Theory and Experiment in the Quantum-Relativity Revolution

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by

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Abstract

Does new scientific knowledge come from theory (whose predictions are confirmed by experiment) or from experiment (whose results are explained by theory)? Either can happen, depending on whether theory is ahead of experiment or experiment is ahead of theory at a particular time. In the first case, new theoretical hypotheses are made and their predictions are tested by experiments. But even when the predictions are successful, we can't be sure that some other hypothesis might not have produced the same prediction. In the second case, as in a detective story, there are already enough facts, but several theories have failed to explain them. When a new hypothesis plausibly explains all of the facts, it may be quickly accepted before any further experiments are done. In the quantum-relativity revolution there are examples of both situations. Because of the two-stage development of both relativity ("special," then "general") and quantum theory ("old," then "quantum mechanics") in the period 1905-1930, we can make a double comparison of acceptance by prediction and by explanation. A curious anti-symmetry is revealed and discussed.

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“Science walks forward on two feet, namely theory and experiment. ... Sometimes it is only one foot which is put forward first, sometimes the other, but continuous progress is only made by the use of both – by theorizing and then testing, or by finding new relations in the process of experimenting and then bringing the theoretical foot up and pushing it on beyond, and so on in unending alterations.”

Robert A. Millikan, Nobel Prize Lecture, 1924

(I thank Jack Gaffey for suggesting this quotation)

1. From Princip to Principe

On June 28, 1914, the Archduke Francis Ferdinand of Austria-Hungary was assassinated in Sarajevo by a Serbian nationalist, Gavrilo Princip. This event was the immediate cause of World War I. As we might say today, it was like the flapping of a butterfly's wings, which led to a 4-year hurricane that devastated Europe.

It also had one indirect (one might say beneficial) effect on the fate of Albert Einstein's General Theory of Relativity. A German astronomical expedition led by Erwin Findlay Freundlich went to the Crimea peninsula in Russia, hoping to observe the solar eclipse scheduled for August 21, 1914. They wanted to test Einstein's prediction that starlight will be deflected by an angle of 0.87 seconds near the edge of the sun. But on August 1, 1914, Germany declared war on Russia, and the Russians therefore arrested the German astronomers as enemy aliens, preventing them from making observations. Had the astronomers done so with sufficient accuracy, they would have found that the deflection is actually 1.74 seconds – twice as much as the prediction from Einstein's theory.

Einstein later revised his General Theory, and predicted on November 18, 1915 that the deflection should be 1.74 seconds. Another expedition led by the British astronomer Arthur S. Eddington went to the island of Principe (in the Gulf of Guinea off the west coast of central Africa) to observe a solar eclipse that would occur on May 29, 1919. Fortunately (for science) the war had ended on November 11, 1918 so such observations could be made without risk of military interference.

Eddington analyzed the observations and announced on November 6, 1919 that Einstein's (new) prediction had been confirmed. The result was enormous publicity for Einstein and his theory, starting the next day when the *Times* of London proclaimed a "Revolution in Science" started by "one of the greatest achievements in human thought."

The theory was incomprehensible to almost everyone, but involved tantalizing ideas like "the 4th dimension" and "curvature of space-time." Einstein himself proved to be a journalist's dream: handsome, gave quotable answers to questions, espoused causes like Zionism and peace, answered letters from schoolchildren, and seemed to have accompished the extraordinary feat of bringing the Germans and the British together, at least in science, after a bitterly-fought war confirmed his equation $E = mc^2$.) According to his biographer

Abraham Pais, "*The New York Times Index* contains no mention of him until November 9, 1919. From that day until his death, not one single year passed without his name appearing in that paper, often in relation to science, more often in relation to other issues." Einstein acquired a more sinister side after the atomic bomb confirmed his equation $E = mc^2$.

One factor that may have contributed to Einstein's fame is the large number of books and articles by scientists written to explain relativity to the public. According to historian Peter J. Bowler, in early 20th-century Britain a scientist like Eddington could write for the public without compromising his reputation among other scientists, as long as he continued to produce high-quality research. Many of those books were also published in the United States. The situation seems to have changed after World War II, at least in America, judging by the criticism and disrespect inflicted on scientists like George Gamow, Carl Sagan, and James Watson.

For whatever reasons, Einstein remained the most famous scientist in the world long after his death and was named "person of the century" by *Time* magazine in 1999.

Eddington's "confirmation" of the light-bending prediction was controversial among astronomers; he seemed to have cherry-picked the data that supported the theory, of which he was known to be an enthusiastic advocate. Replication by more objective observers, preferable ones who had no strong opinions about the validity of the theory, was needed. This was supplied by Robert Trumpler of Lick Observatory in California, who traveled to Australia to observe an eclipse in 1922. The results, analyzed by Trumpler and W. W. Campbell, announced on April 12, 1923, again confirmed Einstein's 1.74-second prediction.

Einstein had also predicted, in 1907, that the wave length of light coming from atoms in a strong gravitational field (for example, at the surface of the Sun) would be greater than light from the same atoms in a terrestrial laboratory. This is now known as the "gravitational redshift." In 1907 Einstein thought the solar redshift would be too small to measure, but in a later paper (1911) he was somewhat more optimistic.

Attempts to measure the solar redshift gave conflicting results, but C. E. St. John at the Mt. Wilson Observatory in California concluded that Einstein's prediction was correct. Then in 1925 W. S. Adams, also at Mt. Wilson, announced that he had observed the gravitational redshift of the star Sirius B, which according to Eddington's theory of stellar structure has a very high density. These results, along with the explanation of the variation of Mercury's perihelion (place where it is closest to the sun) and the second confirmation of the light-bending prediction, led most astronomers to accept the General Theory of Relativity by 1930.

As many of you know, the story does not end there; new tests of general relativity, and criticisms of the old tests, continue to be reported. As a historian I have to limit myself to a finite number of years, and as an audience you can listen for only a finite number of minutes.

To summarize: 15 years after Einstein proposed his General Theory of Relativity, the experts were satisfied that it had passed 3 empirical tests: light bending, advance of Mercury's perihelion, and gravitational redshift. Two of these tests were predictions in advance; the third, Mercury's perihelion motion, was an explanation of a previously-known but mysterious fact.

2. What does "Prediction" mean?

While reading the relativity literature of the 1920s, 1930s and 1940s, I suddenly realized something that I must have already known subconsciously but never thought about: *physicists use the word "predict" in a special sense*, different from ordinary language. They mean simply "require" or "imply" or "entail." For example, I often encountered the phrase:

> "The 3 predictions of General Relativity: light bending, advance of the perihelion of Mercury, and gravitational redshift"

But the second one had been well known to astronomers for nearly a century, so how could it be called a "prediction"?

Well, that's just the way physicists talk and write. "Theory T predicts fact X" simply means "X can be deduced from T" (whether or not X is already known). To communicate with non-physicists one should probably use a word like "test."

But suppose you *do* want to make the distinction. If X is *not* yet known, then you would say "T predicts X *in advance*"; if it is known, you might say "T retrodicts X."

3. Can Explanation be better than Prediction?

Beware “The Fallacy of Affirming the Consequent”

The first confirmation of Einstein’s light-bending prediction in 1919 caused a sensation. Einstein quickly became the most famous scientist in the world. People who had no knowledge of his theory and made no effort to understand it proclaimed themselves supporters of “relativity.” Other physicists and astronomers who previously rejected or ignored relativity were now forced to take it seriously. But some of them argued that light bending could be explained by other causes such as refraction in a (hypothetical) extended atmosphere of the Sun, without having to give up accepted theories of the nature of space, gravity, and light.

Logically the critics were right. If “Theory T_1 entails (predicts) fact X,” and X is observed to be true, one cannot correctly conclude that T must be true. Such a conclusion would be an example of what philosophers call “the fallacy of affirming the consequent.” It is possible that some other theory T_2 or T_3 also entails X.

The fallacy also applies to explanation, but is not so seductive.

In science, a critic who proposes an alternative theory must defend it against objections. Thus an extended solar atmosphere dense enough to account for the bending of light would also cause comets to slow down as they pass the Sun, but they don't. It took a few years for supporters of relativity to shoot down the proposed alternative explanations of light bending, but by 1930 the game was over.

As for the Mercury perihelion advance: astronomers had already had several decades to explain it and failed. For example, changing the exponent in the law of gravity (e.g. from 2 to 2.01) might account for Mercury's motion, but only at the exorbitant cost of sacrificing the excellent agreement of other planetary motions with Newton's theory. So, once Einstein had published his explanation, it was quickly accepted by most astronomers and physicists. (The Mercury effect was also considered by the experts to be stronger evidence than light bending because it involved a "deeper" part of the theory; light bending could easily be explained, and had already been explained a century earlier, by the Newtonian particle theory of light, except for a factor of 2).

4. Special Theory of Relativity: Explaining "Nothing"

I discussed General Relativity first because it illustrates the so-called "Scientific Method": make a hypothesis, then deduce predictions that can be tested. In fact it was the confirmation of Einstein's prediction of light bending by Eddington's 1919 eclipse observation that inspired the philosopher Karl Popper to propose "falsifiability" as a criterion for being scientific. Popper was impressed by the contrast between relativity and theories like psychoanalysis, Marxism, and Darwinism – which could explain any given facts but could never be disproved. It was clear to him that if the eclipse test had failed to confirm Einstein's theory, the theory would have been discarded by scientists.

But now we must go back in time to 1905, invoking the fantasy of Flammarion's *Lumen* (1873) who could observe past events by going faster than light, or the limerick of Arthur Buller:

> "There was a young lady named Bright
> Whose speed was far faster than light
> She set out one day
> In a relative way
> And returned home the previous night."
>
> (*Punch*, 10 December 1923)

What were the confirmed predictions (in advance) that led scientists to accept the Special Theory of relativity?

According to Richard Staley , who has thoroughly studied all the relevant historical evidence,

> "Einstein's special theory came to be widely accepted by 1911 without *any* experiment being regarded as offering uncontroversial and definitive proof of his approach." (*Einstein's Generation*)

The most persuasive experimental evidence for special relativity before 1911 was the null result of the Michelson-Morley experiment of 1887. This and earlier experiments showed that one cannot determine the absolute motion of the Earth, i.e. one cannot measure its motion relative to a hypothetical light-transmitting ether. Einstein himself did not cite any experimental evidence in his 1905 paper, and Gerald Holton has shown that (contrary to what used to be said) he did not develop his theory *in order to* explain Michelson-Morley. Einstein did, however, give this as the only empirical support for his theory in a review article published in 1907.

A theory that only explains why a certain experiment gives the result zero is not much use in science. What else can it do?

The first experiment to provide positive support for special relativity was done by Alfred Heinrich Bucherer at Bonn University in Germany. His measurements of the mass of electrons at high speeds were the first to provide definitive support for Einstein's formula, at a time when experiments by Walter Kaufmann gave results closer to those derived from Max Abraham's rival theory. Because of the disagreements between these and other experiments, and the difficulty of doing the measurements accurately to distinguish between the predictions of the two theories, the issue was not settled until 1914 when Kaufmann himself conceded that Einstein's theory had been confirmed.

It may seem strange that a radical new theory like relativity could have been accepted by physicists entirely on the basis of its explanation of negative results. The deciding factor was that theoretical physicists were impressed by the generality, universality, and mathematical elegance of the theory, especially as formulated in terms of four-dimensional geometry by Hermann Minkowski. Here we have another factor influencing the acceptance of a theory: it is so beautiful that it must be true!

5. The Old Quantum Theory:
Many things are predicted, but few are explained

Eugene Wigner, in a famous paper published in 1960, pointed out "The Unreasonable Effectiveness of Mathematics in the Physical Sciences." One may formulate an equation to describe a familiar situation, and suddenly find that an unfamiliar (and perhaps undesirable) physical situation appears when one solves the equation.

That's what happened to Max Planck in 1900: he derived an equation for the "black body radiation" and found that the equation, when mated with Ludwig Boltzmann's formula for entropy, implied that radiation is composed of *particles*. Planck, as a staunch supporter of the *wave* theory of electromagnetic radiation, could not believe what the mathematics was trying to tell him. As historian Thomas Kuhn pointed out in 1978, Planck did not propose a *physical* quantum theory, he used quantization only as a convenient method of approximation.

As Planck clearly stated in his Nobel Lecture, it was Albert Einstein in 1905 who first took seriously the quantum as a physical hypothesis. But he did this in the spirit of Hans Vaihinger's "philosophy of as if": light sometimes behaves *as if* it is a stream of particles; in other situations *as if* it is composed of waves.

In his 1905 paper on light, which I consider the beginning of quantum theory, Einstein discussed many phenomena. But the paper is most famous for the quantum theory of the *photoelectric effect*. The equation derived from this theory was experimentally confirmed by Robert A. Millikan at the University of Chicago. But, like Planck, Millikan refused to accept the idea that light or electromagnetic radiation in general can have a particle (atomistic) nature, in addition to its well-established wave nature.

At least Millikan and Planck avoided the "fallacy of affirming the consequent" by leaving open the possibility that some other theory might also lead to the same successful prediction.

For some physicists, the definitive proof of the quantum nature of radiation was the Compton effect. This effect was predicted theoretically and confirmed experimentally by Arthur Holly Compton at Washington University (St. Louis, Missouri). Compton assumed that X-rays act like particles when they collide with electrons. The result of the collision can then be described simply by using the laws of conservation of momentum and energy. At the same time the X-rays can be treated as waves, and the change in their wavelength is a simple function of the angle between incident and scattered rays.

Compton's own experiment confirmed this hypothesis in

1923. Moreover, his theory led to the prediction that a recoil electron should also emerge with appropriate momentum and energy. This was observed two months later by C. T. R. Wilson at Cambridge University.

Compton is one of the few physicists who has explicitly stated in public that one shoud get more credit for a confirmed prediction *in advance* than for a retrodiction or explanation of a known fact. In particular he argued that he himself should get more credit for his discovery of the Compton effect, including the recoil electron, than Einstein deserved for his confirmed theory of the photoelectric effect. He wrote:

> "Since the idea of light quanta was invented primarily to explain the photoelectric effect, the fact that it does so very well is no great evidence in its favor ..."

The quantum theory (and of course Compton himself) should get more credence for predicting a phenomenon "for which it had not been especially designed."

Compton's claim for extra credit has not been endorsed by either physicists or historians, perhaps because Einstein did not "invent the quantum to explain the photoelectric effect" and did predict an equation for that effect that was not previously known.

I will briefly mention three other predictions of the old quantum theory just to illustrate that Theory was indeed ahead of Experiment in the 1910s:

(A) Einstein’s prediction (1907) that specific heats of solids go to zero as T goes to zero. (Confirmed by Walther Nernst in 1911)

(B) Niels Bohr predicted from his atomic model (1913) that electrons with energy E passing through a gas at low pressure produce no radiation until E is greater than a critical value (derived from his theory). Then, radiation is produced corresponding to the energy difference between the ground state and an excited state. (Confirmed by James Franck and Gustav Hertz, 1914)

(C) Arnold Sommerfeld (1915-1916) generalized the Bohr model to include elliptical orbits, and predicted a relativistic correction because electrons in those orbits would sometimes have higher speeds than those in circular orbits. The corresponding change in the spectrum was confirmed by Friedrich Paschen (1916)

Sommerfeld’s prediction turned out to be an excellent example of the fallacy of affirming the consequent. From 1916 to 1925 it was considered important evidence for both special relativity and the Bohr model. But when quantum mechanics was introduced by Heisenberg and Schrödinger, along with the electron spin hypothesis of Uhlenbeck and Goudsmit, it was found that Sommerfeld’s formula could be derived from the new theory without using relativity (at least not directly). Since the Bohr model was now known to be wrong (though very fruitful), the confirmation of the original Sommerfeld prediction was no longer considered evidence for relativity.

6. Quantum Mechanics: Many Things are Explained, Predictions are Confirmed too Late

By 1925 the old quantum theory was a disgraceful mess: a collection of ad hoc hypotheses, each one able to predict one kind of phenomenon, but inconsistent with the others.

Thus, having started with the simple postulate that energy comes in *integer* multiples of a quantum [$nh\nu$], physicists were forced to postulate half-quanta [$(n + \frac{1}{2})(h\nu)$] for the anomalous Zeeman effect.

Worse, the Bohr model, which seemed to work so well for one-electron atoms, broke down completely as soon as one more electron was added, so that one could not even calculate accurately the ionization potential of helium.

Experiment, stimulated by the quantum hypothesis, was now ahead of theory.

In some alternative universe, Louis de Broglie's (1923, 1925) hypothesis about the wave nature of electrons might have provided a confirmed prediction inspiring the development of a new wave mechanics for subatomic particles. In our own universe the experiments of C. J. Davisson and his colleagues were both too early and too late. His early experiments with C. H. Kunsman (1921) antedated the publication of de Broglie's hypothesis and thus deprived de Broglie of the full glory of making a prediction in advance. E. G. Dymond did attempt to test de Broglie's hypothesis in 1926 but his experiment was faulty and his "confirmation" was withdrawn. By the time Davisson had learned about wave mechanics and, with L. H. Germer, redesigned his diffraction experiment to make a more accurate test (1927), the game was over: quantum mechanics had already been accepted by the experts in atomic physics. The Davisson-Germer experiment did, however, play an important role in persuading other physicists to accept the new theory. Yet, as Schrödinger himself pointed out, the experiment was *not* a confirmation of his own theory but of de Broglie's.

How could a radical new theory, first published in Werner Heisenberg in July 1925 and (in a different but essentially equivalent form) by Erwin Schrödinger in 1926, be accepted by 1927?

First, Niels Bohr gave it his public blessing in December 1925. Max Born, Pascual Jordan, Paul Dirac, and Wolfgang Pauli immediately started working on Heisenberg's theory. Arnold Sommerfeld became a strong and influential advocate for wave mechanics, using his seminar to educate several stars of the next generation including Hans Bethe, Walter Heitler, Fritz London, and Linus Pauling.

There was a veritable “gold rush” to extract as many results as possible from this fertile theory. The best indicator of the immediate impact of quantum mechanics on research is given in a paper by historians A. Kozhevnikov and C. Novick (1989). They cite 203 papers on quantum mechanics (mostly reporting original research) submitted for publication from July 1925 through February 1927. There were 80 authors from 14 countries. The most popular topics were the interpretation of molecular spectra, scattering problems, and dielectric constants of polar gases.

Quantum mechanics quickly explained most of the puzzles that could not be solved by the old quantum theory, such as the mysterious half quantum numbers. The helium atom, the crucial gateway to more complicated atoms, was finally conquered by a Norwegian physicist, Egil Hylleraas (in 1928-29). This success was the most frequently mentioned reason for accepting quantum mechanics in monographs and review articles published in the period 1929-1932. In 1927 Walter Heitler (German-Swiss) and Fritz London (German) applied Quantum Mechanics to the hydrogen molecule, showing how a bond could form between two hydrogen atoms, with a minimum energy at a distance close to the observed value This would be a good start on understanding molecular in general (“quantum chemistry”)

Two predictions-in-advance should be mentioned, even though they did not influence the acceptance of the theory:

Ortho and para hydrogen: diatomic molecules like H_2 can have two forms because the spins of their two nuclei can be aligned parallel or antiparallel. This was one of the achievements for which Heisenberg received the Nobel Prize (the other was matrix mechanics) though his part in the discovery was indirect and he did not even mention it in his Nobel Lecture.

Stark effect intensities (effect of electric fields on spectral lines). Laura Chalk, a graduate student working with J. Stuart Foster at McGill University, measured the intensities of the Stark components in the spectrum of hydrogen, especially those for which the values predicted by Schrödinger's equation disagreed with Stark's experimental values. Aside from a very brief announcement in 1926, Foster and Chalk did not publish their final results– confirming quantum mechanics -- until 1929.

The Foster-Chalk experiment was certainly one of the first tests of a prediction of quantum mechanics (if not *the* first). Has anyone ever heard of it? Chalk seems to be completely unknown to most historians of physics and to physicists interested in publicizing the achievements of women.

The fact that quantum mechanics was accepted by experts in atomic physics before any of its predictions-in-advance had been confirmed was noted by the American physicist Karl K. Darrow in October 1927. It “has captivated the world of physics in a few brief months,” not because of its successful predictions or its superior agreement with experience but “because it seems natural or sensible or reasonable or elegant or beautiful.” Like relativity, it was so beautiful it had to be true. In the same year I. I. Rabi, an Austrian-born American physicist received his Ph. D. from Columbia University; decades later, looking back on those days, he said in a lecture,

> “During the first period of its existence, quantum mechanics didn’t predict anything that wasn’t already predicted before ... The results that came out of quantum mechanics had to a large degree been previously anticipated.”

Based on this statement, in the June 2007 issue of *Physics Today* I challenged readers to “find evidence that the confirmation of *any* prediction in advance, other than electron diffraction, led *any* physicist to accept quantum mechanics before 1928.” So far no one has done so.

The lack of any confirmed predictions-in-advance did not prevent physicists from recognizing the tremendous value of quantum mechanics – with one exception. Have you ever wondered why it took more than 5 years for Heisenberg and Schrödinger to get the Nobel Prize? C. W. Oseen, the chair of the committee in the Swedish Academy that screened nominations for the physics prize, was primarily responsible for the delay. Before 1932, despite nominations and private communications from leading physicists, Oseen argued that quantum mechanics did not deserve the prize since it had not made any successful predictions-in-advance and therefore did not represent new knowledge. (Ironically, this was the same person who was responsible for the award of the Nobel Prize to Einstein for his equation of the photoelectric effect, since the rest of the committee refused to honor relativity.)

Oseen finally changed his mind in 1932 because of Carl D. Anderson's discovery of the positron, predicted by Paul Dirac from his relativistic version of quantum mechanics. Heisenberg received the Prize in 1932, while Dirac and Schrödinger shared the 1933 Prize (Anderson had to wait until 1936).

7. Millikan’s Walk

We may consider the quantum-relativity revolution as a single historical event composed of four parts, taking place during a limited time period (1905-1930) and involving many of the same scientists. Taking time as one variable and the two-valued parameter (Q, R) as the other, we see a rough anti-symmetrical structure: P, E for Q and E, P for R.

Quantum	P	→	→	→	→	* E	→	*
Relativity	E	→	→ *	P →	→ →	→	→	*
	1905		1910	1915	1920	1925		1930

Here “P” means a theory was proposed that made several predictions-in-advance but gave few or no explanations; “E” means a theory that offered several explanations but few predictions-in-advance. “*” indicates the approximate date when the theory was accepted by experts.

Notice that E→ * is generally faster than P → *; this is because by the time the new theory is introduced, alternative theories have already failed. P is slower because the opponents try to explain the predicted new facts by their own theories, and the new theory is accepted only after the alternatives have been refuted.

The results of this study suggest four generalizations that may be applicable to other cases in the history of science:

(1) Within a single subfield there is an alternation between periods when theory is ahead, with theories being evaluated mostly by the success of their predictions, and periods when experiments are ahead, and theories are evaluated mostly by their ability to explain ("retrodict") previously-known facts.

(2) Evaluation by prediction-testing generally takes longer to produce a consensus than evaluation by explanation.

(3) In either case, a theory that is considered beautiful and gives a unified account of several types of phenomena is more likely to be accepted.

(4) Any statement that "scientists follow a single method based on based on proposing hypotheses and testing predictions-in-advance" is refuted by the most important revolution of 20th-century physics.

Notes

The biography by Abraham Pais, *'Subtle is the Lord...': The Science and the Life of Albert Einstein* (Oxford: Oxford University Press, 1982), is an excellent introduction to this subject for readers not put off by equations. Helge Kragh, *Quantum Generations, A History of Physics in the Twentieth Century* (Princeton, NJ:Princeton University Press) places the Quantum-Relativity Revolution in a broader context.

The best source for scholarly research is the wonderful scholarly edition of Einstein's published and unpublished works: *The Collected Papers of Albert Einstein*, edited by John Stachel *et al.* (Princeton, NJ: Princeton University Press, 1987-). Volumes 1-12 cover writings and correspondence through 1921. Volume 11 is a cumulative index, bibliography, list of correspondence, chronology, and errata to the first 10 volumes. English translations of selected items are published in separate volumes (which do not include the editorial notes and commentaries). Cited here as *CPAE*.

A convenient collection of scholarly studies is *Science and Society: The History of Modern Physical Science in the Twentieth Century*, ed. Peter Galison et al. (New York: Routledge, 2001): vol. 1 on Special Relativity, vol. 2 on General Relativity, vol. 4 on Quantum theory.

Physicists and historians interested in teaching a course on the Quantum/Relativity Revolution may get some useful ideas from the article by Gerd Kortemayer and Catherine Westfall, "History of Physics: Outing the hidden Curriculum?" *American Journal of Physics*, 77 (2009): 875-881

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Hentschel, Klaus. “Einstein’s Attitude towards Experiments: Testing Relativity Theory 1907-1921,” *Studies in History and Philosophy of Science* 23 (1992): 593-624. Questions the accuracy of the story that when Ilse Rosenthal-Schneider asked Einstein how he would have responded if the result of the Eddington eclipse observation failed to confirm his theory, he said “I would have had to pity our dear God. The theory is correct all the same.”

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2. What does "Prediction" Mean?

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Kragh, H., *Quantum Generations* (cited above) mentions "three predictions" of general relativity, including Mercury perihelion motion (p. 95)

Margenau, Henry, *The Nature of Physical Reality* (New York: McGraw-Hill, 1950), p. 105. For further discussion see note 41 of my paper, "Prediction and Theory Evaluation ..." (1989)

Russell, H. N. "The practical significance of Relativity," in Bird, *Einstein's Theories* (cited above), pp. 306-317. States that Einstein's theory "*predicts* the correct direction and amount of the motion of Mercury's perihelion" (p. 316.

3. Can Explanation be better than Prediction?

There is one small exception to the statement that Einstein's explanation of the Mercury perihelion shift was "quickly accepted": In 1918, Ernst Gehrcke, one of the strongest opponents of relativity, argued that Paul Gerber in 1898 had explained it by postulating a specific relation between gravitation and the velocity of light. Einstein had to publish a note pointing out that the Gerber-Gehrcke idea was based on contradictory assumptions. See Helge Kragh, "Fine structure," cited below, on p. 112; CPAE, vol. 7, pp 103-104, 346-347, 349.

Aristotle on Fallacies or *The Sophistici Elenchi* with translation and commentary by Edward Post (1886) is the source for the "fallacy of affirming the consequence" (though Aristotle does not use that phrase, which may have been first introduced by J. N. Keynes in 1884). It arises because people suppose that the relation of consequence is convertible. For whenever, suppose A is, B necessarily is, they then suppose that if B is, A necessarily is. See C. L. Hamblin, *Fallacies* (London: Methuen, 1970), pp. 35-36.

Cordero, Alberto, "Contemporary Science and Worldview-Making," *Science.& Education*, 18 (2009): 747-764. Explains why philosophers give more credit for predictions-in-advance than for explanations.

Kragh, Helge, "The fine structure of hydrogen and the gross structure of the physics community, 1916-26," *Historical Studies in the Physical Sciences* 15, part 2 (1985): 67-125.

Lipton, Peter, "Testing Hypotheses: Prediction and Prejudice," *Science* 308 (2005): 219-221. Brush, Letter to Editor, *ibid.*, 1410 and Lipton's Response, *ibid.* 1411-1412.

Losee, John, *Theories on the Scrap Heap: Scientists and Philosophers on the Falsification, Rejection, and Replacement of Theories* (Pittsburgh: University of Pittsburgh Press, 2005)

4. Special Relativity

Barrett, J., "Oracles, aesthetics, ad Bayesian consensus," *Philosophy of Science Supplement*, 63 (1996): S273-S280. Argues that, for philosophers committed to Bayesian reasoning, the opinion of experts such as Bohr or Einstein may count as "evidence" in favor of a theory. In particular, Einstein's "appeal to the mathematical simplicity of a theory as a reliable indication of its truth ... *supported by historical evidence concerning past success and failure in the practice of science*" is a legitimate argument; on this basis "scientists might reach a consensus without basic empirical evidence, take the consensus to be objective, yet nonetheless prefer basic empirical evidence if they can get it." (Pp S276, S279) This seems to be what happened in the case of special relativity. The *positive* empirical evidence (such as variation of electron mass with speed) came *after* the experts had accepted the theory.

Brush, Stephen G. "Why Was Relativity Accepted?," *Physics in Perspective* 1 (1999): 184-214.

Einstein, "Über die vom Relativitäsprinzip geforderte Trägheit der Energie," *Annalen der Physik* 23 (2907): 371-384, in CPAE, vol. 2, doc. 45; see English translation, vol. 2, p. 247-248.

Elzinga, Aant, *Einstein's Nobel Prize: A Glimpse behind Closed Doors; The Archival Evidence* (Sagamore Beach, MA: Science History Publications USA, 2006). Why Einstein did not get the prize for relativity.

Flammarion, C. *Lumen* (Paris, 1873). Imagined what would happen if you could travel faster than light. See also Einstein, "Über die vom Relativitäsprinzip ...", cited above.

Holton, Gerald, "Einstein, Michelson, and the Crucial Experiment." *Isis* 60 (1969): 133-197; *Thematic Origins of Scientific Thought: Kepler to Einstein* (Cambridge, MA: Harvard University Press, rev. ed. 1988), Chapter 8.

Kragh, *Quantum Generations* (cited above). "Thanks to the works by Planck, Minkowski, Ehrenfest, Laue, and others, by 1910 Einstein's theory of relativity had gained firm support and was probably accepted by a majority of elite theoretical physicists" (p. 93).

Miller, Arthur I., *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretations (1905-1911)* (Reading, MA: Addison-Wesley, 1981).

Sitter, W. de, "Space, Time and Gravitation. An Outline of Einstein's Theory of General Relativity," in Bird (ed.), *Einstein's Theory* (cited above), pp. 206-217: "The great strength and the charm of Einstein's theory do however not lie in verified predictions, nor in the explanation of small outstanding discrepanc ies, but in the complete attainment of its original aim: the identification of gravitation and inertia, and in the wide range of formerly apparently unconnected subjects which it embraces, and the broad view of nature which it affords (p. 216).

Staley, Richard. *Einstein's Generation: The Origins of the Relativity Revolution*. Chicago: University of Chicago Press (2008)

Walter, Scott, "The non-Euclidean style of Minkowskian relativity," in *The Symbolic Universe: Geometry and Physics 1890-1930*, ed. By Jeremy Gray (Oxford University Press, 1999), pp. 91-127.

Walter, Scott, "Minkowski, Mathematicians and the Mathematical Theory of Relativity," in *The Expanding Worlds of General Relativity*, ed. H,. Goenner et al. (Boston: Birkhäuser, 1999)

Warwick, Andrew, "Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell and Einstein's Relativity 1905-1911, Part I, The Uses of Theory," *Studies in History and Philosophy of Science* 23 (1992): 625-656. " ... Part II, Comparing Traditions in Cambridge Physics," *ibid.* 24 (1992): 1-25. See also his book *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Chicago: University of Chicago Press, 2003)

5. The Old Quantum Theory

Bohr, Niels, "The Structure of the Atom. Nobel Lecture, December 11, 1922" In *Nobel Lectures, Physics 1922-1941*, pp. 7-43 (Singapore: World Scientific, 1908). "The predictions of Einstein's theory [of light quanta] have received such exact experimental confirmation in recent years, that perhaps the most exact determination of Planck's constant is afforded by measurements on the photoelectric effect. "In spite of its heuristic value, however, the hypothesis of light-quanta, which is quite irreconcilable with so-called interference phenomena, is not able to throw light on the nature of radiation." (p. 14)

Brush, "How Ideas Became Knowledge: The Light-Quantum Hypothesis," *Historical Studies in the Physical and Biological Sciences*, 37 (2007): 205-246.

Einstein, Albert, *CPAE* vol. 2, pp. 385-386 and editorial note 27, pp. 390-391, cites papers of Nernst on specific heats.

Kragh, Helge. "The fine structure of hydrogen and the gross structure of the physics community, 1916-26," *Historical Studies in the Physical Sciences*, 15, part 2 (1985): 67-125. On Sommerfeld's application of relativity theory to the Bohr model.

Kuhn, Thomas S. *Black-Body Theory and the Quantum Discontinuity, 1894-1912*. (Oxford: Clarendon Press, 1978).

Mehra, Jagdish, and Rechenberg, Helmut, *The Historical Development of Quantum Theory*. Volume 1, Part 1, *The Quantum Theory of Planck, Einstein, Bohr and Sommerfeld: Its Foundation and the Rise of its Difficulties 1900-1925* (New York: Springer-Verlag, 1982). A very comprehensive account with many references to original sources. They quote (on p. 51) Planck's statement in his 1900 paper, "If the quotient [E/ϵ] thus calculated does not happen to be an integral number, then one has to take for *P* [number of energy elements] an integer close to it" yet ignore the argument of Thomas Kuhn (cited above) that in this paper Planck was not proposing a *physical* quantization but used quantization only for mathematical convenience.

Millikan, Robert A. "The Electron and the Light-Quant from the experimental Point of View" (Nobel Lectures, May 23, 1924). In *Nobel Lectures including Presentation Speeches and Laureates' Biographies, Physics 1922-1941* (Singapore: World Scientific, 1998), pp. 54-66.

Pais, *'Subtle is the Lord'* (cited above) Chapter 20 on specific heats.

Pais, Abraham, *N iels Bohr's Times* (Oxford: Clarendon Press, 1991), Chapter 10.

6. Quantum Mechanics

Brush, "Dynamics of Theory Change: The Role of Predictions," cited above.

Brush, Stephen G., *Statistical Physics and the Atomic Theory of Matter, from Boyle and Newton to Landau and Onsager* (Princeton, NJ: Princeton University Press, 1983, Chapters III-V.

[Chalk] Rowles, Laura, "Long Experience and a Happy Existence," in *Autobiographical Essays by Women associated with McGill University*, ed. by Margaret Gillett and Ann Beer (Montreal" McGill-Queen's University Press, 1995), pp. 33-46.

Friedman, Robert Marc *The Politics of Excellence: Behind the Nobel Prize in Science* (New York: Freeman, 2001), pp. 171-174, on Oseen's role in delaying the Nobel Prizes for Heisenberg and Schröndiger. The stance of strong opposition to quantum mechanics is partly contradicted by a letter from Oseen to Richard von Mises in 1930, urging that an account of wave mechanics should be included in the second edition of the Frank-von Mises book, *Die Differential- und Integralgleichungen der Mechanik und Physik* (1925). In response, Frank and von Mises asked Guido Beck to write an article on wave mechanics for their second edition. See Reinhard Siegmund-Schultze, "Philipp Frank, Richard von Mises, and the Frank-Mises," *Physics in Perspective*, 9 (2007): 26-57.

Hylleraas, Egil. A. "Reminiscences from early Quantum Mechanics of Two-Electron Atoms," *Reviews of Modern Physics* 35 (1963): 421-431. On the helium atom problem.

Kojevnikov, A. & Novik, C., "Analysis of Informational Ties Dynamics in early Quantum Mechanics (1925-1927), *Acta Historiae Rerum Naturalium necon Technicarum*, special issue 20 (1989): 115-159; also published in *Revolution in Sciences, Sciences in Revolution*, ed. J. Janko (Prague: Institute of Czechoslovak and General History CSAS, 1989), pp 115-159, Mehra, Jagdish, “Erwin Schrödinger and the Rise of Wave Mechanics. III. Early Response and Applications,” *Foundations of Physics*, 18 (1988): 107-184..

Van Dongen, Jeroen *et al*, eds, “On the History of the Quantum: The HQ2 Special Issue,” *Studies in History and Philosophy of Modern Physics*, 40, no. 4 (2009)

7. Conclusions

Philosophers of science tend to take an “either/or” approach: either science is based on testing predictions of previously unknown facts, or on explaining (“accommodating”). Science educators who wrote on the “Nature of Science” were predictivists until about 10 years ago when Norman Lederman and his colleagues recognized that scientists use a variety of methods. Yet there is still a tendency to assume that within any one field a single method is used; for Dodlick’s group, the question is to distinguish between the method followed by “experimental” sciences like chemistry and “historical” sciences like paleontology. What I have tried to show here (and what I believe most working scientists would believe) is that within a single field different methods may be used.

Brush, S. G. “Dynamics of Theory Change: The Role of Predictions,” in *PSA 1994: Proceedings of the 1994 Biennial Meeting of the Philosophy of Science Association,* ed. D. Hull *et al.,* vol. 2, pp. 133-145 (East Lansing, MI: Philosophy of Science Association, 1995.

Dodlick, Jeff; Argamon, Shlomo; Chase, Paul. “Understanding Scientific Methodology in the Historical and Experimental Sciences via Language Analysis,” *Science & Education* 18 (2009): 985-1004

Lederman, Norman G.; Abd-El-Khalick, Fouad; Bell, Randy L.; Schwartz, Renée S. “Views of Nature of Science Questionnaire: Toward valid and meaningful Assessment of Learners’ Conceptions of Nature of Science,” *Journal of Research in Science Teaching* 39 (2002): 773-792.

Since relativity says the speed of light in a vacuum is constant, space should look the same in every direction, no matter what. For instance, if you move at half the speed of light toward or away from a flashlight, you will see the beam always move at about 186,000 miles per second, no more or less.Â In the experiment, the team measured the kinetic energy of the electrons 10 times every second, for a day. If the theory of relativity is correct, then the difference between the electrons' energies should be a constant. [Images: The World's Most Beautiful Equations]. This may seem like a strange way to test a well-established theory, but HÃ¤ffner said experiments like this have been done with other particles. An odd space experiment has confirmed that, as quantum mechanics says, reality is what you choose it to be. Physicists have long known that a quantum of light, or photon, will behave like a particle or a wave depending on how they measure it. Now, by bouncing photons off satellites, a team has confirmed that an observer can make that decision even after a photon has made its way almost completely through the experimentâ€”seemingly well past the point at which it would become either a wave or a particle. Such delayed-choice experiments might someday probe the fuzzy frontier between quantum theory... Unlike relativity theory, the birth of quantum theory was slow and required many hands. It emerged in the course of the first quarter of the twentieth century with contributions from many physicists, including Einstein. Theories of Matter at the End of the Nineteenth Century.Â The most celebrated interference effect arises in the two slit experiment. Waves of light (depicted as parallel wavefronts moving up the screen) strike a barrier with two holes in it. Secondary waves radiate out from the two slits and interfere with each other, forming the characteristic cross hatching pattern of interference. These are the same patterns seen on the surface of a calm pond in the ripples cast off by two pebbles dropped in the water. Quantum mechanics, information theory, and relativity theory are the basic foundations of theoretical physics. The acquisition of information from a quantum system is the interface of classical and quantum physics. Essential tools for its description are Kraus matrices and positive operator valued measures (POVMs). Special relativity imposes severe restrictions on the transfer of infor-mation between distant systems. Quantum entropy is not a Lorentz covariant concept. Lorentz transformations of reduced density matrices for entangled systems may not be completely posi-tive maps. Quantum eld th...