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Terry M. Christensen for the Degree of Master of Science in History of Science presented on June 12, 2006

Title: Theoretical Physics Takes Root in America: John Archibald Wheeler as Student and Mentor

Abstract approved:

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Mary Jo Nye, Ph.D.

John Archibald Wheeler (09 July 1911 –) is a familiar name to physicists and historians of physics alike. Among his many contributions to the corpus of knowledge, in 1939 John Wheeler and Niels Bohr co-authored the first paper on the generalized mechanism of nuclear fission. Beyond that seminal work, Wheeler was a key player in the production of the 'Fat Man' plutonium weapon in the Manhattan project, and later, in the development of the Hydrogen Bomb. Wheeler introduced the scattering matrix (or S-matrix) to account for all possible final quantum states of collisions between nucleons. After turning his attention to general relativity, Wheeler and his students made a number of significant contributions to cosmology and cosmology. In fact, John Wheeler coined the term "black hole," and developed the concepts of a "Planck Length," a Planck-time," "quantum foam," and "wormholes" in space-time.

Outside the physics community however, considerably less is known about John Wheeler as a mentor of physicists. Mentoring is important because, while there can be no progress in physics without contributions to the corpus of knowledge, these contributions are, by their very nature additive. In contrast, the contributions of skilled mentors such as John Archibald Wheeler are multiplicative through a number of intellectual generations. Until quite recently, studies of mentoring in science were limited to 'laboratory' and/or 'field' disciplines such as chemistry and the life sciences. Clearly, mentoring styles are highly individualized. Nonetheless, a comprehensive census of elite mentors can offer considerable insight into the practice of mentoring in theoretical physics. This examination of the mentoring style and outcomes of John Archibald Wheeler traces his work as an apprentice under mentors Karl Herzfeld, Gregory Breit, and Niels Bohr, through Wheeler's career as a mentor in his own right at Princeton University during the years 1938-1977.

Theoretical Physics Takes Root in America: John Archibald Wheeler as Student and Mentor

by
Terry M. Christensen

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Terry M. Christensen, Author

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Every thesis is, to some extent, a collaborative effort. Since as an author, I tend to verbally process the data at hand, this particular project owes a good deal to a good many individuals who have helped with generous amounts of assistance, counsel, and support.

Here, I must begin with Dutton. Guide Dogs for the Blind has provided me with two exceptional guides, Shippey and Dutton. Shippey steered me through my first years of graduate education at Marylhurst University. As an example of the importance of a guide in my life, I would like the reader to know that three weeks after our 1996 graduation from Guide Dogs for the Blind, Shippey backed me out of the path of a vehicle that had failed to notice either the red light or a visually impaired man in the crosswalk. Although Dutton does not have a similarly dramatic intervention to his credit (at least as far as I know), his guide work is actually more crisp than that of Shippey. More to the point, any campus is a daunting navigational challenge for the visually impaired. Oregon State University is no exception. Without the support of Guide Dogs for the Blind in general, and the superlative guide work of Dutton in particular, this enterprise, indeed, graduate school would have been several orders of magnitude more difficult.

For their timely doses of encouragement and coaching, the author wishes to acknowledge History of Science cohort members Nathan Boltseridge, Erik Ellis, Melinda Gormley, Erica Jensen, Kristen Johnson, Christopher Jolly, Rachel Koroloff, Tully Long, Leslie McCabe, Katie Morris, and Leandra Swanner; all of whom, often perhaps involuntarily, have done more than their fair share of sounding-board duty.

I have also been blessed with friends who have shown an uncommon amount of patience with my endless ramblings as I verbally processed what I knew of John Wheeler. Specifically here, I am thinking of Terry Anderson, Stephen Bard, Steven Black, Peter Collier, Haakon Hofstad, Steve Lucker, Chuck Meitle, Ron Smith, and Michael Stewart. As with members of the OSU graduate cohort, these men have all provided timely doses of encouragement.

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One individual from this group deserves particular recognition. Kenneth W. Ford, a former Wheeler student who helped craft Wheeler's autobiography *Geons, Black Holes and Quantum Foam: A Life in Physics*, enthusiastically supported this enterprise almost from its inception. His insight into character of John Wheeler was invaluable. Moreover, as a former Executive Director of the American Institute of Physics, Kenneth Ford's perspective on Wheeler's place in the community of American theoretical physicists offered the project a unique and perceptive frame of reference.

The Department of History at Oregon State University includes a number of gifted, conscientious, and thoughtful faculty members who are generous with their time and counsel. Among those who have helped me shape my thinking of various aspects of mentoring and professional socialization, I want to acknowledge Ben Mutschler, William Robbins, Lisa Sarasohn and Jeffrey Sklansky. A subset of this group, Ron Doel, Paul Farber, and Robert Nye, have been unsparing in the gift of their advice and counsel.

A thesis on mentoring, of course, requires a mentor, and Professor Mary Jo Nye served this author and this project in that capacity. In the process of completing two Master's thesis concerning mentors, I have come to be an informed consumer of the mentoring process. Consequently, two aspects of Mary Jo's mentoring style are especially noteworthy. First of all, her constructive criticism, as well as her words of praise, are always thoughtful and exquisitely timed. Beyond that important skill, however, Mary Jo has shown herself to be unusually gifted as a mentor. It is one thing to see the full potential of a scholar. It is quite another to be able to extract that scholar's best work. Mary Jo has the combination of wisdom and skill to do both. In sum, I can unequivocally state that no scholar has profited more from an association with a mentor than I have in my apprenticeship with Professor Mary Jo Nye.

Finally, over the course of my lifetime, it has been my great blessing to have associated with some remarkable role models and life-skill mentors. Among these I must include Professor David Scott Arnold, Warren and Verna Blakslee, Sidney and Carol Cadwallader, the Hon. Robert Chopping, Calvin Thorwald and Judith Christensen, Coach John Mattila, Capt. Reino Mattila, Marc Pemberton, and Coach Fred O. Wilson. This enterprise, as much a product of their faith as it is of my effort, was developed with their indomitable spirit in mind.

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Dutton and I

Dedicate this thesis to

four people who have given my life new meaning:

Betsy Cadwallader, Steve Adams, Ben Adams, and Jay Jones

Theoretical Physics Takes Root in America: John Archibald Wheeler as Student and Mentor

Chapter One: Introduction

Section 1.1 Overview

Between 1930 and 2000, the annual production of physics doctorates in the United States increased by a factor of twelve.[1] How was such dramatic expansion possible? Certainly a primary prerequisite was the availability of skilled mentors. Thus, we are led to the central question that forms the rationale for this enterprise.

What role do mentors play in the practice of science? By several accounts, skillful mentoring is critical to the careers of the scientific elite.[2] Donald Kennedy, past president of Stanford University has written that

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[1] In 1930 the U.S. produced 99 Ph.D.s in physics. By 2000, the annual average was over 1200. Source: Katherine Russell Sopka, *Quantum Physics in America, 1920-1935* (New York: Arno Press, 1980), 4.65. Also cited in Peter Galison, *How Experiments End* (Chicago: University of Chicago Press, 1987), 138; American Institute of Physics, "Number of Physics Ph.D.s Conferred in the United States, 1900-2003", available online: <http://0-www.aip.org.oasis.oregonstate.edu/statistics/trends/highlite/ed/figure5.htm> (05 Jan 2006).

[2] The list of examples includes, but is by no means limited to: Harriet Zuckerman, *Scientific Elite: Nobel Laureates in the United States* (New York: The Free Press, 1977; reprint, New Brunswick, NJ: Transaction Publishing. 1996), xxi, 14-15, 96 et seq; Frederic Lawrence Holmes, *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists* (New Haven, CN: Yale University Press, 2004), xix, 27; Robert Kanigel, *Apprentice to Genius: The Making of a Scientific Dynasty* (Baltimore, MD: The Johns Hopkins University Press, 1986), x, xiii.

mentoring is "the highest form of academic duty."[3] In his autobiography *Geons, Black Holes, and Quantum Foam: A Life in Physics,* John Wheeler states unequivocally that "a good mentor" is the most important element in the early career of a researcher. "In two postdoctoral years," Wheeler continues, "I was blessed with two wonderfully strong mentors, Gregory Breit and Niels Bohr."[4] Certainly Breit and Bohr were major factors in John Wheeler's leadership as a physicist and his prolific contributions to the corpus of knowledge.[5] Wheeler, in turn, became one of the most influential of mentors in theoretical physics in the United States. But where and how do such mentors

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[3] Donald Kennedy, *Academic Duty* (Cambridge, MA: Harvard University Press, 1997), 116.

[4] John Archibald Wheeler with Ken Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York: W. W. Norton, 1998), 50.

[5] Wheeler's leadership in the areas of nuclear physics, quantum physics and general relativity have been noted by several historians. See, for example Peter Galison, "Physics Between War and Peace," in *Science, Technology, and the Military*, ed., Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart (Boston: Kluwer Academic Publishers, 1988), 57-58; Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Knopf, 1977), 328; Helge Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe* (Princeton, NJ: Princeton University Press, 1996), 369-372; Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century* (Princeton, NJ: Princeton University Press, 1999), 207-215, 279-280, 361-365, 410, 422; Silvan S. Schweber, "Quantum Field Theory Form QED to the Standard Model," in *The Modern Physical and Mathematical Sciences*, ed. Mary Jo Nye, vol. 5 of The Cambridge History of Science Series, General eds. David C. Lindberg and Ronald L. Numbers (New York: Cambridge University Press, 2003), 382-383; Herbert F. York, *Arms and the Physicist* (Woodbury, NY: American Institute of Physics Press, 1995), 117-118; Kip S. Thorne and Wojciech H. Zurek "John Archibald Wheeler: A Few Highlights of His Contributions to Physics," in *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler* ed. Wojciech Hubert Zurek, Alwyn van der Merwe, and Warner Allen Miller (Princeton, NJ: Princeton University Press, 1988), 3-13.

originate? Is it nature, nurture, or simply a matter of professional competence? This thesis undertakes a study of these questions with a focus on John Archibald Wheeler.

Still, a further refinement is necessary. To be sure, one can fill hundreds of pages with testimonials to John Wheeler without gaining any novel or significant insight. In order to produce a product of scholarly value, this thesis will situate John Wheeler's work as a mentor within the extant literature of scientific research schools.[6]

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[6] The literature on research schools is formidable. A list of sources includes, but is not by any means limited to the following: William H. Brock, "Liebigania: Old and New Perspectives," *History of Science* 19 (Sep 1981): 201-218; William H. Brock, *Justus von Liebig: The Chemical Gatekeeper* (New York: Cambridge University Press, 1997); Maurice Crosland, "Research Schools of Chemistry from Lavoisier to Wurtz," *The British Journal for the History of Science* 36, no. 3 (2003): 333-361; Joseph Fruton, "The Liebig Research Group: A Reappraisal," *Proceedings of the American Philosophical Society* 132 (1988): 1-66; Joseph Fruton, *Contrasts in Scientific Style: Research Groups in the Chemical and Biochemical Sciences* (Philadelphia: American Philosophical Society, 1990); Gerald L. Geison, "Scientific Change: Emerging Specialties and Research Schools," *History of Science* 19 (Mar 1981): 20-40; Gerald L. Geison and Frederic L. Holmes, eds., *Research Schools: Historical Reappraisals,* Osiris, 2d ser., vol. 8 (1993); Owen Hannaway, "The German Model of Chemical Education in America: Ira Remsen at The Johns Hopkins (1876-1913)," in *Ambix: The Journal of the Society for the History of Alchemy and Chemistry* 23 (1976): 145-164; Frederic Lawrence Holmes, *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists,* (New Haven, CN: Yale University Press, 2004); J. B. Morrell, "The Chemist Breeders: The Research Schools of Liebig and Thomas Thomson," *Ambix: The Journal of the Society for the History of Alchemy and Chemistry* 19 (Mar 1972): 1-46; Mary Jo Nye, "National Styles? French and English Chemistry in the Nineteenth and Early Twentieth Centuries," in *Research Schools: Historical Reappraisals*, ed. Gerald L. Geison and Frederic L. Holmes, Osiris, 2d ser., vol. 8 (1993), 30-49; Mary Jo Nye, "Scientific Disciplines: The Construction of Identity," Chap. 1 in *From Chemical Philosophy to Theoretical Chemistry: Dynamics of Matter and Dynamics of Disciplines, 1800-1850* (Berkeley, CA: University of California Press, 1993); Kathryn M. Olesko,

Section 1.2 An Underdeveloped Area of Scholarship

In 1981, Gerald Geison suggested that since research schools have been, "the predominant concrete organizational form in science since the mid-nineteenth century," any study of scientific change that does not involve individual research schools as an analytical unit of study, "is bound to be inadequate or incomplete in some respects."[7] Geison's 1981 paper (as well as his 1993 edited volume) explicitly defined research schools as, "small groups of mature scientists pursuing a reasonably coherent program of research side-by-side with advanced students in the same institutional context and engaging in direct, continuous social and intellectual interaction."[8] This definition, it seems to me, very aptly describes John Wheeler and his Ph.D. students at Princeton during the years 1938-1977. In any event, since Geison first promulgated his definition of research school and his argument for making them an analytical unit of study, a number scholars have sought to compare and contrast research schools by investigating their guiding philosophies, social characteristics, and productivity (i.e. output of students) across regional, disciplinary, or national boundaries.

Physics as a Calling: Discipline and Practice in the Konigsberg Seminar for Physics (Ithaca: Cornell University Press, 1991); Kathryn M. Olesko, "Tacit Knowledge and School Formation," in *Research Schools: Historical Reappraisals*, ed. Gerald L. Geison and Frederic L. Holmes, Osiris, 2d ser., vol. 8 (1993), 16-29; John W. Servos, "Research Schools and Their Histories," in *Research Schools: Historical Reappraisals*, ed. Gerald L. Geison and Frederic L. Holmes, Osiris, 2d ser., vol. 8 (1993), 1-15.

[7] Gerald L. Geison, "Scientific Change," 37

[8] Gerald L. Geison, "Scientific Change,20, 23 ; Geison and Holmes, *Research Schools*, 228.

This project augments that body of scholarship by approaching the issue from a more focused frame of reference. It is useful to recall here that early in his discussion, Geison incorporated J. B. Morrell's description of an "ideal" research school. A prominent feature of that model was the presence of a "charismatic director."[9] Yet, while scholars affirm the Morrell-Geison comment that charismatic leadership is a prerequisite for the success of a research school, the art or practice of mentoring is not discussed in any of these studies.[10] Nor is there any discussion of mentoring practice or proficiency in the studies which compare and contrast leadership styles in various research schools. In my view, the absence of a mentoring discourse in the context of research schools presents itself as an underdeveloped area of scholarship which this thesis can address.

This project is also novel in that it addresses the discipline of theoretical physics. To be clear, some very recent and quite engaging work by David Kaiser is notable in part because it addresses pedagogy in theoretical physics. Kaiser has chosen to concentrate on "paradigms" (i.e. worldviews)

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[9] Geison, "Scientific Change," 23; J. B. Morrell, "The Chemist Breeders," (Mar 1972), 36-37.

[10] Pamela M. Henson, "The Comstock Research School in Evolutionary Entomology," in Geison and Holmes, *Research Schools,* 175-176; Kanigel, *Apprentice to Genius*, ix [Introduction]; David Kushner, "Sir George Darwin and a British School of Geophysics," in Geison and Holmes, *Research Schools*, 220; Alan Rocke, "Group Research in German Chemistry, 78; R. Steven Turner, "Vision Studies in Germany: Helmholtz versus Hering," in Geison and Holmes, *Research Schools*, 87, 89; Andrew Warwick, *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Cambridge: Cambridge University Press, 2003), 352; Harriet Zuckerman, *Scientific Elite*, 126.

and pedagogical tools (e.g. Feynman Diagrams) as his fundamental units of analysis, while this present study chooses an individual mentor as the unit of analysis. [11]

With the exception of Kaiser's work, virtually all of the research school literature has focused on experimental and observational disciplines. Much of this scholarship deals with artisanal competencies (some tacit, some explicit) that were passed along from master to apprentice. The same can be said of those studies which explicitly target mentoring in science, with two notable exceptions (Christensen and Zuckerman).[12]

In a 2001 study focusing on Niels Bohr and Richard Feynman, I examined the impact of a mentor's world-view (specifically the degree to which the mentor's approach was interdisciplinary) on the relative success of that mentor. The earlier study did not however, address the art and practice of mentoring.[13] In the present project, I intend to demonstrate in detail that the study of mentoring in a specific setting and in theoretical context will augment the efforts of earlier scholars in the study of research schools and scientific change. Finally, it appears that certain elements of pedagogical style

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[11] David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics*, (Chicago: University of Chicago Press, 2005); David Kaiser, "Making Tools Travel: Pedagogy and the Transfer of Skills in Postwar Theoretical Physics," in *Pedagogy and the Practice of Science*, ed. David Kaiser (Cambridge, MA: MIT Press, 2005), 41.
[12] The two exceptions are Terry M. Christensen, "Creating Chains of Wisdom: The Role of Interdisciplinarity in Mentoring" (Master's Thesis, Marylhurst University, 2001) and Harriet Zuckerman, *Scientific Elite*. While Zuckerman discusses aspects of mentoring, her emphasis is on the sociological contexts which foster Nobel laureates rather than the practice of mentoring.
[13] Christensen, "Creating Chains of Wisdom."

(particularly those elements that are tacitly communicated) may act as genealogical markers through intellectual generations.[14]

Section 1.3 Delimiting the Discipline: Theoretical Physics

Theoretical physics was first taught as a discrete subject in 'Germanic' universities during the later half nineteenth century. Late in his career, Georg Simon Ohm (1789-1854) became one of the first recipients of a theoretical professorship in theoretical physics. Historians Christa Jungnickel and Russell McCormmach suggest that theoretical physics began to be seen as a separate discipline after 1870 when Gustav Kirchhoff (1824-1887) became a professor of theoretical physics in Berlin.[15]

By 1894, the French physics community had also concluded that a more generalized reference frame was necessary for a full comprehension of physical phenomena. The esteemed historian Mary Jo Nye describes a Faculty of Sciences Council meeting which at the University of Bourdeaux where it was decided to request the French Educational Ministry to create a

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[14] Michael Polanyi, *The Tacit Dimension* (New York: Doubleday, 1966), 21-23; Kaiser, *Pedagogy and the Practice of Science*, (2005), 2, 7 ["Introduction"] and also 66-67 [Kaiser, "Making Tools Travel: Pedagogy and the Transfer of Skills in Postwar Theoretical Physics"]; Also in *Pedogogy and the Practice of Science,* see Hugh Gusterson, "A Pedagogy of Diminishing Returns: Scientific Involutions Across Three Generations of Nuclear Weapons Science," 91; and Kathryn Olesko, "The Foundations of a Canon: Kohlrausch's Practical Physics," 323, 340-341; Olesko, "Tacit Knowledge and School Formation," in *Geison and Holmes, Research Schools,* 16-17, 28; Mary Jo Nye, "National Styles?" in Geison and Holmes, *Research Schools,* 49.
[15] Christa Jungnickel and Russell McCormmach, *Intellectual Mastery of Nature: Theoretical Physics From Ohm to Einstein,* 2 vols (Chicago: University of Chicago Press, 1986), xvi-xvii.

new chair of physics for Pierre Duhem (1861-1916), with the title mathematical physics. This chair in fact came to be called a chair of theoretical physics. Note what was said in the Council:

> Physics has made great progress in recent years and developed so that the number of people charged with presenting it has greatly increased. A deep schism has been produced between what one calls, on the one hand, experimental physics---which seeks the numerical properties of bodies---and on the other hand, theoretical physics, which attempts to encompass the ensemble of phenomena in laws or mathematical formulas.[16]

In France, as in Germany and Great Britain, the necessity of a global perspective—a generalized frame of reference in which to situate physical phenomena was clear.[17]

Even with designated professorships, and the increasing incorporation of higher mathematics in the practice of physics, it was not until early in the twentieth century that physicists came to think of themselves in terms of theoretician or experimentalist.[18] Part of this cultural inertia is due to the lag in adequate mathematical training in secondary schools. Although this deficiency was initially prevalent on both sides of the Atlantic, it took somewhat longer to correct in the U.S. than it did in Germany.[19]

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[16] Mary Jo Nye, *Science in the Provinces: Scientific Communities and Provintial Leadership in France, 1860-1930* (Berkeley: University of California Press, 1986), 213.
[17] Nye, *Science in the Provinces,* 213.
[18] Jungnickel and McCormmach, *Intellectual Mastery of Nature*, 41-42; in Helmholtz' mind, a complete physicist should be able to do both mathematical physics and experimental physics; Peter Galison, *How Experiments End,* 138.
[19] Jungnickel and McCormmach, *Intellectual Mastery of Nature*,, 6-7; John W. Servos, "Mathematics and the Physical Sciences in America," in *The Scientific Enterprise in America: Readings From Isis,* ed. Ronald L. Numbers and

I also want to be careful here not to give the impression of conflating applied or 'real-world' physics with experimental physics and/or conflating abstract or 'pure' physics with theoretical physics. In fact, during the formative years of theoretical physics in Germany, the extraordinary professors who were responsible for theoretical instruction were often assigned to lecture on technical or applied physics as well.[20] Coincidentally, in that same time frame, elements of the scientific leadership in the United States publicly disdained applied physics (i.e. the pursuit of science solely for profit). In any event the classification criteria was not terribly clear. As the historian Daniel Kevles observes, the term 'pure' referred more to a scientist's motives rather than their area of study.[21]

I hasten to note here that nothing in this study should be construed to suggest that one of these frames of reference (e.g. theoretical physics) can claim primacy over the other. These are complementary—though not necessarily synchronized—modes of attacking problems. A breakthrough in

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Charles E. Rosenberg (Chicago: University of Chicago Press, 1996), 145-148, 153-159.

[20] Jungnickel and McCormmach, *Intellectual Mastery of Nature*, 55-58.

[21] Daniel J. Kevles, "The Physics, Mathematics, and Chemistry Communities: A Comparative Analysis" in *The Organization of Knowledge in Modern America, 1860-1920*, ed. Alexandra Oleson and John Voss (Baltimore, MD: The Johns Hopkins University Press, 1979), 141. Among others, Kevles was doubtlessly referring to The Johns Hopkins physicist Henry Augustus Rowland. See Henry Augustus Rowland, "A Plea for Pure Science" [Address as Vice-President of Section B of the American Association for the Advancement of Science, Minneapolis, MN (15 Aug 1883)], in *The Physical Papers of Henry Augustus Rowland*, Compiled by A Committee of the Faculty of The Johns Hopkins University (Baltimore, MD: The Johns Hopkins University Press, 1902.), 594.

theory (e.g. special relativity) does not necessarily suggest an imminent and/or congruent breakthrough in experimental physics.[22]

In sum, the term "theoretical" physics, as employed here indicates a somewhat broader spectrum of inquiry that employs mathematical analysis to address the general nature of a class of phenomena. Mathematical Physics is typically focused on either mathematical descriptions of a given phenomenon (as opposed to a class of phenomena) and/or the development of mathematical techniques that can be applied to describe physical phenomena. Experimental Physics employs measuring and/or detection instruments situated in a laboratory or field setting to address the specific machinations of an individual phenomenon. Put simply, Mathematical Physics and Experimental Physics are distinguished from one another by their methods, the requisite equipment and the locale in which they are employed. Theoretical Physics is distinguished from both Mathematical Physics and Experimental Physics by its generalized frame of reference.

Section 1.4 The Choice of Subject

Why choose John Wheeler? One obvious answer is his position among the "ultra-elite" of American physicists.[23] Among his many contributions to the corpus of knowledge, in 1939 John Wheeler and Niels Bohr co-authored the first paper on the generalized mechanism of nuclear fission. Beyond that

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[22] Galison, *How Experiments End*, 12.
[23] Harriet Zuckerman, *Scientific Elite,* 104.

seminal work, Wheeler was a key player in the production of the 'Fat Man' plutonium weapon in the Manhattan project, and later, in the development of the Hydrogen Bomb. Wheeler introduced the scattering matrix (or S-matrix) to account for all possible final quantum states of collisions between nucleons. After turning his attention to general relativity, Wheeler and his students made a number of significant contributions to cosmology and cosmology. In fact, John Wheeler coined the term "black hole," and developed the concepts of a "Planck Length," a Planck-time," "quantum foam," and "wormholes" in space-time.

Another element is Wheeler's effectiveness as a mentor. One measure of that effectiveness is output. David Goodstein, Vice Provost of Caltech, has observed that a typical professor of physics can be expected to 'produce' fifteen doctorates in physics over the course of his or her career.[24] Over the course of his career, John Wheeler supervised the dissertations of fifty Ph.D.s.[25] In other words, John Wheeler exceeded the average Ph.D. production by more than three-fold.

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[24] David L. Goodstein, "Scientific Ph.D. problems". *American Scholar* 62, no.2 (Spr 1993): 215-221, available online: <http://0-search.epnet.com.oasis.oregonstate.edu:80/login.aspx?direct=true&db=aph&an=9304060251> (05 Jan 2006), 217.

[25] John Archibald Wheeler and Kenneth Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York: W. W. Norton, 1998), 180. Here, Wheeler remarks that he "guided the work of more than fifty Ph.D. students." Hard numbers are elusive in this particular because no comprehensive list of Wheeler Ph.D. advisees is extant. Based on their letters, some forty-five of the contributors to *Family Gathering* were Ph.D. students of Wheeler. However, it is not clear that all of Wheeler's former Ph.D. advisees submitted a letter to

To be clear, mentoring is much more than dissertational obstetrics. Often the most influential professional role models are encountered as an post-doctoral fellow. Recall here Wheeler's comments about his good fortune in having both Gregory Breit and Niels Bohr as post-doctoral mentors. In some cases, scientists report that the person who most influenced the course of their career was a professor during their undergraduate career.[26] In other instances, even after a scientific career has been well established, a scientist may encounter an 'elder statesmen' who serves as an informal mentor within a specific (and usually novel) area of study.[27]

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this commemorative volume. Moreover, a number of the *Family Gathering* contributors did not specify their relationship with Wheeler.

[26] See, for example, *Family Gathering,* 336 [Michael Stern], 449-452 [Charles Patton], 465-469 [Larry Smarr]. These pages contain glowing tributes penned by scientists whose direct professional experience with John Wheeler was very limited. Michael Stern took undergraduate courses from Wheeler, completed his coursework for a physics Ph.D. at M.I.T., changed focus and became an M.D. Stern said of Wheeler, "The History of Science is the history of man's learning to see the world with new eyes... By having been your student, I have been able, in a small way, to participate in the tradition of Copernicus, Newton, Planck, and Einstein." Charles Patton also took classes from Wheeler as an undergraduate and went on to do graduate work and earn his doctorate at S.U.N.Y Stonybrook. And yet, despite a relatively modest amount of time working with Wheeler, Patton felt compelled to note, "I do not yet have any students, but if I can manage to offer my students but a fraction of what you have offered me, I will have served them well." Larry Smarr was never a Princeton student. He had read Wheeler's *Geometrodynamics* as an undergraduate, corresponded with Wheeler , and as a graduate student, met with Wheeler at a number of relativity conferences. Nonetheless, he wrote to Wheeler, "It was always your unconventional approach to physics that drew me onward," and "I am honored to be able to say thank you for all you've done."

[27] Peter J. Frost and M. Susan Taylor, eds., *The Rhythms of Academic Life: Personal Accounts of Careers in Academia* (Thousand Oaks, CA: Sage Publications, 1996), 498.

These odd moments of conveyed inspiration and informal mentoring are problematic in that they are very difficult to quantify. This is analogous to the problem faced by sociologist Harriet Zuckerman as she researched and wrote *Scientific Elite.* Even though there are some three-thousand awards available to scientists just in North America, the Nobel Prize remains the 'gold standard' by which all other awards are evaluated.[28] Because of the status of the Nobel prize, data surrounding its recipients is relatively easy to find in comparison with other symbols of scientific achievement. Similarly, although dissertation supervision is hardly the only professional assignment that involves scientific mentoring, it is a fruitful avenue of research in that it has the advantage of being well-documented on an administrative level. Put simply, it is among the very few aspects of mentoring that can be measured.

Another measure of mentoring effectiveness is the output of one's students. Harriet Zuckerman, Walter T. Scott, J. B. Morrell, and Joseph Fruton have all commented that elite mentors turn out an extraordinary amount of work by comparison to the average scientist. Furthermore, Zuckerman, and Fruton both have observed that this trait is passed on to the mentees of the elite.[29] In the following chapters and appendices, I believe that I can show that

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[28] Zuckerman, *Scientific Elite,* xxx [Introduction to the Transaction Edition]; Here, Zuckerman cites the Gale directory of Awards, Honors, and Prizes; Zuckerman uses the term 'gold standard' in association with the Nobel prize on several occasions beginning on xiii [Introduction to the Transaction Edition].
[29] Zuckerman, *Scientific Elite, 145*; Walter T. Scott, "Creativity in Chemistry," in Rutherford Aris, H. Ted Davis, and Roger Stuewer, eds., *Springs of Scientific Creativity: Essays on Founders of Modern Science* (Minneapolis, MN:

John Wheeler and his students follow that pattern observed by Zuckerman and Fruton.

Still another factor in choosing our subject is timing. John Archibald Wheeler came of age as a physicist just as theoretical physics was becoming established—taking root—in America. As early as 1930, a substantive cadre of American theoreticians had become established. Included in this grouping were renowned physicists such as Robert Oppenheimer (1904-1967), Iisador Isaac Rabi (1898-1988), Edwin C. Kemble (1889-1984), Carl Eckart (1902-1973), John C. Slater (1900-1976) , Robert S. Mulliken (1896-1986), Gregory Breit (1899-1981), Edward U. Condon (1902-1974), Philip M. Morse (1903-1985), and John H. Van Vleck (1899-1980).[30] Among these luminaries, all but two (Rabi and Breit) were born in the United States.[31] With the exception of Oppenheimer, all received their doctorates from American Universities. Essentially these were home-grown professionals who had spent just enough time in Europe (on an international fellowship) to become fluent in quantum mechanics and/or atomic physics. With their professional ascension, America became the new center of theoretical physics. As Slater recalled in 1968, as

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University of Minnesota Press, 1983), 285, 298; Fruton, *Contrasts in Scientific Style*, 23, 36, 38; Morrell, "The Chemist Breeders, 27, 30

[30] John W. Servos, "Mathematics and the Physical Sciences in America," 152.

[31] Gregory Breit's family came to America when he was a boy; I. I. Rabi's family emigrated to the United States when he was an infant.

theoretical physics took root in America, even established Europeans were coming over, "to learn as much as to instruct."[32]

Additionally, the rise of Fascism and its ethnic oppression in Europe precipitated an influx of elite scientists—many of whom had known or worked with members of the American cohort in Europe. Among these were Enrico Fermi (1901-1954), Edward Teller (1908-2003), John von Neumann (1903-1957), Hans Bethe (1906-2005), and (of course) Albert Einstein (1879-1955). That combination intellectual horsepower coupled with the large experimental apparatus (e.g. the cyclotrons developed by American experimental physicist Ernest O. Lawrence (1901-1958)) seemed to push America on the verge of supplanting Europe as the world's epicenter of physics. Then came the war.

Military mobilization during World War II utilized physics—particularly theoretical physics—to a level beyond all precedence. Two aspects of this phenomenon are germane to our study. First of all, as a result of the Manhattan Project and the subsequent military projects associated with the Cold War (e.g. the development of a thermonuclear weapon), the physics community was awash in research funding. In essence, within two decades, John Wheeler and his colleagues saw the entire mode of doing theoretical physics change. Secondly, the demand for manpower placed a premium on the ability to educate—and mentor—the physicists that would keep the U.S. technologically ahead of its adversaries. Because of their ability to train

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[32] John C. Slater, "Quantum Physics in America Between the Wars," *Physics Today* 21 no. 1 (Jan 1968), 43; Also cited in Kevles, *The Physicists*, 221.

physicists at the graduate level, skillful mentors (such as John Wheeler) were considered strategic assets.[33]

Specifically, this study addresses three primary questions. First, what were the personal and professional characteristics that contributed to John Archibald Wheeler's success as a mentor? Ancillary to that inquiry, how does Wheeler's personality and professional habits compare with other well-known and/or studied mentors? Second, is there any evidence that these characteristics were inculcated into Wheeler's students and/or succeeding intellectual generations? If the answer is yes, is Wheeler the origin of a 'chain of wisdom' or simply a link in a much longer chain? And finally, are any of Wheeler's mentoring practices generalizable into a broader pedagogy for graduate studies in physics? If so, what are the key elements of Wheelers style on which to focus? These questions require us to come to a shared understanding of the role of a mentor.

Section 1.5 The Role of Mentors: Molding the Scientific Elite

First of all, let us consider first the original and generalized meaning of 'mentor' and then turn to its characterization in recent scientific literature. The word "mentor" comes to us from the Greek poet Homer in *The Odyssey.* Recall here that Odysseus was a legendary Greek hero who ruled the island of Ithaka. He also led an army into the Trojan War. Before sailing off to war,

[33] David Kaiser, "Cold War Requisitions: Scientific Manpower and the Production of American Physicists after World War II" *Historical Studies in the Physical and Biological Sciences* 33, no. 1 (2002), 143.

Odysseus sought the counsel of the goddess Athene. Based on that advice, he entrusted the education and training of his son Telemachos, to his friend and counselor Mentor. Occasionally, over the twenty years that Odysseus was absent from Ithaka, Athene would appear to either Odysseus or Telemachos in the form of Mentor.[34] Thus, for Telemachos, Mentor was a teacher, surrogate father, counselor, and spiritual leader. Ultimately, the proper name Mentor became the common noun mentor, which the *Oxford English Dictionary* defines as: a person who offers support and guidance to another; an experienced and trusted counselor or friend; a patron, a sponsor. Since 1976, mentor has also come into use as a verb. This study will employ both the noun and verb forms of mentor. The context of the passage in question will make the meaning clear.

Here, I need to make clear my distinction between mentoring and teaching. Unfortunately, even within the mentoring literature, this objective has proven elusive.[35] There is no bright red line that categorically distinguishes

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[34] See Richmond Lattimore, trans., *The Odyssey of Homer* (New York: Harper & Row, 1967; Perennial Classics Edition, New York: HarperPerennial, 1991), 46 [Book II, Line 268] is the first of many examples.

[35] There is large body of mentoring literature: Chungliang Al Huang and Jerry Lynch, *Mentoring: The Tao of Giving and Receiving Wisdom* (San Francisco: HarperSanFrancisco, 1995); Association for Women in Science, *Mentoring Means Future Scientists: A Guide for Developing Mentoring Programs Based on the AWIS Mentoring Project* (Washington, DC: Association for Women in Science, 1993); Stephanie J. Bird and Robert L. Sprague, eds. *Mentoring and the Responsible Conduct of Research*, Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 449-640; Robert Kanigel, *Apprentice to Genius: The Making of a Scientific Dynasty* (Baltimore, MD: The Johns Hopkins University Press, 1986); Shalonda Kelly and John C. Schweitzer, "Mentoring Within a Graduate School Setting," *College Student Journal* 99, no.

teaching from mentoring. That said, it is possible to contextualize mentoring in a formally structured framework. One other caution: The instructional scenarios described below are somewhat simplified. Although all educational methodologies can be located within a pedagogical continuum, very few instructors' styles can be located at one and only one place within that spectrum. Nonetheless, some aspects of teaching technique will be dominant in any particular course. Consider, for example, undergraduate lecture-based courses in university-level education. In these instances, teaching is a unilateral didactic process. In other words, teachers interact with the class as a whole, and with the exception of student recitation for the purpose of evaluation, the flow of information is one-way. A key element here is question selection. In a lecture-based format, the instructor determines which questions he or she will address to the students. By these means, the scope and content of the course is established.

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1 (Mar 1999): 130-148; National Academy of Sciences, National Academy of Engineering, Institute of Medicine (U.S.), *Adviser, Teacher, Role Model, Friend: on Being a Mentor to Students in Science and Engineering* (Washington DC: National Academy Press, 1977), Available online: <http://oasis.oregonstate.edu/search/cQ181+.A35+1999/cq+++181+a35+1999/-2,-1,0,E/l856~2152434&FF=&1,0,,1,0> (27 Feb 06); Alice G. Reinarz and Eric Robert White, eds., *Beyond Teaching to Mentoring* (San Francisco: Jossey-Bass, 2001); Gordon F. Shea, *Mentoring: How to Develop Successful Mentoring Behaviors* [Rev. Edn.] (Menlo Park, CA: Crisp Publications, 1992); Mark A. Templin, "A Locally Based Science Mentorship Program for High Achieving Students: Unearthing Issues that Influence Effective Outcomes, *School Science and Mathematics* 99, no. 4. (Apr 1999): 205-212 , available online: EBSCOhost/Academic Search Elite/AN1877598 (15 Jan 2001); Lois J. Zachary, *The Mentors Guide: Facilitating Effective Learning Relationships* (San Francisco: Jossey-Bass, 2000).

Next in the spectrum of education methodology, we find seminar-based courses. In these instances, the instructor acts as a moderator for discussion of selected topics and issues. Here, while there is a bi-lateral flow of information, the instructor still interacts primarily with the class as a whole. Also, we again find that the instructor-moderator determines the investigative framework (i.e. the scope and content) of the discussion. We also find that the selection of questions is the key element in determining this scope and content. The difference is that in lecture-based classes, the instructor determines which questions she or he will take up while in seminar-based classes the instructor uses question selection to determine which questions the *students* will address.[36] Nonetheless, in each of these cases, the choice of questions to be addressed is in the hands of the instructor rather than the student. This hierarchy begins to relax and students get their first taste of a mentoring relationship when they begin writing research papers.

In such an enterprise, students are encouraged to formulate and refine the questions they will explore. Imbedded in this pedagogy is the art of question selection. John Wheeler, for example, was known to emphasize that aspect of scholarship. He strongly believed that, "The right ANSWER is seldom as important as the right QUESTION."[37] Moreover, as students are guided in the methodology of research and evaluation of source material, the instructor-student relationship becomes far more individualized. This process

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[36] Kathryn M. Olesko, *Physics as a Calling,* 1-2.

[37] J. Peter Vajk in an email to the author (21 Sep 05). The emphasis originates with Professor Vajk.

begins in upper division undergraduate work and continues through the early part of graduate training.

By the time a student pursues a doctorate, a substantial knowledge base has been established (and verified through examination). Nearly all of the instruction that takes place is individualized.[38] In contrast with lecture-based teaching models, students at the Ph.D. level are expected to be somewhat self-reliant where the acquisition of data is concerned. Similarly, in contrast to seminar-based teaching, they are expected to somewhat autonomously formulate the questions that drive their investigation. There is also the element of time. These are long-term relationships that evolve as the work proceeds. In sum, the mentor, in contrast to other types of instructors, does not dispense data or steer discussion. Rather the role of a mentor is to instruct a student *how to think about* information already in the student's possession.[39]

Recall here that the goddess Athene instilled confidence in Telemachos so that "among people he might win a good reputation."[40] This is also true of modern mentors. Sociologist Harriet Zuckerman observes that an important aspect of scientific mentoring is the inculcation of professional standards and conduct—a process that she refers to as "socialization."[41] We will explore the

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38 Kennedy, *Academic Duty*, 97.
39 Zuckerman, *Scientific Elite,* 122.
40 Lattimore, *The Odyssey of Homer,* 53 [Book III Line 75].
41 Zuckerman, *Scientific Elite,* 123. For more on professional socialization, Zuckerman cites Robert K Merton, George G. Reader and Patricia L. Kendall, eds. *The Student-Physician: Introductory Studies in the Sociology of Medical*

socialization of scientists at length below. For now, we note that Terrence Sejnowski, a former Wheeler Ph.D. student, summed up his professional socialization nicely:

> From John Wheeler, I learned that with a sufficiently good intuition it is often possible to guess the solution to a difficult problem. But of more importance, I came to realize the extent to which science is a social enterprise; not one man, not a single group, but rather the collective effort of a community.[42]

So, where and how did John Wheeler become so skilled at the craft of mentoring?

In the following section, I will further establish the foundation of this investigation by presenting a biographical sketch of Wheeler, paying particular attention to those events and circumstances that appear to bear on his career as a mentor.

Section 1.6 The Makings of a Mentor

As noted in the section above, a large number of publications that address the practice of mentoring have been released in the last fifteen years. Although many of these are of a general nature (or aimed largely at business leaders and educators), a few specifically address mentoring in science.[43]

Education (Cambridge, MA: Harvard University Press, 1957); Orville G. Brim, "Adult Socialization," *International Encyclopedia of the Social Sciences* 14: 555-562; David A. Goslin, *Handbook of Socialization Theory and Research* (Chicago: Rand-McNally, 1969).

[42] Terrence J. Sejnowski to John Wheeler, Princeton University, Jan 1977 (included in the Wheeler Festschrift commemorative *Family Gathering*).

[43] See, for example: Association for Women in Science (A.W.I.S.), *Mentoring Means Future Scientists: A Guide for Developing Mentoring Programs Based*

However, within both the general mentoring literature and that subset that addresses scientific mentoring, there are common threads of thought. On a personal level, we are told, in recent literature on mentoring in science that a good mentor is a "careful listener", a reliable (i.e. available and even-tempered) communicator. An effective mentor is sensitive to minority, gender and/or cultural issues, and is compassionate in regard to family concerns. On a professional level, the competent mentor is a role model who inculcates mentees with a sense of professional ethics and assists them in building disciplinary networks.[44] While these characteristics are part of the definition that we seek, they do not capture the relative value that these attributes will have in establishing a scientific career nor do they adequately describe the particular attributes that scientific mentors convey to their intellectual progeny.

Perhaps the most important convention that a mentor can inculcate is the need for a robust work ethic. Note the word choice. Hard work in and of itself is insufficient for a scientist aspiring to the elite levels of her or his discipline. A "robust" work ethic can best be described as follows: "It is good to

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on the AWIS Mentoring Project; Bird and Sprague, eds., *Mentoring and the Responsible Conduct of Research*; Robert Kanigel, *Apprentice to Genius*; National Academy of Sciences (N.A.S.-U.S.), *Adviser, Teacher, Role Model, Friend: on Being a Mentor to Students in Science and Engineering*).

[44] What follows is synthesized from, National Academy of Sciences (N.A.S.-U.S.), *Adviser, Teacher, Role Model, Friend: on Being a Mentor to Students in Science and Engineering*, 5. However similar lists can be extracted or developed from: A.W.I.S., *Mentoring Means Future Scientists*; Bird and Sprague, *Mentoring and the Responsible Conduct of Research*; Fort, *A Hand Up: Women Mentoring Women in Science*; Reinarz and White, *Beyond Teaching to Mentoring*; Zachary, *The Mentors Guide: Facilitating Effective Learning Relationships*.

work hard. It is better to work smart. If you can work hard *and* smart, you'll always find success."[45] Thus in studying Wheeler's biography, we should be alert for incidents that convey the synergetic value of applying intelligence to labor.[46]

Another quality that the best mentors pass on is intellectual rigor. In the literature we see references to keeping an "open mind" and being "non-judgmental."[47] Such intellectual rigor demands active engagement. An illustration by analogy seems apropos here.

Imagine you are in Portland, Oregon. To the east is Mount Hood, a landmark with a distinctive silhouette. If the outline of that silhouette were to be drawn on a chalkboard, it is likely that every one in the room would recognize the shape as emblematic of Mount Hood *as seen from Portland.* Similarly a mirror image of the outline would be perceived as a representation of Mount Hood's outline *as seen from the east.* But would we recognize Mount Hood's outline from the north, or the south, or the northeast, or the southeast? Probably not—at least initially. Stated alternatively, a full comprehension of the mountain is not possible unless we circumnavigate it.

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[45] I am indebted to my grandfather Thorwald Christensen for this insight.

[46] Wheeler and Ford, *Geons*, passim. In fact, Wheeler comments on the work habits of nearly every collaborator, associate, or student that is mentioned in the text. In most cases the assessment is positive and adjectives such as "conscientious," "scrupulous," "methodical," "tireless," and/or "effective" are employed.

[47] The need for an keeping an open mind is from National Academy of Sciences (U.S.), *Adviser, Teacher, Role Model, Friend: on Being a Mentor to Students in Science and Engineering,* (27 Feb 06), 59. The desirability for being non-judgmental is expressed in Reinarz and White, *Beyond Teaching to Mentoring*, 37.

Scientific constructs, like mountains, cannot be fully comprehended unless they are examined from multiple perspectives. Simply keeping an 'open mind' is insufficient to the practice of science. Intellectual rigor requires a scientist to actively engage the issue in question from multiple reference frames and skilled mentors will instill that practice in their mentees.[48] Wheeler himself states, "There are many modes of thinking about the world around us and our place in it. I like to consider all the angles from which we might gain perspective on our amazing universe and the nature of existence."[49]

A conscientious mentor will train her or his mentee to repeatedly examine problems with "new eyes" in the hope of eradicating false or misleading presuppositions. Such erroneous assumptions can be particularly insidious. Alfred North Whitehead famously asserted that:

> There will be some fundamental assumptions which adherents of all the variant systems within the epoch unconsciously presuppose. Such assumptions appear so obvious that people do not know what they are assuming because no other way of putting things has ever occurred to them. With these assumptions a certain limited number of types of philosophic systems are possible, and this group of systems constitutes the philosophy of the epoch.[50]

Overcoming such fundamental presuppositions requires more than just 'new eyes.'

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[48] I am deeply indebted to Sr. Cecilia Ranger SNJM, Ph.D. of Marylhurst University for the Mount Hood analogy to intellectual rigor.
[49] Wheeler and Ford. *Geons,* 153.
[50] Alfred North Whitehead, *Science in the Modern World: The Lowell Lectures, 1925* (New York: The Macmillan Co, 1925; reprint, New York: The Free Press, 1967), 48.

It also requires intellectual courage—the confidence to adopt a carefully constructed conceptualization despite its unconventional nature. On 31 January 1958, Niels Bohr and Abraham Pais listened to a lecture by Wolfgang Pauli concerning elementary particles. Afterward Pauli approached Bohr and said, "You probably think these ideas are crazy." "I do," Bohr replied, "but unfortunately they are not crazy enough."[51] Like his mentor Bohr, John Wheeler was no slave to conventional thinking. One night at Princeton, he called his (then) graduate student Richard Feynman to suggest that "positrons were simply electrons moving backward in time."[52] To be sure, this inventory is incomplete. Nonetheless, we have a sense of the types of events we are seeking in the early years of John Wheeler and in the analysis of his later career.

Section 1.7 Method, Strategy, and Tactics.

The obvious starting point for a study of John Wheeler as a mentor is *Family Gathering,* a commemorative volume assembled by Georgina Witt of the Princeton University Department of Physics. The full title, *Family Gathering: Students and Collaborators of John Archibald Wheeler Gather Some Recollections of Their Work with Him and of His Influence on Them and through Them on Their Own Students. Assembled with best wishes as John*

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[51] This anecdote is reported in Abraham Pais, *Niels Bohr's Times in Physics, Philosophy, and Polity* (New York: Oxford University Press, 1991), 29. Pais was a party to the conversation.
[52] Wheeler and Ford, *Geons,* 117.

moves on to a New Career in Texas, virtually tells the story of Wheeler's career as well as precipitating this thesis. [53]

Family Gathering consists of two volumes which contain letters of appreciation and career data from one hundred of Wheeler's former students and associates. It was presented to John Wheeler by former student and co-author Charles Misner at the Eighth International Conference on General Relativity and Gravitation at the University of Waterloo in Ontario, Canada on 11 August 1977.[54] At a personal level, *Family Gathering* reflects a remarkable career that profoundly influenced dozens of physicists. Certainly, no investigation of John Wheeler's Princeton years could be undertaken without a thorough review of its contents.

As a research tool however, *Family Gathering* has significant shortcomings. One issue is that the relationship between Wheeler and a given contributor to *Family Gathering* is not always obvious. The mix includes colleagues (e.g. Aage Bohr), post-doctoral students, Ph.D. students, and undergraduates who completed either a junior or senior thesis under the supervision of Wheeler. Thus, a considerable amount of follow-up is required in order to make effective use of the volume. Another problem is that all the

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[53] After leaving Princeton, Wheeler became Director of the Center for Theoretical Physics at the University of Texas in Austin. He was in Austin from 1977 until 1987 when he unequivocally retired and settled back in Princeton as an emeritus.

[54] *Family Gathering*, iii-iv. Misner, Kip S. Thorne and John Wheeler co-authored the 1273 page opus *Gravitation* (San Francisco: W. H. Freeman, 1973). Despite its size and cost ($249.00 hardcover; 111.95 paperback), this defining text remains in print and continues to sell.

information submitted by Wheeler's students is, at this point in time, nearly thirty years out of date. Many contributors have changed university and/or laboratory affiliation. Some have passed away. Still others seem to have disappeared without an evidentiary trace. Moreover, each of the contributors to *Family Gathering* has had thirty years to add to their curriculum vitae. In 1977, many former Wheeler students proudly announced that they had produced a number of intellectual "grandchildren" in the Wheeler mold.[55] Obviously, more 'Wheelerian' descendants have become part of the physics community in the intervening decades. In order to assess Wheeler's long-term influence, a significant percentage of these people must be located, and wherever possible, their publication data needs to be retrieved. However, since these 'grandchildren' didn't exist (in a professional sense) in 1977, location and documentation of publication data can prove troublesome.

Another concern is that former students' memories of Wheeler anecdotes may well have become colored and codified by repetition and passage of time.[56] Of course this is also true of Wheeler himself. Certainly,

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[55] Among the first to use the term grandchildren in relation to Wheeler's academic influence is John S. Toll, then President of State University of New York at Stony Brook. See John S. Toll to John Archibald Wheeler 23 Jun 1977 in *Family Gathering.* See also Dieter Brill to John Archibald Wheeler (n.d.) in *Family Gathering.*

[56] The literature is vast: for a discussion on the difficulties of distinguishing memory and history see Ronald J. Grele, "Movement Without Aim: Methodological and Theoretical Problems in Oral History," in *The Oral History Reader*, ed. Robert Perks and Alistair Thomson (London: Routledge, 1998); Soraya de Chadarevian, "Using Interviews to Write the History of Science," in *The Historiography of Contemporary Science and Technology,* edited by Thomas Söderqvist. Studies in the History of Science, Technology, and

more then mis-remembering is involved here. Even in the short term, variations in perception and perspective will spawn differing memories of the same conversation or incident. Despite these problems, I am resistant to rejecting these recollections out of hand. Whenever practicable, I have sought independent corroboration of the facts. Often, when authentication was not possible (e.g. Wheeler's memories of interaction with his parents), factual particulars were less important than the thrust of the story. On these occasions, I have tended to accept the story at face value. If however, the facts and the timing were integral to the meaningfulness of the event, and no second source was available, then my policy has been to refrain from including the episode in this narrative.

The second stage of investigation was to contact as many former Wheeler Ph.D. students as possible. *Family Gathering* appears to contain material from forty-five of Wheeler's Ph.D. students. Of these, five have passed away. Despite several attempts, I have not been able to discover any contact information for ten others. Two more do not have working email addresses and other avenues of contact are not apparent. I have attempted to

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Medicine, vol. 4 (Amsterdam: Harwood Academic Publishers, 1997); Frederic L. Holmes, "Historians and Contemporary Scientific Biography," in *The Pauling Symposium: A Discourse on the Art of Biography,* ed. Ramesh S. Krishnamurthy, Clifford S. Mead, Mary Jo Nye, Sean C. Goodlett, Marvin E. Kirk, Shirley A. Golden, and Lori L. Zielinski (Corvallis, OR: Special Collections, Oregon State University Libraries, 1996), 201.

contact the remaining twenty-eight, and as of this writing, nineteen have responded.[57]

On the face of it, nineteen responses to twenty-eight inquiries (approximately 68%) may seem to be a smallish sample. Still, many of those who contributed to *Family Gathering* were in the prime of their careers thirty years ago. Therefore, it is likely that many of those who failed to respond are retired, and in terms of scholarly communications, somewhat out of the academic loop. Then too, there are others whose professional obligations required them to postpone a response. Cheuk-Yin Wong, for example, was engaged in a conference in Hawaii when he heard of this project. His response arrived almost five weeks after the original contact.[58] It is not difficult to imagine similar circumstances delaying other responses to the point where they are ultimately overlooked.

In any event, when it seemed that I had located a Wheeler student, I sent an email which introduced this enterprise and asked to confirm his or her relationship with John Wheeler. Presuming an affirmative answer, I further requested an updated curriculum vitae, a list of publications, and a list of Ph.D. students.

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[57] Actually, there have been more than twenty responses. However, not all of these individuals had had Wheeler as a Ph.D. advisor. In fact some of the most eloquent letters in *Family Gathering* are from individuals who completed an undergraduate thesis under Wheeler's supervision.

[58] See email correspondence from the author to Cheuk-Yin Wong (21 Sept 05) and Wong's responses (21 Sept 05 and 25 Oct 05).

The third track of the investigation involved database research. This strategy was particularly helpful to get a sense of an individual's bibliography prior to contacting the individual directly. In cases where Wheeler students could not be located, this evidence stood in for their curricula-vitae and/or publication lists. The three databases are the SLAC-SPIRES High Energy Physics Literature Database maintained at Stanford University's Stanford Linear Accelerator Center (SLAC), the Mathematics Genealogy Project at North Dakota State University, and Google Scholar. All of these resources are useful to some extent. Nonetheless, there are shortcomings with each.[59]

The SLAC-SPIRES High Energy Physics Literature database, for example, features a robust compilation of physics publications. Unfortunately, its heavy emphasis on one particular subject area (high energy physics), also serves to exclude a number of scholarly publications from the collection. Google Scholar, on the other hand, is a novel method of searching for bibliographic information that ambitiously aims to be quite comprehensive. Using the author search utility, I was able to retrieve recent data for nearly all of Wheeler's former students. However, the results obtained from both Google Scholar and the SLAC-SPIRES database are highly dependent on the choice of search terms. In John Wheeler's case, varying the employed search terms (i.e. John Archibald Wheeler, John A. Wheeler, and J. A. Wheeler) in Google

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[59] The SLAC-SPIRES database can be found at: <http://www.slac.stanford.edu/spires/hep/>; Google Scholar (Advanced) is available at: <http://scholar.google.com/advanced_scholar_search>; The North Dakota State Mathematics Genealogy Project is sited at: <http://www.genealogy.math.ndsu.nodak.edu/>.

Scholar produced a six-fold difference in the number of matching publications. In some cases, this deficiency might have been mitigated to some degree by cross-referencing with the SLAC-SPIRES database. Even so, in the cases where an updated personal bibliography was available, it is clear that some number of publications were missed and others counted more than once.[60]

The Mathematics Genealogy Project at North Dakota State University was also utilized in the attempt to track the academic careers of former Wheeler students. This new enterprise aims to document the intellectual lineage of leading mathematicians. For example, after entering John Wheeler in the search engine, we can see that one of his students, Arthur Wightman completed his Ph.D. from Princeton in 1949 with a dissertation titled, The Moderation and Absorption of Negative Pions in Hydrogen. The North Dakota database lists some fourteen doctoral students of Wightman and some 274 "descendants."[61]

Unfortunately, there are significant omissions in this database as well. In the case of John Wheeler himself, only nine students are listed.[62] However,

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[60] Using all three variations on Wheeler's name (John Archibald Wheeler, John A. Wheeler, and J. A. Wheeler) the SLAC-SPIRES database returned a total of 36 matches. These same variations in a Google Scholar search produced the following results: the "John Archibald Wheeler" search had 81 matches, the "John A. Wheeler" search found 88 matches, and the "J. A. Wheeler" search found 496 matches. Wheeler's personal bibliography (as supplied by Ken Ford) lists 386 publications.

[61] One of these is the historian of science, S. Silvan Schweber.

[62] On the Mathematics Genealogy database, the search terms "John Archibald Wheeler", "John A. Wheeler", and "J. A. Wheeler" yield no matches. "John Wheeler" came up when I sought a listing for Arthur Wightman, a former Wheeler Ph.D. advisee.

Wheeler is credited with some 323 "descendants" or intellectual grandchildren. The omission of some thirty six of Wheeler's students may be due, at least in part, to the focus on mathematics. Still, it is hard to imagine that eighty percent of Wheeler's students lacked a sufficient mathematical pedigree to be included here. While this venture shows great promise, as of this writing, it remains a work in progress.

Section 1.8 Review

This thesis addresses two areas of underdeveloped scholarship. One object is to illuminate the art and practice of mentoring as it is situated in a research school setting. A second, and related objective is to examine scientific mentoring in a theoretical context. Because of his evident skill as a mentor and his position on the timeline of theoretical physics in America, John Archibald Wheeler is an ideal subject for this investigation. Finally, while I have uncovered a number of evidentiary challenges, it is also apparent that this investigation promises significant insights into the production of science.

Moving from this point forward, Chapter 2 will look into situations and individuals that seemed to have influenced Wheeler's work habits and his conceptions of doing physics. Chapter 3 will examine Wheeler's role as a mentor, as reflected in his own writings and in the reflections of his students, postdoctoral associates, and colleagues. Finally, in Chapter 4, we will consider how the study of mentorship can contribute both specifically and more broadly to our understanding of the mechanisms by which scientific pedagogy and research groups or research schools function in modern science, and explicitly in theoretical physics.

Chapter Two: The Nature and Nurture of a Mentor: John Archibald Wheeler as Student

Section 2.1 Overview

John Archibald Wheeler's success as a mentor can be traced to a number of factors—some of which are biographical (as opposed to professional) in origin. That said, a systematic approach to the issue necessarily includes the obvious (i.e. Wheeler's eminence in theoretical physics). As noted in Chapter 1, John Archibald Wheeler was one of the United States' most celebrated physicists and among the few to make significant contributions in both quantum physics and general relativity. In her study of the scientific elite and Nobel laureates in the United States, social historian Harriet Zuckerman refers to Wheeler as a member of the "ultra-elite" among scientists.[1]

However, professional virtuosity and intellectual lineage do not by any means guarantee excellence as a mentor.[2] Einstein was, of course, famous

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[1] Harriet Zuckerman, *Scientific Elite: Nobel Laureates in the United States* (New York: The Free Press, 1977; reprint, New Brunswick, NJ: Transaction Publishing, 1996), 104. See also, Kip S. Thorne, and Wojciech H. Zureck "John Archibald Wheeler: A Few Highlights of His Contributions to Physics," in *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler,* ed. Wojciech Hubert Zurek, Alwyn van der Merwe, and Warner Allen Miller (Princeton, NJ: Princeton University Press. 1988): 3-13.
[2] Zuckerman, *Scientific Elite*, 101-103, 105, 109, 150; See also Robert Kanigel, *Apprentice to Genius: The Making of a Scientific Dynasty*, (Baltimore, MD: The Johns Hopkins University Press, 1986), 234-235; J. B. Morrell, "The Chemist Breeders: The Research Schools of Liebig and Thomas Thomson," *Ambix: The Journal of the Society for the History of Alchemy and Chemistry* 19 (Mar 1972), 19; William Thomson, "Scientific Laboratories," *Nature* 31 (Nov

for not having any students. The late Richard Feynman, a Nobel laureate (and former Wheeler Ph.D. student) is another case in point. Despite wide acclaim for his ability to present concepts with clarity and verve, Feynman was not a prolific mentor. Over a career that spanned four years at Cornell and thirty-five years at Caltech, Feynman had at most a handful Ph.D. students.[3] Another Nobelist, P. A. M. Dirac, was also notoriously reluctant to take on graduate students. Over his career, Dirac officially supervised a total of seven Ph.D. students.[4] Clearly, talent in and of itself is no guarantee of productivity in mentoring. So what does matter?

By way of understanding the factors that contributed to Wheeler's development of a personal style and method for mentoring, this chapter will present a chronological adumbration of the first twenty-four years of John

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1884 – Apr 1885): 409-413, see 410 where Thomson writes, "The world renowned laboratory of Liebig brought together all the young chemists of the day. If I were to name the great men who studied at Giessen I should have to name almost every one of the great chemists of the present day who were young forty years ago."; Also quoted in Joseph Fruton, "The Liebig Group: A Reappraisal," *Proceedings of the American Philosophical Society* 132 (1988), 3. In a footnote, Fruton quotes William Thomson, "all the eminent chemists who were young in 1845 were pupils of Liebig."

[3] Feynman's skill as a classroom and/or public lecturer was well known. Moreover, his text *The Feynman Lectures on Physics* is considered a must for any physicist's library (In this regard see James Gleick *Genius: The Life and Science of Richard Feynman* (New York: Vintage Books, 1992), 363-364). For more on Feynman as a mentor see Terry M. Christensen, "Creating Chains of Wisdom: The Role of Interdisciplinarity in Mentoring," Master's Thesis, Marylhurst University, 2001. The number of Feynman Ph.D. students is addressed on p.3 and pp. 59-61.

[4] R. H. Dalitz and Rudolf Peierls, "Paul Adrien Maurice Dirac: 8 August 1902—20 October 1984," *Biographical Memoirs of Fellows of the Royal Society* 32 (1986), 154-156. Dirac also had some mentees for whom he was not the dissertation supervisor of record. Notable among these were Dennis Sciama and Subrahmanyan Chandrasekhar.

Wheeler's life. These years include his childhood and early education, followed by his experience studying and doing physics with Karl Herzfeld, Gregory Breit, and Niels Bohr. What follows is a selective analysis of these years with a view to thinking about the character of mentors and mentorship, as discussed in Chapter 1.

Section 2.2 Nature and Nurture: The Young Wheeler

Like most accounts of the life of an unusually gifted and influential physicist, the sources for John Wheeler's life depict an exceptional young man.[5] Many of the standard stories and themes associated with biographical studies of scientists in their youth are present in Wheeler's life story. Though there is some evidence that the nature of these stories varies with discipline, the stories of Wheeler's youth resonate with those of other American physicists (e.g. Richard P. Feynman (1918-1988)).[6] That said, these elements

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[5] As yet, a scholarly biography of John Wheeler does not exist. The primary sources for learning about his youth are: John Archibald Wheeler and Kenneth Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York: W. W. Norton, 1998); Jeremy Bernstein, *Quantum Profiles* (Princeton, NJ: Princeton University Press, 1991); John Archibald Wheeler, "Wheeler, John Archibald, 1911 – ," interview by Charles Weiner and Gloria Lubkin (transcript), Princeton, NJ, 05 April 1967, American Institute of Physics, Oral History Interviews [OH537]; John Archibald Wheeler, "Wheeler, John Archibald, 1911 – ," interview by Kenneth W. Ford (transcript), Princeton, NJ and Meadow Lakes, NJ, 06 Dec 1993 – 18 May 1995, American Institute of Physics. Oral History Inteviews [OH5].

[6] For the variation of childhood stories among disciplines see Ronald E. Doel, "Oral History of American Science: A Forty Year Review," *History of Science* 41, no. 4 (Dec 2003): 349-378, 360-361, available online: <http://oasis.oregonstate.edu/search/tHistory+of+Science/thistory+of+science/1%2C2%2C2%2CE/c8561053566&FF=thistory+of+science&1%2C1%2C%2C

are nonetheless important to the narrative. Among the themes to explore in the context of this study on mentorship are influences from family, friends, and teachers. Other areas of interest include the young Wheeler's attitudes toward education as well as his style of thinking and working. Finally, this chapter also examines the interactions of the young Wheeler with three remarkable and effective teachers and mentors in physics: Karl Herzfeld, Gregory Breit, and Niels Bohr.

John Archibald Wheeler, the oldest of four children, was born on the ninth of July, 1911 in Jacksonville, Florida. Wheeler's parents, Joseph Lewis Wheeler and Mabel Archibald Wheeler, were both librarians. Although Mabel Wheeler left her career in order to raise her children and manage the Wheeler household, she remained active in library affairs by helping her husband evaluate books for library purchase. As they became old enough to participate, the Wheeler children joined in these discussions. As one might expect, the Wheeler household was filled with books. In addition to the typical childhood favorites *Swiss Family Robinson* and *Robinson Crusoe,* Wheeler reports that, early on, he had an appetite for technical books. Included in these were

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1%2C0> (24 June 2006). See also Richard P. Feynman and Ralph Leighton, *Surely You're Joking Mr. Feynman: Adventures of a Curious Character* (New York: W. W. Norton & Co, 1985), 16-21, Feynman too, was fascinated by gadgets during his youth and achieved neighborhood acclaim for fixing radios by "thinking."

Franklin Day Jones' *Mechanisms and Mechanical Movements* (1920) and J. Arthur Thomson's *Introduction to Science* (1911).[7]

In his autobiography, John Wheeler notes that, although his mother seemed very happy in marriage, throughout her life she was "sensitive about not having a college degree." Perhaps because of that perceived shortcoming, Mabel Wheeler "made sure that all her children were encouraged in their academic pursuits." Wheeler continues:

> As the firstborn son, with an inclination toward mathematics and science, I got a disproportionate share of my mother's attention. My brothers and sister felt this imbalance. I didn't feel smothered, but I was aware of the expectations that she held for me.[8]

In addition to the foregoing, the Wheeler autobiography contains numerous anecdotes that underscore a family life that emphasized the importance of learning. Of course, a child is also influenced by adults, teachers in particular, who are outside the family circle.

In John Wheeler's case, numerous family relocations complicate the issue of identifying influences outside the family. Although the point is not emphasized in the Wheeler autobiography, John Wheeler's father, Joseph Wheeler, was no ordinary librarian. Over the course of his career he wrote several books on the topics of library management and the place of the public library in American communities. Wheeler said of his father, "He saw the

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[7] Wheeler interview with Weiner and Lubkin, 05 April 1967; Wheeler and Ford, *Geons,* 82; See also Franklin Day Jones, *Mechanisms and Mechanical Movements* (New York: Industrial Press, 1920); J. Arthur Thompson, *Introduction to Science* (New York: H. Holt & Co., 1911).
[8] Wheeler and Ford, *Geons,* 65-66.

public library as the university of the people."[9] In addition to numerous consulting assignments, Wheeler managed exhibits for the American Library Association at the (1915) San Francisco and (1926) Philadelphia World's Fairs.[10]

In order to advance in his profession, the elder Wheeler accepted positions at a series of libraries. For example, in September, 1912 (after only eighteen months in Florida), Joseph Wheeler took a position as assistant director of the Los Angeles Public Library. Shortly thereafter, the Wheeler family moved from Jacksonville to Glendale, California. In 1916, after he completed the San Francisco assignment for the American Library Association, Joseph Wheeler became head librarian of the Youngstown, Ohio public library. However, his stay in Youngstown was intermittent. During the war years (1917-1918), Wheeler's father worked for the Libraries War Service and was responsible for all book selections sent to overseas Armed Forces Libraries. As a result of a 1912 bout with scarlet fever, Joseph Wheeler had a weak heart. In 1921, in order to build up his health, Joseph Wheeler took a sabbatical from the Youngstown library and relocated his family to a farm near Benson, Vermont. The Wheeler family returned to Youngstown in October of

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[9] Wheeler interview with Weiner and Lubkin, 05 April 1967, 2.

[10] Wheeler and Ford, *Geons,* 67; In fact, the elder Wheeler's papers are presently housed in the Joseph Wheeler Collection at the College of Information of Florida State University. In a 20 Mar 2006 email to the author, Pamela J. Doffek (Librarian, Goldstein Library, College of Information, Florida State University) confirms that the papers of Joseph Wheeler are in the University's collection. As of this writing (2006) the collection remains unprocessed.

1922. However, In 1926, after working for the American Library Association at the Philadelphia World's Fair, Joseph Wheeler was hired as the director of the Enoch Pratt Free Library in Baltimore.[11]

Consequently John Wheeler's early education began in Washington, DC and continued (sequentially) in Youngstown, Ohio, in Benson, Vermont, continued back in Youngstown again, and concluded in Baltimore. Under these circumstances (i.e. repeatedly having to adjust to a new school), one might presume that Wheeler's public school experience was something less than optimal. In fact the moves—particularly the move to Vermont—advanced rather than hindered Wheeler's educational progress. More to the larger point, the family did not remain in a community long enough for Wheeler to establish meaningful relationships with any non-family adults other than teachers.

Two teachers are prominently mentioned in *Geons.* The first is Mary Donovan who taught between twenty-five and thirty-five pupils (spanning eight grades) in a one room schoolhouse near Benson, Vermont.[12] After completing the first grade in Washington, DC, Wheeler completed the second and third grades in Youngstown. He was finishing his fourth grade year when the family moved to Vermont. There, in Mary Donovan's classroom, Wheeler made remarkable progress. In *Geons,* he remarks:

> I don't remember being considered especially precocious, and I don't remember getting any special attention from Mary

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[11] Wheeler and Ford, *Geons,* 67, 71-73, 83.

[12] Wheeler interview with Weiner and Lubkin, 05 April 1967, 5. Here Wheeler recalls twenty-five students in Mary Donovan's school. In *Geons,* (p80) Wheeler remembers the number of students as thirty-five.

> Donovan, but somehow, after a little more than one school year in Vermont, I moved into the eighth grade back in Youngstown, four grades beyond the one I had left. Part of the reason, I think, is that I could listen in on the teacher's instruction of the older children and quietly work along with them. Also, I had time during the day to move at my own pace through the available books, and I did as much mathematics as I could. Since the first grade, when my grandfather Archibald had introduced me to mathematics, I had loved it and found that it came naturally to me.[13]

Mary Donovan's influence is more apparent later in Wheeler's career when Wheeler became known for giving his students "barely enough advice to keep [them] from floundering and but never so much that [they] felt that he had solved the problem for them."[14]

Although Mary Donovan did not openly extol Wheeler's academic ability, once Wheeler was back in Ohio, a number of his teachers took a more proactive role in his development. Most prominent among these was Wheeler's mathematics teacher, Lida F. Baldwin. "She gave me extra work, extra reading, and extra encouragement," recalls Wheeler. Nor did her commitment to Wheeler's academic success stop at the schoolhouse door. One afternoon, according to Wheeler, she called on his father at the Youngstown Library, "to make sure, I suspect, that my parent's commitment to my education matched her own."[15] Wheeler also mentions Professor [Francis]

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[13] Wheeler and Ford, *Geons,* 80.
[14] Kip S. Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: W. W. Norton & Co., 1994), 262.
[15] Wheeler and Ford, *Geons,* 80-81; Wheeler interview with Weiner and Lubkin (05 April 1967), 3.

Murnaghan (1893-1976) who taught calculus at The Johns Hopkins.[16] Murnaghan was [other than Karl Herzfeld, Wheeler's dissertation advisor], "The best teacher I ever had as far as exposition [and clarity are] concerned."[17] Coming from Wheeler, a man famous for his word-smithery, that is quite an endorsement.

Clearly, Wheeler's childhood was one in which he was inculcated with the importance of education. Desire alone however is insufficient to achieve academic goals. The pursuit of knowledge—particularly at the highest levels—takes tenacity and a great deal of work. An elite mentor must possess these qualities and, be able to inculcate that same robust work ethic in her or his mentees. So, where are the roots of John Wheeler's work ethic?

John Wheeler seems to have developed a tacit understanding of the importance of industriousness largely through the example of his parents. In Wheeler's autobiography, there is little evidence that the inherent worth of work was a frequent discussion topic. He recalls that, "It was an era when children's character and intellect were supposed to be developed through discipline and hard work, not through rewards and flattery."[18] As he got older, Wheeler became responsible for certain family chores such as mowing the

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[16] J. J. O'Connor and E. F. Robertson, "Francis Dominic Murnaghan." MacTutor History of Mathematics (October 2003), Available Online: <http://www-history.mcs.st-andrews.ac.uk/Biographies/Murnaghan.html> (21 Mar 2006); North Dakota State University, Department of Mathematics, "Francis Dominc Murnaghan," The Mathematics Genealogy Project [Online], Available:<http://www.genealogy.math.ndsu.nodak.edu/html/id.phtml?id=11540> (21 Mar 2006).

[17] Wheeler interview with Weiner and Lubkin (05 April 1967), 6.

[18] Wheeler and Ford, *Geons,* 80.

lawn and gathering eggs (after returning to Youngstown from Vermont, the Wheelers kept chickens in their back yard). Additionally, in both Youngstown and Baltimore, Wheeler had a paper delivery route.[19] One should not however conclude that John Wheeler was above a little mischief. From time to time, in Wheeler's late adolescence, he would evade certain tasks with the excuse that the chore in question, "might not be the best way for me to spend my time if I am going to earn a scholarship for college."[20]

Outside the family, several adults set an example for John Wheeler with regard to the importance of work. Wheeler speaks fondly of the many high school teachers in Youngstown (including Lida Baldwin) who encouraged him to make the most of his talent. Wheeler recollects, "They were not the common variety of teacher who treats a fast learner as someone who can safely be ignored or even as someone who is a nuisance." The first sentence describing Mary Donovan, with whom Wheeler completed the work of four academic years in one calendar year, notes that she walked to school every day from a nearby farm.[21] Reading beyond the text, it seems clear that Mary Donovan's daily slog through the Vermont winter very effectively reinforced other tacit lessons in the value of conscientiousness and diligence.

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[19] Wheeler and Ford, *Geons,* 85. Here, Wheeler recalls having paper delivery routes in Ohio and Baltimore. In his 05 April 1967 interview with Charles Weiner and Gloria Lubkin (p7) however, Wheeler only recalls delivering papers for one year in Ohio.
[20] Wheeler and Ford, *Geons,* 83, also 74, 85.
[21] Wheeler and Ford, *Geons,* 80.

Still, most of John Wheeler's work ethic is traceable to his family. In *Geons,* Wheeler discusses the pioneering spirit of the Archibald clan—several of whom homesteaded in Kansas as Free-Staters prior to the Civil War. From Kansas, the clan spread to Colorado, New Mexico, and Texas. On his father's side of the family, Wheeler descended from Puritan stock that settled in Massachusetts. He reports that, "within a year of the founding of Concord, Massachusetts (1640), thirty-five Wheeler families lived there. Wheeler was the most common family name in Concord."[22] Implicit in these family narratives is a high regard for the hard work and perseverance required of settlers in a new land.

Joseph Wheeler seems to have had the most telling influence in this regard. John Wheeler warmly recalls his father's fondness for aphorisms. "'There isn't anything that can't be done better,'" was a favorite along with "'Do what you can, with what you have, where you are.'" These stayed with John Wheeler throughout his career as a scientist and a mentor. At the close of the *Geons* chapter describing his youth, Wheeler speaks with particular reverence for his father:

> As I look at my own childhood and wonder what made me think I could grapple with nature's greatest mysteries, I have to give credit to a few teachers who saw some potential in me, and most of all to my father, for whom no mountain was insurmountable. He was no scholar, but he knew how to make his visions come true. ... I grew up in an environment where problem solving and achievement (as well as service) were the respected virtues,

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[22] Wheeler and Ford, *Geons,* 68-70.

> where the mind was supposed to do something, not just know something.[23]

It would appear that John Wheeler acquired a strong work ethic as a consequence of both the guidance and example of the adults who interacted with him in his youth. In any event, industriousness was a quality that John Wheeler appreciated—and promoted—throughout his career. In fact, throughout the autobiography *Geons,* Wheeler nearly always begins the discussion of an individual with an assessment of their work habits.[24] Two prominent examples help to illustrate the point.

One example is Ed Cruetz, then a young physicist with whom Wheeler worked on the Manhattan Project. Wheeler notes, "Ed Cruetz was a pleasure to work with. He was ready to sweep floors if that's what it took to get a job done." Based on his evaluation of Cruetz' attitude toward work, Wheeler subsequently recommended him for a senior position at General Atomics corporation. The work habits of the team of young physicists that Wheeler assembled to help in the development of the H-bomb received similar praise. The team included John Toll, now Chancellor emeritus of the University of Maryland and Ken Ford now-retired director of the American Institute of Physics and co-author of *Geons.*[25]

Another example is the theoretical physicist Maria Goeppert Mayer. Mayer had been one of Wheeler's professors at The Johns Hopkins. Later,

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[23] Wheeler and Ford, *Geons,* 84.
[24] Wheeler and Ford, *Geons,* passim.
[25] Wheeler and Ford, *Geons,* 218-219.

she became a colleague in the Manhattan Project, and she would win a share of the Nobel prize for physics in 1963 for her work on nuclear shell structure. Unfortunately, Mayer's gender seemed to keep academic promotion out of her reach.[26] Consequently, she waited thirty years to be appointed to a full professorship. Beyond her talent as a physicist, she earned Wheeler's admiration for remaining positive and enthusiastic about theoretical physics despite the prejudice and devaluation that she endured for the bulk of her career. In *Geons* (1998) Wheeler noted, "To her colleagues she was a valued full partner, whatever status she might be assigned by local administrations."[27]

At the elite levels of science, the importance of a solid work ethic is matched by the necessity of clear thinking. Are there clues in Wheeler's youth about the way he approached problems? While specific problem solving approaches were imparted to Wheeler later in life, one particularly significant element of thinking style seemed to emerge in his younger years. Fred Archibald, Wheeler's maternal grandfather, was a figure of early significance in this context. John Wheeler, along with his mother and siblings, had two extended stays with his grandparents in Washington, DC. The first occasion occurred when Joseph Wheeler was managing the American Library Association exhibit at the 1915 San Francisco World's Fair. Later (1917-1918), while the elder Wheeler was working for the Library War Service, the Wheeler family again lived in the Archibald home. During these intervals, Fred

[26] Wheeler and Ford, *Geons,* 97.
[27] Wheeler and Ford, *Geons,* 97.

Archibald spent quite a lot of time with his grandson. While John Wheeler was in the first grade, his father "introduced him" to mathematics—including the rudiments of algebra.[28]

More importantly, Wheeler learned from his grandfather how to look at various sides of an issue:

> Sunday dinners at my grandparents' home were special occasions, spiced by political argument. My great-uncle John W. Reid, my grandmother's brother, was a frequent guest at these dinners. He and my grandfather loved to debate issues of the war then in progress. ... My grandfather was an accomplished debater. After convincing everyone of his position over a Sunday dinner, he reversed himself and argued the other side. I was old enough [Wheeler was six at the time] to appreciate the give and take.[29]

Later, as a high school senior in Baltimore, Wheeler performed well on the debate team. In addition to learning to consider a given issue from various perspectives, Wheeler credits this experience with solidifying the self-confidence that is requisite to the practice of science.[30]

Independence of thought, the willingness and ability to consider issues with 'fresh eyes' and without regard to conventional wisdom is an important component of careful reasoning. Here, both John Wheeler's parents seem to have had an enduring influence. While attending the first grade in Washington, DC, Wheeler and his classmates were compelled to recite the Pledge of Allegiance. Joseph and Mabel Wheeler found this practice objectionable. For them, compulsory recitation of this oath evoked the specter of state religion in

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[28] Wheeler and Ford, *Geons,*73.
[29] Wheeler and Ford, *Geons,*74.
[30] Wheeler and Ford, *Geons,*84.

a public school. I would note here that the year is 1917—some thirty-seven years before the U.S. Congress acted to insert the phrase "under God" into the pledge. In the end, though mindful of his parents' convictions, Wheeler kept his own counsel and recited the pledge with the rest of his class.[31]

Later, while walking with his mother in Youngstown, Wheeler observed some workmen connecting pipe in a ditch. Rather than presuming that experienced workers such as these must have known what they were doing, John Wheeler reportedly announced, "'They are connecting it wrong. It won't work that way.'" Someone in the crew heard the comment, examined the work and saw that the boy [Wheeler] was right. The workmen immediately set about to correct the error. As Wheeler notes, such is the stuff of family legends.[32] This last anecdote is, again, standard fare in scientific biography: The young scientist sees something that all the adults miss completely. Still it points to another crucial element in the practice of science or—for that matter—mentoring.

Curiosity is a fundamental prerequisite for a life in science and, John Wheeler possesses an abundance of it. Beginning in his youth, Wheeler was particularly fascinated with mechanical devices. Like many youngsters, he made extensive use of a Meccano set (similar to an erector set) in the construction of all manner of gadgets. In 1920, when Wheeler was nine, he built a crystal radio receiver so that he could hear KDKA Pittsburgh, the first

[31] Wheeler and Ford, *Geons,*73.
[32] Wheeler and Ford, *Geons,* 82.

commercial radio station in the United States. Later, Guided by Franklin Jones's *Mechanisms and Mechanical Movements* and, working with wood, Wheeler and a high school friend built a combination lock, a repeating pistol, and an adding machine.[33] As impressive as these feats are, an excess of any quality—particularly curiosity—is an invitation to trouble.

Wheeler learned this lesson on the family farm in Vermont. Along with his fascination with mechanical contraptions, John Wheeler was enticed by explosions. By the time he was four, he had learned that if he put a marble in an empty electric light socket, the marble would shoot out with a pop when he switched the socket on.[34] With his first chemistry set, Wheeler learned to make gunpowder and that a mixture of acetylene and water would blow the cap off a bottle. In Vermont, while Joseph Wheeler and some neighbors were using dynamite to blast holes in the rocky ground for utility poles, John Wheeler was reading extensively about explosives. He knew that the dynamite was set off when a flame burned down a fuse cord to the blasting cap. Therefore, Wheeler reasoned, if a flame was brought in direct contact with a blasting cap, the cap should explode. Wheeler relates the sequence of events:

> I couldn't resist the temptation. I took two or three dynamite caps from the pig barn and went across the road to a secluded spot in the vegetable garden. I stuck a match in the ground, lit it, and then dropped caps onto it. I kept missing, so I got lower and lower before I released the caps, in hopes of scoring a bull's-eye. Finally, my point of release was only an inch or two above the match flame. With a mighty bang, the cap exploded before I had even let go of it. For weeks afterwards, I was digging little pieces

[33] Wheeler and Ford, *Geons,* 82-83.
[34] Wheeler and Ford, *Geons,* 82.

> of copper out of my chest and arms and legs. By great good fortune, none of them landed in my eyes.[35]

Although the experiment cost Wheeler the tip of one finger and a small piece of his thumb, it did absolutely nothing to mitigate his fascination with explosions.[36] More importantly, his curiosity remained intact throughout his career.

Another vital quality for a scientist to possess is faith—specifically, the faith that a solution exists for every problem. This faith grew stronger in John Wheeler as a result of one of his part-time jobs. During his last year of high school and throughout his years at The Johns Hopkins, John Wheeler worked Saturday nights in the public library. His job was help people research technical and/or industrial problems. Wheeler recalls:

> And here is the greatest variety of questions that people bring in to you: "Where can I find out how to build such-and-such?" or "Where can I get the best information on reinforced concrete?" or "How can I tell about anticorrosion metals?" So this business of feeling that anything could be tackled, and, by George, if you just gritted your teeth hard enough, you could find one way or another some information that would help somebody, was very inspiring. I kept on with that and kept learning from it, of course.[37]

John Wheeler's father Joseph played a role here as well (beyond helping Wheeler get the job). Although he does not recall the German phrase *"Die Probleme existieren um überwinden zu werden"* [Problems exist to be overcome] among his father's aphorisms, Wheeler has

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[35] Wheeler and Ford, *Geons,* 81-82; Bernstein, *Quantum Profiles,*101-102.
[36] Wheeler and Ford, *Geons,* 82; Jeremy Bernstein, *Quantum Profiles*, 102.
[37] Wheeler interview with Weiner and Lubkin (05 April 1967), 7.

observed that his father also subscribed to that sentiment.[38] As with curiosity, Wheeler's faith in the existence of a solution for every problem, as will be shown, served his career and his mentees well.

In September, 1927, after graduating from Baltimore City College (actually a public high school) John Wheeler enrolled as an engineering major at The Johns Hopkins University. He was sixteen years old.

Section 2.3 The Johns Hopkins University and Karl Herzfeld

John Wheeler never really considered an alternative to The Johns Hopkins University for his college education.[39] As the first graduate research university established in America, The Johns Hopkins was a prestigious institution which, throughout its history, had attracted an excellent faculty.[40]

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[38] Wheeler and Ford, *Geons,* 67. The translation is Wheeler's.

[39] Wheeler and Ford, *Geons,* 84.

[40] The place of The Johns Hopkins in American graduate education is well documented. See Burton R. Clark, ed., *The Research Foundations of Graduate Education: Germany, Britain, France, United States, Japan* (Berkeley: University of California Press, 1993); John Calvin French, *A History of the University Founded by Johns Hopkins* (Baltimore, MD: The Johns Hopkins University Press, 1946); Daniel Coit Gilman, *The Launching of a University, and Other Papers: A Sheaf of Remembrances* (New York: Dodd, Mead, & Co., 1906); Hugh Hawkins, *Pioneer: A History of the Johns Hopkins University, 1874-1889* (Baltimore, MD: The Johns Hopkins University Press, 2002); Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century* (Princeton, NJ: Princeton University Press, 1999); Alexandra Oleson and John Voss, eds., *The Organization of Knowledge in Modern America, 1860-1920* (Baltimore, MD: The Johns Hopkins University Press, 1979); Sheldon Rothblatt and Bjorn Wittrock, eds., *The European and American University since 1800: Historical and Sociological Essays* (New York: Cambridge University Press, 1993); Will Carson Ryan, *Studies in Early Graduate Education, The Johns Hopkins, Clark University, The University of Chicago* (New York: The Carnegie Foundation for the Advancement of

Perhaps equally important to the Wheeler family, The Johns Hopkins was located in Baltimore. Therefore, John Wheeler could live at home and save on expenses. The fact that Wheeler was awarded a state scholarship to The Johns Hopkins further eased the financial burden on the family. In 1912, as a condition for receiving a bond from the state of Maryland, The Johns Hopkins University committed to establish a "school or department of applied science and advanced technology." The Johns Hopkins was further obliged to offer some 129 scholarships "to worthy men of this state."[41] John Wheeler, in the estimation of a local politician, was one of those worthy men.[42] As it turns out, The Johns Hopkins education served John Wheeler's career as a mentor particularly well. Novel approaches to education were factors here.

From the beginning, the focus of The Johns Hopkins University had been graduate education. However, for a variety of reasons it was not feasible to exclude undergraduate programs. One innovation was implemented at the inception of the university by The Johns Hopkins first president, Daniel Coit Gilman. Gilman devised a system in which students could achieve a bachelor's degree after three years of study so they could move quickly into a

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Teaching, 1939 [Note: Also listed as Bulletin no. 30]); Laurence R. Veysey, *The Emergence of the American University* (Chicago: University of Chicago Press, 1965).

41 The Johns Hopkins University, "The Johns Hopkins Chronology" [Online], Available: http://webapps.jhu.edu/jhuniverse/information_about_hopkins/about_jhu/chronology/index.cfm?window=print (06 Jan 2005), n.p.; Wheeler and Ford, *Geons,* 85.

42 Wheeler and Ford, *Geons,* 85.

graduate program.[43] By the time Wheeler arrived at The Johns Hopkins, it was possible to "fly non-stop" from freshman to Ph.D. in six years without intermediate degrees (i.e. Bachelor of Arts and/or Master of Arts).[44] Thus, John Wheeler was able to graduate from The Johns Hopkins University with a Ph.D. in physics before his twenty-first birthday.

The problem however with staying in the same university for the whole of one's education is that one can become too indoctrinated to the dominant world-view at that particular institution. This is not always an easy concept for undergraduates to grasp. Richard Feynman, for example, was shocked that he couldn't remain at MIT to complete his graduate work. Feynman's re-creation of his conversation about graduate school with John C. Slater, chair of physics at MIT, helps to illustrates the point. The conversation began with Feynman's announcing his intent to apply for admission to the MIT graduate program in physics:

> **[Slater]** We won't let you in here.
>
> **[Feynman]** What?
>
> **[Slater]** Why do you think you should go to graduate school at MIT?
>
> **[Feynman]** Because MIT is the best school for science in the country.
>
> **[Slater]** You think that?
>
> **[Feynman]** Yeah.

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[43] French, *A History of the University Founded by The Johns Hopkins*, 137-138; Gilman, *The Launching of a University,* 66-71.
[44] Wheeler and Ford, *Geons,* 86-87.

> **[Slater]** That's why you should go to some other school. You should find out how the rest of the world is.[45]

With the problem of institutional myopia in mind, the physics department at The Johns Hopkins University established a program that rotated upper division, advanced students from professor to professor, spending a month with each.

This innovative practice insured that, prior to being accepted by a dissertation supervisor, each upper division student had the experience of working with a master in a given field of physics. The cast of characters present at The Johns Hopkins at that time is impressive. August Pfund (1879-1949; discoverer of Hydrogen Pfund lines) taught physical optics. Robert Wood (1968-1955; famous for his ultraviolet light work and the chromospheric flash spectrum) also worked with advanced students in optics. Theoretician Gerhard Dieke (1901-1965) showed students how to apply quantum mechanics to atomic and molecular spectral Joyce Bearden offered instruction in x-ray spectra. Wheeler was introduced to nuclear physics by Norman Feather (1904-1978), who was fresh from his Ph.D. work with the Nobelist (and mentor of Niels Bohr) Ernest Rutherford at Cambridge's Cavendish Laboratory.[46] Rutherford in fact, had specifically recommended Feather for the position at The Johns Hopkins.[47]

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[45] Feynman and Leighton, *Surely You're Joking Mr. Feynman*, 59.
[46] Wheeler interview with Weiner and Lubkin (05 April 1967), 11; Wheeler and Ford, *Geons,* 94; W. Norman Brown, comp., *John Hopkins Half-Century Directory: A Catalogue of the Trustees, Faculty, Holders of Honorary Degrees, and Students, Graduates and Non-graduates 1876-1926* (Baltimore, MD: The

Another objective of rotating students throughout the faculty was for them to become familiar with both laboratory and theoretical techniques.[48] Perhaps most importantly, it also helped aspiring physicists to become accustomed to working with varying methodologies—and personalities. Although Wheeler does not specifically articulate this thought, it seems clear that his working relationships with future mentors and mentees benefited from this exposure to a wide variety of intellects.

For Wheeler, there was yet another advantage in attending The Johns Hopkins. Because of its proximity to Washington, there was a long-standing relationship between the The Johns Hopkins University physics department and the scientific staff at the National Bureau of Standards (NSB).[49] In June of 1930, after Wheeler had completed his third year at The Johns Hopkins, he was able to secure a summer job at NSB. For three months, Wheeler had the benefit of working with William F. Meggers, a renowned spectroscopist, on diatomic spectrum analysis. As a consequence of this work, John Archibald Wheeler became a published scientist at the age of nineteen in a paper

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Johns Hopkins University Press, 1926), 420-423; R. B. Lindsay, "Wood, Robert Williams." *Dictionary of Scientific Biography* Vol. XIV, ed. Charles Coulson Gillispie (New York: Charles Scribner's Sons, 1976), 497-499.

[47] Wheeler and Ford, *Geons,* 94; John Archibald Wheeler, "Some Men and Moments in the History of Nuclear Physics: The Interplay of Colleagues and Motivations," working paper, *Nuclear Physics in Retrospect: Proceedings of a Symposium on the 1930's* ed., Roger H. Stuewer (Minneapolis, MN: University of Minnesota Press, 1979): 217-284, 224.

[48] Wheeler and Ford, *Geons,* 94.

[49] Wheeler and Ford, *Geons,* 107-108; Wheeler interview with Weiner and Lubkin (05 April 1967), 5.

coauthored with Meggers.[50] Meggers evidently enjoyed working with Wheeler as well. He invited Wheeler to return to work at NBS for each of the next two summers (1931 and 1932).

The transformation of John Wheeler from future engineer to future theoretical physicist took almost two years. One contributing factor was that, at The Johns Hopkins, the physics and engineering departments shared a small library. So, early on Wheeler was exposed to a number of physics texts and journals, many of which he found fascinating.[51] Then there was a chance encounter on campus with Joseph Ames, a renowned physicist who, at the time, was serving as president of The Johns Hopkins University. Ames asked what Wheeler's major was and Wheeler naturally replied that he was in engineering. John Wheeler recalls Ames' response as, "Well, maybe you'll get interested in physics."[52]

Another factor was the nature of the work in the two disciplines. In 1928, the summer after his first year at The Johns Hopkins, John Wheeler worked at a silver mine in Mexico for his uncle John Archibald (for whom he had been named). Wheeler's job was to inspect, maintain, and rebuild the electrical motors that operated the pumps which kept the mine dry enough to

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[50] The paper was: W. F. Meggers and J. A. Wheeler, "The Band Spectra of Scandium-, Yttrium-, and Lanthanum Monoxides." *National Bureau of Standards Journal of Research* 6, (1931): 239-275; See also: Spectroscopist of the Century ... William F. Meggers." *Arcs & Sparks* (21 Nov 2002) [Online]. Available: <http://www.cstl.nist.gov/acd/839.01/meggers.html> (20 Mar 2006); Wheeler and Ford, 97.
[51] Wheeler and Ford, *Geons,* 86.
[52] Wheeler interview with Weiner and Lubkin (05 April 1967), 4.

work. The mine environment was particularly hard on electrical motors. Therefore, a good deal of Wheeler's time was spent repairing or, more often, replacing the windings of these motors.[53] As he worked, Wheeler began to ponder the sort of problems engineers solved in contrast with the sort of problems physicists solved. In *Geons,* Wheeler recalled his thoughts: "an engineer builds a bridge or whatever it is that lasts 20 or 50 years, but if somebody discovers something in science, well, that's a permanent acquisition of the human race."[54] In any case, after a summer of winding copper wire around electrical motors, physics began to seem more interesting.

The collegial atmosphere at The Johns Hopkins was another factor in Wheeler's decision. The small library that the physics and engineering departments shared also served as a sort of communal work area. There, Wheeler made friends in the in the physics department including Robert Murray. Murray and Wheeler would have long discussions about developments in quantum mechanics. Classes in the physics department, even for undergraduates, tended to be taught in a seminar style. As Wheeler reports, "Students gave the reports instead of the professor talking all the time. So that made a person feel a sense of commitment to what he was talking about."[55] There were also weekly colloquia where a particular topic would be the focus of discussion for the entire academic year. For example, one year

[53] Wheeler and Ford, *Geons,* 87-89.
[54] Wheeler interview with Weiner and Lubkin (05 April 1967), 7.
[55] Wheeler interview with Weiner and Lubkin (05 April 1967), 6, 8.; Wheeler, "Some Men and Moments in the History of Nuclear Physics," 226.

(not specified in the source material) Karl Herzfeld, Maria Goeppert Mayer, and Gerhard Dieke facilitated a seminar on treatment of quantum mechanics by Max Born.[56] The book *Problems of Modern Physics* by the Nobelist Hendrik Antoon Lorentz (1853-1928), was another particularly strong influence for Wheeler's move into physics. Finally a coincidental meeting with R. Bowling Brown, who was at the time a teaching assistant for Wheeler's physics professor John C. Hubbard (1879-1954), sealed the deal. Wheeler officially changed his major at the outset of his third year at The Johns Hopkins.[57]

By 1931, Wheeler's career as a scientist was beginning to unfold. He had learned a good deal of physics and acquired a formidable mathematical toolbox. John Wheeler was ready for a mentor and Karl Herzfeld (1892-1978), the leading theoretician at The Johns Hopkins was ready to have Wheeler as a student.

Herzfeld viewed physics in the broadest possible context. He was ever mindful of how the topic that was under discussion fit into the larger context. In class, he recited that relationship for his students as he began each and every course that he taught.[58] Wheeler remembers that Herzfeld did not deliver "canned" lectures. Rather, Herzfeld's lectures seem to redevelop themselves

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[56] The particular text is not specified. However a likely candidate is: Max Born and Pascual Jordan, *Elementare Quantenmechanik : Zweiter Band der Vorlesungen Über Atommechanik* (Berlin, Julius Springer, 1930).
[57] Wheeler interview with Weiner and Lubkin (05 April 1967), 8-9; Wheeler and Ford, *Geons,* 86-88; The book cited by Wheeler is, H. A. Lorentz, *Problems in Modern Physics: A Course of Lectures Delivered in the California Institute of Technology by H. A. Lorentz,* ed. H. Bateman (Boston, New York: Ginn and Company, 1927).
[58] Wheeler interview with Weiner and Lubkin (05 April 1967), 6.

as he spoke.[59] What seemed to impress Wheeler most of all was Herzfeld's reverence for the enterprise. In an obituary of Herzfeld for *Physics Today*, Wheeler wrote, "Physics for Herzfeld was not a secular, but a religious calling; it aimed, in his view, to make clear the structure and beauty of God's creation."[60]

Implicit in Herzfeld's view of physics as a religious calling is the faith in a rational and comprehensible universe. This is the same faith that resonated in Wheeler—a belief that every problem has a solution—from his days in the Enoch Pratt Free Library assisting library patrons who needed answers to technical questions. Wheeler came away from these Saturday evenings with the strong conviction that," anything could be tackled, and, by George, if you just gritted your teeth hard enough, you could find one way or another some information that would help."[61] Of course, whether or not a given problem lies within our capability to solve it is a separate question. The key element to take from this episode is Wheeler's explicit incorporation of the belief that a solution exists for every problem.

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[59] Wheeler and Ford, *Geons,* 95-96; Wheeler, "Some Men and Moments in the History of Nuclear Physics," 226.
[60] John Archibald Wheeler, "Karl Herzfeld" [Obituary], *Physics Today* 32, no.1 (Jan 1979): 99.
[61] Wheeler interview with Weiner and Lubkin (05 April 1967), 7.

Here is also an echo of Einstein. Einstein's biographer, Abraham Pais, has suggested that, "if [Einstein] had a God, it was the God of Spinoza."[62] In a letter to his friend, Maurice Solovine, Einstein wrote:

> I can understand your aversion to the use of the term 'religion' to describe an emotional and psychological attitude which shows itself most clearly in Spinoza. [But] I have not found a better expression than 'religious' for the trust in the rational nature of reality that is, at least to a certain extent, accessible to human reason.[63]

Inherent in this doctrine of comprehensibility is an optimistic world-view that is an important element of a mentor's charisma in that it inspires mentees and expands the horizon of the doable. John Wheeler's Ph.D. work is a fine example of this phenomenon.

For Wheeler's dissertation, Herzfeld suggested a study of the scattering and absorption of light by helium atoms. Because the calculations involved three bodies (one nucleus and two electrons) this problem involved very complex computations. Beyond these difficulties, Wheeler's dissertation problem offers two important insights. First of all, Wheeler's craftsmanship in the art of problem solving begins to take form:

> As I look back now at that paper written when I was a twenty-one-year-old student, I am startled to find in it approaches to physics that have appeared again and again in my work throughout the rest of my career. First is my way of tackling problems (the practical doer in me). Second is my way of

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[62] Abraham Pais, *Subtle is the Lord: The Science and Life of Albert Einstein* (New York: Oxford University Press, 1982), 17.

[63] A. Einstein letter to M. Solovine; quoted in John Archibald Wheeler, "Albert Einstein March 14 1879—April 18, 1955." in National Academy of Sciences, *Biographical Memoirs*, vol. 51 (Washington, DC: National Academy of Sciences, 1980), 101-102.

> thinking about nature (the dreamer and searcher in me). I fearlessly jumped into mathematical analysis -and surely must have had to learn much of the needed mathematics as I went along. Equally fearlessly, I jumped into numerical calculation. There was, of course, no such thing as a computer at that time, nor even an electrically driven calculator. I used a hand-cranked mechanical calculator.[64]

This passage also demonstrates the sense of the joy with which Wheeler approached his work and the satisfaction that he derived from solving complex problems.

Secondly, there is the development of Wheeler's aesthetics in physics and sense of the allure in a problem. He observes, "The problem suggested by Herzfeld had a special charm. It brought out the beautiful connection that exists in physics between absorption and scattering."[65] The resultant paper, "Theory of the Dispersion and Absorption of Helium", was submitted *Physical Review* in January 1933. It is also noteworthy that, despite the tribulations inherent in performing multifaceted numerical calculations in the 1930's, John Wheeler was able to predict the refractive index of Helium to within three percent of its currently measured value.[66]

Section 2.4 Gregory Breit

After receiving his Ph.D. from The Johns Hopkins University, John Wheeler was selected as one of fourteen recipients of National Research

[64] Wheeler and Ford, *Geons,* 100.
[65] Wheeler and Ford, *Geons,* 100.
[66] Wheeler and Ford, *Geons,* 100; Wheeler interview with Weiner and Lubkin (05 April 1967), 9; See also J. A. Wheeler, "Theory of the Dispersion and Absorption of Helium." *Physical Review* 43 (1933): 258-263.

Council (NRC) post-doctoral fellowships in physics. As part of the application process, Wheeler was required to make a decision about where he would study. In fact, this was a two part decision. By choosing a location, Wheeler was making a decision about the kind of physics he was going to do and, with whom he was going to work. In the end, the decision came down to a choice between studying with Robert Oppenheimer (1904-1967) in California or Gregory Breit (1899-1981) in New York. Wheeler chose Breit and the reasoning is instructive:

> Although I scarcely knew Breit at the time, I had formed a good opinion of him from hearing him speak at Physical Society meetings. I resonated with his style. Like me, he seemed to be always puzzling and was not afraid to let his puzzlement show.[67]

Wheeler's reasons for *not* choosing Oppenheimer help complete the picture:

> There was no doubt about his stature in physics or about his abilities as a teacher. Yet there was something about Oppenheimer's personality that did not appeal to me. He seemed to enjoy putting his own brilliance on display-showing off, to put it bluntly. He did not convey humility or a sense of wonder or of puzzlement.[68]

Clearly, for Wheeler, the solving of a problem was every bit as important—and informative—as the solution itself.

It is useful to keep in mind that physicists are puzzlers and problem solvers by nature.[69] The worst gift one can offer a puzzler is a solved puzzle. Implicit in Wheeler's remarks is a desire to see a mentor's mind at work.

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[67] Wheeler with Ford, *Geons,*107.
[68] Wheeler with Ford, *Geons,*107.
[69] This assertion is corroborated in virtually every scientific biography that has been written from Galileo to Feynman and beyond.

Wheeler was savvy enough to know that even if there was only one solution to a problem, there was certainly more than one path to that solution. From that perspective, Oppenheimer's somewhat teleological presentation of a *fait accompli* path to an answer was not only off-putting, it denied Oppenheimer's mentees the opportunity to observe the solution taking shape. Gregory Breit, by contrast, took a more collaborative—perhaps even more social approach to problems. Working with Breit, Wheeler concluded, would offer him the opportunity to examine multiple pathways to a solution.[70]

That said, Breit was something of a change from Herzfeld. Recall that Herzfeld tended to see a "grand design" in nature. Wheeler once said of Herzfeld that he, "had two religions, Catholicism and physics."[71] Similarly, in nearly all his non-technical writing, Wheeler repeatedly speaks of beautiful solutions or the beauty in nature.[72] However, in Wheeler's case, the pastoral language is misleading. Ken Ford, coauthor of Wheeler's autobiography, speaks of Wheeler the combatant:

> Above all, Wheeler saw physics as a struggle, a challenge. Problems were to be grappled with and conquered. I think he often used the language of contests, or even war. One might see Wheeler vs. nature as analogous to a fencing match or a wrestling match, in which finesse and adroitness counted for a

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[70] Wheeler, "Some Men and Moments in the History of Nuclear Physics," 229; Wheeler interview with Weiner and Lubkin (05 April 1967), 9-10.

[71] Wheeler and Ford, *Geons,* 98.

[72] Wheeler and Ford, *Geons,* 84, 148, 236, 355; See also, Wheeler interview with Weiner and Lubkin (05 April 1967), 9, 13, 24, 25, 27, 26; John Archibald Wheeler, "Some Men and Moments in the History of Nuclear Physics," 224, 226, 227, 250, 255, 260; I believe these three publications from three distinct time periods establish the pattern.

> lot and the beauty was in the execution and in the administration of the *coup de grace*.[73]

In any event, Wheeler's next mentor took a far less metaphorical approach to physics.

Gregory Breit had been trained as an electrical engineer and, he brought an engineer's down-to-earth approach to physics. While Wheeler was inclined to wonder about the "big-picture" implications in the relationships of electrons, positrons, and photons, this kind of reasoning was, as Wheeler delicately phrases it, "not congenial to Breit."[74] In this respect, Gregory Breit's style as a physicist was more similar to that of Wheeler's intellectual grandfather, Ernest Rutherford than it was to either Herzfeld or Niels Bohr.[75] As far as Breit was concerned, if a phenomenon was not subject to measurement and/or calculation, it was not interesting in a professional sense. Rather than worrying about phenomena that is too poorly understood for study, physicists should "do what is doable" and calculate the results that can be measured.[76]

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[73] Ken Ford in a 24 Mar 2006 email to the author.
[74] Wheeler and Ford, *Geons,* 119.
[75] See John Archibald Wheeler, "Niels Bohr, the man," *Physics Today* (Oct 1985), 70. Rutherford held a very matter-of-fact view of physics and was not particularly fond of theorists. "When a young man in my laboratory uses the word 'universe,' " he [Rutherford] once thundered, "I tell him it is time for him to leave." "But how does it come," he was asked on another occasion, "that you trust Bohr?" "Oh," was the response, "but he's a football player!"
[76] Wheeler interview with Weiner and Lubkin (05 April 1967), 17; Wheeler and Ford, *Geons,* 119; Wheeler, "Some Men and Moments in the History of Nuclear Physics," 232-233.

Even so, Breit was a formidable theorist. Writing in 1979. Wheeler said of Breit, "Insufficiently appreciated in the 1930s, he is today the most unappreciated physicist in America."[77] Breit began as an experimentalist and, like Fermi, he always kept a foot in the experimentalist's camp. On the theory side, Breit did some important early work with quantum electrodynamics and later, on nucleonic interactions (i.e. the interaction of two identical particles).[78] The work with nucleons (protons and neutrons) was in fact the drawing card for John Wheeler.[79] However, early on, Wheeler became interest in pair theory (i.e. the interaction of light particles such as electrons, positrons, and photons that are external to the nucleus). Later in the year, Breit taught Wheeler how to use Coulomb wave functions as an analytical tool in particle interaction calculations. Despite the change in research focus and the intensive numerical calculations inherent in the later work, it was a very fruitful year. Out of this collaboration with Breit came five papers and a number of ideas that would "haunt" [Wheeler] for many years."[80]

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[77] Wheeler, "Some Men and Moments in the History of Nuclear Physics," 234. Also quoted in McAllister Hull, "Gregory Breit: July 14, 1899-September 11. 1981," *National Academy of Sciences: Bibliographic Memoirs* [Online]. (n.d.). <http://www.nap.edu/html/biomems/gbreit.html> (08 Dec 2003), n.p.
[78] Hull, "Gregory Breit," n.p.
[79] Wheeler interview with Weiner and Lubkin (05 April 1967), 10-11.
[80] Wheeler and Ford, *Geons,* 114-115, 119. The papers include: J. A. Wheeler and G. Breit. Li+ Fine Structure and Wave Functions near the Nucleus. *Physical Review* 44 (1933), 948; J. A. Wheeler. Interaction Between Alpha Particles. *Physical Review* 45 (1934), 746; G. Breit and J. A. Wheeler. Collision of Two Light Quanta. *Physical Review* 46 (1934): 1087-1091; F. L. Yost, J. A. Wheeler, and G. Breit, Coulomb Wave-Functions. *Terrestrial Magnetism* 40 (1935), 443-447; F. L. Yost, J. A. Wheeler, and G. Breit.

Unfortunately, Breit was also known to have a temper. John Wheeler, for his part, contends that Breit excluded students from his ire:

> Breit was short, intense, sometimes pugnacious. He had a high forehead and wore small circular eyeglasses. Although he was stubborn and difficult with some of his colleagues, that was a side of him that his research students did not see.[81]

Wheeler's recollection notwithstanding, many students did see Breit's anger. A former student of Breit's, McAllister Hull (author of Breit's biographical memoir for the National Academy of Sciences), reports that there was no special immunity for research students where Breit's temper was concerned:

> Others of my colleagues were not so lucky. Gerry Brown, who remembers Breit as a second father, was regularly a target, and I was present when Gregory took the hide off a graduate student who had wished him 'a good talk' at a meeting: of course his talk would be good! There is no point in detailing more examples: they occurred regularly, and were simply a fact of life for his students (and on occasions) his colleagues.[82]

On the other hand, Hull notes that Breit was quick to apologize and contrite whenever he found himself in the wrong.[83]

Temper or not, by all accounts, Breit was devoted to his students. Wheeler describes Breit as "presiding over a brood of students like a mother hen."[84] McAllister Hull remembers that Breit was very concerned with the health of his students. "Any ailment," Hull notes, "was cause for concern and advice." According to both Wheeler and Hull, Breit was very accessible to

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Coulomb Wave Functions in Repulsive Fields. *Physical Review* 49 (1936), 174-89.
[81] Wheeler and Ford, *Geons,* 108.
[82] Hull, "Gregory Breit,", n.p.
[83] Hull, "Gregory Breit," n.p.
[84] Wheeler and Ford, *Geons*, 108.

students (particularly Wheeler since he and Breit shared an office) and generous with his time.

Breit also invested a good deal of time in building a sense of community among his apprentices. For example, there were frequent Saturday afternoon excursions to the suburbs of New York which included a vigorous hike through the forest. Wheeler recalls:

> I don't think we felt we had any choice in this matter, but we would certainly have had no inclination to excuse ourselves from the outings. We saw them as a privilege, not a duty. They provided a wonderful opportunity to get to know Breit as a person, and they knitted us together as a group. Needless to say, physics was not entirely forgotten as we marched through the woods.[85]

Beyond the Saturday afternoon hikes, Breit filled his students' calendars.

There were weekly group lunches which, Hull reports, were sometimes nerve-racking for those who didn't think well on their feet because one never knew when Breit might pose a difficult question.[86] On occasion the group would board a train for Princeton to attend a talk. One evening per week, Breit and I. I. Rabi co-facilitated a joint New York University-Columbia University seminar. Afterward, most of the attendees traveled to Rabi's house to continue the discussion. Breit's wife, Marjorie, actively socialized with the wives of research group members and orchestrated frequent get-togethers for the whole group at the Breit home. In short, Breit's students were socialized

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[85] Wheeler and Ford, *Geons,* 108-109.

[86] Hull, "Gregory Breit," n.p; Here, Hull is using the memory of former Breit pupil Jack McIntosh. Hull also notes that the lunch-time questions involved a "great deal" of learning "including how to think on our feet!" [The exclamation point originates with Hull].

professionally (in the Zuckerman sense of the term) by being immersed in physics and the social customs of the physics community.[87]

Section 2.5 Niels Bohr

When John Wheeler had first applied for the NRC postdoctoral fellowship, he had considered spending a year in Leipzig with Werner Heisenberg.[88] After some reflection however, Wheeler chose to start his postdoctoral work in the United States with Gregory Breit. Nonetheless, the plan to study in Europe remained in place. After a few months working under Breit, Wheeler (with Breit's encouragement and support), decided that a year with Niels Bohr (1885-1962) in the Copenhagen Institute of Theoretical Physics would benefit his career more than a year with Heisenberg in Leipzig.

Actually, it wasn't much of a decision. By 1934, Copenhagen had become established as the crossroads of theoretical physics in Europe and Germany was no longer an attractive site for Americans abroad. As Breit noted, if Wheeler went to Copenhagen and studied with Bohr, there was a good chance over the course of a year that he would meet most of the leading European theorists, including Heisenberg. On the other hand, if he went to Leipzig and studied with Heisenberg, the chances were rather smaller

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[87] Zuckerman, *Scientific Elite,* 123.
[88] Wheeler and Ford, *Geons*, 104.

(especially given the 1934 political climate in Germany) that he would meet many first rank theorists unless he had the time and money to travel.[89]

Then too, over time, Wheeler had come to see Niels Bohr as the foremost theoretician of nuclear physics. On the application to the Fellowship Committee of the National Research Council Wheeler wrote, "Bohr is the best man under whom to investigate the nucleus. He is the man with the great mind and imagination who stimulates and foresees all the others."[90] It is hard to imagine Wheeler making a more auspicious choice. During the time that Niels Bohr directed the Institute for Theoretical Physics in Copenhagen, from 1921 to 1962, eleven Nobel laureates worked or studied there in the capacity of undergraduate, postdoctoral fellow, or visiting fellow. This list includes Felix Bloch, Aage Bohr (1922– ; Aage was, of course, something of a captive audience), Subrahmanyan Chadrasekhar (1910-1995), Max Delbrück (1906-1981), Werner Heisenberg (1901-1976), George de Hevesy (1885-1966), Lev Landau (1908-1968), Ben R. Mottelson (1926–), Wolfgang Pauli (1900-1958), Linus Pauling (1901-1994), and Harold C. Urey (1893-1981). While the

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[89] Wheeler and Ford, *Geons,* 123; Wheeler, "Some Men and Moments in the History of Nuclear Physics," 238.

[90] While the sentiment remains constant, there are varying versions of this statement. c.f. Wheeler and Ford, *Geons,* 123; Wheeler interview with Weiner and Lubkin (05 April 1967), 17-18; Wheeler interview with Aaserud (04 May 1988), n.p.; Wheeler, "Some Men and Moments in the History of Nuclear Physics," 238;

character of each relationship with Bohr varied, all but two (Chandrasekhar and Mottelson) acknowledged the work with Bohr in their Nobel biography.[91]

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[91] Felix Bloch, "Biography" [Online], Available: <http://nobelprize.org/physics/laureates/1952/bloch-bio.html> (24 Mar 06), also in *Nobel Lectures, Physics 1942-1962* (Amsterdam: Elsevier Publishing Co., 1964); Aage Bohr, "Autobiography" [Online]. Available: <http://nobelprize.org/physics/laureates/1975/bohr-autobio.html> (24 Mar 2006), also in *Les Prix Nobel*, ed. Wilhelm Odelberg (Stockholm: Nobel Foundation, 1976); David C. Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (New York: Freeman, 1993); Subrahmanyan Chandrasekhar, "Autobiography "[Online], Available: <http://nobelprize.org/physics/laureates/1983/chandrasekhar-autobio.html> (24 Mar 2006), also in *Les Prix Nobel* ed. Wilhelm Odelberg (Stockholm: Nobel Foundation, 1984); Max Delbrück, "Biography"[Online], Available: <http://nobelprize.org/medicine/laureates/1969/delbruck-bio.html> (24 Mar 06), Also in *Nobel Lectures, Physiology or Medicine 1963-1970* (Amsterdam: Elsevier Publishing Company, 1972); Werner Heisenberg, "Biography" [Online], Available: <http://nobelprize.org/physics/laureates/1932/heisenberg-bio.html> (24 Mar 2006), also in *Nobel Lectures, Physics 1922-1941* (Amsterdam: Elsevier Publishing Co., 1965); George de Hevesy, "Biography" [Online], Available: <http://nobelprize.org/chemistry/laureates/1943/hevesy-bio.html> (24 Mar 2006), also in *Nobel Lectures, Chemistry 1942-1962* (Amsterdam: Elsevier Publishing Co., 1964); Lev Landau, "Biography" [Online], Available: <http://nobelprize.org/physics/laureates/1962/landau-bio.html> (24 Mar 2006), also in *Nobel Lectures, Physics 1942-1962* (Amsterdam: Elsevier Publishing Co., 1964); Ben R. Mottelson, "Autobiography" [Online], Available: <http://nobelprize.org/physics/laureates/1975/mottelson-autobio.html> (24 Mar 2006), also in *Les Prix Nobel en 1975*, ed. Wilhelm Odelberg (Stockholm: Nobel Foundation, 1976); Abraham Pais, *Niels Bohr's Times in Physics, Philosophy, and Polity* (New York: Oxford University Press, 1991); Wolfgang Paul, "Biography" [Online], Available: <http://nobelprize.org/physics/laureates/1945/pauli-bio.html> (24 Mar 2006), also in *Nobel Lectures, Physics 1942-1962* (Amsterdam: Elsevier Publishing Co. 1964; Linus Pauling, "Biography" [Online], Available: <http://nobelprize.org/chemistry/laureates/1954/pauling-bio.html> (24 Mar 2006), also in *Nobel Lectures, Chemistry 1942-1962* (Amsterdam: Elsevier Publishing Co., 1964); Harold C Urey, "Biography" [Online], Available: <http://nobelprize.org/chemistry/laureates/1934/urey-bio.html> (24 Mar 2006), also in *Nobel Lectures, Chemistry 1922-1941* (Amsterdam: Elsevier Publishing Co., 1966).

Bohr, like Herzfeld, assumed a broad world view in physics. As Wheeler has stated:

> And of course there was a completely different spirit between Bohr's approach to nuclear physics and Breit's—Bohr looking over the whole thing without getting down to detailed calculation on any one aspect and always looking for a paradox that would throw light on *a* whole new approach, and Breit, on the other hand, focusing on a very careful comparison of a detailed model with experiment and the soul of integrity and giving one the feeling that any part of physics should in principle, if one understood it properly, be subject to calculations so you could really hope to check the theory against your experiment and not just talk.[92]

And yet talk was intrinsic to Bohr's methodology of physics.

As the product of five generations of academicians, Niels Bohr acquired the practice of scholarly dialogue very early in life. His father, Christian Bohr, a renowned Danish scientist, had been nominated for a Nobel prize twice (1907, 1908) for his work on the physiology of respiration. Christian Bohr was also a prominent member of the Videnskabernes Selskab [the Royal Danish Academy of Sciences and Letters]. After academy meetings, Bohr would often invite a number of colleagues to his home for extended discussions. This after-meeting meeting usually included the famous philosopher of religion Harald Höffding, the physicist Christian Christiansen, and the linguist Vilhelm Thomsen. As soon as they were old enough to benefit from the conversation, Niels Bohr and his younger brother Harald were permitted to sit in on these

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[92] Wheeler interview with Weiner and Lubkin (05 April 1967), 17.

discussions.[93] It appears that the Bohr sons were subjected to tacit learning at an early age. It would also appear that the habit of auditory analysis stuck.

Throughout his career, Bohr seemed to need to verbalize concepts as if by hearing them spoken he could detect the presence or absence of a "ring of truth." The physicist Abraham Pais, who is also Bohr's biographer, and John Wheeler have both noted that Bohr worked best when at least one other physicist was present to serve as a sounding board.[94] Wheeler observes:

> He always liked to have at least one other person present, even if he were lost in his own thoughts. When the moment came that he wanted to pull forth an idea and examine it, he needed a foil, someone with whom he could toss the idea back and forth. Léon Rosenfeld filled this role for some years. So did Bohr's son Aage.[95]

Where Gregory Breit had subjected concepts to trial by calculation, Niels Bohr, employed trial by oration.

Whenever and wherever Bohr set to work, the day would begin with verbally rehearsing the arguments that formed the basis for quantum and/or nuclear theory. Since Bohr had been an accomplished football (soccer) player, this ritual is often described with athletic metaphors. Bohr's biographer, Abraham Pais, describes Bohr's practice as "an athlete warming up before

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[93] Abraham Pais, *Niels Bohr's Times in Physics, Philosophy, and Polity* (New York: Oxford University Press, 1991), 33-36, 98-99. See also: Leon Rosenfeld, "Bohr, Niels Henrik David," in *Dictionary of Scientific Biography* vol. II, ed. Charles Coulston Gillispie (New York: Charles Scribner's Sons, 1975), 239-254

[94] Pais, *Niels Bohr's Times,* 3, 7-8, 421-422; Wheeler and Ford, *Geons,* 126; John A. Wheeler, " 'No Fugitive and Cloistered Virtue'—A Tribute to Niels Bohr," *Physics Today* 16, no. 1 (Jan 1963), 31; Wheeler, "Niels Bohr, the Man," 66-72

[95] Wheeler and Ford, *Geons,* 126.

entering the sports arena."[96] John Wheeler, who also tended to view physics as a contest, saw Bohr's custom as a more vigorous endeavor. Wheeler characterized Bohr's routine as "a one-man tennis match."[97]

There was another element of Bohr's method which, for Wheeler, must have induced fond memories—even if only at a subliminal level. In order to ferret out the weakness or contradictions in a hypothesis, Bohr would temper concepts by alternatively building them up and then tearing them down. Wheeler offers a synopsis of the process:

> Usually the new issue became a focal point for discussion in the next days. Those days could almost have been numbered odd and even. One day was a day of building. "If so-and-so is true, such-and-such follows. That will give us the chance to understand thus-and-so. That means it will be absolutely central to measure this-and-this cross section. Then we will be able to predict such-and-such with great assurance." No criticism. That was reserved for the next day. If at its end anything survived, that battle-tested core became the starting point of yet another day of building—and so on, up to a conclusion that could be played out as a complete tennis match.[98]

Although Wheeler does not articulate the thought, Bohr's method of alternatively supporting and attacking a concept was reminiscent of Sunday evenings in Baltimore when Wheeler's grandfather Archibald would promote one side of a political argument before dinner and attack it afterward.[99] By this practice, Bohr tacitly communicated to his students the manner by which raw

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[96] Pais, *Niels Bohr's Times,* 8.
[97] Wheeler, "Niels Bohr, the man," 66.
[98] Wheeler, "Niels Bohr, the man," 68. See also. Edwin F. Taylor, "The Anatomy of Collaboration," in *Magic Without Magic: John Archibald Wheeler; A Collection of Essays in Honor of His Sixtieth Birthday,* ed, John R. Klauder (San Francisco: W. H. Freeman, 1972): 474-485, 477.
[99] Wheeler and Ford, *Geons,* 74.

concepts must be refined before they can be woven into the tapestry of science.

Even paper writing was an intense verbal endeavor. From the outset, Bohr seldom wrote papers in the sense of putting pen to paper. Instead, Bohr preferred to dictate to an amanuensis of the moment. If Rosenfeld or Aage Bohr were not available, Bohr would enlist whomever he could find. Pais suggests this was, at least in part, a consequence of Bohr's poor penmanship. [100] However, Bohr's wife Margrethe recalls that, "'he had so much in his head that just had to be put down, and he could concentrate while he dictated."[101] Since there has been no evidence presented that Bohr evaluated the penmanship of his "scribes," Margrethe Bohr's recollection is more resonant with the widely acknowledged need for Bohr to think aloud.

Certainly getting a new idea onto paper was no guarantee of imminent publication for either Bohr or his collaborators. The editing process with Bohr could be extraordinarily thorough. According to Pais, Bohr defined a manuscript as "a document on which to make corrections."[102] Two factors were at play. One element, very likely stemming from his boyhood conversations with the philosopher Harald Höffding, was that Bohr was acutely sensitive to the nuances in the spoken and written word. Pais recalls Bohr's thoughts on the matter:

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[100] Pais, *Niels Bohr's Times,* 10, 102-103.
[101] Pais, *Niels Bohr's Times,* 102-103.
[102] Pais, *Niels Bohr's Times,* 103.

> What is it that we human beings depend on? We depend on our words. We are suspended in language. Our task is to communicate experience and ideas to others. We must strive continually to extend the scope of our description, but in such a way that our messages do not thereby lose their objective or unambiguous character.[103]

Plainly, for Bohr, word choice was more than mere auditory cosmetology. It seems safe to surmise that by repeated revisions, Bohr was tacitly communicating the importance of craftsmanship in language. On a less esoteric plane, there is also the story of Wheeler and Bohr, in the spring of 1939, combing through dictionaries in Princeton's Fine Hall for more than an hour because Bohr disliked the term "fission" for the splitting of a nucleus. Wheeler recalls, " 'If fission is a noun,' he said to me, 'what is the verb? You can't say 'a nucleus fishes!' "[104] Despite their heroic efforts to find a suitable verb, the noun 'fission' has endured.

Of course, language was secondary to accuracy. Science historian Gerald Holton has listed four reasons why he sees Niels Bohr as an exemplar of scientific integrity. The very first (and presumably most significant) rationale Holton offers is that Bohr tried, "to get it right at all costs, sparing no effort." As a corollary to this notion, Holton maintains that once a concept has been thoroughly tested, one must also possess the courage of conviction to hold to one's hypothesis even "before it is fashionable or safe." To support his

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[103] Pais, *Niels Bohr's Times, 445-446.*
[104] Wheeler and Ford, *Geons,* 21-22.

contention, Holton cites the "Bohr atom" paper of 1913 as a novel concept that was rigorously examined and submitted to a very skeptical community.[105]

Wheeler got the message. In *Geons*, Wheeler recalls that Bohr had "little concern for priority." Rather he preferred to "ruminate on a topic at length, patiently polishing its details." This, of course is in stark contrast to the typical late twentieth century physicist—especially one just embarking on a career—for whom precedence in publication is an (albeit justified) obsession. In fact, a common practice is to publish something—even a letter to the *Physical Review Letters* and fill in the details later.[106] As it turns out, during their time in Copenhagen (1934-1935), Wheeler and Milton Plesset had written a paper on gamma-ray (high-energy photons) scattering in interactions with atomic nuclei. In the early days of cosmic ray research, they believed that they had made significant progress in an area of interest. Bohr however, believed that more could and should be done before the paper was submitted to a journal. Although Wheeler and Milton worked at the refinements suggested by Bohr, they ultimately ran out of time and, their work went unpublished.[107]

A similar situation arose in the spring of 1939. Bohr and Wheeler had collaborated on the first study of the generalized mechanism of nuclear

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[105] Gerald Holton, "Niels Bohr and the Integrity of Science," *American Scientist* 74, no. 3 (May-Jun 1986), 240

[106] Wheeler and Ford, *Geons*, 129-130; Caltech Vice-Provost David Goodstein in a 17 Mar 2006 email to the author, reports that if a scientist has one or two real contributions to make, they will divide them up into a number of letters which are submitted in advance of the main papers.

[107] Wheeler and Ford, *Geons*, 129-130.

fission.[108] Unfortunately, Bohr needed to return to Denmark in April of 1939, well before the editing process was complete. Wheeler recalls (with a hint of pride):

> Bohr's usual habit to go back and forth with his coauthors, often for an extended period, as he struggled for the precision, generality, and clarity that he always held forth as a goal. This time, uncharacteristically, he gave me permission to edit and submit the paper without sending the final version to him for review.[109]

Wheeler also reports that Victor Weisskopf and Rudolph Peierls, two physicists familiar with Bohr's work habits, were amazed (and envious) when they learned how smoothly the fission paper had been handled. The paper was submitted in June of 1939 and published on 1 September 1939, the day that Germany invaded Poland and World War II began.[110]

In June of 1935, John Wheeler left Copenhagen for the United States. His fiancé, Janette Hegner, and an assistant professorship at the University of North Carolina awaited his return. John Archibald Wheeler was ready to become a mentor. He was twenty-four years old.

Section 2.6 Einstein's Protégé

Two commonplaces in the historiography of Albert Einstein are; 1) he had no apprentices and 2) by the time he emigrated to the United States, he was no longer in the forefront of theoretical physics. This latter sentiment was

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[108] The paper in question is: N. Bohr and J. A. Wheeler, "The mechanism of nuclear fission" *Physical Review* 56 (1939): 426-450.
[109] Wheeler and Ford, *Geons,* 31.
[110] Wheeler and Ford, *Geons,* 31-32.

almost certainly (at least in part) a carry-over from the 1927 Solvay Congress during which Niels Bohr had clearly won the great debate with Einstein over the validity of quantum theory.[111] Recall that in a 4 December 1926 letter to Max Born, Einstein famously asserted:

> Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing. The theory produces a good deal but hardly brings us closer to the secret of the Old One. I am at all events convinced that He is not playing at dice.[112]

Einstein's decline in status was not so much a result of his loss in the debate as it was in his adamant (some might say 'stubborn') disavowal of the quantum mechanical world view.

Albeit very gently, John Wheeler acknowledged Einstein's diminished influence in a series of talks which marked the centenary of Einstein's birth. In an 8 May (1979) lecture at Leed's University, Wheeler described his first meeting with Einstein. It was in the autumn of 1933; Wheeler was a post-doc studying with Gregory Breit and Einstein had just recently emigrated to the United States. The meeting came about on one of Breit's periodic sojourns away from the NYU campus.[113] Breit and his students were invited to a "carefully unannounced" seminar in which Einstein would discuss his latest

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[111] Kragh, *Quantum Generations*, 213.
[112] Albert Einstein, Max Born, and Hedwig Born *The Born Einstein Letters: Correspondence between Albert Einstein and Max and Hedwig Born from 1916 to 1955 with Commentaries by Max Born*, trans. Irene Born (New York: Walker and Company, 1971), 90-91; This particular sentence is quoted in virtually every biography of Einstein as well as in countless other texts. Two more scholarly examples are: Pais, *Subtle is the Lord*, 443 and Pais, *Niels Bohr's Times*, 318.
[113] Wheeler, "Some Men and Moments it the History of Nuclear Physics," 232; Wheeler and Ford, *Geons*, 108-109, 111-112.

work. Reflecting on Einstein's remarks, Wheeler observed, "It was clear on this first encounter that Einstein was following very much his own line, independent of the interest in nuclear physics then at high tide in the United States."[114] Put simply, physics seemed to have moved beyond Einstein.

In 1936, while teaching at North Carolina, Wheeler applied for a leave of absence so that he could accept a visiting appointment to the Institute for Advanced Study in Princeton. John Wheeler intended this "mini-sabbatical" to allow him to complete some thinking and writing about nuclear physics without the encumbrance of classroom responsibilities. Wheeler also intended to establish a personal relationship with the rhetorician Eugene Wigner (1902-1995) and the mathematicians Herman Weyl (1885-1955) and John von Neumann (1903-1957). John Wheeler also wanted to get to know Albert Einstein even though, "our interests were then so different that I didn't expect to learn very much from him."[115] So, why would Wheeler want to better know a man from whom he "didn't expect to learn very much?"

One important part of the attraction Wheeler felt for Einstein was that they shared world-view based on comprehensibility:

> There was one extraordinary feature of Einstein the man I glimpsed that [first] day, and came to see ever more clearly each

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[114] John Archibald Wheeler, "Einstein: His Strength and His Struggle," working paper, Twentieth Selig Brodetsky Memorial Lecture, University of Leeds, 8 May 1979 (Leeds, UK: Leeds University Press, 1980), 3; John Archibald Wheeler, "Albert Einstein March 14 1879—April 18, 1955." in National Academy of Sciences, *Biographical Memoirs,* vol. 51 (Washington, DC: National Academy of Sciences, 1980), 99; Wheeler and Ford, *Geons,* 111-112.

[115] Wheeler and Ford, *Geons*, 150.

> time I visited his house climbed to his upstairs study, and we explained to each other what we did not understand. Over and above his warmth and considerateness, over and above his deep thoughtfulness, I came to see, he had a unique sense of the world of man and nature as one harmonious and someday understandable whole, with all of us feeling our way forward through the darkness together.[116]

This sentiment is the very same doctrine of comprehensibility that was evident in Herzfeld's 'faith' in physics. It is the same conceptual optimism—the belief that anything can be tackled and further, that sooner or later every problem will yield a solution—that grew out of Wheeler's work as an assistant librarian for technical literature in Baltimore. Finally, in a March 1979 lecture John Wheeler extolled Einstein and several other scientists and inventors specifically because they approached their work with a "larger" —and therefore more comprehensive—frame of reference.[117]

The dynamics of John Wheeler's relationship with Einstein changed when, according to his own metaphor, Wheeler came under the conceptual influence of gravity (as it is understood in general relativity). This attraction to gravity came about as consequence of Wheeler's work in nuclear physics. Early in 1952, he revisited two 1939 papers by Robert Oppenheimer (one with George Volkoff, the other with Hartland Snyder) that predicted the gravitational collapse of a star that had consumed its nuclear fuel. Wheeler believed that the mathematical singularity predicted by Oppenheimer and his associates

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[116] Wheeler, "Albert Einstein March 14 1879—April 18, 1955," 99-100; Wheeler, "Einstein: His Strength and His Struggle."3-4.

[117] John A. Wheeler, "Einstein and other seekers of the larger view," *Science and Public Policy* 6 (Dec 1979), passim.

had to be incorrect, and he set out to rectify the situation. Wheeler observed, "I wanted to teach relativity for the simple reason that I wanted to learn the subject."[118] On 6 May 1952, Wheeler obtained permission to teach a graduate level course in general relativity.

From the outset of the course, Wheeler and his students worked to get beyond the mathematical formalism that had come to dominate the subject.[119] In this endeavor, Wheeler found a kindred spirit in Einstein. Although Einstein's name is forever linked to equations—one in particular—he was not (at least by professional standards) a particularly skilled mathematician. Like Bohr (and unlike Breit) Einstein approached physics through intuition and articulated concepts rather than through applied calculation. The mathematician David Hilbert once remarked, "Every boy in the streets of our mathematical Göttingen understands more about four-dimensional geometry than Einstein. Yet, despite that, Einstein did the work and not the mathematicians."[120] Why would this be true?

Wheeler suggests that Einstein's years of work in the patent office forced him to adopt a world-view that was more general (and therefore more comprehensive) than that held by the mathematicians who, at least professionally, were more narrowly focused. For seven years, on a daily basis,

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[118] Wheeler and Ford, *Geons,* 228-229.
[119] Wheeler and Ford, *Geons,* 228, 231.
[120] Philipp Frank, *Einstein, Sein Leben undseine Zeit* (München: Paul List Verlag, 1949), p. 335, quoted in Wheeler, "Einstein: His Strength and His Struggle," 5.

Einstein was required to examine novel (or not-so-novel) attempts to apply the laws of physics in everyday life. As concisely as possible, he would have to explain to the patent applicant why their invention was (or was not) worthy of a patent. In the course of denying a patent, Einstein was often obliged to explain some general principle of physics that rendered the applicant's invention unworkable. [121] It is also worth noting here that Einstein and Wheeler shared a youthful (and probably lifelong) fascination with mechanical contraptions.[122]

The dividends of Wheeler's choice to explore relativity from a generalist's (i.e. conceptualist) world-view were handsome. Over the course of that first year, Wheeler quickly realized that decades of a strict mathematical treatment of relativity had only just scratched surface of relativity's conceptual bounty:

> What I learned in teaching the course was that the riches of Einstein's theory had been far from fully mined. Hidden beneath the equations, simple in appearance, complex in application—was a lode waiting to be brought to the surface and exploited.[123]

Small wonder that the enterprise of unearthing this lode dominated the next quarter century of John Wheeler's life.

Wheeler and Einstein also shared a high regard for the value of colleagueship. This colleagueship, it must be noted, included the participation

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[121] John Archibald Wheeler, "Albert Einstein March 14 1879—April 18, 1955." in National Academy of Sciences, *Biographical Memoirs,* vol. 51 (Washington, DC: National Academy of Sciences, 1980), 102-103.
[122] Wheeler and Ford, *Geons,* 83; Wheeler, "Albert Einstein March 14 1879—April 18, 1955," 100-101.
[123] Wheeler and Ford, *Geons,* 231.

of students in a seminar format. Wheeler asserts, "No tool of colleagueship is more useful than the seminar." In such a context, professors are not to pontificate from a pedestal. Rather, Wheeler declares that a seminar setting obligates students to question their professors. In the end, Wheeler and Einstein agreed that theoretical constructs are best strengthened (or most efficiently eliminated) by the rigorous examination of both students and peers.[124]

Given their mutually held fondness for the seminar method of investigation, it is not surprising that Einstein made himself available to Wheeler's relativity seminar twice in the last years of his life. The first of these was on 16 May 1953, when Einstein invited Wheeler's seminar group over to his house for tea. The following year, on 14 April 1954 (one year and four days before his death), Einstein addressed Wheeler's seminar group in Fine Hall on the Princeton campus.[125]

One example of the benefits that colleagueship with Einstein provided stands out for Wheeler. In response to a question regarding radiation damping, Einstein referred Wheeler to a 1909 article in which he and Walter Ritz set out their respective positions clearly and distinctly. The dialogue was summed in one sentence, " 'Ritz treats the limitations to retarded potentials as one of the foundations of the second law of thermodynamics, while Einstein

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[124] Wheeler, "Albert Einstein March 14 1879—April 18, 1955," 103-104.

[125] John A. Wheeler, "Mercer Street and other Memories," in *Albert Einstein: His Influence on Physics, Philosophy, and Politics,* ed. Peter C. Aichelburg and Roman U. Sexl (Braunschweig, Germany: Friedr. Vieweg & Sohn, 1979), 202; Wheeler, "Einstein: His Strength and His Struggle," 104.

believes that the irreversibility of radiation depends exclusively on considerations of probability.' "[126]

Three other examples of the nature of John Wheeler's relationship with Einstein are useful to this discussion. One such instance is John Wheeler's invitation to author Einstein's biographical memoir for the National Academy of Sciences. Obviously a large number of academy members were capable of writing Einstein's memoir; the fact that John Wheeler was chosen certainly seems significant. Some background on author selection for these memoirs may prove illuminating. In the National Academy of Science, selecting an author for a given Biographical Memoir falls to the scientific peers of the deceased. The academy is divided into twenty sections (ranging from applied physics to plant biology) that correspond to the various sub-disciplines of science recognized by the academy. To assign a memoir, the chair of the appropriate section (in Einstein's case, physics) works with other members in that section to identify someone who "has an intimate knowledge of the life and scientific work of the deceased." It is also noteworthy that in order to choose the individual best qualified (i.e. one with an 'intimate' knowledge of the deceased), the members of a section are free to choose authors who are not members of the National Academy of Sciences.[127]

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[126] A. Einstein and W. Ritz, *Physikalisches Zeitschrift,* 10 (1909): 323-34, quoted in Wheeler, "Albert Einstein March 14 1879—April 18, 1955," 104.
[127] Stephen Mautner, Executive Editor of National Academies Press, Joseph Henry Press, 13 April 2006, in voice mail to author (10:59 AM PDT).

Another example of Wheeler's affection for Einstein is found in *Albert Einstein: His Influence on Physics, Philosophy, and Politics* edited by Peter C. Aichelburg and Roman U. Sexl appeared in 1979—the centenary year of Einstein's birth. The book contained sixteen chapters, contributed by fifteen authors. John Wheeler submitted two chapters, "Black Hole: An Imaginary Conversation with Albert Einstein." and "Mercer Street and Other Memories."[128] The latter selection is a fond remembrance of Wheeler's relativity class joining Einstein for tea in his Mercer Street home. The former selection is more telling of the relationship. Certain passages in this dialogue very much have the flavor of a junior colleague reporting to a mentor:

> **[Wheeler]** I and my colleagues have to confess that we have made only a bare beginning at studying the approach to singularity both in cosmology and in black hole physics.
>
> **[Einstein]** To understand that approach is really important.
>
> **[Wheeler]** Our Soviet colleagues propose fascinating physical insights as to what goes on in the final stages of collapse, but not convincing mathematical methodology. Colleagues in the West have the mathematical methodology but so far it has not sufficed to provide the insight that we all want.
>
> **[Einstein]** This is an old story in physics. We know in the end everything comes together in a new and better and larger unity.

And further:

> **[Wheeler]** I don't have to tell you that there is still a non-negligible body of our colleagues who think that an asymptotically flat universe is more natural than a closed universe.

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[128] Peter C. Aichelburg and Roman U. Sexl, eds., *Albert Einstein: His Influence on Physics, Philosophy, and Politics* (Braunschweig, Germany: Friedr. Vieweg & Sohn, 1979).

> **[Einstein]** But that view takes the geometry of faraway space out of physics and makes it part of theology, to be discovered by reading Euclid's bible. It puts us back to the days before Riemann, days when space was still for physicists, a rigid homogeneous something, susceptible of no change or conditions. Only the genius of Riemann, solitary and uncomprehended, had already won its way by the middle of the last century to a new conception of space, in which space was deprived of its rigidity, and in which its power to take part in physical events was recognized as possible.

Finally:

> **[Wheeler]** But whether you call particles geometry or something else, does it not trouble you that collapse should mean their end?
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> **[Einstein]** To me the problem of collapse is no greater than the problem of the big bang. Both are a warning that the universe presents deeper issues than we ever realized. That to me is the lesson of the black hole. Alas, I can say no more. I feel myself being carried away, not to return for another hundred years. But let me leave you hope for the work of all your colleagues. "All of these endeavors are based on the belief that existence should have a completely harmonious structure. Today we have less ground than ever before for allowing ourselves to be forced away from this wonderful belief.

It is very difficult to read these words without visualizing a mentor encouraging a mentee to press on.

The mentor-mentee relationship also surfaces in events surrounding Wheeler's first paper on geons.[129] In the fall of 1954, Wheeler sent a copy of his paper to Einstein. A relatively long interval passed before Einstein contacted Wheeler and suggested that they discuss the paper orally. Wheeler

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[129] Wheeler and Ford, *Geons,* 236. Wheeler defines a "geon" as a "hypothetical entity, a gravitating body made entirely of electromagnetic fields." The name is derived from (g for "gravity," e for "electromagnetism," and on as the word root for "particle." Hence geon.

recalls that Einstein had considered the concept of a geon, but that he had concluded it was not important since "he saw no link with anything in nature." Moreover, Wheeler continues, " With his usual astonishing intuition, Einstein said in this conversation that he was prepared to admit that his equations of relativity allowed for geon solutions of the kind I was exploring, but he doubted the stability of a geon" —a conclusion Wheeler independently proved a few years later.[130]

For the purpose of this project, the details of Wheeler's paper are less important than the nature of the interaction. Here again, interplay of Wheeler and Einstein is very similar to that of a younger scholar working (albeit very independently) with an older mentor. As noted above, there is far more to mentoring than parenting a dissertation. At the time of the geons consultation, Wheeler was forty-three years old. Einstein was seventy-five. In light of the foregoing and, given John Wheeler's quarter century commitment to general relativity, it seems clear that Albert Einstein served as a mentor for John Wheeler.

Section 2.7 Review

So, what has been learned? First of all, it has been shown that many qualities that make for the character of an exceptional mentor were present in John Wheeler's youth. Certainly, he was a curious child. Then too, there were incidents and occasions that stand out. One such occasion is the year in

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[130] Wheeler and Ford, *Geons,* 238.

Vermont when John Wheeler completed the work of four academic years in one. Here, Wheeler learned (at least implicitly) that with motivated students, less direction is often more effective. Other elements of character surface sporadically in the narrative of Wheeler's life.

From the beginning, John Wheeler was an independent thinker. Witness his choice to respect his parents objections regarding the Pledge of Allegiance and then deciding that their convictions were not necessarily his. The anecdote about correcting the workmen in a ditch who were improperly connecting pipe, demonstrates that Wheeler was always ready to look a situation over for himself—with 'fresh eyes.' At Sunday dinners with his grandfather Archibald, Wheeler learned that there are always (at least) two sides to any proposition and, that a careful thinker will consider them all. From his teachers in Vermont and Youngstown, John Wheeler learned the importance of teachers who cultivate the learning habits and expand the curriculum of gifted students. More than anyone else, Joseph Wheeler taught his son the worth of work and the pride in a job well done. Finally, from his entire family—though most of all from his parents—John Wheeler learned the Joy of learning. So what did his mentors provide?

Wheeler has been asked more than once to compare Gregory Breit's approach to physics with that of Niels Bohr. There is no point in reciting that answer here. A better question might be, "What did you, both as a physicist and mentor, take from your experience with these mentors?" The most compelling clue is contained in Wheeler's reflections on his first (sole author) published paper. For the convenience of the reader, the salient section of the block quotation has been re-posted here:

> As I look back now at that paper written when I was a twenty-one-year-old student, I am startled to find in it approaches to physics that have appeared again and again in my work throughout the rest of my career. First is my way of tackling problems (the practical doer in me). Second is my way of thinking about nature (the dreamer and searcher in me). I fearlessly jumped into mathematical analysis -and surely must have had to learn much of the needed mathematics as I went along. Equally fearlessly, I jumped into numerical calculation.[131]

It is useful to keep in mind that this paper was written before Wheeler had extensive contact with either Breit or Bohr.

Here it is interesting to see how Wheeler refers to the way he tackles problems as being "a doer" This approach is very much in the spirit of Breit. However, in the very next line Wheeler refers to himself as a "dreamer and a searcher". This sentiment is very much in the spirit of Bohr. Finally there is the confidence (or perhaps faith) that a solution exists for every problem. A notion which was very congenial to Herzfeld and Einstein.

Plainly, there is more to the story of Wheeler's success as a mentor than his experience as an apprentice to Herzfeld, Breit, and Bohr. John Wheeler came from a family that emphasized the importance of acquiring knowledge, inculcated a robust work ethic, and encouraged independent thinking. A number of adults including extended family and teachers reinforced these values. Still, Wheeler's professional skills, standards, and philosophy

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[131] J. A. Wheeler, "Theory of the Dispersion and Absorption of Helium," *Physical Review* 43 (1933), 258-263.

were not products of his youth; they were the result of a process of professional development that, according to science historian Frederic Holmes, takes an average of ten years.[132]

Frederic Holmes and others have reported the conventional wisdom of twentieth century scientists that "the most effective way to win a Nobel Prize is to be trained by a Nobel Prize winner."[133] Likewise, It seems reasonable that skillful mentors quite often served as apprentices to other skillful mentors. Such groupings form a master-apprentice chain of wisdom that may well stretch over multiple generations of science.

So, what is the single most important thing that Wheeler took from his mentors? The answer is nurture. Consider the analogy of a track coach. The finest track coach on the planet cannot teach a slow runner to run fast. At best that coach will be able to help a slow runner become less slow. The same is true of mentors.

There are certain qualities which, taken together, characterize most successful scientists. These include academic talent, independent and careful thinking, a robust work ethic or even taking joy of learning almost anything. None of these elements are 'teachable' in the standard sense of the word. A skillful mentor who can recognize the potential in a young scientist has the

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[132] Frederic Lawrence Holmes, *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists* (New Haven, CN: Yale University Press, 200), xix [introduction].

[133] Holmes, *Investigative Pathways,* 28; others who observe this tendency include Harriet Zuckerman, *Scientific Elite,* 99-100 and tables on 101-103; Kanigel, *Apprentice to Genius,* xiv [introduction] and elsewhere.

opportunity to nurture that nascent talent into full bloom.[134] Therefore, in analyzing the qualities that established John Wheeler as a skillful mentor, a useful approach has been to look upstream for the professional practices, standards, and philosophy that Wheeler's mentors were most likely to inculcate in him.

This chapter has shown how, in John Wheeler's early years, the personal qualities of a mature scientific mentor were developing. The next chapter deals with Wheeler's ability to nurture the potential in succeeding generations of scholars.

[134] Zuckerman, *Scientific Elite,* 110-112.

Chapter Three: Mentoring Theoretical Physics in America: John Archibald Wheeler at Princeton, 1938-1977

Section 3.1 Overview and Organization

At Waterloo University, in Ontario, Canada, former Wheeler student Kip Thorne delivered a lecture during the opening session of the Eighth International Congress on General Relativity and Gravitation. The date was Thursday 11 August 1977. At the close of Thorne's talk, another former Wheeler student, University of Maryland physicist Charles Misner, approached the podium. There, Misner presented John Archibald Wheeler with the commemorative volume *Family Gathering.*[1] In his remarks, Misner explained that the aim of the project's initiator (who chose to remain anonymous) was to present John Wheeler with a collection of personal letters that "could show in practice some of the workings of the apprenticeship system by which research attitudes and methods are passed on."[2] Professor Misner went on to quote the *Family Gathering* letter from Kenneth W. Ford:

> In John Wheeler's own professional development, the influence of Niels Bohr was deep and lasting. John, in turn, has had a profound influence on the style as well as the achievement of a large number of people who worked with him. I and many others, in our turn, have transmitted some part of this legacy to our students. There is an army of physics students in the United States whose view of nature and whose view of physics is more powerfully colored by the personalities and intellects of Niels

[1] The full title is *Family Gathering: Students and Collaborators of John Archibald Wheeler gather some recollections of their work with him and of his Influence on them and through them on their own students. Assembled with the best wishes as John moves on to his new career in Texas.*
[2] *Family Gathering,* 1977, n.p.

> Bohr and John Wheeler than they know. Like the oral traditions that dominate some Indian tribes, powerful threads of influence run through generations of scientists. John Wheeler is one of the "medicine men."[3]

For Charles Misner, Ken Ford and others, John Wheeler was far more than a mere teacher; he was part of a 'chain of wisdom' that stretched back to (and perhaps through) Niels Bohr.

This sense of Bohr's influence on John Wheeler is echoed by the physicist Jeremy Bernstein who observes, "Every scientist—Einstein being a notable exception—can find in his or her career a decisive teacher. For Bohr it was Ernest Rutherford. For Feynman it was Wheeler, and for Wheeler it was Bohr." James Gleick, biographer of former Wheeler student and Nobelist Richard Feynman (1918-1988, Nobel prize 1965) , described John Wheeler as the "apostle of Niels Bohr."[4]

Notwithstanding the analysis of former students such as Misner and observers such as Bernstein and Gleick, Bohr is only part of the story. As the previous chapter has shown, several factors shaped John Wheeler's career as a physicist and a mentor. In addition to Bohr's influence on Wheeler, Gregory Breit provided Wheeler with an important complementary model for doing theoretical physics during his apprenticeship. Karl Herzfeld is a third

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[3] *Family Gathering,* 1977, n.p.
[4] Jeremy Bernstein, *Quantum Profiles* (Princeton, NJ: Princeton University Press, 1991), 107; James Gleick, *Genius* (New York: Vintage Books, 1992), 93.

apprenticeship mentor whose influence on Wheeler's career must not be discounted.[5]

In fact, Wheeler felt privileged to have studied under all three men. Of Herzfeld, Wheeler wrote: "No one who came so early from Europe to America continued longer to give so richly to this country out of the great European tradition of theoretical physics." Wheeler concluded the obituary of his former dissertation advisor by observing:

> In saying farewell to a man of great human warmth, one who deeply cared, one treasures all the more his contributions to kinetic theory, statistical mechanics, and the structure of matter—and the high human standard he made for what it is to be a physicist.[6]

In light of this eulogy and keeping in mind the discussion of Herzfeld in Chapter 2, any discussion of John Wheeler's interactions with students must certainly include the influence of Karl Herzfeld.

Similarly, John Wheeler's experience as a student of Gregory Breit had an impact on the way Wheeler interacted with his students. It is also quite possible that Wheeler's experience with Breit taught him how NOT to behave with colleagues. Although Wheeler claims not to have seen that side of Breit himself as a student, Wheeler was well aware that Breit's relationships with his

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[5] John Archibald Wheeler and Kenneth Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York: W. W. Norton, 1998), 107. When Wheeler was considering his choices for post-doctoral work after leaving Hopkins, Herzfeld told Wheeler that Breit "would be right" for him.

[6] John Archibald Wheeler, "Karl Herzfeld" [Obituary], *Physics Today,* 32, no.1 (Jan 1979): 99; The first statement was also quoted in Joseph F. Mulligan, "Karl Herzfeld," Biographical Memoirs, National Academy of Sciences, available online: <http://newton.nap.edu/html/biomems/kherzfeld.html> (20 Mar 06).

colleagues were often "prickly."[7] Still, Wheeler remained one of Breit's admirers. The reader may recall from Chapter 2 that at a May, 1977 symposium (less than three months before Wheeler was honored in Ontario) he described Breit by observing of him: "Insufficiently appreciated in the 1930s, he is today the most unappreciated physicist in America."[8] In an interview with Charles Weiner and Gloria Lubkin, Wheeler was asked to compare the relative influence on his career of Breit (who tended to focus on the elements of a theory that can be calculated) and Bohr (who tended to emphasize a broader, more schematic perspective). Wheeler responded, "I don't think one can get along without both. Bohr certainly would never have proposed to get along without it [Breit's approach]. He was most conscious of these checks but content to let other people make them."[9] Some years later, Wheeler reiterated the importance of Breit to his career. "I don't think I could have built a better base for a career in theoretical physics," Wheeler noted,

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[7] Wheeler, John Archibald. "Wheeler, John Archibald, 1911 – ". Interview by Kenneth W. Ford (transcript), Princeton, NJ and Meadow Lakes, NJ, 06 Dec 1993 – 18 May 1995, American Institute of Physics. Oral History Inteviews [OH5], 108.

[8] John Archibald Wheeler, "Some Men and Moments in the History of Nuclear Physics: The Interplay of Colleagues and Motivations," in *Nuclear Physics in Retrospect: Proceedings of a Symposium on the 1930's* ed. Roger H. Stuewer (Minneapolis, MN: University of Minnesota Press, 1979): 217-284, 234; Wheeler's statement is also quoted in McAllister Hull, "Gregory Breit: July 14, 1899-September 11. 1981," *National Academy of Sciences: Bibliographic Memoirs* (n.d.), available online: <http://www.nap.edu/html/biomems/gbreit.html> (08 Dec 2003), n.p.

[9] John Archibald Wheeler, "Wheeler, John Archibald, 1911 - ," interview by Charles Weiner and Gloria Lubkin (transcript), Princeton, NJ, 05 April 1967, American Institute of Physics, Oral History Interviews [OH537], 17.

"than I did at New York University with Breit and at the University Institute for Theoretical Physics in Copenhagen with Bohr."[10]

Among Wheeler intimates, there is a pervasive perception of Wheeler as the intellectual progeny of Bohr and Bohr alone. Prior to co-authoring the Wheeler autobiography *Geons*, Ken Ford conducted an extensive series of interviews with John Wheeler. In one of the later taped interview sessions (session ten of twelve), Ford asked a question about Niels Bohr.[11] The wording of that question indicates the extent to which many view Wheeler almost exclusively in terms of Bohr's mentorship to the exclusion of Breit and Herzfeld:

> It is often said that your style, your approach to physics, even some of your mannerisms, are derived from Bohr. Do you agree with this assessment? In what ways did your postdoctoral year with Bohr change you as a person and/or as a physicist? Was Bohr's influence a factor much later when you had the courage to tackle fundamental puzzles of the quantum and its relation to the universe?[12]

It is interesting to note that at no point in the twelve sessions (conducted over several months) did Ford ask a similar question about Wheeler's relationship with either Gregory Breit or Karl Herzfeld.

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[10] Wheeler and Ford, *Geons,* 103.
[11] Wheeler interview with Ford (transcript), Princeton, NJ, 06 De 1993 – 12 Apr 1995; the first twelve sessions were tape recorded and transcribed; the last "tapes" (05 Oct 1994 – 12 Apr 1995) are remarks transcribed directly from dictation, after the writing of *Geons* had commenced. This particular interview was conducted on 15 Mar 1994 in Wheeler's office (in Jadwin Hall) at Princeton University.
[12] Wheeler interview with Ken Ford (15 Mar 1994), 1803.

Wheeler's response to Ford's question is as informative for what he does not say as it is for what he does:

> In what way did my postdoctoral year with Bohr change me as a person or as a physicist or both? I can remember what an inferiority complex I felt as colleagues at the Institute would sit around talking in German or Danish and me having trouble just keeping up with what they were saying, let alone trying to say anything myself ... It was a great encouragement to know James Franck. He was a marvelous people person ...
>
> One of the features about life in Copenhagen, [with] Bohr, Franck and others, [was] the willingness to discuss questions all over the map—politics, business, what-not. The feeling that it was all part of the scene that went on to take an interest in.
>
> I can recall Bohr taking the better part of the summer to write an obituary of Rutherford. He had such an admiration for Rutherford that he wanted to do it right. He had a special responsibility in Denmark, because he occupied the House of Honor. In that status, he was supposed to stand up for learning and matters of principle. It's almost like being named Archbishop, I suppose, except dealing with a wider range of issues. He and his wife, for example, spent quite a little effort in looking after the students in the field of art to give them encouragement, afternoon teas from time to time. The courage to tackle fundamental puzzles of the quantum and its relation to the universe.
>
> Courage is one word, but another word that might be more accurate would be desperation. That is some way to get through. Some day things will look so much simpler than they do today, and a desperate search to find a way through to that later day.[13]

While Wheeler speaks of Bohr's courage or "desperation" to arrive at a more comprehensive understanding of physics, there is no mention of Bohr's influence on the way that he (Wheeler) did physics.

It appears that John Wheeler very much preferred to see himself as his own man and distinct from the intellectual shadow of Bohr. This point comes

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[13] Wheeler interview with Ford (15 Mar 1994), 1804-1805.

through clearly in an 1988 interview with the historian and director of the Niels Bohr archive, Finn Aaserud. The discussion takes place in the context of Aaserud's asking about Wheeler's working relationship with Bohr during the 1939 nuclear fission paper in contrast with their working relationship when Wheeler was first in Copenhagen:

> **[Aaserud]** But he must have been very difficult to work with. I mean, he was all-consuming in some sense. I spoke for example to Weisskopf about it. Of course he loves Bohr, but also I got the impression that he could only be there for a little because, you know, it takes your own independence out of you, because it's so demanding and you become a part of Bohr in the discussion process, in a way. I don't know if that's the way he put it, but isn't that true? Or do you think that you could work as equals?
>
> **[Wheeler]** Well, I can recall, in the paper on nuclear fission, the formula for example for the rate of fission. I came with that to Bohr, and I had to argue it and persuade, but he accepted it. But he wouldn't take anything just on somebody's say so. He wanted to understand it through and through.
>
> **[Aaserud]** Was that different by virtue of your being at Princeton then? I mean, then you were more equals?
>
> **[Wheeler]** Yes. Perhaps so.
>
> **[Aaserud]** I mean, the visitors at the Bohr Institute had a very different role, of course, and I don't know if Bohr saw himself more as a mentor for them, than with you in Princeton at that time.
>
> **[Wheeler]** It's odd, I never thought of him as a mentor at all.
>
> **[Aaserud]** No?
>
> **[Wheeler]** No. I thought of our not facing each other, but facing a common difficulty, to try to understand something. And I'm not sure that it would have made any difference to be in Copenhagen. Well, after all, the paper on the collective model of the nucleus, which eventually just David Hill and I published, we

> worked out ... [The interview was interrupted by a telephone call; when the discussion resumes, the subject has changed.][14]

Still, Wheeler's assertion of intellectual parity with Bohr needs to be taken in context. It may be recalled from Chapter 1 that, in his 1998 autobiography (ten years after the Aaserud interview), Wheeler himself described Bohr as a mentor: "What does a young researcher need at the beginning of a career? Perhaps, most of all, a good mentor." Wheeler concluded this passage by noting "In two postdoctoral years, I was blessed with two wonderfully strong mentors, Gregory Breit and Niels Bohr."[15]

So, what can be discerned in these evidently disparate narratives? Kenneth Ford, co-author of Wheeler's autobiography, notes that:

> By any external measure, Wheeler is a very modest man. If asked whether he is in the same league as Bohr and Einstein, he would surely laugh and say, 'Of course not.' Yet, deep down, Wheeler has a sense of his own stature and, in my opinion, does see himself as in the same league as Bohr and Einstein.[16]

Nonetheless, Ford continues, "Wheeler revered (and still reveres) Bohr." It is worth noting here that to this day (2006), Bohr's portrait hangs in Wheeler's office.[17]

In sum, Wheeler seems torn between pride in his physics oeuvre and his veneration for Bohr. This is not an unusual circumstance in science. As the

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[14] John Archibald Wheeler, "Wheeler, John Archibald 1911 – ", interview by Finn Aaserud [transcript], Princeton, NJ (04 May 1988), American Institute of Physics, Oral History Interviews [OH30194].
[15] Wheeler with Ford, *Geons,* 103; Wheeler also refers to Bohr as his mentor on page 91.
[16] Kenneth W. Ford, letter to author (02 May 2006).
[17] Ibid.

historian Frederic L. Holmes has noted, the transition from apprentice to independent scientist is a very complex process.[18] To the case in point; for Wheeler to distinguish himself from the historical shadow of a giant such as Bohr was (and is) a difficult prospect at best. Here it is useful to consider the phrasing of Aaserud's question, specifically his reportage of Victor Weisskopf's experience. Based on Weisskopf's remarks, Aaserud noted that working with Bohr could be "all-consuming" in the sense that it "takes your own independence out of you, because it's so demanding and you become a part of Bohr in the discussion process."[19] The situation with Bohr stands in contrast to Wheeler's relationship with Gregory Breit. Wheeler has also described Breit as a mentor and yet, unlike the situation with Niels Bohr, Wheeler has not been inclined to offer a similar declaration of independence from Breit either in interviews or in print.

In light of the foregoing, several questions emerge. Given the complexity of Wheeler's relationship with Bohr, how did Wheeler see himself in relation to his own students? How did Wheeler's students see themselves in relation to him? Are (or were) there aspects of Wheeler's style of doing physics that Wheeler's former students consciously transmit (or transmitted) to their intellectual progeny? If so, what are they? Finally, as their own research

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[18] Frederic Lawrence Holmes, *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists* (New Haven, CN: Yale University Press, 2004), 42

[19] Wheeler interview with Aaserud (04 May 1988).

and mentoring careers wind down, have the assessments of Wheeler's students changed between 1977 and 2006? If so, how?

With an eye to these questions, this chapter will review the sentiments expressed by the contributors to *Family Gathering* in 1977 and attempt to see John Wheeler through the eyes of his students. In parallel, the chapter will review Wheeler's assessment of the mentoring styles of Herzfeld, Breit, and Bohr. The overriding question here is, are there aspects of doing theoretical physics that John Wheeler acquired from his mentors and transmitted to (or nurtured in) his apprentices?

The main focus of this study is on John Wheeler's Ph.D. students. This emphasis should not imply however, that Wheeler directed all his pedagogical energy toward doctoral students. There are also contributions to Family Gathering from those individuals who did postdoctoral work with John Wheeler or whose Master's thesis was supervised by him. Unfortunately (as noted in Chapter 1), unless the individual's professional relationship to John Wheeler is explicitly stated, it is not currently possible to reliably distinguish between Master's candidates and post-doctoral scholars who worked with Wheeler.

In his time at Princeton, John Wheeler also supervised more than thirty-seven senior theses. These are catalogued by discipline (and can therefore be tracked) in Princeton University's Seeley G. Mudd Manuscript Library. Tracking a relationship to Wheeler is possible because the catalog entry also lists the supervisor(s) of the thesis.[20] It should also be noted that Wheeler continued advising Princeton seniors even after his return from Texas in 1987.[21] Additionally, the Princeton physics department requires junior-year students to write a historical paper and develop a short independent project. Since (unlike the Senior Theses) the junior-year papers and projects are not catalogued, there is no way to know how many of these projects and papers were supervised by John Wheeler.

A number of Wheeler's former undergraduate students contributed to *Family Gathering* and expressed their gratitude for the inspiration, insight, and guidance they had received from Wheeler.[22] Wheeler himself declared that, "I have supervised many a senior thesis in my years at Princeton, and some of them rate in quality and significance with Ph.D. dissertations."[23] Viewed in that light, the remarks submitted by those individuals who completed their Senior Thesis under the supervision of John Wheeler are likely to enhance our comprehension of Wheeler as a mentor. Before proceeding however, it will be

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[20] Princeton University, "Princeton University Senior Theses Catalog Brief Display," available online: <http://libweb5.princeton.edu/theses/thesesvw.asp?Lname=&Fname=&Submit=Search&Title1=&Title2=&Title3=&department=PHY&Class=&Adviser=> (22 Aug 2005); A second copy of Physics Department Senior Theses are also kept in the Physics-Mathematics Library in Fine Hall.
[21] Wheeler and Ford, *Geons,* 239; Wheeler Interview with Ken Ford, Meadow Lakes, NJ (24 Mar – May 1995), 2402; Princeton University, "Daniel E. Holz," Princeton University Senior Thesis Full Record, available online: <http://libweb5.princeton.edu/theses/thesesid.asp?ID=79257> (03 May 2006);
[22] *Family Gathering,* James B. Hartle, 206; R. Bruce Partridge, 236; Anthony Zee, 331; Adam Burrows, 464; Gary Horowitz, 486.
[23] Wheeler and Ford, *Geons,* 155.

useful to explore a common theme in the *Family Gathering* letters to Wheeler—namely, his lecture style.

Section 3.2 A Professor with an Anschaulich Perspective

A frequent topic raised (and admired) by Wheeler's former students is his ability to make the physical quality of a phenomenon stand out from the mathematical formalism that describes it. As will be seen below, that is no small talent. A *Family Gathering* letter from Edward F. Redish, whose Princeton senior thesis was supervised by Wheeler, helps to frame this discussion. In regard to Wheeler's lecture style, Redish wrote:

> [Y]ou have a particular style of thinking about problems in physics. Beneath whatever algebra represents a phenomenon, you always find the working-model; a real thing with nuts, bolts, and rust, with moving parts and real world limitations, and, above all, a picture that you can draw. You always showed a deep empathy for physical phenomena.
>
> This is a stylistic aspect of physics which didn't come naturally to me. Like many of my own students, I was more adept at manipulating equations than in extracting the "real physics." I have had to work hard to develop a physical empathy, but the struggle to do so has been rewarding and the results intensely satisfying.[24]

So, what does it mean to 'extract the real physics?'

As the historian Arthur Miller has noted, visual representation has long been associated with science. In the case of Galileo, diagrams of his falling body experiments enabled him to show that weights fall at consistent rate of acceleration regardless of their horizontal motion. As proof of his hypothesis,

[24] *Family Gathering,* Edward F. Redish, 270.

Galileo developed a thought experiment; if a weight is dropped on the forward side of a ship's mast, the weight falls to the forward side of the mast's base—even if the ship is in motion (so long as the motion is uniform). From this thought experiment, Galileo demonstrated a *quality* of motion (i.e. vertical and horizontal movement are separate components of the total motion of a body).[25] Differential calculus, had it been available to Galileo, would have served to *quantify* the vertical motion of the falling body. In and of itself, however, the calculus could not have provided a qualitative description of the fall or the mutual independence of horizontal and vertical motion.

In the wake of Newton (1642-1727) and Leibniz (1646-1716), differential and integral calculus evolved into more sophisticated analytical tools through the advances of Leonhard Euler (1707-1813), Joseph-Louis Lagrange (1736-1813) Pierre Simon Laplace 1749-1824), Jean-Baptiste Fourier (1768-1830), and others. Concurrently, the physical phenomena that scientists were investigating became more complex. The qualitative analysis of Galileo's falling ball only involved the vertical dimension. Real world physics, however happens in three dimensions. As Ludwig Boltzmann observed:

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[25] Arthur I Miller, "Image and Representation in Twentieth Century Physics," in *The Modern Physical and Mathematical Sciences,* ed. Mary Jo Nye, Vol. 5 of *The Cambridge History of Science,* General eds. David C. Lindberg and Ronald L. Numbers (New York: Cambridge University Press, 2003): 198-215, 191-194; See also James T. Cushing, *Philosophical Concepts in Physics: The Historical Relation between Philosophy and Scientific Theories* (Cambridge, UK: Cambridge University Press, 1998), 80, for Galileo's thought experiment.

> Surfaces of the second order, represented by equations of the second degree between the rectangular co-ordinates of a point, are very simple to classify, and accordingly all their possible forms can easily be shown by a few models, which, however, become somewhat more intricate when lines of curvature, loxodromics and geodesic lines have to appear on their surfaces.[26] On the other hand, the multiplicity of surfaces of the third order is enormous, and to convey their fundamental types it is necessary to employ numerous models of complicated, not to say hazardous construction.[27]

Since real-world models were so difficult to construct, physicists used common experiences and knowledge as metaphors. Such metaphors added a qualitative sense to the quantized understanding that emerged from analysis by differential equations. These metaphors also offered a way to visualize what cannot be seen.

For example, James Clerk Maxwell (1831-1879) developed a set of four differential equations that described the oscillating and reciprocating motion of electromagnetic fields. Nowhere in these equations is the tiniest hint of a wave. Nonetheless, the metaphor of waves in water was employed to explain the interference, refraction and diffraction of light "waves." Note the difference between the phenomenon of light and Galileo's falling weight. Many people,

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[26] A loxodromic line is equivalent to a rhumb line. Each makes the same angle with successive meridians of longitude regardless of the latitude at which they intersect. On a Mercator projection (also known as a loxodromic projection) a loxodromic or rhumb line is straight. However on the surface of a sphere (or an oblate spheroid) a loxodromic line is neither straight nor the shortest distance between two points. The contrast here is with a Great Circle which appears curved on a Mercator projection, but is in fact a straight line on the surface of a sphere.

[27] Ludwig Boltzmann, "Model," in The Encyclopaedia Britannica, 11th ed., Volume 18 (New York: Encyclopaedia Britannica, 1911): 638-640, 638.

particularly in Galileo's day, have seen an object dropping from the mast of a ship; it was therefore a matter of common perception. On the other hand, no one has ever seen a light wave; it can be visualized, though not seen.

In his "Image and Representation in Twentieth Century Physics," Arthur Miller employs the language of Immanuel Kant (1724-1804) and introduces the terms "*Anschaulichkeit*" and "*Anschauung.*" *Anschaulichkeit*, translated as visualizability, is used to describe a phenomena that "is immediately given to the perceptions or what is readily graspable in the *anschauung* [visual perception]" (e.g. a weight falling from a ship's mast). *Anschauung*, translated by Miller as images of visualization, is more abstract, and in Kant's frame of reference, superior to the more concrete *Anschaulichkeit*. *Anschauung* can also be translated as, "intuition." Intuition in this sense, Miller explains, "meant the intuition of phenomena that results from a combination of cognition and perception." From the related concepts of *Anschaulichkeit* and *Anschauung*, including the compound meaning of *Anschauung*, Miller coins the term "*anschaulich*," by which he means a concept that, in English, most nearly matches the word "intuitive." Miller continues, "Translating this formalism to the way in which scientists in the German-language milieu understood it is to say that the *Anschauung* of an object or phenomenon is obtained from a combination of cognition and mathematics."[28]

Of course, in the case of weights falling from a mast, there is no reason to distinguish between what one has seen and what is vizualizable;

[28] Miller, "Image and Representation," 197.

Anschaulichkeit and *Anschauung* are equivalent. In the case of quantum mechanics, the wave-particle duality of light, the physics of nucleons (particles that make up a nucleus), or even with the mass-induced curvature of a four-dimensional space however, a perspective that involves what is *anschaulich* enables both a qualitative and quantitative assessment of a phenomenon.[29]

That said, the development of an *anschaulich* perspective is not trivial; at some point in the process, the theoretician begins to get a sense of diminishing returns on his or her effort. Ergo, as quantum mechanics became more complex, it became increasing a matter of mathematical analysis. This is particularly evident in the work of Werner Heisenberg (1901-1976). By the late 1920s, there was a general retreat from incorporating physical representations into theoretical formalisms. The exception to this trend was Erwin Schrödinger (1887-1961) who promulgated his equation for quantum wave-mechanics in 1926. Even so, Schrödinger was aiming to eliminate the discontinuities in quantum theory rather than to bring graphical representation back into the practice of theoretical physics. Schrödinger's fling with physicality did not stop the swing toward mathematical formalism. This is seen in the quantum electrodynamics work of Paul Adrien Maurice Dirac (1902-1984). Galileo's famous assertion, "the Grand book of the universe was written in the language

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[29] Miller, "Image and Representation," 197-199.

of mathematics," seemed to be the guiding philosophy in the quantum physics community.[30]

During the 1930s and immediately following World War II, the hot topic of theoretical physics was quantum electrodynamics (QED). There were flaws in Dirac's early work (ca 1930) that needed to be addressed in order for the new sub-discipline of particle physics to move forward. The National Academy of Sciences organized a conference of the leading QED theorists, which was held on Shelter Island, New York in June of 1947. While some progress was shared, shortly after the Shelter Island meeting, there was a consensus among the participants that another conference would be useful. That conference, also organized and funded by the National Academy was held in the Pocono mountains of Pennsylvania from 30 March through 2 April, 1948.[31] Mathematical formalism, in the manner of Julian Schwinger (1918-1994) dominated both conferences but especially the latter. In fact, at the 1948 Pocono conference, Feynman utterly failed to communicate his analysis, in part because his graphical representation of path integrals (now known as

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[30] Galileo Galilei, *Il Saggiatore (The Assayer),* trans. George MacDonald Ross, 1998, Available online: <http://www.philosophy.leeds.ac.uk/GMR/hmp/texts/modern/galileo/assayer.html> (20 May 2005). The full quotation is: "Philosophy is written in this grand book the universe, which stands continually open to our gaze," Galileo believed. "But the book cannot be understood unless one first learns to comprehend the language and to read the alphabet in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures, without which it is humanly impossible to understand a single word of it; without these, one wanders about in a dark labyrinth."

[31] Richard P. Feynman, "Pocono Conference," *Physics Today,* 1, no. 2 (Jun 1948): 8-10, 8.

Feynman Diagrams), completely alienated a number of the older physicists, including Niels Bohr.[32] There seemed to be no room for an *anschaulich* perspective in QED.

Nonetheless, from the first, John Wheeler, who attended both QED conferences, recognized that teaching subjects as complex as nuclear physics, quantum mechanics, or general relativity required him to provide an analysis from as many perspectives as possible. Wheeler evidently realized (as did Bohr), that while mathematical formalisms of physical phenomena offer precise quantization, they are often qualitatively (i.e. physically) ambiguous. To rely exclusively on mathematical formalisms, even if students such as Redish were more accustomed to (or enamored with) an intensely mathematical methodology, was to do his students a disservice.

Karl Herzfeld was also a man who utilized an *anschaulich* perspective, and the next section will address the influence of Herzfeld in John Wheeler's mentoring style.

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[32] Gleick, *Genius,* 257-259; The alienation Bohr is significant because Bohr had a well-known aversion to an over-reliance on mathematics in the explication of physical phenomena. For more on this see Abraham Pais, *Niels Bohr's Times in Physics, Philosophy, and Polity* (New York: Oxford University Press, 1991), 20, 178-179; See also Feynman, "Pocono Conference," 10, Adding salt to the wound, Feynman was assigned the task of writing up John Wheeler's notes from the conference. The report on Schwinger's presentation occupied half a column. Feynman's presentation merited only five lines, beginning with the phrase, "There was also presented by Feynman ..."

Section 3.3 Wheeler as Mentor: The Influence of Herzfeld

Kip Thorne, former Wheeler student and currently (2006) the Feynman Professor of Theoretical Physics at Caltech, used his 1977 *Family Gathering* letter to catalogue the most important things that he had learned from John Wheeler. First among these lessons was a tacitly communicated resolve to maintain rigorous scientific integrity [the underlining originates with Thorne]:

> The most important thing that I learned from you, and have tried to pass on to my own students, is a <u>code of ethics for scientific research</u>: You never verbalized that code; rather, you instilled it in your students by your own example and by the advice you gave when they faced decisions: Research should be a cooperative quest for truth, you implied; not a competitive quest for recognition and individual credit. When two groups have done similar work nearly simultaneously, they should try to publish jointly, taking the best from each effort and sharing the credit.[33]

Stated alternatively, the first lesson that Kip Thorne absorbed from John Wheeler was that the work of physics should be considered sacrosanct and beyond professional and/or personal envy. Anything less than this level of integrity only serves to demean the profession. In this respect, John Wheeler seems to have echoed the sentiments of Karl Herzfeld who, in Wheeler's own words, considered physics, "not a secular, but a religious calling."[34] As reported in Chapter 2, Wheeler observed, "Herzfeld had two religions, Catholicism and physics."[35] So, what does it mean to have physics as a religion?

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[33] *Family Gathering,* Kip S. Thorne, 306.
[34] Wheeler, "Karl Herzfeld" [Obituary], *Physics Today* (Jan 1979), 99.
[35] Wheeler and Ford, *Geons,* 98.

For one thing, Herzfeld and Wheeler, both saw physics as a vocation or a calling that transcended ethnic or gender boundaries. Wheeler's very first Ph.D. student at the University of North Carolina was Katherine Way, who went on to a distinguished research career at the National Bureau of Standards. In *Geons* as well as his interviews with Ken Ford, Wheeler describes Way as one of a "tiny handful" of women in physics in the 1930's. Although women physicists are "more numerous now," Wheeler asserted, "they still [1990s] are not nearly numerous enough." For Wheeler, the sex of Katherine Way is far less important than her contributions to the corpus of knowledge in physics. On three separate occasions in the interviews with Ken Ford, Wheeler recalls that Way had some important insights that, in retrospect, should have pointed him toward the mechanism of nuclear fission. Wheeler's final comment on Katherine Way speaks to his sense of collaboration with his students. Wheeler seems to recall thinking at the time (1937) that her thesis would offer him, "a wonderful opportunity for me to learn more nuclear physics."[36]

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[36] Wheeler interview with Ken Ford (10 Jan 1994-10 Jan 1995), notes Katherine Way as his first Ph.D. student, 903, 1805, 2311; Ibid, 708, 902, 1004 notes that Katherine Way's work on physics of the nucleus adds insight that (in retrospect) pointed toward the mechanism of nuclear fission; Ibid, Wheeler notes that Way's dissertation gave him "an opportunity to learn more nuclear physics; Wheeler and Ford, *Geons,* 150 notes that Way was among a "tiny handful of women in physics at the time (1930s) and while there are more now (1990s) there still are not nearly enough; See also Murray Martin, Norwood Gove, Ruth Gove, Subramanian Raman, and Eugene Merzbacher. "Katharine Way" [Obituary], *Physics Today* 49 no. 12 (Dec 1996): 75, available online: Academic Search Premier <http://0-

In fact, Karl Herzfeld was responsible for John Wheeler's first direct experience with women in the discipline of physics. At The Johns Hopkins University, Herzfeld and Maria Goeppert Mayer jointly conducted a seminar on quantum physics. Even then, Mayer had been doing some impressive work on the Fermi model of the atom.[37] Two years after graduating from The Johns Hopkins University, Wheeler saw the impact that prejudice can have on a department.

Despite her obvious qualifications (as reported in Chapter 2, Mayer won the 1963 Nobel prize in physics for her work on the shell model of the nucleus), Maria Mayer was never offered a tenured position at The Johns Hopkins University, In 1935, Isaiah Bowman became president of The Johns Hopkins University and Maria Mayer's prospects for permanent employment at The Johns Hopkins plummeted. While it was true that the depression of the 1930's caused severe financial problems for Hopkins, John Wheeler and the physicist Joseph Mulligan (author of Karl Herzfeld's National Academy of Sciences Biographical Memoir) have each observed that, "a negative attitude toward foreigners," coupled with her sex, effectively eliminated any possibility that Maria Mayer could become part of The Johns Hopkins' regular faculty.

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search.epnet.com.oasis.oregonstate.edu:80/login.aspx?direct=true&db=aph&an=9612171661> (13 Sep 2005).

[37] Wheeler interview with Ken Ford (06 Dec 1993-04 Feb 1994), 104, 908, discusses Herzfeld-Mayer seminar. Also in Wheeler and Ford, *Geons*, 97; Wheeler interview with Ford (03 Jan 1994), 605 discusses Mayer's work on the Fermi model of the atom. See also Joseph F. Mulligan, "Karl Herzfeld." Biographical Memoirs, National Academy of Sciences, available online: <http://newton.nap.edu/html/biomems/kherzfeld.html> (20 Mar 06), n.p.

Wheeler and Mulligan differ in that Mulligan tends to see this xenophobia and sexism originating within the physics department while Wheeler finds more fault with Bowman. In either case, as a consequence of these prejudices, Wheeler notes that The Johns Hopkins University lost three first-rate scientists. Accompanied by Maria Mayer, Joseph Mayer (Maria's husband and a top-notch chemist) went on to Columbia, then Chicago, and finally to UC San Diego where Maria Mayer was at long-last offered a tenured position. In addition, at least in part because he was unhappy about The Johns Hopkins' unwillingness to employ Mayer, Herzfeld left The Johns Hopkins University for Catholic University in Washington, DC in 1936. Herzfeld was still associated with Catholic University when he died in 1978.[38]

Even a casual survey of the surnames on the letters incorporated into *Family Gathering* reveals a broad spectrum of ethnicity. While this level of ethnic inclusion is all but assumed in 2006, such was certainly not the case through much of John Wheeler's career. In 1936, for example, future Nobel Laureate Richard Feynman was not accepted into the undergraduate program at Columbia University because the university faculty already had its quota of Jews. Later, despite the fact that Feynman had been the best undergraduate

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[38] See Joseph F. Mulligan, "Karl Herzfeld," Biographical Memoirs, National Academy of Sciences, n.p. With regard to Mayer and departmental dissension, Mulligan cites a 16 May 1936 letter from Herzfeld to his old professor Arnold Sommerfeld in Munich, Germany. This letter is in the Sommerfeld Archive at the Deutsches Museum in Munich; For John Wheeler's thoughts on Isaiah Bowman and the departure of Mayer, Mayer, and Herzfeld, see Wheeler interview with Ford (20 Dec 1993-04 Feb 1994), 406, 908; See also Wheeler and Ford, *Geons,* 97.

that the MIT physics department had seen in years and despite his achieving a perfect score in the physics section of the Graduate Record Exam, it took two letters from John Slater, the chair of physics at MIT, to Harold Smyth, the chair of physics at Princeton, to get Feynman admitted. In the second, Slater assured Smyth that even though Feynman was Jewish, "as compared for instance with Kanner and Eisenbud he is more attractive personally by several orders of magnitude."[39] While Princeton did not accept female undergraduates until 1968, Wheeler's remarks concerning Katherine Way, Maria Goeppert Mayer, and the under-population of women in the field of physics (noted above) make clear his disagreement with that policy. In sum, we have every indication that throughout his career John Wheeler, like his mentor Karl Herzfeld, judged students and colleagues based on their willingness to work and their ability to contribute to the corpus of knowledge rather than their gender, race, or ethnicity.[40]

Then too, there is the matter of personal involvement with students. Quite a number of the contributions to *Family Gathering* remark on the personal kindness, hospitality, and concern for a student's welfare that John

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[39] Gleick, *Genius,* see 50 for Feynman not being admitted to Columbia as an undergraduate; see 84 for the quotation in the letter from Slater to Smyth.
[40] Mulligan, "Karl Herzfeld," Biographical Memoirs, n.p; It is noteworthy that while he was a Catholic University, Herzfeld made an informal arrangement with the physics department of (largely black) Howard University to steer their best and brightest students toward graduate work at Catholic University, thereby offering black physics students an avenue to graduate education. Also, during Herzfeld's time at Catholic University (1936-1962) 85 Ph.D.s were awarded in physics; nearly 10% of these went to women—a huge percentage in that era.

Wheeler demonstrated in his work with his mentees. In fact, to guarantee his accessibility to students, Wheeler regularly scheduled several consecutive advising appointments on Saturdays. In practice, as one appointment overlapped another, these meetings became small-group learning sessions in which the participants had an opportunity to assist others on their various projects.[41] Similarly, Karl Herzfeld regularly had come in on Saturday to meet with students. For at least one student, who happened to be an orthodox Jew, Herzfeld scheduled appointments on Sundays.[42]

Finally, there is the matter of contextualizing problems in physics. Kip Thorne has written of his experience as Wheeler's graduate student and the first problem that John Wheeler assigned him. The problem stemmed from a discovery by Wheeler's colleague Mael Melvin, then at Florida State University. The conventional thinking about magnetism was that magnet field lines (recall here the grammar school experiment with iron filings on paper) are mutually repulsive and only held together by the metal bar that they pass through. As Thorne reports, Melvin had shown (using Einstein's field equation) that magnetic field lines can also be held together by gravity without the aid of any physical magnet. Melvin's reasoning was that magnetic field lines are a form of energy, and since energy is a form of mass, it gravitates. Wheeler

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[41] *Family Gathering,* regarding Wheeler's concern for the well-being of his students, see David Lawrence Hill, 47; Kenneth W. Ford, 84; Arthur Komar, 107; B. Kent Harrison, 182; John R. Klauder, 190; Jacob Bekenstein, 423; J. R. "Hugh" Dempster, 489; For the Saturday meetings see Fred K. Manasse, 258; Cheuk-Yin Wong, 287.

[42] Mulligan, "Karl Herzfeld," Biographical Memoirs, n.p.

believed that Melvin had overlooked an inherent instability and, "like a pencil balanced on its point," any perturbation would cause the field lines to collapse—possibly into some sort of singularity (e.g. a miniature black hole).

The problem Wheeler assigned Thorne was to perform the calculations and see if his [Wheeler's] hunch could be verified. With this assignment from his brand new professor in hand, Thorne set to work:

> For many months I struggled with this problem. The scene of the daytime struggle was the attic of Palmer Physical Laboratory in Princeton, where I shared a huge office with other physics students and we shared our problems with each other, in a camaraderie of verbal give-and-take. The nighttime struggle was in the tiny apartment, in a converted World War II army barracks, where I lived with my wife, Linda (an artist and mathematics student), our baby daughter, Kares, and our huge collie dog, Prince. Each day I carried the problem back and forth with me between army barracks and laboratory attic. Every few days I collared Wheeler for advice. I beat at the problem with pencil and paper; I beat at it with numerical calculations on a computer; I beat at it in long arguments at the blackboard with my fellow students; and gradually the truth became clear. Einstein's equation, pummeled, manipulated, and distorted by my beatings, finally told me that Wheeler's guess was wrong. No matter how hard one might squeeze it, Melvin's cylindrical bundle of magnetic field lines will always spring back. Gravity can never overcome the field's repulsive pressure. There is no implosion.

Here, some students might well begin to feel some fear for their professional future; in his very first assignment in graduate school, Thorne had disappointed his professor by failing to prove the professor's new pet hypothesis. As we have seen however, for John Wheeler (as with Karl Herzfeld) the physics was sacred; it was far more important than any particular physicist's ego. This attitude is reflected in the reaction Thorne received when he presented Wheeler with the fruit of his labor:

> This was the best possible result, Wheeler explained to me enthusiastically: When a calculation confirms one's expectations, one merely firms up a bit one's intuitive understanding of the laws of physics. But when a calculation contradicts expectations, one is on the way toward new insight.[43]

As noted in Chapter 2, Wheeler and Herzfeld (one should include Einstein here as well) shared a deep and abiding faith in physics and the comprehensibility of the universe.

At least one of John Wheeler's students saw this side of Wheeler and articulated his perception in *Family Gathering.* Brendan Godfrey, a Wheeler Ph.D. student (1970) and current (2006) Director of the Air Force Office of Scientific Research, described John Wheeler in a context that was considerably more philosophical than physical. In 1977, Godfrey wrote, "I am most struck by you not so much as a scientist, per se, but as a man of religion and philosophy, with a thirst for learning and a deep insight into history.[44] As to the origins of this faith in physics as a philosophy of science, Wheeler said of Karl Herzfeld, "I'm immensely indebted to [Herzfeld] for his wonderful perspectives on physics."[45]

Of course, Herzfeld was only one of the principal mentors in John Wheeler's career. What aspects of the mentoring styles associated with

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[43] Kip S. Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: W. W. Norton & Co., 1994), 262-265.
[44] *Family Gathering,* 391; Air Force (U.S.), Office of Scientific Research, "Dr. Brendan B. Godfrey" [Biography], available online: <http://www.afosr.af.mil/pages/godfrey.htm> (16 Sep 2005).
[45] Wheeler interview with Ken Ford (20 Dec 1993), 408.

Gregory Breit and Niels Bohr resonate with Wheeler's students? Let us now turn to the influence of Gregory Breit in John Wheeler's mentoring style.

Section 3.4 Wheeler as Mentor: The Influence of Breit

One finds that many of the more compelling testimonials in *Family Gathering* were penned by students whose only direct experience with John Wheeler appears to have occurred during their undergraduate career. Consider the letter of Jim Ritter, whose senior thesis, "The Cauchy Problem for the Klein-Gordon and DeWitt Equations" was supervised by John Wheeler.[46] Ritter wrote:

> It is no easy thing, I think, for a former student to write of what he owes to a teacher; particularly when that teacher was for him a truly formative influence. Indeed, to say 'a former teacher' is not really accurate, for a truly great teacher leaves within each of his students, a slice of himself, a small kernel which forms such an integral part of the student that it grows, develops, and changes along with its host throughout all the years that follow.[47]

More than his eloquent homage to Wheeler, the title of Jim Ritter's thesis shows another reason to look to Wheeler's undergraduates.

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[46] Princeton University, "James G. Ritter," Princeton University Senior Thesis Full Record, available online: <http://libweb5.princeton.edu/theses/thesesid.asp?ID=79578> (22 Aug 2005). The Cauchy Problem is a partial differential equation that describes unique solutions to mathematical functions that have are centered at the origin of a coordinate system and describe a boundary with unique and particular features. The Klein-Gordon Equation is a relativistic version of the Schrödinger equation that describes quantum motion. The DeWitt (or Wheeler-DeWitt) equation describes a wave function of the universe in the context of quantum gravity.

[47] *Family Gathering,* Jim Ritter, 531-532.

Undergraduate students are more likely than graduate students to have acquired (or polished) particular skills—especially mathematical skills—as a result of their experience with John Wheeler. Jim Ritter's thesis, by way of example, dealt with the Cauchy Problem and the Klein-Gordon and DeWitt (now known as Wheeler-DeWitt) equations. It is all but certain that Ritter was obliged to acquire mathematical skills that were not present at the beginning of the enterprise. Recall from Chapter 2 that Breit placed nearly all his emphasis on the immediately do-able (i.e. calculable) in theoretical physics. Thus, the development of sophisticated computational skills in mathematical analysis among Wheeler's students is more likely traceable to the influence of Breit rather than to Herzfeld or Bohr. An illustrative event occurred early in Richard Feynman's career.

One day, while working at Los Alamos on the Manhattan Project (1942-1945), Richard Feynman needed to compute the cube root of 2 ½ . Hans Bethe, then Feynman's supervisor, happened to be standing close at hand. As Feynman reached for the table of data necessary to program the Marchand calculator (the most advanced electro-mechanical calculator of its time), Bethe said, "It's 1.35." Hans Bethe had come up with a cube root before Feynman could even begin to program the calculator. After some discussion, Bethe proceeded to teach Feynman how to do cube roots in his head.[48] In the days before programmable and/or graphing hand-held calculators (which includes

[48] Richard P. Feynman and Ralph Leighton, *Surely You're Joking Mr. Feynman: Adventures of a Curious Character* (New York: W. W. Norton & Co, 1985), 194-195; Gleick, *Genius,* 177-178.

all but the final three years of Wheeler's career at Princeton) this sort of skill at calculating saved a considerable amount time and effort. Recall here the dictum to "work hard and smart." In the middle of a race (or at least a perceived race) to build an atomic weapon, possessing this level of computational skill was no small thing. Feynman's recollection of his cube root lesson from Bethe raises the question of longevity; how long did the influence of Wheeler last with students who had comparatively brief experiences with him?

Several former Wheeler undergraduate students went on elsewhere to earn their doctorates. As with many of Wheeler's Ph.D. students, these individuals could evaluate their experience with John Wheeler from two perspectives (i.e. through the eyes of a teacher, as well as from the reference frame of a student). As such, their analysis may also be informative with regard to Wheeler's style.

One of these is Joel Primack who, under Wheeler's guidance submitted a senior thesis, "Unified Model Calculations in Fission Theory." While this work plainly involved a good bit of complicated analysis, Primack was sensitive to the context in which Wheeler framed the physics. In 1977, Primack wrote:

> Both by instruction and example, you have helped to shape my career in physics ... You inspired your students to take the entire natural world for our arena as physicists, discouraging narrow specialization, and you taught us to approach all physical problems in a challenging and productive way ... there is one other thing that I learned as your student, and that is the realization that physics at its best is a warmly human enterprise.

> For this great lesson, and for your friendship, I am deeply grateful.[49]

After completing his A.B. in physics at Princeton in 1966, Primack earned his Ph.D. at Stanford in 1970. Therefore, his letter was written some eleven years after he had worked with Wheeler.

Robert Marzke went from Princeton (A.B. 1959) to earn a Ph.D. at Columbia (1966). Under John Wheeler's guidance, he wrote a senior thesis titled, "The Theory of Measurement in General Relativity." Marzke speaks of the confidence that Wheeler inculcated in his students as an exemplar for physics education:

> While perhaps not as important as your work with graduate students, your willingness to direct many undergraduates in their first attempts at research sets an example for everyone in the area of higher education, I feel. Those of us who worked with you recall the wealth of ideas and projects, as well as your confidence in our ability to tackle them despite our inexperience. This made us especially determined to produce results, and on occasion we even did so. The value of this kind of learning to a student is inestimable. It is university education at its best.[50]

Here it is useful to reflect on Wheeler's view that self-confidence is a pre-requisite to the practice of science. Even though Wheeler came to The Johns Hopkins University and later, to Breit at NYU with confidence in his abilities, the experience of producing five papers out of his work with Breit most certainly enhanced his [Wheeler's] conviction that he could solve any

[49] *Family Gathering,* Joel R. Primack, 506.
[50] *Family Gathering,* Robert Marzke, 141.

problem.[51] Judging by Marzke's letter, Wheeler effectively transmitted that confidence (or alternatively, the unwillingness to back down from complicated problems) to his students.

While these testimonials are impressive, here again one should keep in mind that these are letters from students whose experience with Wheeler was on the undergraduate level. In that context, one wonders how much of Wheeler's style could actually have been passed on through these students to succeeding generations of physicists.

The previously examined letter of Edward F. Redish (AB Princeton, 1963; Ph.D. M.I.T. 1968) is also informative on this score. Redish reports:

> It isn't always possible to tell with whom a person studied, but there are particularly aspects of the Wheeler style that many of us who had the good fortune to work with you have tried to emulate. First of all you have always had a wide-ranging enthusiasm for all of science and for physics in particular ... Your excitement about understanding everything from brain waves to gravity waves struck a resonant chord in us, heightening our own love of science.

After discussing Wheeler's ability to 'extract the physics from the mathematics,' Redish continues:

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[51] Wheeler and Ford, *Geons,* 84, self-confidence is necessary to the practice of science; Ibid, 277, Wheeler notes that even as a boy he had "not been short on confidence."; Ibid, 114-115, 119. The papers (also cited in Chapter 2) include: J. A. Wheeler and G. Breit, "Li+ Fine Structure and Wave Functions near the Nucleus," *Physical Review* 44 (1933), 948; J. A. Wheeler, "Interaction Between Alpha Particles," *Physical Review* 45 (1934), 746; G. Breit and J. A. Wheeler, "Collision of Two Light Quanta" *Physical Review* 46 (1934): 1087-1091; F. L. Yost, J. A. Wheeler, and G. Breit, "Coulomb Wave-Functions," *Terrestrial Magnetism* 40 (1935), 443-447; F. L. Yost, J. A. Wheeler, and G. Breit, "Coulomb Wave Functions in Repulsive Fields," *Physical Review* 49 (1936), 174-89.

> I try to emphasize this outlook in my own teaching at all levels, from graduate students to non-calculus premeds. Every one of my courses begins with the Wheelerian: "Redish's First Moral Principle: Always make a mental picture," followed by the direct Wheelerian commandments: "Guess the answer." and "Build up your tool kit."
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> You also taught me that nothing is too hard to be taught to anyone. Your ability to distill difficult concepts into a clear and simple presentation has strongly influenced my teaching style ... I feel that my attitude toward physics and my entire career was influenced in an important way by your teaching even though our interaction was limited to a single year.[52]

Based on this report from Edward Redish, it is evident that even undergraduates who enjoyed a very limited window of direct interaction with John Wheeler, were nonetheless strongly influenced by him to the point where they transmitted his style of doing physics on to their own students.

The renowned cosmologist James Hartle (AB. Princeton 1960), for example, seems to have had only one class in which John Wheeler was the professor of record. Hartle's senior thesis ("The Gravitational Geon") was written under the supervision of Dieter Brill (a former Wheeler student), and he went on to Caltech to earn a Ph.D. under the supervision of (future Nobelist) Murray Gell-Mann.[53] Nonetheless, despite a very limited scope of direct

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[52] *Family Gathering,* Edward F. Redish, 270-271.
[53] *Family Gathering,* James B. Hartle, 206-207; Princeton University, "James B. Hartle," Princeton University Senior Theses Full Record, available online: <http://libweb5.princeton.edu/theses/thesesid.asp?ID=79685> (23 Aug 2005); See also James B Hartle, "James B. Hartle's Homepage," available online: <http://www.physics.ucsb.edu/~hartle/> (06 May 2006), and Stanford University, SLAC-SPIRES High-Energy Physics Literature Database, "Hartle, J.," available online: <http://www.slac.stanford.edu/spires/find/hep/www?rawcmd=FIND+a+hartle,+j&SKIP=50> (06 May 2006); Among other work, Hartle achieved considerable

interaction with John Wheeler, Wheeler's influence on his [Hartle's] career appears to have been substantial. He concluded his letter:

> You suggested looking into variational principles for rotating relativistic stars and together with David Sharp [a Wheeler undergraduate advisee], I did. This led to my early work on relativistic stellar structure much of which was pursued with your student Kip Thorne. Eventually, at Santa Barbara [UC Santa Barbara] I came to see so many interesting but solvable problems in relativity that I made it my dominant area of research and it has remained so since.
>
> Even now in reading this over I am impressed with the crucial role you have played at the significant stages of my career. It is therefore with appreciation for your teaching, thanks for your counsel, and admiration for your example that I send you and Janette my best wishes.[54]

Beyond the superlatives and testimony of pedagogical embodiment, we also see more subtle concepts emerge in this collection of letters.

In each of the above letters, one gets a sense of Wheeler's contagious enthusiasm for physics. Ken Ford, co-author of Wheeler's autobiography, reports that Wheelers enthusiasm—even about classical mechanics—convinced him [Ford] that John Wheeler was the best choice to guide his dissertation.[55] Joel Primack wrote that doing physics with Wheeler was "a warmly human enterprise," and Robert Marzke spoke of Wheeler's "confidence in our ability to tackle [complex problems]." Edward Redish very clearly demonstrated a sense of intellectual lineage when he explicitly stated

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distinction for his 1983 paper "Wave Function of the Universe" (co-authored with Stephen Hawking). As per the SLAC-SPIRES database, this paper has been cited more than 1000 times.

[54] *Family Gathering,* James B. Hartle, 207.

[55] Ken Ford, in a telephone conversation with the author (03 May 2006).

that Wheeler's enthusiasm is a quality that he [Redish] consciously attempted to emulate with his own students.

Edward Redish's letter also speaks indirectly to the issue of Breit's influence on John Wheeler as a mentor. The reference to a "Wheelerian commandment" to "build up your toolkit" is significant. As we have seen, John Wheeler spent much of his postdoctoral year with Breit doing very involved calculations. As noted in Chapter 2 (and above), five of Wheeler's published papers stemmed from his year with Breit. Along the way, Wheeler was able to expand his mathematical toolkit (e.g. when Breit taught him to use Coulomb Wave functions in analysis).[56]

The idea of a mathematical toolkit, especially as it relates to the craft of doing theoretical physics, is an important concept to grasp. Richard Feynman attributes much of his success to having taught himself a good deal of mathematics. Because he was self-taught, Feynman had a "different box of [mathematical] tools."[57] Of course, having the tools is only a part of becoming a physicist. One also must learn how and where to apply the tools.

Consider the art of carpentry. There is a profound difference between an amateur handyman and a master craftsman. Put simply, the former knows how a tool works; the latter knows how to work a tool. So, too, with physicists and mathematics. Virtually all physicists possess the mathematical literacy to

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[56] Wheeler and Ford, *Geons,* 114-115, 119; The papers stemming from Wheeler's year with Breit are listed in a footnote in Chapter 2 and are numbers 4, 5, 7, 9, and 10 in Wheeler's bibliography.
[57] Feynman and Leighton, *Surely You're Joking Mr. Feynman*, 77-78.

know how a given function works. The best theoreticians however, not only know the functions, they know how and where to most profitably apply them. Returning to the carpentry analogy, even though a handyman and a craftsman may each complete a cabinet, there is likely to be a substantial difference in quality. In the case of John Wheeler, although the five papers that grew out of his year of collaboration with Gregory Breit each added to the corpus of knowledge, the craftsmanship Wheeler acquired was multiplicative in that it was passed on to succeeding generations of physicists.

Note too, the Wheelerian commandment: "Guess the answer." This dictum (or something like it) occurs often in the reminiscences of Wheeler's former students.[58] The point that Wheeler was communicating was 'one must apply one's intelligence and look beyond the imminent details of a problem.' Hard work (i.e. laborious calculation) in and of itself, is insufficient to the task of theoretical physics. Recall here the characterization of a robust work ethic from Chapter 1: "It is good to work hard. It is better to work smart. If you can work hard and smart, you'll always find success."[59] In the context of theoretical physics, it is advisable to begin by developing a sense of magnitude: how big or little is the phenomenon one is attempting to calculate. Also, before undertaking a detailed computation, it is often useful to perform a dimensional

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[58] For example, *Family Gathering,* J. R. "Hugh" Dempster, 489; Jacob Bekenstein, email to the author (16 Sep 2005); Peter Vajk, email to the author (21 Sep 2005); Edwin F. Taylor, "The Anatomy of Collaboration," in *Magic Without Magic: John Archibald Wheeler; A Collection of Essays in Honor of His Sixtieth Birthday,* ed. John R. Klauder (San Francisco: W. H. Freeman, 1972): 474-485, 484-485.

[59] Again, this insight is the gift of my grandfather, Thorwald Christensen.

analysis (i.e. determine the dimensions or units of the final answer that is sought). If the final answer will be a unit of force in the cgs (centimeter-gram-second) system of measurement, how will the units associated with the variables in the problem need to be algebraically manipulated so that the final answer is in dynes? Hence, one is well advised to "guess the answer" before beginning to calculate.

On the face of it, these suggestions are straightforward. In fact, nearly all first year physics and chemistry students are taught dimensional analysis. As the calculations become more complex however (e.g. a three-body problem), keeping the dimensions and their magnitudes in algebraic order becomes more challenging. On the scale of elementary particles, simply keeping track of the magnitude of forces can be problematic. The difficulty is that electromagnetic forces are inversely proportional to the square of the distance between the two (or three) charged particles. Thus, as the distance between particles approaches the sub-atomic scale (the radius of a proton is on the order of 10^{-15} meters) the forces exerted between the particles increase exponentially.[60] These and other complications (e.g. even though the spectrum of mathematical solutions is continuous, the energy of any individual particle is quantized), require one to perform 'reality' checks (i.e. "guess the answer") before computing each step of the calculation. While there is no instance in which Wheeler directly ascribes this bit of wisdom to Gregory Breit,

[60] Francis W. Sears, Mark W. Zemansky, and Hugh D. Young, University Physics 6th Ed. (Reading, MA: Addison Wesley, 1992), 596-603.

it seems reasonable to presume the tacit communication of this lesson over the several months that John Wheeler sat calculating in the same office with Breit.

Assertive vision is yet another element of mentoring skill that emerges from Edward Redish's letter to John Wheeler. Here, I am not referring to vision in the sense of being visionary, though by all accounts Wheeler also had that quality. Rather, I am referring to the ability to visualize the end product (the same vision that enables a craftsman to see a finished cabinet in a stack of wood) and further, to enable others (i.e. Wheeler's students) to visualize the end product of their labors. This goes well beyond developing a sense of magnitude and the unit dimensions of the answer. In Redish's words, John Wheeler helped him see beyond the mathematics to, "the working model; a real thing with nuts, bolts and rust."[61] In other words, at least in part because of his formidable mathematical skill, John Wheeler was able to see through the mathematics to the end product, the physical reality that his students were attempting to model. This sort of revelation was not confined to undergraduates.

Richard Feynman recalls his early work in quantum electrodynamics. He had begun wrestling with the problem of an electrons force on itself during his undergraduate years at M.I.T., eventually setting the calculation aside. Later, in graduate school at Princeton, Feynman returned to the problem. In the fall of 1940, Feynman believed that he had made a breakthrough. He

[61] *Family Gathering,* Edward F. Redish, 270-271.

showed his calculations to John Wheeler, (then) Feynman's thesis advisor. Feynman reports:

> Wheeler said right away: Well, that isn't right because it varies inversely as the square of the distance of the other electrons, whereas it should not depend on any of these variables at all. It'll also depend inversely upon the mass of the other electron; it'll be proportional to the charge on the other electron.

Feynman continued:

> What bothered me was, I thought he must have done the calculation. I only realized later that a man like Wheeler could immediately see all that stuff when you give him the problem. I had to calculate, but he could see. Then he [Wheeler] said: And it'll be delayed—the wave returns late so all you've described is reflected light.[62]

This sort of assertive vision with regard to mathematics is the product of having done countless calculations. Wheeler could 'see' what Feynman had to calculate because he [Wheeler] had performed far more calculations that involved light quanta; and these are precisely the kind of calculations that Wheeler had performed under the supervision of Gregory Breit.[63]

Perhaps more importantly, because of these enhanced abilities with sophisticated analytical tools, John Wheeler was able to effectively communicate with junior physicists (such as Redish and Feynman) who

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[62] Feynman and Leighton, *Surely Your Joking,* 77-78; Feynman also shared this anecdote in his Nobel Lecture. See, Richard P. Feynman, "The Development of the Space-Time View of Quantum Electrodynamics," Nobel Lecture (11 Dec 1965), available online: <http://nobelprize.org/physics/laureates/1965/feynman-lecture.html> (24 Mar 06); Also in *Nobel Lectures, Physics 1963-1970* (Amsterdam: Elsevier Publishing Company, 1972.), n.p.

[63] Wheeler and Ford, *Geons* 114-115, 119; Wheeler interview with Ford, 603 (03 Jan 1994).

tended to think in equations rather than physical phenomena. Wheeler could look at a board filled with dense, closely reasoned equations and reveal Redish's 'working model' and Feynman's reflected light. David L. Hill, a Wheeler Ph.D. student who co-authored an important paper on the structure of the nucleus with him, described Wheeler's assertive vision very succinctly: "You show a virtuoso facility for applying analytical and mathematical stratagems to elicit glimpses of the terrain and possibly of the solution before a massive attack is made on the problem."[64]

Finally, there is the matter of Breit's concern for his students. Although his prickly personality may have obscured this quality to some, Breit cared very deeply about his students' welfare. This concern took several forms. The Maryland physicist McAllister Hull, author of Breit's biographical memoir, reports that the health of his students was always a concern. Breit evidently admonished Gary Herling (then his student) that, "an hour of exercise a few times during the week is much better than several hours of exercise every few weeks." Wheeler has recalled that he and other of Breit's students were often "invited" to accompany Breit on vigorous walks through the suburbs of New

[64] *Family Gathering,* David L. Hill, 47; The paper ("Nuclear Constitution and the Interpretation of Fission Phenomena," *Physical Review,* 89, no. 5 (01 March1953):1102-1145) has been cited more than 100 times. Stanford University, SLAC-SPIRES High-Energy Physics Literature Database. "Hill, D. L.," available online: <http://www-spires.slac.stanford.edu/spires/find/hep/www?rawcmd=find+a+hill%2C+d+l> (31 Aug 2005); See also Wheeler interview with Ken Ford (14 Feb 1994 – 21 Mar 1994), 1207, 1901, 1902, 1906 and esp. 1703, 2320; Wheeler interview with Finn Aaserud (04 May 1988), n.p.

York.[65] In matters of publication, Breit was very careful to see that his students got proper credit for their contribution to a paper. McAllister Hull, noted that John Wheeler spoke of Breit's "kindness in crediting his work with joint authorship on papers." This conscientiousness with regard to sharing credit is echoed by Wheeler's students.[66]

Another aspect of Breit's concern for his students were his unrelenting efforts to find employment and career opportunities. Wheeler believes that a letters from Breit to the National Research Council and to Niels Bohr helped secure the renewal of Wheeler's postdoctoral fellowship and get him to Copenhagen for his second postdoctoral year. Hull observed that Breit was extremely well connected in the physics community. In 1968, more than 200 colleagues and former students attended a symposium in Breit's honor at Yale. Breit was well known to use these connections to the benefit of students and colleagues. In fact, Hull refers to Breit's efforts on his student's behalf as "legendary." As part of this process, Breit would frequently invite his students to parties at his house where they would meet and socialize with luminaries of physics (e.g. Werner Heisenberg). Breit's colleagues also benefited from his

[65] McAllister Hull, "Gregory Breit: July 14, 1899-September 11. 1981" *National Academy of Sciences: Bibliographic Memoirs* (n.d.), available online: <http://www.nap.edu/html/biomems/gbreit.html> (08 Dec 2003); Wheeler interview with Ken Ford (03 Dec 1994), 504. Here Wheeler also remarks that Breit, "had something of the German professor's sense of responsibility to his research students"; See also Wheeler and Ford, *Geons,* 108, for the notion that Breit's 'invitations' were less than completely voluntary.

[66] Hull, "Gregory Breit," Biographical Memoir, n.p. [Since the electronic copy of this memoir is not paginated it is impossible to direct the reader to specific locations for these quotations.]; In the case of Wheeler's students, see *Family Gathering,* Dieter Brill, 164; Fred K. Manasse, 258; Kip S. Thorne, 306.

stature in the profession. When (future Nobelist) Eugene Wigner lost his position at Princeton, Breit was instrumental in helping Wigner find a suitable position at Wisconsin.[67] Here too, we find a resonance in Wheeler's students; many of whom specifically credit Wheeler with advancing their career.[68] During the early 1950's Wheeler lobbied Harold Smyth, chair of Princeton's physics department, to release some of his [Wheeler's] graduate students to work on the hydrogen bomb:

> Insofar as graduate students are going to have to get part of their training working on university sponsored war projects"—an assertion seemingly so obvious that Wheeler felt no need to justify it—"it will be hard for them to do better than on the thermonuclear project for all-around range of ideas.[69]

In sum, the evidence indicates that, at a minimum, Breit reinforced the people skills that Wheeler had learned and/or developed under Herzfeld. Most significantly however, Breit helped Wheeler become a craftsman in the use of mathematics. In the next section, we move from Wheeler's skill at calculation to his skill at conceptualization.

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67 Wheeler interview with Ken Ford (10 Jan 1994), 701; Hull, "Gregory Breit," Biographical Memoirs, n.p.

68 See *Family Gathering,* David L. Hill, 47; Charles Misner, 125-126; Daniel Sperber, 144; John G. Fletcher, 200; Masami Wakano, 231; Cheuk-Yin Wong, 287; Kip S. Thorne, 309; Robert Geroch, 351.

69 David Kaiser, "Cold War Requisitions: Scientific Manpower and the Production of American Physicists after World War II," *Historical Studies in the Physical and Biological Sciences* 33, no. 1 (2002): 131-160, 144.

Section 3.5 *Wheeler as Mentor: The Influence of Bohr*

As has been noted above, many of John Wheeler's former students and outside observers see a clear linkage between the mentoring styles of Wheeler and Niels Bohr. So what, in the eyes of Wheeler's students, makes Wheeler seem like Bohr? Was it Wheeler's penchant for explication in terms of physical constructs (e.g. what Edward Redish referred to as a 'working model complete with nuts, bolts, and rust'), his philosophy of science, or (beyond a carefully reasoned philosophy) some deeply-rooted faith in the rationality of the physical universe?

Jacob Bekenstein, who achieved considerable distinction for his work linking the surface area of a black hole with entropy, sees John Wheeler as more prophet than philosopher. In a letter of 16 September 2005, Bekenstein observed:

> Wheeler is often prophetic. Two little known examples: In a review in 1966 he suggested that the Crab Nebula gets its energy from the spin of a neutron star, mentioning that this requires good coupling between star's magnetic field and surrounding plasma clouds. A year later the pulsars were discovered and soon interpreted by Gold as magnetized rotating neutron stars. When the Crab pulsar was discovered, it became clear that it indeed powers the emissions and some of the expansion of the Crab nebula. Another example: back in the 40's Wheeler studied the theoretical properties of what he called a "polyelectron", an analog of the ionized hydrogen molecule with the protons replaced by positrons. It is interesting as a pure QED three-body problem. Polyelectrons were first prepared at Bell Labs in 1981.[70]

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[70] Jacob Bekenstein, email to author, 16 Sep 2005; Wheeler's conjecture on the rotating neutron star in the Crab Nebula is also recounted in *Family Gathering,* 423; See also, Stanford University, SLAC-SPIRES High-Energy

Whether one sees John Wheeler as a physicist, a philosopher or a prophet, it is clear that Wheeler (like Bohr) tended to look for physical phenomena—for *anschaulich* properties—to support the mathematical formalisms of theoretical physics. Why this is so becomes apparent when we look to Richard Feynman's 1965 Nobel lecture.

The most famous of Wheeler's physical conjectures occurred while he and his (then) student Richard Feynman were attempting to eliminate some persistent and troublesome infinities in the mathematics that describe quantum electrodynamics (QED).[71] One evening, Wheeler telephoned Feynman with a novel conceptualization:

> **[Wheeler]:** Feynman, I know why all electrons have the same charge and the same mass.
>
> **[Feynman]:** Why?
>
> **[Wheeler]:** Because, they are all the same electron! ... Suppose that the world lines which we were ordinarily considering before in time and space – instead of only going up in time were a tremendous knot, and then, when we cut through the knot, by the plane corresponding to a fixed time, we would see many, many world lines and that would represent many electrons, except for one thing. If in one section this is an ordinary electron world line,

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Physics Literature Database, "Bekenstein, Jacob," available online: <http://www.slac.stanford.edu/spires/find/hep/www?rawcmd=find+a+Bekenstein%2C+Jacob&FORMAT=WWW&SEQUENCE=> (15 Sep 2005).Bekenstein's 1973 paper, "Black Holes and Entropy" (*Physical Review D* 7, no. 8 (15 Apr 1973):2333-2346) has been cited more than 1000 times; His 1974 paper, "Generalized Second Law of Thermodynamics in Black Hole Physics" (*Physical Review D* 9, no. 12 (15 Jun 1974):3292-3300) has been cited more than 500 times.

[71] The problem was that the mathematical terms describing finite physical phenomena went to infinity in the equations. Quantum Electrodynamics (QED) is the study of the interaction of charged particles at the quantum level (i.e. electrons, photons, etc.).

> in the section in which it reversed itself and is coming back from the future we have the wrong sign to the proper time - to the proper four velocities - and that's equivalent to changing the sign of the charge, and, therefore, that part of a path would act like a positron.
>
> **[Feynman]:** But, Professor, there aren't as many positrons as electrons.
>
> **[Wheeler]:** Well, maybe they are hidden in the protons or something.

Feynman concludes:

> I did not take the idea that all the electrons were the same one from him as seriously as I took the observation that positrons could simply be represented as electrons going from the future to the past in a back section of their world lines. That, I stole! [72]

Later in his speech, Feynman credits John Wheeler's conjecture about the physical nature of positrons as important clue in the QED work for which Feynman was awarded the Nobel prize.[73]

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[72] Richard P. Feynman, "The Development of the Space-Time View of Quantum Electrodynamics," Nobel Lecture (11 Dec 1965), available online: <http://nobelprize.org/physics/laureates/1965/feynman-lecture.html> (24 Mar 06); Also in *Nobel Lectures, Physics 1963-1970* (Amsterdam: Elsevier Publishing Company, 1972.), n.p.

[73] Feynman, " The Development of the Space-Time View of Quantum Electrodynamics," n.p.; Oddly enough, there is no mention of this story or Wheeler's contribution to Feynman's work in either of Feynman's autobiographical collections of anecdotes (i.e. Richard Feynman and Ralph Leighton, *Surely You're Joking Mr. Feynman: Adventures of a Curious Character* (New York: W. W. Norton & Co, 1985) and Richard P. Feynman with Ralph Leighton, *What Do You Care What Other People Think* (New York: Bantam Books, 1988)); Moreover, neither the story nor Wheeler's name appear in Richard P. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton, NJ: Princeton University Press, 1985); The 'all the same electron' story is however, retold by Feynman's biographer James Gleick (James Gleick, *Genius: The Life and Science of Richard Feynman* (New York: Vintage Books, 1992), 122-123) and Feynman's former colleague and Nobelist Murray

Feynman also alerts us indirectly to the importance of physical conceptualization of phenomena (*anschaulich*) in mentoring. Here it will be useful to revisit the QED controversy of the late 1940s. The reader may recall that Feynman shared his 1965 Nobel prize with Sin-Itiro Tomonaga (1906-1979) and Julian Schwinger (1918-1994). Each of the three men took a different approach to QED, and the formalisms developed by Feynman and Schwinger seemed particularly far removed from one another. These widely disparate formalisms were eventually shown to be equivalent by the mathematician Freeman Dyson.[74] This circumstance is, of course, similar to the situation in quantum mechanics in the late 1920s when the Nobelists Werner Heisenberg and Erwin Schrödinger adopted two very different approaches to the problem of quantum states. And yet, Heisenberg's matrix algebra and Schrödinger's wave equations described exactly the same phenomena.[75] On its face, this situation would not seem to be problematic. Just as there are no preferred frames of reference, there are bound to be multiple perspectives from which to view or analyze a physical process.

The drawback, as Feynman noted in his Nobel lecture, is that even though varying approaches to a problem may be equivalent mathematically, they are not typically equivalent conceptually:

Gell-Mann (Gell-Mann, Murray. "Dick Feynman—The Guy in the Office Down the Hall." *Physics Today* 42, no.2 (Feb 1989): 50-54, 52).

[74] Gleick, *Genius,* 267-270.

[75] David C. Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (New York: Freeman, 1993), 212-213.

> Physical reasoning does help some people to generate suggestions as to how the unknown may be related to the known. Theories of the known, which are described by different physical ideas may be equivalent in all their predictions and are hence scientifically indistinguishable. However, they are not psychologically identical when trying to move from that base into the unknown. For different views suggest different kinds of modifications which might be made and hence are not equivalent in the hypotheses one generates from them in one's attempt to understand what is not yet understood. I, therefore, think that a good theoretical physicist today might find it useful to have a wide range of physical viewpoints and mathematical expressions of the same theory (for example, of quantum electrodynamics) available to him.

Feynman went on to say, "This may be asking too much of one man."[76]

Whether or not it is asking too much of one man, Feynman's statement describes the *anschaulich* methodology of John Wheeler. In *Geons,* Wheeler observes, "There are many modes of thinking about the world around us and our place in it. I like to consider all the angles from which we might gain perspective on our amazing universe and the nature of existence."[77] Cheuk-Lin Wong, a Wheeler Ph.D. protégé observes, "He [Wheeler] has an inventive mind that bodes no boundaries. His 'blackhole,' 'wormhole,' 'geons,' [and] 'quantum foams' have now become familiar terms in physics vocabulary."[78] A key point to be re-emphasized here (in paraphrase of Feynman) is that, although the language of mathematics lends itself to precise description, as often as not, physical processes can be mathematically ambiguous, Feynman,

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[76] Feynman, Nobel Lecture (11 Dec 1965), n.p.
[77] Wheeler and Ford, *Geons,* 153; This thought is also expressed in the Wheeler interview with Weiner and Lubkin (05 Apr 1967), 12; and also the Wheeler interview with Finn Aaserud (04 May 1988), n.p.; *Family Gathering,* B. Kent Harrison, 182; Also in Jacob Bekenstein, email to author (16 Sep 05).
[78] Cheuk-Yin Wong, email to the author (25 Oct 2005).

Schwinger, and Tomonaga all provided separate and precise mathematical descriptions of QED. Given this circumstance, Niels Bohr (despite his objection to Feynman's use of diagrams at Pocono) was reluctant to place too much reliance on mathematical formulations.[79] Similarly, John Wheeler chose to emphasize physical models and let the physics drive the development of equations rather than allowing the mathematics to be the conceptual engine.[80]

Section 3.6 Wheeler as Mentor: A Style of His Own

This chapter has aimed to correlate the sentiments of John Wheeler's students with what we know of Wheeler's relationship with his mentors. Several questions prompted these comparisons. First among these was: If Wheeler saw Bohr more as a collaborators than a mentors, how did he see himself in relation to his own students? A number of Wheeler apprentices have written about the priority he placed on helping his students as well as the respect that they were accorded. Ken Ford observed that "we learned [physics] by watching John Wheeler learn."[81] Kip Thorne has written that, from their very first meeting, Wheeler made him [Thorne] feel like a colleague rather than a student. Moreover, Thorne continues, "Wheeler's paramount goal was

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[79] Pais, *Niels Bohr's Times*, 20, 178-179.
[80] See *Family Gathering,* Kip Thorne, 306-307; Frank Zerilli, 533; B. Kent Harrison, 182; Jacob Bekenstein, 423-424; Fred K. Manasse, 258-259, among others.
[81] *Family Gathering,* Kenneth W. Ford, 84.

the education of his fledglings, even if that slowed the pace of discovery."[82] Wheeler's assistance, however, was not limited to professional matters such as research problems, thesis work, and publication. Many of the *Family Gathering* letters speak to Wheeler's "warmth," "courtesy," and "concern for his students."[83] For his part Wheeler has observed that, "I can learn only by teaching." From that conviction, he has developed the axiom: "Universities have students to teach the professors.[84] Plainly, Wheeler sees his students more as collaborators than as apprentices.

This chapter also sought to address the question of pedagogical heritage. Specifically, what aspects of Wheeler's style of doing physics did (or do) Wheeler's former students transmit to their intellectual progeny? Again, a number of contributors to *Family Gathering* (including Dieter Brill, Daniel Sperber, Jacob Bekenstein, John Toll, and Larry Shepley) allude to adopting elements of Wheeler's style in the classroom or when advising their students.

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[82] Thorne, *Black Holes and Time Warps;* the reference to collegiality is from 262; the quotation is taken from 270. Kip S. Thorne, "Nonspherical Gravitational Collapse: A Short Review," in *Magic Without Magic: John Archibald Wheeler: A Collection of Essays in Honor of His Sixtieth Birthday,* ed. John R. Klauder (San Francisco: W. H. Freeman, 1972), 231. Here, Thorne emphasizes Wheeler's collegial approach to a brand new graduate student.

[83] See *Family Gathering,* Dieter Brill, 164-165; B. Kent Harrison, 182; Cheuk Yin Wong, 287; Kip S. Thorne, 306-309; Brendan Godfrey, 391; Jacob Bekenstein, 423-424; J. R. Hugh Dempster, 489-450.

[84] Wheeler interview with Ken Ford (14 Feb 1994-10 Jan 1995). The sentiment 'Universities have students to teach professors," is expressed on 1209, 1906, and 2318. The conviction that he has to teach in order to learn is expressed on 1704. See also Wheeler interview with Charles Weiner and Gloria Lubkin (05 April 1967). The sentiment of learning by teaching is also expressed on 8; See also Wheeler and Ford, *Geons,* 150.

Others, most notably Kip Thorne, Ken Ford, and Fred Manasse remark that they have consciously worked to emulate John Wheeler's style over the spectrum of activities in their professional careers. Thorne, in particular, wrote extensively about attempting to incorporate John Wheeler's code of ethics for scientific research, as well as Wheeler's style of research, writing and lecturing into his own pedagogy.[85] Thorne also recalls one particularly memorable day at Caltech when some of his students approached him with a passage from the Misner-Thorne-Wheeler opus *Gravitation.*[86] Their complaint was that the passage in question was too "Wheeleristic" and that Thorne should have used his influence with Wheeler to "tone it down." Thorne gleefully replied, "Wheeler did not write that section: *I* wrote it!" [Thorne's emphasis].[87]

Finally, have the assessments of Wheeler's students changed between 1977 and 2006? If so, how? If anything, Wheeler's students' fondness for him has grown over the years. As any student of oral history knows, admiration tends to appreciate over time. Even so, the hope was to uncover some articulation of how Wheeler's mentoring methodology had evolved over time.

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[85] *Family Gathering,* John Toll, 67-68; Ken Ford, 84-86; Daniel Sperber, 144; Dieter Brill, 164-165; Fred K. Manasse 258-259; Larry Shepley, 300; Kip Thorne 306-310; Jacob Bekenstein, 423-424.

[86] See Charles Misner, Kip S. Thorne and John Archibald Wheeler, *Gravitation* (San Francisco, W. H. Freeman, 1973). This 1259 page opus continues to be the defining work on relativistic gravity.

[87] *Family Gathering,* Kip S. Thorne, 309.

This was only partially successful.[88] On 27 October 1976, Cheuk-Yin Wong wrote a letter to be included in *Family Gathering.* It began as follows:

> In looking back on my happy years of apprenticeship under your guidance, I was reminded of the traditional Confucian definition of a great teacher as someone who is able to pass on to others what was transmitted from the past, and in the process, opens up great avenues for future generations.[89]

On 25 October 2005, Professor Wong sent an email that listed six areas in which John Wheeler made lasting contributions to the lives and careers of his students. While Wong's 2005 correspondence was more analytical than his letter of 1976, it is no less laudatory.[90] The same can be said of more recent communications from John S. Toll, Charles Misner, Jacob Bekenstein, Peter Vajk, and Robert Fuller among others.[91]

Here, I am compelled to insert a disclaimer. A large portion of the primary source material for this thesis has come from documents included in various Wheeler festschrifts (esp. *Family Gathering*) and the author's correspondence with various contributors to those volumes. By their very nature, such documents will likely be written in a condition of benign myopia in which the subject's faults lay outside the author's field of vision.

While John Wheeler is widely admired, that admiration is not universal. Ken Ford has mentioned that, on occasion, Wheeler's determination to

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[88] In a sense, this avenue of inquiry affirmed the well-known Wheelerism; "The right question is more important than the right answer."
[89] *Family Gathering,* Cheuk-Yin Wong, 287.
[90] Cheuk-Yin Wong, email to author (25 Oct 2005).
[91] Emails to the author from Robert Fuller (01 Sep 2005), Charles Misner (01 Sep 2005), Jacob Bekenstein (16 Sept 2005), Peter Vajk (21 Sep 2005), and John S. Toll (20 Feb 2006).

evaluate all sides of an issue made Marvin Goldberger (a former Princeton colleague and former president of Caltech) want to "wring his [Wheeler's] neck."[92] Kip Thorne, a close friend and admirer of Wheeler has noted his strong disagreement with Wheeler in the matter of the Edward Teller—Robert Oppenheimer controversy.[93] In sum, John Wheeler's faults may be subtle and

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[92] Telephone conversation between Ken Ford and the author (03 May 2006). Goldberger's frustration with Wheeler is also captured in Finn Aaserud, "Sputnik and the 'Princeton Three:' The National Security Laboratory that was not Meant to Be," *Historical Studies in the Physical and Biological Sciences* 25 no. 2 (1995): 185-240, 219. The context of Goldberger's irritation was that he, Wheeler, and Princeton economist Oskar Morgenstern had, in the wake of Sputnik, concluded that the United States needed a National Security Laboratory. The new lab would be located at Princeton. The difficulty was that none of the three men wanted to serve as director of the lab (a position that would require them to abandon their academic career for the two to three years it would take to get the lab up to speed). In a letter to their Princeton colleague Eugene Wigner, Goldberger expressed his disappointment in Wheeler: "I was induced to go back to Washington for a day after you left as perhaps you heard. John and Oskar worked on me to take the job; I worked on John in turn. Nobody yielded. I must say, however, that my reservations about John's being director, which I'm sure you sensed from our earlier discussions, were reinforced by seeing him in action as a leader. He has many great virtues and his halo is the finest gold. There is however an amorphous quality about him both in his reception of ideas and in his transmission of information to others. I find myself wanting to shake him to make him say something straight out and incisively. I have difficulty in putting this idea into words, but Oskar described his own feelings to me in a similar way."

[93] Thorne, *Black Holes and Time Warps,* 235. The night before his testimony before the Atomic Energy Commission (28 April 1954), Teller came to Wheeler's hotel room in Washington, DC (Wheeler was in Washington on separate business and not involved in the hearings) and expressed his [Teller's] misgivings about the impact of his testimony on Oppenheimer's career. Wheeler told Teller that he should be guided by his integrity and tell the whole truth as he saw it. See also Wheeler and Ford, *Geons,* 201-202. Wheeler's version of events largely matches Thorne's, although Wheeler sees Teller as the martyr rather than Oppenheimer. Wheeler's reasoning is that Teller knew he was putting nearly all of his professional relationships at risk, and yet he chose to tell the truth as he saw it.

benign in nature; perhaps even relatively few in number. Nonetheless, they are present.

Section 3.7 Review

This chapter has examined the mentoring skill of John Wheeler as seen through the eyes of his students. In particular, the chapter addressed six questions: If Wheeler saw Bohr more as a collaborator than a mentor (presumably Breit and Herzfeld were also seen in this light), how did he see himself in relation to his own students? How did Wheeler's students see themselves in relation to him? Are (or were) there aspects of Wheeler's style of doing physics that Wheeler's former students consciously transmit (or transmitted) to their intellectual progeny? If so, what were they? Finally, as their own research and mentoring careers wind down, have the assessments of Wheeler's students changed between 1977 and 2006? If so, how?

Consciously or not, John Wheeler synthesized the best attributes of Herzfeld, Breit, and Bohr into a mentoring style of his own. Wheeler's students report that he unfailingly treated his students with courtesy and respect; he communicated an uncommon and inspiring enthusiasm for physics; he inculcated both mathematical craftsmanship and *anschaulich* conceptualization such that his students could 'extract the physics from the mathematics' for their own students. Beyond the physics, Wheeler's students have indicated that his concern for their welfare, personal as well as professional, was second to none.[94]

John R. Klauder, editor of an earlier Wheeler festschrift volume (*Magic Without Magic*), summed the prevalent attitude of Wheeler's apprentices: "I have never met a Wheeler product who didn't speak warmly of his experience—and I never expect to."[95]

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[94] See *Family Gathering,* Gilbert Plass, 34; John S. Toll, 67; Kenneth W. Ford, 84; James J. Griffin, 103; Dieter Brill, 164; B. Kent Harrison, 182; John R. Klauder, 190; Fred K. Manasse, 258; Andris Suna, 283; Robert Geroch, 351; James York, 366; Jacob Bekenstein, 423; Bahram Mashoon, 429; J. R. Hugh Dempster, 489; S. Fred Singer, 516; Frank Zerilli, 533.

[95] John R. Klauder, ed., *Magic Without Magic: John Archibald Wheeler: A Collection of Essays in Honor of His Sixtieth Birthday* (San Francisco: W. H. Freeman, 1972); The quotation is from *Family Gathering,* John R. Klauder, 191.

Chapter Four: John Archibald Wheeler Considered in the Context of Research School Literature

Section 4.1 Overview and Organization

In previous chapters, this thesis has presented an overview of the literature dealing with research schools as an analytical unit of study; a synopsis of the biography of John Archibald Wheeler with respect to his career as a physicist and mentor at Princeton University; and an assessment of Wheeler's expertise as a mentor as seen through the eyes of his former students.

This chapter aims to synthesize what has been learned about the mentoring practices of John Wheeler with the generalized attributes of a successful research school. In particular, the chapter begins by reviewing the work of historian Gerald Geison who established the comprehensive criteria that defines a research school. The ensuing sections of this chapter will correlate specific aspects of research school literature (e.g. charismatic leadership, ready access to publication) to the history of Wheeler's relationship with his students. This chapter also highlights evidence that Wheeler's former students have self-consciously incorporated specific pedagogical methods into their own mentoring style. Finally, the chapter concludes by establishing John Wheeler, his mentors and his mentees in a chain of wisdom specific to theoretical physics.

Section 4.2 A Brief Review of Research School Literature

In 1981, building on J. B. Morrell's 1972 article "The Chemist Breeders: The Research Schools of Justus Liebig and Thomas Thomson," the historian of science Gerald L. Geison established the now (2006) standard definition of research schools: "[S]mall groups of mature scientists pursuing a reasonably coherent programme of research side-by-side with advanced students in the same institutional context and engaging in direct, continuous social and intellectual interaction."[1] Note here that by inclusion of the phrase, "in the same institutional context," Geison's definition of a research school is, at least inferentially, tied to a specific location.

Here, it is necessary to pause briefly and acknowledge the literature that articulates the distinction of research school from "research group." The scholarship of historian Joseph Fruton overlaps that of Geison in the study of Justus von Liebig and his students. In contrast to Geison's term 'research school' Fruton suggests that Liebig and others were actually a "research group." In Fruton's view, the term 'research group' preserves a focus on a single institution. He notes:

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[1] Gerald Geison, "Scientific Change: Emerging Specialties and Research Schools," *History of Science* 19, Part 1, no. 43 (Mar 1981): 20-40, 23; See also Gerald L. Geison, "Research Schools and New Directions in the Historiography of Science," in *Research Schools: Historical Reappraisals,* ed. Gerald L. Geison and Frederic L. Holmes, *Osiris*, 2d ser., vol. 8 (1993): 227-238, 227-228; J. B. Morrell, "The Chemist Breeders: The Research Schools of Liebig and Thomas Thomson," *Ambix: The Journal of the Society for the History of Alchemy and Chemistry* 19 (Mar 1972): 1-46; Jack Morrell, "W. H. Perkin, Jr., at Manchester and Oxford: From Irwell to Isis," in *Research Schools: Historical Reappraisals,* ed. Gerald L. Geison and Frederic L. Holmes, *Osiris*, 2d ser., vol. 8 (1993): 104-126, 124-125.

> I prefer the latter term [research group] because *research school* has also been applied to a community of scientists, not necessarily located at a single institution, or even in the same country, who are united solely by a common interest in a particular direction of research.[2]

For further explication, Fruton refers his readers to the Russian scholar V. L. Gasilov.[3]

While Fruton's distinction may be useful in other contexts, it is not especially relevant for this study. The reader may recall that, regardless of how other scholars have employed the term. Geison's 'research school' is specifically tied to location ("in the same institutional context") and pedagogy ("mature scientists ... side-by-side with advanced students"). Moreover, the emphasis in this thesis is on the individual mentor during a particular time frame rather than the institutional framework in which the mentor and his apprentices labored. In short, the Geison-Morrell term 'research school,' as defined by Geison and Morrell (hereafter the Geison-Morrell model) is both adequate and apropos for the purposes of this thesis.

This study's focus on an individual mentor does raise the question of whether the leader of a research school is necessarily a mentor. Conceivably, it could be argued that a mentor's primary concern is the advancement of his

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[2] Joseph Fruton, *Contrasts in Scientific Style: Research Groups in the Chemical and Biochemical Sciences*, Philadelphia: American Philosophical Society, 1990, footnote on 1-2; See also, Joseph Fruton, "The Liebig Research Group: A Reappraisal," *Proceedings of the American Philosophical Society* 132 (1988): 1-66, 4: Here, Fruton appears to use the terms "research group" and "research school" interchangeably.

[3] Fruton cites V. L. Gasilov, Voprosy Optimizatsii Nelineinykh Sistem Avtomaticheskogo Upravleniia (Moscow: Biblioteka Akademii nauk SSSR, 1977).

or her apprentices while a research school leader concentrates on the production of knowledge. Stated alternatively, are all research school leaders also mentors? In principle, yes. To the extant that research school leaders instruct their apprentices in the craft of doing science, or ways to think about science, or the professional standards of quality and production that will be expected of the apprentices once they become independent scientists, research school directors necessarily serve as mentors. That said, just as all scientists are not equally capable, so too all mentors are not equally skillful. Indeed, one reason for choosing John Wheeler as the subject for this thesis was his effectiveness in the role of mentor. Moreover, the production of knowledge and advancement of students are not mutually exclusive propositions. As Frederic L. Holmes, J. B. Morrell, and others have pointed out, even though Liebig moved away from the frontiers of organic chemistry to 'agricultural chemistry', he still continued to produce chemical knowledge and knowledgeable chemists at a prodigious rate.[4]

The case of John Wheeler serves to reinforce the argument that the production of large amounts of knowledge and scientists are not mutually exclusive. As the reader may recall from Chapter 3, one of Wheeler's most prominent students, Kip Thorne, recalled that "Wheeler's paramount goal was

[4] Fruton, "The Liebig Research Group: A Reappraisal," 2-5; Fruton, *Contrasts in Style,* 16-19; Holmes, F. L. "Justus von Liebig," in *Dictionary of Scientific Biography,* ed. Charles Coulston Gillispie (New York: Scribner and Sons, 1973), 344-347;

the education of his fledglings, even if that slowed the pace of discovery."[5] Still, as we have seen, Wheeler was an extraordinarily productive scientist. The reader may also recall that the sociologist Harriet Zuckerman places Wheeler among the "ultra-elite" of physicists.[6] To recap a few highlights of Wheeler's research career: He co-authored the first paper on the generalized mechanism of nuclear fission; he played a key role in the Manhattan Project (particularly the development of reactors for plutonium production); he made significant contributions to the field of quantum electrodynamics; he was an important member of the research team that developed the hydrogen bomb; Wheeler and his students have made substantial progress in general relativity, especially in regard to cosmology. Furthermore, John Wheeler has 386 publications to his credit, a great many of which have been cited in the work of other physicists. At least twenty-three Wheeler publications have been cited more than twenty times; at least fourteen Wheeler publications have been cited more that fifty times; at least seven Wheeler publications have been cited more than 100 times; at least three Wheeler publications have been cited

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[5] Kip S. Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: W. W. Norton & Co., 1994), 270.

[6] Harriet Zuckerman, *Scientific Elite: Nobel Laureates in the United States* (New York: The Free Press, 1977. Reprint with a new introduction by the author, New Brunswick, NJ: Transaction Publishing. 1996) 104. See also, Kip S. Thorne, and Wojciech H. Zurek, "John Archibald Wheeler: A Few Highlights of His Contributions to Physics," in *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler,* ed. Wojciech Hubert Zurek, Alwyn van der Merwe, and Warner Allen Miller (Princeton, NJ: Princeton University Press. 1988): 3-13; John R. Klauder, "An Introduction," *Magic Without Magic: John Archibald Wheeler: A Collection of Essays in Honor of His Sixtieth Birthday,* ed. John R. Klauder (San Francisco: W. H. Freeman and Co., 1972), 10-11.

more than 200 times; at least two Wheeler papers have been cited more than 300 times and *Gravitation* has been cited more than 1000 times.[7]

It bears reiterating that a common thread in the extant literature of research schools (and a good bit of the scholarly literature on scientific mentoring) is a focus on laboratory craftsmanship.[8] Geison specifically makes this point:

> Morrell's ideal model of the research school grew out of his investigation of nineteenth-century chemical laboratories, and almost all efforts to extend his model to other cases have likewise been restricted to laboratory-based research schools.

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[7] See Google Scholar, "find a Wheeler, J. A.," Available online: <http://scholar.google.com/scholar?num=100&hl=en&lr=&safe=off&q=author%3A%22J+A+Wheeler%22&btnG=Search> (20 Feb 06);

[8] Jerome R. Ravetz, "Science as Craftsman's Work," chapter 3 in *Scientific Knowledge and its Social Problems* (Oxford: Clarendon Press, 1971), 75-108: The author was alerted to this source by a quotation in H. M. Collins in "The TEA Set: Tacit Knowledge and Scientific Networks," *Science Studies* 4 (1974): 165-186. On p. 183, Collins quotes Ravetz: "in every one of its aspects, scientific inquiry is a craft activity depending on a body of knowledge which is informal and partly tacit." Unfortunately, this quote does not appear as cited on p. 40 or on the surrounding pages. It does however, appear as quoted in chapter 3 of Ravetz, *Scientific Knowledge,*103; See also, Hugh Gusterson, "A Pedagogy of Diminishing Returns: Scientific Involution across Three Generations of Nuclear Weapons Science," in *Pedagogy and the Practice of Science,* ed. David Kaiser (Cambridge, MA: MIT Press, 2005): 75-108, 78; Frederic Lawrence Holmes, *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists* (New Haven, CN: Yale University Press, 2004), xix [introduction], 22-23, 28, 34-35; Morrell, "The Chemist Breeders," 1-46, 12, 23, 25-26; Morrell, "W. H. Perkin, Jr., at Manchester and Oxford," 104-126, 126; Mary Jo Nye, *From Chemical Philosophy to Theoretical Chemistry: Dynamics of Matter and Dynamics of Disciplines, 1800-1850* (Berkeley, CA: University of California Press, 1993), 24; Kathryn M. Olesko, "Tacit Knowledge and School Formation," in *Research Schools: Historical Reappraisals,* ed. Geison and Holmes. *Osiris*, (1993): 16-29, 16, 18-20, 24-25, 28; Kathryn M. Olesko, "The Foundations of a Canon: Kohlrausch's Practical Physics," in *Pedagogy and the Practice of Science,* ed. David Kaiser (Cambridge, MA: MIT Press, 2005): 321-356, 324, 327, 330, 338, 341, 346;

> That includes my article of 1981, where I simply ignored the question of how far, if at all, Morrell's model could be applied to small groups of scientists whose interactions took place outside the laboratory.[9]

Later, in the Research School thematic *Osiris* volume of 1993, Geison applauded the (then) recent work of Joel Hagen, Pamela Henson, and David Kushner on research schools "outside the laboratory."[10] Still, even in the work of Hagen, Henson, and Kushner, the scholarship is focused on the development of technical skills (i.e. instrumentation and/or observation) rather than cognitive ability (i.e. how to *think* about problems). To be clear, there exists a somewhat small subsection of the mentoring literature that deals with the cultivation of scientific *thinking* skills. Much of this scholarship however, is also specific to a laboratory setting.[11] In a non-laboratory setting we have Andrew Warwick's *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Cambridge University Press, 2003), David Kaiser's

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[9] In support of Geison's assertion and in addition to his (1981) "Scientific Change: Emerging Specialties and Research Schools in *History of Science,* as well as his (1993) "Research Schools and New Directions in the Historiography of Science" (esp. 231-233), see Maurice Crosland, "Research Schools of Chemistry from Lavoisier to Wurtz," *The British Journal for the History of Science* 36, no. 3 (2003): 333-361; Fruton, "The Liebig Research Group: A Reappraisal," 1-66; Fruton, *Contrasts in Scientific Style* (1990); Holmes, *Investigative Pathways* (2004).

[10] Pamela M. Henson, "The Comstock Research School in Evolutionary Entomology," in *Research Schools: Historical Reappraisals.* ed. Geison and Holmes, *Osiris*, (1993): 157-177; David Kushner, "Sir George Darwin and a British School of Geophysics," in *Research Schools: Historical Reappraisals.* ed. Geison and Holmes, *Osiris*, (1993): 196-224;

[11] Robert Kanigel, *Apprentice to Genius: The Making of a Scientific Dynasty* (Baltimore, MD: The Johns Hopkins University Press, 1986), 234-235; John W. Servos, "Research Schools and Their Histories," in *Research Schools: Historical Reappraisals,* ed. Geison and Holmes, *Osiris*, (1993): 1-15, 14; Ravetz, *Scientific Knowledge,* 103.

Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics (University of Chicago Press, 2005), and selected chapters in Kaiser's edited volume, *Pedagogy and the Practice of Science* (MIT Press, 2005).[12]

While this scholarship provides useful background, in each case the emphasis is outside the focus of this enterprise. Warwick's *Masters of Theory,* for example deals with mathematical physics, which is, as the reader may recall from Chapter 1, distinct from the discipline of theoretical physics. Moreover, as the historian Peter Galison has pointed out, mathematicians and theoreticians work in very different cultural frameworks.[13] Also, as David Rowe has observed, mathematical 'schools' have tended to be rather loosely organized and often are not set in the context of a single institution.[14]

Similarly, the scholarship of David Kaiser, and those who contributed to his edited volume, emphasizes the role of the "tools" of pedagogy. These tools, be they Feynman Diagrams or quantum theory textbooks, are in fact didactic apparatus, which fail to account for role of mentor-apprentice

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[12] See David Kaiser, "Making Tools Travel: Pedagogy and the Transfer of Skills in Postwar Theoretical Physics" (41-74); Karl Hall, "Think Less about Foundations": A Short Course on Landau and Lifshitz's Course of Theoretical Physics" (253-286); Boom Soon Park, "'Context of Pedagogy': Teaching Strategy and Theory Change in Quantum Chemistry" (287-319); David Kaiser and Andrew Warwick, "Conclusion: Kuhn, Foucault, and the Power of Pedagogy" (319-410) in *Pedagogy and the Practice of Science*, ed. David Kaiser (Cambridge, MA: MIT Press, 2005).

[13] Peter Galison, "Material Culture, Theoretical Culture, and Delocalization," Chapter 34 in *Science in the Twentieth Century,* ed. John Krige and Dominque Pestre (Amsterdam: Harwood Academic Publishers, 1997): 669-682, 669.

[14] David E. Rowe, "Mathematical Schools, Communities and Networks," in *The Modern Physical and Mathematical Sciences,* ed. Mary Jo Nye, Vol. 5 of *The Cambridge History of Science,* general eds. David C. Lindberg and Ronald L. Numbers (New York: Cambridge University Press, 2003):113-132, 120-121.

interaction in the transfer of ways of thinking about science. Stated alternatively, these tools are useful—and useful to study—because they *facilitate* the transfer of ways of thinking, and in their dispersion, reveal intra-disciplinary lines of communication. In and of themselves however, such tools do not transfer ways of thinking about science. As the science historian Frederic Holmes has observed, an undue emphasis on such tools may obscure the craftsmanship by which the tools are employed.[15] A simile comes to mind here.

After a concert, an admirer once approached the legendary violinist Isaac Stern backstage. Noting that Stern played a Guarnerius del Gesù violin, the fan observed that the instrument produced marvelous music. "Oh really?" Stern replied. Then, proffering the violin to visitor, he said "Let's see what you can get out of it."

It appears that the scholarship most applicable to this thesis is the Geison-Morrell model of an ideal research school. So, what are the elements that Geison and Morrell have identified as characteristic of a successful research school?

In the Geison-Morrell model, there are fourteen separate qualities whose presence or absence determines the success of a given research school. These are: the presence of a charismatic leader; the presence of a leader with a research reputation; the presence of an informal setting and leadership style; the presence of a leader with institutional power; the

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[15] Holmes, *Investigative Pathways,* xix [Introduction].

presence of social cohesion, loyalty, and esprit de corps; the presence of a focused research program; the presence of simple and rapidly exploitable experimental techniques; the invasion into a new field of research; the presence of a pool of potential recruits; the presence of access to or control of publication outlets; students are able to publish early under their own names; the school had produced and placed a significant number of students; the school is institutionalized in a university setting; the presence of adequate financial support.[16] Geison's 1981 essay also includes a chart developed by David Edge and Michael Mulkay, which addresses the emergence of scientific specialties.[17] While these are interesting questions to ponder, they pose a non-trivial digression from the stated objective of this thesis. The next section of this chapter will address that objective and examine John Wheeler as a mentor during his Princeton years (1938-1977) within the framework of the Geison-Morrell model of a successful research school.

Section 4.3 The Wheeler Research School at Princeton

In his 1981 article Gerald Geison developed a chart, which incorporated the features of J. B. Morrell's ideal research school, and enabled a side-by-side comparison of various research schools with respect to the fourteen

[16] Geison, "Scientific Change," (1981), 25.
[17] Geison, "Scientific Change," (1981), 25; See also David O. Edge and Michael Mulkay, *Astronomy Transformed: The Emergence of Radio Astronomy in Britain* (New York: Wiley, 1976), 382 . This chart, which has been replicated by Geison, details conditions that lead to the development of a scientific specialty.

salient indicators of a given research school's long-term success.[18] Among the eight schools chosen for Geison's comparison were three research schools that had shown sustained success (Justus von Liebig's school of Chemistry at the University of Giessen; Michael Forster's school of physiology at the University of Cambridge; Arthur A. Noyes' school of physical chemistry at Caltech), two schools that had achieved temporary success (Pierre-Simon Laplace and Claude Louis Berthollet's "Arcueil c. 1800-1813 School" of physics and Chemistry; Enrico Fermi's school of nuclear physics at the University of Rome), and four schools that were partial or relative failures (Thomas Thomson's school of chemistry at the University of Glasgow; Burdon-Sanderson's schools of physiology at University College London and Oxford University; Ira Remsen's school of chemistry at The Johns Hopkins University; Wilder D. Bancroft's school of physical chemistry at Cornell University).[19]

In the paragraphs that follow, this thesis will evaluate John Wheeler as a mentor using the fourteen indicators of research-school success included in the Geison-Morrell model. At the conclusion of that discussion, the reader will find a table, adapted from Geison's 1981 article, which places Wheeler in a side-by-side comparison with three other research schools. For comparison to Wheeler in this table, the author has chosen, from among Geison's selections, a school which had sustained success (Justus von Liebig in Giessen), a school which had temporary success (Enrico Fermi in Rome) and a school

[18] Geison, "Scientific Change" (1981), 24.
[19] Geison, "Scientific Change" (1981), 22.

which was a partial or relative failure (Ira Remsen at The Johns Hopkins). This tabular comparison of Wheeler's work as a mentor with other research schools may serve to illustrate the utility of choosing a mentor as a unit of analysis.

The first condition for a successful research school in the Geison-Morrell model is the presence of a "charismatic" leader. Unfortunately, Geison did not elaborate on his meaning of "charismatic" in either his 1981 article or in his summary of the 1993 *Osiris* volume.[20] Given that Geison pays homage to J. B. Morrell at the outset of his 1981 article, one might look to Morrell for an explication of charisma. If nothing else, Morrell is certainly effusive on the subject:

> The creation, maintenance and growth of the school's loyalty, cohesion and confidence depended, too, on the director's charismatic powers, which at best reinforced his institutional power ... the term is useful if it conveys the idea of extraordinarily effective, indeed messianic, leadership. Such charisma which was most effectively exerted in informal pre-bureaucratic contexts, helped to draw students in sufficient numbers to make the school viable. It enforced the standards and styles of work adopted by the school. It exacted from the students an unflagging almost fanatical devotion to research, particularly at times of intellectual failure and disappointment, and on occasion it also imposed fervent specialization. It contributed strongly to the school's sense of its own novel and distinctive identity and importance. And it compelled unquestioning and unswerving loyalty to the master and his school. Though a research school existed primarily to advance knowledge, its atmosphere could be highly evangelical as the prophet broke through accepted conventions and led his devoted followers into unexplored and promising lands of enquiry ... Indeed the extent to which students

[20] Geison, "Scientific Change" (1981), 25; Geison "Research Schools" (1993), 234.

> wished to be known as the pupils of a certain director indicates the strength of his charisma.[21]

Morrell's statement, insofar as it is applied to modern research schools, seems to overstate the case. There is no evidence that John Wheeler or any of his colleagues consider themselves messianic. Nor is there any indication that they required an "unquestioning and unswerving loyalty." Indeed, as was shown in the previous chapter, Wheeler tends to see himself more as a collaborator than a mentor. Witness his oft repeated aphorisms, "Universities have students to teach the professors," or "the right answer is seldom as important as the right question."[22] But does this mean that Wheeler lacked charisma? Hardly.

Charisma, according to German sociologist Max Weber (1864-1920), takes a number of forms. Among these forms is a type of charisma that is specific to a given context, or in Weber's language, "qualitatively particularized." This type of charisma seems somewhat less 'messianic' and more appropriate to the modern research school than the form of charisma described by Morrell. Weber elucidated this contextual charisma as follows:

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[21] Morrell, "Chemist Breeders" (1972), 6-7.
[22] John Archibald Wheeler, "Wheeler, John Archibald, 1911 – ," interview by Kenneth W. Ford (transcript) Princeton, NJ and Meadow Lakes, NJ, 06 Dec 1993 – 18 May 1995, American Institute of Physics. Oral History Inteviews [OH5]; the sentiment 'Universities have students to teach professors,' is expressed on 1209, 1906, and 2318. These particular interviews were conducted 14 Feb 1994 – 10 Jan 1995; See also John Archibald Wheeler and Kenneth Ford. *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York: W. W. Norton, 1998), 150; The 'right question' aphorism was cited in an email of 21 Sep 06 to the author from former Wheeler student J. Peter Vajk.

> Charisma can be, and of course regularly is, qualitatively particularized. This is an internal rather than an external affair, and results in the qualitative barrier of the charisma holder's mission and power. In meaning and in content the mission may be addressed to a group of men who are delimited locally, ethnically, socially, politically, occupationally, or in some other way. If the mission is thus addressed to a limited group of men, as is the rule, it finds its limits within their circle.

Of course, Weber continues, charisma is impermanent at best and fleeting at worst:

> By its very nature, the existence of charismatic authority is specifically unstable. The holder may forego his charisma; he may feel 'forsaken by his God,' as Jesus did on the cross; he may prove to his followers that 'virtue is gone out of him.' ... The charismatic leader gains and maintains authority solely by proving his strength in life. If he wants to be a prophet, he must perform miracles; if he wants to be a war lord, he must perform heroic deeds. Above all, however, his divine mission must 'prove' itself in that those who faithfully surrender to him must fare well. If they do not fare well, he is obviously not the master sent by the gods.[23]

Synthesizing these concepts, it appears that charismatic mentoring in science is evidenced by both a distinguished career and the production of successive generations of elite scientists. The sociologist Harriet Zuckerman makes this case when she traces the intellectual lineage of Hans Krebs (1900-1981) through four generations of Nobel laureates and three generations of eminent chemists (including Justus von Liebig) all the way to Antoine-Laurent Lavoisier (1743-1794).[24]

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[23] Max Weber, *From Max Weber, Essays in Sociology*, trans and ed. H. H. Gerth and C. Wright Mills (London: Oxford University Press, 1946; reprint New York: Galaxy, 1965), 247, 248-249.

[24] Zuckerman, *Scientific Elite*, 150. Krebs (1900-1981, Nobel prize 1953) studied with Otto Warburg (1883-1970, Nobel prize 1931); Warburg studied

In this respect, we can say that John Wheeler was a charismatic leader. As has been shown, Wheeler was a renowned physicist. Moreover, quite an number of Wheeler's former students (e.g. Richard Feynman, Dieter Brill, John Toll, Ken Ford, Charles Misner, Kip Thorne, Jacob Bekenstein, among others) have gone on to distinguished careers. While many of the contributors to *Family Gathering* discuss Wheeler's continuing influence on their students, the letter of John S. Toll is particularly striking. Toll, who is now (2006) President Emeritus of Washington College and Chancellor Emeritus of the University of Maryland, also served as Professor and Chair of the Department of Physics and Astronomy at the University of Maryland from 1953 to 1965. At the time of his *Family Gathering* letter to Wheeler (23 June 1977), Toll was president of SUNY at Stony Brook and making preparations to serve as president of the University of Maryland. In that letter, Toll described his own students as Wheeler's "grandchildren" and their students as Wheeler's "great-grandchildren." Moreover, since a number of Wheeler's students were among the faculty of the department of physics and astronomy at Maryland, Toll observed that Wheeler had, in effect, inspired the whole department. Toll even

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with Emil Fischer (1852-1919, Nobel prize 1902); Fischer studied with Adolf von Baeyer (Adolf von Baeyer (1835-1917, Nobel Prize 1905); Baeyer studied with Friedrich August Kekulé (1829-1896), who is credited with the discovery of the benzene ring; Kekulé studied with Justus von Liebig (1803-1873), one of the subject of J. B. Morrell's 1972 article; Liebig studied with Joseph-Louis Gay-Lussac (1778-1850) who performed some of the earliest experiments with gasses; Gay-Lussac studied with Claude Louis Berthollet (1748-1822) who did early work on chemical reactions and helped found the Ecole polytechnique; Berthollet studied with Lavoisier (1743-1794) to revise the standard system of chemical nomenclature.

spoke of building SUNY in the "Wheeler spirit." Regarding Wheeler's charisma as a mentor, Toll wrote:

> I remember your [Wheeler] speaking of the "charismatic chain" that was so essential to good scientific work—a sequence of apprenticeships in which the spirit of research was passed from one person to another. Certainly you have been a uniquely effective source of such a large charismatic chain.[25]

In light of the foregoing, and employing Max Weber's definition of particularized charisma, John Wheeler seems to have satisfied the charismatic mentor criterion that Geison and Morrell have established for a successful research school.

As for the second Geison-Morrell criterion ("Leader with research reputation"), this issue has been addressed above (pp 149-150) in this chapter. As we have seen, John Wheeler was an extraordinarily productive theoretical physicist. Therefore, as a mentor, Wheeler has met the second Geison-Morrell criterion for a successful research school.

The Geison-Morrell ideal research school model also calls for an "informal setting and leadership style." Here again, this aspect of Wheeler's mentoring has been addressed above. To what has been said earlier, we can

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[25] *Family Gathering,* John S. Toll, 66-72; For John Toll's career see, University of Maryland, "John Sampson Toll, Curriculum Vitae," available online: <http://www.physics.umd.edu/people/faculty/cv/TollCV.pdf> (21 Aug 2005) and Washington College, "Meet the Administration: John S. Toll," available online: <http://faculty.washcoll.edu/admin_bios/toll.html> (26 May 2006). See also *Family Gathering*, 34, 103, 125, 164, 429: In addition to Toll, the former Wheeler students at Maryland included Gilbert Plass, James J. Griffin, Dieter Brill, and Charles Misner. Also, at the time of Toll's letter, Bahram Mashoon had just completed a two year post-doc at Maryland.

add a report from *Family Gathering*. In his undated letter, Fred K. Manasse recalled numerous Saturday "group advising" sessions:

> The best general description of it I would now call a combination of apprenticeship with small group instruction. It was not a seminar, nor a lecture, nor the classical one-on-one advising. However, elements of each of these were present ... Although Johnny always made specific appointments, and for a precise time, our discussions were rarely just for the two of us. As a matter of fact, he deliberately arranged for several of us to be scheduled within 30-45 minutes of each other and thus there were almost always 4 or 5 people there at any one time. We sat around in his combination library-office in Palmer Hall discussing each other's problems, obtaining references from his shelves, getting advice from each other and from John and generally discussing physics, relativity, research approaches etc. Whatever he did as catalyst to each of us apparently worked, because we all got our unique thesis ideas and eventually our PhD's without really seeing Johnny alone more than half a dozen times during our three or four years at Princeton. I can still remember that familiar "Come In" at the appointed time, and in each instance being greeted by a different assortment of student colleagues all eagerly waiting to discuss their own problem while critiquing the current holder of the ear and/or chair nearest the "great man". Perhaps this is the true and modern version of the Socratic system.[26]

Of course, in certain ways, Manasse's report brings to mind recollections of discussion groups at Bohr's institute in Copenhagen; with students competing for the ear (and approval) of Bohr.[27] Still, Kip Thorne recalls that Wheeler's discussions featured a cooperative spirit and an unspoken code that sharply discouraged treading on the self-esteem of others.[28] In sum, Wheeler, as a

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[26] *Family Gathering,* Fred K. Manasse, 258-259.
[27] David C. Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (New York: Freeman, 1993), 184-185.
[28] *Family Gathering,* Kip Thorne, 306-307.

mentor, has satisfied the Geison-Morrell criterion for an informal setting and leadership style.

The Geison-Morrell ideal model also calls for a "leader with institutional power." On the face of it, this criterion is more difficult to demonstrate; John Wheeler has never served as chair of the Department of Physics at Princeton. Even so, Wheeler was not without influence. He served as an advisor to several corporations (e.g. Dupont, Battelle, and Convair) and numerous government agencies (e.g. the General Scientific Advisory Board of the U.S. Air Force, the Advisory Committee of the Oak Ridge National Laboratory, and the General Advisory Committee on Arms Control and Disarmament). Wheeler mitigated a recruiting problem for the H-Bomb project when he succeeding in creating Project Matterhorn (which involved two areas of thermo-nuclear research—weapons development and fusion reactor development) at Princeton's Institute for Advanced Study. He created Project Jason as another avenue of recruitment to bring members of the scientific community into defense related projects on a temporary basis without these scientists having to forego their academic research. Wheeler also came very close to establishing a national security laboratory at Princeton.[29] Still, it would appear

[29] Wheeler interview with Ken Ford (14 Feb 1994 – 08 Nov 1994); For Wheeler's advisory committee work see 1201, 1407-1408, 1607-1608, 1705, 2003-2004, 2323; For Project Matterhorn see esp. 1407-1410; For Project Jason and the proposed national laboratory at Princeton see John Archibald Wheeler, "Wheeler, John Archibald 1911 –," interview by Finn Aaserud, [transcript] Princeton, NJ, (04 May and 28 November 1988), American Institute of Physics, Oral History Interviews [OH30194], n.p. and Finn Aaserud, "Sputnik and the 'Princeton Three:' The National Security Laboratory that was

that Wheeler did not meet the Geison-Morrell requirement for institutional power.

The Geison-Morrell model for a research school also lists the criterion of, "social cohesion, loyalty, and esprit de corps or discipleship." This condition seems readily apparent in the case of Wheeler as a mentor. The title *Family Gathering* certainly suggests social cohesion, loyalty, and esprit de corps. Then too, both John Toll and Kip Thorne have (as noted above) commented favorably on the "Wheeler spirit" that they hoped to infuse in their students and/or institutions. In addition to *Family Gathering,* two other Wheeler festschrifts have been compiled and published.[30] In each case these volumes feature numerous essays by former Wheeler students; who occasionally collaborated on a chapter. Finally, an overview of the bibliographies of former Wheeler students reveals several instances in which former Wheeler apprentices of various academic generations collaborated with each other. Most notable of these is the now (2006) canonical opus *Gravitation* by Charles

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not Meant to Be," *Historical Studies in the Physical and Biological Sciences* 25 no. 2 (1995): 185-240, esp. 236-239; See also David Kaiser, "Cold War Requisitions: Scientific Manpower and the Production of American Physicists after World War II," *Historical Studies in the Physical and Biological Sciences* 33, no. 1 (2002): 131-160, 138; Bringing physicists into defense related work was seen by many as a matter of national urgency. Kaiser cites Princeton physics department chair Henry DeWolf Smyth who characterized scientific manpower as a "war commodity," a "tool of war," and a "major war asset," which therefore should be "stockpiled" and "rationed."

[30] The festschrift volumes are: John R. Klauder, ed., *Magic Without Magic: John Archibald Wheeler: A Collection of Essays in Honor of His Sixtieth Birthday* (San Francisco: W. F. Freeman and Co., 1972) and Wojciech Hubert Zurek, Alwyn van der Merwe, and Warner Allen Miller, eds., *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler* (Princeton, NJ: Princeton University Press, 1988).

Misner, Kip Thorne, and John Wheeler.[31] It certainly would seem that Wheeler, as a mentor, fulfills the Geison-Morrell condition of social cohesion and esprit de corps.

The Geison-Morrell model also calls for a "focused research program." Wheeler, as a mentor, has met this criterion—at least twice. In *Geons,* John Wheeler talks about three stages of his professional life; "Everything is Particles," "Everything is Fields," and "Everything is Information." Only two of these stages ("Everything is Particles" and "Everything is Fields") correspond to Wheeler's years at Princeton. In the 'Everything is Particles' stage Wheeler believed that, "all basic entities - neutrons, protons, mesons, and so on – [could be constructed] out of the lightest, most fundamental particles – electrons and photons." While he was at Hanford, Wheeler continued, "I submitted a paper on this subject. It won a prize and appeared later, in 1946, in Proceedings of the New York Academy under the title 'Polyelectrons.' "[32] Indeed, particle work dominated Wheeler's career until the early 1950's. In addition to polyelectrons, other products of this particle fixation include Wheeler's well known Scattering Matrix and his QED work with Feynman.[33]

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[31] See *Gravitation* (San Francisco: W. H. Freeman and Co., 1973); This 1279 page opus, like the *Feynman Lectures*, remains in print, readily available, and continues to be a staple of physicists' libraries; Thorne earned his Ph.D. from Princeton in 1965; Misner earned his Ph.D. from Princeton in 1957.

[32] Wheeler with Ford, *Geons,* 63; Jacob Bekenstein, in 16 Sep 05 letter to the author reports that in 1981 Bell Labs produced a polyelectron atom. In 1988, Cheuk-Yin Wong (another former Wheeler student) submitted a paper to Oak Ridge, *Proceedings* suggesting that polyelectrons are a source of anomalous positron peaks in heavy ion reactions.

[33] Wheeler with Ford, *Geons,* 63.

In 1952, Wheeler "fell in love with relativity" and came to see, "a world made of fields, one in which the apparent particles are really manifestations of electric and magnetic fields, gravitational fields, and spacetime itself." Later Wheeler observed that this attraction was more than a matter of aesthetic appreciation:

> What I learned in teaching the course was that the riches of Einstein's theory had been far from fully mined. Hidden beneath the equations, simple in appearance, complex in application-was a lode waiting to be brought to the surface and exploited.[34]

Stated alternatively, Einstein's theory of general relativity offered Wheeler and his students a good deal of 'low-hanging [conceptual] fruit' that he and they could harvest for quite some time. Here again, with his sequential concentrations on particle physics and relativity, Wheeler (as a mentor) has satisfied a Geison-Morrell condition for a successful research school.

The Geison-Morrell model further requires "simple and rapidly exploitable experimental techniques." At first glance, this criterion would not seem to apply to a theoretical school. On the other hand, theoretical breakthroughs often yield rapidly exploitable ancillary problems. Jacob Bekenstein recalls that Wheeler would seize on the really significant ideas and exploit their publication value while the topic was fresh.[35] Bekenstein, in fact, encourages his students to quickly build on important discoveries. David Goodstein, Vice-provost at Caltech, has also suggested that, "most people, if they have two real contributions to make, will carve them up and publish a

[34] Wheeler with Ford, *Geons,* 63, 231.
[35] Jacob Bekenstein, email to the author, 16 Sep 2006.

number of Letters, etc. in addition to the two main papers."[36] Even though it appears that theoretical work can be exploited for bursts of publication, there is no evidence of the sort of sustained production that oftentimes grows out of experimental breakthroughs. Therefore, it is not clear that Wheeler and his students satisfy the seventh Geison-Morrell criterion for Research School success.

Another condition that the Geison-Morrell model specifies for a successful research school is the "invasion of a new field of research." In the case of Wheeler, as a mentor, this is less obvious in the particle work than it is in relativity. It is however, clear that Wheeler and his students made some important innovations in particle work (e.g. quantum electrodynamics and the collective nucleus model).[37] Still the real "invasion" was Wheeler's decision to pursue general relativity and to explore its relationships to cosmology and astronomy. Of John Wheeler's twenty-five most cited publications, seventeen originated in his 'Everything is Fields' period, while only eight stem from his

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[36] David Goodstein, email to the author 17 March 2006.

[37] See Stanford University, Stanford Linear Accelerator Center. SPIRES High-Energy Physics Literature Database Available online: <http://www-spires.slac.stanford.edu/spires/hep/> (21 Aug 2005); Search terms: find "a Wheeler, J. A." and "find a Hill, D. L. ; Wheeler's paper with Richard Feynman ("Interaction with the Absorber as the Mechanism of Radiation," *Reviews of Modern Physics* 17 (1945): 157-181) has been cited more than 130 times; Wheeler's paper with David L. Hill ("Nuclear Constitution and the Interpretation of Fission Phenomena," *Physical Review* 89 (1953): 1102-1145) has also been cited more than 130 times;

'Everything is Particles.' timeframe.[38] Granted, one could argue that since Wheeler's field work was more recent, it was likely to attract more attention. Still, a quantitative overview of the early work on general relativity shows that the Wheeler family (the term 'family' includes Wheeler's students, his students' students, and post-docs who studied with Wheeler) was responsible for a significant percentage of the most influential publications.[39] While I am hesitant to employ the term "invasion," it seems clear that Wheeler, as a mentor, had a notable impact in the sudden expansion of general relativity work. Consequently, Wheeler, as a mentor, satisfied the Geison-Morrell condition for a successful research school.

The Geison-Morrell model of an ideal research school includes the requirement for a "pool of potential recruits." This criterion has obviously been met. Wheeler's reputation as a researcher has been well documented above. Moreover, since the days of Joseph Henry, Princeton's Department of Physics has remained among the United States' elite physics departments. The Princeton Department of Physics never suffered a lack of graduate students during Wheeler's career. Plainly, the Geison-Morrell condition for an available pool of recruits was satisfied.

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[38] See Google Scholar; Search term: "find a Wheeler, J. A.," available online: <http://scholar.google.com/scholar?num=100&hl=en&lr=&safe=off&q=author%3A%22J+A+Wheeler%22&btnG=Search> (20 Feb 06).

[39] See Stanford University, Stanford Linear Accelerator Center, SPIRES High-Energy Physics Literature Database (28 May 2006); Between 1952 and 1972 some sixteen publications that included the keyword search phrase "general relativity" were cited 50 or more times; Wheeler family members were the authors of five of ten most cited publications returned by this search criteria.

The ideal Geison-Morrell research school also features "access to, or control of, publication outlets" as a condition for a successful research school. Here too, is a circumstance that is relatively easy to demonstrate. Wheeler himself authored some 215 publications during his Princeton years (1938-1977), and fifty-four of these were co-authored by at least one Wheeler student, former student, or post-doc. In 1957 alone, Wheeler published ten papers, and seven of these were with students, former students, or post-docs. In fact, Wheeler and his students were the recipients of what Wheeler characterized as, "some good natured finger pointing" by colleagues who suggested that he and his students were attempting to 'take over' *Reviews of Modern Physics* by publishing eight papers in the July 1957 issue.[40] This circumstance indicates how Wheeler often found a way to get articles into print; sometimes without the enthusiastic support of journal editors. In 1952, for example, Wheeler (with David Hill) struggled to complete an important paper that was originally slated to be published in the *Annual Review of Nuclear Science.* Unfortunately, the paper turned out to be too long and was submitted too late for publication. Despite the paper's length and the inclusion of numerous illustrations, Samuel Goudsmit, editor of *Physical Review,*

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[40] See "Bibliography of John Archibald Wheeler;" a draft form of this unpublished document has been made available to the author by Kenneth W. Ford. See also Wheeler with Ford, *Geons,* 266-267.

accepted it for publication and the paper appeared in 1953.[41] Six years later, in 1959, Goudsmit was the recalcitrant editor. Wheeler reports:

> Ken [Ford] and I turned out three papers on semi-classical scattering. For one of them, we brought in two other colleagues to help. One was David Hill, who had completed his Ph.D. work with me a decade earlier on the mechanics of nuclear fission. The other was Masami Wakano, then my graduate student, later my colleague and coauthor on numerous papers. When I submitted our three papers to Physical Review for publication, I got a cool reception—not for the first time-from that journal's editor, Sam Goudsmit ... Goudsmit didn't like wordiness and he didn't like pedagogy. I probably published less in Physical Review than most American physicists did, because I liked to be discursive and I liked to teach. Many of my papers appeared in another journal of the American Physical Society, *Reviews of Modem Physics*. The papers on semi-classical scattering Goudsmit found to be both too long and too pedagogical. Instead of abbreviating them, as he suggested, I submitted them to *Annals of Physics*, whose editor, Phil Morse, had been receptive in the past. There they appeared, unedited, in 1959.[42]

It appears that Wheeler's predilection for teaching theoretical physics carried over into his peer-reviewed publications. More to the point, it also appears that Wheeler, as a mentor, has met the Geison-Morrell requirement for ready access to publication outlets.

Another criterion for a successful research school is for the students to publish early and under their own names. This certainly seems to have been the case with Wheeler's apprentices. Among the contributors to *Family Gathering*, Dieter Brill, Fred K. Manasse, and Kip Thorne have all commented

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[41] Wheeler interview with Ken Ford (14 Feb 1994), 1208; Wheeler and Ford, *Geons,* 224; The paper referenced is: David Lawrence Hill and John Archibald Wheeler, "Nuclear Constitution and the Interpretation of Fission Phenomena," *Physical Review* 89, (1953): 1102-1145; as of 31 January 2006, this paper had been cited 510 times.

[42] Wheeler and Ford, *Geons,* 291.

that Wheeler was quick to share credit for joint work. Thorne also remarked that he conscientiously tried to emulate and pass on the "Wheeler code of ethics" to his students. Among other stipulations, the "Wheeler ethic" demanded that, "When working jointly with a student, put your name on the paper only if your contribution was very great; put the student's on even if his was small." In his *Family Gathering* letter of 27 August 1976, James York acknowledged Wheeler's assistance in promoting his [York's] work:

> I have you to thank for the guidance, encouragement, and opportunity that I needed in that crucial phase of my efforts in research. Moreover, you went a step further, as you have always done for your students and colleagues, in making the work known to others through your writings, talks, letters, and seminars. Your efforts in this direction were instrumental in helping me obtain my present position at the University of North Carolina, where John Wheeler is especially admired and respected![43]

Here, I should also note that on virtually every occasion where Wheeler has published jointly with a student or post-doc, Wheeler's name appeared last among the authors.[44] This evidence, coupled with the joint authorship data above, seems to indicate that Wheeler's students were able to publish early with their own names prominently featured in the publication.

The Geison-Morrell model of an ideal research school also requires the production and placement of a "significant number of students." John Wheeler has done very well by his students. In Chapter 1, this thesis cited David Goodstein, Vice-Provost of Caltech, who has observed that, on average, a

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[43] *Family Gathering,* Dieter Brill, 164; Fred K. Manasse, 258; Kip S. Thorne, 306; James W. York, 366.
[44] See Google Scholar; Search term: "find a Wheeler, J. A.," (20 Feb 06).

professor of physics at a research university will produce fifteen Ph.D.s over the course of his or her career. John Wheeler has produced in excess of fifty Ph.D.s; more than triple the Goodstein average.[45] This study has only uncovered one Wheeler student who did not move on to a successful career in either academics, research, or industry; the memory of that failure clearly troubles Wheeler:

> Between that senior thesis and his Ph.D. in physics a dozen years later, Peter [Putnam] followed a circuitous route-and an even more convoluted route later. First, following his mother's wishes, he enrolled in the Yale Law School. His only brother had been killed in action in World War II, and his father had died soon after. His mother, Mildred, active in business in Cleveland, Ohio, was wealthy and strong-willed. But Peter's heart wasn't in the law. He dropped out of law school and took a part-time job with an electronics firm in New Hampshire, leaving time for him to read physics and philosophy. Through letters and visits, Peter kept in touch with me. Under the influence of Sir Arthur Eddington's *The Nature of the Physical World*, he had come to believe that all the laws of nature can be deduced by pure reasoning. Try as I might, I couldn't seem to disabuse him of this belief ...
>
> Finally, Peter followed my suggestion that he say good-bye to Eddington and get back to something timely and tractable in the world of physics. He enrolled as a graduate student in physics at Princeton, and asked to accompany me to Leiden. He audited my lectures and contributed some beautiful large drawings 'to illustrate ideas I was covering, but [Peter] didn't get seriously into research until he got back to Princeton. Then he finished a Ph.D. dissertation on the distribution of mass and energy in a star that is radiating at a prodigious rate ...

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[45] David L. Goodstein, "Scientific Ph.D. problems". *American Scholar* 62, no.2 (Spr 1993): 215-221, available online: <http://0-search.epnet.com.oasis.oregonstate.edu:80/login.aspx?direct=true&db=aph&an=9304060251> (05 Jan 2006), 217; Wheeler and Ford, *Geons,* 180; The student was Peter Putnam.

> During a postdoctoral teaching stint at Columbia University, Peter offered a physics course so full of philosophy that it attracted students from the nearby Union Theological Seminary. Before long, he obtained a teaching post at Union, where he was, as one fellow teacher there told me, the only person who could out-argue the great theologian Reinhold Niebuhr.
>
> Whatever mechanism in Peter's head propelled him through this world, it produced a jagged path. When, around 1971, his appointment at Union Theological Seminary was not renewed - largely, I suspect, for lack of publications -he decided to cast his lot with the civil rights movement and moved to Houma, a town in the bayou country of Louisiana, where he offered legal services to blacks for little or no fee. To provide simple food and rent on a tiny house that he shared with a companion, he worked as a night janitor in a church. When Janette and I, on our way to Texas in 1976, stopped to visit Peter, one look told us that he was truly impoverished. His mother visited more than once but was unsuccessful in getting him to leave Houma or to accept money. One night in 1987, cycling between his residence and his janitorial job, Peter was struck by a drunk driver and killed ... Peter was not one of my better students, and made no lasting contributions to physics. His talents did not flower in publications. He was perhaps a bit mad. Yet he deeply affected a few people, me among them. In our long correspondence over many years and in our occasional long conversations, he always had a way of raising questions and challenging accepted explanations that helped me sharpen my thinking about physics and about the way we humans describe and understand the world around us. [46]

At times in the interview, Wheeler's regret seems palpable:

> Thinking back on it now, I realize I didn't do my duty by Peter. I should have realized that he had this shortcoming of not getting things written up. His senior thesis at Princeton was so impenetrable that neither I nor anybody else in the department could make head or tail of it. I recommended the policy we finally followed: that is to give him a grade on it that was the average of his grades in his courses. But I would have done better if I had sat on him sentence by sentence.[47]

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[46] Wheeler and Ford, *Geons,* 254-256. Wheeler interview with Ford (04 Mar 1994) 1602; and later (24 Mar 1995-12 Apr 1995) 2406-2410.
[47] Wheeler interview with Ford (04 Mar 1994), 1602.

It is interesting to note that in Wheeler's interviews with Ken Ford and in the autobiography *Geons,* John Wheeler wrote (and spoke) about Peter Putnam at greater length and with more emotion than any other of his students. It is obvious from Wheeler's productivity as a physicist and from the discussion of Wheeler relationship with his mentors in Chapter 2, that physics was a passion in Wheeler's life. From the discussion above, it is also clear that Wheeler had a passion for teaching. By accounts, Peter Putnam appears to the sole exception to Wheeler's success with placing his apprentices.

The Geison-Morrell model seems to emphasize the percentage of former students that have been placed. In my view however, the kinds of positions that Wheeler's former students have held, as well as the honors that they have earned, are more significant than the fact that they were merely placed. An adumbration of Wheeler's students' significant accomplishments follows: Richard Feynman won the Nobel prize in 1965; John S. Toll served as president of three academic institutions; Ken Ford served as Executive Director of the American Institute of Physics; Kip Thorne, Robert Wald, Jacob Bekenstein, and James York were all appointed to endowed professorships; Gilbert Plass, James Griffin, and Robert Wald all served as chair of their physics departments; Brendan Godfrey became Director of the U.S. Air Force Office of Scientific Research; Clifford E. Rhoades Jr. served as Director of Mathematics and Space Science for U.S. Air Force Office of Scientific Research; Terrence Sejnowski became Director of the Computational Neuroscience Laboratory at the Salk Institute. There are, to be clear, other noteworthy accomplishments among Wheeler's apprentices. Space and time however, preclude a complete listing.[48]

Plainly, Wheeler has produced and placed significant numbers of students. Since Wheeler's mentoring took place within a university setting, it appears that Wheeler, as a mentor, has satisfied the twelfth and thirteenth criteria for the Geison-Morrell model of a successful research school.

The fourteenth and final condition in the Geison-Morrell model of a successful research school is "adequate financial support." It is difficult to imagine a research setting in which additional funds could not be put to

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[48] *Family Gathering,* Richard P. Feynman, 12; Gilbert N. Plass, 34; John S. Toll, 67; Kenneth W. Ford, 84; James J. Griffin, 103; Kip S. Thorne, 306; James W. York, Jr., 366; Brendan B. Godfrey, 391; Terrence Sejnowski, 420; Robert Wald, 422; Wheeler and Ford, *Geons,* 101 [Toll]; "Dr. Gilbert Plass" [Obituary], *The Bryan – College Station Eagle,* available online: <http://www.theeagle.com/region/records/obituaries/march2004/030304obits.php> (12 Sep 2005); John Sampson Toll, "John Sampson Toll, Curriculum Vitae," available online: <http://www.physics.umd.edu/people/faculty/cv/TollCV.pdf> (21 Aug 2005); Washington College. "Meet the Administration: John S. Toll," available online: <http://faculty.washcoll.edu/admin_bios/toll.html> (26 May 2006); Kenneth W. Ford, "Kenneth W. Ford -- Personal Web Page," available: <http://www.ianford.com/kenford/> (21 Aug 2005); James J. Griffin, "James J. Griffin Curriculum Vitae," available online: <http://www.physics.umd.edu/people/faculty/cv/GriffinCV.pdf> (21 Aug 2005); California Institute of Technology, "Kip S. Thorne, The Feynman Professor of Theoretical Physics" [Home Page], available online: <http://www.its.caltech.edu/~kip/> (26 May 2006); Cornell University, Department of Physics, "James W. York, Jr., Professor of Physics" [profpages], Available online: <http://www.physics.cornell.edu/profpages/York.htm> (25 May 2006); Air Force (U.S.), Office of Scientific Research. Biography: "Dr. Brendan B. Godfrey," available online: <http://www.afosr.af.mil/pages/godfrey.htm> (16 Sep 2005); Salk Institute, "Terrence J. Sejnowski," available online: <http://www.salk.edu/faculty/faculty/details.php?id=48> (21 Aug 2005); Robert M. Wald, "Robert M. Wald, Curriculum Vitae," available online: <http://physics.uchicago.edu/t_rel.html#Wald> (21 Aug 2005).

productive use. That said, Wheeler, through his extensive contacts in government and industry, seems to have kept his department and his students reasonably well-funded. The story of the Princeton cosmic ray laboratory is a useful example here. As World War II was winding down, high-energy particle physics became an important area of research. Wheeler, like many of his peers, believed that this area of research held great promise.[49] In June of 1945, Wheeler suggested three goals for physics research in the post-war era.[50] The goal nearest and dearest to his heart was a cosmic ray investigation. As the historian Peter Galison notes, given the evidence of protons being transformed into mesons in the upper atmosphere, Wheeler had a hunch that "that matter could be directly transformed into energy."[51] He contended:

> Discovery [of] how to release the untapped energy on a reasonable scale might completely alter our economy and the basis of our military security. For this reason we owe special attention to the branches of ultranucleonics - cosmic ray phenomena, meson physics, field theory, energy production in supernovae, and particle transformation physics - where a single development may produce such far-reaching changes.[52]

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[49] Wheeler interview with Ford (14 Feb 1994), 1206.
[50] J. A. Wheeler, "Three Proposals for the Promotion of Ultranucleonic Research #6: H. D. S.," 15 June 1945, copy to Smyth, in Physics Departmental Records, Chairman 1934-35, 1945-46, no. 1, Princeton University Archives, cited by Peter Galison, "Physics Between War and Peace," in *Science, Technology, and the Military*. Vol. 12, part 1, of Sociology of the Sciences, ed. Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart (Boston: Kluwer Academic Publishers, 1988), 58.
[51] Galison, "Physics Between War and Peace," (1988), 58.
[52] J. A. Wheeler, "Three Proposals for the Promotion of Ultranucleonic Research #6: H. D. S.," 15 June 1945, copy to Smyth, in Physics Departmental Records, Chairman 1934-35, 1945-46, no. 1, Princeton

At first Wheeler believed that the research would be most expeditiously accomplished by having U.S. Air Force bombers carrying the experimental apparatus at an altitude of 40, 000 feet.[53] When that idea failed to gain traction, Wheeler, who was well aware that a high-energy particle accelerator was not in Princeton's immediate future, opted for a cosmic ray laboratory that would be located on or near the Princeton campus. He needed money and some allocated space.

Here, Wheeler's contacts in government and industry were most helpful:

> Fortunately, an ancillary building at Princeton that Walker Bleakney had used for wartime shock-wave experiments was available. We established our cosmic-ray beachhead there. Most of the subsequent funding for the work of the laboratory came from the federal government. Some came also from the generous private contributions of many of my old Du Pont friends, including Crawford Greenewalt (who, as I noted before, became Du Pont's president), Dale Babcock, Lombard Squires, Charles Wende, Hood Worthington, H. C. ("Ace") Vernon, and George Graves. They established a fund named the Friends of Elementary Particle Research, from which I was able to allocate expenditures, especially to support students. By drawing on it sparingly to meet special needs when other funds were not available, I made it last many years.[54]

Here too, it would appear that Wheeler, as a mentor, has satisfied the Geison-Morrell condition of adequate funding for a successful research school.

University Archives, cited by Galison, "Physics Between War and Peace" (1988), 58.

[53] Galison, "Physics Between War and Peace" (1988), 58.

[54] Wheeler and Ford, *Geons,* 170; Wheeler interview with Ford (14 Feb 1994), 1206.

In view of the foregoing evidence, two things seem clear. First of all, as a mentor, John Wheeler satisfies each of the Geison-Morrell criteria for a successful research school. The notion that a research school must be linked to experimental or observation science is unduly restrictive. If, on the other hand, historians of science adapt and apply the Geison-Morrell model to mentors of theoretical studies, there seems to be good reason to expect useful insight. The following table should server to illustrate this point.

Table 4.1 Comparison of Factors Affecting the Success of Research Schools[55]

School	Liebig	Wheeler	Fermi	Remsen
Charismatic Leader	yes	yes	yes	no
Leader with research reputation	yes	yes	yes	yes
Informal setting and leadership style	yes	yes	yes	no
Institutional power	yes	?	yes	yes
Social Cohesion esprit de corps discipleship	yes	yes	yes	?
Focused research program	yes	yes	yes	yes
Simple and rapidly exploitable experimental techniques	yes	?	yes	yes
Invasion of new field of research	yes	yes	yes	no

Legend: "yes" indicates that the feature appears to be present
"no" indicates that the feature appears to be absent
"?" indicates that the presence or absence in unclear

[55] Adapted from Geison, "Scientific Change" (1981), 24.

Table 4.1 Comparison of Factors Affecting the Success of Research Schools (cont.)

School	Liebig	Wheeler	Fermi	Remsen
Pool of potential recruits (graduate students)	yes	yes	?	yes
Access to or control of publication outlets	yes	yes	yes	yes
Students publish early and under own name	yes	yes	?	?
Produced and placed significant numbers of students	yes	yes	?	yes
Institutionalization in university setting	yes	yes	?	yes
Adequate financial support	yes	yes	yes	yes
Total number of "yes" answers	14	12	10	9

Legend: "yes" indicates that the feature appears to be present
"no" indicates that the feature appears to be absent
"?" indicates that the presence or absence in unclear

Table 4.1 Comparison of Factors affecting the success or failure of a research school (adapted from Gerald L. Geison "Emerging Specialties and Research Schools"). Here, John Wheeler's 'school' is shown in comparison to a research school that Geison considers to be a sustained success (Justus von Liebig), a research school that Geison considers to have had temporary success (Enrico Fermi) and a research school that Geison considers to be a relative failure (Ira Remsen).

Section 4.4 Conclusion

So, what can or does a theoretical mentor pass along to his protégés? It has been well documented that mentors in laboratory and field settings pass along specialized and/or technical knowledge to their apprentices. Generally, there is some explicit instruction. In many cases however, the explicit didactic instruction is supplemented by the transfer of tacit knowledge. Laboratory techniques and observational practices are learned by imitation as much as instruction. What then, do theoretical mentors pass on to their apprentices?

The foremost answer is that theoretical mentors can recognize and nurture talent in their apprentices. As noted in Chapter 2, Wheeler's mentors certainly recognized his abilities. Beyond recognition however, Herzfeld, Breit, and Bohr inculcated Wheeler with distinctive philosophies of physics and its place in the world; all of which shaped Wheeler as a physicist and a mentor.

Another answer is that theoretical apprentices learn to look at problems in depth; they learn to think about physical phenomena from multiple frames of reference; they develop an ability to see the non-visible in physics with, in the rich language of Immanuel Kant, *anschaulich* vision (e.g. they see more than a ball moving through space—they see the forces that will shape a trajectory before the ball ever moves).

A maritime analogy seems apropos here. As a seaman, I could look at the water in an anchorage and discern the stage of the tide, the strength and direction of the tidal current, the strength and direction of the wind, the likelihood of precipitation within the previous twenty-four hours, and the relative efficiency of the local sewage treatment facility. A person unfamiliar with a maritime environment (i.e. a "lubber"), surveying that same area from that same vantage point is likely to discern water ... exclusively. That deeper vision—that *anschaulich* seeing of the non-visible—is part of what a skillful mentor will impart to his or her apprentices.

It may be useful here to recall another passage from Harriet Zuckerman's *Scientific Elite*. To set the stage, at this point in Zuckerman's narrative a physicist is reconstructing the key elements of what he or she was learned from their mentor:

> I knew the techniques of research. I knew a lot of physics. I had the words, the libretto, but not quite the music. In other words, I had not been in contact with men who were deeply imbedded in the tradition of physics: men of high quality. This was my first real contact with first-rate creative minds at the high point of their power.[56]

Zuckerman's narrative brings to mind an analogy in nature.

Let us consider Darwin's finches in the Galapagos Islands. One method by which some species (e.g., *G. conirostris*) of finches remain relatively homogenous is the imprinting of a conspecific song (i.e. a song that is specific to that species of finch). Over a decade of observation on the Galapagos, Peter and Rosemary Grant have found that in some species, "Sons copy their father's song, even in the fine details of the structure." Rosemary Grant has produced sonographs which reveal the precision of this imprinting. Moreover, this imprinting of song takes place during a very particular period in the

[56] Zuckerman, *Scientific Elite,* 123.

fledglings life.[57] This is not to say that the songs are immutable. There are occasions when songs are either improperly learned or perhaps learned and forsaken. Then too, there are occasional incidents of cross-breeding, after which the male fledglings may well learn a song that does not otherwise correspond to their morphology. That said, far more often than not, the father's song is exactly imprinted on the son. In an April, 2006 lecture at Oregon State University, Peter Grant recalled that one finch under observation had suffered a throat injury from a cactus thorn. Consequently, his song was more guttural and lower in pitch. Nonetheless, the healthy throated son learned his father's modified song and passed it on his [the son's] children. In fact, Grant reported that the modified song persisted for at least four generations.[58]

The parallel is that patterns of thought or ways of seeing, both the *anschauend* (intuitive, contemplative) and *anschaulich* (clear, vivid, concrete) vision, like a finch's song are passed from mentor to apprentice—often tacitly. Also, it appears from our detailed review of Wheeler and his apprentices, that these thinking patterns or ways of seeing tend to persist for a number of intellectual generations. Moreover, since most mentors have several apprentices, there will be a multiplicative effect. Yet Zuckerman's narrative of the socialization of elite scientists elite raises another question; are all socializations equivalent?

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[57] Peter Grant, *Ecology and the Evolution of Darwin's Finches* (Princeton, NJ: Princeton University Press, 1986), 242-243, 246-247.
[58] Peter Grant, Lecture: "Darwin's Finches," Oregon State University, LaSells Stewart Center Auditorium, 12 April 2006.

On its face, the proposition that all socializations are equivalent seems unlikely. Science is a creative process, and just as art historians gain insight by studying the training of an artist, so too historians of science can profit from tracing the professional development of scientists in a given discipline. We have seen that Wheeler's influence has been self-consciously transmitted by his former students on to their students. It seems likely and sensible that "Wheelerisms" and/or the "Wheeler spirit" will continue (with minor modifications) to be passed along to ensuing generations of physicists and cosmologists. As was noted at the outset of this thesis: Contributions to the corpus of knowledge are critical; without them, there would be no physics. Still, contributions to the corpus are by their very nature, additive. This circumstance contrasts with the influence of a skilled mentor, who, as his influence is passed through successive generations, may well have a multiplicative effect on the discipline.

Given this transmission of *anschauend* and *anschaulich* vision over multiple generations, I am suggesting that in theoretical sciences, studies that focus on an individual mentor will add texture to the research school literature. In sum, I believe that making theoretical mentors a fundamental unit of analysis in research school studies will allow historians to more readily discern the 'chains of wisdom' that shape theoretical physics.

Sources Consulted

Aaserud, Finn. “Sputnik and the ‘Princeton Three:’ The National Security Laboratory that was not Meant to Be.” *Historical Studies in the Physical and Biological Sciences* 25 no. 2 (1995): 185-240.

Adler, Carl G. and Byron L. Coulter. “Galileo and the Tower of Pisa Experiment.” *American Journal of Physics* 46, no. 3 (Mar 1978): 199-201.

Air Force (U.S.), Office of Scientific Research. "Dr. Brendan B. Godfrey" [Biography]. Available online: <http://www.afosr.af.mil/pages/godfrey.htm> (16 Sep 2005)

Air Force (U.S.), Office of Scientific Research. "Dr. Clifford E. Rhoades" [Biography]. Available online: <http://www.afosr.af.mil/pages/afrrhoa.htm> (21 Aug 05).

Al Huang, Chungliang and Jerry Lynch. *Mentoring: The Tao of Giving and Receiving Wisdom*. San Francisco: HarperSanFrancisco, 1995.

American Institute of Physics. “Citizenship of Physics Ph.D.s,1966-2003” Available online: <http://0-www.aip.org.oasis.oregonstate.edu/statistics/trends/highlite/ed/figure6.htm> (05 Jan 2006).

American Institute of Physics. "Focus and Coverage." *Journal of Mathematical Physics* 47, no. 3 (Mar 2006) n.p. Available online: <http://jmp.aip.org/jmp/> (22 Apr 2006)

American Institute of Physics. “Number of Physics Ph.D.s Conferred in the United States, 1900-2003” Available online: <http://0-www.aip.org.oasis.oregonstate.edu/statistics/trends/highlite/ed/figure5.htm> (05 Jan 2006).

American Philosophical Society – Membership in the APS. (n.d.). <http://www.oldcity.dca.net/amphilsoc/default_test.cfm>. (25 Oct 03)

American Physical Society – Prizes and Awards (n.d.) Available online: <http://www.aps.org/praw/einstein/03winner2.html> (25 Oct 03).

Aris, Rutherford, H. Ted Davis, and Roger Stuewer, eds. *Springs of Scientific Creativity: Essays on Founders of Modern Science*. Minneapolis, MN: University of Minnesota Press, 1983.

Association for Women in Science. *Mentoring Means Future Scientists: A Guide for Developing Mentoring Programs Based on the AWIS Mentoring Project.* Washington, DC: Association for Women in Science, 1993.

Badash, Lawrence. *Scientists and the Development of Nuclear Weapons: From Fission to the Limited Test Ban Treaty, 1939-1963.* The Control of Nature. Amherst, NY: Humanities Press, 1998.

Bernstein, Jeremy. *Quantum Profiles.* Princeton, NJ: Princeton University Press, 1991.

Bevilacqua, F. "The Emergence of Theoretical Physics in the Second Half of the Nineteenth Century." In *Natural Sciences and Human Thought.* Edited by Robert Zwilling. New York: Springer-Verlag, 1995.

Ben-David, Joseph. *The Scientist's Role in Society: A Comparative Study.* Englewood Cliffs, NJ: Prentice-Hall, 1971.

Bird, Stephanie J. "Mentors, Advisors, and Supervisors: Their Role in Teaching Responsible Research Conduct." *Mentoring and the Responsible Conduct of Research.* Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 455-468.

Birr, Kendall. "Industrial Research Laboratories." In *The Sciences in the American Context: New Perspectives*, edited by Nathan Reingold. Washington, DC: Smithsonian Institution Press, 1979.

Bloch, Felix. "Biography" Available online: <http://nobelprize.org/physics/laureates/1952/bloch-bio.html> (24 Mar 06). Also in *Nobel Lectures, Physics 1942-1962.* Amsterdam: Elsevier Publishing Co., 1964.

Bohr, Aage. "Autobiography" Available online: <http://nobelprize.org/physics/laureates/1975/bohr-autobio.html> (24 Mar 2006). Also in *Lex Prix Nobel.* Edited by Wilhelm Odelberg. Stockholm: Nobel Foundation, 1976.

Boltzmann, Ludwig. "Model." In *The Encyclopaedia Britannica.* 11th ed. Vol. 18. New York: Encyclopaedia Britannica, 1911: 638-640.

Brock, William H. "Liebigania: Old and New Perspectives." *History of Science* 19 (Sep 1981): 201-218.

Brock, William H. *Justus von Liebig: The Chemical Gatekeeper.* New York: Cambridge University Press, 1997.

Broome, Taft H. “Of Snow and Smith: Commentary on ‘Notes on a Pilgrimage to Science: A Fly on the Wall (David Smith)” *Mentoring and the Responsible Conduct of Research.* Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 635-638.

Brown, W. Norman, comp. *John Hopkins Half-Century Directory: A Catalogue of the Trustees, Faculty, Holders of Honorary Degrees, and Students, Graduates and Non-graduates 1876-1926.* Baltimore, MD: The Johns Hopkins University Press, 1926.

Bush, Vannevar. *Science: The Endless Frontier: A Report to the President.* Washington, DC: U.S. Government Printing Office, 1945.

Bynum, W. F., E. J. Browne and Roy Porter, eds. *Dictionary of the History of Science.* Princeton, NJ: Princeton University Press, 1981.

California Institute of Technology. "Kip S. Thorne, The Feynman Professor of Theoretical Physics" [Home Page]. Available online: <http://www.its.caltech.edu/~kip/> (26 May 2006).

Cassara, Ernest, ed. *Universalism in America: A Documentary History.* Boston: Beacon Press, 1971.

Cassidy, David C. *Uncertainty: The Life and Science of Werner Heisenberg.* New York: Freeman, 1993.

de Chadarevian, Soraya. "Using Interviews to Write the History of Science." In *The Historiography of Contemporary Science and Technology*, edited by Thomas Söderqvist. Studies in the History of Science, Technology, and Medicine, vol. 4. Amsterdam: Harwood Academic Publishers, 1997.

Chandrasekhar, Subrahmanyan. "Autobiography "Available online: <http://nobelprize.org/physics/laureates/1983/chandrasekhar-autobio.html> (24 Mar 2006). Also in *Lex Prix Nobel.* Edited by Wilhelm Odelberg. Stockholm: Nobel Foundation, 1984.

Chomsky, Noam, Ira Katznelson, R. C. Lewontin, David Montgomery, Laura Nader, Richard Ohmann, Ray Siever, Immanuel Wallerstein, and Howard Zinn. *The Cold War and the University: Toward an Intellectual History of the Postwar Years.* New York: The New Press, 1997.

Christensen, Terry M. "Creating Chains of Wisdom: The Role of Interdisciplinarity in Mentoring." Master's Thesis, Marylhurst University, 2001.

Clark, Burton R., ed. *The Research Foundations of Graduate Education: Germany, Britain, France, United States, Japan*. Berkeley: University of California Press, 1993.

Collins H. M., "The TEA Set: Tacit Knowledge and Scientific Networks." *Science Studies* 4 (1974): 165-186.

Committee on Science, Engineering, and Public Policy (U.S.). *Enhancing the Postdoctoral Experience for Scientists and Engineers: A Guide for Postdoctoral Scholars, Advisers, Institutions, Funding Organizations, and Disciplinary Societies*. Washington, DC: National Academy Press.

Cooke, George Willis. *Unitarianism in America: A History of its Origin and Development*. 1902. Reprint. St. Claire Shores, MI: Scholarly Press, 1969[?].

Cornell University, Department of Physics, "James W. York, Jr., Professor of Physics" [profpages]. Available online: <http://www.physics.cornell.edu/profpages/York.htm> (25 May 2006).

Crosland, Maurice. "Research Schools of Chemistry from Lavoisier to Wurtz." *The British Journal for the History of Science* 36, no. 3 (2003): 333-361.

Cushing, James T. *Philosophical Concepts in Physics: The Historical Relation between Philosophy and Scientific Theories*. Cambridge, UK: Cambridge University Press, 1998.

Dalitz R. H. (Richard Henry) and Rudolf Peierls. "Paul Adrien Maurice Dirac: 8 August 1902—20 October 1984." *Biographical Memoirs of Fellows of the Royal Society* 32 (1986): 139-185.

Delbrück, Max. "Biography" Available online: <http://nobelprize.org/medicine/laureates/1969/delbruck-bio.html> (24 Mar 06). Also in *Nobel Lectures, Physiology or Medicine 1963-1970*. Amsterdam: Elsevier Publishing Company, 1972.

Department of Commerce (U.S.), Bureau of the Census. *Historical Statistics of the United States: Colonial Times to 1957*. Herman P. Miller, Project Director. Washington, DC: U.S. Government Printing Office, 1960.

Deutsch, David. "On Wheeler's Notion of "Law Without Law" in Physics." In *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler* edited by Wojciech Hubert Zurek, Alwyn van der Merwe, and Warner Allen Miller. Princeton, NJ: Princeton University Press. 1988, 583-591.

"Dr. Gilbert Plass" [Obituary]. *The Bryan – College Station Eagle*. Available online: <http://www.theeagle.com/region/records/obituaries/march2004/030304obits.php> (12 Sep 2005).

Drake, Stillman, "Galileo's Experimental Confirmation of Horizontal Inertia: Unpublished Manuscripts." *Isis* 64 (1973): 291-305.

Drake, Stillman and James MacLachlan. "Galileo's Discovery of the Parabolic Trajectory." *Scientific American* 232, no. 3 (Mar 1975): 102-108.

Drake, Stillman. *Galileo: Pioneer Scientist*. Buffalo, NY: University of Toronto Press, 1990.

Dupree, A. Hunter. *Science in the Federal Government A History of Policies and Activities to 1940*. Cambridge, MA: Belknap Press of Harvard University Press, 1957. Reprint, Baltimore, MD: The Johns Hopkins University Press, 1986.

Edge, David O. and Michael Mulkay. *Astronomy Transformed: The Emergence of Radio Astronomy in Britain*. New York: Wiley, 1976.

Einstein, Albert, Max Born, and Hedwig Born. *The Born-Einstein Letters: Correspondence between Albert Einstein and Max and Hedwig Born from 1916 to 1955. With Commentaries by Max Born*. Translated by Irene Born.. New York: Walker and Company, 1971.

Einstein, Albert. *Letters to Solovine*. Trans. by Wade Baskin. New York: Philosophical Library, 1987.

Family Gathering: Students and collaborators of John Archibald Wheeler gather some recollections of their work with him, and of his influence on them and through them on their own students, Assembled with the best wishes as John moves on to a new career in Texas. Princeton, NJ: n.p., 1977.

Feibelmen, Peter J. *A Ph.D. is not Enough: A Guide to Survival in Science*. Reading, MA: Addison-Wesley, 1993.

Feynman, Richard P. "Pocono Conference." *Physics Today* 1, no. 2 (Jun 1948): 8-10.

Feynman, Richard P. "Biography" Available online: <http://nobelprize.org/physics/laureates/1965/feynman-bio.html> (24 Mar 06). Also in *Nobel Lectures, Physics 1963-1970*. Amsterdam: Elsevier Publishing Company, 1972.

Feynman, Richard P. "The Development of the Space-Time View of Quantum Electrodynamics," Nobel Lecture, 11 December 1965 Available online: <http://nobelprize.org/physics/laureates/1965/feynman-lecture.html> (24 Mar 06). Also in *Nobel Lectures, Physics 1963-1970*. Amsterdam: Elsevier Publishing Company, 1972.

Feynman, Richard P. *QED: The Strange Theory of Light and Matter*. Princeton, NJ: Princeton University Press, 1985.

Feynman, Richard P. and Ralph Leighton. *Surely You're Joking Mr. Feynman: Adventures of a Curious Character*. New York: W. W. Norton & Co, 1985.

Feynman, Richard P. with Ralph Leighton *What Do You Care What Other People Think: Further Adventures of a Curious Character*. New York: Bantam Books, 1988.

Fogg, Piper. "The Catalytic Mentor: An Award Winning Chemist at Rutgers University Takes Students under Her Wing" [The Faculty]. *The Chronicle of Higher Education* 49, no. 47 (Aug 2003): A-10 [Online]. Available: <http://oasis.oregonstate.edu/search/tThe+Chronicle+of+Higher+Education/tchronicle+of+higher+education/1%2C2%2C5%2CE/c856105611 6&FF=tchronicle+of+higher+education&2%2C%2C4%2C1%2C0> (22 Jan 06).

Ford, Kenneth W. "Working (and not Working) on Weapons." Working paper. Sigma Pi Sigma Congress, Albuquerque, NM, 15 Oct 2004.

Ford, Kenneth W. "Kenneth W. Ford -- Personal Web Page." Available online: <http://www.ianford.com/kenford/> (21 Aug 2005).

Forman, Paul, John L. Heilbron, and Spencer Weart. "Physics circa 1900." *Historical Studies of the Physical Sciences* 5 (1975): 3-185.

Fort, Deborah C., ed. *A Hand Up: Women Mentoring Women in Science*. Washington DC: Association for Women in Science, 1995.

Frank, Philipp. *Einstein: His Life and Times.* Translated by George Rosen, Edited by Shuichi Kusaka. New York: Alfred A. Knopf, 1947.

French, John Calvin. *A History of the University Founded by Johns Hopkins.* Baltimore, MD: The Johns Hopkins University Press, 1946.

Frisch, Otto and John A. Wheeler. "The Discovery of Fission." *Physics Today* 20, no. 11 (Nov 1967): 43-52.

Frost, Peter J. and M. Susan Taylor, eds. *The Rhythms of Academic Life: Personal Accounts of Careers in Academia.* Thousand Oaks, CA: Sage Publications, 1996.

Frugoli, Julia A. "Commentary on 'Mentors, Advisors and Supervisors: Their Role in Teaching Responsible Research Conduct': It Really Does Take a Village." *Mentoring and the Responsible Conduct of Research.* Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 469-470.

Fruton, Joseph. "The Liebig Research Group: A Reappraisal." *Proceedings of the American Philosophical Society* 132 (1988): 1-66.

Fruton, Joseph. *Contrasts in Scientific Style: Research Groups in the Chemical and Biochemical Sciences.* Philadelphia: American Philosophical Society, 1990.

Galilei, Galileo. *On Motion and On Mechanics: Comprising De Motu* (ca.1590) *and Le Meccanishe* (ca.1600). Publications in Medieval Science. Translated by I. E. Drabkin and Stillman Drake. Madison, WI: University of Wisconsin Press, 1960.

Galilei, Galileo. *Il Saggiatore (The Assayer).* Translated by George MacDonald Ross, 1998. Available online: http://www.philosophy.leeds.ac.uk/GMR/hmp/texts/modern/galileo/assayer.html (20 May 2005).

Galilei, Galileo. *Dialogue Concerning the Two Chief World Systems* (1632). Translated by Stillman Drake. Available online: <http://www.law.umkc.edu/faculty/projects/ftrials/galileo/dialogue.html> (22 Apr 2006).

Galilei, Galileo. *Dialogues Concerning Two New Sciences* (1638). Translated by Henry Crew and Alfonso de Salvio with an introduction by Antonio Favaro. New York: The MacMillian Co. 1914.

Galison, Peter. *How Experiments End.* Chicago: University of Chicago Press, 1987.

Galison, Peter. "Physics Between War and Peace." In *Science, Technology, and the Military.* Vol. 12, part 1, of Sociology of the Sciences, edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Boston: Kluwer Academic Publishers, 1988.

Galison, Peter, and Barton Bernstein. "In Any Light: Scientists and the Decision to Build the Super bomb, 1952-1954." *Historical Studies in the Physical and Biological Sciences* 19 (1989): 267-347.

Galison, Peter. *Image and Logic: A Material Culture of Microphysics.* Chicago: University of Chicago Press, 1997.

Galison, Peter. "Material Culture, Theoretical Culture, and Delocalization." In *Science in the Twentieth Century.* Edited by John Krige and Dominque Pestre. Amsterdam: Harwood Academic Publishers, 1997.

Gardenier, John. "Commentary on 'Mentoring and the Impact of the Research Climate' (Roberts, Kavussano and Sprague)" *Mentoring and the Responsible Conduct of Research.* Edited by Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 538-540.

Gearhart, Mirjana R. Forum: John A. Wheeler, "From Big Bang to Big Crunch". *Cosmic Search Magazine* 1, no. 4 (1979) Available Online: <http://www.bigear.org/vol1no4/wheeler.htm> (22 Oct 2003).

Gell-Mann, Murray. "Dick Feynman—The Guy in the Office Down the Hall." *Physics Today* 42, no.2 (Feb 1989): 50-54.

Geison, Gerald L., "Scientific Change: Emerging Specialties and Research Schools." *History of Science* 19, Part 1, no. 43 (Mar 1981): 20-40.

Geison, Gerald L. "Research Schools and New Directions in the Historiography of Science." In *Research Schools: Historical Reappraisals.* Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993), 227-238.

Geroch, Robert P. "Robert P. Geroch, Curriculum Vitae" Available online: <http://physics.uchicago.edu/t_rel.html#Geroch> (21 Aug 2005).

Gilman, Daniel Coit. *The Launching of a University, and Other Papers: A Sheaf of Remembrances.* New York: Dodd, Mead, & Co., 1906.

Gleick, James. *Genius: The Life and Science of Richard Feynman.* New York: Vintage Books, 1992.

Gleick, James. *Isaac Newton.* New York: Pantheon Books, 2003.

Goldberg, Stanley. "Inventing a Climate of Opinion: Vannevar Bush and the Decision to Build the Bomb." In *The Scientific Enterprise in America: Readings from Isis.* Edited by Ronald L. Numbers and Charles E. Rosenberg. Chicago: University of Chicago Press, 1996.

Goodstein, David L. "Scientific Ph.D. problems". *American Scholar* 62 [Online] no.2 (Spr 1993): 215-221. Available online: http://0-search.epnet.com.oasis.oregonstate.edu:80/login.aspx?direct=true&db=aph&an=9304060251 (05 Jan 2006).

Google Scholar. "find a Wheeler, J. A." Available online: <http://scholar.google.com/scholar?num=100&hl=en&lr=&safe=off&q=author%3A%22J+A+Wheeler%22&btnG=Search> (20 Feb 06).

Grant, Peter. *Ecology and the Evolution of Darwin's Finches.* Princeton, NJ: Princeton University Press, 1986.

Green, John C. "A Liberal Dynamo: The Political Activism of the Unitarian Universalist Clergy." *Journal for the Scientific Study of Religion* 42 [Online], no 4 (Dec 2003): 577-590. Available online: Academic Search Premier <http://0-web17.epnet.com.oasis.oregonstate.edu/Delivery> (07 May 2005).

Greenberger, Daniel M. Preface to "Fundamental Problems in Quantum Theory: A Conference held in Honor of Professor John Archibald Wheeler." *Annals of the New York Academy of Sciences* 755. Edited by Daniel M. Greenberger and Anton Zeilinger. New York: New York Academy of Sciences, 1995, xiii-xiv.

Grele, Ronald J. "Movement Without Aim: Methodological and Theoretical Problems in Oral History." In *The Oral History Reader*, edited by Robert Perks and Alistair Thomson. London: Routledge, 1998. Originally published in Ronald J. Grele, *Envelopes of Sound: The Art of Oral History* (Chicago: Precedent Publishing, 1985.

Griffin, James J. "James J. Griffin Curriculum Vitae." Available online: <http://www.physics.umd.edu/people/faculty/cv/GriffinCV.pdf> (21 Aug 2005).

Gusterson, Hugh. "A Pedagogy of Diminishing Returns: Scientific Involution across Three Generations of Nuclear Weapons Science." In *Pedagogy and the Practice of Science*. Edited by David Kaiser. Inside Technology, ed. Wiebe E. Bijker, W. Bernard Carlson, and Trevor Pinch. Cambridge, MA: MIT Press, 2005: 75-108.

Hagen, Joel. "Clementsian Ecologists: The Internal Dynamics of a Research School." In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 178-195.

Hahn, Alexander J. "The Pendulum Swings Again: A Mathematical Reassessment of Galileo's Experiments with Inclined Planes." *Archive of the History of Exact Sciences* 56 (2002): 339-361.

Hannaway, Owen. "The German Model of Chemical Education in America: Ira Remsen at Johns Hopkins (1876-1913)." *Ambix: The Journal of the Society for the History of Alchemy and Chemistry* 23 (1976): 145-164.

Harmon, Lindsey R. and Herbert Soldz, comps. *Doctorate Production in United States Universities, 1920-1962: With Baccalaureate Origins of Doctorates in Sciences Arts and Professions*. Washington, DC: National Academy of Sciences – National Research Council, 1963.

Hartle, James B. "James B. Hartle's Homepage." Available online: <http://www.physics.ucsb.edu/~hartle/> (06 May 2006).

Hawkins, Hugh. *Pioneer: A History of The Johns Hopkins University, 1874-1889*. Baltimore, MD: The Johns Hopkins University Press, 2002.

Heilbron, John L. Dilemmas of an Upright Man: Max Planck as Spokesman for German Science. Berkeley, CA: University of California Press, 1986.

Heisenberg, Werner "Biography" Available online: <http://nobelprize.org/physics/laureates/1932/heisenberg-bio.html> (24 Mar 2006). Also in *Nobel Lectures, Physics 1922-1941*. Amsterdam: Elsevier Publishing Co., 1965.

Henson, Pamela M. "The Comstock Research School in Evolutionary Entomology." In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 157-177.

Hershberg, James G. " 'Over My Dead Body:' James Bryant Conant and the Hydrogen Bomb." In *Science, Technology, and the Military*. Vol. 12, part 2, of Sociology of the Sciences, edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Boston: Kluwer Academic Publishers, 1988.

Hevesy, George de. "Biography" Available online: <http://nobelprize.org/chemistry/laureates/1943/hevesy-bio.html> (24 Mar 2006). Also in *Nobel Lectures, Chemistry 1942-1962*. Amsterdam: Elsevier Publishing Co., 1964.

Hill, David K. "Dissecting Trajectories: Galileo's Early Experiments on Projectile Motion and the Law of Fall." *Isis* 79, no. 299 (Dec 1988): 646-668.

Hoch, Paul. "The Crystallization of a Strategic Alliance: The American Physics Elite and the Military in the 1940's." In *Science, Technology, and the Military*. Vol. 12, part 1, of Sociology of the Sciences, edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Boston: Kluwer Academic Publishers, 1988.

Holmes, F. L. "Justus von Liebig" In *Dictionary of Scientific Biography,* edited by Charles Coulston Gillispie. New York: Scribner and Sons, 1973.

Holmes, Frederic L. "Historians and Contemporary Scientific Biography." In *The Pauling Symposium: A Discourse on the Art of Biography*. Edited by Ramesh S. Krishnamurthy, Clifford S. Mead, Mary Jo Nye, Sean C. Goodlett, Marvin E. Kirk, Shirley A. Golden, and Lori L. Zielinski. Corvallis, OR: Special Collections, Oregon State University Libraries, 1996.

Holmes, Frederic Lawrence. *Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists*. New Haven, CN: Yale University Press, 2004.

Holton, Gerald. "Niels Bohr and the Integrity of Science." *American Scientist* 74, no. 3 (May-Jun 1986): 237-243.

Hu, Bei-Lok Bernard. "Bei-Lok Bernard Hu, Curriculum Vitae" Available online: <http://www.physics.umd.edu/people/faculty/cv/HuCV.pdf> (22 Aug 2005).

Hull, McAllister, "Gregory Breit: July 14, 1899-September 11. 1981" *National Academy of Sciences: Bibliographic Memoirs* [Online]. (n.d.). <http://www.nap.edu/html/biomems/gbreit.html> (08 Dec 2003).

Isenberg, Jim. "Jim Isenberg," Curriculum Vitae Available online: <http://physics.uoregon.edu/~jim/CV.pdf> (25 Aug 2005).

The Johns Hopkins University. “Johns Hopkins University Chronology” Available online: http://webapps.jhu.edu/jhuniverse/information_about_hopkins/about_jhu/chronology/index.cfm?window=print (06 Jan 2005).

Jungnickel, Christa and Russell McCormmach. *Intellectual Mastery of Nature: Theoretical Physics From Ohm to Einstein*. 2 vols. Chicago: University of Chicago Press, 1986.

Kaiser, David. "Cold War Requisitions: Scientific Manpower and the Production of American Physicists after World War II." *Historical Studies in the Physical and Biological Sciences* 33, no. 1 (2002): 131-160.

Kaiser, David. Nuclear Democracy: Political Engagement, Pedagogical Reform, and Particle Physics in Postwar America," *Isis*, 93 (2002), 229-268.

Kaiser, David. *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics*. Chicago: University of Chicago Press, 2005.

Kaiser, David I. "Whose Mass is it Anyway? Particle Cosmology and the Objects of Theory." *Social Studies of Science* [forthcoming].

Kaiser, David, ed. *Pedagogy and the Practice of Science*. Inside Technology, ed. Wiebe E. Bijker, W. Bernard Carlson, and Trevor Pinch. Cambridge, MA: MIT Press, 2005.

Kanigel, Robert. *Apprentice to Genius: The Making of a Scientific Dynasty*. Baltimore, MD: The Johns Hopkins University Press, 1986.

Kelly, Shalonda, and John C. Schweitzer. "Mentoring Within a Graduate School Setting." *College Student Journal* 99, no. 1 (Mar 1999): 130-148 [Online], Available online: EBSCOhost/Academic Search Elite/AN1713855, (15 Jan 2001).

Kennedy, Donald. *Academic Duty*. Cambridge, MA: Harvard University Press, 1997.

Kevles, Daniel J. *The Physicists: The History of a Scientific Community in Modern America*. New York: Knopf, 1977.

Kevles, Daniel J. "An Analytical Look at R&D and the Arms Race." In *Science, Technology, and the Military*. Vol. 12, part 2, of Sociology of the Sciences, edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Boston: Kluwer Academic Publishers, 1988

Kevles, Daniel J. "The National Science Foundation and the Debate over Postwar Research Policy." In *The Scientific Enterprise in America: Readings from Isis,* edited by Ronald L. Numbers and Charles E. Rosenberg. Chicago: University of Chicago Press, 1996.

Klauder, John R. "Magic Without Magic: John Archibald Wheeler: An Introduction." In *Magic Without Magic: John Archibald Wheeler; A Collection of Essays in Honor of His Sixtieth Birthday.* edited by John R. Klauder. San Francisco: W. H. Freeman, 1972, 1-14.

Kragh, Helge. *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*. Princeton, NJ: Princeton University Press, 1996.

Kragh, Helge. *Quantum Generations: A History of Physics in the Twentieth Century*. Princeton, NJ: Princeton University Press, 1999.

Koyré, Alexandré. *Galileo Studies*. 1939. Reprint, Atlantic Highlands, NJ: Humanities Press, 1978.

Kushner, David. "Sir George Darwin and a British School of Geophysics." In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 196-224.

Landau, Lev "Biography" Available online: <http://nobelprize.org/physics/laureates/1962/landau-bio.html> (24 Mar 2006). Also in *Nobel Lectures, Physics 1942-1962*. Amsterdam: Elsevier Publishing Co., 1964.

Lattimore, Richmond, trans. *The Odyssey of Homer*. New York: Harper and Row, 1967; Perennial Classics Edition, New York: HarperPerennial, 1999.

Leslie, Stuart W. "Science and Politics in Cold War America." In *The Politics of Western Science, 1640-1990*. Edited by Margaret C. Jacob. Atlantic Highlands, NJ: Humanities Press, 1994.

Lindsay, R. B. "Wood, Robert Williams." *Dictionary of Scientific Biography* Vol. XIV. Edited by Charles Coulson Gillispie. New York: Charles Scribner's Sons, 1976.

Marckworth, M. Louise, ed. *Dissertations in Physics: An Indexed Bibliography of All Doctoral Theses Accepted by American Universities, 1861-1959*. Stanford: Stanford University Press, 1961.

Marsh, Herbert W. and John Hattie. "The Relation Between Research Productivity and Teaching Effectiveness: Complementary, Antagonistic, or Independent Constructs?" *The Journal of Higher Education* 73, no.5 (2002): 603-641.

Marshall, George N. *Challenge of a Liberal Faith.* 3rd ed. Boston: Skinner House – Unitarian Universalist Association, 1991.

Martin, Murray, Norwood Gove, Ruth Gove, Subramanian Raman, and Eugen Merzbacher. "Katharine Way" [Obituary]. *Physics Today* 49, no. 12 (Dec 1996): 75. Available online: Academic Search Premier <http://0-search.epnet.com.oasis.oregonstate.edu:80/login.aspx?direct=true&db=aph&an=9612171661> (13 Sep 2005).

McMillan, Edwin M. "Early History of Particle Accelerators." Working Paper. In *Nuclear Physics in Retrospect: Proceedings of a Symposium on the 1930's.* Edited by Roger H. Stuewer. Minneapolis, MN: University of Minnesota Press, 1979.

Melosh, H. Jay. "H. Jay Melosh, Curriculum Vitae" Available online: http://www.lpl.arizona.edu/~jmelosh/Bibliography_vita.doc (20 Aug 05).

Mendelsohn, Everett, Merritt Roe Smith, and Peter Weingart. "Introduction: Science and the Military: Setting the Problem. In *Science, Technology, and the Military.* Vol. 12, part 1, of Sociology of the Sciences, edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Boston: Kluwer Academic Publishers, 1988.

Miller, Arthur I. "Image and Representation in Twentieth Century Physics." In *The Modern Physical and Mathematical Sciences,* edited by Mary Jo Nye, Vol. 5 of *The Cambridge History of Science,* General eds. David C. Lindberg and Ronald L. Numbers. New York: Cambridge University Press, 2003.

Misner, Charles W., Kip S. Thorne, John Archibald Wheeler. *Gravitation.* San Francisco: W. H. Freeman and Co., 1973.

Morrell, J. B. "The Chemist Breeders: The Research Schools of Liebig and Thomas Thomson." *Ambix: The Journal of the Society for the History of Alchemy and Chemistry* 19 (Mar 1972): 1-46.

Morrell, Jack. "W. H. Perkin, Jr., at Manchester and Oxford: From Irwell to Isis." In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 104-126.

Mottelson, Ben R. "Autobiography" Available online: <http://nobelprize.org/physics/laureates/1975/mottelson-autobio.html> (24 Mar 2006). Also in *Les Prix Nobel en 1975*. Edited by Wilhelm Odelberg. Stockholm: Nobel Foundation, 1976.

Mulligan, Joseph F. "Karl Herzfeld." Biographical Memoirs, National Academy of Sciences Available online: <http://newton.nap.edu/html/biomems/kherzfeld.html> (20 Mar 06).

National Academy of Sciences, National Academy of Engineering, Institute of Medicine (U.S.). *Adviser, Teacher, Role Model, Friend: on Being a Mentor to Students in Science and Engineering*. Washington DC: National Academy Press, 1977 [Online] Available online: <http://oasis.oregonstate.edu/search/cQ181+.A35+1999/cq+++181+a35+1999/-2,-1,0,E/I856~2152434&FF=&1,0,,1,0> (27 Feb 06).

National Research Council. *A Century of Doctorates: Data Analyses of Growth and Change*. Washington DC: National Academy of Sciences, 1978.

"Niels Bohr" [Obituary]. *Physics Today* 16, no. 1 (Jan 1963): 102.

Niels Bohr Institute for Theoretical Physics. "NBI History." Available online:<http://www.nbi.dk/nbi-history.html#history> (23 Apr 2006).

North Dakota State University, Department of Mathematics. "Arthur Strong Wightman." The Mathematics Genealogy Project Available online: <http://www.genealogy.ams.org/html/id.phtml?id=11904&fChrono=1> (21 Aug 2005).

North Dakota State University, Department of Mathematics. "Francis Dominic Murnaghan." Mathematics Genealogy Project Available online: <http://www.genealogy.math.ndsu.nodak.edu/html/id.phtml?id=11540> (21 Mar 2006).

Nye, Mary Jo. *Science in the Provinces: Scientific Communities and Provintial Leadership in France, 1860-1930*. Berkeley: University of California Press, 1986.

Nye, Mary Jo. “National Styles? French and English Chemistry in the Nineteenth and Early Twentieth Centuries.” In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 30-49.

Nye, Mary Jo. "Scientific Disciplines: The Construction of Identity." Chap. 1 in *From Chemical Philosophy to Theoretical Chemistry: Dynamics of Matter and Dynamics of Disciplines, 1800-1850*. Berkeley, CA: University of California Press, 1993.

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800-1940*. New York: Twayne Publishers, 1996. Reprint. Cambridge, MA: Harvard University Press, 1999.

O’Connor, J. J. and E. F. Robertson. “Francis Dominic Murnaghan.” MacTutor History of Mathematics, October 2003 Available online: <http://www-history.mcs.st-andrews.ac.uk/Biographies/Murnaghan.html> (21 Mar 2006).

Olesko, Kathryn M. *Physics as a Calling: Discipline and Practice in the Konigsberg Seminar for Physics*. Ithaca: Cornell University Press, 1991.

Olesko, Kathryn M. “Tacit Knowledge and School Formation.” In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 16-29.

Olesko, Kathryn M. "The Foundations of a Canon: Kohlrausch’s Practical Physics." In *Pedagogy and the Practice of Science*. Edited by David Kaiser. Inside Technology, ed. Wiebe E. Bijker, W. Bernard Carlson, and Trevor Pinch. Cambridge, MA: MIT Press, 2005.

Oleson, Alexandra, and John Voss, eds. *The Organization of Knowledge in Modern America, 1860-1920*. Baltimore, MD: The Johns Hopkins University Press, 1979.

Pais, Abraham. *Subtle is the Lord: The Science and Life of Albert Einstein*. New York: Oxford University Press, 1982.

Pais, Abraham. *Niels Bohr's Times in Physics, Philosophy, and Polity*. New York: Oxford University Press, 1991.

Partridge, R. Bruce. "R. Bruce Partridge, Curriculum Vitae” Available online: <http://www.haverford.edu/physics-astro/Partridge/cv.html> (24 Aug 2005).

Pauli, Wolfgang. "Biography" Available online: <http://nobelprize.org/physics/laureates/1945/pauli-bio.html> (24 Mar 2006). Also in *Nobel Lectures, Physics 1942-1962.* Amsterdam: Elsevier Publishing Co. 1964.

Pauling, Linus "Biography" Available online: <http://nobelprize.org/chemistry/laureates/1954/pauling-bio.html> (24 Mar 2006). Also in *Nobel Lectures, Chemistry 1942-1962.* Amsterdam: Elsevier Publishing Co., 1964.

Pauling, Linus. Papers. Diary, Speech Transcripts, and Letters. Special Collections (Ava Helen and Linus Pauling Papers), Oregon State University Library.

Poggendorff, J. C. *Biographisch-Literarisches Handwörtenbuch der Exakten Naterurwissenschaften.* Edited by Prof. Dr. Rudolph Zaunick and Prof. Dr. Hans Salié. Berlin: Akademie-Verlag, 1956.

Poggendorff, J. C. *Biographisch-Literarisches Handwörtenbuch der Exakten Naterurwissenschaften.* Edited by Prof. Dr. Hans Salié. Berlin: Akademie-Verlag, 1967.

Polanyi, Michael. *Science, Faith, and Society.* Chicago: University of Chicago Press, 1964. (Appeared originally in 1945).

Polanyi, Michael. *The Tacit Dimension.* New York: Doubleday, 1966.

Princeton University, Office of Communications. "Battelle to Establish Professorship in Physics." 18 May 2001. Available online: <http://www.princeton.edu/pr/news/01/q2/0518-battelle.htm> (24 Oct 2003).

Princeton University. “Princeton University Senior Theses Catalog Brief Display” Available online: <http://libweb5.princeton.edu/theses/thesesvw.asp?Lname=&Fname=&Submit=Search&Title1=&Title2=&Title3=&department=PHY&Class=&Adviser=> (22 Aug 2005).

Ravetz, Jerome R. *Scientific Knowledge and its Social Problems.* Oxford: Clarendon Press, 1971.

Reinarz, Alice G. and Eric Robert White, eds. *Beyond Teaching to Mentoring.* San Francisco: Jossey-Bass, 2001.

Reingold, Nathan. “Reflections on 200 years of Science in the United States.” In *The Sciences in the American Context: New Perspectives,* edited by Nathan Reingold. Washington, DC: Smithsonian Institution Press, 1979.

Rhodes, Richard. *The Making of the Atomic Bomb.* New York: Simon & Shuster, 1987. Reprint. New York: Simon & Schuster, 1995.

Rhodes, Richard. *Dark Sun: The Making of the Hydrogen Bomb.* Sloan Technology Series. New York: Simon & Shuster, 1995. Reprint. New York, Simon & Shuster, 1996.

Roberts, Glyn C., Maria Kavussanu and Robert L. Sprague. “Mentoring and the Impact of the Research Climate.” *Mentoring and the Responsible Conduct of Research.* Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 525-537.

Robinson, I., A. Schild, and E. Schucking. “Relativistic Theories of Gravitation.” *Physics Today* 16, no. 8 (Aug 1963): 17-21.

Rocke, Alan J. “Group Research in German Chemistry: Kolbe's Marburg and Leipzig Institutes.” In *Research Schools: Historical Reappraisals.* Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 51-79.

Rohrlich, Daniel. “Daniel Rohrlich,” Publications Available online: <http://www.tau.ac.il/~quantum/who-r-we/dr-pub.txt> (22 Aug 2005).

Rosenberg, Charles E. “Science in American Society: A Generation of Historical Debate.” In *The Scientific Enterprise in America: Readings from Isis.* Edited by Ronald L. Numbers and Charles E. Rosenberg. Chicago: University of Chicago Press, 1996, 3-20.

Rosenfeld, Leon. “Bohr, Niels Henrik David.” In *Dictionary of Scientific Biography* Vol. II. Edited by Charles Coulston Gillispie. New York: Charles Scribner's Sons, 1975.

Rothblatt, Sheldon, and Bjorn Wittrock, eds. *The European and American University since 1800: Historical and Sociological Essays.* New York: Cambridge University Press, 1993.

Rowe, David E. "Mathematical Schools, Communities and Networks." In *The Modern Physical and Mathematical Sciences,* edited by Mary Jo Nye, Vol. 5 of *The Cambridge History of Science,* General eds. David C. Lindberg and Ronald L. Numbers. New York: Cambridge University Press, 2003.

Rowland, Henry Augustus. “A Plea for Pure Science” [Address as Vice-President of Section B of the American Association for the Advancement of Science, Minneapolis, MN (15 Aug 1883)]. In *The Physical Papers of Henry Augustus Rowland*. Compiled by A Committee of the Faculty of Johns Hopkins University. Baltimore, MD: The Johns Hopkins University Press, 1902. Previously published in *Proceedings of the American Association for the Advancement of Science,* XXXII (1883): 105-126; *Science,* II (1883): 242-250; *Journal of Franklin Institute,* GXVI (1883): 279-299.

Ryan, Will Carson. *Studies in Early Graduate Education, The Johns Hopkins, Clark University, The University of Chicago*. New York: The Carnegie Foundation for the Advancement of Teaching, 1939 [Note: Also listed as Bulletin no. 30].

Salk Institute. "Terrence J. Sejnowski." Available online: <http://www.salk.edu/faculty/faculty/details.php?id=48> (21 Aug 2005).

Sapolsky, Harvey M. “Academic Science and the Military: The Years Since the Second World War.” In *The Sciences in the American Context: New Perspectives*, edited by Nathan Reingold. Washington, DC: Smithsonian Institution Press, 1979.

Schweber, Silvan S. “The Mutual Embrace of Science and the Military: The ONR and the Growth of Physics in the United States after World War II.” In *Science, Technology, and the Military*. Vol. 12, part 1, of Sociology of the Sciences, edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Boston: Kluwer Academic Publishers, 1988.

Schweber, Silvan S. “Theoretical Physics and the Restructuring of the Physical Sciences: 1925-1975.” In *Big Culture: Intellectual Cooperation in Large Scale Cultural and Technical Systems. An Historical Approach*. Proceedings of the International Meeting held in Bellagio “Villa Serbelloni” (September 7-11, 1992). Edited by Guiliana Gemelli. Bologna: Cooperativa Libraria Universitaria Editrice Bologna, 1994.

Schweber, S. S. [Silvan S.]. “Writing the Biography of a Living Scientist: Hans Bethe.” In *The Pauling Symposium: A Discourse on the Art of Biography*. Edited by Ramesh S. Krishnamurthy, Clifford S. Mead, Mary Jo Nye, Sean C. Goodlett, Marvin E. Kirk, Shirley A. Golden, and Lori L. Zielinski. Corvallis, OR: Special Collections, Oregon State University Libraries, 1996.

Schweber, Silvan S. *In the Shadow of the Bomb: Bethe, Oppenheimer, and the Moral Responsibility of the Scientist*. Princeton, NJ: Princeton University Press, 2000.

Schweber, Silvan S. "Quantum Field Theory Form QED to the Standard Model." In *The Modern Physical and Mathematical Sciences,* edited by Mary Jo Nye, Vol. 5 of *The Cambridge History of Science,* General eds. David C. Lindberg and Ronald L. Numbers. New York: Cambridge University Press, 2003.

Sears, Francis W., Mark W. Zemansky, and Hugh D. Young. *University Physics*. 6th ed. Reading, MA: Addison Wesley, 1992.

Segré, Emilio. *From X-Rays to Quarks: Modern Physicists and Their Discoveries*. San Francisco: W. H. Freeman, 1980.

Servos, John W. "Research Schools and Their Histories." In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 1-15.

Servos, John W. "Mathematics and the Physical Sciences in America." In *The Scientific Enterprise in America: Readings From Isis*. Edited by Ronald L. Numbers and Charles E. Rosenberg. Chicago: University of Chicago Press, 1996, 141-159.

Shea, Gordon F. *Mentoring: How to Develop Successful Mentoring Behaviors* [Rev. Edn.]. Menlo, Park, CA: Crisp Publications, 1992.

Simpson, James B., comp. *Simpson's Contemporary Quotations*. Boston: Houghton Mifflin, 1988. <http://www.bartleby.com/63/96/2596.html> (08 Dec 2003).

Singer, S. Fred. "S. Fred Singer, Ph.D., Professional Background" Available online: <http://www.sepp.org/bios/singer/cvsfs.html> (23 Aug 2005).

Slater, John C. "Quantum Physics in America Between the Wars." *Physics Today* 21 (Jan 1968): 43.

Smarr, Larry and Joseph Smarr. "Larry Smarr's Personal Home Page" Available online: <http://www.jacobsschool.ucsd.edu/~lsmarr/> (21 Aug 2005).

Smith, David H. "Notes on a Pilgrimage to Science: A Fly on the Wall." *Mentoring and the Responsible Conduct of Research*. Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 615-634.

Sopka, Katherine Russell. *Quantum Physics in America, 1920-1935*. New York: Arno Press, 1980.

"Spectroscopist of the Century ... William F. Meggers." *Arcs & Sparks* (21 Nov 2002) Available online: <http://www.cstl.nist.gov/acd/839.01/meggers.html> (20 Mar 2006).

Stanford University, Stanford Linear Accelerator Center. SPIRES High-Energy Physics Literature Database Available online: <http://www-spires.slac.stanford.edu/spires/hep/> (21 Aug 2005).

Swazey, Judith P. "Graduate Students and Mentors: The Need for Divine Intervention: Commentary on 'Mentoring: Some Ethical Considerations' (Weil)." *Mentoring and the Responsible Conduct of Research.* Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 483-485.

Taylor, Edwin F. "The Anatomy of Collaboration." In *Magic Without Magic: John Archibald Wheeler: A Collection of Essays in Honor of His Sixtieth Birthday.* edited by John R. Klauder. San Francisco: W. H. Freeman, 1972: 474-485.

Templin, Mark A. "A Locally Based Science Mentorship Program for High Achieving Students: Unearthing Issues that Influence Effective Outcomes." *School Science and Mathematics* 99, no. 4 (Apr 1999): 205-212 [Online], Available online: EBSCOhost/Academic Search Elite/AN1877598 (15 Jan 2001).

The Enrico Fermi Award - A Presidential Award. Updated November 2001. <http://www.pnl.gov/fermi/citations/wheeler-cit.html>. (25 Oct 2003).

The Royal Society Library and Archives - List of Fellows. (n.d.) <http://www.royalsoc.ac.uk/library/fellows/w.htm>. (25 Oct 2003).

Thomson, William. "Scientific Laboratories." *Nature* 31 (Nov 1884 – Apr 1885): 409-413.

Thorne, Kip S. "Nonspherical Gravitational Collapse: A Short Review." In *Magic Without Magic: John Archibald Wheeler: A Collection of Essays in Honor of His Sixtieth Birthday.* edited by John R. Klauder. San Francisco: W. H. Freeman, 1972: 231-258.

Thorne, Kip S. and Wojciech H. Zurek "John Archibald Wheeler: A Few Highlights of His Contributions to Physics." In *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler* edited by Wojciech Hubert Zurek, Alwyn van der Merwe, and Warner Allen Miller. Princeton, NJ: Princeton University Press. 1988, 3-13.

Thorne, Kip S. *Black Holes and Time Warps: Einstein's Outrageous Legacy*. New York: W. W. Norton & Co., 1994.

Toll, John Sampson. "John Sampson Toll, Curriculum Vitae." Available online: <http://www.physics.umd.edu/people/faculty/cv/TollCV.pdf> (21 Aug 2005).

Turner, R. Steven. "Vision Studies in Germany: Helmholtz versus Hering." In *Research Schools: Historical Reappraisals*. Edited by Gerald L. Geison and Frederic L. Holmes. *Osiris*, 2d ser., vol. 8 (1993): 80-103.

Uchii, Soshichi. "John Archibald Wheeler". *Gallery of Philosophy and History of Science*. Kyoto University. Available online: <http://www.bun.kyoto-u.ac.jp/phisci/Gallery/wheeler_note.html>. (23 Oct 2003).

Unitarian-Universalist Congregation of Princeton. "The History of UUCP." Available online: <http://www.uuprinceton.org/historyuucp.htm> (25 May 2005).

University of Maryland. "John Sampson Toll, Curriculum Vitae." Available online: <http://www.physics.umd.edu/people/faculty/cv/TollCV.pdf> (21 Aug 2005).

Urey, Harold C. "Biography." Available online: <http://nobelprize.org/chemistry/laureates/1934/urey-bio.html> (24 Mar 2006). Also in *Nobel Lectures, Chemistry 1922-1941*. Amsterdam: Elsevier Publishing Co., 1966.

Van De Mark, Brian. *Pandora's Keepers: Nine Men and the Atomic Bomb*. Boston: Little, Brown, and Co., 2003.

Veysey, Laurence R. *The Emergence of the American University*. Chicago: University of Chicago Press, 1965.

Vitale, Bruno, ed. *The War Physicists: Documents about the European Protest Against the Physicists Working for the American Military Through the JASON Division of the Institute for Defense Analysis (IDA), 1972*. Naples: Istituto di Fisica Teorica, 1976.

Wald, Robert M. "Robert M. Wald, Curriculum Vitae" Available online: <http://physics.uchicago.edu/t_rel.html#Wald> (21 Aug 2005).

Warwick, Andrew. *Masters of Theory: Cambridge and the Rise of Mathematical Physics*. Cambridge: Cambridge University Press, 2003.

Washington College. "Meet the Administration: John S. Toll." Available online: <http://faculty.washcoll.edu/admin_bios/toll.html> (26 May 2006).

Weart, Spencer R. "The Physics Business in America, 1919-1940: A Statistical Reconnaissance." In *The Sciences in the American Context: New Perspectives,* edited by Nathan Reingold. Washington, DC: Smithsonian Institution Press, 1979.

Weber, Max. *From Max Weber, Essays in Sociology.* Translated and Edited by H. H. Gerth and C. Wright Mills. London: Oxford University Press, 1946. Reprint. New York: Galaxy, 1965.

Weil, Vivian. "Mentoring: Some Ethical Considerations." *Mentoring and the Responsible Conduct of Research*. Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 471-482.

Wheeler, John Archibald. "Wheeler John Archibald, 1911 – ." Interview by Thomas S. Kuhn and John L. Heilbron. Transcript [partial transcript, neither full transcript nor tape recording survive.]. Berkeley, CA, 24 March 1962. American Institute of Physics, History of Quantum Physics Project.

Wheeler, John A. " 'No Fugitive and Cloistered Virtue'—A Tribute to Niels Bohr." *Physics Today* 16 no. 1 (Jan 1963): 30-32.

Wheeler, John Archibald. "Niels Bohr and Nuclear Physics" [Talk delivered at Niels Bohr Memorial Session, American Physical Society Conference in Washington, DC on 22 April, 1963] *Physics Today* 16, no. 10 (Oct 1963): 36-46.

Wheeler, John Archibald. "Wheeler, John Archibald, 1911 – ". Interview by Charles Weiner and Gloria Lubkin. Transcript. Princeton, NJ, 05 April 1967. American Institute of Physics. Oral History Interviews [OH537].

Wheeler, John Archibald. *Einsteins Vision: Wie steht es heute mit Einsteins Vision, alles als Geometrie aufzufassen?* Berlin: Springer-Verlag, 1968.

Wheeler, John Archibald. "Karl Herzfeld" [Obituary]. *Physics Today* 32, no.1 (Jan 1979): 99.

Wheeler, John A. "Black Hole: An Imaginary Conversation with Albert Einstein." In *Albert Einstein: His Influence on Physics, Philosophy, and Politics.* Edited by Peter C. Aichelburg and Roman U. Sexl. Braunschweig, Germany: Friedr. Vieweg & Sohn, 1979.

Wheeler, John A. "Mercer Street and other Memories." In *Albert Einstein: His Influence on Physics, Philosophy, and Politics.* Edited by Peter C. Aichelburg and Roman U. Sexl. Braunschweig, Germany: Friedr. Vieweg & Sohn, 1979.

Wheeler, John Archibald. "A Decade of Permissiveness" [letter to William Carey, American Association for the Advancement of Science]. *The New York Review of Books* 26 no. 8 (17 May 79). Available online: <http://www.nybooks.com/articles/7813> (23 Oct 2003).

Wheeler, John Archibald. "Some Men and Moments in the History of Nuclear Physics: The Interplay of Colleagues and Motivations." In *Nuclear Physics in Retrospect: Proceedings of a Symposium on the 1930's.* Edited by Roger H. Stuewer. Minneapolis, MN: University of Minnesota Press, 1979: 217-284.

Wheeler, John A. "Einstein and other seekers of the larger view." *Science and Public Policy* 6 (Dec 1979): 396-404.

Wheeler, John Archibald. "Einstein: His Strength and His Struggle." Working Paper. Twentieth Selig Brodetsky Memorial Lecture, University of Leeds, 8 May 1979. Leeds, UK: Leeds University Press, 1980.

Wheeler, John Archibald. "Albert Einstein March 14, 1879—April 18, 1955." In National Academy of Sciences. *Biographical Memoirs,* Vol. 51. Washington, DC: National Academy of Sciences, 1980.

Wheeler, John Archibald. "Niels Bohr, the man." *Physics Today* 38, no. 10 (Oct 1985): 66-72.

Wheeler, John A. Foreword to *The Anthropic Cosmological Principle,* by John D. Barrow and Frank J. Tipler. New York: Oxford University Press, 1986.

Wheeler, John Archibald. "Herman Weyl and the Unity of Knowledge." *American Scientist* 74, no. 4 (Jul-Aug 1986): 366-375.

Wheeler, John Archibald. "Wheeler, John Archibald 1911 – ". Interview by Finn Aaserud. Transcript. Princeton, NJ, 04 May and 28 November 1988. American Institute of Physics. Oral History Interviews [OH30194].

Wheeler, John Archibald. "The Young Feynman." *Physics Today* 42, no.2 (Feb 1989): 24-28.

Wheeler, John Archibald. *A Journey into Gravity and Spacetime.* New York: Scientific American Library, 1990.

Wheeler, John Archibald. "The Young Feynman." In *"Most of the Good Stuff:" Memories of Richard Feynman*. Edited by Laurie M. Brown and John S. Rigden. New York: American Institute of Physics, 1993, 19-32.

Wheeler, John Archibald. "Wheeler, John Archibald, 1911 – ". Interview by Kenneth W. Ford. Transcript. Princeton, NJ and Meadow Lakes, NJ, 06 Dec 1993 – 18 May 1995. American Institute of Physics. Oral History Interviews [OH5].

Wheeler, John Archibald and Kenneth Ford. *Geons, Black Holes, and Quantum Foam: A Life in Physics*. New York: W. W. Norton, 1998.

Whitbeck, Caroline. "Group Mentoring to Foster the Responsible Conduct of Research." *Mentoring and the Responsible Conduct of Research*. Edited By Stephanie J. Bird and Robert L. Sprague. Special Issue: *Science and Engineering Ethics* 7, no. 4 (Jul 2001): 541-558.

Whitehead, Alfred North. *Science in the Modern World: The Lowell Lectures, 1925*. New York: The Macmillan Co, 1925; Reprint, New York: The Free Press, 1967.

Wright, Conrad. *Congregational Polity: A Historical Survey of Unitarian and Universalist Practice*. Boston: Skinner House Books, 1997.

York, Herbert F. *Arms and the Physicist*. Masters of Modern Physics. Edited by Robert N. Ubell. Woodbury, NY: American Institute of Physics Press, 1995.

Zachary, Lois J. *The Mentor's Guide: Facilitating Effective Learning Relationships*. San Francisco: Jossey-Bass, 2000.

Zuckerman, Harriet. *Scientific Elite: Nobel Laureates in the United States*. New York: The Free Press, 1977. Reprint with a new introduction by the author, New Brunswick, NJ: Transaction Publishing. 1996.

Zurek, Wojciech Herbert, Alwyn van der Merwe, and Warner Allen Miller, eds. *Between Quantum and Cosmos: Studies and Essays in Honor of John Archibald Wheeler*. Princeton, NJ: Princeton University Press, 1988.