How do you find the acceleration due to gravity using a simple pendulum

Extracts from this document... My investigation is on determining the acceleration due to gravity by using simple pendulum. Also the G apparatus (freely falling mass) can be used to determine the acceleration due to gravity.What is acceleration due to gravity? It is the force or pull of the gravity of the earth according to Newton’s first law a=F/m Objects accelerate because spacetime moves past them. The surface of the earth accelerates upwards at the rate of about 10 m/s2 with respect to spacetime. We have been told that the acceleration due to gravity of earth is 9.81 m/s^2 or g= 9.81 m/s^2, however, due to myriad of factors, g in one place differs slightly to other, as u increase the altitude the g decreases.PLANMy plan for this investigation is to perform various experiment the determine acceleration due to gravity such as the pendulum, free falling object which is the g apparatus and also byAIM The aim of this investigation is to measure the earth’s gravitational field strength, which is also the acceleration due to gravity. This involves mass, which is the amount of matter an object contains and weight, which is the force of gravity pulling down on an object with a mass. Mass is measured in Kg (kilograms) and weight is measured in Newton’s. Gravity is the weakest of the four fundamental forces, yet it is the dominant force in the universe for shaping the large-scale structure of galaxies, stars. Etc. the earth’s gravitational strength is calculated by weight (N) / mass (Kg) as stated above a =F/m therefore the earths gravitational field strength (g) ...read more. 25.201.261.590.5028.351.422.010.6030.901.552.390.7033.501.682.810.8035.851.793.210.9037.801.893.571.0039.902.003.98GRAPH OF LENGTH AGAINTS T2As can be seen the points plot into a straight line. A line of best fit was added to the chart as shown. The line can be sent to go through the origin as expected, it there is a tiny pendulum, it will have a tiny period and if there is an infinitely small pendulum, an infinitely small period. The gradient was calculated to be ¼ and this was inserted into the above equation to result in g=22π2¼. This equates to g=π2. As this is 9.8696 the experiment was remarkably accurate. The units of acceleration are ms-2 which agrees with the value above. It should be observed that the graph of length over time2 was plotted. The constants π and 2 have no units so have no effectESTIMATION OF UNCERTAINTIES. Uncertainties while measuring the time period T, Systematic errors are introduced if my stopwatch is systematically off by a certain amount, and by delays due to my eye-hand reaction time. The stopwatch systematic uncertainty should be listed by the manufacturer of the instrument, whereas the eye-hand uncertainty has to be estimated by myself, e.g. by measurement against a known time interval. The statistical uncertainty on T comes from the fact that my eye-hand reaction time varies from one trial to the next; it fluctuates (around the systematic value). This statistical uncertainty can be reduced by making many individual (i.e. independent) measurements and averaging; the systematic uncertainty then decreases with the square root of the number of measurements: making 10 measurements will reduce the statistical uncertainty by a factor of about √(10) = 3.2ErrorsActions taken to reduce the errors.-Line eye up with fixed object for timing accuracy.-Accurate stop clock (decimal seconds).-Averaging two readings to remove human error-Averaging twenty readings to improve accuracy b   Y factor of 20 ...read more. Overall the free falling object method was a fair and simple experiment to determine the acceleration due to gravity. From the results my acceleration due to gravity is about 9.8054 ms-2. According to the books the value of g is 9.81ms-2 that gives a difference of about 0.0046, to calculate the percentage error it comes to about 0.046%, which states clearly my experiment, is almost as accurate it can be. Therefore I conclude that my experiment to determine the acceleration due to gravity was successful and I have achieved my aim for this experiment. EVALUATION My experiment of the free falling object method to determine the acceleration due to gravity was very simple and straightforward. To improve my experiment I could have repeated this experiment several times then I could get more accurate results, which could have taken more time out of my schedules. So time was one of the limiting factors. To improve my experiment even further I could have used modern instruments to improve and get more accurate results and also I could have used other falling object with different masses to see how the value of g varies according to their masses. I could have also used different lengths between the release mechanism and the receiver pad but measuring the distance greater than 1m was a problem because I used meter rulers to measure my lengths of the experiment this was another limiting factor that I had to overcome by taking lengths less and equal to 1m. ...read more. This student written piece of work is one of many that can be found in our GCSE Forces and Motion section. The pendulum has a great relevance in physics and it has been explored in educational papers from many theoretical or experimental points of view (see, for example, Refs. 1-12 and references therein). Here a method for the measurement of the gravitational acceleration with a large number of trials is presented; we assume that the systematic errors can be neglected. The experiment has been carried out with 250 first-year university students (students not enrolled in physics). Although the pendulum can be considered as a standard part of the introductory courses in physics laboratory, the approach described here allows students to handle various aspects of data analysis.The pendulum has a great relevance in physics and it has been explored in educational papers from many theoretical or experimental points of view (see, for example, Refs. 1-121. S. Li and S. Feng, “Precision measurement of the period of a pendulum using an oscilloscope,” Am. J. Phys.35, 1071–1073 (Nov. 1967). . R. A. Nelson, “The pendulum – Rich physics from a simple system,” Am. J. Phys. 54, 112–121 (Feb. 1986). . D. P. Jackson, “Rendering the ‘not-so-simple’ pendulum experimentally accessible,” Phys. Teach. 34, 86–89 (Feb. 1996). . D. P. Randall, “Student-friendly precision pendulum,” Phys. Teach. 37, 390–393 (Oct. 1999). . A. Dupré and P. Janssen, “An accurate determination of the acceleration of gravity g in the undergraduate laboratory,” Am. J. Phys. 68, 704–711 (Aug. 2000). . T. Lewowski and K. Wozniak, “The period of a pendulum at large amplitudes: A laboratory experiment,” Eur. J. Phys. 23, 461–464 (2002). . M. Vannoni and S. Straulino, “Low-cost accelerometers for physics experiments,” Eur. J. Phys. 28, 781–787 (2007). . J. Sinacore and H. Takai, “Measuring g using a magnetic pendulum and telephone pickup,” Phys. Teach. 48, 448–449 (Oct. 2010). . Khairurrijal, E. Widiatmoko, W. Srigutomo and N. Kurniasih, “Measurement of gravitational acceleration using a computer microphone port,” Phys. Educ. 47, 709–714 (2012). . J. Briggle, “Analysis of pendulum period with an iPod touch/iPhone,” Phys. Educ. 48, 285–288 (2013). . V. Oliveira, “Measuring g with a classroom pendulum using changes in the pendulum string length,” Phys. Educ. 51, 063007 (2016). . L. A. Ladino and H. S. Rondón, “Determining the damping coefficient of a simple pendulum oscillating in air,” Phys. Educ. 52, 033007 (2017). and references therein). Here a method for the measurement of the gravitational acceleration with a large number of trials is presented; we assume that the systematic errors can be neglected. The experiment has been carried out with 250 first-year university students (students not enrolled in physics). Although the pendulum can be considered as a standard part of the introductory courses in physics laboratory, the approach described here allows students to handle various aspects of data analysis. The 250 students of the course were divided in groups of four or five. First of all, students measured the period T of a fixed-length simple pendulum: they investigated how to reduce the error. Without any hint, each group was required to measure five times the period of the pendulum (time for a complete oscillation) in the best possible way, by using a digital stopwatch whose sensitivity is 0.01 s. Usually students choose the time interval between the two subsequent ends on the same side with respect to the equilibrium position. As an example, the values measured by one of the groups are reported in Fig. 1(a) on the time axis. The same students were then required to measure the period again with the following instruction: when the swinging bob crosses the equilibrium position, start timing and count 10 periods, finally dividing the overall time by 10. Data obtained by the same group with this method are reported in Fig. 1(b). In the figure, the red line indicates the mean value Tm for each set of data. Blue strips are the regions corresponding to Tm ± ΔT. The uncertainty ΔT is estimated as (TMAX − TMIN)/2, with the result being about 0.1 s for the first set of data and 0.01 s for the other one. Students could clearly observe that values are much less scattered in the second set. In the latter method, only 1/10 of the personal reaction time (an error larger than the sensitivity of the stopwatch) affects the period: this is the main advantage. Furthermore (with smaller benefit on the uncertainty) the stopwatch should be started and stopped when the bob speed has a maximum, in the central point of the oscillation (with the reference of a vertical bar). Conversely, it is not easy to capture the instant at which the bob stops before reversing the motion. After this preliminary training, many students showed a good ability in timing; only a minority (approximately 10%) still had difficulties and required some additional hints or explanations. Thereafter students used this procedure for measuring the period in order to reduce uncertainties. In principle students may repeat the measurements by using the same fixed-length pendulum, but with different bob masses and different amplitudes, to discover that, within the experimental errors, the period does not change. A nylon thread (fishing line), approximately 1 m long, was prepared for each group: it was fastened to a high enough support, leaning on a table. The oscillating mass is composed of a bolt, a nut, and two thick square washers (Fig. 2), and can be positioned along the thread. In this way, students can make an arbitrary long pendulum. Each group was required to make five different pendula, by placing the mass at different positions along the thread, and to measure length (with a folding rule whose sensitivity is 1 mm) and period (with a digital stopwatch) of each one. The aim of the experiment is to obtain a measurement of the gravitational acceleration g by using the formula of the period T for small oscillations of a simple pendulum: Students were warned to work in the “small oscillation regime” (they were required to maintain an angular amplitude smaller than 10°). Probably, the prescription has not been satisfied in some cases; however we expect a small effect on the result.1313. The period of the pendulum is T=2πlg(1+θ2/16+⋯), where θ is the maximum angular displacement from the equilibrium position. For θ = 10°= 0.17 rad, the second term in the parentheses is about 0.002. The departure from isochronism can be perceived when the angle is wide enough, as in the student lab reported in Ref. 14. Time measurements were taken only once (after the training performed in the previous steps with the fixed-length pendulum), but each time included 10 periods. As a rough a priori estimation of the uncertainties, we assumed ± 0.1 cm on the length of the pendulum (this is the sensitivity error of the rule) and ± 0.01 s on the period (because on the complete measurement, covering 10 periods, the estimated error is ± 0.1 s, as discussed before). As an example, the measurements taken by one of the groups are reported in Table I. Table I. L (cm) 26.3 33.4 46.7 57.1 76.1 T (s) 1.01 1.15 1.37 1.51 1.74 After all the groups collected their data, the students and the teacher merged values together to obtain a cumulative measurement of g. The value of the gravitational acceleration was calculated with a computer spreadsheet for all the pairs of values (Li, Ti). The distribution is shown in Fig. 3: a few values of g exhibit a large discrepancy from the expected value (Δg/g > 10%). Let us assume that our values follow a Gaussian distribution G(x). When G(x) is normalized to 1 and centered in x = 0, the probability to obtain any value within a distance l from the center is given by the integral The expected events in this range are ni = Np(l), N being the number of measurements, and ne = N[1 – p(l)] are expected outside the interval. We apply Chauvenet’s criterion1616. J. R. Taylor, An Introduction to Error Analysis (University Science Books, Sausalito, 1982). to the data sample to check if some value must be rejected. According to Chauvenet, we reject a suspect value if ne ≤ 0.5 (no more than 0.5 events as deviant as the suspect are expected). If ne = 0.5 and N = 280, the above equation gives p(l) = 0.9982: this probability corresponds to l = 3.1σ, as obtained from tabulated integrals of the Gaussian function. In our case we found nine measurements that are placed beyond such limit (red bars in Fig. 3) and these values have been rejected. No further data rejection is applied: according to a common practice, the Chauvenet’s criterion should be applied only once.1616. J. R. Taylor, An Introduction to Error Analysis (University Science Books, Sausalito, 1982). With the surviving 271 values, the histogram’s mean is 9.81 m/s2 and the standard deviation is 0.28 m/s2. This has the following statistical meaning: choosing a student in the sample to perform another measurement, 68% is the probability to find the new value of g within a standard deviation around the mean. However the error on the mean value of the distribution is σ/N≅0.02m/s2.. The average has greater precision than any other measurement, being obtained from all measured values. When the length Li varies in the range Li ± 0.3 cm (three times the a priori estimated error), the corresponding point is displaced from its position and moves horizontally within the (narrow) band delimited by the blue straight lines. Similarly, when the period Ti varies in the range Ti ± 0.03 s (again three times the estimated error), the corresponding point moves vertically within the band delimited by the orange straight lines. From the picture, the effect of the time error on the angular coefficient seems to be predominant. Red points in the graph correspond to the discarded measurement and they are not included in the calculation of g. From Fig. 4 we see that all red points have too small values of T. Probably this can be explained with a quite common wrong procedure: sometimes students count nine periods instead of 10. In fact, if the time values of the red points are multiplied by 10/9, they move on the “main sequence” of the other points. We can calculate the best interpolating straight line of the form y = kx. When and the uncertainties in y all have the same magnitude (unweighted fit), the angular coefficient of the fitting straight line can be obtained by minimizing the function F(k) defined as: When the uncertainties σi on y are different (weighted fit), the associated function F(k) is slightly more complicated1717. I. G. Hughes and T. P. A. Hase, Measurements and their Uncertainties (Oxford University Press, New York, 2010).: To account for uncertainties in both time and distance, we introduced the equivalent error σi2=(Δyi)2+(kΔxi)2, as suggested in Ref. 1414. N. G. Holmes and D. A. Bonn, “Quantitative comparisons to promote inquiry in the introductory physics lab,” Phys. Teach. 53, 352–355 (Sept. 2015). . Here an approximated value can be used for k. We computed the value of k for which F(k) has a minimum. The result for the reciprocal of the slope is: This is our measurement of the gravitational acceleration g and it is in agreement with what is expected1818. Department of Defense World Geodetic System 1984, NIMA TR8350.2, 3rd ed., Table 3.4, Eq. 4-1. for the latitude 44°N (g = 9.805 m/s2), where the experiment was carried out. The experiment is simple enough to be within the grasp of a first-year university student. Also the experimental apparatus is very simple and can be replicated on several workstations for courses that have many students. The final result is obtained through data processing that allows students to review the Gaussian statistics and the criteria for data rejection. The author is indebted to Prof. Massimo Bongi for useful suggestions about this article. 1. S. Li and S. Feng, “Precision measurement of the period of a pendulum using an oscilloscope,” Am. J. Phys.35, 1071–1073 (Nov. 1967). Google ScholarScitation, ISI2. R. A. Nelson, “The pendulum – Rich physics from a simple system,” Am. J. Phys. 54, 112–121 (Feb. 1986). Google ScholarScitation, ISI3. D. P. Jackson, “Rendering the ‘not-so-simple’ pendulum experimentally accessible,” Phys. Teach. 34, 86–89 (Feb. 1996). Google ScholarScitation4. D. P. Randall, “Student-friendly precision pendulum,” Phys. Teach. 37, 390–393 (Oct. 1999). Google ScholarScitation5. A. Dupré and P. Janssen, “An accurate determination of the acceleration of gravity g in the undergraduate laboratory,” Am. J. Phys. 68, 704–711 (Aug. 2000). Google ScholarScitation, ISI6. T. Lewowski and K. Wozniak, “The period of a pendulum at large amplitudes: A laboratory experiment,” Eur. J. Phys. 23, 461–464 (2002). Google ScholarCrossref7. M. Vannoni and S. Straulino, “Low-cost accelerometers for physics experiments,” Eur. J. Phys. 28, 781–787 (2007). Google ScholarCrossref8. J. Sinacore and H. Takai, “Measuring g using a magnetic pendulum and telephone pickup,” Phys. Teach. 48, 448–449 (Oct. 2010). Google ScholarScitation9. Khairurrijal, E. Widiatmoko, W. Srigutomo and N. Kurniasih, “Measurement of gravitational acceleration using a computer microphone port,” Phys. Educ. 47, 709–714 (2012). Google ScholarCrossref10. J. Briggle, “Analysis of pendulum period with an iPod touch/iPhone,” Phys. Educ. 48, 285–288 (2013). Google ScholarCrossref11. V. Oliveira, “Measuring g with a classroom pendulum using changes in the pendulum string length,” Phys. Educ. 51, 063007 (2016). Google ScholarCrossref12. L. A. Ladino and H. S. Rondón, “Determining the damping coefficient of a simple pendulum oscillating in air,” Phys. Educ. 52, 033007 (2017). Google ScholarCrossref13. The period of the pendulum is T=2πlg(1+θ2/16+⋯), where θ is the maximum angular displacement from the equilibrium position. For θ = 10°= 0.17 rad, the second term in the parentheses is about 0.002. The departure from isochronism can be perceived when the angle is wide enough, as in the student lab reported in Ref. 14. Google Scholar14. N. G. Holmes and D. A. Bonn, “Quantitative comparisons to promote inquiry in the introductory physics lab,” Phys. Teach. 53, 352–355 (Sept. 2015). Google ScholarScitation, ISI15. D. Freedman and P. Diaconis, “On the histogram as a density estimator: L2 Theory,” Z. Wahrscheinlichkeitstheorie verw. Gebiete 57, 453–476 (1981). Google ScholarCrossref16. J. R. Taylor, An Introduction to Error Analysis (University Science Books, Sausalito, 1982). Google Scholar17. I. G. Hughes and T. P. A. Hase, Measurements and their Uncertainties (Oxford University Press, New York, 2010). Google Scholar18. Department of Defense World Geodetic System 1984, NIMA TR8350.2, 3rd ed., Table 3.4, Eq. 4-1. Google Scholar© 2019 American Association of Physics Teachers. Please Note: The number of views represents the full text views from December 2016 to date. Article views prior to December 2016 are not included. Page 2 In the modern and exciting world of particle physics, in which scientists talk of Higgs bosons and supersymmetry, it would be natural for someone to dismiss the common proton as a particle too pedestrian to be interesting. Yet in the centennial year of the announcement of its discovery, studies of the humble nucleus of the hydrogen atom continue to teach us fascinating lessons about the subatomic world.In the modern and exciting world of particle physics, in which scientists talk of Higgs bosons and supersymmetry, it would be natural for someone to dismiss the common proton as a particle too pedestrian to be interesting. Yet in the centennial year of the announcement of its discovery, studies of the humble nucleus of the hydrogen atom continue to teach us fascinating lessons about the subatomic world.As recently as 2018, scientists found themselves unable to definitively determine as simple a parameter as the radius of the proton. And uncertainties in the detailed internal structure of the proton continue to be the dominant limitation of precision measurements conducted at such particle accelerators as the Large Hadron Collider. Indeed, the final story of the proton has yet to be told. As familiar as the proton is, it’s valuable to remember that it wasn’t all that long ago that even its existence wasn’t known to science.1,21. D. Lincoln, Understanding the Universe: From Quarks to the Cosmos (revised) (World Scientific, 2014);R. Crease and C. Mann, The Second Creation: Makers of the Revolution in Twentieth-Century Physics (Rutgers University Press, 1996);L. Lederman and D. Teresi, God Particle: If the Universe Is the Answer, What Is the Question? (Mariner Books, 2006).2. J. Campbell, “Rutherford, Transmutation and the Proton,” CERN Courier (May/June 2019), p. 27, . Ernest Rutherford is most famously known for his experiments shooting alpha particles at a thin gold film, which resulted in the then-surprising observation that some of the alpha particles ricocheted backward, “as if a 15-inch shell had bounced off a sheet of tissue paper.” J. J. Thomson, Rutherford’s thesis advisor and discoverer of the electron, had proposed what is called the Plum Pudding model of the atom, in which tiny and negatively charged electrons were embedded in some sort of positively charged goo. However, Rutherford’s experiment proved Thomson’s model was incorrect and, after a year or so thinking about the implications of his experiment, Rutherford realized that atoms consisted of a small and dense positively charged core, surrounded by a diffuse cloud of electrons. But the nature of the nucleus of the atom was not immediately apparent. In fact, there was a school of thought that treated atomic nuclei as objects that were not able to be split into smaller units. It was in 1913 that Rutherford directed his assistant Ernest Marsden to “play marbles” with alpha particles and light nuclei, especially hydrogen nuclei. From simple classical calculations (of a one-dimensional collision with the proton initially at rest and by using a statistical treatment of a charged particle slowing in matter from repeated collisions with atomic electrons), one can determine that in a head-on collision between an alpha particle and a hydrogen nucleus (called at the time “H” particles, but what we now call the proton), the nucleus should recoil with a speed 1.6 times that of the alpha particle and penetrate material to a depth four times deeper than the initial alpha.33. M. Tanabashi et al. (Particle Data Group), “Passage of particles through matter,” Phys. Rev. D 98, 030001 (2018), . Note that the velocity of the outgoing proton is determined by assuming a one-dimensional elastic scattering between an alpha particle (mα = 4 mp), moving at velocity v, hitting a stationary proton (mp). The depth of penetration is determined by using Eq. (33.5) in this reference. Marsden did indeed see H particles with the appropriate range. However, Marsden also saw H particles when alpha particles were passed through air. Where those particles came from was not known, whether it was the air itself, water vapor, or some contaminant. World War I intervened, and Rutherford turned his attention to submarine detection and it wasn’t until 1917 that he returned to experiments involving alpha particles. He continued to shoot alpha particles at a variety of materials, including hydrogen, hydrogen-rich solids, carbon dioxide, and nitrogen. He found that in alpha/nitrogen collisions he saw a lot of H particle emission. He deduced that what was happening was, in the collision, H particles were being knocked off the nitrogen nucleus. From that insight, it was a short intellectual step to propose that atomic nuclei were made of an assemblage of hydrogen nuclei. And, in 1919, he announced his conclusions to the world. It was in 1920 that Rutherford coined the term “proton.” Rutherford also hypothesized that there existed in the nucleus of atoms another, electrically neutral, particle, with a mass similar to the proton. He suggested that James Chadwick, a student of his, investigate this hypothesis and Chadwick discovered the neutron about a decade later. The triumvirate of advisor, researcher, and student (Thomson, Rutherford, and Chadwick) had unraveled the structure of the atom. In short order, the properties44. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018), . of the proton were determined. It has an electrical charge of 1.602176634×10−19 coulombs, equal in magnitude but opposite in sign to the electron. Precisely why these two subatomic particles have exactly the same magnitude is still unknown. The proton has a mass of 1.007276466879 ± 0.000000000091 amu, or 938.2720813 ± 0.0000058 MeV/c2. Its radius, as defined by the distribution of electrical charge, is about 0.85 fm, although two measurements, using different techniques and both quoting very precise uncertainties, are in disagreement. More will be said of that below. The lifetime of the proton, including all decay modes, is > 2.1×1029 years, with an estimated lifetime of the theoretically attractive decay mode of p+ → e+π° of > 8.2 × 1033 years. (The lower limit on the proton’s lifetime reflects limited experimental sensitivity to all possible decay modes, while the much higher limit on the single decay chain reflects increased instrumental sensitivity to that particular decay mode.) The proton has a spin of ħ/2, where ħ is the reduced Planck’s constant. The proton has a magnetic moment of 2.79284734462 ± 0.00000000082 Bohr magnetons and an electric dipole moment of < 0.021 × 10−23 e.cm, which means that it is incredibly spherical. With such precise measurements of the properties of this well-known particle, it would seem that the proton would hold few mysteries. However, the proton is far more complex than the simplified version that plays a role in atomic and nuclear physics. The 1950s were an exciting time for particle physics. By converting energy into mass, researchers used particle accelerators to create subatomic particles that were not typically found in nature. These particles had a diverse set of properties, but a subset called baryons were qualitatively similar to the familiar proton and neutron (e.g., similar in mass and experienced the strong nuclear force). In addition, there were the lighter mesons, which were superficially similar to the proton and neutron, but with a smaller mass and different subatomic spin. Mesons are all bosons, with integer spin in units of ħ, while the baryons were fermions, with half-integer spin. For over a decade, researchers grappled with the patterns of charges, masses, lifetimes, and other properties until 1964 when Murray Gell-Mann and George Zweig independently realized1,51. D. Lincoln, Understanding the Universe: From Quarks to the Cosmos (revised) (World Scientific, 2014);R. Crease and C. Mann, The Second Creation: Makers of the Revolution in Twentieth-Century Physics (Rutgers University Press, 1996);L. Lederman and D. Teresi, God Particle: If the Universe Is the Answer, What Is the Question? (Mariner Books, 2006).5. M. Gell-Mann, “A schematic model of baryons and mesons,” Phys. Lett. 8 (3), 214 (1964); 64)92001-3G. Zweig, An SU(3) Model for Strong Interaction Symmetry and its Breaking, CERN Report No. 8182/TH.401 (1964). that the patterns could be explained if protons contained smaller particles within them. Gell-Mann called them “quarks,” while Zweig used the term “aces.” Gell-Mann’s choice has been adopted by the scientific community. In Gell-Mann’s initial paper, three distinct varieties of quarks were proposed, with the names up, down, and strange. The names have historical significance, with up and down connected to nuclear isospin,66. D. Griffiths, Introduction to Elementary Particles, 2nd ed. (Wiley-VCH, 2008). and strange having to do with a conserved quantity observed in the production of certain baryons.11. D. Lincoln, Understanding the Universe: From Quarks to the Cosmos (revised) (World Scientific, 2014);R. Crease and C. Mann, The Second Creation: Makers of the Revolution in Twentieth-Century Physics (Rutgers University Press, 1996);L. Lederman and D. Teresi, God Particle: If the Universe Is the Answer, What Is the Question? (Mariner Books, 2006). Since the model was initially proposed, three additional quarks have been discovered, called charm, bottom, and top. The up, charm, and top quarks have an electrical charge of +2/3 that of a proton, while the down, strange, and bottom quarks have a charge of –1/3 that of a proton. All quarks are fermions with spin of ±1/2 in units of ħ. Baryons contain three quarks, with the proton containing two up quarks and one down quark. Neutrons contain one up quark and two down quarks. In order for the fermion quarks to create a fermion proton with a spin of ½, the spin of the quarks must be oriented with two parallel and one antiparallel. Baryons contain any combination of quarks and, at the time the model was proposed, the configuration containing three strange quarks had not been observed. However, very shortly after the quark model was proposed, the Ω− baryon was discovered.77. V. E. Barnes et al., “Observation of a hyperon with strangeness minus three,” Phys. Rev. Lett. 12, 204 (1964). This particle contained three strange quarks and thus the quark model was validated. The Ω− baryon posed a problem for physicists. It has a spin of 3/2,88. B. Aubert et al. (BABAR Collaboration), “Measurement of the spin of the Ω− hyperon,” Phys. Rev. Lett. 97, 112001 (2006). which means that it has three strange quarks, all with spin of ½. Quantum mechanics forbids identical fermions to exist in the same quantum state,99. K. Krane, Modern Physics, 3rd ed. (Wiley, 2012). so this particle runs afoul of very basic physical principles. This problem was resolved in 1964 by Oscar Greenberg, although his treatment differed from a modern methodology, and Greenberg has mentioned Han and Nambu as an improved approach.1010. O. Greenberg, “Spin and unitary-spin independence in a paraquark model of baryons and mesons,” Phys. Rev. Lett. 13, 598–602 (1964); . Y. Han and Y. Nambu, “Three-triplet model with double SU(3) symmetry,” Phys. Rev. 139, B1006 (1965). These researchers proposed a new quantum number called “color” as a way to distinguish between the three quarks. Each quark has a unique color (red, green, blue), while the proton as a whole has none (e.g., white). The term color has nothing to do with color as the word is generally understood, but it mirrors the property of red, blue, and green light to appear white when mixed. While the quark model made some predictions, many physicists, including Gell-Mann, thought quarks as representing an organizing mathematical structure and were not actual particles. That view started to change in 1968 when data recorded using the SLAC accelerator began to reveal that protons were definitely composite particles.1111. E. D. Bloom et al., “High-energy inelastic e–p scattering at 6° and 10°,” Phys. Rev. Lett. 23 (16), 930–934 (1969); . Breidenbach et al., “Observed behavior of highly inelastic electron–proton scattering,” Phys. Rev. Lett. 23 (16), 935–939 (1969). These experiments shot high-energy electrons at a stationary proton target. In principle, the kinematics of the collisions between an electron and point-like proton is simple two-body elastic scattering, governed by the same mathematics as taught in any introductory physics course. Further, by simply measuring the energy of the incoming and outgoing electron and assuming the proton was at rest, the energy and momentum of the collision are fully determined. When researchers performed these experiments (and eventually with follow-on experiments using both muons and neutrinos as beam particles), they found that the simplest prediction did not work. While collisions at lower energy followed the predictions of electron-proton elastic collision theory, when the collisions became more violent, the collisions became increasingly inelastic. The data very definitely suggested that protons contained constituent particles that carried a fraction of the energy and momentum of the proton. In 1969, Richard Feynman coined the term “partons” to describe these quark constituents,1212. R. Feynman, “The behavior of hadron collisions at extreme energies,” in High Energy Collisions: Third International Conference at Stony Brook, N.Y. (1969), pp. 237–249. and his approach was followed by James Bjorken and Emmanuel Paschos in interactions between electrons and protons. The SLAC experiment revealed that protons contained many particles that interacted with one another. Further, they demonstrated that protons contained more than the three quarks postulated by Gell-Mann. The measurement determined the proton consisted of many partons, each carrying a fraction x of the momentum of the proton, e.g., x = pparton/pproton. In each collision, an electron passed near the proton and emitted a photon that probed deeply inside the proton and interacted with one of the electrically charged partons. Each collision interacted with a single parton and, event after event, researchers were able to reconstruct the distribution of the fraction of the momentum carried by electrically charged partons. Further, this measurement reveals a great deal about the distribution of momentum within protons. Figure 3 illustrates this point. If the photon emitted by the electron interacted with a solid and structureless particle, the momentum fraction would always be simply 1. In the Gell-Mann non-interaction quark model, each of the three quarks would carry precisely 1/3 of the proton’s momentum. If the proton’s constituent quarks were able to interact with one another, we would expect a momentum fraction distribution peaked near 1/3, but with some variation. And if the quarks not only exchanged momentum, but also emitted force-carrying particles that could then subsequently convert into quark matter/antimatter pairs, the distribution would be further modified to have more of the proton’s momentum concentrated at very low momentum fraction. It is this fourth possibility that is what is observed. These observations led to the development of the theory of quantum chromodynamics, which is the model of strong nuclear force interactions.1,151. D. Lincoln, Understanding the Universe: From Quarks to the Cosmos (revised) (World Scientific, 2014);R. Crease and C. Mann, The Second Creation: Makers of the Revolution in Twentieth-Century Physics (Rutgers University Press, 1996);L. Lederman and D. Teresi, God Particle: If the Universe Is the Answer, What Is the Question? (Mariner Books, 2006).15. D. J. Gross and F. Wilczek, “Ultraviolet behavior of non-abelian gauge theories,” Phys. Rev. Lett. 30 (26), 1343–1346 (1973); . Politzer, “Reliable perturbative results for strong interactions,” Phys. Rev. Lett. 30 (26), 1346–1349 (1973). Briefly, in this model, a proton consists of three “valence” (e.g., persistent) quarks as predicted by Gell-Mann, but the force between the quarks is mediated by the exchange of force-carrying particles called gluons. These gluons can briefly turn into quark matter/antimatter pairs (called “sea” quarks), before they annihilate and become a gluon, which is then absorbed by other quarks. The structure of a proton is extremely complicated. The structure of the proton is further complicated by the fact that there is a large range of the physical size of those structures. Because the wavelength of the probe photon is inversely proportional to its momentum, higher momenta photons can resolve smaller structures, as seen in Fig. 4. Accordingly, the structure of the proton becomes more complex and a larger fraction of the proton’s momentum can be seen to be stored in low-momentum, small-size structures. Physicists must thus not only study the structure of the photon as a function of the momentum fraction they are investigating, but also as a function of the scale of the wavelength of the probing photon. Further, it is possible to make a measurement at one momentum fraction and photon wavelength scale and extrapolate to other scales. An accurate knowledge of the distribution of momentum among partons is crucial for accurate predictions of high- energy experiments. Of special concern is the distribution of momentum carried by gluons at high-x. Because gluons (being neutral and not subject to either the electromagnetic or weak forces) cannot be directly probed by electron, muon, or neutrino beams, this distribution remains relatively poorly measured. It can only be investigated in collisions involving pairs of hadrons. These measurements have constrained this distribution, but further work is needed. A proton is a fermion with spin ½. In the simplest quark model, it contains three fermion quarks of spin ½. Accordingly, in the quark model, the spin of the proton resides in the alignment of its constituent valence quarks, with two quarks having parallel spin and one antiparallel. However, in 1988, the European Muon Collaboration (EMC) fired a beam of muons with known spin polarization at a target of polarized protons (e.g., ones where the spin of the protons are aligned) and measured the spin of the proton carried exclusively by the intrinsic spin of the quarks and antiquarks, and found that they amounted to only a fraction of the spin of the proton. Essentially, they found that the spin of the quarks and antiquarks were (on average) equally parallel and antiparallel to the proton.1616. R. Jaffe, “Where does the proton really get its spin?” Phys. Today 48 (9), 24–30 (1995). The EMC experiment used a muon beam, which emitted a photon, which then interacted exclusively with the charged partons (e.g., quarks and antimatter quarks) in the proton. EMC was not able to study the contribution to the spin of the proton from gluons. Gluons are spin 1 bosons. It took two decades before spin information for gluons began to become available. These measurements arose from data recorded from collisions between two polarized beams of protons at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. In 2008, the first studies revealed a gluonic contribution to the spin of the proton. However, there were large experimental uncertainties and it took yet another decade to get a better picture of what is going on. More recent measurements1717. J. Adam et al. (STAR Collaboration), “Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at √s = 510 GeV,” Phys. Rev. D 99, 051102 (2019). show that the spin of a proton comes from a very complicated admixture of the intrinsic spin of both the valence quarks and sea quark/antiquark pairs, as well as their orbital angular momentum. In addition, the gluons contribute spin from both their intrinsic and orbital motion. The specific fractions from each component continue to be studied at various locations including the Thomas Jefferson National Accelerator Facility, in Newport News, VA. Figure 5 illustrates the differences between our understanding of the structure of the proton in 1980 compared to it now. This figure highlights the color (e.g., strong force charge) of the proton, along with a simplified (but modern) depiction of how the proton spin is distributed among the valence quarks, the sea quarks, and the motion of the partons, including the gluons. This figure should be contrasted to the depiction of the proton on the cover of this issue. In that artistic rendition, representation of the strong force charge and the spin is entirely missing. Instead, that image focuses on the flavor (e.g., quark type) of the partons. There, the blue spheres represent up quarks and the red ones denote down quarks. The smaller spheres represent quark/antiquark sea pairs, with the ones with a highlighted rim being the antiquarks. And in the cover image, the dashed lines give the smallest flavor of the cacophony of gluons that are constantly jumping throughout the proton. The contrast between the cover and Fig. 5 demonstrates the difficulty of illustrating the entire complexity of the partonic content of the proton, as it contains a variety of properties, including particle flavors, strong force charge (color), electrical charges, spins, motion, and both matter and antimatter components. The structure of the proton is exceedingly rich. To determine the size of a proton, one first needs to have an accurate mental image of the particle. Protons are not hard objects, like bowling balls. Instead, the surface of a proton is more analogous to Earth’s atmosphere, denser near the surface of Earth and more rarified at larger distances. This distribution has been probed by scattering electrons off protons and a root mean square radius of the charge distribution of a proton has been determined to be about 0.88 fm. Since about the year 2000, other studies have employed very precise measurements of spectral transitions in electrons surrounding the proton to extract a precise measurement of the proton’s radius. Because some atomic orbitals extend to the center of the atom, these transitions are sensitive to the charge distribution of protons. When all experiments of these nature are combined, the RMS charge radius of the proton is 0.8751 ± 0.0061 fm.44. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018), . Measurements of the spectral transitions in muonic hydrogen (e.g., atoms in which the electron is replaced by a muon) are also sensitive to the RMS charge radius of the proton. Further, because muonic hydrogen is 0.5% the size of regular hydrogen, these measurements are more sensitive to the charge distribution of the proton. These measurements result in a different number, specifically 0.84087 ± 0.00039 fm.44. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018), . These numbers disagree in a statistically significant way and this is called the proton-radius puzzle. Initially, the solution to the puzzle was thought to arise from differences between electrons and muons, and there was the exciting prospect that perhaps new physical phenomena might be the cause. However more recent measurements1818. A. Beyer et al., “The Rydberg constant and proton size from atomic hydrogen,” Sci. 358, 79 (2016). of the size of proton using ordinary hydrogen (i.e., protons + electrons) have resulted in a lower estimate for the proton’s radius. It is appearing that the “electron vs. muon” solution is not the answer. The problem appears to arise between atomic and scattering measurements, and it may well be that the disagreement is rooted in limitations in the scattering technique. In scattering experiments, the proton recoils against the probing particle and this must be taken into account. At the moment, experimental groups must make measurements as a function of the energy of the probe and extrapolate to zero scattering energy. Recent measurements of the radius of the proton are now available at much lower collision energies, and they report a smaller proton radius of 0.810 ± 0.082 fm.1919. M. Mihovilovič et al., “First measurement of proton’s charge form factor at very low Q2 with initial state radiation,” Phys. Lett. B 771, 194 (2017). Other low energy measurements report a similarly low measurement of the proton’s radius.2020. As of this writing, these measurements have not been published and exist only in unpublished conference talks. Additional studies are currently under preparation or under way2121. M. Aghasyan et al. (COMPASS Collaboration), “First measurement of the transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process,” Phys. Rev. Lett. 119, 112002 (2017); . Kohl, for the MUSE Collaboration, “The Muon Scattering Experiment (MUSE) at PSI and the proton radius puzzle,” EPJ Web Conf. 81, 02008 (2014). at a variety of laboratories around the world, and it would appear that a future world average estimate of the radius of the proton will be smaller than that reported in Ref. 44. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018), . . The proton is one of the fundamental building blocks of atomic matter and we’ve known of its existence for a century. Yet the reality is that it remains an interesting particle, with many mysteries still to be resolved. It is fitting that, in its centennial year, we can wish that studies of the proton will continue for years to come. Happy birthday, proton! 1. D. Lincoln, Understanding the Universe: From Quarks to the Cosmos (revised) (World Scientific, 2014); Google ScholarR. Crease and C. 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Lett. 119, 112002 (2017); Google ScholarCrossrefM. Kohl, for the MUSE Collaboration, “The Muon Scattering Experiment (MUSE) at PSI and the proton radius puzzle,” EPJ Web Conf. 81, 02008 (2014). , Google ScholarCrossref© 2019 American Association of Physics Teachers. Please Note: The number of views represents the full text views from December 2016 to date. Article views prior to December 2016 are not included.