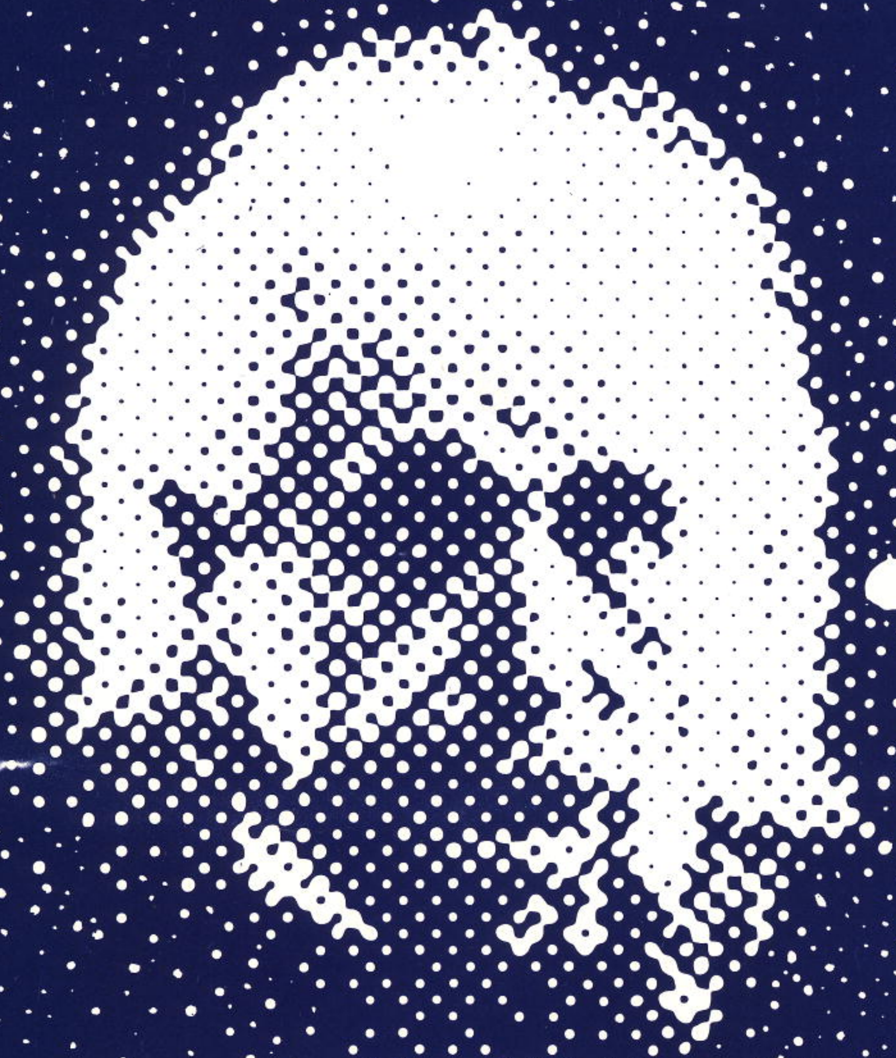
CONTINUUM



A Study Guide

JEFFREY CRELINSTEN, M.Sc.

National Film Board of Canada
Office national du film du Canada

CONTINUUM

a study guide

Prepared by Jeffrey Crelinsten, M.Sc.

THE FILM

Dr. Banesh Hoffmann, a biographer and one-time collaborator of Einstein, appears as host. At various locations in Princeton, in New York and on Mount Washington in New Hampshire, Dr. Hoffmann explains Einstein's development of the theory. Film animation sequences are employed to illustrate the basic concepts and to simulate actual experiments.

The title **Continuum** has been derived from the recognition that we live in a space-time continuum.

Produced and distributed by
National Film Board of Canada
16 mm Color
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Script Writer and
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Jeffrey Crelinsten

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Kenneth Horn

Original Music:
Richard Gresko

Violin played by
Calvin Sieb

Producer:
Sidney Goldsmith

Executive Producer:
Derek Lamb

RELATIVITY: SPECIAL AND GENERAL THEORY

This film concentrates mainly on the basic elements of Einstein's Special Theory of Relativity. It's called "special" because it restricts itself to a consideration of uniform motion only (motion at a constant velocity in a straight line). It was developed before Einstein's later General Theory that includes all motion – accelerated and curved.

The Theory of Special Relativity became well-known, in part, because some of its predicted effects seemed to contradict common sense. Here are a few examples:

- *Slowing down of moving clocks;*
- *Contraction of moving lengths;*
- *Increase of mass with motion;*
- *The speed of light is the fastest speed possible for any object in motion or for any transfer of information.*

All of these effects were derived by Einstein from his two postulates:

1. *The laws of physics are the same for all observers whether at rest or in a state of uniform motion (principle of relativity).*
2. *The speed of light is independent of the motion of its source.*

NEWTON'S WORLD

Isaac Newton lived from 1642-1727, two hundred years after Nicolas Copernicus took the Earth from its central position in the universe and set it flying around the sun in its orbit that we take for granted today. Newton's contemporaries still thought the sun was the center of the universe. The planets and their moons moved around it in celestial orbits according to a heavenly law and, on Earth, the ordinary objects of daily experience moved according to earthly laws. Newton's great achievement was to explain all the motions in the heavens and on Earth using the same laws, three laws of motion and the law of gravitation.

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Newton's Absolute Space *is the container in which the material universe resides. This implies that:*

- *when we are at rest relative to space, we are in a state of absolute rest. Our state of rest is an objective fact, true for all observers;*
- *when we are in motion relative to space, we are in a state of absolute motion. The motion is an objective fact, true for all observers.*

These implications lead to the idea that a state of rest and a state of motion are fundamentally different, and that this difference can always be detected. As we will see, this was to cause problems.

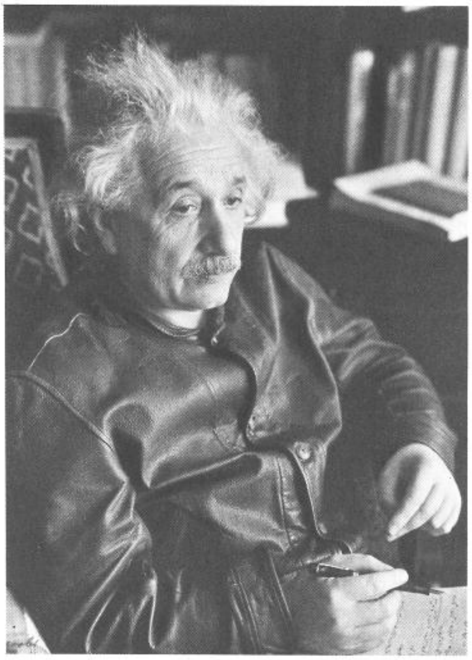
Newton also needed to measure changes of position in standard units of time. To do this, he thought of Time as an absolute, unchanging sequence against which the duration of all events could be measured.

Newton's Absolute Time *is the universal sequence by which we mark the passage of events. This implies that:*

- *a moment of "now" exists for the entire universe;*
- *when an event occurs, everyone, everywhere can know about it immediately, "now".*

These implications lead to the idea that there must be an infinitely fast signal speed bringing the information of the event everywhere, "now".

THE TRANSITION PERIOD



The concept of Absolute Space was already under discussion by physicists when Einstein came upon the scene. It contradicted a basic fact of everyday experience, a fact that was expressed as a fundamental principle of physics and referred to as the "principle of relativity."

The principle of relativity was not discovered by Einstein.

The principle of relativity states that:

- *being at rest and being in uniform motion feel the same;*
- *no experiment can determine whether you are at rest or in uniform motion;*
- *the laws of mechanics are the same for all observers moving uniformly relative to one another.*

The problem was that Absolute Space implies that there is a fundamental difference between rest and motion, whereas the principle of relativity (and experience) tells us that uniform motion is relative. This paradox troubled physicists, but they lived with it because Newton's mechanics was so useful. A breakthrough was made in the late 19th century when James Clerk Maxwell showed that light is an electromagnetic wave that propagates through space at 300 000 km/sec. Physicists figured that the material through which light propagates, called the ether, could be thought of as Absolute Space. Motion relative to the ether should be detectable using optical experiments. In this case, the principle of relativity would have limited validity, holding only for motion of mechanical objects (like billiard balls, trains, and people), but not for light. But Einstein pursued a different theoretical course than that of his contemporaries.

As he developed his theory, he realized that the principle of relativity must be fundamental, and that it should apply to all phenomena, including light.

To derive his laws of motion mathematically, Newton had to express motion of an object in terms of a change in its position. But position relative to what? Newton replied "relative to Absolute Space."

note

Erratum (will be added) : Paragraph bottom page 3 should be on top of page 2.

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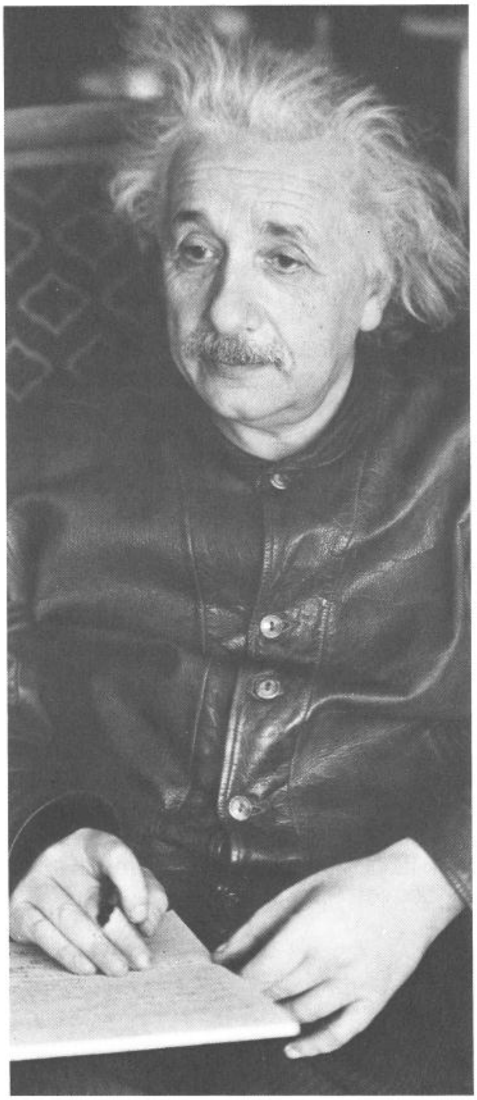
EINSTEIN'S TWO POSTULATES



Einstein's approach to physics was theoretical. As a young boy he had loved studying a geometry book in which basic simple assumptions were made, called postulates. An amazing variety of consequences could be derived from the few postulates. Einstein's theory of relativity begins with two postulates from which everything else is deduced.

Postulate 1:
The Principle of Relativity

"All the laws of physics are the same for all observers moving uniformly relative to one another."

Postulate 2:
The Constancy of the Velocity of Light

"The speed of light is independent of the velocity of its source. No matter how fast a light source is moving, the emitted light always moves at the same speed."

These two postulates led to an apparent contradiction that, when resolved, led Einstein to question the notion of Absolute Time. The resolution hinged on how the speed of light is measured.

To appreciate the "contradiction" between the two postulates, imagine the following situation:

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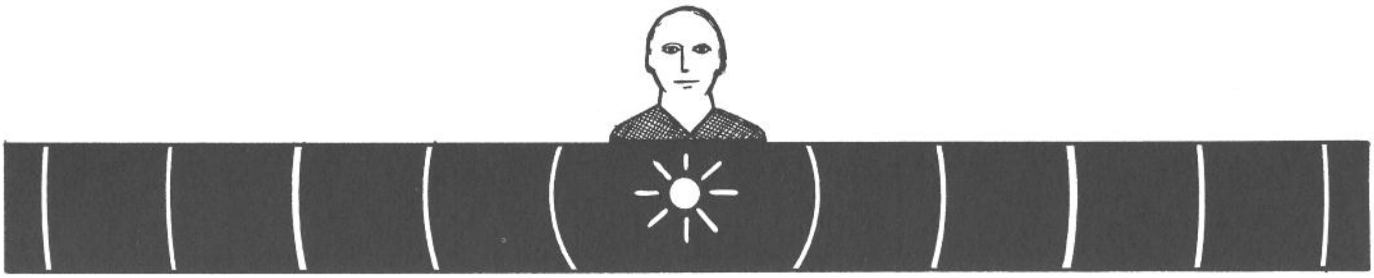
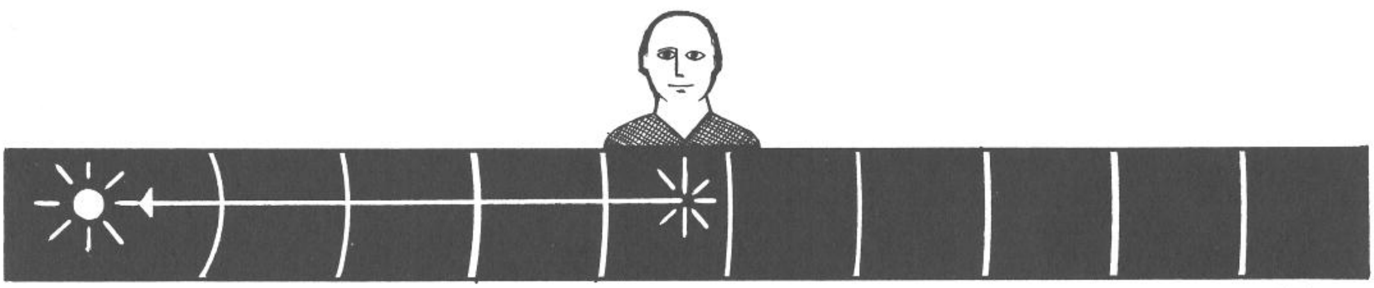
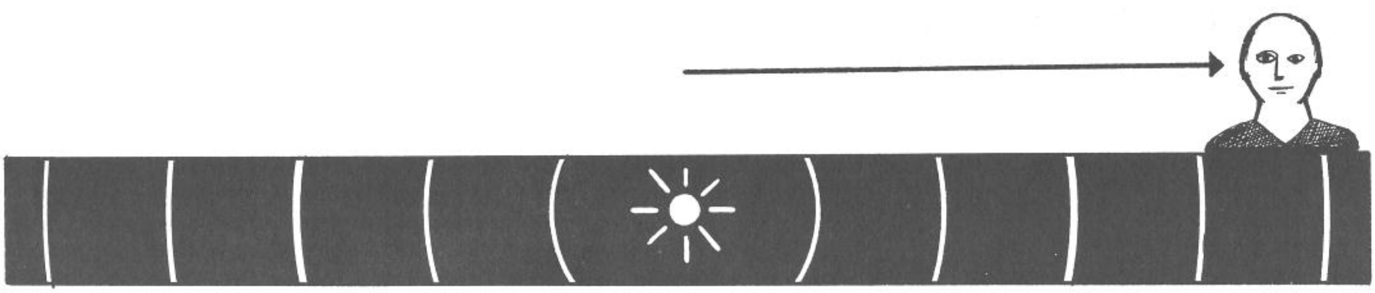


Suppose you're standing next to a light bulb. As the light spreads from the bulb, you measure its speed. You will find the speed of the emitted light is 300 000 km/sec.



Now, suppose the light bulb moves away from you at high speed. The emitted light has no connection to the bulb. When you measure its speed it will still be 300 000 km/sec. (This commonsense fact is the same as Einstein's second postulate.)



But according to the principle of relativity (Einstein's first postulate), the bulb can be considered at rest and you are moving away from the bulb at high speed. If you measure the speed of the light in this case, will it still be 300 000 km/sec.?

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Now if uniform motion really doesn't affect things, then both situations should physically be the same. In that case, even when you are moving away from the stationary bulb, the speed of the light you measure should still be 300 000 km/sec. This conclusion makes complete sense. It is also entirely consistent with Einstein's two postulates. However, think about it again. Our usual way of thinking about velocities does not agree with the above conclusion. A bulb is shining in a street lamp, and the light is propagating out from the lamp at 300 000 km/sec. We are in a car speeding down the street away from the street lamp, and if we were to measure the speed of light coming from the lamp, our normal way of thinking tells us that we should measure a speed of 300 000 km/sec PLUS the speed of our car. But Einstein's two postulates tell us that we should get 300 000 km/sec whether we're standing next to the lamp or moving away from it in a speeding car! What he is saying is that the speed of light should be the same for ALL observers, regardless of their state of motion. By thinking for ten years about why this seems to violate common sense, Einstein finally came up with the idea that our long-held notions about time were wrong, and that Newton's theory of Absolute Time had never been valid.

Historical note: a nice little irony is that about the time young Einstein was beginning to think about this problem, physicists of the day were actually doing optical experiments to detect effects of the Earth's motion through the ether. If such effects could be detected, as they thought they would, that would be confirmation that uniform motion could be detected optically, and that the principle of relativity had only limited application. Much to their astonishment, no effect was detected, and they were forced to conclude that the speed of light is the same for all observers regardless of their state of motion. This was exactly Einstein's second postulate, which he had arrived at theoretically, by conducting what he called "thought experiments." While Einstein pondered the advantages of the principle of relativity to understand the concept of Time, other physicists were confused and upset about it, and still wanted to disprove the principle of relativity.

EINSTEIN'S INSIGHT ABOUT TIME

Einstein's key insight was that all measurements of Time involve judgements of simultaneous events:

"If we wish to describe the **motion** *of a material point, we give the values of its co-ordinates (i.e. its position) as functions of the time. Now we must bear carefully in mind that a mathematical description of this kind has no physical meaning unless we are quite clear as to what we understand by time. We have to take into account that all our judgements in which time plays a part are always judgements of simultaneous events. If, for instance, I say, that train arrives here at 7 o'clock, I mean something like this: 'The pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events.'"*

– Albert Einstein, "On the Electrodynamics of Moving Bodies", 1905. (Einstein's original scientific paper on relativity)

The above statement must have seemed simple-minded to many physicists who read it at the time. However, it was the seed that brought forth the "relativity revolution" that rocked the foundations of physics. To

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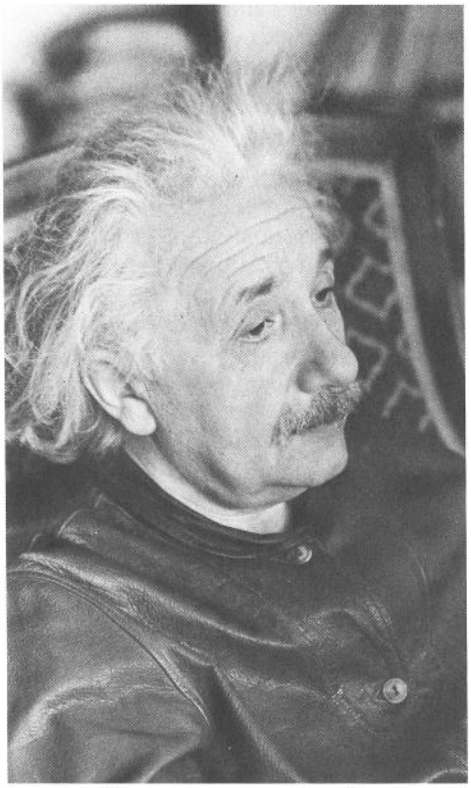

appreciate the idea that simultaneity lies beneath our notion of time, it's revealing to look at ordinary expressions and see the simultaneous events behind them. Here are a few:

I ate at noon.	*I ate.* *The sun was on the meridian.*
The American Declaration of Independence was signed on July 4, 1776.	*The Declaration of Independence was signed.* *The calendar read July 4, 1776.*
The train arrived in the station at 7 o'clock (Einstein's example).	*The train arrived in the station.* *My watch (and the station clock) read 7.*

Now, the interesting part comes when we talk about the time of events far away from each other or from us. To judge the time of events separated in space we need clocks at each event, and these clocks must be synchronized. Two separated clocks can be synchronized using light signals, and this is shown in the film. Only when they're synchronized can we talk about the time of the events. Here are some examples:

My friend's train arrived in the station 400 km away from here, at 7 o'clock.	*My friend's train arrived in the station 400 km away from here.* *My watch read 7 o'clock and I knew that it was synchronized with the station clock 400 km away from here, so it must have read 7 o'clock, too.*
The spacecraft landed on the moon at 0700 hours Eastern Standard time.	*The spacecraft landed on the moon.* *The clock on the spacecraft read 0700 and it was synchronized to the clocks at ground control which were set to Eastern Standard time.*

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Before Einstein, the simultaneity of the above separated events would have been assumed as immediately obvious from experience and left unquestioned by physicists. The conventional understanding of time had been based on such experiences. Einstein maintained that this belief was an illusion. He wrote:

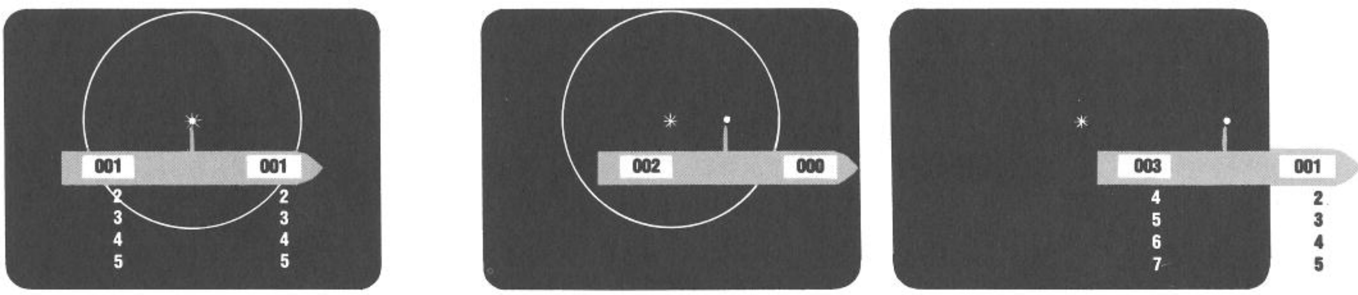
"This illusion had its origin in the fact that in our everyday experience we can neglect the time of propagation of light. We are accustomed on this account to fail to differentiate between 'simultaneously seen' and 'simultaneously happening'; and, as a result, the difference between time and local time is blurred".

– Albert Einstein, "Physics and Reality", 1936 (From **Ideas and Opinions,** *New York: Dell, 1973)*

Einstein realized that the meaning of simultaneity of separated events, and thus the physical meaning of time, was NOT obvious.

The key insight that unlocks the secret of special relativity is the realization that two events which are simultaneous for one person are not simultaneous for another person moving relative to the first at high speeds close to the speed of light. This can be deduced directly from Einstein's two postulates, the principle of relativity and the independence of the speed of light from the motion of its source (constancy of light velocity).

In the film, this is illustrated by two spacecraft crews observing each other synchronize clocks.



OBSERVER'S FRAME **OBSERVER'S FRAME** **OBSERVER'S FRAME** **(LATER)**

(NO RELATIVE VELOCITY) **(RELATIVE VELOCITY)**

Note that the centre of the expanding light ring always remains fixed relative to the spacecraft that is observing the event:

- *Each crew defines Time according to its own synchronized clocks;*
- *Each crew considers itself at rest and the other spacecraft as moving;*
- *Each crew sees the other's clocks as unsynchronized. The trailing clock is ahead.*

SUGGESTED TOPICS FOR DISCUSSION

- *Why do we not notice this effect in everyday life?*
- *If observers in fast relative motion with respect to each other disagree about simultaneity, can there be one moment of "now" that exists for the entire universe?*
- *It was technically possible for the Americans to ignite their bicentennial flame using starlight from a star 200 light years away. For observers moving close to the speed of light relative to the Earth, would they agree that the light left the star simultaneously with the signing of the Declaration of Independence?*
- *If you observe someone drop a banana peel and another person slips on the peel and falls, can someone else moving close to the speed of light relative to you see the person fall before the banana peel is dropped? Why or why not?*
- *A supernova explodes, and before the light from the explosion has time to reach another star some distance away, that star explodes too. If astronomers on Earth see the supernova flash before the other star explodes, can another observer moving close to the speed of light relative to the Earth-astronomers see the order of explosion reversed? Why or why not?*

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IMPLICATIONS OF THE SPECIAL THEORY OF RELATIVITY

The rest of the film deals with the strange effects that have been predicted by Einstein's theory.

RELATIVITY OF TIME

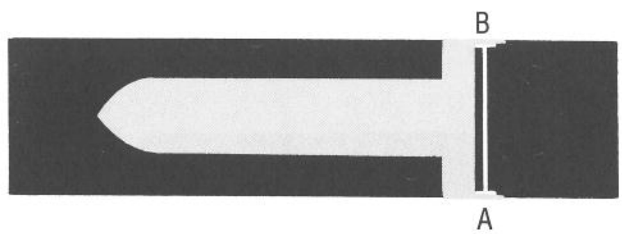
When looking at the animated sequences with digital clocks ticking away, it is important to realize that the emphasis on clocks is really about the nature of Time.

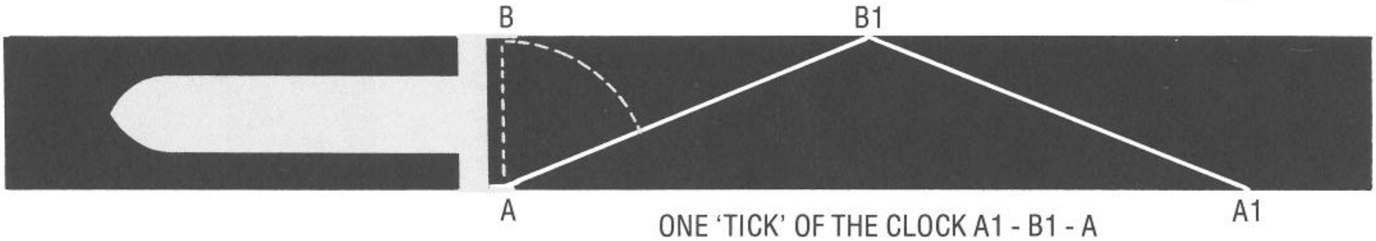
Einstein had asked the basic question "what do we mean by 'Time'?" and had concluded that we must measure Time by comparing events by clock readings. Events separated in space must be compared with two different clocks located at each event. These clocks must be synchronized by the observer of the events. Each observer synchronizes his clocks differently. So Einstein reduced the problem of Time to the problem of clocks.

In the film we see how Einstein's two postulates lead to the conclusion that moving clocks appear to run slowly, or that time slows down on a vehicle in motion relative to you. This is done using a beam of light bouncing between two mirrors as a clock.

NO RELATIVE VELOCITY

ONE 'TICK' OF THE CLOCK A - B - A





ONE 'TICK' OF THE CLOCK A1 - B1 - A

RELATIVE VELOCITY

The distance A1 B1 A is longer than A B A.
Since speed of light is constant, time interval is longer.
The 'clock' has slowed down.

Remember that while you think time is running slowly on the vehicle whizzing by you, the person in the vehicle thinks your time is running slowly.

RELATIVITY OF LENGTH

In the film, a space-age experiment is simulated illustrating the length contraction of a space freighter two kilometres long. The measurements of lengths are calculated by the spacemen, using clock readings. The film sequence does not show how this result can be derived from Einstein's two postulates; it is merely a dramatization of a stated result. However, once the slowing of clocks for moving observers is understood, then the fact that lengths change too should be no surprise. This is because, to measure the length of an object, we must measure the position of two ends at the same time. If moving observers disagree about simultaneity and rates of clocks, they must also disagree about lengths.

ARE THESE EFFECTS REAL?

The fact that each observer sees the other's clock slow down and length contract makes us wonder whether these effects are real. This problem can launch us into interesting speculations on the meaning of "real" and other such problems. But if we concentrate on the physics of the matter, then it is clear that concrete, physical things happen in the world that can be only explained in terms of these relativistic effects. The film illustrates one of the best known examples. When the number of mu-mesons (subatomic particles) was measured at the top and the bottom of Mt. Washington in New Hampshire, there were more at the bottom than expected, given the length of time it takes for mu-mesons raining down from the atmosphere to reach the bottom.

In one version of the experiment, a special detector selected mu-mesons moving at 99.5% of the speed of light. At the top of the mountain, it detected about 560 of these particles per hour, while about 1900 meters lower (near sea level) about 410 were detected every hour. The half-life of mu-mesons is about 1.5 microseconds. This means that after 1.5 micro-seconds, a group of 560 mu-mesons should be reduced to about 280, after 3 microseconds it should be reduced to 140, and so on. Now, it takes about 6 microseconds for the mu-mesons to get from the top to the bottom of the mountain, so there should only have been about 35 of them per hour. For as many as 410 per hour to be arriving at the bottom, the mu-mesons' clocks must have been running much slower. In fact, when the calculation was done, it was found that the clocks were slow by exactly the amount predicted by special relativity for relative velocities of 99.5% the speed of light.
See James H. Smith, **Introduction to Special Relativity** (New York: W. A. Benjamin, 1965), pp 57-60.

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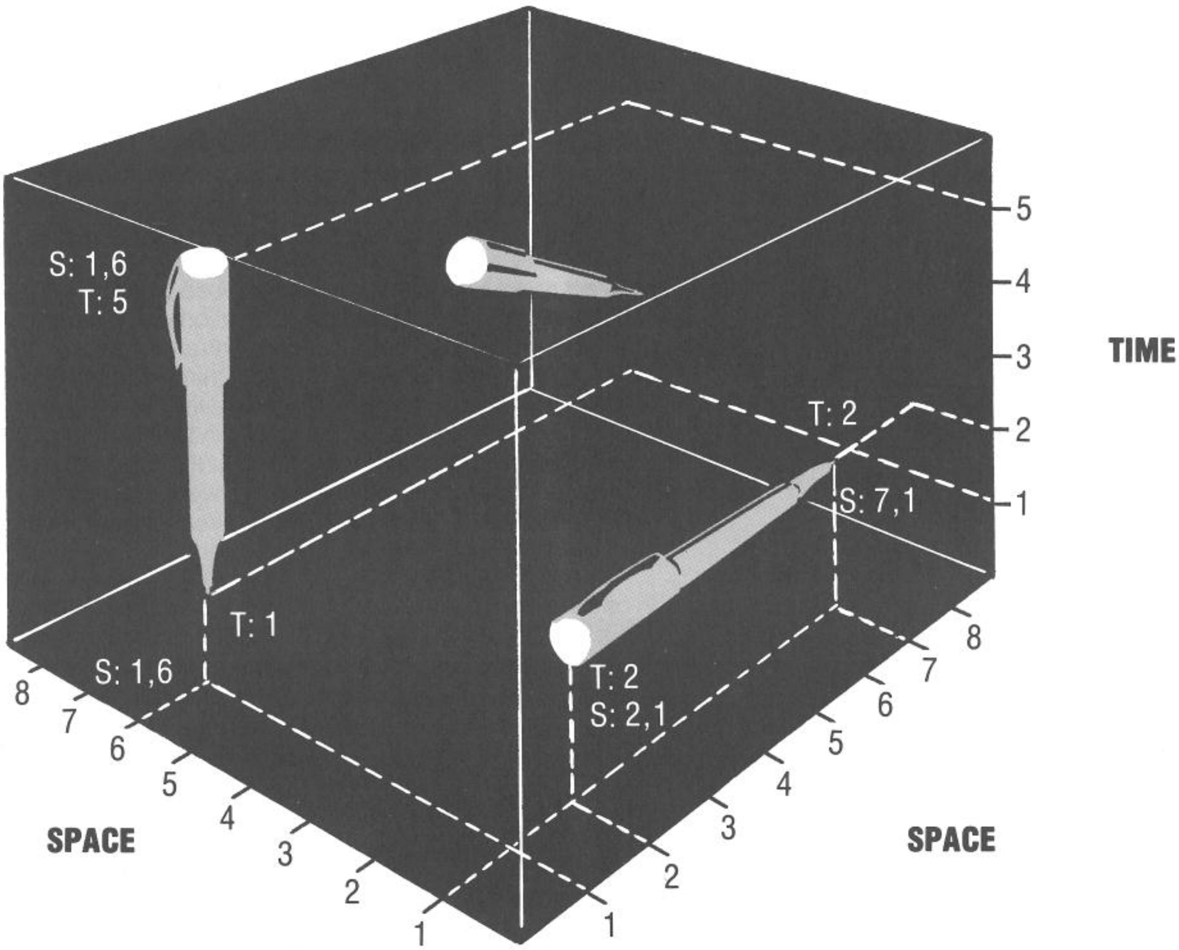
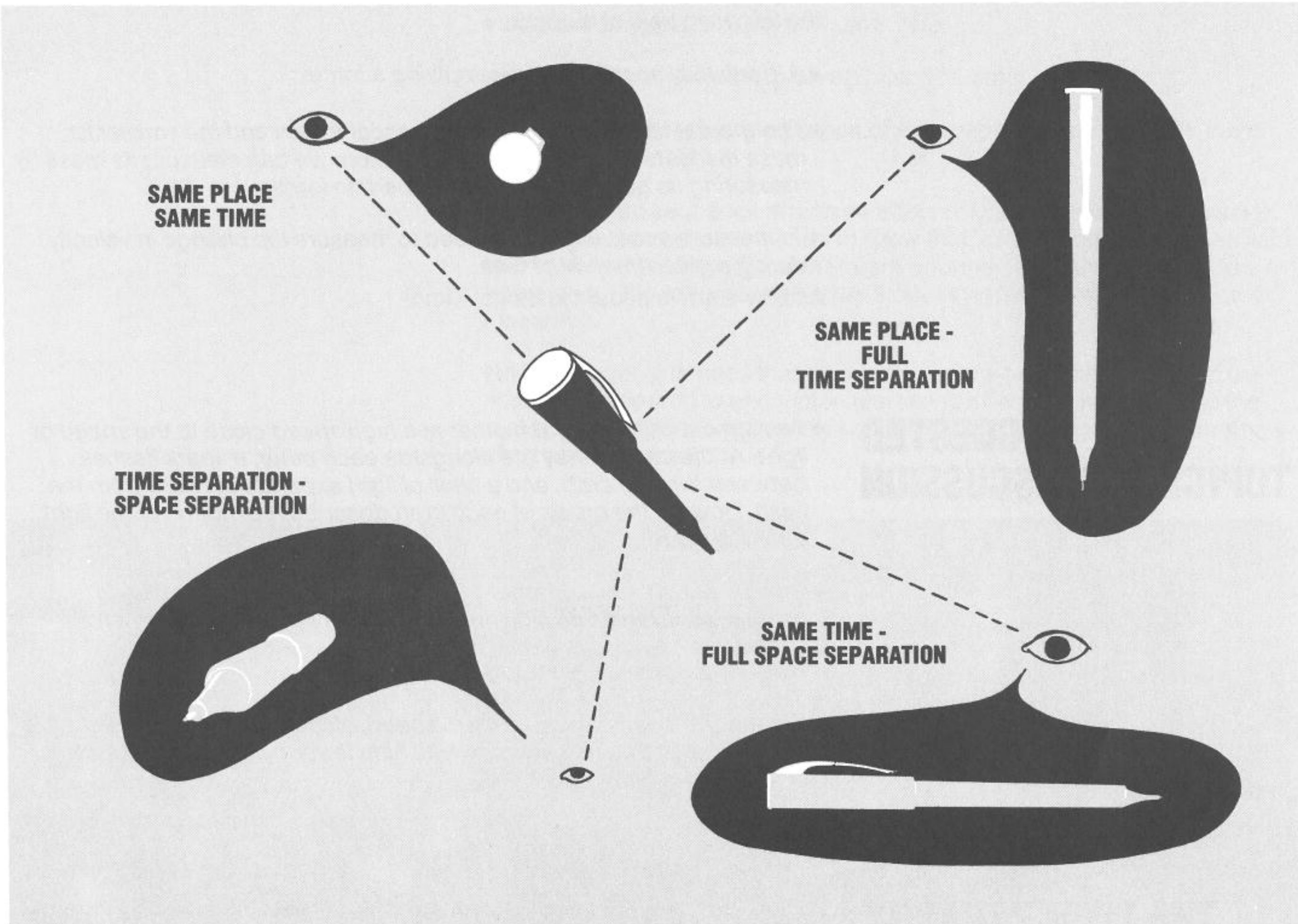
SPACE, TIME AND SPACE-TIME

There is a scene in the film, in which Dr. Hoffmann uses a pen to explain the meaning of the contractions of length and slowing down of Time. He uses the analogy of perspective. Two events can be thought of as being the two ends of a pen.



Take a pen and hold it vertically. Viewed this way, the pen can represent two events at the same place, the lower end occurring before the upper end. Held horizontally, it would represent two simultaneous events separated from each other in space by the length of the pen. Held at an angle, the events are separated in time and in space by a time represented by the length of the pen.

If the event-pen is oriented a certain way for one observer, an observer moving past will see the pen rotated, so that lengths and time intervals between the two events look different, but the actual "space-time length" of the pen is the same.



Remember that all **physical** results will be the same for all observers in relative motion to one another. It is just their individual measurements that can be different. For example:

- *all observers agree on the number of mu-mesons at the top and at the bottom of Mt. Washington;*
- *all observers agree that in a head-on collision between two spacecraft, the event of impact occurs when the two spacecraft are at the same place (zero separation) at the same time (simultaneity).*

If you had trouble before with the banana peel and supernova explosions in the suggested topics for discussion (p. 9) try again with this in mind. Hint: Causality

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RELATIVITY OF MASS

In the film, the increase of mass of a particle being accelerated in a linear accelerator is simulated. Like the length contraction scene with the space freighter, the increase of mass is not deduced from Einstein's two postulates. It is only dramatized here. However, again we can see that the effect is to be expected once the relativity of time is accepted. Consider the following train of thought:

- *A particle is accelerated by applying a force;*
- *The greater its mass the slower the acceleration and the smaller its mass the faster the acceleration; therefore we can measure its mass by measuring its acceleration, given a certain force;*
- *To measure acceleration, we need to measure the change in velocity during a given interval of time.*

Again we arrive at our old friend, Time!

SUGGESTED TOPICS FOR DISCUSSION

- *Two spacecraft pass each other at a high speed close to the speed of light. At the instant they are alongside each other, a spark flashes between the two craft, and a shell of light expands outward from the flash. How do the crews of each craft describe the motion of the light after the flash?*
- *How does each crew account for the other crew's description in comparison with its own?*
- *Why are particle accelerators so long?*
- *If someone moves by you at high speed, close to the speed of light, his clock seems to be running slowly to him. Is your clock running slower or faster than his?*

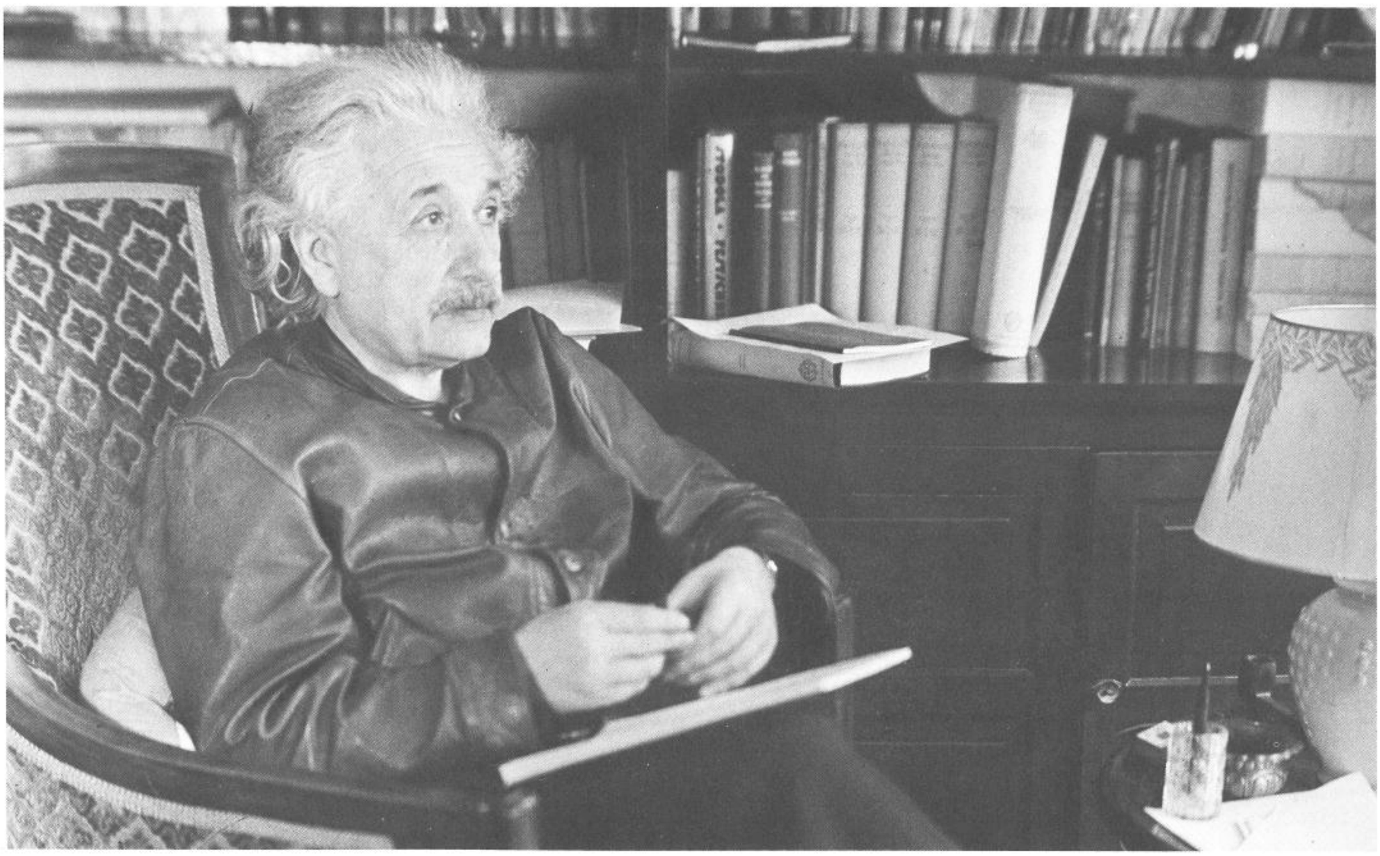
THE TWIN PARADOX

We couldn't resist tackling this one! The last scientific item dealt with in the film is the famous "twin paradox." This is how it goes: one twin leaves on a space voyage and returns. The other twin remains at home. When they say good-bye they are the same age. When they re-unite, the theory of relativity predicts that the travelling twin will come back younger than the stay-at-home. This is certainly strange, but why is it called a "paradox?" Well, say the doubters, according to the principle of relativity, we can take the point of view of the travelling twin, assumed to be comfortably at rest, and the stay-at-home can be thought of as going away and coming back. Why then, in this case, couldn't this twin be the younger one? How do we know which one will come back younger? The key is that the travelling twin has to stop and turn around, so his trip is unique and not interchangeable with the other. In the film, Dr. Hoffmann shows that there is really no paradox, by referring to the concept of space-time:

- *both twins age at exactly the same rate;*
- *but they travel different intervals in space-time;*
- *the result is that the time portion of the space-time path for the travelling twin is shorter.*

In an animated sequence, the three effects of simultaneity, time slowing, and length contraction are used to show that, in fact, both twins agree with the result that the traveller comes back younger, even though they disagree about the rates of each other's clocks and the length that the other measures.

Nothing better illustrates that we live in a space-time continuum and we should be prepared to encounter interesting effects as we enter into the realm of high speeds, extremely small and large distances, and extremely short and long times.



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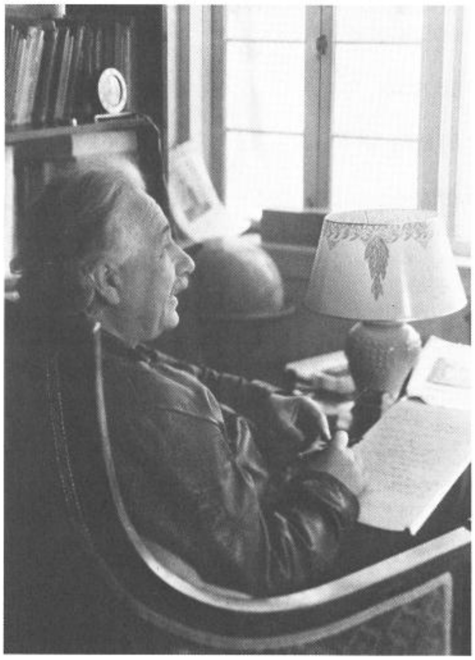
SELECTED BIBLIOGRAPHY



The following is a short list of non-technical writings on relativity and Einstein.

Einstein, Albert. **Relativity. The Special and General Theory.** Trans. Robert W. Lawson. Crown, New York, 1961.

Einstein, Albert. **Ideas and Opinions.** Trans. Sonja Bargmann. Dell, New York, 1965 (especially Part Five).

Einstein, Albert. Infeld, Leopold. **The Evolution of Physics: From Early Concepts to Relativity and Quanta**.Simon and Shuster, New York, 1938.

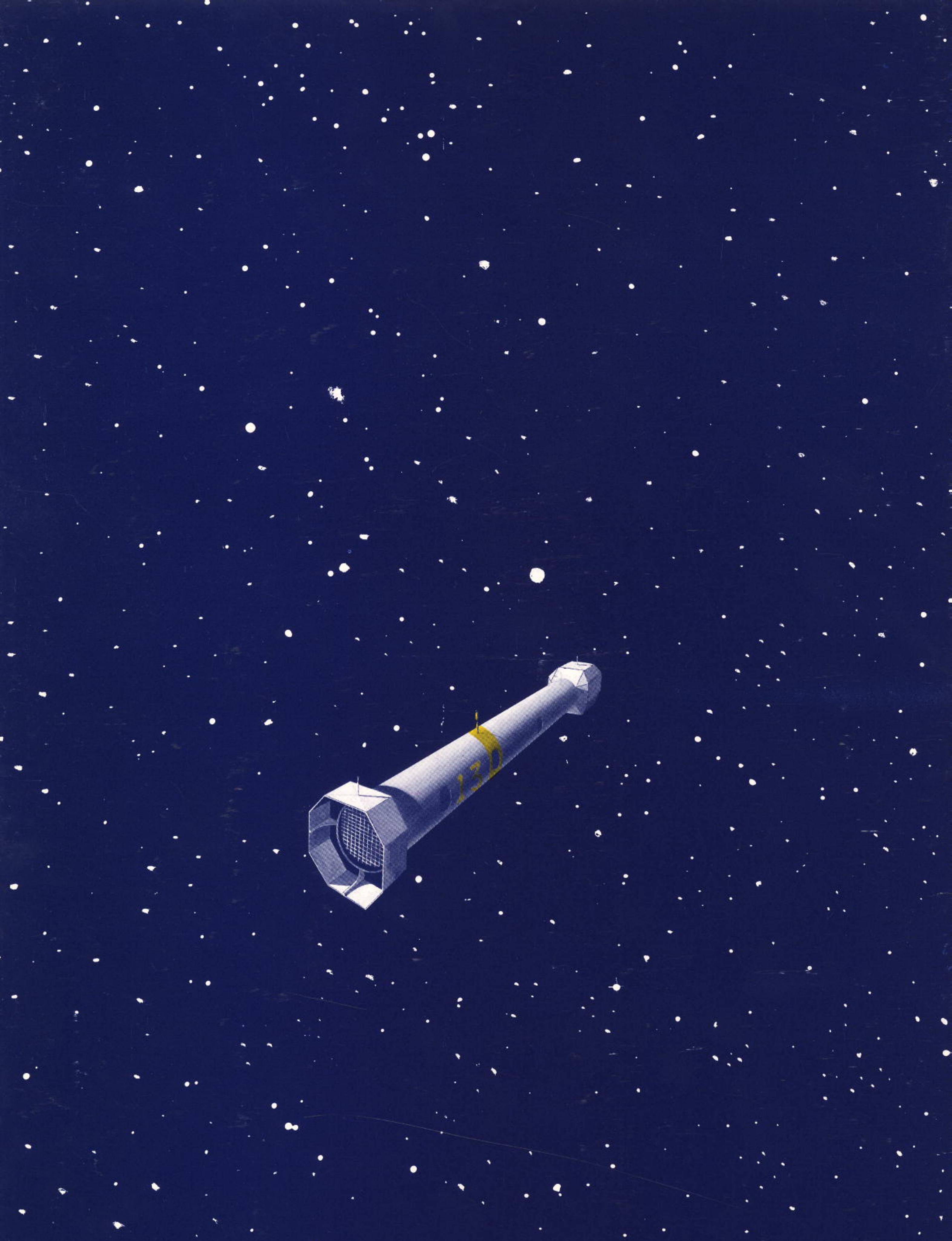
Hoffmann,Banesh. Dukas, Helen. **Albert Einstein: Creator and Rebel.** New American Library, New York, 1972.

Bernstein, Jeremy. **Einstein**.Viking, New York, 1973.

Gardner, Martin. **The Relativity Explosion**.Random House, New York, 1976.

The first three books are Einstein's own attempts to popularize his theories. They are excellent reading and require no mathematics.

It is also worth looking at Einstein's original 1905 special relativity paper, "On the Electrodynamics of Moving Bodies," in Albert Einstein et. al. **Principle of Relativity**. Dover, New York, 1952. The first part of this paper, called the Kinematical Part, requires little mathematics, and is a fascinating introduction to how Einstein used the most basic concepts to build this theory.



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