration is 0. It's the most orderly configuration we can have.

- With 1999 atoms on the left of our box and 1 atom on the right, the number of combinations was 2000, and the logarithm of 2000 is 3.3. With 1998 atoms on the left and 2 on the right, the number of combinations was almost 2 million, and the logarithm of that is 6.3. The highest number of combinations was 2×10^{600}, and the logarithm of that is just 600.3.

- Remember that before Boltzmann, Clausius had given us a notion of entropy that was very specific about exchanging heat. Boltzmann wanted to give a much more general definition, but he still wanted his general definition to match with Clausius's specific definition in the same arrangement.
  - One of the properties of entropy as it was already understood is that if we have two systems, each with a certain entropy, and we put them together to make one larger system, the total entropy is the sum of the individual entropies.

  - But Boltzmann wanted to define entropy in terms of the number of arrangements, and when we connect two systems, we open up many more ways to arrange the individual particles. The number of arrangements is not the sum of the individual arrangements but the product.

  - We take the number of arrangements we had in one system and multiply it by the number of arrangements in the other system. If we try to define entropy as the total number of ways we could arrange the atoms, that would give us an incorrect formula.

- The magic of the logarithm is that it fixes this problem. It has this wonderful property that the logarithm of a product is the sum of the logarithms. The logarithm of 10×10 is the logarithm of 10 + the logarithm of 10, which is 1 + 1, which is 2.

- Boltzmann realized that putting the entropy proportional to the logarithm of the number of arrangements preserves the property that the entropy of two systems added together is the entropy of each system added to the entropy of the other system.

Coarse Graining

- The microstate of a system is the exact Laplacian state. It is what we need to predict the future and to retrodict the past. If we know the microstate, then the evolution of the system would be perfectly reversible.

- But if we look at a glass of water with an ice cube in it, we don't see the exact microstate of every atom inside the glass of water. We know that it is a glass of water; it has a certain temperature; and maybe it has an ice cube. We call that information the macrostate.

- In the process of coarse graining, we define ahead of time what it is that we can macroscopically observe, and two arrangements of atoms that look the same according to our macroscopic observations are put into the same macrostate. We take all the possible states we could have and chunk them up into microstates that look the same macroscopically. The set of all those microstates is the macrostate.

- What Boltzmann's entropy tells us is that the entropy of an individual configuration of particles is the logarithm of the total number of other configurations in the same macrostate. We coarse grain by making some observations; we calculate how many particles and how many arrangements look the same, take the logarithm, and that's the entropy.

Summing Up Boltzmann

- Once we have Boltzmann's program in place, we have an understanding of how entropy works at a quantitative level. We take all the ways that a state can be—all the microstates of some system—and we divide up that space of states into macrostates. We calculate in each macrostate how many microstates there are, we take a logarithm of that number, and that is the entropy. Given that understanding, the fact that entropy increases makes sense.

- With Boltzmann's definition of entropy, high entropy means there are more ways to arrange things in a certain way and low entropy means there are fewer ways. Given a system that has low entropy, if we just let it evolve, it will naturally move to a higher-entropy configuration simply because there are more ways to be high entropy than to be low entropy.

Suggested Reading

Albert, *Time and Chance*.

Carroll, *From Eternity to Here*, chapter 8.

Questions to Consider

1. Imagine you have two liquids that tend to unmix themselves when you try to mix them together. What can you conclude about the behavior of the molecules from which they are made?

2. Can you think of some different ways we could coarse-grain all the states of gas molecules in a box? Why do some coarse-grainings seem more appropriate than others?

Playing with Entropy
Lecture 10

In the last lecture, we learned what entropy really is: The world around us is made of atoms that have many different ways of arranging themselves, but when we look at things in the universe, we do not see the individual atoms. There are many different ways that atoms look the same to us. Boltzmann taught us that entropy is just a logarithm of the number of ways to arrange the atoms so that they look macroscopically indistinguishable. In this lecture, we will compare Boltzmann's ideas about entropy with those of Clausius and Carnot; we'll then refine our definition and look at some of its philosophical implications.

Boltzmann v. Clausius

- Boltzmann's version of the second law of thermodynamics is that entropy increases because there are more ways to be high entropy than to be low entropy. We need to make sure that this idea of entropy is compatible with the formulations of Carnot and Clausius.

- According to Clausius, if we put together two boxes of gas with different temperatures, the temperatures will even out. With Boltzmann, we saw that if we opened a small hole between one box that was full of atoms and one box that was empty, the density of atoms would generally tend to even out. We want to check that that is also true for temperature, and we can do so with a fairly easy thought experiment.
    - o Temperature tells us how fast individual atoms are moving. With a high-temperature box and a low-temperature box, we can think of fast- and slow-moving atoms as different-colored grains of sand.

    - o In the boxes of gas with different temperatures, there are more arrangements with an equal number of hot atoms in the left and right boxes and an equal number of cold atoms in the left and right boxes; therefore, the highest-entropy state is one in which the temperature is the same.

- Boltzmann's reasoning gets us back to Clausius's version of the second law of thermodynamics: Temperatures tend to come to equilibrium. Boltzmann has unified the entropy of heat with the entropy of mixing. His one formula lets us understand both circumstances.

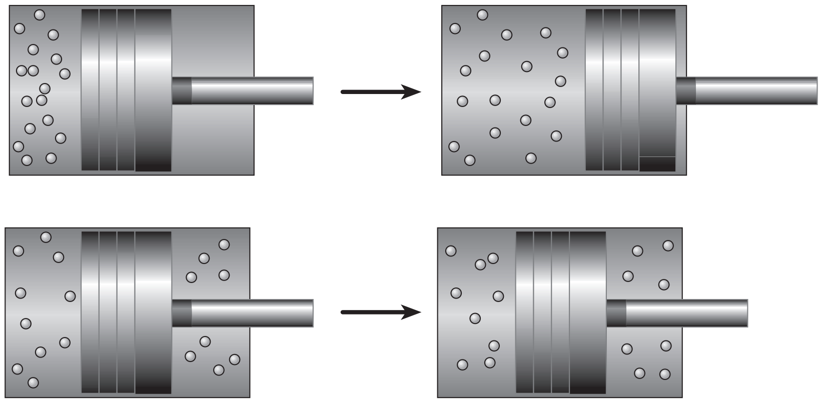
Boltzmann v. Carnot

- Carnot's interest in building the perfect steam engine led him to invent a cycle—a way of running a steam engine—that was maximally efficient. He realized that this maximally efficient steam engine requires a reversible process but that most real-world steam engines were irreversible.

- We would like to use Boltzmann's language of entropy to distinguish between efficient and inefficient steam engines. Another way of phrasing the question is: Can we get useful work out of a certain arrangement of atoms? A box of gas has energy it. Can we use that energy for some purpose?
    - o For this experiment, we start with a thin piston dividing a large cylinder, and we reconstruct our two boxes of gas. If we put all the gas on one side of the piston and the other side remains empty (a vacuum), we know that the piston will push away from the gas. It will move in the direction of the vacuum and expand the volume of the region that has the gas in it.

    - o In other words, the atoms moving around do useful work; they push the piston in one direction. We are extracting energy from the gas because as we expand its volume, we are cooling it down. We have lowered the temperature of the atoms.

    - o This is a low-entropy configuration, and we can do useful work with it. It's not that energy is created or destroyed; we are just taking energy out of the atoms and putting it into the piston.



Two configurations of gas in a piston: They have the same energy, but one is low entropy and the other is high entropy.

- Now imagine the same amount of energy but in a different configuration. Consider the same gas atoms with the same temperature and the piston in the middle of the cylinder, but put half the atoms on one side of the piston and half on the other side. The total energy is the same as we had before, but the distribution of atoms is different.
  - With the same amount of gas on either side of the piston, there is no net force, and the piston doesn't move. Even though the same amount of energy is in the piston now as before, we cannot extract that energy.

  - The reason for this, of course, is that the energy is in a high-entropy form. High entropy is an even distribution of gas atoms on both sides of the piston, and even though the energy is present, we cannot take it out.

- Boltzmann's way of looking at entropy, which says that entropy will be highest when there is a large number of arrangements, recovers Carnot's insight that low-entropy energy can do useful work and high-entropy energy cannot.

Refining Entropy

- We have said that entropy measures the disorderliness of a certain configuration of stuff. However, the true statement of entropy is that it is the logarithm of the number of configurations that look macroscopically the same.

- To get this notion exactly straight, consider again gas in a large box, a room-sized box. Imagine that the whole atmosphere in the room is squeezed into a tiny cube in the middle, just 1 mm on a side. This is not literally a cube but a randomly chosen configuration of all the gas atoms in the room.
  - Such a cube is a very low-entropy configuration. There are very few arrangements of the atmosphere in a room that, just by chance, have all the atoms squeezed into a 1-mm cube.

  - We could also consider a random arrangement of the atmosphere in the room squeezed into a 10-cm-tall version of the Statue of Liberty. This is also a very low-entropy configuration, but it is a much higher-entropy configuration than the 1-mm cube, simply because it is larger. There are more configurations that look like a 10-cm-tall Statue of Liberty than look like a 1-mm cube.

- It's important that we don't confuse complexity or simplicity with low entropy and high entropy. We also shouldn't get the idea that high entropy means more things are mixed together. What we really care about is the number of configurations.

Philosophical Implications of Boltzmann's Entropy

- The most important implication of Boltzmann's way of thinking about entropy is that the second law of thermodynamics is not really a law; it's a statistical statement about probabilities.
  - The reason entropy increases is that there are more ways to be high entropy than to be low entropy. Thus, it's probable that a random configuration that isn't already at maximum entropy will tend toward maximum entropy.

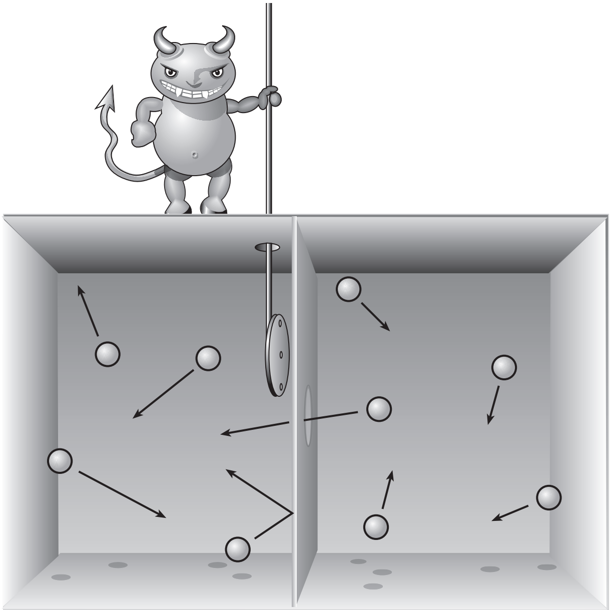
- Although it's improbable, entropy can decrease. With a box of gas in equilibrium—its highest-entropy state—there will occasionally be fluctuations that decrease entropy. However, the period of time it would take for a noticeable decrease in entropy to occur is probably much longer than the age of the universe.

- Once we accept the idea that entropy increasing is probable but not necessary, we can do experiments that intentionally decrease entropy.
  - Imagine we have a box of gas that starts in a low-entropy state, such as all the gas in one corner, and we let it evolve so that all the gas spreads out—entropy increases. Laplace's demon, which can see the position and momentum of every atom, can simply reverse the velocity of every atom from the end configuration to the initial configuration.

  - Because the laws of physics are reversible, the box of gas will experience an exactly backward evolution, from high entropy to low entropy. This is a gross violation of the second law of thermodynamics, but of course, it wouldn't happen spontaneously; we have arranged it to happen as a thought experiment.

  - However, any tiny deviation will spoil the experiment. We might know the position and velocity of all the atoms of gas in the box, but any disturbance of even one atom will change its precise velocity and position and spoil the experiment. Entropy will not decrease because we would be unable to accurately arrange all the velocities and positions of atoms in the box.

  - Even if we can imagine an isolated box of gas with decreasing entropy, once that box starts interacting with the outside world, the velocities and positions of the atoms in the box will be disturbed and entropy will no longer decrease.



Maxwell's demon decreases entropy by regulating the flow of high- and low-entropy particles.

Maxwell's Demon

- James Clerk Maxwell, known for unifying electricity and magnetism, proposed his own thought experiment to investigate the statistical nature of the second law in relation to Boltzmann's ideas about entropy.

- Consider again our box of gas with a partition in the middle at thermal equilibrium. Maxwell's demon stands on top of this box with a switch he can use to allow some atoms to go from right to left and others to go from left to right in the box. In particular, he allows the high-velocity atoms to go from left to right and the low-velocity atoms to go from right to left, but not vice versa.

- The demon does not disturb the velocity of any of the atoms, but because of his work, we end up with a box that has a high temperature on the right and a low temperature on the left. Again, we have violated Clausius's formulation of the second law. Heat seems to have flowed from thermal equilibrium out of thermal equilibrium.

- Obviously, the demon himself somehow creates entropy, but it is far from obvious how he does so. Over the years, people showed that the demon's door could operate without increasing entropy and that he could observe the atoms without increasing entropy.

- In 1960, Rolf Landauer, a physicist at IBM, made a model in which he showed that the demon could observe the atoms without increasing entropy by simply recording their measurements to make the experiment a reversible process. He showed that irreversible computations are the ones that generate entropy.

- It wasn't until 1982 that Charles Bennett, a computer scientist at IBM, finally solved the problem in a satisfactory way. What Bennett realized, using Landauer's ideas, is that Maxwell's demon can keep track of only a finite amount of information.
    - To convince ourselves that the atoms are going only one way and not the other, the demon must constantly update his information about where the atoms are. He needs to keep track of a potentially infinite amount of information.

    - That's possible as long as he can erase the previous entries in his notebook, but Bennett saw that erasing information is irreversible. Once something has been erased, we don't know where the information went.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 8.

Von Baeyer, *Warmth Disperses and Time Passes*.

Questions to Consider

1. Imagine you are a screenwriter, and your science fiction movie script includes a character who truly lives backward in time. Can you invent a plausible dialogue that character would have with someone experiencing the ordinary arrow of time?

2. Can you think of a Maxwell's demon–like experiment that lets you decrease entropy in a box without increasing it anywhere else? (Answer: No, but it's fun to try.)

The Past Hypothesis
Lecture 11

You should be convinced by now that Boltzmann's understanding of entropy is the correct one and that it can be reconciled with our previous understandings of the second law of thermodynamics from Carnot and Clausius. In this lecture, however, we'll see that there are some loose ends. It's true that Boltzmann's explanation gives us the right answer under certain assumptions, but these assumptions are not unproblematic. As we'll see, Boltzmann helps us understand why entropy will be higher in the future but not why it was lower in the past.

A Space of States

- To begin, let's imagine that we have a set of medium-entropy microstates in one macrostate and a larger set of high-entropy microstates in a larger macrostate. Keep in mind here that a state evolves through time, which means that every state lies on a unique trajectory. Given the laws of physics and given the state we are in, the complete definition of a state is that it is all the information we need to predict the future and reconstruct the past.

- Every state is on a trajectory, and trajectories never end. That is a consequence of the reversibility of the laws of physics. Trajectories do not stop evolving, nor do two trajectories come together or one split apart. Every trajectory is unique and will continue to evolve uniquely forever.

- This space of states that we are thinking about is full of trajectories passing through it, with every state on a unique trajectory. We know that the entropy now in the universe is not as high as it could possibly be or as low as it could possibly be, so we are, in some sense, in a medium-entropy state right now.

- Boltzmann points out that if we follow all the medium-entropy states, some of them will evolve into other medium-entropy states, some of them will go to higher entropy, and some of them will go to lower entropy. Remember, it's not an absolute law that medium entropy must go to higher entropy; it is possible to go to low entropy. But if we count, we will find that many more medium-entropy states will evolve to high entropy than to low entropy

A Typical Microstate?

- This picture raises two puzzles, the first of which relates to the statement that if we pick a typical trajectory, the entropy will increase.

- We have many trajectories in the medium-entropy macrostate; this is basically our current world—all the different arrangements of the particles that make us up. Boltzmann says that to predict what happens next, we randomly choose a typical microstate within this macrostate and ask what typically happens. If many more of the microstates increase in entropy, it's probable that entropy will increase.

- But who's to say what is typical? How do we know that we are on one of the trajectories that goes up rather than going down? The answer is that we don't. We have made an assumption that our trajectory will take us to higher entropy.

- The idea behind this kind of assumption goes back to Laplace and his principle of indifference: Every allowed possibility should be treated as equally likely.
    - o Laplace's principle tells us that if we want to predict the behavior of the universe, it is acceptable to consider what happens to a typical microstate; we simply count the microstates that do one thing versus another thing and turn that counting into a probability. If we don't know what's going to happen, we assume that every alternative is equally likely.

    - o It's true that if you knew the microstate of the universe, you could flip a coin and know whether it would come up heads or tails. But we don't know the microstate of the universe;

therefore, we say that it's 50/50. We assign equal weight to undistinguishable alternatives.

- Of course, there is only one universe, and it does have a microstate, so the justification for this assumption is a little bit shaky. Nevertheless, most people are happy to say that our microstate is probably typical within the macrostate we're in.

Lohschmidt's Reversibility Objection

- A larger problem with our picture of microstates goes back to the origins of Boltzmann's ideas. This problem is known as Lohschmidt's reversibility objection, named for Boltzmann's mentor, the Austrian physicist Josef Lohschmidt.

- Lohschmidt's reversibility objection basically comes down to a simple fact about the evolution of microstates within a space of all possible states, namely, that the trajectories don't begin or end. As a simple consequence of that fact, there are just as many trajectories along which entropy is decreasing as there are trajectories along which entropy is increasing.

- Boltzmann's statement is also true: If we start with medium entropy and let it evolve, entropy will usually increase. But how can we reconcile this with the statement that there are just as many trajectories in which entropy is decreasing as increasing? The answer comes down to a matter of which question we are asking.

- Boltzmann phrased his question in a particular way: Start with a medium-entropy macrostate and ask what happens to it. But that question is already sneaking in some directionality of time. Lohschmidt says that we could just as easily ask: Where did the medium-entropy state come from? What is a typical past of a state that is now in medium entropy? This is exactly the same kind of calculation, but with the arrow of time reversed.

- Because the laws of physics are reversible, the features of the past are the same as the features of the future. Therefore, for all the states that have medium entropy, many more of them came from high-entropy states in the past than came from low-entropy states. If we are going to take seriously Boltzmann's claim that most medium-entropy states increase in entropy as time goes on, then we must take seriously Lohschmidt's point that most of these medium-entropy states came from a higher-entropy past.

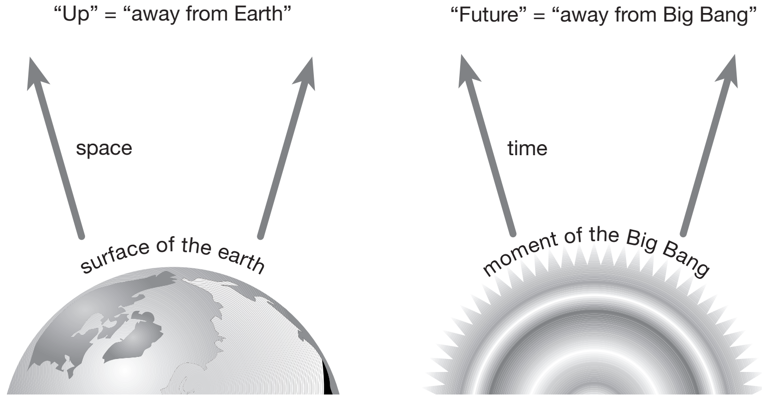
- Boltzmann gave us a convincing argument that starting from our medium-entropy configuration, it is natural for entropy to increase. There are more ways to be high entropy than to be low entropy. The same argument says that it is natural to come from a higher-entropy past because there are more ways to be high entropy than to be low entropy in the past, as well.

- Ultimately, Lohschmidt's reversibility objection is valid. If all we have to work with are underlying laws of physics that are symmetric with respect to past and future and Boltzmann's statistical ideas that we chunk up the space of states into macrostates that look the same to our macroscopic observation, we do not derive a different behavior for the future than we do for the past. We need to add something to Boltzmann's machinery, an extra assumption that is explicitly asymmetric with respect to past and future.

The Past Hypothesis

- This extra piece of machinery, the past hypothesis, is the assumption that the entropy of our observable universe was, not long ago, much lower than it is today. Further, the universe was the kind of low-entropy configuration that, under natural thermodynamic evolution, would get us to where we are today. There are many ways to be low entropy, but there is a specific low-entropy state that naturally grows into the universe we see.

- The past hypothesis for the universe talks about what we would call conditions near the Big Bang. Obviously, Boltzmann and Lohschmidt didn't know about the Big Bang, but they knew that the correct way to justify the second law of thermodynamics within



Just as space gets a direction because we live in the vicinity of an influential object, the Earth, time gets a direction because we live in the vicinity of an influential event, the Big Bang.

Boltzmann's framework was to add this assumption that explicitly broke the symmetry of past and future.

- The past hypothesis teaches us that the arrow time—the real difference between the past and the future—is not a matter of atomic theory, statistical mechanics, or anything like that. It's not deeply engrained in the nature of time; it is a feature of our environment, a feature of the universe in which we find ourselves.

- Given this assumption, Laplace's principle of indifference, and the definition of entropy as the logarithm of the number of microstates in a macrostate, Boltzmann gives us a convincing argument for why the entropy of the universe tomorrow should be higher than it was today. He doesn't give us an argument for why it would have been lower yesterday.

- The past hypothesis tells us that the reason the entropy of the universe was lower yesterday than it is today is that it was even lower the day before yesterday. The reason it was even lower the day before yesterday is that it was even lower the day before that, and so on, back 13.7 billion years to the Big Bang.

- We can't derive the history of the universe as we know it on the basis of purely dynamical grounds. We have to put in an assumption about the boundary condition in the past. There is no matching assumption about the boundary condition of the future. We get the answers right by assuming that there is nothing special about the future; it will be a typical state. This is where the imbalance between past and future comes from. We make a past hypothesis, but there is no future hypothesis.

A Future Hypothesis?

- Craig Callender, a philosopher of physics, has asked us to imagine what a future hypothesis would be like. His seemingly bizarre thought experiment involving Fabergé eggs collecting in your dresser drawer is actually no more bizarre than to imagine that there is a past condition in which the universe was in some very specific low-entropy macrostate among all the possible configurations it could have been in.

- The past hypothesis seems to be necessary and true if we want to understand the past, but it doesn't come from any underlying theory. It must come from cosmology. In other words, it's the conditions near the Big Bang—13.7 billion years ago—that are what we refer to when we talk about the past hypothesis.

- With that in mind, we understand the statement that the arrow of time is like the arrow of space. The arrow of space here on Earth is not something intrinsic to the laws of physics; it is a feature of our local environment, distorted by the gravitational field of Earth. The past hypothesis tells us that the arrow of time is the same. It doesn't come from the laws of physics but from our local environment—the observable universe—influenced by the Big Bang.

Suggested Reading

Albert, *Time and Chance*.

Carroll, *From Eternity to Here*, chapter 8.

Price, *Time's Arrow and Archimedes' Point*.

Questions to Consider

1. Can you imagine inventing new laws of physics—not like those in our world—that naturally have entropy increasing in one direction of time and decreasing in the other?

2. What are some other examples of the principle of indifference that we use to calculate probabilities? Do you think this kind of principle is warranted?

3. Following Callender's thought experiment, can you think of some other interesting future boundary conditions and how they would manifest themselves without violating the microscopic laws of physics?

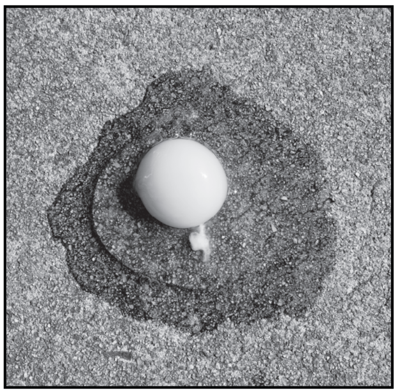
Memory, Causality, and Action

Lecture 12

With Boltzmann's idea of entropy and the past hypothesis, we now understand why there is an arrow of time. But remember that there is more than one version of the arrow of time. In addition to melting ice cubes in a glass of water, the fact that we can remember yesterday but not tomorrow is an example of the arrow of time. We've claimed that these kinds of examples also reduce to the fact that entropy is increasing. In this lecture, we will try to justify that grandiose claim, to connect the human aspects of the arrow of time to the physical aspects of increasing entropy.

The Past Hypothesis in Everyday Life

- The past hypothesis creates an imbalance between the past and the future; it gives us extra information about the past.
  - The past hypothesis modifies Laplace's principle of indifference in that it doesn't allow us to assume that we're equally likely to be in any of the microstates contained within some macrostate.
  - We happen to be in one of the very specific microstates in which, if we evolve them into the past, entropy would decrease.
- This information is deeply ingrained in how we think. If you're walking down the street and you see a broken egg on the sidewalk, you can retrodict the past of the



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We don't look at the macrostate of the broken egg and imagine that it is from some random microstate that we can't identify; we imagine that the microstate of the egg was one that came from a lower-entropy past.

egg much more readily than you can predict its future because of the past hypothesis.

- o You don't look at the macrostate of the egg and imagine that it has some random microstate that you don't know. You imagine that the microstate of the egg was one that came from a lower-entropy past.

- o You know that the way the real world creates broken eggs is first by making unbroken eggs. That is the likely evolution if you want to connect the past hypothesis—the low-entropy past of the Big Bang—to the current situation, where there is a broken egg lying on the sidewalk.

- This is where our asymmetry of epistemic access comes from. We are able to say more about the likely past given our current information than about the likely future because we know more about the past. We have a boundary condition in the past at the Big Bang of very low entropy. There is no boundary condition of the future.

- We think that the macroscopic information we have about the egg is all we need to talk about the past of the egg and the future of the egg, but if that were true, the set of things we could say about the egg's future would be the same as the set of things we could say about the egg's past.

- It is not just the knowledge of the state of the egg that lets us say it was unbroken. We pick out the possible trajectory of the history of the universe along which the egg was unbroken when we say that that's what we construct the past to be. That selection is based on the idea that there is a past hypothesis that fixes the universe to start in a state of very low entropy.

- This is why there is a directionality to our knowledge of the universe. If we didn't know about the past hypothesis, we wouldn't be able to remember the past any more than we think we can remember the future.

- We tend to think that the past is real and fixed, but there is a tension with that way of thinking and our belief that the underlying laws of physics are reversible.
    - At the deep level of our best understanding of the laws of nature, there is no more reality or fixedness to the past than there is to the future. The real difference between the past and the future is not how real or settled it is but how much we know about it.

    - We can infer much more accurately about the past because we know not only the current macrostate but also the past hypothesis. When it comes to predicting the future, all we have is the current macrostate. There is no future hypothesis.

Memory

- Let's think about an abstract notion of memory, the idea that we have something in the present world that tells us something about the past world. This is some artifact or record—a photograph, for example—that testifies to something that was really true in the past.

- Imagine that you have a photograph of yourself taken with John Lennon back in the 1970s. Why is it that this photograph is evidence that you actually met John Lennon? What reason do we have to say that just because you have a photograph, that event probably happened in the past?
    - Let's talk about the photograph in the same language that we talked about the egg on the sidewalk. What will happen to the photograph in the future? We cannot predict the exact future state of the photograph, but we know that it will eventually decay.

    - What about the past of the photograph? The reason there is a photograph now is that a real event took place and someone took a picture of it. But why do we treat the past of the photograph differently from the future of the photograph?

- The answer is the past hypothesis. Just as the most likely future of the photograph is to decay and have its molecules scattered throughout the universe, if it weren't for the past hypothesis, the most likely way for that photograph to come into existence would be by randomly becoming assembled out of molecules throughout the universe.

- Note that the way we justify using the photograph as evidence of the event is to say that if the event hadn't happened, the photograph wouldn't be likely. But we are not asking how likely is the photograph given the event or not given the event; instead, we're asking, given the photograph, how likely is the event?

- Given the photograph today—given some information about the macrostate of the current world—what can you conclude about the past? The answer is that without the past hypothesis, you could certainly not conclude that the event actually happened.

- To go from the photograph today to the actual event would generally lead you to a sort of random collection of things happening unless you could narrow down the trajectory of the universe by also including a low-entropy boundary condition in the past. It is the past hypothesis that lets us believe our memories, that lets us take for granted that what we think is documentation of past events is actually reliable.

Cause and Effect

- Another aspect of the arrow of time is that causes precede effects. But if we believe that the laws of physics are reversible, we can explain any moment in the history of the universe in terms of any other moment.

- Why is it that, in our phenomenological real-life world, we think that causes happen first and events happen second?
  - Given pieces of broken glass on the floor, we don't think about every possible way for the molecules of glass to arrange themselves in the form of a broken window.

- We imagine there was a past low-entropy boundary condition and given the past hypothesis, then the most likely way to get pieces of broken glass from the window on the floor is to have an unbroken window that something broke.

- What we call the cause of the broken window on the floor is the event that connects the unbroken window to the broken window. It is the past event that is lower entropy that needs to be connected to the future event that tells us that the cause must have happened before the effect.

- It is ultimately because we know more about the past (because of the past hypothesis) that what we call causes always precede what we call effects.

Free Will

- The same logic applies to the human ability to make choices, what we call free will. We think we have the ability to decide what to have for dinner tomorrow night. We don't think we have the ability to decide what to have had for dinner last night.

- But again, the laws of physics treat the two events the same. There is the future, and there is the past, and they are connected by the laws of physics to the present. If we knew the microstates, there would be no difference between predicting the future and retrodicting the past. But we don't know them. We have less information.

- Of course, the reason we think we have free will about the future and not about the past is the past hypothesis. The past hypothesis fixes enough about what happens in the past that we don't think we can affect it because there is no future hypothesis. The set of things that are open to us in the future is very large. We conceptualize that large set of possibilities in terms of choices, in terms of free will.

- Determinism—the idea of starting with the current state of the universe and predicting what will happen in the future—has a bad reputation because it is confused with fatalism. But the determinism of the laws of physics isn't the same as fatalism.

- Physics tells us that if we knew the microstate, we could say what our fate might be in the future, but we will never know the microstate—we can't.

- Physics can be determined yet not fatalistic exactly because there is no simple future boundary condition.

The Effects of the Past Hypothesis

- The arrow of time is not just a physics problem. Everything about how we live our lives relies on the arrow of time in an absolutely intimate way. The arrow of time, in turn, relies on the combination of the past hypothesis and our incomplete knowledge of the current state of the universe.

- This is not the usual way we think, but it is the right way of matching our best description of reality with the everyday reality in which we live. It is a reconciliation of the fundamental laws of physics with what we do in everyday life.

Suggested Reading

Albert, *Time and Chance*.

Carroll, *From Eternity to Here*, chapter 9.

Price, *Time's Arrow and Archimedes' Point*.

Questions to Consider

1. If entropy were higher in both the past and the future, would it be possible to have a reliable record of events in the past?

2. Why do we generally say that causes precede effects?

3. Do you think conservation of information robs us of free will? What would be the consequences of that view for how we live our lives?

Boltzmann Brains

Lecture 13

Boltzmann's story of what entropy is and why it tends to increase is compelling: Entropy goes up because there are more ways to be high entropy than to be low entropy. But to make the past work, we have to add this extra ugly ingredient, the past hypothesis. People have argued about this ingredient ever since Boltzmann came up with the idea. What does the past hypothesis really mean, and where does it come from? Our larger goal is to try to find a theory that explains the past hypothesis, and we start in this lecture by looking at a particular explanation that didn't work out.

Poincaré's Recurrence Theorem and Zermelo's Objection

- The 19th-century mathematician and physicist Henri Poincaré gave us the recurrence theorem: If there are particles in some system that can take on only a finite number of states or can move only within a bounded region, then whatever state we find that system in at one point in time will repeat itself an infinite number of times toward the future.

- This doesn't sound particularly surprising. If there are a finite number of things you can do and you have an infinite amount of time to do them, then you will keep doing the same thing over and over again. But when you think about the implications of this idea for the real world, it becomes disconcerting.
  - If we put an ice cube in a glass of warm water, the ice will melt; entropy will increase. But if we leave the glass of water on the table for an arbitrarily long period of time, Poincaré's recurrence theorem says that the ice cube will re-form.

  - In other words, Poincaré says that if we wait long enough, entropy will spontaneously decrease. In fact, his theorem says that the lower-entropy configuration will certainly happen. Fundamentally, this is simply a consequence of reversibility.

- The recurrence theorem of Poincaré was turned Boltzmann by a German mathematician named Ernst Zermelo. According to Zermelo, if motion is periodic, anything that goes up will eventually go back down and then go up again.
    - We can't prove that entropy will increase if we can prove that entropy will eventually decrease and then increase again, going on forever.

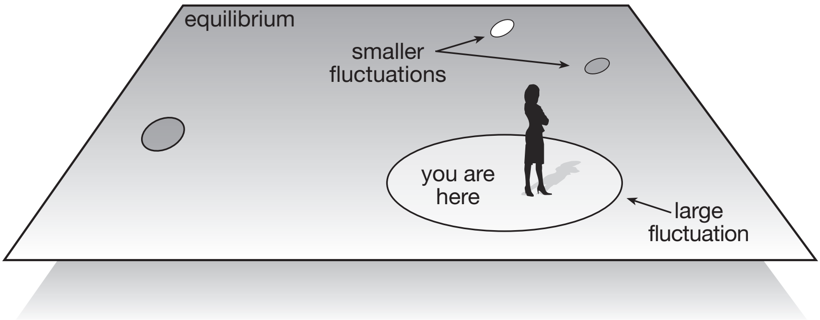
    - Zermelo's recurrence objection is stronger than Lohschmidt's reversibility objection: If entropy is increasing now, the recurrence theorem says that at some time in the future, it will certainly decrease. Thus, it can't be shown that there is a tendency for entropy to go one way or the other. We haven't really established a true arrow of time.

    - The simple answer to Zermelo's objection is that in the visible world—the observable part of reality—entropy was, in fact, very low in the observable past. There's a period of time in the universe that we have access to—about 13.7 billion years—but that period of time is much shorter than the timescale over which, according to the recurrence theorem, anything interesting would recur.

Boltzmann and the Anthropic Principle

- Because Boltzmann worked in a world that was governed by Newtonian physics, he thought of space and time as absolute and eternal. He saw the universe as an infinitely big space scattered throughout with infinitely many particles that were in thermal equilibrium most of the time.
    - In Newtonian physics, time doesn't begin or end; in an infinitely long time, the particles would come to thermal equilibrium. But Boltzmann also knew that thermal equilibrium doesn't last forever; it fluctuates.

    - If we wait long enough, arbitrarily large fluctuations to lower-entropy configurations will eventually happen. It may take a



In a thermal-equilibrium Newtonian universe, there are times and places where a large fluctuation happens, large enough to form a galaxy; we can live in these multiverses.

very long time, but in this Newtonian eternal universe, we have forever to wait.

- Boltzmann then made an argument based on the anthropic principle, the idea that we human beings don't get to see the typical parts of a big universe—a universe where there are many different conditions in many different places.
  - If typical parts of the universe are inhospitable to the existence of life, then we are going to find ourselves only in those regions that are hospitable.
  - The anthropic principle says that our job is not to construct a theory of cosmology in which the entire universe is hospitable to us. Our job is to construct a theory in which those regions that are hospitable look like the universe in which we actually live.
  - Boltzmann's strategy was to take this eternal Newtonian universe with fluctuating entropy and apply to it the anthropic principle.
- Even today, the anthropic principle has a somewhat shady reputation. It can seem empty. It's obviously true that we live where

we can live, but that's irrelevant unless we live in a universe where we can live in some places and not others.

- For example, there is a lot more volume in the space in between the planets in our solar system than on the surface of any one of the planets. Should we be surprised that life arose on the surface of the Earth rather than in between the planets? Of course not; life would just not survive for long in the interplanetary space of the solar system.

- The anthropic principle may or may not be the right way to think about the universe, but it is certainly an important part of cosmology. If we live in a universe that is big enough to have very different regions, then the anthropic principle tells us why we live here rather than somewhere else.

- Boltzmann said that most of the places in this large universe—most of which is in thermal equilibrium—cannot support life. But there will be fluctuations—regions of space in which the molecules randomly find themselves in a low-entropy configuration. If we wait long enough, there will be large fluctuations, and if we wait for a very long time, there will be a fluctuation large enough to form an entire galaxy.

- Without knowing about the Big Bang or the existence of other galaxies, Boltzmann suggested that there could be random, smoothly distributed gas and dust in the universe, and if we wait for eternity, it will simply happen that the random motions of that stuff will collect into something that looks like our galaxy. Outside that region, it will not look like our galaxy, but here, it will.

- In Boltzmann's scenario, entropy does not increase forever. It can decrease locally because of some fluctuation, and then it will increase again. The overall evolution of entropy is actually symmetric; it goes up and down equally often. Is Boltzmann going to predict that entropy increases just as much as it decreases? That's not the right way to think about it.

- As we argued, the direction of time in which entropy was lower is the direction we remember (the past). The region of time in which entropy is higher is the direction where we can make choices (the future). It doesn't matter what coordinates you use; what matters is that we always define the past to be the direction in which entropy was lower.

- If entropy fluctuates, there are two possible places we can live: while it's going down or while it's going up. People living in either place would define the past as the minimum point of entropy. This scenario is potentially compatible with the data.

- Boltzmann's idea that the random evolution of chaos ultimately creates the universe is compelling, but in the end, his hypothesis fails. This was pointed out in the 1930s by Sir Arthur Eddington, an astrophysicist in England, who noted that small fluctuations in entropy are much, much more likely than large fluctuations.
  - Boltzmann's scenario makes a prediction, namely, we make whatever we want in this Newtonian universe via the tiniest fluctuation possible. If we want to make a star with some planets, we make the star and the planets; we would not make billions of other stars or an entire galaxy.

  - If we want to make a person, we wouldn't need to make the Earth. We could just fluctuate random molecules into the shape of a person. Of course, that's very unlikely, but it's much more likely than fluctuating the entire Earth with many, many people on it.

  - If we are in an eternal Newtonian universe with random fluctuations, the easiest way to make an apple pie—contrary to what Carl Sagan said—is just to fluctuate the apple pie.

Boltzmann Brains

- What does Boltzmann's scenario say about you and the past hypothesis? In this eternal universe where things fluctuate into existence, it's immensely more probable that you fluctuated into existence with your memories randomly out of the surrounding chaos than that your memories actually happened.

- In fact, you don't even need you. A thinking person is defined by his or her brain and central nervous system. If that's the case, then we don't need to fluctuate a whole body into existence; we can just fluctuate a brain with whatever memories or thoughts we want it to have. This horrible implication of Boltzmann's scenario is called Boltzmann brains.

- If we live in chaos—if the universe simply fluctuates—almost all observers in that universe would be disembodied brains. The fact that we are not disembodied brains means that we don't live in that universe. But how do we know that we're not Boltzmann brains?
    - The simple and short argument against that statement is this: If you believe that you're in some city and outside of your current location, the city exists, Boltzmann's scenario says that the impression of that city is much easier to put into your brain by itself than actually creating the city. Thus, once you leave where you are, there shouldn't be any city there.

    - The real reason that Boltzmann wasn't right is something called cognitive instability. If you fluctuate into existence randomly, all of your impressions about physics, math, logic, and philosophy are most likely to also have fluctuated randomly into your brain.

    - If this scenario is true, you can never have any rational justification for believing that the scenario is true. You can never have any reason to believe the thoughts you think you have if you live in this universe. That's why it's called cognitive instability. Once you believe it, you realize you have no rational reason for believing it.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 10.

Questions to Consider

1. What kind of collection of matter do you think it takes to make a functioning "brain"? Can something that fluctuates randomly into existence be just as alive and conscious as something that evolves and ages normally?

2. What is the best argument that we are not Boltzmann brains? What's the best reason to think that the universe as a whole is not a random fluctuation from a higher-entropy state?

Complexity and Life

Lecture 14

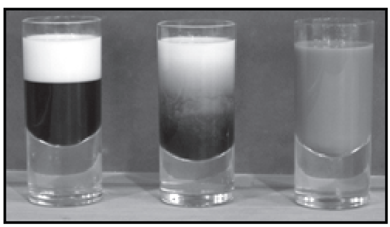
In the last lecture, we talked about a cosmological scenario that attempted to account for the arrow of time just by imagining that the universe was infinitely big and lasted infinitely long and there were random fluctuations that could give rise to people like us. We found that it didn't work. If we lived in that universe, individual complex creatures could be made through random fluctuations, not through billions of years of evolution. In the next few lectures, we'll return to the real world and see how what we know about the actual features of life on Earth—including how human beings think and perceive time—matches up with what we think about the arrow of time.

Defining Complexity

- In the 1960s, the Soviet mathematician Andrey Kolmogorov defined the complexity of something as the length of the shortest description that captures everything relevant about that thing.

- When we talk about the complexity of some living being or nonliving object in the universe, we coarse grain. We don't list the position and momentum of every atom; instead, we describe a certain living being as having a certain number of proteins, molecules, and so forth. The complexity of an organism is Kolmogorov's complexity applied to that coarse-grain description.

- It's important to understand that low entropy or high entropy doesn't necessarily correspond to simple or complex. The example of milk stirred into coffee shows us that complexity can arise when entropy is in between very low and very high.



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Neither low entropy nor high entropy corresponds to simple or complex; complexity can arise when entropy is in between very low and very high.

- What's true for the cup of coffee is also true for the universe. Basically, the universe began 13.7 billion years ago in a low-entropy state and a simple state. It was homogeneous. It was smooth everywhere, and everything was densely packed.
    - o The far, far future of our universe is also very simple. Everything will scatter to the winds, and we will have empty space once again.
    - o The middle universe that has medium entropy is complex. It is today that we have galaxies and stars and planets and life on those planets.

- Complexity depends on entropy; it relies on the fact that entropy is increasing. We don't have to worry about how complexity can arise in a universe evolving toward a heat death. The simple fact that entropy is increasing is what makes life possible.

Erwin Schrödinger's Definition of Life

- A careful construction of the second law of thermodynamics says that in a closed system—an isolated system that is not interacting with the rest of the world—entropy either always increases or remains constant. But a living being is not a closed system; it interacts with its environment constantly. The second law does not, however, rule out the existence of a living organism. In fact, it allows for life to exist.

- One of the best ways of thinking about this was put forward by Erwin Schrödinger, the pioneer of quantum mechanics. Schrödinger came up with a wonderful definition of what life is: It is something that goes on doing something much longer than you would expect it to.
    - o To understand what Schrödinger had in mind, imagine a glass of water with an ice cube in it. Over the course of a few minutes, the ice cube melts, and the water in the ice cube comes to equilibrium with the water around it. Once that equilibrium is reached, everything stops.

- Now imagine a glass of water with a goldfish in it. The goldfish does not come to equilibrium with the water around it. It maintains its integrity even though, by mass, most of the goldfish is also water. If you give it food, you're allowing that goldfish to take advantage of energy in a low-entropy form, and it can last a long time. This is what Schrödinger had in mind: A living being can put off the approach to thermal equilibrium for a long time.

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Schrödinger tells us that life is something that goes on doing something much longer than we would expect it to.

- What's going on here is actually very similar to the action of Maxwell's demon in maintaining a low-entropy situation without violating the second law. The demon is making use of the fact that he lives in a low-entropy world to keep his box of gas in a low-entropy situation. By itself, the box would equilibrate; both sides would come to the same temperature. The demon increases the entropy of the universe by writing things down in his notebook and later erasing them.

- If the external world were already in equilibrium, the demon could not do that. The entropy of a system that is in equilibrium cannot be increased.

• This is a general paradigm for thinking about how life persists. Schrödinger tells us that the complexity of a living being can last longer than you would expect it to. It does not come to thermal equilibrium because there is plenty of room for entropy to grow.

Low Entropy in the Biosphere

- We typically say that the Sun is the source of energy for living beings on Earth. But it's not the energy we get from the Sun that matters; it's the fact that the energy is in low-entropy form. The Sun is a hot spot in an otherwise cold sky. If the whole sky were the temperature of the Sun, we would get much more energy than we get now, but we would come to equilibrium with the sky very quickly, and all life would cease.

- Likewise, if the whole day and night sky were the temperature of the real night sky—completely dark and cold—the Earth would quickly come to the temperature of the night sky, and life would cease. The reason we have life is that the whole sky is not at the same temperature, and we do not quickly come to thermal equilibrium.

- We give back to the universe just as much energy as we get from the Sun. But if we don't get a net gain of energy from the Sun, what is it that drives life on Earth? The answer can be found in the fact that the energy we get from the Sun is in the form of visible light.
    - For every 1 photon of visible light we get from the Sun, we give back 20 photons to the universe, each with about 1/20 of the energy. We radiate infrared light to the universe, which means that we increase entropy by a factor of 20.

    - Our biosphere is far from a closed system. Energy comes in, we increase its entropy by a factor of 20, and then we give it back to the universe in the form of infrared radiation.

- Can we account for the increase of entropy quantitatively when we compare the amount that we have increased the entropy of the universe through infrared radiation to the amount that we have decreased the entropy of the universe by inventing life here on Earth?
    - The answer is yes, we can do the necessary calculations, and when we do, we find that the Earth has increased the entropy of

the universe over the course of the history of life by 4 billion times the amount that the biosphere has decreased the entropy of the universe.

- The bottom line here is this: The origin of life on Earth and the existence of life on Earth do not violate the second law.

The Origin of Life

- Before we talk about the origin of life, it's important to note that the process of evolution is not working toward the goal of greater complexity—or any goal at all. The way evolution works is that individual species and the genes and DNA they carry flourish or don't in whatever environment they are in, and when they flourish, they reproduce and create more of themselves. Sometimes flourishing means being complex, but sometimes it doesn't.

- There are two schools of thought about the ways in which life could have started on Earth, one of which is called "replication first." In this view, the most important feature of life is that a living being can reproduce itself. Some biologists argue that RNA molecules could have come first and reproduced themselves. Later, these reproducing molecules formed cells around themselves and became the first single-celled organisms. We can think of this as software before hardware.

- The competing school of thought is called "metabolism first." This school argues that the use of complex chemical reactions to take advantage of the low-entropy environment on the early Earth came first. This is hardware before software.

- From one point of view, it makes sense to have hardware without software. The metabolism first school says that the first life was just a chemical reaction, something like fire, taking advantage of the fuel around it to get going.
    - The early Earth most likely had an atmosphere that was rich in hydrogen and carbon dioxide. The interesting thing about this atmosphere is that it was low entropy. To increase entropy—

which is what the world wants to do—that hydrogen and carbon dioxide would be converted into methane and water.

- The problem is that to go from the original situation of low entropy to the situation of higher entropy requires a chain of reactions that is very difficult to get started. The hypothesis is that those complicated series of reactions started in very specific geological formations.

- If this story is true, the reason life started is that it was trying to increase the entropy of the primitive atmosphere on Earth. There were many ways to rearrange the fundamental structure of the things in the Earth's early atmosphere that would have had a higher entropy, but to get there required something complicated, like life.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 9.

Gell-Mann, *The Quark and the Jaguar*.

Schrödinger, *What Is Life?*

Questions to Consider

1. What is the best definition of "life"? Is a virus alive? A computer program? A forest fire? A galaxy?

2. What are the different ways in which living organisms increase the entropy of the universe around them? Could life as we know it exist in a high-entropy (equilibrium) environment?

The Perception of Time

Lecture 15

In this lecture, we'll try to answer a question that many of us have when we're talking about the mysteries of time: Why am I always late? Of course, we can't come up with a specific answer, but we can talk about how our brains and bodies measure the passage of time and how we perceive that passage. The reason we feel the passage of time is that our bodies have clocks in them, such as our heartbeats and our breathing. But as we'll see, biological clocks are not very reliable compared to mechanical or electronic clocks because our bodies are affected by many things that are outside of our control.

Biological Rhythms

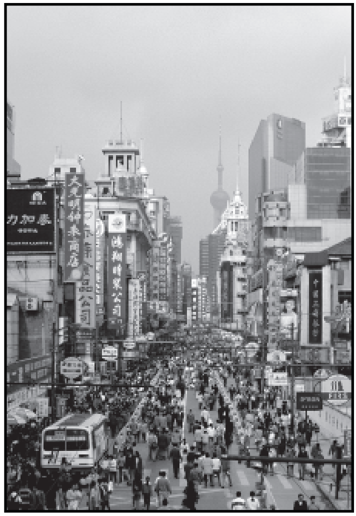
- One way of thinking about an advanced organism, such as a mammal, is as a network that includes the brain and the different systems in the body, such as the nervous system, circulatory system, and so on. On the basis of network theory, we can make predictions of how the rhythms cascade through the body.

- Biological networks move faster in smaller animals, and smaller animals have faster heartbeats than larger animals. They also have shorter life-spans. It's an interesting feature of our biology that somehow a shrew and an elephant have similar "blueprints," although these take reality in different forms—a tiny form for the shrew and a larger one for the elephant. This kind of scaling law goes all the way down to the cellular level.

- Unlike shrews and elephants, human beings are affected by another variable, the culture in which we find ourselves. We all know that different cultures approach time differently. In fact, various studies have been done to try to measure the pace of life in different cultures.

- o Not surprisingly, people in higher-population areas have been found to walk faster than they do in smaller-population areas.

- o Researchers comparing the pace of life in cities over time have found that over the last 20 years, the pace of life has increased by 10 percent. In areas that are rapidly industrializing, the increase in the pace of life is even greater.



The areas of the world that are developing, industrializing, and gaining high technology the most quickly also see their pace of life increasing the most quickly.

Perceiving the Passage of Time

- We might think that the human brain is similar to a computer because it clearly computes in some sense, but the way the brain came together is very different than the way a computer program is written. The brain evolved over billions of years by an incremental process in which random possibilities were tested. A computer program, in contrast, is usually written to address a task from the top down.

- In the brain, information for any task you might want to do is probably shared among many different structures. In particular, keeping time is a highly distributed feature in the brain.
  - o Neuroscientists have discovered that they can remove the cerebral cortex (the advanced parts of the brain) in rats, and the rats are still able to tell time. This means that whatever we are doing when we are measuring duration and time, it's not a matter of our conscious brain; there are unconscious things going on.

- Another experiment showed that mice with intact brains could keep track of at least three different rhythms.

- Inside our brains is more than one timekeeping device. In fact, we can sort of roughly categorize the different kinds of timekeeping. One part of the brain keeps track of what time of day it is, another part keeps track of how much time has passed during certain tasks, and yet other parts are more or less like alarm clocks. They keep track of time before some relevant future event.

- Neuroscientists have been able to isolate at least three different things that affect our perception of the passage of time: (1) pulses in the brain, (2) sensory input and focus, and (3) the accumulation of memories.

Pulses in the Brain

- Different neurons in the brain do work via pulses, and together, multiple levels of pulses help us perceive the passage of time.

- These pulses can be affected by stimulants, such as caffeine, and depressants, such as alcohol. When you drink caffeine, your internal clock seems to speed up compared to the outside world. Stimulants or depressants are believed to affect the neurotransmitters that send signals from neurons to other cells in the brain.

- The neurons send these neurotransmitters, such as dopamine, in the form of pulses. Caffeine, alcohol, and other drugs can make it easier or harder for these neurotransmitters to be sent, and that's what speeds up or slows down our internal clocks.

Sensory Input and Focus

- When you are focused on a task, you don't pay as much attention to the outside world, and in some sense, you also don't pay as much attention to your internal clock. Your internal timekeeping device seems to slow down while the outside world speeds up.

- In contrast, if you're bored or are not focused on any one task, the opposite effect happens. Your internal clock seems to go faster while the outside world slows down.

Accumulation of Memories

- Often, in high-stress situations, time seems to slow down, by which we mean that your internal clock speeds up, but the rest of the world seems to slow down.

- Researchers have found that conditions that create stress and speed up the internal clock do not help us perceive the outside world. Still, subjects in high-stress experiments report that time slowed down for them in recollecting a stressful event.

- One theory explaining this phenomenon is that the more memories we accumulate, the more time seems to have passed. When you are in a high-stress situation, your brain does its best to record absolutely everything. It accumulates a huge amount of data, even though it does not perceive things any more quickly than it would otherwise. When you think about the situation afterward, you have more memories—more data to leaf through—and, therefore, it seems as if more time has passed.

- This hypothesis gets some support from the fact that time seems to pass more quickly as we age. For example, when you were a child, summer seemed to last forever, but when you get older, it seems to rush by.
    - It may be that when you were young in the summertime, such activities as going to the beach were new to you, but when you get older, you've been to the beach and you don't take in as much new information about the experience as a child would. Thus, time seems to pass more quickly for you compared to when you were a child.

    - Experiments in which 20-year-olds and 60-year-olds are asked to estimate the passage of time show that younger subjects are much more accurate in their estimations than older ones. For older people, it takes longer for the same amount of subjective time to pass.

- Another hypothesis tries to quantify this experience of the passage of time by saying that the amount of time we experience grows logarithmically with our age.
    - If you've ever been on a boring plane ride, it seems to last forever while you are experiencing it, but when you recall it after the fact, it seems to go by quickly. You might remember that you were bored, but you don't have some elaborate memory of every single event because none of the events was interesting.

    - Because you were not making new memories, your subjective time after the fact seems to make the trip quite short.

Experiencing the Present Moment

- We all think that there is a moment called "now" that we are perceiving. But if you think about it, what we call the present moment isn't the present moment. It takes time for the information we are gathering to get to us and for our brains to process that information.

- If you touch your nose and your toes at the same time, you will notice that you feel the touch simultaneously, although you shouldn't. The amount of time it takes the nerve signal to travel from the nose to the brain is much less than the amount of time for the signal to travel from the foot to the brain. The brain takes into account that our feet are farther away than our faces.

- It turns out that what we consider to be the correct moment right now is actually about 80 milliseconds in the past. You can measure this by watching a person dribbling a basketball and moving away from you. You see and hear the sound at the same time in your brain until the person gets so far away that it takes more than 80 milliseconds for the sound to reach you. At that point, there is a mismatch between the sound and the sight.

The Stanford Marshmallow Experiment

- The Stanford marshmallow experiment shows that our orientation toward time is a crucial component of how we live the rest of our lives.

- In this experiment, children are given one marshmallow and offered another one if they can wait a few minutes before eating the first. Psychologists claim that the difference between eating the first marshmallow immediately and waiting to get two marshmallows later shows something about a person's orientation toward time.

- There are some people who, in some sense, dwell in the past; what they care about most is what happened in the past. Others live in the present; they want that marshmallow right now. Still others are future oriented; they will sacrifice the opportunity to eat the marshmallow in front of them to get the marshmallow in the future. This ability to take the future just as seriously as we take the present is a good predictor for how we approach many situations in our lives.

Suggested Reading

Levine, *A Geography of Time*.

Zimbardo and Boyd, *The Time Paradox*.

Questions to Consider

1. Can you think of reasons why the pace of life is faster in dense, developed areas? How would you test these hypotheses?

2. When do you perceive time to be moving faster and slower? How would you interpret that perception in terms of your biological rhythms and the accumulation of memories?

3. How would you describe your personal orientation toward time?

Memory and Consciousness

Lecture 16

Both remembering the past and predicting the future are crucial for human consciousness, for how we process information and make sense of our lives. In this lecture, we'll return to psychology and neuroscience, and we'll see even more clearly that the human brain is a complicated place—much harder to understand than the physical universe. The single lesson we will learn over and over again is that the brain does things in a very distributed way, which is exactly as we would imagine given evolutionary theory about how the brain came to be.

The Hippocampus and Place Memory

- Probably the single most important part of the brain related to memory is the hippocampus. The hippocampus is part of the limbic system, which is interior to the cerebral cortex. Many specific kinds of memory functioning are served by the hippocampus, such as place memory—the memory we have for different places in the world.

- To study various functions of the brain, neuroscientists look at the firing of individual neurons when certain mental procedures are taking place. From such research, the hippocampus has been found to have place cells that give us place memories. These cells always fire when we are trying to recognize places we are in or places in photographs or other depictions. It's fascinating that memory of places is confined to a different part of the brain than, say, memory of a person or a song.

- Of course, it's not true that the place cells in the hippocampus have one cell per location. There is a pattern of cells in the brain that lights up when you're in one place and a different pattern that lights up when you are somewhere else. These location memories are some of the strongest memories we have.

- In complicated memories, it's sometimes true that a single neuron will always fire. One researcher discovered that whenever he showed any individual patient a picture of Jennifer Aniston or a picture of the TV show *Friends*, the same neuron would light up. It is not that the "Jennifer Aniston neuron" contains everything you know about Jennifer Aniston, but that the concept of Jennifer Aniston gets that neuron to light up.

Other Brain Regions and Memory

- The hippocampus is located inside the medial temporal lobe, and the combination of those two structures helps with memory formation, with consolidation of memories, and with explicit memories—facts, events, and the order of different sequences in time.

- The cerebellum, which is in the back of the brain, next to the cerebral cortex, helps with motor learning and procedural memory. The mammillary bodies are associated with recognition memory and unconscious memory.

- The amygdala is the region of the brain that gives rise to emotions. It fires strongly whenever you have a strong emotion; in particular, fear is associated with the amygdala. In the phenomenon known as memory enhancement, if you are experiencing strong emotions and perceiving something for the first time, your memory of that experience will be vivid. This phenomenon is not seen when the amygdala is damaged.

Unreliable Memory

- People who suffer from anterograde amnesia cannot form new memories. This condition can be caused by drugs or brain injuries, in particular, damage to the hippocampus.
    - A person who can't form new memories seems to have lost something that is central to what we think of as being a person. He or she can't learn anything new.

    - However, those who suffer from this condition inevitably score happier on psychological tests than people with fully functioning memories.

- Even for people whose brains are fully functioning, we all know that memories are not perfectly reliable. Not only do we misremember things, but we can have dramatically detailed false memories that are as vivid and true to our perception as any real memory is.

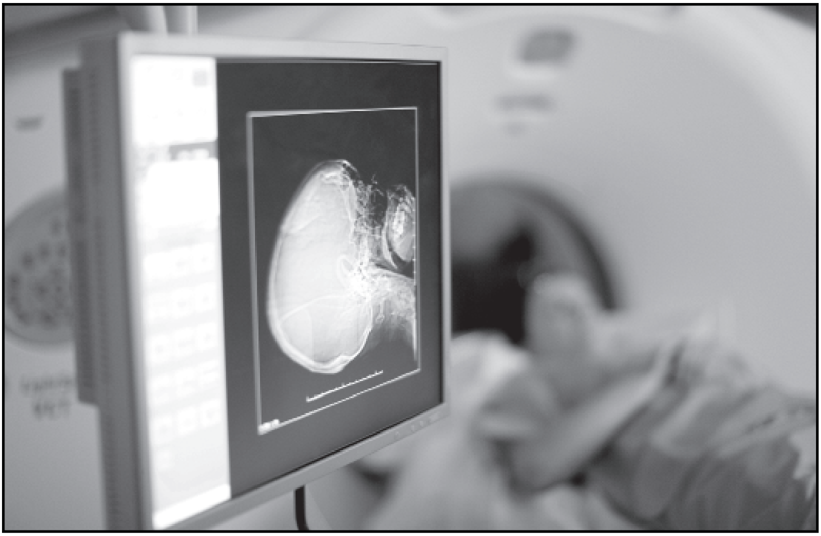
- Misperception, misinterpretation, and false similarity between different things can cause you to misremember what happened.
    - In one famous experiment, subjects were presented with a list of words that had some similarities, such as sugar, candy, honey, and so on.

    - When asked to remember the words later, not surprisingly, they added related words, such as chocolate, to the list and remembered them as being on the list just as vividly as the words that were actually on the list.

- True memories in our brains can be degraded by interference with the process of remembering. Researchers have shown that suggesting a false aspect of a scene (a stop sign in place of a yield sign) caused subjects to incorrectly remember other things about the scene.

- Wholly new memories can also be put into the brain. In the "Lost in the Mall" study, subjects were told five stories about their childhoods, knowing that one of the stories was false. They were then asked to fill in details about the stories—anything they could remember—or say that they didn't remember the event. About 25% of the subjects "remembered" the false story and filled in the details with no problem.

- In addition to false memories, people can also experience false forgetting. Research has shown that the hippocampus has suppressed activity and the frontal cortex has increased activity in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Researchers use functional magnetic resonance imaging (fMRI) to study the brain while it is thinking.

people who are told to suppress thoughts of certain words. It's as if the conscious brain is beating up on the unconscious brain, trying to get it not to remember certain words.

A Theory of Memory

- We don't have a full theory of memory yet, but we do have clues about some aspects of memory. One such clue is that remembering the past seems to be a similar function in the brain as imagining the future.

- This clue has yielded a theory that the brain stores data from which it can reconstruct or re-create images and details. This helps us understand why false memories are just as vivid as true memories. If false memories require only a "script" in the brain—not a fully detailed set of pictures—it is much easier to imagine how they could be introduced and how we could be convinced that they are true.

Consciousness

- Imagining the future is perhaps an even more important part of being human than remembering the past. Thinking about the future is the key to what makes us conscious. Consciousness is not well understood, but it has certain key features: symbolic thinking; abstract thinking; the ability to contemplate alternatives; and the ability to determine what is real, what might be real, and what might happen in the future.

- Like memory, all these functions are highly distributed in the brain and very complex. There are probably many stepping stones along the way in evolution to get from a single-celled organism to a conscious being, and it's impossible to say at which step actual consciousness arose. It's likely that different steps contributed to consciousness in different ways.

- Linguists have argued that a crucial step in the development of consciousness was the development of grammar, in particular, the ability to use language in the subjunctive mood, to say, if you do this, I will do that. The ability to use language in that way enables people to make agreements and develop more elaborate societies based on thinking about the future. This is a relatively late step in the history of consciousness.

- An earlier step in the development of consciousness is the ability to make decisions. Malcolm MacIver, a biomedical engineer at Northwestern University, has an interesting theory in this regard.
    - MacIver pointed out that the visual field of ocean-dwelling organisms is limited. Thus, such organisms must react quickly to what they see.

    - Once organisms crawled onto land, they could see for much longer distances and had more time to consider threats or opportunities. Evolution would favor organisms whose brains allowed them the ability to contemplate alternatives and the future.

- Still, the actual process by which we consider alternative futures and make decisions about them is still mysterious. It seems to be the case that human consciousness is more like Congress—operating by subcommittee—than like a dictatorship, with one totalitarian self giving instructions from the top down. Some researchers have shown that the brain may make decisions before we even know about it.

- Such studies raise numerous questions: How conscious are we really? How much free will do we have? If my brain decides to do something before I even know about it, who is it that is doing the deciding? Science can't give us definitive answers; it can only explore how the brain works. It may be best to think of our selves as the emerging phenomenon that results from all the different parts of the brain coming together to make us who we are.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 9.

Schacter, *The Seven Sins of Memory*.

Questions to Consider

1. Do you think your own memory has improved or deteriorated over time? What kinds of memory are you best at?

2. Do you think it's possible that any memories you feel are completely true are actually false? Have you ever been confronted with evidence that something you remember vividly didn't actually happen that way?

Time and Relativity

Lecture 17

In earlier lectures, we talked about the arrow of time and the problem of entropy; in this last part of the course, we turn to the question of why the early universe had such low entropy. Cosmologists don't know the answer to this question, but we will look at some plausible explanations. This means that we need to understand cosmology and the force that is most important for cosmology: gravity. Of course, when we're talking about gravity, we also need to understand relativity, Albert Einstein's theory of space and time. This lecture compares Newton's and Einstein's views of spacetime and gives us a new way to picture the idea that time is not universal but personal.

A Four-Dimensional Viewpoint

- A four-dimensional understanding of the universe is optional in a Newtonian viewpoint but becomes absolutely necessary with relativity.
  - In three dimensions, we have particular points in space, but in four dimensions—spacetime—instead of points, we have events. An event is neither a place nor a time; it is both. It is a location in spacetime.

  - Spacetime, the four-dimensional reality of our universe, is a collection of an infinite number of events, just as space is a collection of an infinite number of points indexed by the three dimensions of space.

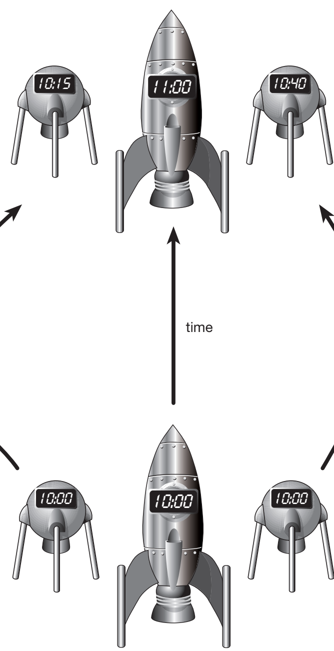
- Both the Newtonian view of the universe and the Einsteinian view encompass three dimensions of space and one dimension of time; the difference is that the two views divide up spacetime into space and time in very different ways.

- Newton thought that space and time were separate and absolute. If we think of an event as a point in space at a moment in time, in this view, for any one event, there is something called the present moment. This is a three-dimensional slice through reality, and that moment is the same time as the event. It is all of space at one moment in time. Any one moment has a present; everything before it is its past, and everything in front of it is its future.

A Robot Army

- Let's think about how we could use clocks to construct Newtonian spacetime, in which any one event has a three-dimensional slice associated with it—the whole universe at one moment in time.

- Imagine that we have a large robot army, and each robot has a clock and a spaceship. We synchronize the clocks on our robots and send them throughout the universe to every point in space.



If we send two robots with synchronized clocks into space on different paths, their clocks will not be synchronized when they return.

- We now have a label at every event in spacetime. We know where each robot is in space and we know when it is in time. What we mean by the universe at one moment is simply the set of events where all the robot clocks read the same time. When they all say 6:00 p.m. on November 5, that is a moment in the history of the universe.

- With Einstein's relativity, there is no such thing as one moment of time all throughout the universe that everyone agrees on. To Einstein, space and time are combined into spacetime, but space by itself and time by itself are not absolute; they are relative. What we call space and what we call time are different for different observers.

- The way we send our robots equipped with clocks throughout the universe affects the answer we get in our thought experiment. Different observers with different sets of robots that were sent throughout the universe using different spaceships would get different notions of simultaneity. They would divide the universe up into space and time in different ways.

- If we send out robots following different paths through the universe and bring them back, their clocks will have measured different amounts of elapsed time. It's not that there is anything wrong with our robots; it is that the amount of time elapsed on a particular trajectory through the universe depends on how the robot moves through the universe. If the robot is moving on a curved path at high velocity, it will always measure less elapsed time when it comes back.

A Muon Clock

- There is no such thing as one moment spread throughout the universe that everyone can agree on. What time it is at one point depends on who does the measuring. One of the most dramatic and immediate experimental verifications of this fact comes from an elementary particle called a muon, a heavier cousin of the electron.

- Pions decay into muons, which then decay into electrons and other particles. Muons decay very quickly, in about 2 microseconds. They can be used, in some sense, as a clock.

- Traveling through interstellar space in the form of cosmic rays are protons that smash into atoms in Earth's upper atmosphere. They create pions and other elementary particles, and those quickly decay into muons. The upper atmosphere where the muons are created is about 15–20 km above the Earth, and the muons should decay after traveling about 1 km, yet they're able to reach the ground on Earth.

- Why do muons reach us before decaying? The answer is that their clocks—their lifetimes—are not ticking in the same way as ours. Because muons are moving so fast with respect to us here on Earth, they "feel" less elapsed time. To them, it takes less than 2 microseconds to go from the Earth's upper atmosphere to the Earth itself.

Notions of Time

- At a fundamental level, there are different notions of time, which sometimes coincide and sometimes do not.
  - We can define one idea of time as the time measured by an observer, the time that is elapsed by a clock.

  - Another notion of time that is a bit more abstract is time as a label to measure what moment of the universe we're talking about.

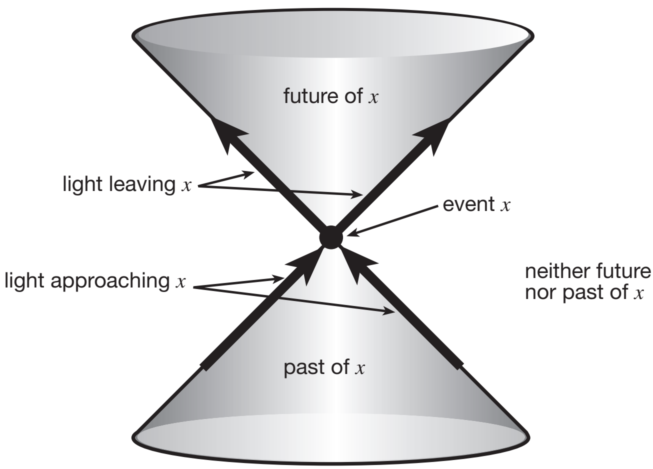
  - To Newton, these two notions of time were the same. But Einstein says these notions are not the same. Time is personal; how much time passes depends on how you move through the universe. The time that you feel depends on your trajectory through the world.

- Consider the universe as a football field. In this universe, one way of measuring how much distance the running back has traveled is to say what yard line he reaches. That is like the Newtonian idea of absolute time. But the actual distance the running back travels involves running back and forth to avoid tacklers. To get from the 10 yard line to the 20 yard line, the actual amount of distance the running back has to go is usually more than 10 yards.

- In space, this makes sense to us, and Einstein says that the same thing is true in time, but the amount of time that has elapsed for us, measured by our clocks, depends on how we connect two different events in the universe by our motions through spacetime. What Einstein is doing is replacing the idea of space at any one moment in time with a much more subtle way of thinking about spacetime.

A Light Cone

- According to relativity, everyone measures the same speed of light: about 300,000 km per second. With that in mind, think about an experiment in which you flick a light bulb on and off quickly. As you do so, photons move away from the light bulb, so there is a sphere of space that is the distance reached by all the photons. Let's say you flick the light bulb on and off very quickly, so that just one small shell of photons will leave it.

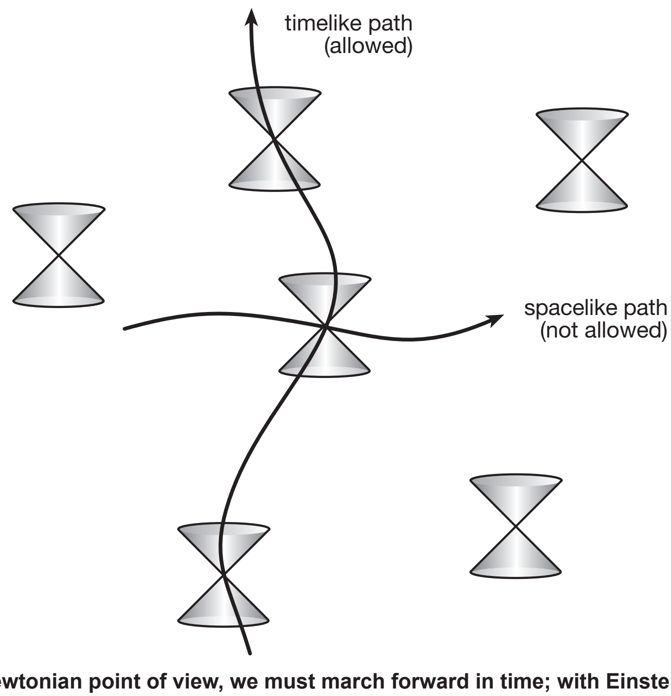


Relativity replaces "space at one moment of time" with light cones—the paths of all possible light rays in spacetime to and from a fixed event.

o In space at any one moment of time, there would then be a spherical region that is where the photons from the light bulb have traveled given a certain amount of time.

o Now imagine that we took a picture of every three-dimensional moment in space to track the expansion of all those photons and we stacked those moments on top of each other, like the pages of a book.

o At the moment you flicked the light bulb on and off, the photons were all very close; they were at the point where the light bulb is. A second later, all those photons were 300,000 km away; 2 seconds later, they were 600,000 km away. As



In a Newtonian point of view, we must march forward in time; with Einstein, we must stay inside our light cones.

we stack up these different pictures of space, we see that the photons going from a point out in all directions form a cone in spacetime, a light cone.

- The fact that the speed of light is the same to everybody means that different observers construct the same light cones. If somebody else moving by you at a speed of some hundreds of thousands of km per second in a spaceship also flicked on a light bulb at the same event as you did, those photons would do the same thing as yours did; they would form the same light cone in spacetime.

- Einstein tells us that instead of dividing the universe into space and time, we need to divide the universe into the light cones that we can imagine making.

- The light cones give us a structure on spacetime because we cannot travel faster than light. If I flick the light bulb on and off very quickly right now, I will get a bunch of photons leaving, and I can never catch up to them. They will always be receding from me at the speed of light.
  - If I draw that light cone in spacetime, what I am drawing is my personal future. My future is only the points inside that light cone. An event outside that light cone is inaccessible to me. I can reach a particular point in space outside the light cone but not a particular point in spacetime.

  - Newton would have divided spacetime into past, present, and future. Einstein divides spacetime into the past of my event, that is, the interior of the light cone that is approaching me at this point in spacetime; the future of my event, the interior of the light cone that spreads out from me in spacetime; and the unreachable parts of the universe, the parts that I would have to travel faster than the speed of light in order to reach.

- The lesson is that in special relativity, time is not universal; it is personal. We can slice the universe up into equal moments of time, but there is no one right way to do that. The division of spacetime into space and time is not absolute anymore; it's not a Newtonian universe.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 4.

Greene, *The Fabric of the Cosmos*.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. Why is it that relativity seems so counterintuitive to us? Can you imagine a world in which the speed of light was much slower—say, 100 miles an hour or just 5 miles an hour—but everything else was unchanged?

2. Can you think of other experiments (feasible or otherwise) that would test Einstein's description of spacetime?

Curved Spacetime and Black Holes

Lecture 18

In the last lecture, we talked about special relativity, the theory that replaces Newtonian absolute space and absolute time with a single four-dimensional spacetime. But that spacetime is still rigid and fixed. In this lecture, we'll talk about general relativity, Einstein's theory of gravity in which spacetime can bend and twist. This is what gives rise to the force we call gravity. As we'll see in a future lecture, the fact that spacetime can evolve will be important for our understanding of the past hypothesis and the event known as the Big Bang.

The Principle of Equivalence

- Special relativity is not a theory of physics but a backdrop, a meta-theory. It is a stage on which other theories, such as electromagnetism or the strong and weak nuclear force, play out. But Einstein was unable to make a theory of gravity that would fit with special relativity.

- Einstein realized that gravity is different than all the other forces of nature because it is universal. Electromagnetism, for example, is not universal; it acts on different particles in different ways. But in a gravitational field, those particles will all fall down and will all fall at the same rate. The principle of equivalence is Einstein's way of formalizing this idea. The equivalence is between gravity and acceleration.

- Imagine that you are in a sealed room, and you decide to do some physics experiments, such as dropping different objects and measuring the rates at which they fall or measuring the frequency of radiation from an atom.
    - In the room, you are in a gravitational field; however, Einstein says that if you imagine doing those same experiments in a zero-gravitational field, in a rocket ship that is accelerating, you will get exactly the same answers.

- An accelerating rocket ship pushes you in the direction in which it's accelerating; you are pulled to the ground, just as you are when there's a gravitational field beneath you. According to Einstein, this is not just a similarity but an equivalence. You can do all those experiments in the rocket ship that is accelerating, and you will get exactly the same answers as if you did them in a gravitational field.

- Gravity is impossible to detect in a local region of spacetime. There is no experiment you can do to determine whether or not you are in the field of gravity or in a rocket. This is completely different than electromagnetism.

The Geometry of Spacetime

- Einstein tells us that if gravity is universal, then perhaps gravity isn't a field on top of spacetime; perhaps it is a feature of spacetime itself, in particular, the curvature of spacetime. Matter and energy can bend spacetime, and that bending is what we call gravity.

- Euclidean geometry is a kind of flat geometry; it's the geometry of ordinary three-dimensional space. But Einstein thought that spacetime might not obey the rules of Euclid. This way of thinking about gravity is usually illustrated by the image of a rubber sheet with a bowling ball in the middle. The bowling ball distorts the shape of the rubber; the effect of this bending of the rubber sheet is analogous to the effect of gravity.

- In general relativity, just as in special relativity, there are light cones at every point, but because spacetime is curved, those light cones can bend and twist. Further, the curvature can be great in some places and small in others, positive in some places and negative in others. The light cones that form the structure of spacetime in special relativity still do that in general relativity, but now, they can move around.

- It's that distortion of light cones in the solar system caused by the gravitational field of the Sun that makes the Earth orbit rather than moving in a straight line.
    - One way to think about general relativity is to think that particles, including the Earth, are doing their best to move in straight lines. But because spacetime itself is curved, there are no straight lines. That is what gives rise to what we call gravity.

    - This is why the Moon goes around the Earth and the Earth goes around the Sun. They're trying their best to move in straight lines, but spacetime itself is curved.

    - If the gravitational field becomes very strong, the light cones can tilt so much—spacetime can be affected so strongly by gravity—that black holes are formed, regions of the universe where gravity is so strong that light itself cannot escape.

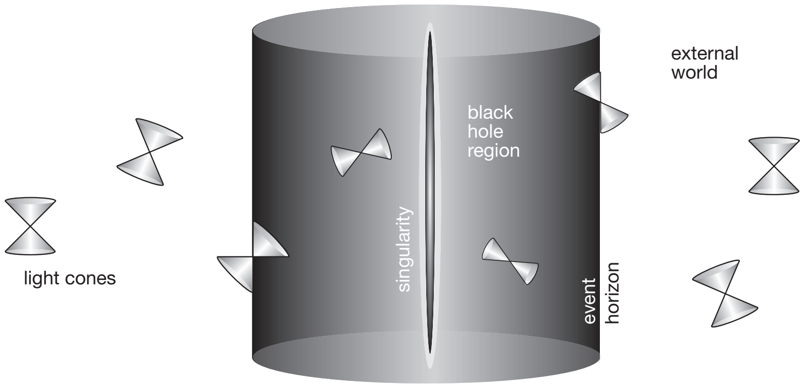
Entering a Black Hole

- As we said, light cones tell us where light can go and, because we cannot travel faster than the speed of light, where we can go. At any one point in your lifetime, there is a light cone moving forward into spacetime away from you, and according to the rules of relativity, you need to stay inside that light cone; that is your future.

- It's also true that gravity can be so strong that spacetime becomes curved in such a way that the light cones tilt and form black holes. Moving slower than the speed of light, the only thing you can do is to move into a black hole, and you can never come out.

- Inside the black hole is a place where the curvature of spacetime becomes infinite. This is what we call the singularity. The gravitational field is so strong that everything shrinks to an infinite density.

- Note that the singularity is not a place but a moment in time. It is in the future.



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A black hole is a region where gravity is so strong that light itself cannot escape.

- When you enter the black hole, you are forced to hit the singularity because everything inside your light cone becomes focused onto that singularity.

- In fact, if you're inside a black hole and you try to fire your rocket engines to move away from the singularity, you will hit it even faster because less time will elapse for you as you age forward in time. You don't travel toward the singularity; you age into it.

- At the singularity, time comes to an end. Past that, we can't say what happens. In general relativity, all we can say is that it is a boundary, known as the event horizon. It is the edge of spacetime itself.

- If you were to fall into a black hole, you wouldn't notice as you passed by the event horizon. If it is a big enough black hole, you wouldn't even be aware that you are doomed, that you are going to hit the singularity and you can never get out.
  - If the black hole has the same mass as the Sun, the time it takes you to go from the event horizon to the singularity is about 1 millionth of a second.

   - If you fall into a black hole feet first, your feet will be pulled apart from your head by the stronger gravitational field they feel. The technical term for this is spaghettification.

Varieties of Black Holes

- Although we can't see them, we believe that we have strong evidence for real black holes in the universe. A black hole affects the gravitational field around it so strongly that other forms of matter near the black hole react in very noticeable ways. Gas and dust fall into the black hole, heat up, and give off x-rays, gamma rays, and other forms of radiation. We can detect that radiation and infer that a black hole is present.

- Black holes seem to come from different places and, therefore, have slightly different properties. The most well-known kind of black hole comes from the collapse of a massive star.
   - A star is actually held up by the heat energy inside it. At the center of the Sun, nuclear fusion is taking place that emits radiation. This radiation heats up the gas and plasma around it, and the pressure of that plasma is what keeps the Sun in its shape. Someday, that fuel will be exhausted, and the Sun will collapse.

   - A star typically collapses to a white dwarf, but if it's heavy enough, it will become a neutron star. A neutron star that is, say, 20 times the mass of the Sun will collapse and make a black hole that is about 3 times the mass of the Sun.

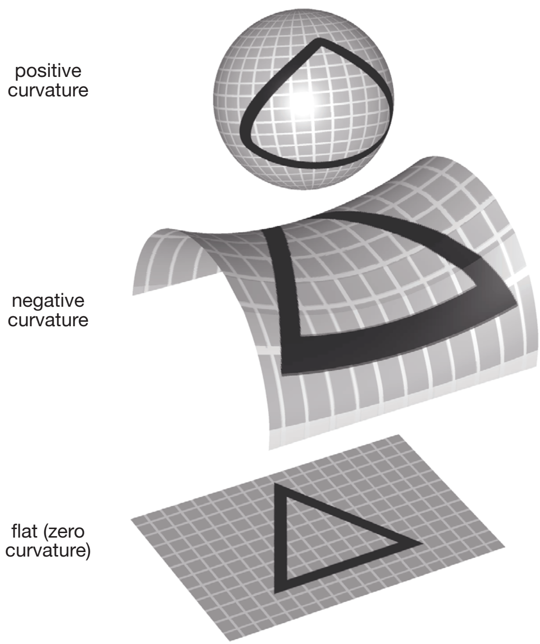
- There is a supermassive black hole at the center of our galaxy. Cosmologists believe that most galaxies in the universe have giant black holes at the center. These black holes may be a million or a billion times the mass of the Sun. The black hole in the Milky Way has 4.1 million times the mass of the Sun and is spinning extremely rapidly.

- Middle-weight black holes may be thousands or hundreds of thousands of times the mass of the Sun. There are also primordial black holes from the very early universe that perhaps weigh only grams. Some physicists have speculated that we could even make black holes ourselves in the Large Hadron Collider.

The Expansion of the Universe

- A separate consequence of the curvature of space and time is that space itself can expand; the size of the universe can change over time.

- In trying to model the universe as a uniform distribution of matter using general relativity, Einstein discovered that the universe must be either expanding or contracting; it could not be static. To account for this apparent contradiction with the data, he posited a cosmological constant that balanced the force of matter and yielded a static solution to cosmology.



Uniform curvature in space may be manifested in different ways.

- In the 1920s, Edwin Hubble made the prediction that Einstein should've made: The universe is expanding. Given that fact, we can run the movie forward and the universe will get increasingly dilute, but we can also run the movie backward. In the past, things were closer together and, therefore, the gravitational fields were stronger.
    - Winding the movie backward in time is similar to following the formation of a black hole forward in time. Inside the black hole is a singularity in the future because all the matter collects in one place.

    - In the universe, there is a singularity in our past, which is what we call the Big Bang.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 5.

Susskind, *The Black Hole War*.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. A "white hole" is just a time-reversed black hole. How would you describe a white hole without referring to the concept of a black hole?

2. Imagine you're falling into a black hole, all the way into the singularity. What do you see as you look "outward" along your trip?

Time Travel
Lecture 19

In this lecture, we'll look at the question: Is time travel possible? Like many of the other issues we've discussed, the answer gives us a kind of good news/bad news situation. The good news is that general relativity, Einstein's theory of gravity in which space and time are flexible, allows us to talk about the possibility of time travel in a scientific way. The bad news is that it's probably not possible, although interestingly, we can't say that it's definitely not possible.

Traveling to the Past?

- We travel through time every day, but we travel to the future. Special relativity allows us to talk about changing the rate at which we travel to the future. Because the amount of time that passes depends on our trajectory through the world, we can actually get to the future faster but not slower.

- The real question most people are interested in, however, is: Can we travel to the past? If Newton had been right that space and time were absolute, then the answer would be no. The laws according to Newton are that there are separate moments in the history of the universe, and you march forward through them; you cannot help but do that.

- In special relativity, the answer is also no. Special relativity replaces the Newtonian division of space and time with spacetime structured by light cones. You are forced to move into the interior of your light cone—that's the same as saying that you must move slower than light—and the light cones point into the future. They don't go into the past.

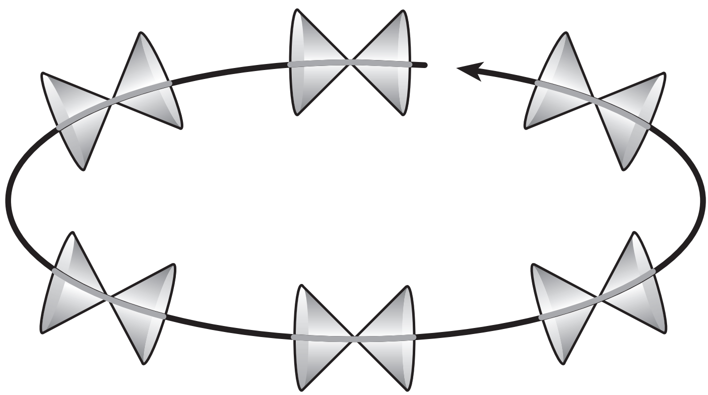
- In general relativity, the answer is probably not, but at least we can wonder whether we could tilt the light cones enough to travel into our personal futures and nevertheless end up in the past. In general relativity, a time machine would be a twisting of light cones, focusing them back on themselves so far that we could go into the past while still moving forward in time.

A Realistic Time Machine

- If time travel were possible, it would not be what we generally see in science fiction movies. It would not involve some kind of dematerialization in the present and rematerialization in a different time. Real time travel would be a journey through spacetime, and a true time machine would be some vehicle that moves you through space and time but in a spacetime that allows you to visit your past.

- The most realistic version of time travel we can imagine is not about building a machine but about building spacetime. Our goal as potential time travelers is to warp spacetime so much that we can personally move forward in time and nevertheless visit ourselves in the past.

- To think about spacetime, we need to think locally, in this case, about what is happening to you.



The trick to time travel isn't to build a machine; it's to warp spacetime so much that we can keep moving forward in time yet come back to where we started, that is, bending our light cones so much that we can move in a circle—a closed timelike curve.

- What's happening to you is that you're growing older; you are moving locally forward in time. In other words, you are staying inside your light cone.

- As we said, general relativity tells us that light cones can be twisted. Thus, we can imagine a light cone twisting so that you could locally move forward but visit your past self because the light cone had closed in on itself.

- This formation is called a closed timelike curve. A timelike curve is simply a path through spacetime that is moving slower than the speed of light. We ordinarily move on open timelike curves, but a time machine would be a closed timelike curve.

- There are spacetimes that allow closed timelike curves, but is that our universe? If we started in a universe that didn't have closed timelike curves, could we create them? Could we warp space and time so much that we were able to visit our own past? These questions remain open.

Kurt Gödel's Version of Spacetime

- The most famous example of a kind of spacetime that has the possibility of time travel built into it comes from Kurt Gödel, a German mathematician. Gödel dabbled in general relativity and was curious about Laplacian determinism, just as we are. He wondered whether it was possible to start with one moment in time, evolve it forward, and then evolve it backward.

- Neither quantum mechanics nor special relativity gets in the way of doing that, but what about general relativity?
  - In Gödel's cosmological answer to this question, instead of expanding, the universe is rotating. The stuff that sits inside Gödel's hypothetical universe is vacuum energy—the cosmological constant energy that is inherent in space itself—and swirling matter particles. The energy and particles cause the curvature of spacetime to be light cones that are tilting gradually as we travel through the universe.

- Every event in this universe sits on a closed timelike curve. Everywhere you start, you can travel through some trajectory in spacetime and eventually visit your past.

- It's not difficult to write solutions to Einstein's equation in general relativity that look like time machines, such as an infinite rotating cylinder or cosmic strings, but all these examples in Gödel's universe have the property that they are infinitely large.
    - If we ask whether we can start with a universe that doesn't have time travel built in and create a situation that resembles any of these, the answer seems to be no.

    - The naïve solutions require an infinite amount of energy. If we try to make a finite cylinder or finite cosmic strings or a finite amount of dust rotating, we don't seem to get closed timelike curves.

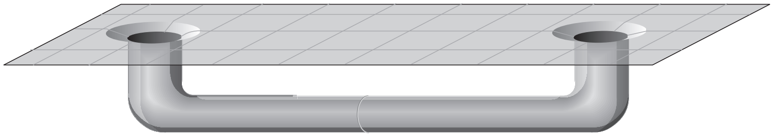
    - These solutions are curiosities, but they are not realistic ways to go about engineering a time machine.

Wormholes

- The most well-known way to construct a time machine in a finite region of space is to use wormholes. A wormhole is a tube through spacetime. It's as if you enter some sphere locally and you are spit out somewhere else arbitrarily far away. Wormholes can connect different regions of spacetime, and you can use them to travel in much shorter time periods than if you went the ordinary route.

- If it is possible to build a wormhole connecting two different regions of space, it is also possible to build a wormhole that connects two different moments in time. Again, it's relatively easy to write down the equations to qualify this as a solution to Einstein's theory of relativity.

- The problem here is that wormholes involve physics that we don't think works in our world. In particular, wormholes collapse instantly into black holes. To get around this problem, we need



Wormholes connect two distant parts of space; although this concept cannot be rendered graphically with complete accuracy, the physical distance could be much shorter than the usual distance between the two openings.

negative energy—something that supplies us with a repulsive gravitational force.

- o Everything we know about in the universe has the gravitational effect of pulling things toward it—positive energy—but to keep a wormhole from collapsing, negative energy is needed to push it apart.

- o The mathematical physicist and cosmologist Frank Tipler, as well as Stephen Hawking, have posited that manipulating matter and energy in such a way as to create any form of closed timelike curve will inevitably create some sort of singularity. The density of curvature and energy in the universe would go to infinity somewhere.

The Paradoxes of Time Travel

- The grandfather paradox is one of the most famous problems that arises from the idea of time travel: What stops me from traveling backward in time and killing my grandparents before they ever met so that neither my parents nor I were born? In that situation, who committed the murders?

- One problem with this scenario is that we can't pick the time we travel back to. The entrance to a wormhole is like a portal; you go in one end, and you come out somewhere else and some when else.

It’s also true that if you can go backward, then someone else can come forward.

- Logic must still work even if there is time travel. You cannot kill your grandparents and then be born to go back in time and kill your grandparents. You can’t change the present moment because you are in the present moment and you know what the present moment has. It has you, for example, so nothing you do can truly prevent you from coming into existence.

- If time travel were possible, the most likely scenario is that even if you made it into the past, something would prevent you from changing things that really happened.

- What is truly bothering us here is the arrow of time, which is absolutely built into how we think about the past, present, and future. As we said, we believe that we can make choices that affect the future but not choices that affect the past. The past is tied down in our epistemic knowledge because of the past hypothesis. If you have a memory of something happening and your memory is valid, then that is what happened and you can’t change it.

- If you put the possibility of time travel into this situation, then your personal future becomes mixed up with the past of the universe. You personally always age into your future light cone, but you go off in a spaceship, zoom around a closed timelike curve, and come to the past. Now, something that you thought was fixed—the past—gets mixed up with something you thought was alterable—your personal future.

- It’s likely that time travel isn’t possible, but the many-worlds interpretation of quantum mechanics offers a tiny loophole to the impossibility of time travel.
    - It is conceivable that if we had a closed timelike curve, we could imagine going back into the past, truly changing the past, and by doing so, bringing into existence a new world, a new branch of the wave function of quantum mechanics.

- o You could travel back in time from one branch of the wave function, in which your grandparents did exist and you were born, into another branch of the wave function, in which your grandparents were killed and you were never born.

Conceptual Implications of Time Travel

- For our purposes, the most significant implication of time travel is that it would destroy the universality of the arrow of time.

- When we have the possibility of time travel, we no longer have Laplace's demon. We cannot slice the universe into moments of time. The moments of time intersect with each other in complicated ways, so that we cannot record the data of the universe at any one moment and imagine running it forward and backward.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 6.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. Think of movies or stories that make use of time travel. Are they logically consistent? Can you think of an interesting plot for a movie that treats time travel seriously?

2. Stephen Hawking has joked that time travel must be impossible because we haven't been invaded by tourists from the future. Is this a good argument, as well as a clever joke?

Black Hole Entropy
Lecture 20

Gravity was of crucial importance in the early universe, and the Big Bang clearly plays some crucially important role in understanding why the early universe had such low entropy. Unfortunately, we don't understand the Big Bang very well. We don't understand gravity at the microscopic level, but such an understanding is exactly what we need when it comes to the Big Bang and entropy. The good news for us in our quest to understand entropy is that black holes are places where gravity is incredibly important, and in this lecture, we'll see that we do know the entropy of black holes.

Classical Black Holes and Black Hole Mechanics

- In classical general relativity, black holes are actually very simple things. We can completely specify a black hole by knowing its mass, its electric charge, and how fast it's spinning. The idea that black holes possess only these properties is known as the no-hair theorem: All black holes are bald.

- We think of a black hole as a place from which nothing can emerge. It was therefore extremely surprising when, around 1970, Roger Penrose showed that energy can be extracted from a rapidly spinning black hole if it is slowed down. The mass of a black hole actually decreases as it spins more and more slowly.

- Of course, there's only a finite amount of energy that can be extracted. The black hole is spinning at some rate. We can get energy out of it, but we slow it down in the process. Once it is slowed down to the point that it's no longer spinning, there is no more useful work we can extract from the black hole.

- This is exactly the situation we saw when we were talking about a thermodynamic system approaching thermal equilibrium. Just like the gas in our piston, if it's in a low-entropy state, we can extract useful work from it, but once it reaches equilibrium, there's nothing more we can do. This idea was developed in the 1970s into the subfield of black hole mechanics.

- The idea here is that there is an analogy between the behavior of black holes and thermodynamics. In thermodynamics, we have the energy of a system; for a black hole, we have its mass, and $E = mc^2$ tells us that mass is just a type of energy, so the analogy is obvious.

- The analogy to temperature in thermodynamics is surface gravity in black holes. Thermodynamic entropy is analogous to the area of the event horizon, which increases as energy is extracted from the spinning black hole.

- The zeroth law of thermodynamics, which states that systems in thermal equilibrium will all have the same temperature, is analogous to the zeroth law of black hole mechanics, which states that the surface gravity is the same everywhere on the horizon, whether the black hole is spinning, charged, and so on.

- The first law of thermodynamics says that energy is conserved, and the first law of black hole mechanics says that mass is conserved.

- The second law of thermodynamics says that the entropy of a closed system only increases; the analogy in black holes is that the area of the event horizon only increases. In fact, this is a theorem that was proven by Stephen Hawking. The area of the event horizon only increases; its shape can be changed, but it cannot be made smaller.

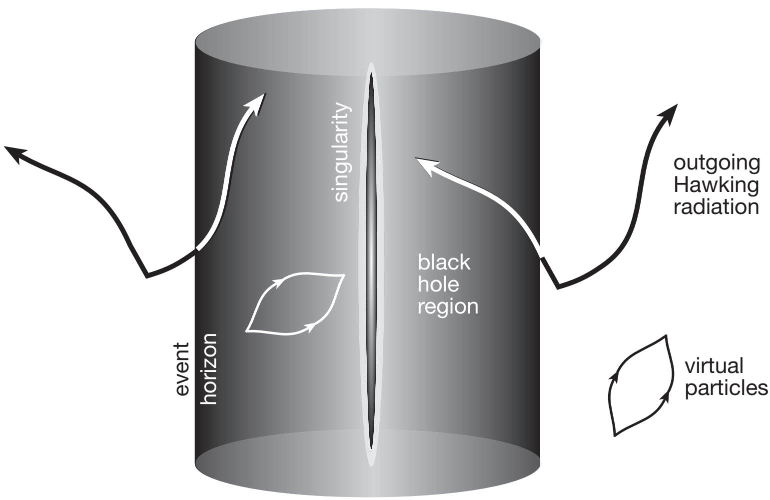
- The third law of thermodynamics says that zero temperature cannot be reached; the third law of black hole mechanics says that zero surface gravity cannot be reached.

Jacob Bekenstein v. Stephen Hawking

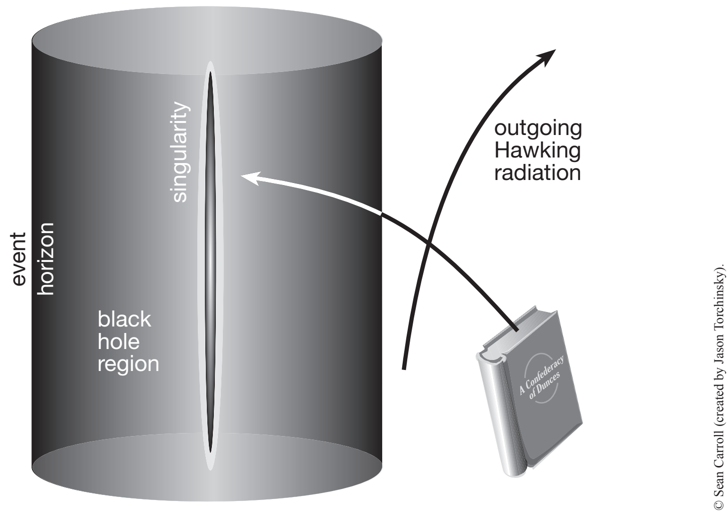
- The set of rules in the thermodynamics regime is spookily analogous to the set in the black hole mechanics regime. This prompted a graduate student named Jacob Bekenstein to make the radical suggestion that the laws of thermodynamics and the laws of black hole mechanics aren't separate.

- Bekenstein said that there is one form of generalized thermodynamics that includes black holes in it and that what we call the area of the event horizon isn't analogous to entropy but is entropy. He further said that the entropy of a black hole is proportional to the area of its event horizon.

- Boltzmann had said that entropy is found by counting the number of microstates that are macroscopically indistinguishable. If Bekenstein was right, black holes must have many indistinguishable microstates because they have a large degree of entropy.



Hawking showed that black holes do radiate—in precisely the fashion to make the black hole mechanics/thermodynamics analogy perfect!



Information falls into a black hole; meanwhile, the radiation should be conveyed outward, but how can it be in two places at once?

- But in the classical general relativistic description, those microstates are nowhere to be found, just as they're nowhere to be found in thermodynamics. A black hole is specified by its mass, charge, and spin and nothing else. Every mass, charge, and spin equal black hole should be the same as every other one with the same values. How can it be that black holes secretly have a huge number of states to accommodate all the entropy they have?

- Further, thermodynamics tells us that a system with a temperature will radiate. If black holes are ordinary thermodynamic systems, then the surface gravity of a black hole should radiate, but we knew that black holes don't radiate.

- Stephen Hawking set about proving Bekenstein wrong by applying quantum mechanics to black holes. He found that in the vicinity of black holes, virtual pairs of particles could be created, one of which could fall into the black hole, but the other could escape. In this scenario, the black hole is actually losing mass to its environment because the escaping particle carries away mass, while the particle that falls into the black hole has a negative mass. The black hole gradually shrinks.

- In particular, Hawking derived a formula for the temperature of a black hole, $T = x/m$, which basically says that the temperature is inversely proportional to the mass of the black hole. He showed that the temperature of a black hole is not zero, but it is smaller for large black holes.
    - A tiny black hole gives off a furious amount of radiation, but a large black hole is very cold. A black hole with 1 solar mass has a temperature of about one-billionth of the background radiation that suffuses the universe.

    - In ordinary black holes, we will never observe Hawking radiation.

- If black holes do give off radiation, then they lose mass. As a black hole gets smaller, its mass goes down, and when it gets smaller, a black hole gets hotter. In a finite period of time, the black hole completely evaporates and disappears. The lifetime of a black hole is given by $t = yM^3$, a constant times the mass of the black hole cubed.

The Entropy of Black Holes

- If black holes radiate—if the analogy between thermodynamics and black hole mechanics is good—that means that black holes have entropy. This is our single most important handle on how entropy works when gravity is relevant.

- As Bekenstein said, the entropy of a black hole is proportional to the area of its event horizon. Why does the entropy go in conjunction with the area, not the volume? That question inspired something called the holographic principle: When quantum gravity is important, physics is no longer strictly local; there are correlations between unknown quantum states that all macroscopically look alike and exist on the horizon.

- Hawking gave us a formula for black hole entropy, and the short story is that it is huge. The entropy of a 1 million–solar mass black hole is 10^{90}. For comparison, the entropy of all the non–black hole particles in the observable universe is 10^{88}.

- We think there are something like 10^{12} or 10^{13} million-solar-mass black holes in the observable universe. This tells us that the entropy in our universe today is overwhelmingly in the form of black holes. This is a crucial clue to us when we talk about the evolution of entropy through time.
  - In the early universe, there were no black holes; there was just plasma and gas spread uniformly throughout the universe. Ordinarily, we think of that as a high-entropy state, but when gravity is important, things change, and in the early universe, gravity was very important. There was a huge amount of stuff that was pulling on all the other stuff.

  - This stuff that was pulling could easily have been in the form of black holes, and had it been, the entropy would have been much, much higher. This is a reminder that the entropy of the early universe was actually very low. It's difficult to keep so much stuff in a perfectly smooth configuration.

  - We also see this in the real evolution of the universe. The universe expands and cools, and gravity pulls things together and makes the universe lumpier. That perfectly smooth configuration was not stable. Entropy goes up as structure forms in the universe.

  - Gravity is important in cosmology, yet when we look back at the early universe, we see a very smooth configuration. That's a reflection of the fact that it had very low entropy. Black holes give us the one clue we have about how to relate gravity and entropy. We will have to see if we can use that clue to explain why the early universe was so smooth.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 12.

Hawking, *A Brief History of Time*.

Susskind, *The Black Hole War*.

Questions to Consider

1. Physicists have long debated whether information is conserved or destroyed when black holes evaporate. What do you think? Should it bother us if it turns out that the laws of physics don't actually conserve information?

2. We have never observed Hawking radiation from a black hole. How confident should we be that it really exists?

Evolution of the Universe

Lecture 21

In this lecture, we're going to follow the evolution of entropy through the history of the universe. We start near the Big Bang, 13.7 billion years ago, and follow the physical processes that occurred as the universe expanded and cooled. Along the way, we'll track what the entropy was at each stage. Not surprisingly, we will learn that entropy has been increasing—the second law of thermodynamics is correct. We will then follow the evolution of the universe past the present moment into the future.

The Present Universe

- There are about 100 billion galaxies in the observable universe, each with about 100 billion stars. On very large scales, the universe seems to be uniform.

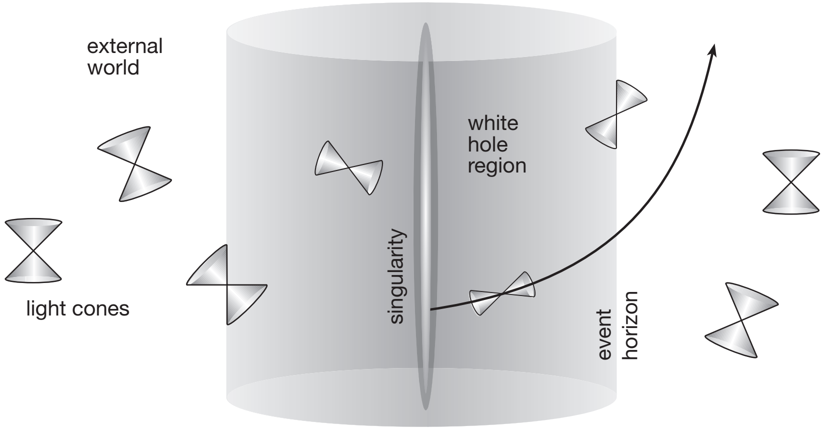
- As we know, the universe is expanding. Distant galaxies are moving away from us, and the farther away they are, the faster they are receding. The amount of space between us and the galaxies is becoming greater.

- Once we know that the universe is expanding, we can play the movie backward. If galaxies are moving away from each other now, in the past, they were closer together.

The Moment of the Big Bang

- If we keep tracing backward in time, 13.7 billion years ago, we hit a point where all the galaxies were on top of each other. That's the Big Bang, the point at which the density of matter was infinite.

- Einstein's general relativity gives us an equation that relates the rate at which the universe is expanding to the amount of stuff in the universe. This gives us a quantitative theoretical understanding of what the universe should have done in the past, and we can compare



We often say that the universe was smaller in the past, but what we really mean is that galaxies were closer together in the past and they will be farther apart in the future.

that to the data. Remarkably, the data we have go all the way back to the first 3 minutes in the history of the universe.

- When all the matter in the universe was much more densely packed, its temperature was extremely high.
  - If we go far enough back, it was so hot that atoms could not exist; electrons could not stick to atomic nuclei.
  - If we go more than a few seconds after the Big Bang, even nuclei could not exist; protons and neutrons could not stick together.
  - In the period between a few seconds and a few minutes after the Big Bang, the universe expanded and cooled, and protons and neutrons could finally join.
  - Protons and neutrons want to fuse together to make heavier elements, but because the universe was expanding so quickly, they didn't have time. Thus, the density of the universe decreased rapidly.

- A certain fraction of the protons and neutrons became helium, lithium, and deuterium. Observations of the abundances of these elements in primordial regions of the universe match scientific predictions about what they should be just a few seconds after the Big Bang.

- That process, called Big Bang nucleosynthesis, occurred when the universe cooled down enough to allow nuclei to form. About 380,000 years after the Big Bang, it cooled enough to allow atoms to form.
    - This process, when electrons can finally stick to atomic nuclei to make atoms, is called recombination.

    - Before recombination—when electrons were free to roam—the universe was opaque. Once recombination occurred, the universe became transparent, and the photons from that period can move all the way across the universe to be detected in our telescopes.

    - In 1964, Arno Penzias and Robert Wilson, two scientists working for Bell Labs, first detected this cosmic microwave background radiation from the Big Bang.

The Formation of Large-Scale Structure

- As we've said, our current universe seems uniform on very large scales, but at the moment that the cosmic microwave background was formed, the universe was uniform on all scales.

- As the universe expanded and cooled, gravity turned up the contrast knob. A region of space with slightly more matter would have a slightly stronger gravitational field than a region with less matter; it would pull nearby atoms toward it. A region that was slightly less dense than average would lose atoms to the rest of the universe. This process is called the formation of large-scale structure in the universe.

- Some small perturbations in space became planets, stars, and black holes. Larger ones formed galaxies, and even larger ones formed large-scale structure. As this process progressed, entropy increased.

- Recall that when gravity is important, high entropy does not necessarily mean smooth. High entropy can be very lumpy. The highest entropy of all would be to have all matter in one large black hole.

- It's not true that the early universe had to be smooth. It could have been much denser in one region than another. That would have been a much higher-entropy configuration.

- If we took a high-entropy version of the current universe and played the movie backward, there's no reason why entropy would have had to go down. The early universe having low entropy is a fact that still needs to be explained.

- Of course, if the entropy of the early universe had been as high as it could possibly be, we would not live in a universe with the second law of thermodynamics. The reason there's a second law is because of the past hypothesis, the fact that the early universe had such a tiny entropy.

Dark Energy

- In 1998, astronomers made the surprising discovery that the expansion of the universe is accelerating. But ordinary stuff—matter, radiation, atoms, even dark matter—does not speed up the expansion of the universe.

- The fact that the universe is accelerating requires some nonordinary stuff: dark energy, which doesn't dilute away as the universe expands.

- In an expanding universe containing nothing but matter and radiation, the number of particles doesn't change in any one volume of the universe. In any fixed cubic centimeter of the universe, the density of particles is going down.

- But dark energy hypothesizes that in every cubic centimeter, some energy doesn't dilute away; some amount of energy is present that provides a perpetual impulse to the expansion of the universe. That impulse actually builds up as space itself gets larger, and that's what makes the universe seem to accelerate.

- The best candidate for dark energy is vacuum energy, a specific example of dark energy in which the dilution is exactly zero and the density of energy is exactly the same in every point in space. Vacuum energy is also called the cosmological constant.

- If vacuum energy is the right answer, it has a profound implication for the future of the universe, namely, that the expansion will continue forever.

The Future Universe

- Right now, the age of the universe is, roughly speaking, 10^{10} years. What will happen in the future if the universe does not recollapse?

- Stars in the galaxies of the universe are burning their fuel. The smallest stars, which are the ones that last the longest, will last about 10^{15} years before they finally burn out.

- Those dead stars will ultimately fall into black holes, which themselves will eventually evaporate. This process will take about 10^{100} years, about 1 googol years.

- The radiation of the black holes will be diluted away as the universe expands and accelerates, so it will be imperceptibly different from having nothing at all. And that, if the dark energy is completely constant, is the end of the story. After a googol years from now, we will have empty space and that empty space will last forever.

- In other words, the highest-entropy state the universe can be in is nothing but empty space. Right now, the universe is not high entropy, but entropy is growing. When entropy hits its maximum value, equilibrium is reached and evolution stops.

- That will be the heat death of the universe. Rather than recollapsing and experiencing a Big Crunch, the universe will calm down and become colder and colder until it reaches equilibrium.

An Inside-Out Black Hole

- There is, however, a fascinating extra fact that is forced on us by the idea of vacuum energy: If the universe is truly accelerating and vacuum energy never goes away, it turns out that the accelerating universe is like living inside an inside-out black hole.

- A black hole is defined by the fact that it has a horizon. If you go inside, you can never escape to the outside. There's a region of the universe from which information can never reach us.

- Likewise, in an accelerating universe, a galaxy that is far away from us now will eventually be moving away from us at a speed faster than light. Any light that galaxy emits will never reach us. In other words, that galaxy is past a horizon.

- Just as Hawking said that black hole horizons give off radiation, our universe, which has a horizon around us, has a temperature and gives off radiation. In the far, far future of our purportedly empty universe, there will still be a nonzero temperature, about $10^{-30\circ}$ Kelvin.

- What this scenario means is that we have an eternal universe that lasts forever. There's a fixed volume that we can see inside our horizon, and inside that volume, there is a temperature that remains constant forever.

- This should remind you of Boltzmann's scenario for understanding why the early universe had low entropy.
    - Boltzmann imagined an eternal universe that had some fluctuations and, every once in a while, would form a low-entropy configuration—a planet, a galaxy, or even the whole universe.

- We said that couldn't be right, but it turns out that our real world seems headed for exactly that situation. It might take an enormously long time to fluctuate back into the whole universe, but we have forever to wait.

- If this is the right cosmological scenario, then we should be Boltzmann brains or the universe around us should have just fluctuated randomly into existence. We don't believe that's true, and therefore, there must be something wrong with our current best understanding of cosmology.

Calculating Entropy across Time

- At very early times in the universe, when there was no structure, the entropy of the universe was about 10^{88}.

- Today, most of the universe has black holes at the centers of galaxies, and most of the entropy of the universe is in those black holes. Adding up the entropy in black holes, we get about 10^{103}.

- In the future, the maximum entropy that we can possibly imagine from all the stuff we see in the universe today will be about 10^{120}. That would be the equilibrium version of the universe, the configuration we could be in with maximal entropy.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 13.

Guth, *The Inflationary Universe*.

Penrose, *The Road to Reality*.

Questions to Consider

1. Before the discovery of the cosmic microwave background, many astronomers took seriously the steady-state theory. In that model, the universe was expanding, but it was constantly creating new matter so that the average density remained the same. What would the status of the arrow of time be in such a universe?

2. Is it surprising that the predicted future of the universe stretches out for a much longer time than its known past? Is this something that science should be working to explain or just a random fact we should accept?

The Big Bang
Lecture 22

So far in these lectures, we have not shied away from speculating. We've talked about time travel, for instance, and Boltzmann brains. But these speculations have been grounded in theories we understand fairly well. In the next couple of lectures, we move into the realm of speculative speculations. We've reached a point where what we know about the universe isn't good enough; we don't know why the entropy of the early universe was so low, so we have to imagine what the possibilities might be.

Time Equals Zero

- If we extrapolate Einstein's equation for general relativity backward, given the conditions in the universe as we understand them, we hit a singularity, a moment when the expansion rate and the density of the universe were infinite. That's what we call the Big Bang.

- Notice that this is a time, not a place. It is a moment in the history of the universe, not a location in a preexisting universe. The Big Bang was not an explosion of stuff in an otherwise empty spacetime. It was all of spacetime as far as we know. The Big Bang is just like the singularity of a black hole except backward in time.

- We know that the early universe was very dense and very smooth. The matter in the universe about 1 second after the Big Bang was essentially in thermal equilibrium. It was as smooth as it could be and as hot as it could be, as long as we ignore gravity. But we can't ignore gravity, of course; that's why we have this mystery in front of us.

- Einstein's general relativity predicts that if we go backward in time, we hit this singularity, but a singularity doesn't mean a boundary to spacetime. What it means is that our equations blow up.

- If general relativity were the correct theory of reality, the Big Bang would be the beginning—we cannot go past that singularity—but we know that general relativity is not right. It is not compatible with quantum mechanics. To reconcile general relativity with quantum mechanics, we need a theory of quantum gravity.

- General relativity tells us that there is geometry to spacetime, a certain amount of curvature. Quantum gravity would say that there's a wave function of spacetime, a set of possibilities for what spacetime would look like if we were to observe it. That's the theory we would like to have, but we don't have it yet.

- Even though we don't have the right theory, we know what quantum gravity should be like in certain regimes. It should, for example, reduce to classical general relativity in our solar system. We know that 1 second after the Big Bang, the universe was doing more or less what general relativity says it should do. We can try to see what a full theory of quantum gravity would tell us and use that to understand the Big Bang.

Creation from Nothing

- One plausible scenario is that, with quantum gravity, the Big Bang is the beginning, just as our classical intuition tells us. There is no such thing as before the Big Bang; time doesn't go forever.
    - In all the ordinary quantum mechanical theories we understand, time goes forever, but gravity is not ordinary in this sense.

    - We have to take seriously the possibility that gravity added to quantum mechanics makes time come to an end at the beginning of the universe. That would be a universe that essentially comes into existence out of nothing.

    - This nothingness is not an absence of anything. It's not even a thing, not a state of the universe, not even a quantum mechanical possibility.

- This kind of scenario is favored by Stephen Hawking. He tries to solve equations for the wave function of the universe that would describe the universe that looks like ours today and came into existence at the Big Bang.

- That is a plausible scenario given what we understand today. Does it help us explain the arrow of time? That depends on what the wave function of the universe is. It could be just a new law of nature that according to this wave function, the universe came into existence at a certain moment, and when it came into existence, the entropy was very low.

A Bouncing Universe

- An alternative to creation from nothing is a bouncing universe, a universe in existence before the Big Bang that essentially was the time reverse of the Big Bang. It was a universe in which matter and energy were contracting and getting denser, and somehow, the magic of quantum gravity, rather than collapsing it to a singularity, caused it to bounce back and create what we call the Big Bang.

- In some sense, it seems natural that entropy would be decreasing as it approached the bounce. If the bounce that we now call the Big Bang is a moment of symmetry in the history of the universe, then the entropy goes up in both directions away from it, both toward the past and the future.

- That's an aesthetically appealing universe, but it still leaves us with the question: Why was entropy so low at that point? What is the principle of nature that says that when the universe bounces, the entropy should be low?

The Multiverse and the Theory of Inflation

- A third possibility is the multiverse. According to this idea, our Big Bang was an event that is really quite small in the history of a much larger universe. We see only a finite bit of the universe; perhaps farther away than what we can see, the universe looks very different. The theory of inflation gives some credibility to this idea.

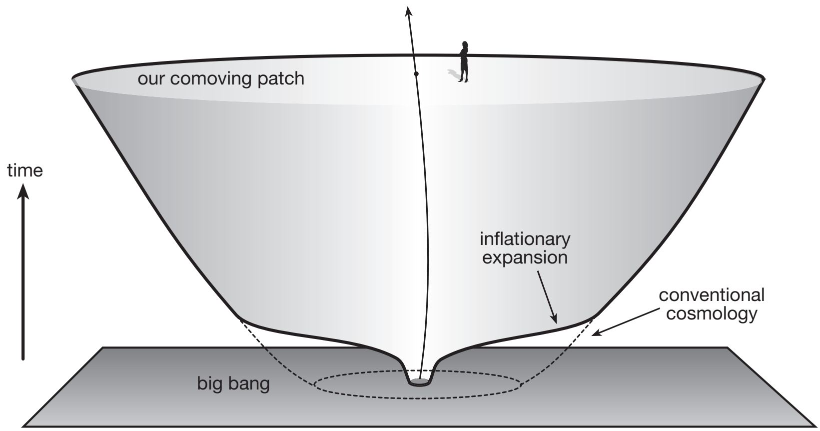
- To understand how inflation works, we need to go back to the idea of dark energy. Remember, dark energy doesn't dilute away as the universe expands. In a universe dominated by dark energy, expansion accelerates because space gets bigger and bigger. Inflation posits much higher energies at the earlier time when the universe began.
    - o What would happen if, instead of ordinary matter and radiation, the early universe was filled with nothing but super–dark energy?
    - o The rate at which something expands depends on the energy density, so if the energy density was very high, the universe would expand very quickly.
    - o At the same time, if the universe was filled with dark energy rather than ordinary matter, it would smooth out.
    - o Thus, after a very short time, the universe would go from whatever state it was in to a much larger configuration, very smooth over very large distances, and full of this super–dark energy.

- In the process known as reheating, this super–dark energy would be converted into ordinary matter and radiation. And, in fact, the quantum field that was responsible for inflation could decay after a certain amount of time, eventually becoming a hot, dense gas.

- What inflation gives us, then, is a universe dominated by super–dark energy that expands and smoothes out by a huge amount, and then suddenly, throughout the universe, all that energy is converted into ordinary matter and radiation. This looks exactly like our Big Bang.

The Benefits of Inflation

- In modern cosmology, inflation has become the dominant paradigm, and there are numerous benefits to believing that inflation happened. One of these is that the universe can start very tiny.
    - o In conventional cosmology, the actual size of the observable universe when the universe started is about 1 centimeter. This



Inflation expands a tiny patch of space to a tremendous size in a fraction of a second (representation not to scale).

seems small to us, but by the standards of particle physics, it's huge.

- The question is: Why would the universe be so incredibly smooth over this 1-centimeter size?

- In inflation, if we trace our currently observable universe backward in time, it can start with a region that's about 10^{-30} centimeters across, and it's much more plausible to particle physicists that the universe started in exactly that state.

- Inflation also explains the spatial geometry of the universe, in particular, that its large-scale spatial geometry appears to be flat. The universe could have had substantial curvature at early times, but the process of inflating would have flattened it out.

- Further, inflation explains the fact that the universe is smooth over great distances. Again, the process of inflating would have smoothed out small-scale perturbations.

- If there was just inflation in a classical universe, there would be no way of understanding why there was any deviation in density from place to place at early times.

- But if we add quantum mechanics to the mix, we find that there will, in fact, be perturbations. The pattern of perturbations predicted by inflation is exactly what has been observed in the cosmic microwave background radiation.

- Inflation does raise a conceptual question: Where does all that energy come from? The short answer is that with the expanding universe, energy is not conserved.
  - In the expanding universe, there is energy in stuff—dark energy, matter, radiation, dark matter, and so on—but there is also energy in spacetime itself, the energy of the curvature of spacetime.

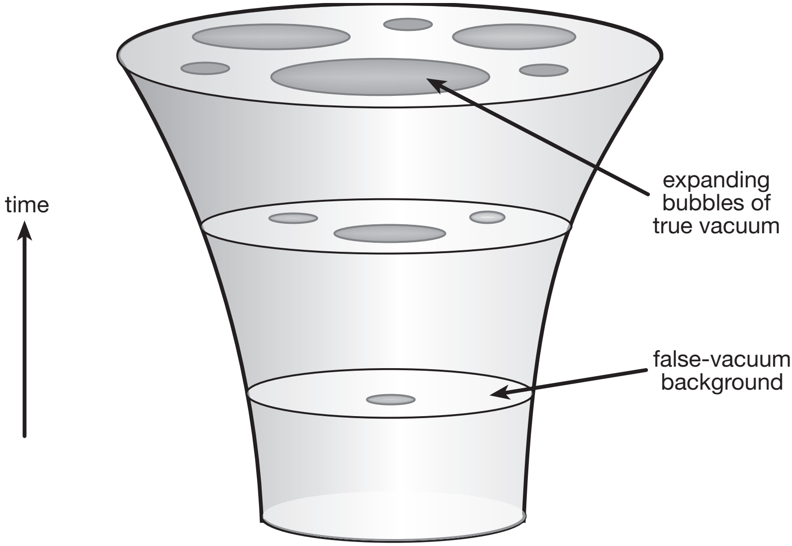
  - The energy of stuff is positive, while the energy of spacetime is negative. In a compact universe or a universe that is perfectly smooth everywhere, the total energy is exactly zero.

  - As this universe expands, tremendously more energy is created in stuff that is compensated by the energy of spacetime itself.

  - Energy in stuff does not remain the same as the universe expands. We can get as much universe as we like from an arbitrarily small amount of energy.

Inflation and Entropy

- Inflation tries to give us a natural explanation for certain features of the universe: the fact that it is spatially flat, that the density was so smooth, and so on. The theory tells us that we shouldn't be surprised by these facts, because if we begin with a small region ready to inflate, that is what we will get. However, the question is: Why did we begin with that small region ready to inflate?



The expanding bubbles never completely collide. During the false-vacuum phase, the amount of space grows forever; inflation never truly ends.

- One way of attacking that question is to think about entropy and calculate the entropy of that proto-inflationary region. This entropy is about 10^{10}, much, much lower than the entropy after reheating.

- Remember, we said that the entropy of the early universe was something like the 10^{88}, and now we're saying that the entropy of the inflating region was something like $10^{10.}$ This follows the second law of thermodynamics, but it doesn't explain why entropy was so low. We've simply started at an even lower-entropy configuration.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 14.

Guth, *The Inflationary Universe*.

Questions to Consider

1. The Big Bang might be a true beginning, a bounce, or part of a larger multiverse. What's your favorite option? What are the advantages and disadvantages of each?

2. Should we be surprised that energy is not conserved in an expanding universe? Can you think of good analogies for this phenomenon?

The Multiverse

Lecture 23

We're beginning to put together a comprehensive theory to explain the origin of the difference between the past and the future. We've said many times that the entropy was lower yesterday, and the reason the entropy was lower yesterday is that it started low near the Big Bang. In the last lecture, we looked at three different ways of thinking about the Big Bang: as the actual beginning of the universe, as a bounce, or as an event that occurred in just one universe of a very large multiverse. In this lecture, we'll dig a little deeper into the possibility of the multiverse.

A Scientific Parable

- To think about the multiverse and how it could be part of science, consider this parable: Imagine there is a planet that is much like ours, except that it's always completely overcast. Scientists on this planet wouldn't know that there are other stars in the sky.
    - o To these scientists, their planet is the whole universe because that is all that they can see. At some point, a philosopher wonders whether there might be many similar planets that can't be seen because of the opaque atmosphere.
    - o Of course, the other philosophers and scientists say, that idea is nonsense. We can't invoke other parts of the universe that can't be seen. That's not how science or philosophy works.
- The point here is that when we talk about the multiverse, we're not invoking a new kind of thing. Instead, we're observing that there is a point in our universe's past that we cannot see. Is there a finite amount of stuff out there? Is there an infinite amount of stuff that works exactly like the stuff we can see? Or is there an infinite amount of stuff and conditions that are very different from place to place?

- In some sense, assuming that the entire rest of the universe is infinitely large and just like the region we see is just as presumptuous as assuming that there's an infinitely large universe where conditions are very different from place to place. The cosmic microwave background in our universe functions exactly like the opaque atmosphere on our hypothetical planet: It's a barrier past which we cannot see.

The Multiverse and the Anthropic Principle

- When we consider a multiverse, we necessarily invoke the anthropic principle: If there are many different conditions throughout our universe, intelligent beings like ourselves will find ourselves only in those conditions that are compatible with us existing.

- The anthropic principle may be the explanation for the vacuum energy that makes the universe accelerate.
    - In ordinary general relativity, there is a classical contribution to the vacuum energy that is present as an unknown constant of nature, but there are also quantum mechanical contributions to vacuum energy.

    - All the particles in the universe vibrate in hidden ways in the virtual particle sense. That is to say, even in empty space, these particles are providing energy. If we add up these contributions to the vacuum energy, we get a huge number.

    - The real puzzle of vacuum energy is not why it exists but why it is so small compared to its natural value. And the answer might be the anthropic principle.

    - If the vacuum energy were huge, space would accelerate very, very quickly. In fact, if the vacuum energy had its natural value, we couldn't have atoms or even nuclei. The vacuum energy would rip things apart so effectively that no molecules could form. Under those conditions, it's unlikely that life could develop.

- We could also have a large negative vacuum energy. Instead of making the universe accelerate, it would make the universe recollapse in a tiny fraction of a second. Even if the local physics allowed for the existence of life, there wouldn't be time for it to evolve.

- However, if the vacuum energy is small but not zero, then there's plenty of time for life to evolve and there's nothing to stop molecules from forming.

- In 1988, Steven Weinberg, a Nobel Prize–winning physicist, made the following prediction: If the vacuum energy is not a constant of nature, if we live in a multiverse where the vacuum energy takes on different values from place to place, then it can't be too large, and it can't be too negative. If we live in a multiverse, we should observe a nonzero vacuum energy with a certain typical value. In 1998, Weinberg's prediction of the energy density was confirmed.

- We cannot, however, explain the entropy of the early universe using just the anthropic principle. If we try to make the same kind of prediction with entropy that Weinberg did with the cosmological constant, we get a prediction that the entropy of the early universe was much, much larger than it actually was.

Inflation and Quantum Mechanics

- According to quantum mechanics, things fluctuate, and we can't predict exactly what will happen; we can predict only different probability distributions.

- As we saw in the last lecture, inflation involves super–dark energy expanding to make a large region of space and then decaying into ordinary matter and radiation; that's the process called reheating. What happens if we add quantum mechanics to that process?

- The answer is that space can expand and grow, but we can't predict that it certainly turns into matter and radiation; we can predict only that this process takes place with a certain probability.

- It's possible that a small region of space expands to a large region and perhaps 90% of that larger region reheats. In the aftermath, we get what we call the Big Bang, but that means that in 10% of the space, inflation does not stop and reheating does not take place.

- That 10% continues to expand, and after a certain period of time, 90% of that region reheats, resulting in a Big Bang. But again, 10% continues to inflate. In other words, we create more and more regions of space where inflation is still going on, even though, in any one region, 90% will stop inflating soon.

- This 10% that keeps inflating grows in size by a tremendous amount. In actual cubic centimeters, the region of space that is still inflating grows without bound. Inflation never ends in this scenario. This is called eternal inflation. It's a natural marriage between inflation and quantum mechanics.

- This theory of eternal inflation tells us that we can get a very different universe from place to place.

String Theory

- Eternal inflation could create many regions of universe just like our own, or it could create many regions, each of which has different local laws of physics. This is a consequence of string theory, the leading candidate to reconcile quantum mechanics and gravity.

- According to string theory, spacetime has at least 10 or 11 dimensions; this seems to be an obvious conflict with experiment because we have only 4 dimensions of spacetime. But it turns out that in general relativity, it's not difficult to hide extra dimensions of space. In fact, there could be as many as 10^{500} ways to hide extra spatial dimensions.

- Every different way of curling up extra dimensions affects the mass and charges of elementary particles, the different forces through which they interact, and the ranges over which those forces stretch.

Basically, every one of these possibilities is a different way the universe can be.

- If we combine string theory with eternal inflation, we bring a wildly varying multiverse to life. Inflation says that we can have different regions of space. String theory says that the local physics in all those regions can be different.

Testing the Multiverse Hypothesis

- The biggest problem with the multiverse hypothesis is that it is difficult to test, given that other regions of the universe are too far away to visit.

- It's possible to look for direct evidence of other universes, that is, instances where another universe with different local physics bumps into our universe.
  - If another universe came into existence because of inflation and reheating, then that universe would leave a tiny relic of radiation and energy heating up our cosmic microwave background.

  - The data we have on the microwave background right now aren't good enough to rule out this idea, but they're also not good enough to confirm that other universes are present.

- The more likely scenario is that we will get indirect evidence in favor of the multiverse. Here, we use the anthropic principle and the multiverse to make statistical predictions for certain parameters of particle physics that haven't yet been measured.
  - Could we use this combination to make predictions about dark matter, the Higgs boson, supersymmetry, or other aspects of particle physics?

  - This is very difficult to do, but it is the more likely way we will discover that the multiverse is on the right track.

The Measure Problem

- The measure problem is a puzzle associated with the multiverse: If we take the multiverse seriously, everything that can happen will happen, and it will happen an infinite number of times.
  - One of the things we want to know, for example, is how many observers would observe a small vacuum energy? How many observers would observe a large vacuum energy?

  - Again, if we take the multiverse at face value, the answer is: An infinite number of observers measures a certain value and an infinite number measures another value. How can we compare these? How can we say that one infinite number is greater than another one?

- This may be a profound problem with the multiverse idea. It may be that even if the multiverse is real, we will never be able to use it to make predictions. As of now, the multiverse is a speculative idea that is not yet developed well enough by theorists to make firm predictions.

The Future of the Multiverse Hypothesis

- The reason we think about the multiverse is not that we know it's there, and it's not even that if we knew it was there, it would make a definite prediction about the universe. It's that when we think about the puzzles we face in explaining the universe we see, whether or not there is a multiverse changes the way we think.

- The way to move forward with the multiverse idea is to understand how gravity, quantum mechanics, and particle physics work together. We need to develop at least one well-defined, unambiguous theory, and right now, when it comes to explaining the past hypothesis, we have no compelling theories.

Suggested Reading

Carroll, *From Eternity to Here*, chapter 14.

Susskind, *The Cosmic Landscape*.

Vilenkin, *Many Worlds in One*.

Questions to Consider

1. Do you think that speculation about the multiverse is a respectable part of science? If not, how should we deal with the possibility that the multiverse is real? And if so, what if we are never able to test the idea?

2. The anthropic principle relies on some idea about what kind of life can possibly exist in the universe (or some other universe). What do you think are the necessary conditions for the existence of life? What is the form of life you can imagine that is least like our own?

3. In 1998, Stephen Weinberg used the anthropic principle to predict the value of the vacuum energy, and his prediction turned out to be correct. How much weight should we give to this success?

Approaches to the Arrow of Time

Lecture 24

Throughout these lectures, our challenge has been to connect two realities: the deep underlying reality that there is no difference between past and future and our phenomenological reality, in which it is obvious that there is an arrow of time. The reconciliation seems to be that we are a complicated system, embedded in an environment that is far from equilibrium. There is something called entropy that characterizes the organization or disorganization of us and our environment. The amazing fact about our world is that all the manifestations of the arrow of time seem to be explained by increasing entropy. But the question remains: Why did the universe start with such low entropy? In this lecture, we'll look at three possibilities for answering that question.

An Intrinsic Arrow of Time?

- The first possibility for addressing our central question is that despite everything we think we know about the fundamental laws of physics, maybe there is an intrinsic arrow of time.
  - Ever since Galileo and Newton, our attempts to develop deep laws of physics have been time symmetric and have conserved information, but maybe that's wrong.

  - Perhaps laws that are yet to be discovered are not reversible and do not conserve information. Maybe entropy is something that has an intrinsic arrow of time.

- If we do have dynamical laws that pick out a direction of time, they need to be laws that make entropy spontaneously decrease. We need to start with a high-entropy universe, apply the laws of physics to it, watch the entropy decrease, and then imagine that we live in that universe, but we perceive it in the other direction.

- It's not hard to imagine laws of physics that are like that.

  - We can conceive of a billiard table that is not frictionless but sticky along the walls.

  - The billiard balls could start in a high-entropy configuration (with the balls scattered around the table) and end with a low-entropy configuration (with the balls "stuck" to one wall of the table).

  - This is an irreversible process, but it doesn't seem to be our world. It seems intuitively implausible that we could start with an empty universe, expanding with dark energy, and then gradually form galaxies all the way back to a reverse-time Big Bang and that the result would be our universe.

- It's worth emphasizing that the past hypothesis, this idea that our early universe started with low entropy, is both necessary and sufficient for explaining the arrow of time. Any new theories about the arrow of time must explain why our early universe was hot, dense, and smooth because these are the conditions that obtained in the early universe.

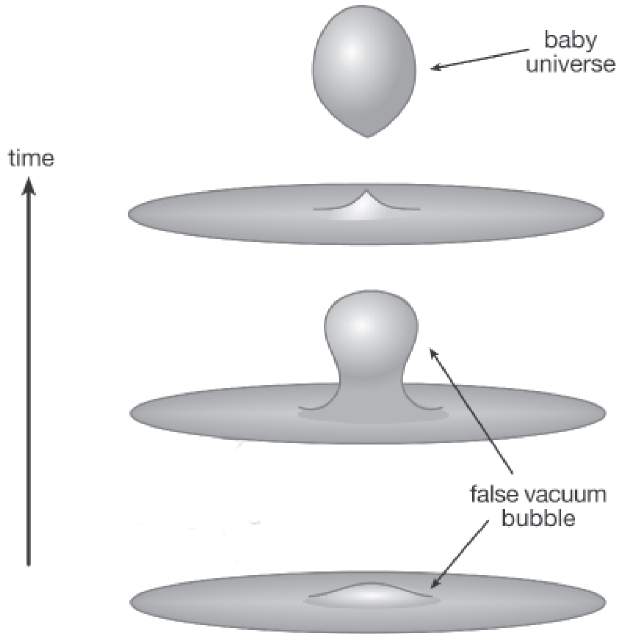
- The idea of an intrinsic arrow built into the laws of physics doesn't seem to explain the past hypothesis.

The Simplest Possible Quantum State?

- The second possible explanation for understanding why entropy was so low in the early universe is that there's just a reason that initial conditions were like that. Maybe it's just a fact that conditions near the Big Bang had low entropy.

- Stephen Hawking and other physicists favor an approach that says the quantum state of the universe is the simplest possible. The Big Bang was the beginning. The entropy was low, and there's some principle of nature that explains why that makes sense.

- That principle of nature can't be that most possible universes look like that because that is simply false. The actual configuration



A baby universe could be created through a quantum fluctuation of a false-vacuum bubble.

of stuff in our early universe is a tiny fraction of all the different possible ways it could have been.

- It might be simpler to start with a low-entropy early universe, but we don't seem to have a principle that says the early universe had to be simple for that reason. It seems fairly arbitrary to simply say that the early universe was just like that; further, this approach doesn't seem to fit the universe we see.

A Spontaneous Arrow of Time?

- The third possibility for answering our question is that the arrow of time arises spontaneously out of the natural, reversible evolution of the universe. In other words, the universe does not have an arrow of time in the laws of physics, but the solutions to the equations of the laws of physics always have an arrow of time.

- This is actually a common phenomenon in physics, where the symmetries of specific solutions to equations are not the same as the symmetries of the equations.
    - As a very simple example, think of Newtonian mechanics, which is perfectly reversible; it has no arrow of time built in. Laplace told us that if we know the state of the universe in Newtonian mechanics at one time, we know it at all other times, but it's not hard to think of systems obeying the rules of Newtonian mechanics in which an arrow of time automatically arises.

    - For example, think of a ball rolling on an infinite hill. The history of this ball is that for an infinite amount of time, it rolls up the hill; it reaches a turning point and then spends an infinite amount of time rolling down the hill. This is the only thing the ball can do in this system; if the hill always has a slope, the ball can never remain stationary.

    - This is a physical system obeying Newton's laws, which are perfectly reversible, but it doesn't have an equilibrium.

    - Could the universe be like that? Could we live in a universe where the fundamental laws of physics say that entropy doesn't have a maximum value? If entropy doesn't have a maximum value, the reason we are not in the maximum-entropy configuration becomes much less mysterious: There is no maximum-entropy configuration. Entropy can always grow without bound.

- Even if entropy can grow forever, that certainly doesn't explain why our local region of the universe once had such low entropy. We need to do much more work to create a physical system in which regions where the entropy had the low value it had at the Big Bang are created naturally.

Inflation and the Multiverse

- What we really want to explain is why we're not in equilibrium, that is, why we don't already have the highest entropy we could possibly have. As we know, the entropy of our universe will continue to increase into the far future, until it becomes empty space.

- When we apply quantum mechanics to this empty space, there will be thermal fluctuations. Very rarely, there will be a random fluctuation of thermal energy that will result in an atom, a molecule, a person, a planet, or the universe. The larger the thing that will be created, the longer we need to wait for the random fluctuations, but they will all eventually happen.

- It sounds difficult to fluctuate the entire universe, which has much greater entropy than a planet or a person. As we said, it's easier to fluctuate entropy a little than a lot, so how can we think that it's easier to fluctuate a whole universe than just a person? It seems like this scenario gets us Boltzmann brains. The answer might lie in inflation.

- Although it might be very rare to fluctuate 100 billion galaxies, it may not be that difficult to fluctuate the tiny region of space that is dominated by super–dark energy and is ready to inflate.
    - Imagine we have empty space, nothing but vacuum energy and the very cold thermal radiation we expect because of quantum mechanics. Random thermal fluctuations occur all the time.

    - Because space itself is flexible, perhaps the shape of space can be fluctuated. Perhaps a small bubble can be pinched off that is full of dark energy and ready to inflate. That little bubble can inflate, expand, reheat, and look exactly like our Big Bang.

    - In this way, what we thought was equilibrium—a state of maximum entropy—could be shown not to be equilibrium. We can always increase the entropy of the universe, according to this way of thinking, by creating new universes that split off and go their own way, and this process continues forever.

- Just as we can evolve this scenario forward in time, we can evolve it backward in time and make more universes toward the past. Inside every one of those universes is an arrow of time that is pointed backward compared to ours. Just as the ball rolling down the hill comes from and goes to infinity, our universe does the same thing into the far past and the far future.

- This kind of scenario takes advantage of the flexibility of the universe according to the laws of general relativity and quantum mechanics to escape the trap of thermal equilibrium. Given the flexibility of space and time, given the quantum mechanical freedom to fluctuate into different things, maybe there is no maximum-entropy state the universe could be in.

The Future of Our Theories

- As of right now, our understanding of the multiverse and inflation isn't good enough to compare these ideas to the data we have. We need to push our understanding of cosmology, particle physics, gravity, and the evolution of complexity and entropy through time to be able to really understand what our theories predict. Once we get there, we can compare the theories to data and try to make a choice about which theory is right.

- We personally are organized systems; we have a great deal of complexity but low entropy. Even so, we are not flouting the second law; in fact, we're manifestations of it. We are side effects of the universe's increasing entropy. If the universe were in thermal equilibrium, intelligent life would not exist.

- In that sense, we are fortunate to live in a universe with such a pronounced arrow of time. The reason we have this arrow of time is because of the early universe. It's because of the conditions in the early universe that we have aging, metabolism, memory, and causality—everything that, to us, distinguishes the past from the future.

Suggested Reading

Albert, *Time and Chance*.

Carroll, *From Eternity to Here*, chapter 15.

Greene, *The Fabric of the Cosmos*.

Lockwood, *The Labyrinth of Time*.

Price, *Time's Arrow and Archimedes' Point*.

Questions to Consider

1. Despite what we currently know about the laws of physics, do you think it's plausible that the ultimate laws are actually not invariant under time reversal?

2. Do you think the multiverse is a promising route to explaining the arrow of time?

3. Would you be satisfied if the ultimate conclusion of cosmologists was that the low entropy of the early universe was simply a brute fact, without any deeper explanation?

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