Physics: A student's guide through the great texts

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Abstract

During the past decade, I have developed and taught a unique and challenging four-semester introductory physics curriculum at Wisconsin Lutheran College (WLC) based on the careful reading, analysis and discussion of selections from foundational texts in physics and astronomy. This curriculum is designed to encourage a critical and circumspect approach to natural science, while also developing a suitable foundation for advanced coursework in physics. It is scheduled to be published by Springer as a textbook/anthology around 2014.

Introduction

The motivation for this project was, at least in part, necessity: WLC is a small liberal arts institution located in Milwaukee. As such, we simply cannot offer the same range of courses as a large institutions might: *Physics for engineers, Physics of music, Physics for pre-meds, Physics of sports, etc.* So what kind of physics curriculum would be appropriate and profitable for a broad constituency of students, given WLC's limited resources? The solution: using classic texts. These texts are classics precisely because they address timeless questions in a thoughtful manner. For instance: both the beginning student and the seasoned scholar can profitably study Sophocles' Antigone–the former for plot and character development, the latter for ethics and political philosophy.

Standard physics textbooks do not make use of classic texts. Their pedagogical method is typically as follows: (1) present accepted laws, usually in the form of one or more equations, (2) provide example problems so students can avoid common conceptual errors, and (3) illustrate the relevance of the laws in contemporary industrial or diagnostic problems. While this method is efficient in preparing students for certain standardized tests, or in solving straightforward problems, it tends to mask how science is actually done: science is presented as an accomplished fact and prescribed problems revolve around technological applications of accepted laws.

In making use of classic texts, the pedagogical emphasis is rather different. Students are encouraged to (1) evaluate competing scientific theories, (2) understand concepts in context, rather than memorize modern terms, and (3) identify assumptions and their implications. Moreover, basing a physics curriculum on classic texts allows topics to arise naturally in the context of a continuing scientific dialogue.

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The textbook which I am developing has three main audiences. First, college and university students. It could be used as a primary textbook for discussion-style natural science classroom or as a supplementary textbook for courses in the history or philosophy of science. Second: advanced home-schooled and high-school students. It could aid senior-level home-schoolers looking for a bridge into college-level work or as a primary textbook for senior-level courses in physics, astronomy or history. Third: practicing physical scientists, social scientists, humanists and motivated lay-readers. It could serve as a structured review of foundational texts.

Project Activities

Evaluation, selection and acquisition of source texts. There were two primary criteria in selecting texts to include in the book: every selection must be significant for development of physical theory and every selection must be appropriate for beginning undergraduates or advanced high-school students. Student research and editorial assistants were involved at this stage of the project in, first, assembling a bibliography of english translations for each text and, second, evaluating articles which review the quality of the translation. These considerations informed the final decision on what to include.

In the following two tables are shown the text selections and topics included in Volume 1 of the textbook. The first table is for Part 1 of Volume 1; it is focused broadly on the themes of astronomy and cosmology. The second table is for Part 2 of Volume 1; it is focused on the themes of space, time and motion.

Volume 2, which is not described in this report, focuses on the themes of *electricity, magnetism, light* and *atoms, nuclei and matter*.

UNIT	AUTHOR	TEXT (TOPICS)
1	Aristotle	*On the heavens* (geocentrism, natural motion of elements)
2	Ptolemy	*The Almages*t (precision geocentrism)
3	Bede	*The reckoning of time* (astronomy & calendars)
4	Waldseemüller	*Introduction to cosmography* (astronomy & cartography)
5	Copernicus	*On the revolutions of the heavenly spheres* (heliocentrism)
6	Kepler	*Epitome of Copernican astronomy* (physical astronomy)
7	Galileo	*The starry messenger* (telescopic observations)
8	Herschel	*Outlines of astronomy* (stellar parallax)

UNIT	AUTHOR	TEXT (TOPICS)
9	Leavitt	*Harvard college observatory circular* (cepheid variables)
10	Shapely	*Galaxies* (measurement of great distances)
11	Einstein	*Relativity* (gravity and cosmology)
12	Hubble	*The realm of the nebulae* (stars, galaxies, Hubble's law)
13	Lemaitre	*The primeval atom* (big bang cosmology)
14	Eddington	*The running down of the universe* (cosmology & thermodynamics)

UNIT	TEXT (TOPICS)
1-6	Galileo's *Dialogues concerning two new sciences*: • strength of materials (scaling laws, equilibrium, levers, torque, fracture, yield strength, anatomy of animals) • projectile motion (falling bodies, drag, buoyancy, pendular motion, harmony, music theory, sympathetic resonance, kinematics, artillery)
7-8	Pascal's *Treatise on the equilibrium of fluids and the weight of air* • hydrostatic pressure, Pascal's principle, specific gravity, buoyancy, siphons, meteorology
9-12	Newton's *Mathematical principles of natural philosophy* • mass, momentum, inertia, force, relative motion, absolute motion, conservation of momentum, center of gravity, mechanical advantage, power, circular motion, fictitious forces, scientific method, Kepler's laws, universal gravitation
13-15	Einstein's *Relativity* • length contraction, time dilation, velocity addition, relativistic energy and momentum, 4-D space-time

Scanning, converting and editing source texts. After having selected the texts, undergraduate research and editorial assistants obtained printed copies of the text. They then scanned the texts and the resulting pdf files were converted into ascii text using an optical character recognition (OCR) program. The ascii text was proofread for errors in OCR and then formatted using LaTeX, a typesetting program conducive to scientific and mathematical publications.

Development of supplementary materials. In Figs. 1-5 in the appendix to this report, I provide some selections from a sample chapter of the textbook. Here I describe the basic components of each chapter.

1. I begin each chapter with a pithy quote, gleaned from the source text, which is selected to arouse the student's interest in the text and to set the stage for a broader conversation.
2. Next, I provide a short introduction to the text selection. If this is the first source text by a particular author, historical and biographical comments are offered so as to provide an appropriate context for the reading. I also include one or two provocative questions to focus the student's attention while studying the text.
3. Next, the source text itself is included, along with the bibliographical information and appropriate footnotes.
4. After the source text comes a series of study questions. These can be employed by the classroom discussion leader or by the independent student. They have been designed to draw out key points in the text and to highlight the author's definitions, methods, analysis and conclusions. They do not include anachronistic concepts or methods, so they encourage the student to approach the text in the same sprit, as it were, as the author.
5. After the study questions are a set of homework exercises which are designed to test the student's understanding of the text and ability to apply key concepts in solving problems. The homework exercises differ from the study questions in that they occasionally require the student to employ mathematical methods beyond those included in the text itself. Students may, for example, be asked to search other texts or website resources.
6. After the homework exercises is a list of vocabulary words which have been extracted from the text. These serve two purposes: to enhance the student's reading comprehension and to prepare the student for standardized tests such as the GRE or LSAT. Selection of vocabulary lists from source texts was the topic the fourth project activity, described below under the heading "Development of computer code for vocabulary lists."
7. Finally, laboratory exercises are included where appropriate.

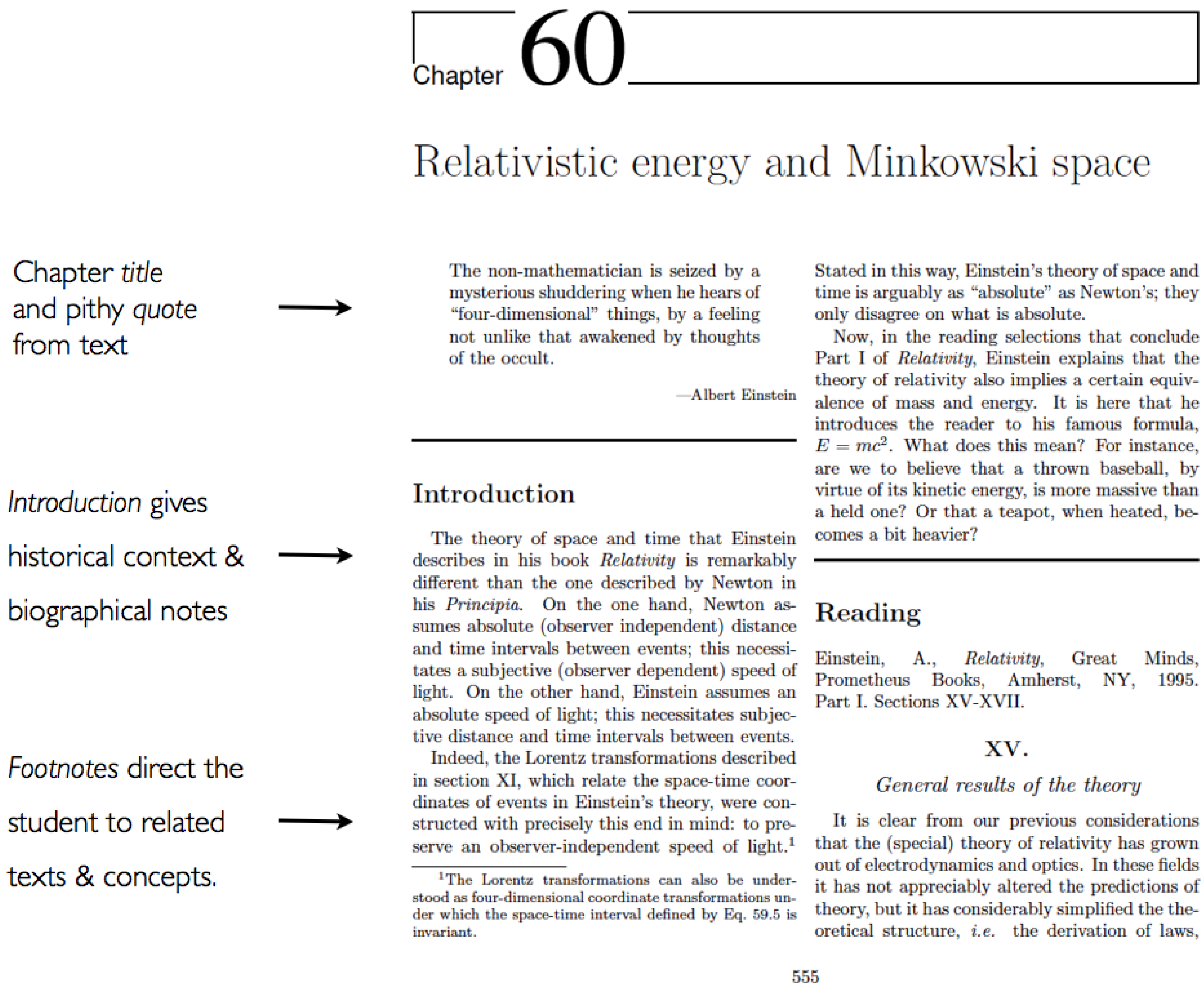
Development of computer code for vocabulary lists. The general problem of selecting a list of appropriate vocabulary words from a source text is one encountered by educators from grade school through post-secondary education. The typical method of assembling a vocabulary list involves reading the source text, picking out "good" words and putting these into a list. Unfortunately for the teacher, such a vocabulary list might change if different translations of the source text are employed from year to year, or if different paragraphs of the source text are omitted from year to year. Moreover, it is difficult to determine what constitute "good" vocabulary words: the longest words? most common words? rarest words? most foreign words?

We have contrived a method to turn the art of assembling vocabulary lists into a science. In particular, two students have developed computer code which facilitates the automatic selection of vocabulary lists from a given source text. The code, written in C++, makes use of the Google Ngrams database, which consists of millions of scanned source texts along with word frequency data. The code works as follows. First, one of Google's Ngram databases is downloaded. Second, the database is compared to a dictionary to eliminate misspellings included in Google's data.   Third, the a searchable source text, such as Blaise Pascal's *Treatise on the Weight of Air*, is read. An algorithm then compares words in the source text to word frequency data in the Ngram database. The algorithm can be manipulated to favor certain types of words: old words, new words, long words, rare words, etc. Here, for instance, is a set of twenty vocabulary words gleaned from Christiaan Huygens' *Treatise on Light* using a particular vocabulary selection algorithm.

1. Propound
2. Presuming
3. Assuredly
4. Ingeniously
5. Intersected
6. Manifestly
7. Diaphanous
8. Impugn
9. Imparts
10. Supposed
11. Suffices
12. Insinuate
13. Fraught
14. Excellently
15. Dissipate
16. Smallness
17. Evenness
18. Sensibly
19. Diminishes
20. Imaginable

At this stage in the project, Cody Morse (a returning sophomore) is taking over the project from Tim Kriewall (a returning senior). He plans to migrate to a PERL/mySQL platform from the working C++ platform. Once we have finished this, our eventual goal is to publish a dedicated website which makes our algorithm widely available. This website will allow educators to upload text files, adjust word priority parameters (old/new, common/rare, etc.) using virtual knobs or sliders, and generate tailored vocabulary lists for use in the classroom.

Appendix



Chapter 60

Relativistic energy and Minkowski space

> The non-mathematician is seized by a mysterious shuddering when he hears of "four-dimensional" things, by a feeling not unlike that awakened by thoughts of the occult.
>
> —Albert Einstein

Introduction

The theory of space and time that Einstein describes in his book *Relativity* is remarkably different than the one described by Newton in his *Principia*. On the one hand, Newton assumes absolute (observer independent) distance and time intervals between events; this necessitates a subjective (observer dependent) speed of light. On the other hand, Einstein assumes an absolute speed of light; this necessitates subjective distance and time intervals between events.

Indeed, the Lorentz transformations described in section XI, which relate the space-time coordinates of events in Einstein's theory, were constructed with precisely this end in mind: to preserve an observer-independent speed of light.[1]

[1]The Lorentz transformations can also be understood as four-dimensional coordinate transformations under which the space-time interval defined by Eq. 59.5 is invariant.

Stated in this way, Einstein's theory of space and time is arguably as "absolute" as Newton's; they only disagree on what is absolute.

Now, in the reading selections that conclude Part I of *Relativity*, Einstein explains that the theory of relativity also implies a certain equivalence of mass and energy. It is here that he introduces the reader to his famous formula, $E = mc^2$. What does this mean? For instance, are we to believe that a thrown baseball, by virtue of its kinetic energy, is more massive than a held one? Or that a teapot, when heated, becomes a bit heavier?

Reading

Einstein, A., *Relativity*, Great Minds, Prometheus Books, Amherst, NY, 1995. Part I. Sections XV-XVII.

XV.

General results of the theory

It is clear from our previous considerations that the (special) theory of relativity has grown out of electrodynamics and optics. In these fields it has not appreciably altered the predictions of theory, but it has considerably simplified the theoretical structure, *i.e.* the derivation of laws,

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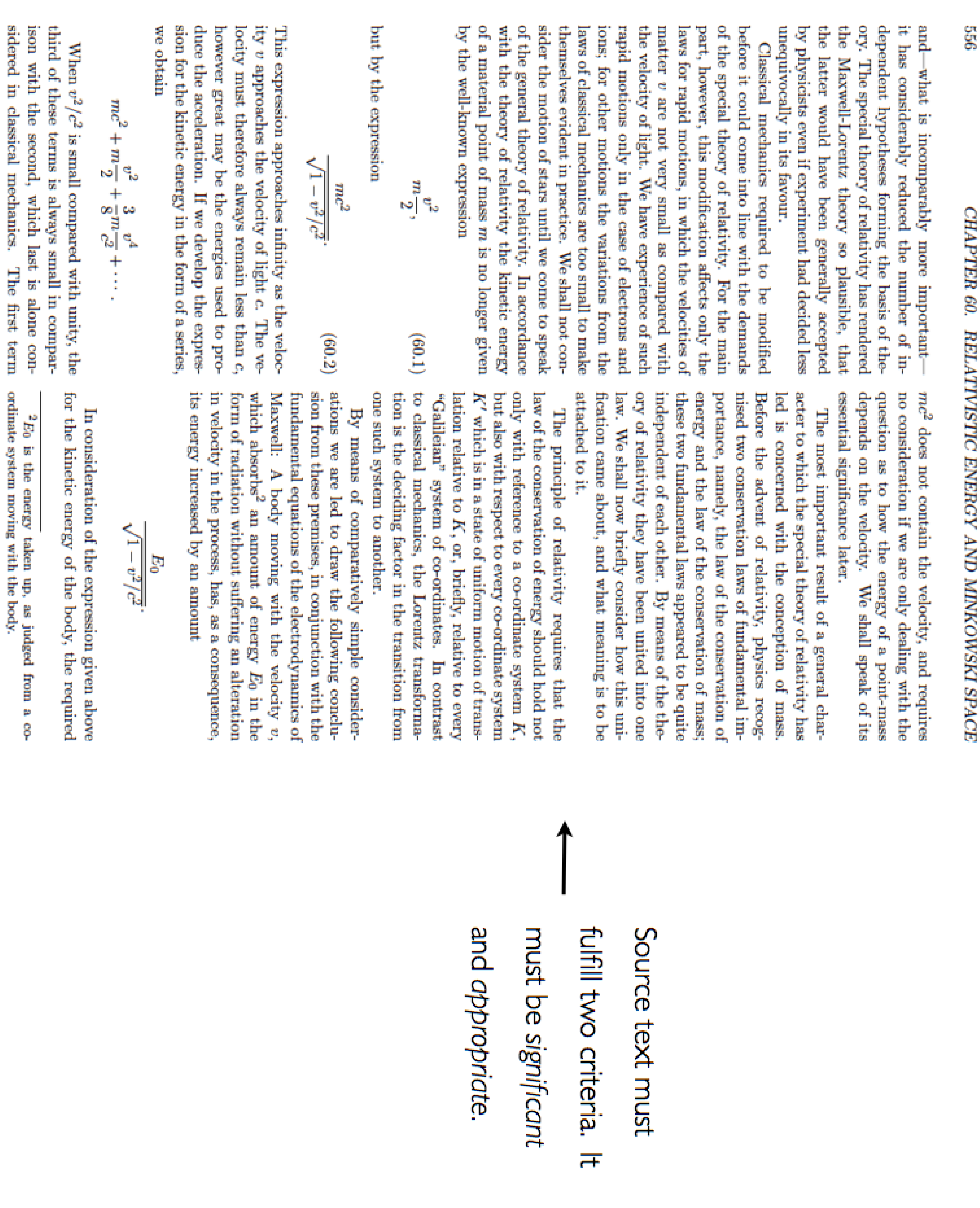
Fig. 1



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and—what is incomparably more important—it has considerably reduced the number of independent hypotheses forming the basis of theory. The special theory of relativity has rendered the Maxwell-Lorentz theory so plausible, that the latter would have been generally accepted by physicists even if experiment had decided less unequivocally in its favour.

Classical mechanics required to be modified before it could come into line with the demands of the special theory of relativity. For the main part, however, this modification affects only the laws for rapid motions, in which the velocities of matter v are not very small as compared with the velocity of light. We have experience of such rapid motions only in the case of electrons and ions; for other motions the variations from the laws of classical mechanics are too small to make themselves evident in practice. We shall not consider the motion of stars until we come to speak of the general theory of relativity. In accordance with the theory of relativity the kinetic energy of a material point of mass m is no longer given by the well-known expression

$$m\frac{v^2}{2}, \qquad (60.1)$$

but by the expression

$$\frac{mc^2}{\sqrt{1-v^2/c^2}}. \qquad (60.2)$$

This expression approaches infinity as the velocity v approaches the velocity of light c. The velocity must therefore always remain less than c, however great may be the energies used to produce the acceleration. If we develop the expression for the kinetic energy in the form of a series, we obtain

$$mc^2 + m\frac{v^2}{2} + \frac{3}{8}m\frac{v^4}{c^2} + \cdots .$$

When v^2/c^2 is small compared with unity, the third of these terms is always small in comparison with the second, which last is alone considered in classical mechanics. The first term mc^2 does not contain the velocity, and requires no consideration if we are only dealing with the question as to how the energy of a point-mass depends on the velocity. We shall speak of its essential significance later.

The most important result of a general character to which the special theory of relativity has led is concerned with the conception of mass. Before the advent of relativity, physics recognised two conservation laws of fundamental importance, namely, the law of the conservation of energy and the law of the conservation of mass; these two fundamental laws appeared to be quite independent of each other. By means of the theory of relativity they have been united into one law. We shall now briefly consider how this unification came about, and what meaning is to be attached to it.

The principle of relativity requires that the law of the conservation of energy should hold not only with reference to a co-ordinate system K, but also with respect to every co-ordinate system K' which is in a state of uniform motion of translation relative to K, or, briefly, relative to every "Galileian" system of co-ordinates. In contrast to classical mechanics, the Lorentz transformation is the deciding factor in the transition from one such system to another.

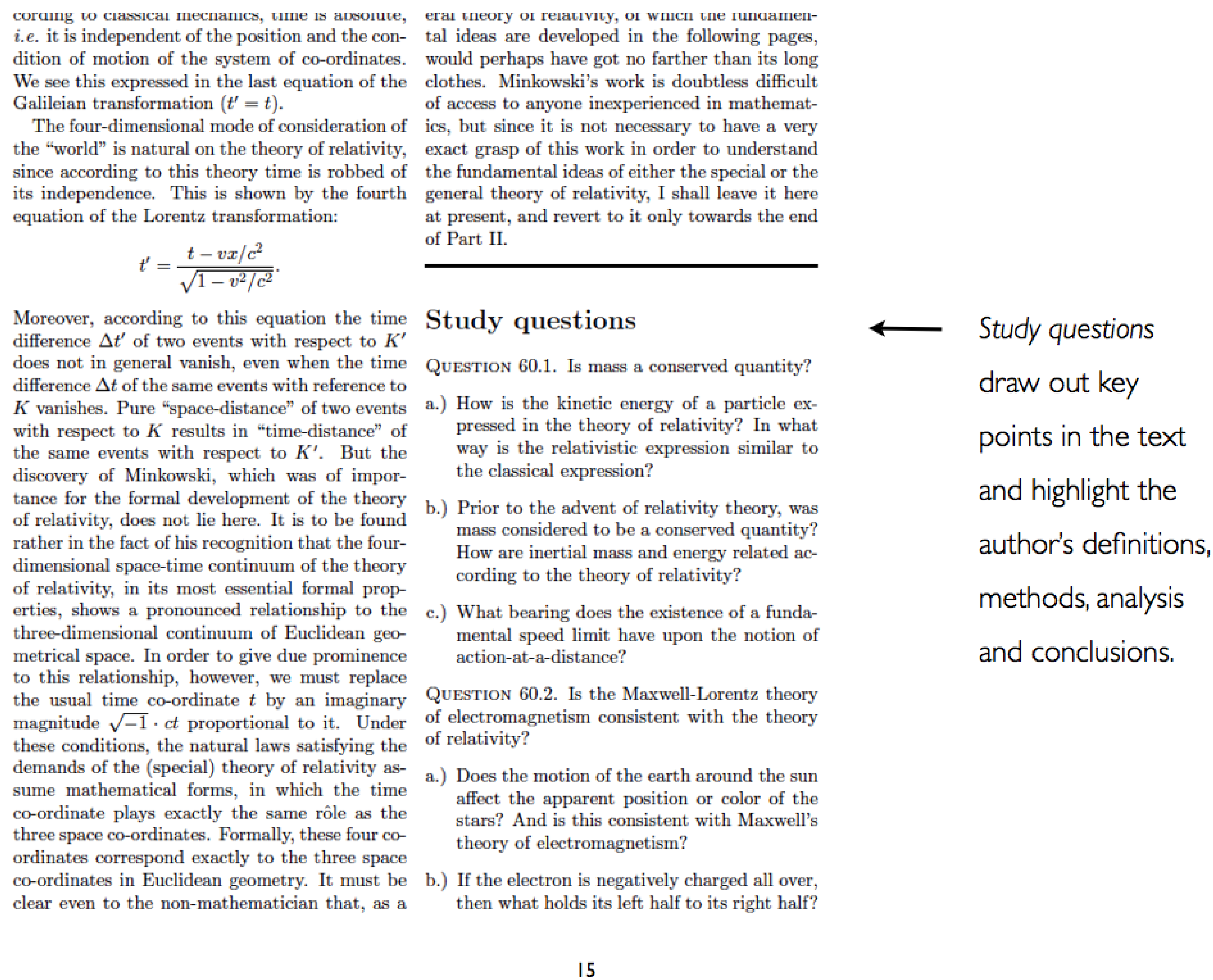
By means of comparatively simple considerations we are led to draw the following conclusion from these premises, in conjunction with the fundamental equations of the electrodynamics of Maxwell: A body moving with the velocity v, which absorbs[2] an amount of energy E_0 in the form of radiation without suffering an alteration in velocity in the process, has, as a consequence, its energy increased by an amount

$$\frac{E_0}{\sqrt{1-v^2/c^2}}.$$

In consideration of the expression given above for the kinetic energy of the body, the required

[2] E_0 is the energy taken up, as judged from a co-ordinate system moving with the body.

Fig. 2



cording to classical mechanics, time is absolute, *i.e.* it is independent of the position and the condition of motion of the system of co-ordinates. We see this expressed in the last equation of the Galileian transformation ($t' = t$).

The four-dimensional mode of consideration of the "world" is natural on the theory of relativity, since according to this theory time is robbed of its independence. This is shown by the fourth equation of the Lorentz transformation:

$$t' = \frac{t - vx/c^2}{\sqrt{1 - v^2/c^2}}.$$

Moreover, according to this equation the time difference $\Delta t'$ of two events with respect to K' does not in general vanish, even when the time difference Δt of the same events with reference to K vanishes. Pure "space-distance" of two events with respect to K results in "time-distance" of the same events with respect to K'. But the discovery of Minkowski, which was of importance for the formal development of the theory of relativity, does not lie here. It is to be found rather in the fact of his recognition that the four-dimensional space-time continuum of the theory of relativity, in its most essential formal properties, shows a pronounced relationship to the three-dimensional continuum of Euclidean geometrical space. In order to give due prominence to this relationship, however, we must replace the usual time co-ordinate t by an imaginary magnitude $\sqrt{-1} \cdot ct$ proportional to it. Under these conditions, the natural laws satisfying the demands of the (special) theory of relativity assume mathematical forms, in which the time co-ordinate plays exactly the same rôle as the three space co-ordinates. Formally, these four co-ordinates correspond exactly to the three space co-ordinates in Euclidean geometry. It must be clear even to the non-mathematician that, as a

eral theory of relativity, of which the fundamental ideas are developed in the following pages, would perhaps have got no farther than its long clothes. Minkowski's work is doubtless difficult of access to anyone inexperienced in mathematics, but since it is not necessary to have a very exact grasp of this work in order to understand the fundamental ideas of either the special or the general theory of relativity, I shall leave it here at present, and revert to it only towards the end of Part II.

Study questions

Question 60.1. Is mass a conserved quantity?

a.) How is the kinetic energy of a particle expressed in the theory of relativity? In what way is the relativistic expression similar to the classical expression?

b.) Prior to the advent of relativity theory, was mass considered to be a conserved quantity? How are inertial mass and energy related according to the theory of relativity?

c.) What bearing does the existence of a fundamental speed limit have upon the notion of action-at-a-distance?

Question 60.2. Is the Maxwell-Lorentz theory of electromagnetism consistent with the theory of relativity?

a.) Does the motion of the earth around the sun affect the apparent position or color of the stars? And is this consistent with Maxwell's theory of electromagnetism?

b.) If the electron is negatively charged all over, then what holds its left half to its right half?

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Fig. 3

Is Maxwell's theory able to account for the nature of the electron? Where, then, does Einstein seek a solution to this problem?

c.) How did Lorentz arrive at a correct law of motion for the magnetic deflection of high-speed electrons? How does Einstein's approach differ? Which is better?

QUESTION 60.3. Did the Michelson-Morley experiment verify the theory of relativity?

a.) How did Michelson and Morley attempt to measure the motion of the earth using terrestrial measurements?

b.) What would constitute a positive result of this experiment? What would a positive result imply? What would constitute a negative result, and what would this imply?

c.) What were the actual results of their experiments? How were the explanations of Lorentz and FitzGerald and of Einstein different? Which explanation is better?

d.) Is Einstein's theory inconsistent with the existence of æther?

QUESTION 60.4. What does Minkowski mean when he says that the world is a four-dimensional continuum?

a.) In what sense is space a three-dimensional continuum? How many numbers does it take to describe a particular event?

b.) Why are space and time coordinates treated differently in classical mechanics? And how is this expressed in the Galileian transformation equations?

c.) In what sense are space and time coordinates treated more symmetrically in the theory of relativity? Are they treated identically?

d.) Is the notion of four-dimensional space-time

Homework exercises

EXERCISE 60.1 (Nuclear fusion reaction). When a gas consisting of the hydrogen isotopes deuterium and tritium is raised to a sufficiently high temperature, the atomic nuclei have enough kinetic energy to overcome their mutual coulomb repulsion, fusing to form stable helium-4 isotopes. This nuclear reaction is given by

$$^2_1H +^3_1 H \longrightarrow^4_2 He +^1_0 n.$$

The superscripts here denote the approximate rest masses of the reactants and products; the more precise rest masses are, from left to right, 2.014, 3.016, 4.003 and 1.009 atomic mass units.

a.) Is rest mass conserved during this nuclear reaction? If not, how much is gained or lost?

b.) How much heat is evolved when one mole of deuterium fuses with one mole of tritium? From where does this heat arise?

c.) Compare the heat evolved during this fusion reaction to that evolved during the combustion of one mole of a conventional explosive, such as dynamite.

EXERCISE 60.2 (Relativistic energy). Shown in Tab. 60.1 are expressions for the mass, momentum and energy of a particle according to both classical (Newtonian) and relativistic (Einsteinian) mechanics.

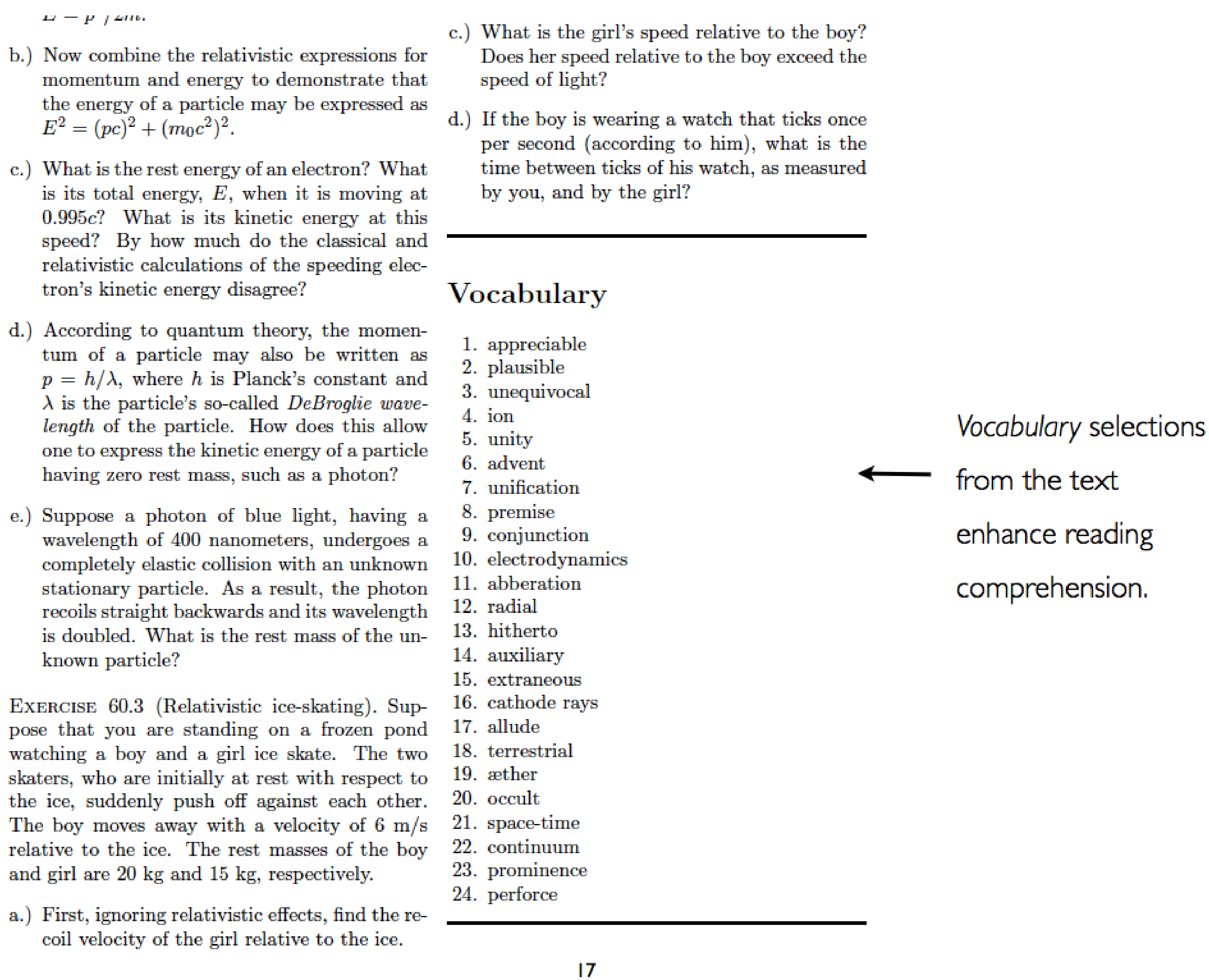
	Classical	Relativistic
mass	$m = m_0$	$m = \gamma m_0$
momentum	$p = mv$	$p = mv$
rest energy	0	$E_0 = m_0c^2$
total energy	$E = \frac{1}{2}mv^2$	$E = mc^2$

Table 60.1

← *Homework exercises* test students' understanding of the text and their ability to apply key concepts.

Exercises occasionally require students to employ mathematical methods beyond those included in the text itself.

Fig. 4



$E = p^2/2m$.

b.) Now combine the relativistic expressions for momentum and energy to demonstrate that the energy of a particle may be expressed as $E^2 = (pc)^2 + (m_0c^2)^2$.

c.) What is the rest energy of an electron? What is its total energy, E, when it is moving at $0.995c$? What is its kinetic energy at this speed? By how much do the classical and relativistic calculations of the speeding electron's kinetic energy disagree?

d.) According to quantum theory, the momentum of a particle may also be written as $p = h/\lambda$, where h is Planck's constant and λ is the particle's so-called *DeBroglie wavelength* of the particle. How does this allow one to express the kinetic energy of a particle having zero rest mass, such as a photon?

e.) Suppose a photon of blue light, having a wavelength of 400 nanometers, undergoes a completely elastic collision with an unknown stationary particle. As a result, the photon recoils straight backwards and its wavelength is doubled. What is the rest mass of the unknown particle?

Exercise 60.3 (Relativistic ice-skating). Suppose that you are standing on a frozen pond watching a boy and a girl ice skate. The two skaters, who are initially at rest with respect to the ice, suddenly push off against each other. The boy moves away with a velocity of 6 m/s relative to the ice. The rest masses of the boy and girl are 20 kg and 15 kg, respectively.

a.) First, ignoring relativistic effects, find the recoil velocity of the girl relative to the ice.

c.) What is the girl's speed relative to the boy? Does her speed relative to the boy exceed the speed of light?

d.) If the boy is wearing a watch that ticks once per second (according to him), what is the time between ticks of his watch, as measured by you, and by the girl?

Vocabulary

1. appreciable
2. plausible
3. unequivocal
4. ion
5. unity
6. advent
7. unification
8. premise
9. conjunction
10. electrodynamics
11. abberation
12. radial
13. hitherto
14. auxiliary
15. extraneous
16. cathode rays
17. allude
18. terrestrial
19. æther
20. occult
21. space-time
22. continuum
23. prominence
24. perforce

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Fig. 5