EINSTEIN FOR THE 21ST CENTURY

HIS LEGACY IN SCIENCE, ART, AND MODERN CULTURE

Peter L. Galison, Gerald Holton, and Silvan S. Schweber, Editors

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EINSTEIN AS A STUDENT

Dudley Herschbach

Introduction

Late in life, when reflecting on his uncanny papers of 1905, Einstein liked to say, "Nobody expected me to lay golden eggs." A century later, nobody can expect to comprehend fully how he did it. Yet much is known about Einstein as a student, enabling us to trace his maverick path as a fledgling scientist. It was a rough path; even with his talent and dedication, help from others was crucial. If Einstein were reincarnated as a graduate student today, it seems unlikely that he would complete a Ph.D. His saga offers perspectives that should embolden current students and prod faculty to reform doctoral programs.

Einstein revered the memory of his great predecessors in physics. In his home at Princeton, he had a portrait of Newton above his bed and portraits of Faraday and Maxwell in his study.[1] At commemorations, Einstein felt homage to scientists was best rendered by striving to understand what they "were aiming at, how they thought and wrestled with their problems." This accords with a kindred credo of Gerald Holton[2] that I have long advocated to students. It thus seemed apt, when invited to take part in this conference, to focus on Einstein as a student.

My paper is addressed to three presumed audiences. First, to many earnest students who find the transition from neophyte to Ph.D. scientist a daunting journey. May you be heartened to see that it was rough even for Einstein, despite his immense talent and passion for science. Second, to earnest faculty concerned that typical Ph.D. programs have evolved into an ill-defined and often demoralizing grind, poorly suited to fostering the creativity of students. May you find that aspects of the Einstein story prove useful in pressing for reforms. Third, to anyone curious about the gestation of ideas that enabled Einstein to

bring forth in 1905 those epochal "golden eggs," along with his Ph.D. thesis. May you discern clues to approaches that can be emulated by lesser mortals.

Einstein's own commentaries and correspondence tell us much about his student years, and a host of outstanding historians of science and biographers have added many insightful books and essays. In this paper I merely sample morsels from this ample smorgasbord. Rather than construct a narrative essay, I invite readers to consult chronologies,[3] annotated in four stages: Einstein's schoolboy era, extending to age seventeen; his four years in a teacher

TABLE 15.1 Chronology, 1879–1896

Age	*Year*	
0	1879	March 14: AE born in Ulm, Germany. Ancestors for two centuries are Swabian Jews, but parents irreligious.
1	1880	Family moves to Munich. Father and uncle Jakob partners in manufacturing firm for plumbing and electrical apparatus.
5	1884	AE enchanted by a compass. Has private lessons at home (too young for admission to public primary school).
6	1885	AE starts violin lessons, continues to age 13. October: Enters Catholic primary school; also begins private Jewish religious instruction (required by law).
9	1888	October: AE enters first year of nine-year *Gymnasium* program.
10	1889	Uncle tells AE of Pythagorean Theorem; AE devises a proof. Max Talmud (later Talmey) begins regular visits, which continue for six years, and brings AE popular science books.
11	1890	AE's intense "religious paradise," lasting about a year. Reading science, including Darwin, disenchants AE with religion; he becomes a "fanatic freethinker."
12	1891	AE enthralled with "holy little geometry book" (from Talmud); finds Euclid's axiomatic-deductive method a trustworthy "road to paradise." Over next four years, learns analytic geometry and calculus outside school.
13	1892	AE disdains bar mitzvah. Captivated by Mozart sonatas ("love is a better teacher than duty"); reads Kant.
15	1894	Family moves to Milan. Intends AE to stay in Munich to complete *Gymnasium*, but in December, AE quits school, joins family in Italy.
16	1895	Summer: Sends uncle essay on the state of ether in magnetic fields. October: Fails entrance exam for ETH; enrolls in cantonal school in Aarau, boards with Winteler family. Ponders *Gedanken* ride on light wave.
17	1896	January: Renounces German citizenship. September: Passes exam for Aarau diploma. Essays on Goethe and on future plans.

training program at the Swiss Federal Polytechnic Institute in Zurich;[4] his first two years as a graduate student, desperate to find a steady job; and his first three years as a patent examiner in Bern, including his *annus mirabilis*. For each stage, I enliven the chronology with some observations and a few quotations, chiefly from Einstein or his contemporaries. After commenting on some aspects of his early papers, I offer my views about lessons that today's academic enterprise should take from the Einstein saga.

Schoolboy: Munich, Milan, and Aarau

A charming source for Einstein's childhood is an affectionate memoir by his younger sister Maja.[5] She describes worries of their parents that little Albert was retarded because he was unusually slow to talk. Einstein himself, decades later, said that one of his earliest memories was "the ambition to speak in whole sentences . . . so I would try each sentence out . . . saying it softly. Then, when it seemed alright . . . say it out loud." Up to at least age seven, the habit of softly and slowly rehearsing his words persisted. Maja reports that Albert avoided play with other children and had wild temper tantrums. At five, "he grabbed a chair and with it struck the woman tutor, who . . . ran away in fear and was never seen again." Another time, "he used a child's hoe to knock a hole in [Maja's] head." Fortunately, his "violent temper disappeared during his early school years." Today, a child with such unusual speech and antisocial behavior might have to contend with therapists and be put on drugs in order to attend preschool or kindergarten.

Maja describes also Albert's early traits of self-reliance, persistence and tenacity. He was fond of puzzles and "building many-storied houses of cards . . . as high as fourteen stories." In primary school, Albert was "self-assured and . . . confidently found the way to solve difficult word problems." He did well, both in primary and high school, but "the style of teaching [by rote learning] in most subjects was repugnant to him." Especially galling at the *Gymnasium* was the "military tone . . . the systematic training in the worship of authority."

Albert's intellectual growth was strongly fostered at home. His mother, a talented pianist, ensured the children's musical education. His father regularly read Schiller and Heine aloud to the family. Uncle Jakob challenged Albert with mathematical problems, which he solved with "a deep feeling of happiness." Most remarkable was Max Talmud, a poor Jewish medical student from Poland, "for whom the Jewish community had obtained free meals with the Einstein family." Talmud came on Thursday nights for about six years, and "invested his whole person in examining everything that engaged [Albert's] interest." Talmud had Albert read and discuss many books with him. These included a series of twenty popular science books that convinced Albert "a lot in

the Bible stories could not be true," and a textbook of plane geometry that launched Albert on avid self-study of mathematics, years ahead of the school curriculum. Talmud even had Albert read Kant; as a result Einstein began preaching to his schoolmates about Kant, with "forcefulness" [F: 25].

By law, a male German citizen could emigrate only before the age of seventeen without having to return for military service. This was impetus for Albert's decision, made without consulting his parents, to conspire with a doctor for a medical release from the Munich Gymnasium, join his family in Italy, and renounce German citizenship. For nine months, he enjoyed freedom from school. He also wrote an essay on his "naive and imperfect" analysis of the state of the ether in a magnetic field, and studied diligently on his own to prepare for the ETH entrance examinations. He was permitted to take the exams for the engineering department, although he was much younger than the prescribed entrance age of eighteen. He failed because he did poorly in modern languages and descriptive sciences, but he did very well in mathematics and physics. That led the ETH Director to urge Albert to enroll in the cantonal school in Aarau, a small town near Zurich, whose graduates were directly admitted to the ETH.

At Aarau, Albert had a happy year, both in the school and lodging in the home of Jost Winteler, one of the teachers. Long after, in contrasting Aarau with Munich, Einstein wrote:

> By its liberal spirit and by the simple seriousness of its teachers . . . this school . . . made me realize how much superior an education towards free action and personal responsibility is to one that relies on outward authority and ambition. True democracy is no empty illusion. [F: 38]

The Wintelers welcomed Albert into their large family. His congenial ties to them proved durable: Maja married a Winteler son, and Michele Besso, one of Einstein's best friends, married a Winteler daughter. In an essay for his graduation exam, written in "execrable French," Albert described with blithe confidence his ambitions:

> A happy person is too content with the present to think much about the future. On the other hand, young people in particular are fond of making bold plans. Besides, it is natural for a serious young man to form as precise an idea of the goal of his strivings as possible.
>
> If I am lucky enough to pass my examinations, I will attend the Polytechnic in Zurich. I will stay there four years to study mathematics and physics. My idea is to become a teacher in these fields of natural science and I will choose the theoretical part of these sciences.

These are the reasons that have led me to this plan. It is primarily a personal gift for abstract and mathematical thought and a lack of fantasy and practical talent. Moreover, my hopes lead me to the same resolution. This is quite natural; one always wishes to do the things one has the most talent for. Moreover, there is a certain independence in the profession of science that greatly appeals to me. [P: 40; C: D22]

College Years: 1896–1900 in Zurich

Perhaps with Jost Winteler as a model, Einstein entered ETH as a candidate for a specialist teacher diploma rather than as an engineering student. He enrolled in Department VI A, which dealt with mathematics, physics, and astronomy. It had only 23 students, 11 of them freshmen—a small fraction of the ETH student body of over 800 students, most of them in engineering fields. Each of the VI A students had an individual study plan, decided at the start of each semester in consultation with the department head. The program comprised a few core courses, which were graded, plus ungraded elective courses. At least one elective each semester had to be taken outside the student's department.

Einstein's transcript shows he followed, at least nominally, a standard program within VI A. About half those courses were mathematics, extending

TABLE 15.2 At Swiss Polytechnic Institute, 1896–1900

Age	*Year*	
17	1896	October: AE to Zurich; enrolls in ETH program for diploma to teach high school math and physics. Among ten other students in that program are Marcel Grossmann (math) and Mileva Marić (physics).
18	1897	Through music, meets Michele Besso (engineer), who urges AE to study Mach.
19	1898	January: AE dismayed by father's bankruptcy. October: AE passes midway oral exams, using Grossmann notes to cram. Gets highest score among math and physics candidates (5.7 out of 6).
20	1899	August: In a letter to Mileva (MM), AE first proposes to discard ether. October: AE applies for Swiss citizenship.
21	1900	Spring: AE and MM write diploma essays, both on heat conduction, for Prof. Weber (scores 4.5/6 and 4/6, respectively). July: AE graduates from ETH. On final diploma exams, of five candidates in math and physics, AE scores fourth (4.9/6); MM scores lowest (4/6) and fails. August: AE is the only one of the four passing diploma candidates not appointed as an assistant at ETH.

beyond theory of functions, projective and differential geometry, and partial differential equations, to number theory and elliptic functions. About a quarter of the VI A courses were laboratory work. Einstein took more than the required minimum of electives outside VI A, among them courses on Goethe's works and worldview, Kant's philosophy, prehistory of man, geology of mountains, politics and cultural history of Switzerland, banking and stock exchange, social consequences of free competition, statistics and personal insurance, and foundations of national economy. To graduate, VI A students had to pass two sets of oral exams on the core math and physics curriculum. One set was usually taken after the first two years, the other at the end of the fourth year. The final required also a written diploma thesis.

Einstein's view of his ETH years was bittersweet. Over fifty years later, he stressed that he lacked qualities expected of a "good" student, easy comprehension and docile focus on what was offered in lectures, but benefited from the freedom allowed by the Swiss system. Among his typical comments are these:

> [Gradually I learned] to arrange my studies to suit my intellectual stomach and my interests. Some lectures I would follow with intense interest. Otherwise I "played hooky" a lot and studied the masters of theoretical physics with a holy zeal at home. [F: 50]

> I really could have gotten a sound mathematical education. However, I worked most of the time in the physical laboratory, fascinated by the direct contact with observation. [E: 15]

> In all there were only two examinations; for the rest one could do what one wanted . . . a freedom, which I thoroughly enjoyed . . . up to a few months before the examinations. [E: 17]

In his self-study of theory, Einstein embraced works almost entirely missing from the VI A courses. He read books by Kirchhoff, Hertz, Helmholtz, Mach, Boltzmann, and Drude, learned Maxwell's electromagnetism from a recent text, and studied papers by Lorentz. In the electrotechnical lab, Einstein's performance matched his zeal; he then "still expected to approach the major questions of physics by observation and experiment" [P: 132]. However, he was not allowed to construct an apparatus that he designed to measure the earth's movement against the ether; "the skepticism of his teachers was too great." In coping with the exams, Einstein gratefully received crucial help from his classmate Marcel Grossmann, who had prepared superb notes on the core courses. Einstein deeply resented the exams:

> It is, in fact, nothing short of a miracle that the modern methods of instruction have not yet entirely strangled the holy curiosity of inquiry; for this delicate

> little plant, aside from stimulation, stands mainly in need of freedom. . . . It is a very grave mistake to think that the enjoyment of seeing and searching can be promoted by means of coercion and a sense of duty. . . . I believe that it would be possible to rob even a healthy beast of prey of its voraciousness, with the aid of a whip, to force the beast to devour continuously, even when not hungry. [E: 17]

Despite his devotion to study, Einstein enjoyed some special social outlets in Zurich. He was regularly invited for weekly lunch or dinner by families (as Max Talmud had been by his family); in a letter of thanks, he wrote that "I often came to you in a dejected or bitter mood and there invariably found joy and an inner equilibrium" [F: 52]. On Saturday nights and holidays he played his violin with chamber music groups.

Most special was his romance with Mileva Marić, his future wife. They studied together, and when apart exchanged many letters. In those from Einstein, usually both playful and ardent, he often reports what he is reading or research ideas he is hatching. His liaison with Mileva was opposed by his parents and puzzled friends, but that did not faze Einstein. Even when Mileva, having failed the diploma exam, was required to repeat it next year, Einstein presumed that she would also go on to get a doctorate. In letters to her during summer vacation in 1900, he wrote:

> Even my work seems to me pointless and unnecessary if I am not telling myself that you are happy with what I am and what I do. . . . I am also looking forward very much to our new studies. You must now continue with your investigation—how proud I will be when maybe I'll have a little Ph.D. for a sweetheart while I am myself still a totally ordinary man. [C: D75]

> So courage, little witch! I can hardly wait to be able to hug you and squeeze you and to live with you again. We'll happily get down to work right away, and money will be as plentiful as manure. [C: D71; F: 71]

Graduate Student: 1900–1902, "The Gypsy Years"

Einstein's antic hope for plentiful money was soon frustrated. During his four years at ETH, although his parents could not give him regular support, he had a monthly allowance from affluent relatives in Genoa, but that ended when he graduated. He expected to be appointed at ETH as a teaching assistant. Because Department VI A provided service courses for the large flux of engineering students, several assistants were needed. The few graduates in math or physics who wanted to be assistants usually were promptly appointed. In 1900, Einstein was the only exception. He felt insulted when Professor Heinrich

TABLE 15.3 Graduate Student, 1900–1905

Age	*Year*	
21	1900	October: AE starts on thermoelectricity as thesis project, in Weber's lab. December: AE submits first paper (on capillarity) to *Annalen der Physik.*
22	1901	February: AE becomes Swiss citizen, completing process begun October 1899. March: AE exempted from military service: "varicose veins, flat and sweaty feet." March–April: AE seeks assistant jobs in several countries, in vain. April: AE criticizes Planck's radiation theory in letter to MM. April 13: AE gets letter from Grossmann about possible job at patent office. May: AE and MM enjoy Lake Como; learn MM is pregnant. May 15–July 15: AE is a substitute teacher of math at Winterthur. AE excited about Lenard's observation of photoelectric effect. July: MM again fails diploma exam. September: AE becomes private tutor at Schaffhausen. November 23: AE submits proposed thesis on gas kinetics theory to Prof. Kleiner. December 11: Patent office job advertised; AE applies on December 18.
23	1902	January: Daughter Lieserl born; in response, AE wishes to give birth himself. February 1: AE withdraws thesis, moves to Bern, advertises private lessons. April: AE forms "Olympia Academy" with Maurice Solovine and Conrad Habicht. April 30: AE submits paper 2 (on electrochemistry) to *Annalen.* May: AE interviewed for patent office job. June 23: AE starts provisional job at patent office as "Expert III Class." June 26: AE submits paper 3 (on statistical thermodynamics). October: AE's father dies in Milan; he is shocked and desolate.
24	1903	January: AE and MM married, with Habicht and Solovine only witnesses. AE writes Besso that he'll not pursue Ph.D.: "comedy." AE submits paper 4 (on foundations of thermodynamics). September: Lieserl survives scarlet fever; likely given up for adoption. December: AE talks on electromagnetic waves at *Naturforschende Gesellschaft.*
25	1904	March 29: AE submits paper 5 (on fluctuations). May: son Hans Albert born. Summer: Besso takes job at patent office as "Expert II Class." September: AE made "definitive" in patent office; still "Expert III Class." Late October: Habicht leaves Bern for teaching post in Schaffhausen.
26	1905	March–November: AE publishes 21 reviews in *Beiblätter zu den Annalen.* March–June: AE completes papers 6, 7, 8, and 9. July 20: AE submits paper 7 as his Ph.D. thesis; accepted July 27. August–December: AE submits slightly revised paper 7, and papers 10 and 11. November: Solovine leaves Bern for University of Lyon.
	1906	January 15: All formalities completed, AE becomes a Ph.D.

Weber, who had supervised Einstein's *Diplomarbeit*, hired two mechanical engineers as assistants. He was also rebuffed by other ETH faculty.

Despite these disappointments, Einstein returned to the ETH for the fall term to pursue an experimental doctoral thesis under Weber. Shortly before, Einstein added this postscript in a letter to Mileva:

> For the investigation of the thermoelectric Thomson effect I have again resorted to another method, which has some similarities to yours for the determination of the dependence of heat conduction on temperature and which indeed presupposes such an investigation. If only we could already start tomorrow! With Weber we must try to get on good terms at all costs, because his laboratory is the best and the best equipped. [C: D74]

While preparing for her repeat try at the diploma exam, Mileva also intended to carry on experiments toward a doctoral thesis. Ever optimistic, Einstein expected her experiments would aid his project and he would complete his thesis by Easter of 1901 [C: D85].

The ETH did not grant doctoral degrees (until 1911), but ETH graduates could obtain a doctorate from the University of Zurich without further ado by merely submitting a dissertation. This policy naturally encouraged graduate students to work on projects proposed or endorsed by their faculty advisor, often related to their *Diplomarbeit*. The plans of Einstein and Mileva conformed to this pattern. By spring, however, both had abandoned Weber's lab, and Einstein was convinced that a "poor reference" from Weber would foreclose prospects elsewhere [C: D94].

Meanwhile, Einstein had submitted in December his first scientific paper, a theoretical analysis of capillarity as a means of characterizing attractive intermolecular forces in liquids. This most likely was stimulated by a lecture by Hermann Minkowski that Einstein had attended at ETH in the spring before his graduation. Minkowski had then just published an encyclopedia article on the subject and gave out reprints to his audience. Ruefully, Einstein remarked to another student, "This is the first lecture on mathematical physics we have heard at the Poly" [F: 58]. He apparently undertook this work entirely on his own initiative. He was proud and excited at contributing results that he took to be "entirely new despite their simplicity and might yield a law of nature" [C: D79]. He had high hopes that this first paper, published in *Annalen der Physik* in early March of 1901, would help him get a job. Within a few weeks, he had also decided to make intermolecular forces the subject of his doctoral thesis [C: D100].

Einstein sent out during March and April more than a dozen letters or postcards (with postpaid return) pursuing job possibilities, all in vain. This went to Wilhelm Ostwald:

Esteemed Herr Professor! Because your book on general chemistry inspired me to write the enclosed article, I am taking the liberty of sending you a copy of it. On this occasion permit me also to inquire whether you might have use for a mathematical physicist familiar with absolute measurements . . . because I am without means, and only a position of this kind would offer me the possibility of additional education. Respectfully yours, Albert Einstein [gives Milan address of parents]. [C: D92]

Three weeks later, Einstein followed up with:

Esteemed Herr Professor! A few weeks ago I took the liberty of sending you from Zurich a short paper which I published in Wiedemann's *Annalen*. Because your judgment of it matters very much to me, and I am not sure whether I included my address in the letter, I am taking the liberty of sending you my address hereby. Respectfully . . . [C: D95]

Unknown to Einstein, on April 13, 1901, his father Hermann also wrote Ostwald:

Esteemed Herr Professor! Please forgive a father who is so bold as to turn to you in the interest of his son. I shall start by telling you that my son Albert is 22 years old, that he studied at the Zurich Polytechnikum for 4 years, and that he passed his diploma examinations in math and phys with flying colors last summer. Since then, he has been trying unsuccessfully to obtain a position as an Assistant, which would enable him to continue his education in theoretical & experimental physics. All those in position to give a judgment in the matter, praise his talents; in any case, I can assure you that he is extraordinarily studious and diligent and clings with great love to his science.

My son therefore feels profoundly unhappy with his present lack of position, and his idea that he has gone off the tracks with his career & is now out of touch gets more and more entrenched each day. In addition, he is oppressed by the thought that he is a burden on us, people of modest means.

Since it is you . . . whom my son seems to admire and esteem more than any other scholar currently active in physics . . . I make the humble request to read his paper . . . and to write him, if possible, a few words of encouragement, so that he might recover his joy in living and working. [C: 99]

Ostwald did not respond. Only nine years later, Ostwald made amends: right after he received the Nobel Prize, he became the first to nominate Einstein for it [P: 45].

On the same day as his father's letter, Einstein received a hopeful message from Marcel Grossmann: his father, a friend of the director of the Swiss patent

office in Bern, had recommended that Einstein be considered for the next vacancy. Einstein responded gratefully:

> Dear Marcel! When I found your letter yesterday, I was deeply moved by your devotion and compassion which did not let you forget your old luckless friend. . . . I would be delighted to get such a nice sphere of activity and I would spare no effort to live up to your recommendation. I came here to my parents three weeks ago in order to search from here for an assistant's position at a university. I could have found one long ago had Weber had not played a dishonest game with me. All the same, I leave no stone unturned and do not give up my sense of humor. . . . God created the donkey and gave him a thick hide. . . .
>
> As for science, I have conceived a few marvelous ideas, which only have to be properly hatched. I now firmly believe that my theory of attractive forces between atoms can be extended also to gases . . . and that the characteristic constants for nearly all elements will be determined without major difficulties. Then the question of the inner kinship of molecular forces and Newtonian forces will move a big step closer its solution. It is possible that experiments already done by others for other purposes will suffice for testing the theory. In that case I shall utilize everything achieved so far about molecular attraction in my doctoral thesis. It is a glorious feeling to recognize the unity of a complex of phenomena, which appear to direct sense perception as quite distinct things. [C: D100]

As things turned out, it was another fourteen months before Einstein was actually hired at the patent office. During that stretch, he had only six months of salaried income from temporary jobs as a substitute teacher and as a private tutor. In May, he learned he had gotten Mileva pregnant and, in late July, that she had again failed the diploma exam. A few weeks before the exam, Einstein had sent her an earnest pledge:

> Rejoice now in the irrevocable decision I have made! About our future I have decided the following: I'll look for a position *immediately*, no matter how modest. My scientific goals and personal vanity will not prevent me from accepting the most subordinate role. As soon as I have such a position I will marry you and take you to live with me. . . . Then no one can cast a stone upon your dear head. . . . your parents and mine [will] just have to reconcile themselves to it as best they can. [HP: 184]

In December, this pledge as yet unmet, Einstein made another earnest proposal that he would not manage to fulfill. Mileva was at home with her parents, waiting to give birth; she anticipated the baby would be a girl and had

even named her Lieserl. Einstein, having just heard that the patent office job was about to be advertised, wrote:

> I'm even happier for you than for myself. . . . We'll be students as long as we live and won't give a damn about the world. . . . The only problem that still needs to be solved is the question of how we can take our Lieserl to us; I do not want us to have to give her up. [C: D127]

Einstein did carry out his plan to prepare a thesis dealing with molecular forces in gases. In November, he submitted this to Alfred Kleiner, the professor of physics at the University of Zurich, and wrote Mileva that "he won't dare reject my dissertation" [C: D126]. It was January before Kleiner read the thesis, and he did reject it, supposedly because Einstein had sharply criticized Boltzmann, but likely also because theoretical results offered in the thesis lacked experimental confirmation [C: 175]. (No copy of the thesis is extant.) Soon after withdrawing his thesis (to avoid forfeiting half the submission fee), Einstein heard from her father that Mileva had given birth to a daughter, Lieserl, after an exhausting labor. His letter in response includes curious comments:

> you must suffer enormously if you cannot even write me yourself. . . . our dear Lieserl too must get to know the world from this aspect right from the beginning! . . . I would like once to produce a Lieserl myself, it must be so interesting! [C: D134]

Graduate Student and Patent Examiner: 1902–1905 in Bern

Einstein more than once gave up on the prospective patent office job [C: D126]. When it was finally advertised, he applied immediately, soon resigned incautiously from a salaried tutorial post, and in early February of 1902 moved to Bern. He advertised "private lessons . . . given most thoroughly . . . trial lessons free." There were few takers, but one led to a lifelong friendship. Maurice Solovine, a Romanian student, found Einstein was eager to discuss philosophy and literature as well as physics. Soon Conrad Habicht, a mathematics student Einstein had known in Zurich, joined their discussions. The trio decided to meet regularly as a book and debate club, which they dubbed the "Akademie Olympia" as a spoof of pompous societies. For about two and a half years, they met regularly, often several evenings a week, had a modest dinner ("sausage, cheese, fruit and tea"), then indulged in intense, typically boisterous debate that sometimes "went on far into the night, to the annoyance of the neighbors" [HD: 38]. The reading was systematic and eclectic; in a memoir Solovine lists Karl Pearson's *Grammar of Science*, Ernst Mach's

Mechanics, John Stuart Mill's *Logic*, David Hume's *A Treatise on Human Nature*, Baruch Spinoza's *Ethics*, as well as Sophocles' *Antigone*, lectures by Hermann von Helmholtz and André-Marie Ampere on physics, and discussions by Bernhard Riemann of the foundations of geometry and by Richard Dedekind of the concept of number. Special attention was devoted to Henri Poincaré's *Science & Hypothesis*, which "held us spellbound for weeks."[6]

While waiting five more months for the patent office job, Einstein completed two more papers, again without a mentor. In an extension of his first paper, which he had anticipated a year earlier [C: D101], he applied his theory of intermolecular forces to systems comprising metal electrodes immersed in dilute salt solutions. However, he concluded with an apology for "only setting out a meager plan for a demanding investigation" that required experimental solution and the hope his paper would "induce some researcher to attack the problem" [F: 100]. In the other paper, possibly related to his rejected thesis, and likewise alluded to in a letter the previous year [C: D122], his aim was to fill what he saw as a gap in Boltzmann's kinetic theory by providing a sounder derivation of the laws of thermal equilibrium and the second law of thermodynamics from statistical mechanics.[7]

In late June, Einstein finally began work at the patent office. He was to continue there for more than seven years, eight hours a day, six days a week. Einstein enjoyed deciphering drawings and elaborate descriptions to decide whether the invention would work and was actually new. He found congenial the instructions issued to his dozen or so "patent slaves" by the director, Friedrich Haller: "When you pick up an application, think that anything the inventor says is wrong. . . . You have to remain critically vigilant" [F: 104]. Indeed, from his boyhood on, Einstein was much interested in the design of machines and experiments, and he patented several devices of his own invention.[8] He became so adept at processing patents that he had time in the office to do some of his own calculations and writing, "guiltily hid in a drawer when footsteps approached" [HD: 39]. Ten years after his Bern era, Einstein recalled fondly "that temporal monastery, where I hatched my most beautiful ideas" [F: 102].

Soon after he entered his temporal monastery, Einstein was stunned when at age fifty-five his father suffered a fatal heart attack. A few months later, Albert and Mileva were married in Bern, with no family members present. People in Bern did not know about Lieserl, and she was not brought there, perhaps for fear of offending propriety because Einstein's appointment was still provisional [F: 114]. The Olympia Academy continued to meet, now usually in the Einstein's apartment. Solovine noted that Mileva, "intelligent and reserved, listened to us attentively without ever intervening in our discussions."[9]

Einstein also now had congenial scientific interactions with colleagues at the University of Bern and the Natural Science Society, as well as the patent

office. Only three weeks after his wedding, Einstein wrote to Besso about completing his fourth paper, which carried further his treatment of the foundations of thermodynamics:

> On Monday I finally sent off my work, after many changes and corrections. Now it is perfectly clear and simple, so that I am quite satisfied with it. . . .
>
> I have now decided to become a Privatdozent, provided of course I can get away with it. On the other hand, I won't become a Ph.D., as this doesn't help me much and the whole comedy has become a bore to me. [F: 112]

He had learned that the University of Bern had an unusual policy, allowing a shortcut to the status of *Privatdozent* (unsalaried, but with the privilege to lecture at the university and collect fees from subscribing students). Scholars with "other outstanding achievements" could skip both a doctoral and habilitation thesis, submitting instead other published work. Einstein applied, offering his third and fourth papers. This ploy failed and soon he wrote Besso again: "The university here is a pigsty. I won't lecture there, it would be a waste of time" [F: 112].

More than a year later, Einstein submitted a fifth paper, completing a trilogy on statistical thermodynamics. He evaluated fluctuations of the internal energy about its average value. This, he emphasized, brought out the significance of Boltzmann's constant, which "determines the thermal stability of the system" because it sets the scale of the fluctuations.[10]

Significant fluctuations soon occurred both at home and work. In May, 1904, Mileva gave birth to a son, Hans Albert. That summer, Einstein was joined at the patent office by his friend Michele Besso, whom he had encouraged to apply. In the fall, Einstein's provisional appointment, after twenty-seven months, was made permanent. However, only after another twenty months was he promoted to Class II, in contrast to Besso, an engineer, who started at that rank. In late October, Habicht departed Bern and the Olympia Academy ended.

In another few months, Einstein erupted in his *annus mirabilis*. During 1905, he submitted six papers. The three most celebrated papers were submitted within a span of fifteen weeks. Within that span he also completed a fourth paper, which became his Ph.D. thesis. Moreover, during the year Einstein contributed twenty-one reports to a review journal, *Beiblätter zu den Annalen der Physik*. His reviews, in the category "theory of heat" [*Wärmelehre*], summarized and commented on papers published in German, French, Italian, and English journals. Evidently he interleaved writing his own papers with preparing these reviews, as eight of his reviews appeared in March, six in June, three in September, and four in November. How much work Einstein had to do at the patent office is not known. In accord with policy, eighteen years later his patent assessments were destroyed. However, it seems likely he would have had more

TABLE 15.4 First Five Papers, 1900–1904

Title	*Received*	*Published*	*No. Pages*
1. Conclusions Drawn from the Phenomena of Capillarity	Dec 16, 1900	Mar 1, 1901	11
2. On the Thermodynamic Theory of the Difference in Potentials between Metals and Fully Dissociated Solutions of Their Salts and on an Electrical Method for Investigating Molecular Forces	Apr 30, 1902	Jul 10, 1902	17
3. Kinetic Theory of Thermal Equilibrium and of the Second Law of Thermodynamics	Jun 26, 1902	Sep 18, 1902	17
4. A Theory of the Foundations of Thermodynamics	Jan 26, 1903	Apr 16, 1903	18
5. On the General Molecular Theory of Heat	Mar 29, 1904	Jun 2, 1904	9

These papers were all published in *Annalen der Physik*. Paper 1 was submitted from Zurich; papers 2–4 from Bern. Paper 1 mentions the work of R. Schiff and compiles data from *Allgemeine Chemie* of W. Ostwald (1891) and the Landolt-Börnstein tables (1894). Papers 1, 2, and 4 have no footnotes or explicit literature references. Paper 3 mentions Maxwell and Boltzmann in the text and has two footnotes to sections of Boltzmann's *Gastheorie*; Paper 5 mentions Boltzmann and Planck in the text and has two footnotes, one to AE's paper 4, the other to Boltzmann's *Gastheorie*.

to do in 1905 than earlier. As nearly all the other examiners were mechanical engineers, Einstein probably had to contend with a flood of electrical engineering patents, generated by the rapid development of electrical industry [G: 248].

Einstein's creative outburst in 1905 is often said to be comparable only to that achieved by Newton in 1666. Both soared in their mid-twenties, but otherwise, what a contrast! With Cambridge University closed by the plague, Newton had retired to his mother's estate and, as a bachelor, was free to concentrate totally on science and mathematics. He is thought to have conceived several of his great ideas during the plague recess, but Newton published little until many years later. Einstein, with much else to do, must have labored mightily to bring forth so quickly his golden eggs. He never identified accelerating factors, but two speculative possibilities seem to me plausible. After the arrival of Hans Albert and the departure of Habicht, Einstein might have begun devoting more of his evenings to putting his ideas in writing. In lieu of the exuberant verbal sparring he'd enjoyed with his Olympia Academy, he had calmer stimulation in talking with Besso at the patent office and on the way home. Also, like the birthing urge induced by Lieserl, the presence of his infant son perhaps spurred Einstein to deliver his intellectual progeny.

Comments on Einstein's Early Papers

The content, antecedents, and response to Einstein's early papers have been amply discussed in editorial commentaries included in the Collected Papers

and in several other excellent sources.[11] Here I note only a few aspects related to his transition from student to scientist.

His first two papers, and presumably also his rejected (and vanished) thesis of late 1901, employed a dubious conjecture about intermolecular forces.[12] In analogy with gravitation, Einstein assumed the potential energy for interaction of a pair of molecules involved a universal function of the distance between them. This was not compatible with the then well-known theory of fluids developed by van der Waals, nor with experimental data indicating that distance dependence does vary for different pairs of molecules. Remarks in Einstein's letters show that, three months before submitting his first paper (treating capillarity), he had finished reading Boltzmann's *Gastheorie*, which presents the theory of van der Waals [C: D75]. A year later, shortly after submitting his ill-fated thesis, Einstein had derived from his own theory a consequence that contradicted the results of van der Waals. Blissfully confident, Einstein then thought his result, if confirmed by experiment (as he seemed to expect), "would be the end of the molecular-kinetic theory of liquids" [C: D127].

He did not realize until several years later that his conjecture about distance dependence was wrong, and then declared his first two papers "worthless beginners' works" [P: 57]. This must have been a disillusioning experience. He had been proud of his first paper; he had sent a copy to Boltzmann as well as to Ostwald [C: D85]. Misled by seeming success in fitting considerable data (but of limited sensitivity) with adjustable parameters, he had hoped to find a "general law." Never again did he succumb to such an approach. Decades after, without mentioning his "beginners' works," he wrote:

> I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results. The example I saw before me was thermodynamics. [E: 53]

Indeed, as well as making much direct use of thermodynamics, Einstein soon came to emulate its character.[13] Rather than pursuing a "constructive theory" that attempts "to build a picture of complex phenomena out of some relatively simple propositions," he strived for "a theory of principle" that starts "from empirically observed general properties of phenomena" and infers from them results "of such a kind that they apply to every case which presents itself, without making assumptions about hypothetical constituents"[E:53]. This became his distinctive approach, especially prominent in his 1905 papers.

Einstein finally wrapped up the Ph.D. comedy in July of 1905. He completed the paper that he submitted for his doctoral thesis (#7) at the end of

TABLE 15.5 Papers of the Annus Mirabilis, 1905

Title	*Received*	*Published*	*No. Pages*
6. On a Heuristic Point of View Concerning the Production and Transformation of Light	Mar 18, 1905	Jun 9, 1905	17
7. A New Determination of Molecular Dimensions	Aug 19, 1905	Feb 8, 1906	17+1
8. On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat	May 11, 1905	Jul 18, 1905	12
9. On the Electrodynamics of Moving Bodies	Jun 30, 1905	Sep 26, 1905	31
10. Does the Inertia of a Body Depend on Its Energy Content?	Sep 27, 1905	Nov 21, 1905	3
11. On the Theory of Brownian Motion	Dec 19, 1905	Feb 8, 1906	11

These papers were all submitted from Bern and published in *Annalen der Physik*. Paper 6 has footnotes citing work of Drude, Planck, Lenard, and Stark, plus some enlarging on details. Paper 7 is AE's doctoral thesis, dedicated to Marcel Grossmann and published separately as a booklet (Buchdruckerei K.J. Wyss, Bern, Jan 1906); both the *Ann. Phys.* version and the booklet are dated April 30, 1905, although the thesis was not submitted until July 20, 1905, and the paper not until mid-August 1905. Both versions have one footnote to Kirchhoff and one to AE's paper 8. The *Ann. Phys.* paper has some minor changes and a short supplement dated Jan 1906 (requested by Drude, the editor) that uses updated data from the latest edition of Landolt-Börnstein (1905). Paper 8 cites AE's paper 3, paper 4, and Kirchhoff. Paper 9 has no literature citations, but has three explanatory footnotes and thanks his "friend and colleague Michele Besso for loyal support and valuable stimulation." Paper 10 cites only paper 9. Paper 11 cites paper 8, Gouy (1888), Planck, and Kirchhoff.

April, but set it aside in favor of turning out an offshoot of it, his Brownian motion paper (#8) in early May, then his relativity paper (#9) during June. Maja reported that Einstein had first submitted the relativity paper as his thesis, only to have it turned down because it "seemed a little uncanny to the decision-making professors" [F: 123]. He then submitted his April paper, which provided a means to determine both molecular size and Avogardro's number from experimental diffusion rate and viscosity data for sugar solutions. It was quickly endorsed by Kleiner and approved by the Zurich faculty. According to a story Einstein liked to tell, after an objection that his thesis was too short, he added a sentence and it was then accepted [P: 88]. The Brownian motion paper was published just before Einstein submitted the thesis, and a footnote citing it was added ("fuller explanation can be found . . ."). That footnote may be the now legendary but unidentified final sentence. When printed as customary in a booklet, the text portion of the thesis was only 16 pages.

Einstein did not have to contend with either mentors or reviewers in producing his papers. Today it seems astonishing that an unknown graduate student could readily publish in a leading physics journal, and that the papers usually appeared in print only two to three months after submission. In the *Annalen* volumes for 1902–1905, each monthly issue typically had fifteen papers, nearly all by single authors. About 20 percent were purely theoretical papers. Those were handled either by the editor, Paul Drude, himself a theorist, or by the only theorist among the five-member advisory board, Max Planck.

Publication appeared to be equally prompt whether or not the author was distinguished, or had an academic affiliation, or whether the paper reported experiments or theory.[14] Nowadays, if a new Einstein were to appear as a graduate student and try to publish in a major journal anything as audacious as most of his early papers, the student would surely be squelched by a withering gauntlet of reviewers. Fortunately, new options are now becoming available in cyberspace.

A curious aspect of Einstein's papers is his meager citation of relevant work by others (itemized in notes to Tables 15.4 and 15.5). This was quite atypical in the *Annalen* even a century ago. Pais suggests he "simply did not much care," and quotes a striking statement made by Einstein in a 1907 paper:

> What is to follow might already been partially clarified by other authors. However, in view of the fact that the questions under consideration are treated here from a new point of view, I believed I could dispense with a literature search which would be very troublesome for me, especially since it is to be hoped that other authors will fill this gap.

Pais comments: "This statement is not arrogant if, and only if, arrogance is a mark of insecurity. To me these lines express ebullience, total self-assurance, and a notable lack of taste" [P: 165]. Most odd is Einstein's failure to acknowledge, in 1905 or later, seminal essays by Henri Poincaré. His *Science and Hypothesis* appeared in German translation in 1904 and kept the Olympia Academy "spellbound for weeks." That edition included an excerpt from his *Measure of Time*, wherein Poincaré explicitly treats issues directly relevant to the nascent theory of special relativity [G: 238]. Moreover, Poincaré also points out, as important unsolved problems, Brownian motion and the photoelectric effect, which soon became Einstein's other two golden eggs [R: 10]. In words that must have gripped the Olympia Academy, Poincaré wrote:

> Let us notice, however, the original ideas of M. Gouy [in 1888] on the Brownian movement. According to this scientist, this singular movement does not obey Carnot's principle [the second law of thermodynamics]. The particles which it sets moving would be smaller than the meshes of that tightly drawn net; they would thus be ready to separate them, and thereby to set back the course of the universe. One can almost see Maxwell's demon at work.[15]

In the introduction to his paper (#8), Einstein likewise featured the challenge to the second law:

> If the movement discussed here can actually be observed . . . then classical thermodynamics can no longer be looked upon as applicable with precision to bodies even of dimensions distinguishable in a microscope: an exact determination of

> actual atomic dimensions is then possible. On the other hand, had the prediction of this movement proved to be incorrect, a weighty argument would be provided against the molecular-kinetic conception of heat. [C2: D16]

Einstein does not mention Gouy until a later paper (#11). Actually, thermal fluctuations such as those that produce Brownian motion do not violate the second law; that was shown in 1922 by Leo Szilard in his Ph.D. thesis, cursed by Maxwell's demon and at first doubted, then blessed by Einstein.[16]

In contrast to his original journal articles, elsewhere Einstein was unstinting in his appreciation:

> A hundred times a day I remind myself that my inner and outer lives are based on the labors of other people, living and dead, and that I must exert myself in order to give in the same measure as I have received and am still receiving.[17]

Lessons for a New Century

Efforts to improve science education and literacy face a root problem: science and mathematics are regarded not as part of general culture, but rather as the province of priest-like experts. Einstein is seen as a towering icon, the exemplar *par excellence* of lonely genius. That fosters an utterly distorted view of science, both in students considering a career and in the wider public.

Among many others, I've tried to combat that distortion by emphasizing two key aspects.[18] First, science enjoys a tremendous advantage over other human enterprises: The goal—understanding nature—*waits patiently to be discovered.* That is why ordinary human talent, given sustained effort and freedom in the pursuit, can achieve marvelous advances. It is also why it is vital to have some maverick scientists willing to explore unorthodox paths, as unanticipated roadblocks often obstruct routes favored by consensus. Second, science is intrinsically a *cooperative, democratic social enterprise.* In contrast to hierarchical organizations, governed by a chain of officers, science relies on independent units free to pursue their own interests. Despite seemingly chaotic freedom, the enterprise is efficiently "coordinated by an invisible hand" because each unit can observe and apply results found by others.[19]

These special aspects of science, and the great variety of its subdomains, make it congenial for people with a huge range of talents and temperaments. That point was nicely made by Enrico Fermi. He was asked if he could think of something his fellow Nobel laureates in physics had in common. After a pause, he replied: "No, I can't think of anything they have in common. Not even intelligence."[20] Thus we certainly cannot expect to divine from the Einstein saga what is necessary or sufficient to produce boldly creative scientists. But his maverick journey to his doctorate highlights aspects that should

compel attention in current discussions of science education, from grammar to graduate school. In summary:

1. *Early enchantment.* At the age of ten to twelve, Einstein's passion for science was aroused. Thanks chiefly to Max Talmud, Einstein read many popular science books and became enamored with geometry and "the purity of pure thinking." He went on, outside of school, to learn calculus on his own. That and his violin taught him the pleasures of taking ownership of subjects by self-study ("love is a better teacher than duty").
2. *Confident sense of mission.* By seventeen (in his Aarau essay), Einstein felt he had a "personal gift" for theoretical science, which offered him a "goal for striving" and "certain independence." These traits were reinforced by disdain of authority, exercised throughout his academic experience, and by his critical, questioning attitude, honed in the patent office.
3. *Freedom for solo initiatives.* The four-year course at ETH required only two major exams. Einstein attended only lectures that interested him and spent much time performing experiments and in intense self-study of theory. After graduation, papers he wrote and submitted on his own were promptly published. The Ph.D. required no further courses, only a single paper of modest length, on a topic he chose without any prior approval.
4. *Supportive friends.* Einstein enjoyed conversation and correspondence, social and scientific, with many friends. At ETH, Einstein often studied with Mileva or Marcel Grossmann. At Bern, the Olympia Academy was a major indulgence. Conversations with Michele Besso helped Einstein recognize the crucial issue in special relativity. He credited his musical friends, Besso among them, for preventing him from "getting sour."
5. *Cultural resonance.* Holton has explored "how the cultural milieu in which Einstein found himself resonated with and conditioned his science."[21] In gymnasium and university, Einstein received a broad humanistic education. In this, Holton finds the cultural roots of Einstein's urge to generalize and unify, as well as the tension seen in his rebellion against and reverence for traditional ideas. Goethe appeared an especially strong influence—on Boltzmann and Planck, as well as on Einstein—to pursue "a Faustian drive toward a *Weltbild* encompassing all phenomena."

The exhilaration of taking ownership at a young age, outside of school, is testified to in memoirs of many scientists. Edward Wilson's love affair with ants[22] and Oliver Sacks' with chemistry[23] are notable recent examples. Arnold Sommerfeld remarked: "Mathematics is like childhood diseases. The younger you get it, the better."[24] That likely applies to much else.

If young Einstein were reincarnated today, he might not have a Talmud as mentor, but he would find abundant opportunities to explore science. I'll be parochial and assume he appears in Princeton, just so I can point to activities of Science Service, a small nonprofit outfit in Washington, DC, that I know about firsthand.[25] It publishes a weekly, *Science News*, written for laypeople. As it covers all fields, it would serve young Einstein like the popular science books he read a century ago and later praised for giving him a broad, qualitative perspective. Science Service also conducts premier science fairs at the middle school and high school levels. Best known is the Science Talent Search (long sponsored by Westinghouse and now by Intel). Largest is the International Science and Engineering Fair (ISEF, now also sponsored by Intel). This brings together more than 1,200 students from fifty countries (as yet over 90 percent from the United States), winners of hundreds of local, state, and regional fairs in which about a million students take part. *Science News*, as well as the projects displayed at the STS and ISEF fairs, are now on the Web; recently a delightful edition has been added, designed for pre–high school kids.

In high school and college today, Einstein would certainly be unhappy about myriad tests and the loss of freedom to cut classes. In graduate school, he might resent having to take some courses rather than concentrate solely on research. On the other hand, unlike his situation in Zurich, he would now find on the faculty many theoretical physicists offering advanced courses. (Perhaps too many!)

Most galling to him as a graduate student, I expect, would be the almost certain loss of opportunity to publish solo papers, and to get a doctorate with a single brief paper, all the while gladly working at a "temporal monastery."

Today, the time to complete a Ph.D. in American universities has expanded to a norm of six or seven years, even in the sciences. For those who seek faculty positions, a postdoctoral stint of two or three years is expected. In my view, how academic science has come to be funded is a major factor: funding is for particular projects, not for people. Most graduate students and postdoctoral fellows, therefore, are supported chiefly by serving as hired hands on a project defined by a research grant. Veteran students are most useful in obtaining results to justify a grant renewal. That vital need works to extend the apprenticeship. Nowadays other options are rare. Mathematics is the only field I know of in which a single paper can earn a Ph.D. (at least at Harvard and some sister universities). There are very few fellowships for independent study. Today's Einstein, unless he could quench his strong yearning for independence, would rebel against this feudal system. I think he would not try for a Ph.D., unless perhaps in mathematics.

Shortening the time to the doctorate is extremely important, in my view. For a student entering graduate school with decent preparation, four years should be enough. Uncoupling support of graduate students from project grants would help them break loose. If support of students (and preferably also postdoctoral fellows) on grants to individual professors were abolished, the same money could be put into expanding greatly the number of fellowships that students can win for themselves, as well as into block training grants to university science departments. Winning a fellowship profoundly influences a student's outlook and approach to research; they are certified as national resources rather than as hired hands. Funding agencies should adopt a policy that a fellowship holder completing the Ph.D. in four years would be rewarded by receiving a postdoctoral stipend for a year to work at a laboratory of his or her choice. This and other reforms I've suggested[26] are surely quite reasonable. More simple is the proposal by Freeman Dyson to award students a Ph.D. "on the day they enter graduate school."[27]

Einstein would likely endorse two pieces of advice recently offered to students by Steven Weinberg: "Learn something about history of science. . . . [You] can get great satisfaction by recognizing that your work is part of history." Also, "Aim for rough water . . . that's where the action is."[28] Einstein advised a former student, "One must develop an instinct for what one can just barely achieve through one's greatest effort" [C8: D87]. Of Shakespeare it has been said that writing his plays "must have been easy or it would have been impossible." For Einstein, producing his golden eggs would have been impossible if it had not been difficult.

Acknowledgments

I am grateful for the opportunity to learn much more about Einstein, at the conference and from the orgy of reading it induced before and after. I thank Gerald Holton and Peter Galison for helpful discussions and Bretislav Friedrich for compiling information about the *Annalen der Physik* a century ago.

NOTES TO CHAPTER 15

Citation style: Books referenced in the text or notes, listed below, are designated by a bracketed letter. When a specific page number is cited, it is shown behind a colon; e.g., [F: 104]. References to the Collected Papers pertain to volume one (unless indicated otherwise) and cite not pages but document numbers; e.g., [C: D127] or [C8: D87]. When more than one item is cited, each is separated by a semicolon; e.g., [HP; JB; R;].

[C] *Collected Papers of Albert Einstein*, John Stachel, et al., eds., vol. 1 (1879–1902): *The Early Years*; vol. 2 (1900–1909): *The Swiss Years* (Princeton, NJ: Princeton University Press, 1987)

[JB] Jeremy Bernstein, *Secrets of the Old One: Einstein, 1905* (New York: Copernicus, 2006)

[DC] David Cassidy, *Einstein and Our World* (Amherst, NY: Humanity Books, 1995)

[E] Albert Einstein, Autobiographical Notes, in Paul A. Schilpp, Ed., *Albert Einstein: Philosopher-Scientist* (Chicago: Open Court, 1970)

[F] Albrecht Fölsing, *Albert Einstein: A Biography* (New York: Viking, 1997)

[G] Peter Galison, *Einstein's Clocks, Poincaré's Maps* (New York: Norton, 2003)

[HA] Gerald Holton, *The Advancement of Science and Its Burdens* (Cambridge, MA: Harvard University Press, 1998)

[HD] Banish Hoffman and Helen Dukas, *Albert Einstein, Creator and Rebel* (New York: Viking, 1972)

[HE] G. Holton and Y. Elkana, eds., *Albert Einstein Historical and Cultural Perspectives: Centennial Symposium in Jerusalem* (Princeton, NJ: Princeton University Press, 1982; Dover, 1997)

[HP] Gerald Holton, *Einstein, History, and Other Passions* (Boston: Addison-Wesley, 1996)

[HT] Gerald Holton, *Thematic Origins of Scientific Thought* (Rev. ed., Cambridge, MA: Harvard, 1988)

[I] Walter Isaacson, *Einstein, His Life and Universe* (New York: Simon and Schuster, 2007)

[P] Abraham Pais, *"Subtle Is the Lord . . ."* (New York: Oxford, 1982)

[R] John S. Rigden, *Einstein 1905: The Standard of Greatness* (Cambridge, MA: Harvard, 2005)

[C] Julian Schwinger, *Einstein's Legacy* (Scientific American Library, 1986)

[W] Harry Woolf, Ed., *Some Strangeness in the Proportion: Centennial Symposium* (March, 1979; Boston: Addison Wesley, 1980)

Remarks: Readers seeking a quick overview will be well served by a new website (http://www/aip.org/history/einstein/) prepared by the Center for History of Physics of the American Institute of Physics, or by the short books by Hoffman and Dukas [HD] and by Cassidy [DC]. For comprehensive biographies, see Fölsing [F] and Isaacson [I]. For scholarly detail, see the editorial commentary included in the collected papers [C]. The scientific biography by Pais [P] is splendid, as are books with less broad focus by Holton, [HP] and [HT], Galison [G], Rigden [R], Bernstein [JB], and Schwinger [S]. Other invaluable sources include Einstein's Autobiographical Notes and exchanges with contemporaries in [E], as well as essays from centennial symposia in [HE] and [W].

[1]See [HD: 46]; the added remark about Newton's portrait was made by Helen Dukas to Gerald Holton (private communication).

[2]Gerald Holton [HA: 197]: "Much of my work has had its origin in the notion that science should treasure its own history, that historical scholarship should treasure science, and that the full understanding of each is deficient without the other."

[3]Specific references to items listed in Tables 15.1–15.5 can readily be found in [C] and [F] or [I], which are also organized chronologically; here for the most part only sources of quotations are given.

[4]The Swiss Polytechnic Institute was later renamed the Eidgenössische Technische Hochschule, usually referred to as ETH, as I do hereafter.

[5]Maja Winteler-Einstein, *Albert Einstein—Beitrag für sein Lebensbild*, manuscript (1924). Excerpt published in [C, V1] with extensive editorial notes, and included in the accompanying paperback English "pony" by Anna Beck.

[6]Maurice Solovine, ed., *Albert Einstein: Lettres à Maurice Solovine, 1906–1966* (Paris: Gauthier-Villars, 1956).

[7]Martin J. Klein, "Thermodynamics in Einstein's Thought," in *Science* 157 (1967), p. 509.

[8]Peter Galison, *How Experiments End* (Chicago: University of Chicago Press, 1987), p. 34.

[9]Solovine, *Lettres* (1956).

[10]Klein, "Thermodynamics," p. 509.

[11]Klein, "Thermodynamics," p. 509; Gerald Holton, "Einstein's Scientific Program: The Formative Years," in [W: 49] and in [HA: 57–76]; Martin J. Klein, "No Firm Foundation: Einstein and the Early Quantum Theory," in [W: 161]; [G; P; R; Sc].

[12]J. S. Rowlinson, *Cohesion: A Scientific History of Intermolecular Forces* (Cambridge: Cambridge University Press, 2002). John N. Murrell and Nicole Grobert, "The Centenary of Einstein's First Scientific Paper," in *Notes Rec. R. Soc.* (London) 56, 1 (2002), pp. 89–94.

[13]Klein, "Thermodynamics," p. 509.

[14]Bretislav Friedrich kindly provided the observations noted here about *Annalen der Physik* (private communication).

[15]Henri Poincaré, *Science and Hypothesis* (New York: Dover, 1952), pp. 179f.

[16]William Lanouette, *Genius in the Shadows* (New York: Scribners, 1992), pp. 60–64.

[17]Albert Einstein, "What I Believe," in *Forum and Century* 84 (1930), p. 193; reprinted as "The World As I See It," in his *Ideas and Opinions*, C. Seelig, ed. (New York: Crown Press, 1954).

[18]Dudley Herschbach, "Changes in the Gardens of Science, Wrought by Women," in *Annals of New York Academy of Sciences* 869 (1999), pp. 66–74

[19]Michael Polanyi, "The Republic of Science. Its Political and Economic Theory," in *Minerva* 54, 1 (1962), pp.54–74.

[20]Story told to me many years ago by Edward Purcell (private communication); I have been unable to find it in print.

[21]Gerald Holton, "Einstein and the Cultural Roots of Modern Science," in *Daedalus*, 127, 1 (1998); and in [HA: xiii–xlix].

[22]Edward O. Wilson, *Naturalist* (Washington, DC: Island Press/Shearwater Books, 1994).

[23]Oliver Sacks, *Uncle Tungsten* (New York: Knopf, 2001).

[24]Remark quoted in a class by George Polya many years ago; I have been unable to find it in print.

[25]Dudley Herschbach, "The Impossible Takes a Little Longer," in *Science Literacy for the Twenty-First Century*, S. P. Marshall, J. A. Scheppler, and M. J. Palmisano, eds. (Amherst, NY: Prometheus Books, 2003), pp. 131–44.

[26]Herschbach, "Changes in the Gardens," pp. 69–72.

[27]Freeman Dyson, "To Teach or Not to Teach," in his *From Eros to Gaia* (New York: Penguin Books, 1992), p. 197.

[28]Steven Weinberg, "Four Golden Lessons," in *Nature* 426 (2003), p. 389.