



THE
GREAT
COURSES®

Topic
Science
& Mathematics

Subtopic
Physics

Mysteries of Modern Physics: Time

Course Guidebook

Professor Sean Carroll
California Institute of Technology



PUBLISHED BY:

THE GREAT COURSES

Corporate Headquarters

4840 Westfields Boulevard, Suite 500

Chantilly, Virginia 20151-2299

Phone: 1-800-832-2412

Fax: 703-378-3819

www.thegreatcourses.com

Copyright © The Teaching Company, 2012

Printed in the United States of America

This book is in copyright. All rights reserved.

Without limiting the rights under copyright reserved above,
no part of this publication may be reproduced, stored in
or introduced into a retrieval system, or transmitted,
in any form, or by any means
(electronic, mechanical, photocopying, recording, or otherwise),
without the prior written permission of
The Teaching Company.



Sean Carroll, Ph.D.

Senior Research Associate in Physics
California Institute of Technology

Professor Sean Carroll is a Senior Research Associate in Physics at the California Institute of Technology. He did his undergraduate work at Villanova University and received his Ph.D. in Astrophysics from Harvard in 1993. His research involves theoretical physics

and astrophysics, with a focus on issues in cosmology, field theory, and gravitation.

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*. ■

Table of Contents

INTRODUCTION

| | |
|---------------------------|---|
| Professor Biography | i |
| Course Scope | 1 |

LECTURE GUIDES

LECTURE 1

| | |
|-----------------------------|---|
| Why Time Is a Mystery | 3 |
|-----------------------------|---|

LECTURE 2

| | |
|---------------------|----|
| What Is Time? | 10 |
|---------------------|----|

LECTURE 3

| | |
|--------------------|----|
| Keeping Time | 17 |
|--------------------|----|

LECTURE 4

| | |
|--------------------|----|
| Time's Arrow | 24 |
|--------------------|----|

LECTURE 5

| | |
|--|----|
| The Second Law of Thermodynamics | 31 |
|--|----|

LECTURE 6

| | |
|---|----|
| Reversibility and the Laws of Physics | 38 |
|---|----|

LECTURE 7

| | |
|---|----|
| Time Reversal in Particle Physics | 45 |
|---|----|

LECTURE 8

| | |
|---------------------------------|----|
| Time in Quantum Mechanics | 52 |
|---------------------------------|----|

LECTURE 9

| | |
|----------------------------|----|
| Entropy and Counting | 58 |
|----------------------------|----|

LECTURE 10

| | |
|----------------------------|----|
| Playing with Entropy | 65 |
|----------------------------|----|

Table of Contents

LECTURE 11

| | |
|---------------------------|----|
| The Past Hypothesis | 73 |
|---------------------------|----|

LECTURE 12

| | |
|-------------------------------------|----|
| Memory, Causality, and Action | 80 |
|-------------------------------------|----|

LECTURE 13

| | |
|------------------------|----|
| Boltzmann Brains | 86 |
|------------------------|----|

LECTURE 14

| | |
|---------------------------|----|
| Complexity and Life | 93 |
|---------------------------|----|

LECTURE 15

| | |
|------------------------------|----|
| The Perception of Time | 99 |
|------------------------------|----|

LECTURE 16

| | |
|--------------------------------|-----|
| Memory and Consciousness | 105 |
|--------------------------------|-----|

LECTURE 17

| | |
|---------------------------|-----|
| Time and Relativity | 111 |
|---------------------------|-----|

LECTURE 18

| | |
|--|-----|
| Curved Spacetime and Black Holes | 119 |
|--|-----|

LECTURE 19

| | |
|-------------------|-----|
| Time Travel | 126 |
|-------------------|-----|

LECTURE 20

| | |
|--------------------------|-----|
| Black Hole Entropy | 133 |
|--------------------------|-----|

LECTURE 21

| | |
|---------------------------------|-----|
| Evolution of the Universe | 140 |
|---------------------------------|-----|

LECTURE 22

| | |
|--------------------|-----|
| The Big Bang | 148 |
|--------------------|-----|

LECTURE 23

| | |
|----------------------|-----|
| The Multiverse | 156 |
|----------------------|-----|

Table of Contents

LECTURE 24

| | |
|---------------------------------------|-----|
| Approaches to the Arrow of Time | 163 |
|---------------------------------------|-----|

SUPPLEMENTAL MATERIAL

| | |
|--------------------|-----|
| Bibliography | 170 |
|--------------------|-----|

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. ■

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.

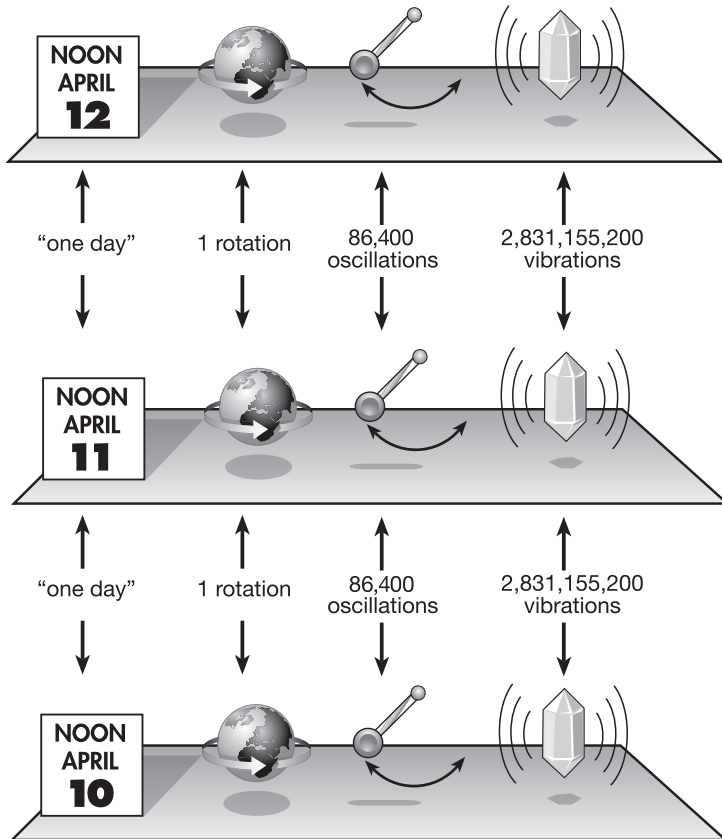
- Eternalism is sometimes called the “block universe perspective” because it’s like stepping outside the universe and seeing all four dimensions as one block of both space and time. Another term for it is the “view from nowhen,” the view not from any one moment in time but outside the whole thing.
-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



© Sean Carroll (created by Jason Torchinsky)

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 $365\frac{1}{4}$ 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?