

HISTORY OF SCIENCE CASES  
FOR HIGH SCHOOLS

*Louis I. Kuslan*  
Case **5**

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# THE SPEED OF LIGHT

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# THE SPEED OF LIGHT

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## INTRODUCTION

In this HISTORY OF SCIENCE CASE, we shall make a critical study of a part of the development of a major scientific idea. Although we want to learn something about this idea, our chief interest in this CASE will be to find out as much as we can about:

- the methods used by scientists
- the means by which science advances and the conditions under which it flourishes
- the role of scientists as people and the personal characteristics of scientists
- the interplay of social, economic, technological, and psychological factors with the progress of science
- the importance of accurate and accessible records, constantly-improved instruments, and free communication

Proper study of this CASE consists of more than simply reading this little booklet. In the narrative outline, which follows this introduction, you will find numerous comments and questions in the margins. These marginal notes are intended to stimulate your thinking and to guide discussion on the points illustrated by the CASE. Space is provided on the left-hand pages for you to write answers to the questions which appear in the marginal notes . . . A most important part of the study of this CASE are the experiments and exercises which are suggested in this booklet, following the narrative outline. You should try to complete as many of these exercises as possible, so that you may get a real "feel" for the situations faced by scientists in creating science. Your teacher may suggest additional exercises and experiments that you can work on in connection with this CASE. On the last page of this booklet, you will find some reading suggestions of books and articles relating to the story of this particular CASE.

Some students will think that this CASE is out of date, because the story is set in the scientific past. Nothing could be further from the truth. The points about science and scientists which are featured in this CASE hold just as cogently in the present as they did in the past. The methods of scientific investigation are much the same today as they have been for several hundred years; similar non-scientific factors now interact with the progress of science as they did then; the character and personalities of scientists are always paramount factors when we think about science; adequate recording, free communication, and improved instrumentation continue as vital needs. These aspects of science held true yesterday, hold true today, and will hold true tomorrow.

As you study this CASE and work through the exercises, you will learn a great deal about scientists and about what goes on in science.

L.E.K.

The principal people you will meet in this CASE are:

Galileo Galilei	Italian astronomer and physicist. Born 15 February 1564 at Pisa. Died 8 January 1642 at Arcetri, Florence.
Ole Roemer	Danish astronomer. Born 25 September 1644 at Aarhus, Jutland. Died 19 September 1710 at Copenhagen.
James Bradley	English astronomer. Born 1693 at Sherborne, Gloucester. Died 1762 at Chalford, Gloucester.
Armand Hyppolyte Louis Fizeau	French physicist. Born 23 September 1819 at Paris. Died 18 September 1896 at Venteuil.
Jean Bernard Léon Foucault	French physicist. Born 18 September 1819 at Paris. Died 11 February 1868 at Paris.
Albert Abraham Michelson	American physicist. Born 19 December 1852 at Strelno, Germany. Died 9 May 1931 at Pasadena, California.

[Use these left-hand pages to take notes and to write out your answers to the questions suggested in the margins of the story.]

Why is it important to obtain an accurate value for the speed of light?

How do we define "speed"?

Why would the speed of light be infinite if it took no time to cover a given distance?

# THE SPEED OF LIGHT

Scientists have been interested in the speed of light for many years. They have wanted to know how fast light travels not only because precise measurement is in itself one of the foundations of scientific work, but also because the speed of light has held and continues to hold an important place in fundamental scientific theories. For instance, in the nineteenth century, a knowledge of the speed of light in air compared with its speed in water was of crucial importance in deciding between the theory of light considered as a stream of particles and the theory of light considered as a wave motion. In this century, the speed of light holds a key place in the theory of relativity, formulated by Albert Einstein.

You probably know already that the speed of light is approximately  $3 \times 10^8$  meters per second (or about 186,000 miles per second), and this is a pretty fast rate of speed, fast enough for light, if it could travel in a circle, to go almost  $7\frac{1}{2}$  times around the earth in a single second!!! How is it possible to accurately measure such a large and elusive quantity? What ideas, devices, knowledge, and skills must be brought to bear on this problem? . . . In this Case, we shall see how a succession of scientists, including some of the most famous and many not so well known, attempted to measure the speed of light. The story of our Case spans approximately three centuries, from the early 1600's up to the present time . . . .

Before we can even think about how to measure the speed of light, we must believe that light has a speed. It might well be that light takes no time at all to cover any given distance, that it is transmitted instantaneously. Indeed, our everyday experiences would lead us to believe that this is so. For example,

How do we define "speed"?

If this were so, the speed of light would be infinite. Why?

What is meant by "hypothesis" in science?

Can a scientist today be both an astronomer and a physicist? Does this happen very often today? If not, why not?

What does Galileo mean by "without sensible error"? -- Is he correct in saying this? If not, what are the chief sources of error in this experiment?

Walk into a dark room, which is equipped with an electric light fixture. Flip on the switch. The light originating from the bulb or bulbs in the fixture immediately fills the room. It seems to take no time at all for the light from the fixture to reach to the furthest corner of the room. Therefore, isn't light transmitted instantaneously?

(This experiment works only if the electric bill has been paid.)

Perhaps you can think of a number of other observations that would lead to the hypothesis that light is transmitted instantaneously. (See exercise 1, page 20.) You will then not be surprised to learn that in the 17th century many scientists believed that light has no measurable speed, for a speed that is infinite cannot be measured. Johann Kepler in Germany and Rene Descartes in France, two of the ablest scientists of the 17th century, believed in the instantaneous transmission of light.

In contrast with this belief, the Italian astronomer and physicist, Galileo Galilei, held that light had a finite speed. Moreover, Galileo suggested an experiment for measuring the speed of light in his last book, Discorsi e dimostrazioni matematiche intorno à due nuove scienze, (Discourses and Mathematical Demonstrations concerning Two New Sciences), published in 1638.

Can a scientist today be both an astronomer and a physicist?

One way in which scientists exchange ideas and information is by publishing books.

Let each of two persons take a light contained in a lantern, or other receptacle, such that by the interposition of the hand, the one can shut off or admit the light to the vision of the other. Next let them stand opposite each other at a distance of a few [yards] and practice until they acquire such skill in uncovering and occulting their lights that the instant one sees the light of his companion he will uncover his own. After a few trials the response will be so prompt that without sensible error the uncovering of one light is immediately followed by the uncovering of the other, so that as soon as one exposes his light he will instantly see that of the other.

What does Galileo mean by "without sensible error"? Is he correct?

Having acquired skill at this short distance, let the two experimenters, equipped as before, take up positions separated by a distance of two or three miles and let them perform the same experiment at night, noting carefully whether the exposures and occultations occur in the same manner as at short distances; if they do, we may safely conclude that the [transmission] of light is instantaneous; but if time is required at a distance of three miles, which, considering the going of one light and the coming of the other, really amounts to six, then the delay ought to be easily observable.

A chain of reasoning connects experimental observations with the idea being tested.



What are "scientific societies"? -- How do they serve science?

How is the specialized equipment needed in scientific work obtained? -- Who makes it? Who pays for it?

Was this "Académie" a French school? What was it? -- Is it still in existence today? What functions does it perform?

How does a scientist depend on the work of his predecessors? What can he learn from the work of previous scientists? -- Does a present-day scientist view the work of earlier scientists in the same way that a present-day artist views the work of earlier artists? Give reasons for your opinion.

The experiment which Galileo suggested was later tried by members of the Accademia del Cimento (Academy of Experiment), one of the earliest scientific societies.

What are "scientific societies"? How do they serve science?

We tried it at a Miles distance (which in the going forward and Return of the Light must be reckon'd Two), and could not observe any Delay. If in a greater Distance it be possible to perceive any sensible Delay, we have not yet had an opportunity to try.

Thus, Galileo's ingenious suggestion to test the hypothesis that the speed of light is finite could not be carried out. The suggestion was a good one, for all later terrestrial measurements of the speed of light used the same idea of measuring the time it takes light to travel over a known distance. Yet, the investigators of the 17th century did not have the necessary equipment available to perform the experiment properly.

Can the speed of sound be found in a similar way?— See exercise 2, page 20.

Specialized equipment is needed in scientific work. — How is it obtained?

Thus it was that the first evidence for the finite speed of light and an estimate of its great speed came from astronomical observations. This was accomplished in a dramatic manner by the Danish astronomer, Ole Roemer. In September 1676, Roemer announced to the Académie des Sciences at Paris that the innermost moon of Jupiter would emerge from an eclipse by its parent planet on the night of 9 November exactly ten minutes behind schedule. Ever since the moons of Jupiter were discovered by Galileo in 1610, they had been much observed, and it was learned that the innermost moon revolved once around the planet in about 42 1/2 hours. On the basis of many observations, tables that predicted the times when its moons would be eclipsed by Jupiter had been prepared. According to these tables, Jupiter's innermost moon was scheduled to emerge from eclipse on the evening of 9 November at 25 minutes and 45 seconds after 5 o'clock, as seen from Paris. However, Roemer pointed out that this prediction did not take into account the

Was this "Académie" a French school? Is it still in existence today?

How does a scientist depend on the work of his predecessors?

Can you explain why this factor would make a difference?

What did Roemer observe? What idea did he infer from this observation?

[We shall be asking you to answer pairs of questions similar to these two several times more in this Case. The reason is that you should be able to distinguish between what is actually seen in a certain observation or experiment and the interpretation that is given to the observation. Often, a lengthy chain of reasoning, involving many assumptions, connects what is actually seen with its interpretation. For example, here Roemer (or someone else) observed the ending of an eclipse of Jupiter's first moon ten minutes behind schedule. But, how did he interpret this? What reasoning led to this interpretation?]

Do you know if 22 minutes is still the accepted value today for the time it takes for light to cross the diameter of the Earth's orbit? -- If not, what may have happened since 1676 to change the value? Has the distance between the Earth and the sun changed?

Does the argument of these doubting astronomers seem reasonable? -- What attitude are these astronomers demonstrating here?

Why do scientists publish papers about their work? -- [This is a double-barreled question... From the point of view of the progress of science, the reasons are quite clear. But, scientists also have personal reasons for publishing papers. Your answer should include both kinds of reasons.]

What did Bradley observe? What did he infer from this observation?

time it takes light to travel over the varying distances between Jupiter and the Earth. By including this factor in his calculations, Roemer made his own prediction of the time when the phenomenon would occur.

Can you explain why this factor would make a difference?

. . .and it hath been lately confirmed by the Emersion of the first Satellit observed at Paris the 9th of November last at 5 a Clock, 35' . 45". at Night, 10 minutes later than it was to be expected, by deducing it from those that had been observed in the Month of August, when the Earth was much nearer to Jupiter.

What did Roemer observe? What idea did he infer from this observation?

By this dramatic confirmation of his prediction, Roemer gained confidence in the idea of light having a finite, measurable speed.

From his observational data, Roemer calculated that light takes 22 minutes to cross the diameter of the Earth's orbit. With this information, he was able to make the first reliable estimate of the speed of light. (You can do this calculation easily yourself; see exercise 3, page 21.) However, Roemer's explanation for the observed delay in the eclipse of Jupiter's moon being due to the finite speed of light was not accepted by all astronomers. Many argued that the observed delay might be due to other unknown causes. They felt that the finite speed of light could not be taken as an established fact simply because it provided a convenient explanation for one isolated astronomical phenomenon. These doubts were not fully dispelled until fifty years after Roemer's dramatic demonstration.

Do you know if this value is still accepted today?

Does this seem like a reasonable argument?

What attitude are these astronomers displaying here?

In 1729, the English astronomer, James Bradley, published a paper in the Philosophical Transactions of the Royal Society entitled "An Account of a New Discovered Motion of the Fixed Stars." In this paper, Bradley announced his discovery of an annual shift in the apparent positions of all the stars. He explained this phenomenon by a combination of the speed of the Earth in its orbit and the speed of light. (See exercise 4, page 21.) Bradley also calculated that the speed of light is 10,210 times as great as the average speed of the Earth. Here then

Why do scientists publish papers about their work?

What did Bradley observe? What did he infer from this observation?

Can you suggest any reasons why the means for carrying out this experiment did not become available until the 19th century? -- What does your answer to this question tell you about the dependence of science on what is going on outside of science?

Do you think Fizeau was able to succeed because he was more clever than the earlier experimenters? Explain your opinion.

was a phenomenon applying to all the stars that could be explained by accepting the finite speed of light. The skeptics were silenced, and scientists no longer doubted that light has a speed.

We have seen that almost a century elapsed between Galileo's suggestion of an experiment to demonstrate the finite speed of light and the general acceptance of this idea. Yet, this acceptance came from astronomical observations and Galileo's experiment had still not been performed successfully. Another century was to elapse before the means for carrying out the experiment became available.

The scientist who was finally able to carry out the first successful terrestrial measurement of the speed of light was the French physicist, Armand Hyppolyte Louis Fizeau. On 23 July 1849, Fizeau read his classic paper titled "Sur un expérience relative à la vitesse de propagation de la lumière" ("On an experiment pertaining to the speed of propagation of light") before the Académie des Sciences at Paris.

I have succeeded in making perceptible the velocity of transmission of light by a method which seems to me to furnish a new way of studying with precision this important phenomenon.

But this "new way" bore a remarkable resemblance to the experiment Galileo had suggested more than two centuries before! Fizeau succeeded because he was able to devise an arrangement of apparatus that could overcome the difficulties of the earlier attempts. Galileo had suggested that the first experimenter should rapidly uncover and cover a lamp by hand. For this slow operation, Fizeau substituted a rotating toothed wheel in front of his light source, so that short pulses of light were sent out as the wheel turned. In place of Galileo's distant observer who would signal with his own lamp as soon as he saw the light from the lamp of the first experimenter, Fizeau used a distant mirror which reflected the light pulse back without any delay.

Can you suggest any reasons why the means for carrying out this experiment did not become available until the 19th century?

Do you think Fizeau was able to do this because he was more clever than the earlier experimenters?

What does Fizeau mean by "will enter in such a way"?

Was M. Froment a scientist?

[Since you probably have no way of knowing whether or not Froment was a scientist, we'll be sporting and tell you the answer to this question. However, we'd like you to answer the more interesting question which follows right after our answer.]

No, Froment was not a scientist. He was a skilled instrument maker who constructed the apparatus used by Fizeau in his experiments. He constructed apparatus not only for Fizeau but also for Foucault, whom we shall meet on page 13 of this Case. The labors of Froment made it possible to carry out the ingenious experiments devised by these scientists.

How does the progress of science depend on the assistance of people who are not scientists themselves? -- Try to think of other ways than that given in the example of Froment.

What kind of lens is a telescope objective? What does it do to rays of light originating from its focal point?

Why was the objective lens of the distant telescope focused on the objective lens of the first telescope? What path will the light take with this arrangement?

What did Fizeau actually observe? What did he infer from this observation?  
[Here's that familiar pair of questions again. (See page 6 above.) Be sure to include in your answer the reasoning that led to Fizeau's interpretation.]

When we consider the effects produced when a ray of light passes through the openings of such a toothed wheel in motion, we arrive at this result: if the pulse of light, after it has passed through, is reflected by a mirror and sent back to the toothed wheel so as to meet it again at the same point in space, the speed of light will enter in such a way that the pulse will pass through the space between two teeth or will be intercepted by a tooth of the rotating wheel. Which of these two possibilities occurs depends upon the speed of rotation of the wheel and the distance at which the light is reflected. . . .

The disc, with 720 teeth, was mounted on a system of wheels moved by weights and constructed by M. Froment; a counter made it possible to measure the rate of rotation. The light was taken from a lamp so arranged so as to give a brilliant source of light.

Fizeau placed the rotating toothed wheel at the focal point of the objective lens of a telescope. He placed the distant mirror at the focal point of the objective lens of another telescope. The distant telescope was focused on the objective lens of the first telescope. (See exercise 5, page 23.)

This arrangement succeeds very well even when the telescopes are separated by a considerable distance; with telescopes of six centimeters aperture the distance may be eight kilometers without the light becoming too feeble. [In the eyepiece of the first telescope,] we see then a luminous point like a star formed by the light which has originated from a space between two teeth on the disc and, after traversing a distance of sixteen kilometers, has come back again to pass exactly through the same point before reaching the eye. . . . The experiment succeeds very well, and we observe that, according as the speed of rotation of the toothed wheel is greater or less, the luminous point shines out brilliantly or is totally eclipsed.

By noting the speed of rotation of the toothed wheel when the "star" is seen in the eyepiece of the observer's telescope, Fizeau calculated a speed for light which was in good agreement with the determinations from the astronomical methods of Roemer and Bradley.

While Fizeau was doing this work, another method for the terrestrial measurement of the speed of light was being developed. In 1834, Charles Wheatstone, an English physicist, devised an apparatus using a rapidly rotating mirror to determine the speed of the electric current.

What does Fizeau mean by "will enter in such a way"?

Was M. Froment a scientist?

What kind of lens is a telescope objective? What does it do to rays of light originating from its focal point?

Why was the distant telescope so arranged?

What did Fizeau actually observe? What did he infer from this observation?

Men from many countries contribute to the progress of science. - See exercise 9, page 27.



What is meant by "theoretical model"? -- How is a theory different from an hypothesis?

How might Arago have learned of Wheatstone's suggestion? -- Mention at least three possible ways.

Can you explain how this experiment could decide between the rival theoretical models?  
 [To answer this question, you must first recall what predication each theoretical model makes regarding the refraction of a beam of light when it passes from a less dense to a more dense medium. Is the prediction the same in each theory?]

Why does it frequently happen in science that two men make the same discovery at about the same time?

What kind of publication is the Comptes Rendus? What functions does it (and publications like it) have?

He also suggested that a similar apparatus might be used to measure the speed of light and to test between the rival theoretical models of the nature of light then being debated by scientists. The debate was concerned with whether light should be considered as a stream of particles or as a wave motion. Wheatstone's suggestion was taken up by Dominique Francois Jean Arago, who, on 3 December 1838, read to the Paris Académie des Sciences a paper with the title, "Sur un système d'expériences à l'aide duquel la théorie de l'émission et celle des ondes seront soumises à des épreuves décisives." In this paper, Arago described the principles and the details of an apparatus for measuring the relative speed of light in air and in water. However, more than a decade elapsed before a workable form of apparatus was devised to do the experiment. Then, at the meeting of the Académie on 6 May 1850, both Fizeau and Jean Bernard Léon Foucault announced that they had each perfected an arrangement of apparatus employing a rotating mirror to carry out Arago's proposed experiment. Foucault completed his determinations first and reported:

These results demonstrate a speed of light less in water than in air, and fully confirm, according to the views of Arago, the indications of the theory of undulations [or wave motion].

Six weeks later, on 17 June 1850, Fizeau reported results obtained with his form of the rotating mirror apparatus in agreement with Foucault.

Foucault did not stop working after establishing the relative speeds of light in air and in water, but continued to improve his apparatus. In 1862, he published a further paper entitled "Détermination expérimentale de la vitesse de la lumière" in the Comptes Rendus des Séances de l'Académie des Sciences.

In the session of 6 May 1850, I presented the result of a differential experiment on the speed of light in two media of unequal densities; and at the same time I suggested that the same method,

What is meant by "theoretical model"?

How might Arago have learned of Wheatstone's suggestion?

(Students of French please translate.)

Can you explain how this experiment could decide between the rival theoretical models?

It frequently happens in science that two men make the same discovery at about the same time. - Why does this happen?

What kind of publication is the Comptes Rendus? What functions does it have?

Why are errors of measurement a problem in science? Can these errors be eliminated from an experiment?

What is the reason for "taking the mean"? -- [Before you answer this question, be sure that you understand what a "mean" is.]

What is the meaning of "precision"? How is it different from "accuracy"? -- Can the given value of a quantity be precise and not accurate? Explain.

Can you suggest some reasons for the lack of notable American physicists during the period between Franklin and Michelson?

Do scientists today generally work as college teachers? If not, in what other places may scientists be employed?

What does the "1480" stand for?

based on the use of a rotating mirror, might be used to measure the absolute speed of light in space. . . .

The apparatus used does not differ essentially from that which has been previously described. [See exercise 6, page 24.] . . . By increasing the distance traversed by the light and by introducing greater exactness in the measurement of time, I have obtained determinations of which the extreme differences do not pass 1/100 and which, combined by taking the mean, very soon give series which are in agreement to about 1/500.

In addition to making possible a higher degree of precision than was achieved before, Foucault's method of measuring the speed of light was the first that could be carried inside a laboratory of moderate size.

Despite its many improvements, Foucault's method did not yield a very accurate value for the speed of light. The problem now passed to Albert Abraham Michelson, the first American physicist since Franklin to attain a notable international reputation in science. In 1878, the young Ensign Michelson carried out his first experimental determinations of the speed of light while he was serving as an instructor at the U.S. Naval Academy at Annapolis. For these determinations, Michelson designed a modified form of Foucault's apparatus. (See exercise 7, page 25.) He used a turbine driven by a blast of air to turn a rapidly rotating mirror. Its speed of rotation was determined with the aid of an electrically-driven tuning fork. The deflection of the light reflected from the rotating mirror was measured by an accurately-machined micrometer. On 21 August 1878, Michelson announced to a meeting of the American Association for the Advancement of Science at St. Louis his newly-determined value for the speed of light of  $300,140 \pm 480$  kilometers per second.

This series of determinations seems to have whet Michelson's appetite for the problem of accurately measuring the speed of light. He continued to improve his apparatus and to make new measurements. In 1883, Michelson announced a new value for the speed of light in

Errors of measurement are always a problem in science. Why? What is the reason for "taking the mean"?

What is the meaning of "precision"?

Can you suggest some reasons for the lack of notable American physicists during all this time?

Do scientists today generally work as college teachers?

Note the improved apparatus available to Michelson.

What does the " $\pm 480$ " stand for?

What is meant by a "standard"?

How do standards become accepted?

What is the Nobel Prize? -- What purposes do such prizes have in science?

Does progress in science depend on how well-developed a country's industries are?  
Explain your answer.

What did Michelson actually observe? What did he infer from his observations?

How large an error is 1 part in 190,000 for a distance of 35 kilometers? -- Give your answer in centimeters.

Why would Michelson use a weighted mean? -- Is his calculation of the weighted mean correct?

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Turns per Second	Mirror	Number of Observations	Speed of Light <u>in vacuo</u>
528	Glass octagon	576	299,797
528	Steel octagon	195	299,795
352	Glass 12-sided	270	299,796
352	Steel 12-sided	218	299,796
264	Glass 16-sided	504	299,796

vacuum of 299,853  $\pm$  60 kilometers per second, which was taken as the accepted standard for four decades. Then, in the 1920's, Michelson, now a celebrated professor at the University of Chicago and a Nobel Prize recipient, undertook an elaborate new experiment.

What is meant by a "standard"?  
How do standards become accepted?

For this work, which involved the transmission of a beam of light over the 35-kilometer distance between Mount Wilson and Mount San Antonio in California, many of the resources of a large industrial nation were enlisted. To replace the rotating mirror of earlier experiments, an octagonal prism, whose angles were made equal to within one-tenth of a second, was furnished by the Sperry Gyroscope Company. The source of light was a brilliant electric arc, originally developed as a high-intensity military searchlight. Time was measured with the aid of an electric tuning fork maintained at a constant vibration by a vacuum tube circuit. (See exercise 8, page 26.) After two years of work, Michelson obtained a mean value of 299,771 kilometers per second for the speed of light in vacuum.

What is the Nobel Prize? What purposes do such prizes have in science?

Does progress in science depend on how well-developed a country's industries are?

This result should be considered as provisional, and depends on the value of  $D$ , the distance between the two stations which was furnished by the Coast and Geodetic Survey, and which it is hoped may be verified by a repetition of the work.

What did Michelson actually observe?  
What did he infer from his observations?

It was also found that a trial with a much larger revolving mirror gave better definition, more light, and steadier speed of rotation; so that it seems probable that results of much greater accuracy may be obtained in a future investigation.

Subsequently, the distance between the Mount Wilson and Mount San Antonio stations was measured to an accuracy of one part in 190,000 by the U.S. Coast and Geodetic Survey.

How large an error was this for a distance of 35 km.?

Observations with the same layout were resumed in the summer of 1926, but with an assortment of revolving mirrors. The first of these was the same small octagonal glass mirror used in the preceding work. The result obtained this year was  $V = 299,813$ . Giving this a weight 2 and the result of the preceding work weight 1, gives 299,799 for the weighted mean.

Why would Michelson use a weighted mean?

The other mirrors were a steel octagon, a glass 12-sider, a steel 12-sider, and a glass 16-sider. The final results are summarized in the table [on the opposite page].

Why did Michelson make so many observations?

Did Michelson construct this tube himself? -- What does your answer to this question tell you about the dependence of scientists on non-scientists?

Why do scientists frequently work together on one problem today?

In this Case, we have followed measurements of the speed of light made with ever-increasing precision. Starting from a rough estimate (Roemer) of this large quantity, we have come to a value with four significant figures (Michelson). Determinations of the speed of light made since the end of World War II have added a fifth significant figure.

Do you think it is possible to obtain a value of the speed of light with much greater precision than this, say down to the number of meters per second? [This would require nine significant figures.]-- Give some reasons for your opinion.

After many hundreds of observations, Michelson submitted a final report of his new determination to the Astrophysical Journal in 1927. Why did he make so many observations?

The new value for the speed of light in vacuum was  $299,796 \pm 4$  kilometers per second. But this value for speed in vacuum had been calculated from observations made in air, and Michelson conceived of measuring the speed in vacuum directly. Although in his late seventies and in poor health, he organized a new experiment to accomplish this. A mile-

long, air-tight steel tube was constructed and the light transmitting and reflecting apparatus was mounted inside it. Large pumps evacuated the air from the tube down to a pressure of half a millimeter of mercury. Did Michelson construct this tube himself?

Many difficulties arose in operating the huge, yet sensitive, experimental set-up, and, before the work could be completed, Michelson died on 9 May 1931. The measurements and calculations were continued by his associates,

Francis Pease and Frederick Pearson. Under the joint authorship of

Michelson, Pease, and Pearson, the paper giving the final result for the speed of light in vacuum was published in the Astrophysical Journal in 1935. The value was  $299,774 \pm 11$  kilometers per second. Scientists frequently work together on one problem today. Why is this so?

Having covered a period of three hundred years on the problem of measuring the speed of light, we shall bring this Case to a close. However, we do this reluctantly, for it is clear that the value of this important constant was not precisely determined even after the monumental efforts of Michelson. There were differences between his best values and experimental errors had not been reduced sufficiently. Thus, efforts to obtain a better value for the speed of light have been made by many physicists since the 1930's and are being made today. However, lanterns and toothed wheels and rotating mirrors are no longer used in such experiments. These have been replaced by various, newly-developed electronic devices, which are more reliable and more convenient to use. But the key points in solving the problem have not changed. Imaginative scientists must plan the experiments; the experimental apparatus must be available; measurements must be made with as little error as possible; careful calculations and interpretations must be made from the observed data -- all these factors go into finding a value for THE SPEED OF LIGHT.



## Experiments and Exercises

1. Hypothesis of Instantaneous Transmission of Light. ::: Perhaps you can suggest some other observations, in addition to the one given on page 2 of this Case, to support the hypothesis that light is transmitted instantaneously. In each instance, can you suggest an alternative hypothesis to instantaneous transmission? Which hypothesis is more reasonable or easier to accept?

Here is an observation in support of the hypothesis of instantaneous transmission put forth by Rene Descartes in the 17th century:

If light takes time to travel from the moon to the Earth, then, at the moment of a lunar eclipse, the moon should not appear to occupy the heavens at a point diametrically opposite the sun, but detectably different from that position. However, observations do not show this, and the moon is seen diametrically opposite the sun at the moment of eclipse. Therefore, light must be transmitted instantaneously.

Do you think this is a good argument? In what other way might this observation be accounted for?

2. Measuring the Speed of Sound. ::: You can readily measure the speed of sound in air by observing the time difference between seeing any sound-producing event and hearing the sound produced at a distance of several hundred feet. (In such an experiment, what value do we assume for the speed of light?) Carefully measure the distance between the place where the sound is produced and the observation point. Use your imagination to think of a device for producing a sound in which the instant that the sound is produced is visible at the observation point. R. W. Machin (in The Science Masters' Book, Series III, Part IV, page 122) has suggested using a wooden clapper.

The wooden clapper is made from two pieces of wood about 70 cm. x 10 cm. x 1.5 cm. thick, hinged together along a short edge. It may be painted white or a white handkerchief may be held behind it, and if held open above the head it is clearly visible from a distance of 200 to 300 m., and clearly heard when it is clapped together. The time interval between seeing this and hearing the report is measured with a stop-watch, and the speed of sound then calculated. Be sure to make at least ten observations of the time interval. ... What value do you obtain for the speed of sound in air?

Another way of obtaining the speed of sound in air is to use a resonating air column and a tuning fork of known frequency. If the resonating air column is closed at one end, the speed of sound when the air column is in resonance with the tuning fork is given by

$$v = n \times 4 (1 + 0.4d)$$

where

$v$  = speed of sound in air

$n$  = frequency of the tuning fork

$l$  = length of the resonating air column

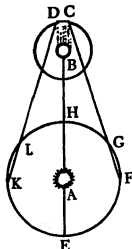
$d$  = diameter of the resonating tube

Can you derive this formula from your knowledge of resonance and from the relationship between frequency and wavelength? ... Can you devise an experimental set-up for obtaining the speed of sound by resonance?

### 3. Roemer's Method for Demonstrating the Speed of Light.

The diagram at the right is reproduced from Roemer's paper, "Demonstration touchant le mouvement de la lumière", (Demonstration Concerning the Motion of Light), of 1676. His explanation was as follows:

Let A be the Sun, B Jupiter, C the first Satellit of Jupiter, which enters into the shadow of Jupiter, to come out of it at D; and let EFGHLK be the Earth placed at divers distances from Jupiter.



Now, suppose the Earth, being in L . . . , hath seen the first Satellit at the time of its emersion or issuing out of the shadow in D; and that about  $42\frac{1}{2}$  hours after, (*viz.* after one revolution of this Satellit,) the Earth being in K, do see it returned in D. It is manifest that, if the Light requires time to traverse the interval [or distance] LK, the Satellit will be seen returned later in D than it would have been if the Earth had remained in L, so that the revolution of this Satellit being thus observed by the Emersions will be retarded by so much time as the Light shall have taken in passing from L to K. [By a similar argument, on the side FG,] where the Earth by approaching goes to meet the Light, the revolutions of the Immersions will appear to be shortened by so much as those of the Emersions had appeared to be lengthened.

Roemer's argument is quite correct. There are differences between the observed periods of revolution of the satellite, depending upon whether the Earth is moving toward or away from the source of light. If you will recall that the period is the inverse of the frequency, you should be able to see how Roemer's argument involves the principle of the Doppler effect, which you probably studied in connection with sound. . . . Can you explain this last remark?

Unfortunately, the speed of light is so great that Roemer was not able to detect any difference in the lengths of the first satellite's period of revolution between two successive observations. The errors in observing the length of a period were greater than the differences between two successive periods. However, by taking a series of observations, Roemer found that

... what was not sensible in two revolutions became very considerable in many being taken together. For example, forty revolutions observed on the side F might be sensibly shorter than forty others observed in any place of the Zodiack where Jupiter may be met with; and that in [the ratio] of twenty two [minutes of time] for the whole interval of HE, which is the double of the interval that is from hence to the Sun.

In Roemer's time, "the interval that is from hence to the Sun", or the Earth-Sun distance, was estimated as 110,000,000 kilometers. Given Roemer's value of the time light takes to cover twice this distance, what is the speed of light?

4. Bradley's Method for Determining the Speed of Light. :: Perhaps you've made the following observation while looking out of the window of a car or train when it was raining. Suppose that when the car was standing still the raindrops were falling vertically. As the car begins to move, the raindrops are seen to fall down the window at an angle. As the car's speed increases, the angle at which the falling raindrops are seen descending also increases. Clearly, the value of this angle is related to the speed of the moving car. On what other variable does the value of the angle depend? ...

... If we were to place a long mailing tube outside the window of the moving car and wanted the raindrops to fall through this tube without hitting the sides, we would have to tilt the tube forward in the direction of the car's motion. We can measure the angle of tilt of the tube from the vertical. The tangent of this angle is equal to the ratio of the speed of the moving car to the speed of the vertically falling raindrops. Knowing two of these quantities, we can easily find the third.

For example, suppose that the speed of the moving car,  $v$ , equals 10.0 meters per second. The tube's measured angle of tilt from the vertical, angle  $A$ , equals  $11^{\circ} 20'$ . What is the vertical speed,  $V$ , of the falling raindrops?

$$\tan A = \frac{v}{V}$$

$$\begin{aligned}\text{Useful information: } \tan 11^{\circ} 20' &= 0.20042 \\ \log \tan 11^{\circ} 20' &= 9.30195 - 10\end{aligned}$$

The above observation and example provide an analogy to the method used by Bradley to determine the speed of light.



In the figure at the left, S represents a star whose direction is at right angles to the motion of the Earth in its orbit. AC represents a telescope pointed vertically upward. This is the direction in which the telescope tube would point to receive the light from the star if the Earth were stationary. But the Earth is moving in its orbit with a speed,  $v$ , in the direction indicated by the arrow. Thus, just as in the above situation, the telescope tube must be tilted forward in the direction of motion to allow the light from S to pass through without hitting the sides. This tilted position of the telescope is shown as AB, and the apparent position of the star is now S'.

[A moment's thought will convince you that, as the Earth travels in its orbit, the angle at which the telescope must be tilted to observe the star changes. Since a star's position is determined partly by the tilt of the telescope, the apparent position, S', of the star changes throughout the annual orbit of the Earth. It was this apparent motion of the stars which Bradley discovered. (See page 7 of this Case.) Actually, Bradley made hundreds of observations before publishing his paper. In this exercise, we have taken as an example only the position of the Earth in its orbit where the telescope's tilt is a maximum.]

Now the tilt necessary to prevent the light from the star from hitting the sides of the telescope is such that the time taken for the light to travel from A to C equals the time taken by B to travel to C. If light has a speed of  $V$ , the time it takes to travel from A to C is  $AC/V$ . Similarly, if the Earth has a speed of  $v$ , the time it takes the telescope (which moves with the Earth) to travel from B to C is  $BC/v$ . Thus, since the two times are equal:

$$\frac{AC}{V} = \frac{BC}{v} \quad \text{or} \quad \frac{v}{V} = \frac{BC}{AC} \quad \text{Since } \frac{BC}{AC} \text{ is the tangent of angle BAC,}$$

angle BAC, we see that, similar to the above example:  $\tan \text{BAC} = \frac{v}{V}$ .

Measurements of the angle BAC give  $20.45''$  seconds. ... What is the speed of light?

[Useful information:

Radius of the Earth's orbit = 149,500,000 km.

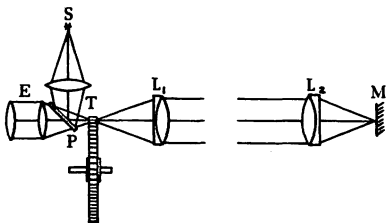
Time for one revolution =  $3.156 \times 10^7$  sec.

$\tan 20.45'' = 0.00009914$

$\log \tan 20.45'' = 5.99626 - 10$ ]

### 5. Fizeau's Method for Measuring the Speed of Light. :::

The essential parts of Fizeau's apparatus are shown schematically in the diagram at the right. S is the source of light, which is focused by a lens at the point T at the edge of the toothed wheel. P is a parallel plate of glass set at an angle of  $45^\circ$  to S.  $L_1$  is the objective lens of the first telescope. When the toothed wheel rotates, the teeth will alternately transmit and cut off the light at T so that pulses of light are sent out through the lens  $L_1$ . The light emerges from  $L_1$  as a parallel beam and travels to the objective lens,  $L_2$ , of the distant telescope. M is a portion of a curved mirror, whose focal point is at the center of the lens  $L_2$ . Hence the light falling on M is reflected back to  $L_2$  and emerges again as a parallel beam. The light then returns along the same path to the lens  $L_1$  and comes to a focus at T, which is the focal point of  $L_1$ .



If, when the light pulse returns to T, there is a space between teeth at that point, the light can pass through. It diverges from T and falls on the glass plate P. Here part will be reflected and part transmitted. The part that is transmitted passes through the eyepiece E, where it is observed. The observer sees the reflected image of S as a bright "star" at the point T. On the other hand, if there is a tooth at the point T when the light pulse returns, the returning light cannot pass through and the "star" is eclipsed. The speed of revolution of the toothed wheel can be varied, and the number of revolutions is measured when there is an eclipse and when the "star" is brightest. Actually, the change in brightness of the "star" as the speed of the toothed wheel increases is gradual, so that there is considerable uncertainty in the observations.

To see how the speed of light can be obtained by measurements made with Fizeau's apparatus, consider the following example.

Let  $V$  = the speed of light

$D$  = the distance between T and M

$t$  = the time it takes for light to travel from T to M and return, or  $2D$

$n$  = the number of revolutions per second of the toothed wheel

$a$  = the angle (in degrees) subtended by a tooth of the wheel or by a space between two teeth (The wheel is cut to make the teeth and spaces equal.)

It is easy to see that  $t = 2D/V$ . Why?

Also, the time it takes for the toothed wheel to turn through the angle  $a$  may be expressed as  $a/360^\circ$  times the period of revolution, or  $\frac{a}{360^\circ} \times \frac{1}{n}$

For a light pulse returning to T from M to be eclipsed by the tooth next to the space through which that pulse went out, the toothed wheel must turn through the angle  $a$  in the exact time that it takes the light to make the trip out and back. In this situation,

$$t = \frac{2D}{V} = \frac{a}{360^\circ \times n} \quad \text{or} \quad aV = 2D(360^\circ \times n) \quad \text{and} \quad V = 2D \left( \frac{360^\circ}{a} \times n \right)$$

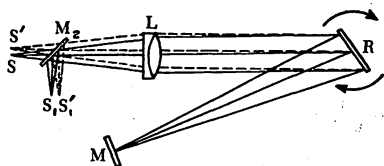
Fizeau's wheel had 720 teeth. Therefore the angle  $a$  =

Eclipse by the adjoining tooth was observed at  $n$  = 12.6 revolutions per second.

The measured distance between T and M was  $D$  = 8633 meters

What is the speed of light?

## 6. Foucault's Method for Measuring the Speed of Light :::



Foucault's experimental arrangement is shown schematically in the drawing. Light from the sun enters through the slit S, passes through the lens L and falls on the surface of a plane mirror R. This mirror can be made to rotate rapidly around an axis which is perpendicular to the plane of the paper. M is a portion of a spherical mirror, whose center of curvature is at R. Hence, the light is reflected from

R to M and back to R. If R is not turning, the light will be reflected back along its original path (solid lines) to S. For convenience of observation, a parallel plate of glass,  $M_2$ , inclined at an angle of  $45^\circ$  is placed near the slit, so that the returning image of the slit is seen at  $S_1$ . Now, if the revolving mirror R is turning rapidly in the direction shown by the arrows while the light travels from R to M and back, the light will not be reflected along its original path but will be deflected, as indicated by the dashed lines. The returning light will be focused by the lens L at  $S'$  and may be observed at  $S_1'$ . By means of an eyepiece and scale at  $S_1$ , the separation between  $S_1$  and  $S_1'$  can be measured. This separation will be equivalent to two times the angle that the revolving mirror turns while the light is travelling from R to M and back to R. The speed of revolution of the revolving mirror was determined stroboscopically by Foucault.

Now, let us see how the speed of light could be determined from this set-up. If we

- let  $V$  = the speed of light  
 $D$  = the distance between R and M  
 $t$  = the time it takes for light to travel from R to M and back, or  $2D$   
 $n$  = the number of revolutions per second of the revolving mirror  
 $a$  = the angle (in degrees) through which the revolving mirror turns in time  $t$

Then, a moment's thought should convince you that  $a = 360^\circ \times n \times t$ .

But,  $t = 2D/V$  (Why?), so that we have  $a = 360^\circ \times n \times \frac{2D}{V}$

or  $aV = 360^\circ \times n \times 2D$

and  $V = \frac{2D (360^\circ \times n)}{a}$ . (Does this equation look familiar?)

In one trial, Foucault measured a distance between R and M of  $D = 20.0$  meters. The speed of revolution of the mirror R in this trial was  $n = 460$  revolutions per second. The observed separation between  $S_1$  and  $S_1'$  was equivalent to an angle of  $160''$ . Therefore, angle  $a$  (in degrees) =

What is the speed of light?

7. Michelson's Work of 1878. ::: The following extract is taken from the Proceedings of the American Association for the Advancement of Science, 27th Meeting, August, 1878.

"EXPERIMENTAL DETERMINATION OF THE VELOCITY OF LIGHT. By ALBERT A. MICHELSON, U.S.N."

Considering the importance of this physical constant as one of the simplest and most accurate means of ascertaining the distance of the sun from the earth, it seems surprising that but three scientists have sought to obtain it experimentally. These were Foucault, Fizeau, and more recently Cornu.

Foucault used the method known as that of 'Wheatstone's revolving mirror', the application of which was first suggested by Arago. Fizeau and Cornu both used another method, known as that of the 'toothed wheel'. . . .

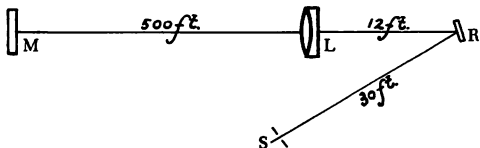
The objection to Foucault's method is that the displacement, . . . [Michelson is referring to the separation between  $S_1$  and  $S_1'$  that is illustrated in Exercise 6 above.] is very small, and therefore difficult to measure accurately. The objection to Fizeau's is that the time of total disappearance of the light was necessarily uncertain. . . .

The object of the experiments which I have undertaken is to increase the displacement in the first method. This can be done . . . by increasing the radius of measurement, i.e., the distance from the revolving mirror to the scale. In Foucault's experiments, the speed of the mirror was [about] 400 turns per second; the radius of measurement was about one metre, and the distance between the mirrors was about [twenty] metres. The displacement was about 0.8 millimetres.

In my experiments, the speed of the mirror was but [about] 130 turns per second -- but the radius of measurement was from fifteen to thirty feet--and the distance between mirrors was about 500 feet. The displacement obtained varied from 0.3 inch to 0.63 inch, or about twenty times that obtained by Foucault. . . .

The following is a description of the apparatus employed in these preliminary experiments.

Fig. 1 represents the plan. The sun's rays are reflected by a heliostat through a slit S, and upon a mirror R, which revolves about a vertical diameter. They are thence reflected to a fixed plane mirror M, upon the surface of which an image of the slit is formed by means of the lens L. The light now retraces its path, and finally forms an image of the slit, which, when the mirror R is at rest, coincides exactly with the slit itself. When the mirror revolves. . . the image is displaced more and more as the revolution becomes more rapid, the displacement being twice as great as the [angle of] displacement of the mirror during the time required for the light to travel from R to M and back again.



It will be observed that the difference between this arrangement and that of Foucault is that the concave mirror is dispensed with, its office being accomplished by the lens and plane mirror; and that this arrangement permits the use of any distance between the mirrors.

Since this method is the same as that used by Foucault, what formula would you use to calculate the speed of light from Michelson's arrangement?

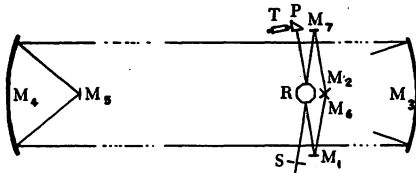
How could you obtain the value of the angle  $\alpha$  (in degrees) from the radius of measurement,  $r$  (= SR in the figure), and the displacement,  $d$  (= SS'), of the image?

From Michelson's description above, we can assume the following data:

Distance between mirrors, MR, --	$D = 512 \text{ feet} = 156.2 \text{ meters}$
Speed of the mirror--	$n = 134 \text{ revolutions per second}$
Radius of measurement, SR--	$r = 30.0 \text{ feet} = 9.14 \text{ meters}$
Displacement of image, SS',--	$d = 0.630 \text{ inch} = 1.60 \text{ centimeter} = 0.0160 \text{ meter}$

What is the speed of light?

8. Michelson's Work of 1924-1926. ::: The schematic drawing shows the essential parts of the experimental set-up in Michelson's final determinations of the speed of light. He again used Foucault's method. The general arrangement had been proposed in 1900 by Cornu. The most novel features were a many-sided revolving mirror in place of a plane mirror and the elimination of the need to measure the displacement of the slit image.



The measurements were made at night. The source of light was a Sperry electric arc focused on the slit S. Two large concave mirrors,  $M_3$  and  $M_4$ , each of 24-inch aperture and 30-foot focal length, replaced the lens and distant plane mirror previously used. (Compare the diagram in Exercise 7.) The mirrors were adjusted so that  $M_3$  sent a parallel beam of light to the distant mirror  $M_4$ , which formed an image of the slit on a small concave mirror,  $M_5$ , at its focal point.  $M_5$  returned the light to  $M_3$ , which sent it back to  $M_3$  at the observing station. Both the outgoing and returning light were reflected from the octagonal revolving mirror, R, but from opposite sides. This was made possible by the use of a system of plane mirrors,  $M_1$ ,  $M_2$ ,  $M_6$ , and  $M_7$ . On the second reflection from R, the light passes through the right-angle prism, P, where it was observed by means of a telescope, T. The path of the light beam was as follows:

S, R,  $M_1$ ,  $M_2$ ,  $M_3$ ,  $M_4$ ,  $M_5$ ,  $M_4$ ,  $M_3$ ,  $M_6$ ,  $M_7$ , R, P, T

The distance over which the light traveled was approximately 35.4 kilometers. The need for measuring the displacement of the returning slit image was eliminated by turning the 8-sided mirror (12- and 16-sided mirrors were also used) at such a speed that the next face of the mirror would be in position to receive it when the beam returned from the distant mirror. Thus, the time taken for the light to travel from R<sub>3</sub> to  $M_4$  and back for an 8-sided mirror, would be  $1/8$  of the period of revolution. The speed of the revolving mirror was measured stroboscopically.

Can you suggest what some of the adjustments and preliminary measurements might be before any determinations of the speed of light could be begun? Where might errors be made?

Some typical data that might be obtained from a run with an 8-sided mirror is:

Distance over which the light travels--  $D = 35.4252$  kilometers

Speed of the 8-sided revolving mirror--  $n = 528.806$  revolutions per second

Derive a formula and calculate the speed of light.

This calculation will give you a value for the speed of light in air. The difference between the speed of light in air and its speed in vacuum may be taken as 67 kilometers per second. When you have calculated the speed in air, should you add or subtract this amount? Why?

What is the speed of light in vacuum?

9. Science is an international activity. We can realize this well when we look at the contributions that scientists from different countries have made to almost any field of investigation. Below are listed the names and nations of men who played a role in the measurement of the speed of light. The Roman numerals preceding the names indicate the century in which they did most of their work. -- Who were these men? What did they contribute to the measurement of the speed of light? What other contributions did they make to science and to society? -- Here are topics for some interesting reports to your class. A visit to the library will surely be helpful.

Denmark	- XVII	Ole Roemer
England	- XVIII	James Bradley XIX - Charles Wheatstone
France	- XIX	Dominique Francois Jean Arago, Armand Hyppolyte Fizeau, Jean Bernard Léon Foucalt, Marie Alfred Cornu XX - Jean Mercier
Germany	- XX	A. Karolus, O. Mittelstädt, A. Hittell
Italy	- XVII	Galileo Galilei
U.S.	- XIX	Simon Newcomb, Albert Abraham Michelson (Also XX)
	XX	E. B. Rosa, N. E. Dorsey, F. C. Pease, F. Pearson, W. C. Anderson

Incidentally, isn't there something peculiar about the above list? Although there are representatives from six countries on the list, there are certainly many more countries than six in the world. Yet there are no scientists from these many other countries on the list. Why not? Can you suggest some reasons why one country may produce a considerable number of scientists at a given time while another does not? What does this mean to us today?



## Sources of Quotations

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- page 5 I. Bernard Cohen, Roemer and the First Determination of the Velocity of Light, (Norwalk, Conn.: Burndy Library, 1944). Page 13. -- As quoted from Essays of Natural Experiments made in the Academie del Cimento, Englished by Richard Waller, (London, 1684).
- pages 7 and 21 Ole Roemer, "A Demonstration concerning the Motion of Light," Philosophical Transactions, 12: 893-894, (1677). -- Translated from Roemer's paper, Demonstration touchant le mouvement de la lumière, "Journal des Sçavans", 7 Decembre 1676.
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- pages 13 and 15 William F. Magie, op. cit. Page 343. [Adapted.] -- Translation from Foucault's paper, "Détermination expérimentale de la vitesse de la lumière," Comptes Rendus, 55: 501, (1862).
- page 17 Albert A. Michelson, Studies in Optics, (Chicago: University of Chicago Press, 1927). Page 137.
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## Reading Suggestions

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