AN ABSTRACT OF THE DISSERTATION OF

Terry M. Christensen for the degree of Doctor of Philosophy in History of Science on April 3, 2009.

Title: John Archibald Wheeler: A Study of Mentoring in Modern Physics

Abstract approved:

Mary Jo Nye

This dissertation has two objectives. The first objective is to determine where best to situate the study of mentoring (i.e. the ‘making of scientists’) on the landscape of the history of science and science studies. This task is accomplished by establishing mentoring studies as a link between the robust body of literature dealing with Research Schools and the emerging scholarship surrounding the development, dispersion, and evolution of pedagogy in the training of twentieth century physicists. The second, and perhaps more significant and novel objective, is to develop a means to quantitatively assess the mentoring workmanship of scientific craftsmen who preside over the final stages of preparation when apprentices are transformed into professional scientists. The project builds upon a 2006 Master’s Thesis that examined John Archibald Wheeler’s work as a mentor of theoretical physicists at Princeton University in the years 1938 – 1976. It includes Wheeler’s work as a mentor at the University of Texas and is qualitatively and quantitatively enhanced by virtue of the author having access to five separate collections with archival holdings of John Wheeler’s papers and correspondence, as well as having access to thirty one tape recorded interviews that feature John Wheeler as either the interviewee or a prominent subject of discussion. The project also benefited from the opportunity to meet with and gather background information from a number of John Wheeler’s former colleagues and students. Included in the dissertation is a content analysis of the acknowledgements in 949 Ph.D. dissertations, 122 Master’s Theses, and 670 Senior Theses that were submitted during Wheeler’s career as an active mentor. By establishing a census of the students of the most active mentors at Princeton and Texas, it is possible to tabulate the publication record of these apprentice groups and obtain objective measures of mentoring efficacy. The dissertation concludes by discussing the wider applicability of the quantitative methodology and the qualitative analysis for the history of science and science studies.

John Archibald Wheeler: A Study of Mentoring in Modern Physics

by
Terry M. Christensen

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented April 3, 2009
Commencement June 2009

Doctor of Philosophy dissertation of Terry M. Christensen
presented on April 3, 2009

APPROVED:

Major Professor, representing History of Science

Chair of the Department of History

Dean of the Graduate School

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

Terry M. Christensen, Author

ACKNOWLEDGEMENTS

I am compelled to begin by thanking the National Science Foundation for its financial support of this endeavor in the form of Dissertation Improvement Grant 0751310. I am also grateful for the financial support and honor of resident fellowships awarded by the American Philosophical Society and the Philadelphia Center for the History of Science (PACHS). I am also indebted to Babak Ashrafi and Bonnie Clause of PACHS, who supplemented that agency's generous financial support with numerous opportunities for professional networking in the Philadelphia-Princeton academic community. Additionally, Finally, I was aided on this project in no small measure by a timely and particularly helpful suggestion from Professor David Kaiser of MIT. I am most appreciative a timely and expeditious Grant-in-Aid awarded to me by the American Institute of Physics.

This project required extensive research in five separate archival collections. Not surprisingly, I have benefited a great deal from the gracious hospitality and copious amounts of assistance from librarians, archivists, and technical support personnel at each of these institutions. At the Niels Bohr Library in the American Institute of Physics, I had the pleasure of working with Melanie Brown, Julie Gass, Stephanie Jankowski, Meghan Petersen, and Jennifer Sullivan, all of whom work under the capable direction of Joseph Anderson. At the American Philosophical Society, Martin Levitt's staff, including Anne Downey, Sandra Duffy, Roy Goodman, Charles Greifenstein, Earle Spamer, and Lydia Vazquez-Rivera, were especially helpful in view of the limited timeframe in which I had to work in that facility. The members of Margaret Schlankey's staff at the Center for American History at the University of Texas, including Catherine Best, Michelle Bogart, Sarah Cleary, Roy Hinojosa, Michelle Lacy, Stephanie Malmros, Carol Mead, Emily Preece, and Shelley Rowland, provided timely and effective assistance. I am also grateful to, Margaret Carneiro, Janice Duff, Alex Marshall, Deborah McCarthy, Tommy Montoya, Pedro Moreno, David Reza, and Susan Rezalie, all of whom are part of Suzanne McAnna's staff in the Circulation Services Department of the Perry-Casteñeda Library the University of Texas at Austin. Molly White, Head Librarian of the Physics, Mathematics, and Astronomy Library also at the University of Texas, was particularly helpful with organizing the research such that I could maximize the use of my limited time in Texas. The most exhaustive research was conducted at Princeton University, where I had the privilege of working with Daniel Linke's staff including, Atrish Bagchi, Tad Bennicoff, Dan Brennan, Jennifer Cole, John Delooper, Sophia Echavarria, Adriane Hanson, Christine Kitto, Christie Lutz, Gene Pope, and Daniel Santamaria. Elizabeth Bennett, Princeton Librarian for the History of Science, and Jane Holmquist, Princeton's Astrophysics, Mathematics, and Physics Librarian were most helpful in organizing the Princeton research and facilitating the transport of dissertations and theses to and from my research area in the Seeley G. Mudd Manuscript Library. The entire Special Collections staff of the Allen Library at the University of Washington went out of their way to make my stay there both pleasant and productive. In particular, I benefited from the conscientious efforts of Katie Blake, Nicole Bouche, Mark Carlson, Sandra Kroupa, and Jim Stack. Kelly Spring, Assistant Curator of Manuscripts, Milton S. Eisenhower Library, Johns Hopkins University, also provided timely and conscientious assistance in response to my questions. Finally, I would be grossly remiss if I failed to acknowledge the sustained and supportive efforts of the staff at Valley Library. Jane Nichols, Librarian for the History of Science, Patricia Narcum-Perez, supervisor for Circulation and Collection Maintenance, and Jeremy Belsher of the Circulation Staff have been particularly helpful throughout my tenure at Oregon State.

Of course getting to those institutions and navigating the campuses on which they are situated was made infinitely easier by Dutton, my traveling companion for nearly eight years. It is very difficult to convey everything that a Guide Dog does for his or her partner as they work together. Some things are tangible—most are not. This much is certain; Dutton and his predecessor Shippey have made it possible for me to build this new career. I cannot imagine how much more difficult this voyage would have been without either Dutton or Shippey. I am deeply indebted to Guide Dogs for the Blind for making these partnerships possible. Similarly, I am obliged to note the work of the Oregon Commission for the Blind which helped me develop the basic skills to navigate in a permanent fog as well as the technical proficiency necessary to exploit the advances in adaptive hardware and software. Philip Bourbeau, Chris Christian, Patricia MacDonnell, and Winslow Parker all deserve special mention in this context.

Even with the benefit of training provided by the Oregon Commission for the Blind and the able assistance of Dutton, there are still significant challenges associated with being a visually impaired scholar. Throughout my career at Oregon State, these difficulties have been considerably mitigated by Dr. Tracy Bentley-Townlin's staff in the Disability Access Services Office. I am particularly indebted to Technology and Production Support Services Manager, Haris Gunadi, his colleague Angela Tibbs, along with work-study assistants, Sheena Chen, Anton Dragunov, Caryn Ong, Jessi Ong, and Scott Shermer. Having corresponded with and-or visited a significant number of universities as part of this research (as well as prior to coming to Corvallis), it is clear to me that there is no better place to be a visually impaired scholar than Oregon State University.

My academic career has also profited handsomely from my associations with Professors, Ron Doel, Paul Farber, Melinda Gormley, William Husband, Ben Mutschler, Robert Nye, William Robbins, Lisa Sarasohn, and Jeffrey Sklansky of the Department of History as well as Professor William Lunch of the Department of Political Science and Professor Sharyn Clough of the Department of Philosophy.

This endeavor would have been exponentially more difficult without the unyielding support and encouragement of family and friends. Here, I particularly want to acknowledge Terry Anderson, Scott Andros, Dave and Pam Baldwin, Bill and Chris Bannerman, Warren and Verna Blakslee, Len and Mary Anne Cadwallader, Michelle Cadwallader, Sarah Cadwallader, Tom and

Katherine Cadwallader, Calvin T. and Judith Christensen, Gary and Jo Christensen, David and Virginia Dugger, Erik Ellis and Kristen Johnson, Darlene Hedin, Rachel Koroloff, Tully Long, Steve Lucker, Chuck Meitle, Ron Smith, Cindy Spencer, Leandra Swanner, and Katie Zimmerman. Many of the aforementioned served—often involuntarily—as sounding boards while I worked out the optimum course to steer through various logical arguments. I am also grateful for the assistance and enthusiastic support offered by many of John Wheeler's former students and colleagues including Jacob Bekenstein, Paul Boynton, Adam Burrows, Freeman Dyson, Val Fitch, Larry Ford, Robert Fuller, Robert Geroch, Kent Harrison, Jim Hartle, Daniel Holz, Jim Isenberg, Daniel Kevles, John Klauder, Daniel Marlow, Bahram Mashoon, Richard Matzner, Alan Mills, Charles Misner, Daniel Rohrlich, Lawrence Shepley, S. Fred Singer, Daniel Sperber, John Toll, J. Peter Vajk, Robert Wald, Steven Weinberg, Cheuk-Yin Wong, and Wojciech Zurek. In addition to those named above, Kip S. Thorne, the Feynman Professor of Theoretical Physics at Caltech, deserves special mention. Professor Thorne's book, *Black Holes and Time Warps: Einstein's Outrageous Legacy*, was a major influence in my decision to return to school and pursue an academic vocation after the loss of visual acuity forced the termination of my seafaring career. Indeed, Kip's remarks about having John Wheeler as a mentor motivated this project and the Master's Thesis which preceded it.

Over the course of my life, I have been blessed with many mentors—both personal and professional. I would be hugely remiss if, in an acknowledgement to a dissertation about mentoring, I failed to name those individuals who provided timely, sustained, and comprehensive counsel when it was needed most. Here I would include Professor David Scott Arnold, MGYSGT Calvin T. Christensen, USMC (Ret.), the Hon. Robert Chopping, Professor Robert Deery, Coach Ray Downs, Sr. Francis Madden, SNJM, Coach John Mattila, Capt. Reino Mattila, USMM, Mr. Marc Pemberton, Sr. Cecilia Ranger SNJM, Coach Dennis Warren, and Coach Fred Wilson.

There are two other individuals whose contribution to my professional success cannot be overstated. Despite the lack of a formal academic relationship, Professor Ken Ford took me under his wing. He provided timely counsel and professional socialization in the community of physicists. Perhaps most significantly, Ken championed my authorship of an article about John Wheeler in the April 2009 issue of *Physics Today*. It is all but impossible to imagine how this project would have taken its present form without Ken's support and encouragement. Finally, I have benefited enormously from the patience, encouragement, patience, empathy, patience, gentle course corrections, patience, and prescient counsel of Professor Mary Jo Nye. More than any other proximate cause, I am a professional historian because she took the time and effort to make me one. Having become something of an authority on mentoring, I can unequivocally assert that as a mentor, Professor Mary Jo Nye is second to none. I am grateful to her beyond measure.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

ABBREVIATION KEY FOR ARCHIVAL COLLECTIONS

APS-JAW	John Archibald Wheeler Papers, American Philosophical Society, Philadelphia, PA
NBL-AIP	Niels Bohr Library and Archives, Center for the History of Physics, American Institute of Physics, College Park, MD
PRIN	Princeton University Archives, Department of Rare Books and Special Collections, Princeton University Library, Princeton, NJ
PRIN-JAW	John Archibald Wheeler, Faculty File, Princeton University Archives, Department of Rare Books and Special Collections, Princeton University Library, Princeton, NJ
PRIN-PHY	Physics Department Records, Princeton University Archives, Department of Rare Books and Special Collections, Princeton University Library, Princeton, NJ
UT-JAW	John Archibald Wheeler Papers, Archives of American Mathematics, The Center for American History, University of Texas at Austin, Austin, TX
UT-PCL	University of Texas Archives, Perry-Casteñeda Library, University of Texas at Austin, Austin, TX
UW-HMJ	Senator Henry M. Jackson Papers, Special Collections, University of Washington Library, Seattle, WA

DEDICATION

This dissertation is dedicated to a very special group of people. First and foremost, I dedicate this work to my wife and the Woman of My Dreams, Elizabeth P. Cadwallader. This work is also dedicated to three fine young men who have given my life new meaning, our sons, Steve Adams, Ben Adams, and Jay Jones. Finally, I dedicate this work to T. Sidney and Carolyn K. Cadwallader, my father and mother-in-law, who have been steadfast role models for living a life that is rooted in integrity.

JOHN ARCHIBALD WHEELER: A STUDY OF MENTORING IN MODERN PHYSICS

Preface

John Archibald Wheeler (1911 – 2008) was clearly among the first rank of twentieth century physicists. Indeed, Wheeler was nominated for the Nobel Prize in Physics on at least two occasions.[1] Wheeler's many contributions to the corpus of physics include, but certainly are not limited to, the development of the scattering matrix that describes all possible outcomes for the collision of sub-atomic particles, his co-authorship of the first generalized description of nuclear fission, his revitalization of general relativity as a fertile research topic, and his pioneering work on the information theoretics in quantum mechanics. In fact, two books, *Gravitation* (co-authored with former students Charles W. Misner and Kip S. Thorne) and *Quantum Theory and Measurement* (co-authored with Wojciech H. Zurek), are among the top one percent of cited publications in physics.[2] What is more, as late as February 2009, one of these texts (*Gravitation*) remained in print, without revision, despite having been first published in 1973, more than thirty-five years ago.

These and other renowned accomplishments notwithstanding, I argue in this dissertation that John Wheeler's many contributions to the *corpus* of

---

[1] Ken Ford, personal communication with author, 05 Jan 2009; Val Fitch, personal communication with author, 06 Jan 2009; Kip Thorne personal communication with author, 06 Jan 2009.

[2] See Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler, *Gravitation* (New York: W. H. Freeman and Co., 1973); John Archibald Wheeler and Wojciech Hubert Zurek, *Quantum Theory and Measurement* (Princeton, NJ: Princeton University Press, 1984). The assertion of citation data is based on citation counts from Google Scholar as detailed in the methodology section of Chapter I.

physics are less important than his contributions to the *community* of physicists. This assertion is based on the nature of scientific knowledge. Obviously, there would be no physics without continued growth in the quality and quantity of what is known about the universe around us. And yet, the bits of evidence that constitute that body are cumulative in nature.

This is not to say that the advancement of physics, or any other discipline for that matter, can be described as a linear chain of ideas, experimental data, and theoretical constructs that build upon one another in an inexorable and triumphant march of progress. Clearly, this model is an oversimplification. Indeed, as Thomas Kuhn (1922 – 1996) pointed out in his oft-quoted *The Structure of Scientific Revolutions*, science advances through fits and starts, rather similar to the "punctuated equilibriums" that characterize biological evolution. Over time, one can discern "Kuhnian cycles" of normal science punctuated by revolutions in which a once dominant theoretical construct is replaced by a more or less rapidly emergent worldview. More specifically, during the periods of normal science, evidence that does not support the presumed theoretical construct is deemed anomalous or even suspect. When however, the amount of anomalous evidence reaches a critical mass, there follows a conceptual upheaval, after which a new theoretical construct becomes dominant.[3] It is important to note here that regardless of which theoretical construct prevails, none of the reproducible evidence is

---

[3] Thomas S. Kuhn, *The Structure of Scientific Revolutions,* 3rd ed. (Chicago: University of Chicago Press, 1962, 1970), 167-169.

discarded. In a scientific revolution, we toss out the conceptual baby, not the evidentiary bath-water.[4]

This mode of operation is also reflected in the training of scientists. Scientific education, as Kuhn has pointed out, is textbook dependent until the last year or two of graduate school. Unlike historians, to cite one of many such examples, scientists in training do not examine a plethora of texts in order to formulate and synthesize a world view that is cognizant of, if not congruent with, the thinking of earlier scholars. Kuhn notes, “Scientific education makes use of no equivalent for the art museum or the library of classics and the result is a sometimes drastic distortion in the scientist's perception of his discipline's past.” Indeed, once a dominant world-view is overturned, Kuhn observes, “a scientific community simultaneously renounces, as a fit subject for professional scrutiny, most of the books and articles in which that paradigm had been embodied.”[5] Such textbooks, of course, carefully present the evidentiary basis for the presumed theoretical construct. Thus, the very training of scientists simultaneously instills a disregard for discarded hypotheses and a predilection to preserve and evaluate evidence in the light of a dominant world view.

The foregoing should not be construed as a critique of scientific education. There are good reasons for training scientists as we have. The point is that as the discipline of physics develops a more comprehensive world model, a series of theoretical constructs will come and go, and even those

---

[4] Kuhn, 1970, 169.
[5] Kuhn, 1970, 167.

constructs that remain have a somewhat transient significance for new generations. As the Nobel Laureate and theoretical father of the meson, Hideki Yukawa (1907 – 1981) has observed:

> However, as time goes on, what seemed initially to be abstract has gradually become something concrete to many physicists and a new sort of intuition took shape in their minds. Nowadays, a four-dimensional space-time world is intuitively grasped by a physicist almost as clearly as Newton's space and time were grasped by those in his time.[6]

In essence, Yukawa is saying that today's stunning conceptual breakthrough is tomorrow's mere building block, upon which future breakthroughs will be predicated. In any case, it is clear that evidentiary contributions to the corpus of knowledge are cumulative.

A proficient mentor, on the other hand, may well have a multiplicative influence on generations of scientists. The sociologist of science Harriet Zuckerman has examined aspects of the 'master-apprentice' relationship among scientists in her book, *Scientific Elite*. Among her examples of a master-apprentice chain, Zuckerman traces six generations of chemists from the Nobel Laureate Hans Krebs (1900 – 1981) through four generations of

[6] Hideki Yukawa, *Creativity and Intuition: A Physicist Looks at East and West,* trans. John Bester (Tokyo: Kodansha International, Ltd., 1973), 103.

Nobel laureates and three generations of celebrated chemists all the way back to Antoine-Laurent Lavoisier (1743 – 1794).[7]

What is true for scientific mentors in general is true for John Archibald Wheeler in particular. Speaking at a 1977 festschrift honoring Wheeler, the former Wheeler student Charles Misner noted that Wheeler and his "family" of students were prime examples of the "workings of the apprentice system by which research attitudes and methods are passed on." Another former Wheeler student, Ken Ford, referring to Wheeler's stylistic influence, wrote, "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 Bohr and John Wheeler than they know."[8] That 'coloring' of perspective may be true of Wheeler's students, but is it true of all physicists?

---

[7] Harriet Zuckerman, *Scientific Elite: Nobel Laureates in the United States* (New York: The Free Press, 1977; Reprint, New Brunswick, NJ, 1996), 150. Krebs (1900 – 1981, Nobel prize 1953) studied with Otto Warburg (1883 – 1970, Nobel prize 1931); Warburg studied 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) who developed what is now the standard system of chemical nomenclature.

[8] *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). There is no number on the page that contains Charles Misner's remarks. Ken Ford's letter appears on pages 84-88.

There are, of course, well known cases of scientists such as Albert Einstein (1879 – 1975) who were enormously influential without having had a scientific mentor. Nonetheless, the work of Zuckerman, the five separate festschrifts that were organized and published by Wheeler's students, and the massive body of scholarly literature dealing with research schools that feature a charismatic director, suggest that a mentor-apprentice relationship is a key element in the career of many, if not most, scientists. That being the case, several other questions come to mind: What, precisely is meant by the term "mentoring" as it is employed in this dissertation, and how is mentoring distinct from other forms of scientific pedagogy? Given the subjective nature of former students' testimonials, how can we objectively measure proficiency in mentoring? Is every physicist a mentor, or do a privileged few assume that role? In either case, what qualities are common among proficient mentors and are these qualities inherent within the particular scientist (i.e. a matter of nature) or inculcated by a mentor's mentor (i.e. a matter of nurture)? Where and how does this study fit in the extant scholarship regarding research schools as well as the developing body of scholarship dealing with the implementation and use of pedagogical instruments in science education? And finally, what are the implications of this study for future investigations in these areas?

Before discussing the individual chapters, I should point out that this dissertation is an extension of research that appeared previously in a Master's Thesis that focused on John Wheeler's work as a mentor to graduate students in physics at Princeton University in the years 1938 – 1976.[9] A significant finding of that Master's thesis, which is also replicated in this study, is that proficient mentors often have, at least in a qualitative sense, a multiplicative influence through generations of scientists. In particular, many of Wheeler's former students report that they frequently incorporated "Wheelerisms" (i.e. aphorisms that seemed to originate with Wheeler) and other of Wheeler's pedagogical practices as they mentored students of their own.

The goal of both the Master's thesis and this project is to develop insights into the teaching and training of scientists and thereby illuminate how scientists, especially those in theoretical studies, have learned to become productive members of the scientific community. It is hoped that by focusing on the historical career and contributions of a particular scientist such as John Wheeler, such insights would be more apparent. In sum, both studies concentrate on Wheeler's contributions to the community of physicists rather than the corpus of physics. It should also be noted that, with the exception of transcripts of interviews with John Wheeler by Charles Weiner (with Gloria Lubkin), Finn Aaserud, and Ken Ford, the 2006 Master's Thesis was developed using published sources (i.e. without access to archival material). Thus, the data supporting this dissertation is significantly more comprehensive, both qualitatively and quantitatively, than that supporting the earlier Master's Thesis, and the interpretations, based in both the data base

[9] Terry M. Christensen, "Theoretical Physics Takes Root in America: John Archibald Wheeler as Student and Mentor" (Master's Thesis, Oregon State University, 2006).

and in further readings and discussions, are broader and more nuanced. A description of the newly incorporated source material follows.

There are five repositories of archival collections relating to John Archibald Wheeler. The vast bulk of Wheeler's papers, including correspondence files and research notebooks, is held by the American Philosophical Society and Philadelphia, PA (APS-JAW). A small, though significant collection is held at the Center for American History, Archive of American Mathematics, located at the University of Texas at Austin, TX (UT-JAW). The Princeton University Archives, Princeton, NJ, hold the Physics Department records of general and internal correspondence (PRIN-PHY) as well as John Wheeler's personnel file (PRIN-JAW). The Niels Bohr Library, Center for the History of Physics, at the American Institute of Physics in College Park, MD (NBL-AIP) holds the papers of John Wheeler's dissertation advisor, Karl Herzfeld, as well as thirty-one audio recordings of Oral History interviews (and transcripts) that were either conducted with John Wheeler or feature Wheeler as a subject. There is also a small, though no less informative, collection of papers relating to John Wheeler's work on defense related research and advocacy in the papers of Senator Henry M. ("Scoop") Jackson, held in the Special Collections section of the Allen Library at the University of Washington in Seattle, WA (UW-HMJ). The Ph.D. dissertations and Senior Theses that were submitted during John Wheeler's tenure at Princeton are held in the Seeley G. Mudd, Manuscript Library at Princeton University (PRIN). Similarly, the Ph.D. dissertations and Master's Theses that were submitted during John Wheeler's tenure at the University of Texas are held in the Perry-Castañeda Library (PCL-UT).

Among the more compelling archival holdings are John Wheeler's research notebooks. Starting in about 1950, John Wheeler began to use bound blank books as research notebooks. These books are characterized by Wheeler's distinctive hand, the effect of which is enhanced by his use of a fountain pen. As it turns out, each of these books is a combination of learning diary and reflection journal. Indeed, it appears that, just as one of Wheeler's own mentors, Niels Bohr, was known to think aloud in discussion with at least one other physicist, Wheeler tended to do at least part of his thinking on paper. Along with notes on calculations, drafts of upcoming lectures, and reflections on talks heard at various conferences, Wheeler often made margin notes to himself regarding interactions with his students and colleagues. Fifty-two of these notebooks are held among the Wheeler papers at APS-JAW, and twenty-four more are held in the John Archibald Wheeler Collection, at UT-JAW in Austin. The Wheeler collection at the APS was examined in October and November of 2007 and the Wheeler collection at UT-JAW was examined in the late spring of 2008.

As with any project of this size, there were unforeseen complications, three of which had a significant impact on the timing and degree of completion for various phases of the research. The first issue was the renovation of the American Philosophical Society's Library Hall (repository of the largest collection of John Wheeler's papers) which caused the collection to be closed to scholars from 15 November 2007 through 01 April 2008. As a consequence of the remodeling schedule, the author was only able to spend six weeks with a very extensive collection. For reasons detailed below, the author chose Wheeler's research notebooks as a priority and was not able, within the timeframe available for the project, to return to complete an examination of Wheeler's correspondence held at that location.

Another setback was due to the condition of the collection of the Wheeler notebooks at APS. To expedite the examination of this part of the collection, and mitigate the time pressure generated by the impending closure of the archive, the author placed orders for several hundred photocopies of pages from Wheeler's research notebooks. Unfortunately, while approximately 300 pages were photocopied, many of the notebooks had deteriorated to the point at which it was no longer possible to photocopy pages from those books without doing additional damage. Since the reopening of the archive, the author has been told of aspirations to digitize the Wheeler collection. Alas, that endeavor awaits funding, and under any circumstances will take some years to complete.

A third complication is that Wheeler's papers (i.e. his correspondence files and research notebooks) seem to have been distributed between APS-JAW and UT-JAW without any evident over-arching plan. While the Wheeler collection at the APS-JAW is considerably larger and more comprehensive, the collection at UT-JAW has a number of significant holdings that were germane to this study. The lack of a systematic plan of allocation is evidenced by the fact that both collections contain Wheeler research notebooks dating from the early 1950s through the 1980s, both collections contain Wheeler correspondence files dating from the early 1950s through the early 1980s, and both collections contain teaching materials and lecture notes from courses taught at both Princeton University and the University of Texas. It would appear to the casual observer that upon Wheeler's decision to return to Princeton in 1986, the material that had been in Wheeler's faculty office in the Center for Relativity on the ninth floor of the Robert Lee Moore Hall (RLM) remained in the UT-JAW archives, while the material that had been kept in Wheeler's home on Wildcat Hollow in Austin was transferred to the APS-JAW collection in Philadelphia. In terms of organizing the research, the absence of a systematic scheme for the distribution of Wheeler's papers made an expeditious survey of the collections (i.e. one guided by subject area or chronology) all but impossible.

Obviously, one primary objective of a study on mentoring is to identify those individuals who apprenticed under a given mentor. Surprisingly, none of the primary Wheeler collections (i.e. APS-JAW, UT-JAW, PRIN-PHY, PRIN-JAW) contain a census of Wheeler's Ph.D., Master's, or Senior Thesis students. To be clear, the Seeley Mudd Manuscript Library does maintain an online database of Senior Theses. In the course of research however, the author discovered a number of inconsistencies between the advisor acknowledged in the thesis itself and the advisor (or lack thereof) listed in the database.

As a consequence of the closure of APS, this primary objective (i.e. the identification of Wheeler's Ph.D. students) was undertaken in the second phase of the research. This task was accomplished in the Winter and early Spring of 2007-2008 in the Seeley G. Mudd Manuscript Library at Princeton University (PRIN), by a systematic evaluation of the 555 physics Ph.D. dissertations and 669 Senior Theses in Physics that were submitted during John Wheeler's tenure at Princeton. Later, in the late spring of 2008, the author conducted a similar survey of the 389 physics Ph.D. dissertations and 122 Master's Theses that were submitted during Wheeler's tenure at the University of Texas at Austin. These dissertations were held in the Perry-Castañeda Library at the University of Texas at Austin (PCL-UT).

Identifying Wheeler's students was, however, not as straightforward a process as it might seem at first glance. During Wheeler's Princeton years, it was not customary to list the advisor of record at the beginning of the dissertation or a Senior thesis. Thus, the author was obliged to perform content analysis on the 949 Ph.D. dissertations (555 at Princeton University and 389 at the University of Texas at Austin), 122 Master's Theses (at the University of Texas) and 670 Senior Theses (669 at Princeton and one in Texas) that were submitted during Wheeler's career as an active mentor. In addition to positively identifying those students who had performed some portion of their apprenticeship under John Wheeler, this content analysis of the dissertation and thesis acknowledgements also provided meaningful insights into the working relationships of Wheeler with his apprentices.

Perhaps the most fruitful activity of this project was the development of a quantitative means of measuring John Wheeler's efficacy of a mentor. This part of the project, it should be noted, benefited from a very timely and insightful suggestion by Professor David Kaiser of the Massachusetts Institute of Technology. The process involved collecting publication data of Wheeler's former students as well as the publication data for former students of Wheeler's colleagues at Princeton and Texas. These publication records were evaluated using two metrics: The total number of publications credited to each former student and the significance of each publication as inferred by citation count. The development and application of these metrics is described, as noted below, in Chapter Four. The foregoing leads us to a discussion of the individual chapters.

Chapter One provides the basic framework for this study by examining the historiography of research schools and the historiography of scientific pedagogy. The focus in the chapter then narrows to specific reasons for choosing the discipline of theoretical physics and for choosing John Archibald Wheeler as the case in point. This chapter also contains a section that draws out the distinction between mentoring and other forms of instruction. Based on this distinction and what has been gleaned from the mushrooming accumulation of literature that addresses mentoring, some preliminary general principles of scientific mentoring begin to emerge. The opening chapter concludes with a discussion of the methods, materials, and strategies employed in this endeavor.

Chapters Two and Three are specific to John Wheeler. Chapter Two opens with a brief biographical sketch, then focuses on Wheeler's student years with sections that describe Wheeler's experience as an apprentice to Karl Herzfeld (1892 – 1978), Gregory Breit (1889 – 1981), and Niels Bohr (1885 – 1962). I have also included a discussion of Wheeler's complicated relationship with Albert Einstein. Chapter Three focuses on John Wheeler as a mentor. In this chapter, Wheeler's former students describe the lessons they took from their apprenticeship and have conveyed to their own students. These descriptions are augmented by Wheeler's own recollections such that it is possible to trace these lessons back through Wheeler to Herzfeld, Breit, and Bohr.

Although Chapter Four is the most quantitative element in this dissertation, I begin this chapter with qualitative insights into the nature of Wheeler's mentoring relationships based on the content analysis of the acknowledgements in the dissertations and theses submitted to the physics departments at Princeton and Texas. In the following sections, I place John Wheeler's 'productivity' of Ph.D. students in the context of (then) Caltech Vice-Provost David Goodstein's 1993 study of Ph.D. production in physics.[10] According to Goodstein's calculations, it should be noted, John Wheeler supervised more than three times the number of Ph.D. students one would expect from a professor in a major research university. With the contextual

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

background of Goodstein's study, I introduce other quantitative criteria that enable the comparison of the quantity and significance of the science done by former Wheeler students in contrast to the former students of his colleagues.

I open the fifth and last chapter with a brief review of relevant scholarly literature regarding both research schools and pedagogical elements in science with the aim to establish this study as a bridge between these distinct, though related, bodies of scholarship. Based on the findings of this study, it is clear to me, and I believe it will be clear to the reader, that this study yields insights regarding the relationship of mentoring and research school literature in general and John Wheeler's success as a mentor in particular. Moreover, given that mentoring styles vary, it seems clear that a broad-based study of mentorship as practiced at various institutions may well have tangible benefits for the enterprise of graduate education in the physical sciences.

A maritime analogy seems apropos here. At sea, the officer who has command and control (i.e. "the con") of a vessel has the ability to set the ship's course and speed. The task of navigation is complicated however, by the effects of wind and current. Unlike the heading indicator or the engine RPM gauge, these influences are not obvious in the moment, and indeed, are only apparent when one compares the intended track of the vessel with a series of actual positions as plotted on a navigation chart. In sum, the ship's officers can only know where they are going by examining where they have been (i.e. a historical analysis). This is also true of mentoring in physics. Given the long-lived influence of skillful mentors, a thorough, well-structured, historical study of mentoring in theoretical physics would seem to be a particularly fruitful enterprise.

Finally, I have also included a number of appendices that support assertions and conclusions found in the main body of the text. A timeline of John Wheeler's accomplishments in physics speaks to his prominent role in the development of physics in the twentieth century. John Wheeler's personal bibliography illustrates the degree to which he collaborated with students and former students, not to mention his habit of listing authors alphabetically so that his students' names usually came first in terms of authorship. There are also tables that list the Ph.D. dissertations, Master's Theses and Senior Theses by advisor so that the reader is able to make a first-hand comparison of Wheeler's work with these groups of students as against that of his colleagues. With the preceding background in hand, we are now prepared to get underway.