Einstein explains: it's all relative

Educator guide

PAPER DETAILS

Original title: Time, space, and gravitation

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Authors: Albert Einstein (Reviewed by Noah Graham)

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Annotator(s): Staci Hill

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DISCUSSION QUESTIONS

1. Why does Einstein begin his discussion of relativity by distinguishing between theories of principle and constructive theories? Do different scientific disciplines (i.e. physics, biology, chemistry, etc.) rely on one type of theory more than others?	**SEP1** **SP6** **SP7** **Nature of Science**
2. Why is it significance that two Englishmen confirmed one of the predictions of Einstein's theory of relativity? How did the political situation in the early 20th century affect scientific progress?	**Nature of Science**
3. Einstein presents a situation where two different, contradictory results can be obtained depending on what system of coordinates is used. Rather than dismissing one of two contradictory results, Einstein attempts to account for the contradictions. What are the benefits and drawbacks to Einstein's approach, i.e., to crafting an explanation that holds contradictory results as equally valid?	**SEP1** **SP6** **SP7**
4. According to the theory of relativity, our intuitive sense that two events can happen at the same time (simultaneity) is incorrect. What are some of the implications of this fact for technology, communication, culture, etc.?	**SEP8** **SP1** **EK1.D.3** **Nature of Science**
5. What are some of the issues with studying phenomena that go against our intuition (as described in question 4)?	**SEP1** **SP6** **SP7**

Science in the Classroom AAAS

ACTIVITIES FOR INTERACTIVE ENGAGEMENT

Writing an abstract

Students write an abstract for the article at a grade-appropriate reading level. For the purposes of this activity, students may treat the letter as a traditional research article.

RST.9-10.2
RST.11-12.2
Nature of Science

Locating this letter in the larger field

Students locate the work of at least one other independent group of scientists who have used relativity theory in their work. Students will evaluate whether data from this research supports or contradicts previous conclusions, and reflect on the statement that scientific knowledge is a "community effort." A good starting point for this activity is to look at the work done in response to Einstein's three suggestions at the end of the letter.

RST.9-10.8
RST.11-12.8
Nature of Science

Science in the news

Students explore news stories in the Related Resources tab of the annotated paper and evaluate the stories for tone, accuracy, missing information, etc. They may then write their own news stories on the article.

RST.9-10.5
RST.11-12.5
RST.9-10.6
RST.11-12.6
RST.9-10.8
RST.11-12.8

How a theory is built

Construct a timeline of how relativity theory was developed, referencing the work of some (or all) of the following scientists: Euclid, James Clerk Maxwell, Hendrik Antoon Lorentz, Galileo, Arthur Eddington, and Isaac Newton.

SEP8
SP6
SP7
PS2.A
PS4.B
EK1.C.4
Patterns
Nature of Science

Results and conclusions

Students diagram each of the examples presented in the study. They may consult other visuals and diagrams that have been produced to explain relativity theory (some of which are linked in the Related Resources tab of the annotated paper).

SEP8
SP6
SP7
Nature of Science

The next steps

Students design experiments to verify or disprove some of the questions and claims Einstein presents in his letter. They may consult work that has already been done in this vein, and consider alternative experimental designs.

SEP1
SP3
Nature of Science

Non-Euclidian geometry

In this activity from Sonoma State University, students will learn one way it is possible to measure the curvature of the universe and work through a basic introduction to non-Euclidian geometry:
https://universe.sonoma.edu/materials/lesson_plans/geometry.html

Systems and System Models
SP6
EK1.D.3
EK3.G.1
Nature of Science

ARTICLE OVERVIEW

Article summary (recommended for educator use only)

In this letter published in *Science*, Albert Einstein describes the basic principles of his special and general relativity theories. He gives credit to his scientific forebears, outlines the once apparent contradictions in the field, and posits the logical consequences of his new theory (and, in doing so, suggests ways it may be experimentally validated). He gives more attention to special relativity theory, which is a bit more intuitive for the casual physicist. It rests on two principles: 1) The laws of physics are the same for all observers in uniform motion relative to one another; and 2) Light in a vacuum has a constant velocity independent of the motion of the observer. These principles lead Einstein to the revelation that $E = mc^2$ (or, as originally published: $m = E/c^2$). Einstein finishes the discussion with the more cumbersome general relativity theory (general because it describes motion with respect to any two coordinate systems, not just inertial coordinate systems that are assumed to be static). He concludes by pointing out that the consequences of general relativity are that we cannot rely solely on Euclidean geometry in our study of motion, and that space and time are interwoven and inseparable.

Importance of this research

Relativity theory is an example of how scientists sometimes revise theories and principles in light of new knowledge. Einstein's theory did not emerge from direct observations of phenomena, but as the result of identifying places that classical physics failed to explain the natural world. Relativity is Einstein's attempt to create a more fundamental and general description of systems of motion (which has consequences for all natural phenomena).

As a theorist, Einstein draws insights from previous thinkers more often than previous studies. He was well-read within and (importantly) outside his field. He mentions other great mathematicians and scientists such as Euclid, Galileo, Newton, Maxwell, and Lorentz. He also alludes to philosophers such as Aristotle, David Hume, and Immanuel Kant. Einstein does cite a few studies, such as the solar eclipse experiment (in which Arthur Eddington and Frank Watson Dyson showed that gravity deflects light). These studies serve to bolster Einstein's account, much like a conventional research paper.

Einstein's theory has held up remarkably well even a century later. Many researchers have independently confirmed its validity, and it has informed many fields and technologies (such as GPS, electron microscopy, and particle accelerators). Although it cannot quite explain the behavior of the entire universe (it breaks down when applied to extremely small bodies), it is an important foundation for all physics.

Experimental methods (Note: Because this is not a true research paper, the experimental methods are all theoretical)

- Constructive vs. analytic theories: Einstein discerns and articulates the fundamental distinction between the two types of physical theories.
- Non-Euclidian geometry: Einstein's theory of relativity relies on an understanding of spacetime that is not coincident with Euclidian geometry.
- Synthesis of previous theories: Einstein's theory of relativity is built on a comprehensive and critical understanding of how physicists and mathematicians have historically understood the universe. By studying, synthesizing, and expanding on their theories, he was able to unify them in a way that provides a more accurate description of how the natural world behaves.

Conclusions

- The equivalence principle: The conservation of mass and the conservation of energy are two sides of the same coin.
- Time and space are inseparable entities.
- Space and time depend on gravitational fields generated by massive bodies. Gravitational fields themselves are the result of warps in spacetime that these bodies create.

LEARNING STANDARDS ALIGNMENT

The following tables provide an overview of the learning standards covered by this article, including the A Framework for K-12 Science Education (Framework), Common Core State Standards English Language Arts-Literacy (CCSS ELA), Common Core State Standards Statistics and Probability (CCSS HSS), AP Science Practices, and Vision and Change for Undergraduate Education. Where applicable, activities and information will be marked with specific standards to which they are linked.

A Framework for K-12 Science Education		
Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking Questions and Defining Problems (SEP1) Evaluate questions and challenge the premise(s) of an argument, the interpretation of a data set, or the suitability of a design. **Obtaining, Evaluating, and Communicating Information (SEP8)** Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically).	**PS2.A: Forces and Motion** Newton's second law accurately predicts changes in the motion of macroscopic objects. Momentum is defined for a particular frame of reference; it is the mass times the velocity of the object. If a system interacts with objects outside itself, the total momentum of the system can change; however, any such change is balanced by changes in the momentum of objects outside the system. **PS4.B: Electromagnetic Radiation** Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. **PS4.C: Information Technologies and Instrumentation** Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them.	**Patterns** Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena. **Systems and System Models** When investigating or describing a system, the boundaries and initial conditions of the system need to be defined.

<table>
<tr><th colspan="3">Common Core State Standards English Language Arts-Literacy</th></tr>
<tr><th>Key Ideas and Details</th><th>Craft and Structure</th><th>Integration of Knowledge and Ideas</th></tr>
<tr>
<td>RST.9-10.1
Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

RST.9-10.2
Determine the central ideas or conclusions of a text; trace the text’s explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.

RST.11-12.1
Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.

RST.11-12.2
Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.</td>
<td>RST.9-10.4
Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics.

RST.9-10.5
Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., force, friction, reaction force, energy).

RST.9-10.6
Analyze the author’s purpose in providing an explanation, describing a procedure, or discussing an experiment in a text, defining the question the author seeks to address.

RST.11-12.4
Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 11-12 texts and topics.

RST.11-12.5
Analyze how the text structures information or ideas into categories or hierarchies, demonstrating understanding of the information or ideas.

RST.11-12.6
Analyze the author’s purpose in providing an explanation, describing a procedure, or discussing an experiment in a text, identifying important issues that remain unresolved.</td>
<td>RST.9-10.8
Assess the extent to which the reasoning and evidence in a text support the author’s claim or a recommendation for solving a scientific or technical problem.

RST.9-10.9
Compare and contrast findings presented in a text to those from other sources (including their own experiments), noting when the findings support or contradict previous explanations or accounts.

RST.11-12.8
Evaluate the hypotheses, data, analyses, and conclusions in a science or technical text, verifying the data when possible and corroborating or challenging conclusions with other sources of information.

RST.11-12.9
Synthesize information from a range of sources (e.g., texts, experiments, simulations) into a coherent understanding of a process, phenomenon, or concept, resolving conflicting information when possible.</td>
</tr>
</table>

AP Science Standards	
AP Science Practices	AP Physics Content Standards
Science Practice 3 (SP3) The student can engage in scientific questioning to extend thinking or to guide investigations. **Science Practice 6 (SP6)** The student can work with scientific explanations and theories. **Science Practice 7 (SP7)** The student is able to connect and relate knowledge across various scales, concepts and representations in and across domains.	**Essential Knowledge 1.C.4 (EK1.C.4)** In certain processes, mass can be converted to energy and energy can be converted to mass according to the equation derived from the theory of special relativity. **Essential Knowledge 1.D.3 (EK1.D.3)** Properties of space and time cannot always be treated as absolute. **Essential Knowledge 3.G.1 (EK3.G.1)** Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales. **Essential Knowledge 3.A.3 (EK3.A.3)** A force exerted on an object is always due to the interaction of that object with another object. **Essential Knowledge 5.B.7 (EK5.B.7)** The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat.

Connections to the Nature of Science	
Vision and Change for Undergraduate Biology Education Core Competencies and Disciplinary Practices	A Framework for K-12 Science Education Understandings About the Nature of Science
Ability to understand the relationship of science and society Science is conducted in a social context and has social and historical dimensions. Important to an understanding of the relationship between science and society is an evaluation of the social context of scientific problems, development of scientific solutions to solve these problems, and a consideration of the ethical implications of research.	**Scientific Knowledge is Open to Revision in Light of New Evidence** Most scientific knowledge is quite durable but is, in principle, subject to change based on new evidence and/or reinterpretation of existing evidence. **Science is a Human Endeavor** Individuals and teams from many nations and cultures have contributed to science and to advances in engineering. **Science is a Way of Knowing** Science knowledge has a history that includes the refinement of, and changes to, theories, ideas, and beliefs over time. **Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena** Theories and laws provide explanations in science. Laws are statements or descriptions of the relationships among observable phenomena.