

Newton to Einstein

the trail of light

从牛顿到爱因斯坦

Ralph Baierlein



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NEWTON TO EINSTEIN

The trail of light

An excursion to the wave-particle duality
and the Special Theory of Relativity

RALPH BAIERLEIN

Wesleyan University, Middletown, Connecticut



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Preface

The college catalog said

Physics 104. Newton to Einstein: The Trail of Light

The course will follow the trail of light from Newton's corpuscles to Einstein's relativity. The major theoretical landmarks will be the wave-particle duality and the special theory of relativity.

It was the spring term of 1987, and the course was brand-new. Out of my previous experience with courses for non-scientists, I expected a class of 20 to 30 students. If enrollment became a fad, then the class might grow to 50 or 60. I was not prepared for what happened. When pre-registration was over, 141 students had signed up.

As an aside, let me remark that I was also scheduled to teach the calculus-based introductory course, ordinarily our largest course. That spring I taught more students than the rest of the department, all put together.

My intention was to teach the course in alternate years (to maximize the number of times I would teach it before burning out). When I taught the course the second time, in the fall of 1988, over 170 students sought admission. Reluctantly, I held the line at 150, my saturation point when reading essays and correcting exams.

During the last week of the semester, I ask my students for advice about improving the course, and I also ask them, "What, for you, is the most valuable thing you learned or 'got' from this course?" In 1988, my younger son, then a senior in high school and ever skeptical of his father's teaching methods, happened to read the responses first. When he handed them back, he remarked laconically, "I'm impressed." I thought to myself, maybe there is something in this course that others would find useful. I had not been able to find a textbook – rather, I had relied on the lectures and on photocopied notes – and so I set out to turn my notes into this book.

How, you may wonder, is the book organized? Since the book grew out of a course, it reflects a specific progress through the course's topics. But I have tried to make the book modular. Few professors want to commit themselves to following an author's development step by step; as a breed, we professors are far too independent-minded for that.

When I taught from a draft in 1990, my own sequence started with section 1.1 and then went directly to chapter 2, returning to other sections of chapter 1 as they were needed in the development. An instructor who does not want to include Newton's particle theory may omit chapter 2 entirely.

In writing the chapters on relativity theory, I deferred the twins so that students can become familiar with time dilation (through homework questions) before the text takes up the twins. Getting to the twins is what I aim for in a semester's course; the chapter on the Lorentz transformations *per se* is there for an instructor with more time or a different set of priorities.

An instructor can even use the relativity chapters independently of the first seven chapters. To be sure, if the development of $E=mc^2$ is to be included, one must get the idea of energy and momentum for a photon from somewhere (if not from chapter 6). The general idea of energy is developed in appendix A, where it is available whatever route an instructor takes through the book. A glossary collects many of the technical terms that are defined at various points in the book.

In the first half of the book, which takes the reader through the wave-particle duality, the development is chronological and historical, broadly speaking. The development of relativity theory, however, is ahistorical. The two fundamental principles are taken as generalizations from everyday experience and from a particularly clean experiment performed in 1964. Let me explain why I adopted this approach.

The first and second times that I taught the course out of which this book grew, I asked my students to read Banesh Hoffmann's *Relativity and Its Roots*. The book is delightfully written, and I enjoy it immensely. Yet in the long, tortuous history of the ether, my students got confused by all the things – new to them – that turned out to be contradictory or wrong or irrelevant. In 1905, Einstein remarked that “the introduction of a ‘luminiferous ether’ will prove to be superfluous.” Good advice. I took it to heart.

When I was in graduate school, the Physical Science Study Committee developed its innovative high school course. I had the privilege of teaching with Eric Rogers, one of the developers, and I absorbed a lot of the PSSC spirit. Anyone familiar with PSSC physics will recognize its influence in the first few chapters of this book and in some of the homework questions.

The book *Revolutions in Physics*, by Barry Casper and Richard Noer, was recommended to me some ten years ago. I have occasionally taught from parts of it, and I have mined it for ideas and homework questions. My acknowledgement and thanks go to Professors Casper and Noer for an excellent book.

Teaching the equation $E=mc^2$ is difficult, primarily because of the mis-

conceptions with which students come to the topic and because there is no uniquely correct way to go about describing the deep connection between inertia and energy. Chapter 11 provides one correct way of presenting the topic; an alternative is discussed in appendix C, More about $E=mc^2$. In both places I take great pains to forestall and combat misconceptions; I welcome correspondence on how I could do the job even better.

Every instructor has his or her own way of approaching a subject and teaching a course. I have no intention of telling people how to go about their work; yet some information about how I teach my course may be useful to some instructors, and so I will say a bit more here.

My goals in the course are the following four: (1) to give my students a positive experience with science; (2) to teach them some intellectually important physics; (3) to give them experience with clear, logical thinking, both mine (in lecture and text) and theirs (in the homework); and (4) to provide some acquaintance with the human and historical sides of physics.

The syllabus tells my students that “homework is for learning, not for testing. The staff and I will *correct* your homework but not grade it. The only record we keep about each question is whether or not you made a serious attempt to answer it.” My students find this policy supportive; it reduces their fear of science. And the policy enables me to pose some quite challenging questions.

My lectures and this book cover the essential physics, but the course includes other books, usually three of them. They have been Edward Andrade’s *Sir Isaac Newton*, Albert Einstein’s *Ideas and Opinions*, and either Banesh Hoffmann’s *Relativity and Its Roots* or Richard Rhodes’s *The Making of the Atomic Bomb*. Of these books, only the Einstein volume is wholly satisfactory in my context, and so I am always on the lookout for other books.

With each book, I assign a short paper (of two or three pages), a practice that has many merits. The papers give my students an opportunity to do what many of them do well, namely, to write, and thus the papers are a good way to build up credit toward a good course grade. Moreover, the essays engage the mind and provide an opportunity for self-expression in what is generally too passive a learning context. The insights into Newton and Einstein prove to be fascinating and to shatter stereotypes. The first batch of Newton papers that I read contained a sentence that I will never forget. Tim Orr wrote, “Suffice it to say that when I read the biography, I was not expecting a very colorful picture of Newton, but, as I found out, the life of the man that I learned to hate in high school is really quite interesting, and I would not mind learning even more about him.”

PREFACE

Demonstrations are a vital part of my teaching, and that is one reason why I teach so often about light: the demonstrations work (for there is no friction!), and they are often beautiful. When I ask my students for advice about the course, one of the questions has been this: "If there is a topic or demonstration that you particularly enjoyed, tell me that, too." In 1988, a student had this to say in response: "Mostly, the demonstrations are a GREAT way of seeing what you say – without them, I don't know how I'd learn any of it or believe you." I agree, and I wouldn't know how to give a lecture without some props. Beyond that, all of us enjoy the demonstrations, and they provide something to look forward to when the alarm clock goes off for an early morning class.

The course has a mid-semester hour exam and a cumulative final exam. Throughout the course, I keep in mind the question, what will my students remember five years from now? The equations? The sense of logic? The demonstrations? The flavor of the course? My personality? It is humbling, and it leads me to do only a few things but to do them well. If anything, I still address too many topics, though by no means all that appear in this book.

Enough of organization; let me go on.

The lecture demonstrations would never have been so varied and so successful without the assistance of our physics curators, first Wlad Miglus and then his son and successor, Vacek Miglus. My thanks go to them for so much help in the prep room before the next class.

My colleagues at the university and in the physics community at large have been a great help to me. My special thanks go to Phyllis Fleming, A. P. French, Stewart Gillmor, Steven Lebergott, Richard Lindquist, Janet Morgan, Stewart Novick, Joseph Rouse, and Penny Russman. Another bouquet of thanks goes to Anne Stevenson, my secretary while the course and book emerged from lecture notes. Some of my students were particularly helpful – reading drafts or asking good questions – and so I send my thanks to Holly Adams, Kathy Booth, and David Lakein.

At the Press, Rufus Neal was encouraging and helpful – always – and to him I express my warm appreciation. Finally, I thank my wife Jean for her good advice and steadfast support.

*Middletown, Connecticut
March 1991*

Ralph Baierlein

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I How light behaves

First gather the facts; then you can distort them at your leisure.

Mark Twain

1.1 First observations

How should we begin? Surely with Isaac Newton. He published his first scientific paper in 1672, and it was on light. In response to an objection raised against his paper, he wrote

For the best and safest method of philosophizing seems to be, first diligently to investigate the properties of things and establish them by experiment, and then to seek hypotheses to explain them. For hypotheses ought to be fitted merely to explain the properties of things and not attempt to predetermine them, except in so far as they can be an aid to experiments.

So let us get a light source and begin investigating. I will suppose that you have access to some apparatus – at least in the sense of seeing lecture demonstrations – and so I will describe things as though we were doing the experiments together.

We take a strong flashlight or a 35-millimeter slide projector and shine the light horizontally. Clapping a pair of well-used erasers produces a cloud of chalk dust, and we see the light beam piercing the cloud as a bright shaft of light. This gives us our first observation:

Observation 1. Light goes in a straight line from a luminous source.

Reflection and refraction

Next we tip our source – the projector, say – so that the light enters the water in an aquarium tank. Figure 1.1 depicts what happens. The beam of light changes direction as it enters the water. This bending is called *refraction* (from the Latin “to break,” as in the word “fracture”). We must augment our first observation to read as follows:

Observation 1'. Light goes in a straight line (so long as it moves through a single uniform substance).

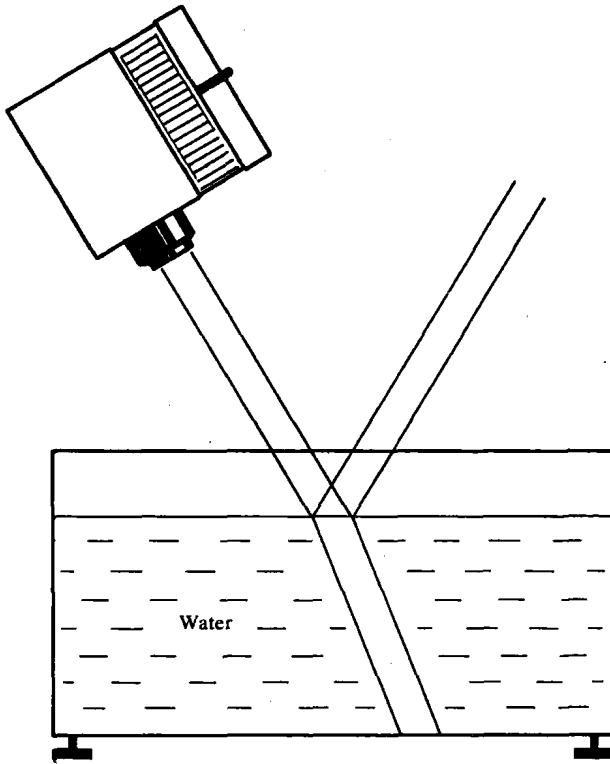


Figure 1.1 A light beam striking the surface of water: refraction and reflection. In a dark room, ordinary tap water gives a visible refracted beam. Chalk dust will reveal the reflected beam.

Before we go on with the experiment, some remarks about the glossary are in order. Many technical terms, like the word *refraction*, are collected and defined once again in the glossary, which is printed near the end of the book. Regard that collection as a valuable resource, particularly when you review. In fact, it is a good idea to take a look at the glossary right now. You will get a further sense of what is to be found there, and a visual impression will make its existence stick in your mind.

Now we return to our light source and the tank of water. In addition to the refracted beam, we note also a reflected beam of light. How can we characterize it geometrically? Figure 1.2 gives a stylized rendition of the situation; beams of light (of some thickness) have been replaced by lines and arrow heads, indicating single rays of light. The perpendicular to the surface has been drawn in; it is called the *normal* to the surface.

To the eye, the angle between the reflected ray and the normal appears

I.1 FIRST OBSERVATIONS

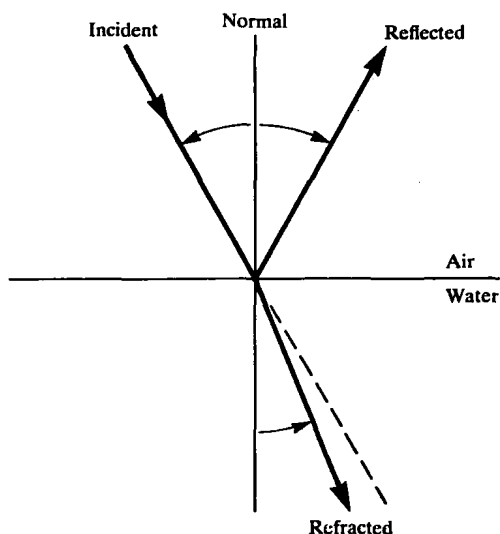


Figure 1.2 A stylized rendition of reflection and refraction. The dashed line shows the path that light would take if it were not refracted. The angle between the normal and the incident ray is called the *angle of incidence*; that between the normal and the refracted ray, the *angle of refraction*; and that between the normal and the reflected ray, the *angle of reflection*.

equal to the angle between the incident ray and the normal. Careful measurement (with more sophisticated apparatus) corroborates this. Moreover, if the incident ray was traveling due east (and downward), then the reflected ray travels due east (and upward). The horizontal motion is the same for both rays. We codify these remarks as

Observation 2.

- (a) The angle of reflection equals the angle of incidence.
- (b) The incident ray, the reflected ray, and the normal lie in the same plane.

As an aside, let me remark that Observation 2 provides the basis for understanding mirrors, both bathroom and funhouse.

Reversibility

Next, we can try sending light back along the path it has taken. To do that, we put a mirror in the path and adjust the orientation until the beam heads straight backward.

What happens when the returning beam encounters a place where the outward-going beam was reflected (as in the upper portion of figure 1.2)? Observation 2 tells us that light coming in along the “reflected” direction

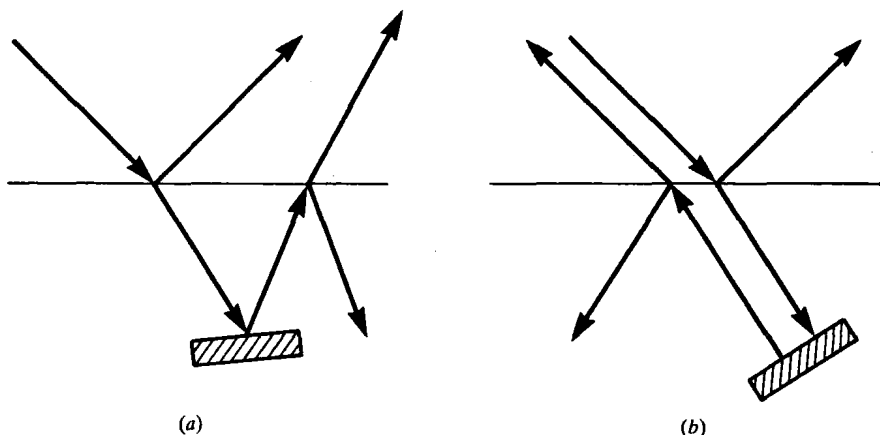


Figure 1.3 A mirror in the water tank. (a) While we are trying to find the correct orientation for the mirror, the light beams will look something like this. (b) When we have achieved the orientation that sends light straight backward *within* the tank, the light goes straight backward also after refraction into air. (The arrows have been displaced sideways for clarity's sake only.)

will be sent out along the “incident” direction. The equality of the angles ensures this. (There may also be a new refracted beam if the reflection is not from a mirror.)

If, however, the returning beam encounters a place where the outward-going beam was refracted, then our observations to date do not tell us what will happen. We need a new experiment. Figure 1.3 shows what happens if we put a mirror into the tank of water. The newly refracted beam retraces the original path in air (and there is an extraneous reflection back toward the bottom of the tank).

We find that each reflection and each refraction is reversible. A light path made up of several such occurrences, in any order, will also be reversible. Thus our investigations lead to

Observation 3. Light paths are reversible.

To be sure, sending a beam back along its original path may lead to extra branching, as in part (b) of figure 1.3, but a portion of the light will make it back all the way along the original path.

More about refraction

Now we turn to characterizing the refracted beam. In figure 1.2, the perpendicular to the surface extends on both sides of the surface, and so we can speak of an angle of refraction as the angle between the refracted ray and

1.1 FIRST OBSERVATIONS

Table 1.1. *Data on refraction for the transition air-to-water. Angles are measured in degrees. The column headed "Ratio of angles" gives a quotient: the angle of incidence divided by the angle of refraction. The fourth column gives a similar quotient: the semi-chord associated with the incident ray divided by that for the refracted ray.*

Angle of incidence	Angle of refraction	Ratio of angles	Ratio of semi-chords
10	7.5	1.33	1.33
20	14.9	1.34	1.33
30	22.1	1.36	1.33
40	28.9	1.38	1.33
50	35.2	1.42	1.33
60	40.6	1.48	1.33
70	45.0	1.56	1.33
80	47.8	1.68	1.33

the normal on its side of the surface. The angles in this figure and in figure 1.1 were drawn faithfully, and so inspection of the drawings gives us

Observation 4. On the transition air-to-water, the angle of refraction is less than the angle of incidence.

In short, the beam is bent toward the normal.

How does the angle of refraction change if we change the angle of incidence? For example, if we double the angle of incidence, does the other angle double also? Table 1.1 provides some experimental data. The ratio of angles is *not* constant, and so the angle of refraction is not proportional to the angle of incidence. The ratio of angles shows a systematic trend, however, and so there is still hope for a simple relationship.

Figure 1.4 lays out the geometry more fully. An incident light ray, the corresponding refracted ray, and the normal are present. In addition, I have drawn a circle of radius R around them and have drawn in the semi-chords. The numerical value of the radius R is inconsequential, for only ratios will be important to us. The point of figure 1.4 is to introduce semi-chords into our description of refraction.

If we examine the ratio of semi-chords in table 1.1, we find that a constant ratio emerges. Thus we have

Observation 5. In refraction, the ratio of semi-chords is the same for all angles of incidence (in the transition air-to-water).

At this point, several thoughts may arise in your mind. First, this relation-

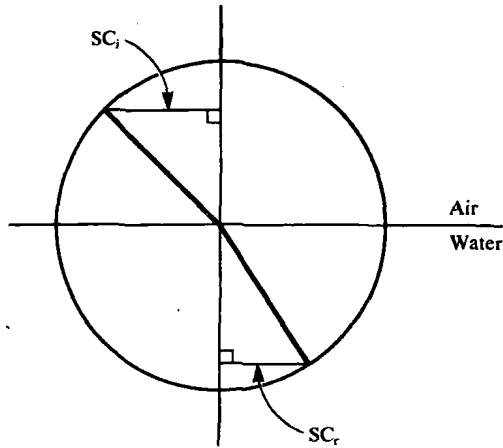


Figure 1.4 Refraction and a circle of radius R . The light ray intersects the circle at two points. The lines drawn from the points of intersection to the normal are the semi-chords. They meet the normal perpendicularly. The letters "SC" denote "semi-chord," and the subscripts "i" and "r" stand for "incident" and "refracted," respectively.

ship really isn't simple. Yes and no. It is not an intuitively obvious result, but any time we can find a direct proportionality – here between semi-chords – we have something at least relatively simple.

Second, why does it work out this way for light? An answer to this question requires some theory building; that comes in chapters 2 and 3. Right now we are still gathering data, as Newton advised us to.

Third, of what use is Observation 5? It has many uses, really. For us, it summarizes table 1.1, and we can use it to calculate refraction for angles not listed in the table. More importantly, we can test any theory of light by asking whether it reproduces Observation 5. And finally, the observation provided the original basis for the systematic design of lenses, from spectacle lenses to telescope lenses.

An illustration of how we can calculate new angles of refraction is in order. Suppose the angle of incidence is 45 degrees. What is the angle of refraction?

For the transition air-to-water, table 1.1 shows that the ratio of semi-chords is equal to 1.33. So we may write

$$\frac{\text{semi - chord of incident ray}}{\text{semi - chord of refracted ray}} = 1.33.$$

When we let "SC" stand for "semi-chord" and let subscripts "i" and "r"