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Bridging the Gender Gap in Quantum Physics

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Chapter 1: Introduction and Motivation

Why is it important to study the gender[1] gap in physics? Despite entering the workforce in increasing numbers over the last fifty years, women remain severely underrepresented in science and technology-related careers, particularly in positions of authority. Simultaneously, numerous studies verify that women have the ability to perform as well as – or better than – males in physics, and, when presented in certain lights, as many women as men show an interest in physics. Changes must be made in order to strive for equality and, given the changing demographic of the workforce, increase our country's diminishing scientific prowess.

While some studies of this gender gap already exist, this report is unique. Most published studies occur in the context of a Newtonian Mechanics introductory course.[2] Here, for the purpose of personal interest and diversity of study, the context is a class on quantum mechanics. This allows for the inclusion of Karen Barad's agential realist approach,[3] heretofore untested with respect to its impact on the gender gap. This study focuses on the impact of such pedagogy on the attitude of students towards learning with the hope of decreasing the gender gap in the interest and understanding of physics. While testing the impact of an agential realist approach on the gender gap, it also compares the effectiveness to the gender gap reducing pedagogy provided by past mechanics-based research.

An abundance of data provided by the National Science Foundation tracks the distribution of science-related jobs and doctoral degrees amongst men and women in the United States. These numbers are telling: in 2003, women made up only 29% of employed physical scientists, despite comprising 42% of the employed labor force.[4] Women received 15% of the physics doctoral degrees awarded in 2005.[5] Of women's bachelor's degrees awarded by four-year colleges across the country in 2004, only 0.7% were in the physical sciences,[6] despite 1.5% of incoming freshmen setting out with that intention in 2000.[7] Most of these degrees were in chemistry or astronomy – only 908 out of the 810,817 degrees earned by women in 2004 were in physics, a proportion of about 0.1%.[8] The farther up the academic ladder, the more the gap widens: in the 1995-1996 school year, women made up 32% of twelfth-graders who performed highly in physics;[9] in 2003, women made up 12% of all physicists with a bachelor's as their highest degree and only 8% of those with a doctorate.[10] This lack translates to an absence of women in positions of authority – currently, academic presidents, deans, and department chairs holding science or engineering doctoral degrees continue to be overwhelmingly male.[11]

Investigations into women's aptitude for physics shine some light onto these well documented disparities in representation. The data reveal a complex situation. International Association for the Evaluation of Education Achievement tests of American eighth-graders found no statistically significant gender-based differences in measurements of mathematics content[12] or science achievement.[13] Later on, particularly in undergraduate years, measurements of physics understanding often find a gap between women and men in traditionally taught classrooms.[14] However, performance is not necessarily linked with the decision to continue in physics. Only 31% of the college freshmen who switched out of science and engineering did so because of finding the course work too difficult.[15] A study by William Perry found that college-age women scored higher than their male counterparts in their ability to deal with complex situations and ambiguity,[16] calling into question the highly concrete culture of most introductory level physics courses, particularly when many fields of physics – quantum mechanics, for example – are based on complex systems still in the process of discovery.

Research from physicists and gender theorists suggests that women's processing of physics differs markedly from the current male-oriented educational paradigm. By considering the findings of past gender gap research, chapter 2 gathers together gender-gap reducing pedagogy from past mechanics-based investigations. One recent study by Mercedes Lorenzo, Catherine H. Crouch, and Eric Mazur on the Harvard introductory mechanics physics courses is analyzed at length.[17] Their results – a complete elimination of the gender gap in student learning – highlight the powerful impact of integrating student experiences, interests, and knowledge; constructing interactive learning environments that focus on activity-based learning; and decreasing competitiveness.

Such novel approaches remain at the forefront in chapter 3, which discusses Karen Barad's theory of agential realism. Dealing particularly with quantum mechanics, Barad draws on feminist and pedagogical theory to emphasize the importance of teaching quantum physics as a complex fact of nature and discouraging instructors from rushing to equations. Simultaneously, agential realism highlights the fundamental influence of participants' social position and historical context in order to stress the socially constructed nature of science.[18] Understanding and implementing these theories could be a way to reduce the gender disparity in performance and interest in physics.

Having introduced key aspects of the relevant theory, chapter 4 focuses on the implementation of this potentially gender-gap reducing pedagogy in an introductory physics course of Pomona College. It covers the development of modified quantum mechanics class sessions. Both offer a more integrated, interactive, and less competitive classroom than traditionally presented, but the first specializes in the mechanics-based pedagogy while the second integrates the agential realist approach. To do this, the first spends more time on a collaborative computer-based student activity that allows students to explore wave-particle duality and the de Broglie relation. The second includes a student-led discussion of the implications of quantum mechanics based on readings from Bohr, Einstein, and Barad as inspired by the text *Boojums All the Way Down*.[19] Details of implementation, such as the choice of a less-biased teacher than the author as the instructor, are discussed at length.

Chapter 5 concentrates on measuring the impact of this modified class session based on pre and post-class questionnaires. While the questionnaires focus on student interest in physics and quantum mechanics, they also provide some quantitative measurement of student understanding of quantum physics.[20] The interviews provide a means of validating the results of the questionnaires and sampling student response to the class sessions. Chapter 6 draws preliminary conclusions about the effect of the modified course on the gender gap in physics understanding and interest, as well as differences between the two approaches. It then indicates opportunities for improvement in future studies and highlights important results, with implied suggestions for improving undergraduate introductory physics treatment of quantum mechanics with respect to the gender gap.

It is essential to recognize the importance and relevancy of this concern. Shirley Ann Jackson, physicist and president of the American Association for the Advancement of Science, recently spoke at Harvard about the urgency of the situation. Emphasizing the particular need for encouraging women and minorities to study science and engage in research, she insists, “Only through the development of science will [the United States] continue assuming a leadership role in the next frontier of the 21st century.”[21] Published in light of growing concerns about a projected shortfall of science workers and growing science illiteracy in America, Sheila Tobias’s paper *They’re Not Dumb, They’re Different* confirms these changes as major issues. In order to avoid a situation in which “the economy [will] bear the brunt of the science shortfall, and government and the general public the ever-increasing burden of scientific illiteracy,” she urges the country “to enlarge what has hitherto been considered the natural pool of recruits to science and be willing to offer new kinds of students a welcome a chance for success.”[22] Existing pedagogy must change in order to better encourage the participation and success of women.

NOTES:

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[1] Here, the author must apologize for his adherence to the outdated concept of a gender binary. Currently, few publications explore the prevalence of a gender gap with respect to other genders besides female and male. Clearly this is an area that deserves investigation, though the limited scope of this paper prevented that possibility here. The performance and representation gap of minorities and persons with disabilities in science are also pressing issues that deserves full attention, but could not be addressed in this work. However, many aspects of this project are useful for consideration in such discussions, as much of the theory is based upon similar systems of oppression and a departure from traditional (white) male learning styles.
[2] For example, M. Lorenzo, Catherine H. Crouch, and Eric Mazur. "Reducing the Gender Gap in the Physics Classroom." *American Journal of Physics* 74 (2006): 118-122, and S. Tobias, *They're Not Dumb, They're Different*. Tucson: Research Corporation, 1990.
[3] See chapter 4, which draws on K. Barad, *Meeting the Universe Halfway*. Duke University Press (2007) and K. Barad, "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995).
[4] National Science Foundation, Division of Science Resources Statistics, *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2007*, NSF 07-315 (Arlington, VA: February 2007), Table H-5.
[5] *Ibid*., Table F-2.
[6] *Ibid*., Table C-4.
[7] *Ibid*., Appendix Table 2-10.
[8] *Ibid*., Table C-5.
[9] I. V. S. Mullis et al., *Gender Differences in Achievement. IEA'S Third International Mathematics and Science Study (TIMSS)*. Boston: TIMSS International Study Center, 2000, Exhibit 2.8.
[10] National Science Foundation, Table H-5.
[11] For example, only 900 out of 4,900 such presidents, provosts, or chancellors are women. Ibid., Table H-24.
[12] I. V. S. Mullis, Exhibit 1.4.
[13] *Ibid*., Exhibit 1.9.
[14] M. Lorenzo.
[15] S. Tobias, p. 14.
[16] W. G. Perry Jr., *Forms of Intellectual and Ethical Development in the College Years: A Scheme* (New York: Holt, Rinehart, and Winston, 1970).
[17] M. Lorenzo.
[18] K. Barad, *Meeting the Universe Halfway*.
[19] N. D. Mermin, *Boojums All the Way Through*. Cambridge University Press: 1990. In particular, the reading on the chapter "The Philosophical Writings of Neils Bohr", pp. 186-189.
[20] Official Pomona College physics department data already show a high quantitative measurement of student understanding, reflecting the *Six Ideas* program's commitment to interactivity and student engagement (T. Moore, *Six Ideas That Shaped Physics*. New York: McGraw-Hill Higher Education, 2003). In addition, the setting of this research in a

small environment over a very limited timeframe precludes a particularly thorough or strong quantitative analysis of student understanding of quantum mechanics.

[21] M. C. Caballero, "More Support for Science, Research Needed in US." *Harvard Gazette*. 13 May 2004. 27 November 2007. <http://www.hno.harvard.edu/gazette/2004/05.13/11-jackson.html> .

[22] S. Tobias, p. 12.

Chapter 2: Lessons from Mechanics-Based Gender Gap Research

Groundbreaking work on the gender gap in introductory mechanics physics courses offers many potential lessons for quantum mechanics education. A survey of different conclusions reached by past gender gap researchers provides a context for the development of a gender gap bridging quantum class. Thorough analysis of the most comprehensive study available – a 1990-1997 investigation of the Harvard introductory mechanics courses by Mercedes Lorenzo, Catherine H. Crouch, and Eric Mazur[1] – highlights four particularly effective techniques for the elimination of the gender gap salient to this paper: in-class interaction, a reduction in competition, an increase in collaboration, and an emphasis on conceptual understanding.

Literature on the gender difference in physics suggests eight particular gender gap narrowing strategies supported by classroom testing and/or student interviews:

(1) Integration of everyday experiences and interests relevant to both genders.
(2) Assessment and continual access of student's prior knowledge to construct new knowledge.
(3) Frequent feedback through a wealth of varied assessment practices.
(4) Creation of interactive classroom environments that enhance cooperation and communication amongst students and instructors.
(5) Combination of group discussion and structured lecture.
(6) Activities that decrease competitiveness.
(7) A focus on connection-based student understanding, as opposed to equation-based rote-learning.
(8) Application of physics to a broader worldview.

A Swiss project by Labudde et al. supports and elaborates on the first three of these claims.[2] Using an IQ test, the researchers selected a large group of students with no significant gender differences in language comprehension and spatial reasoning. Within this group, researchers found that women reported significantly less experience with and interest in technology and physics, but significantly more experience with household activities and more interest in natural phenomena. Furthermore, data indicated a significant discrepancy in self-confidence between genders. Figure 2.1 displays these results, based on scales with a rating from 1 to 5 (from no experiences/interest to many/much).

	Mean values		
Scale	*Girls* $n = 384$	*Boys* $n = 193$	*Level of significance*
Media experiences in physics	1.7	2.2	***
Experiences in technology	1.5	2.0	***
Technology orientated activities	2.0	2.5	***
Household orientated activities	3.5	2.8	***
Interests in natural phenomena	4.1	3.6	***
Interests in technology	2.6	3.1	***
I.Q.: language comprehension	10.8	11.0	n.s.
I.Q.: cubes and spatial ability	11.4	11.6	n.s.
I.Q.: figures and spatial ability	11.1	11.5	n.s.

x: smaller sample; ***: $p<0.001$, **: $p<0.01$, n.s.: not significant

Figure 2.1: Findings from Labudde et al.[3]

Given their equal abilities, the instructors concluded that gender difference in interest and performance in physics came in part out of the failure of the educators to take these different student backgrounds into account. To investigate, the researchers developed two groups of classes, one control group and one in which teachers focused on integrating preconceptions and different backgrounds and interests. The teachers of the modified classes discussed and implemented the following pedagogical ideas, broken down into four sub-sections:

- Interaction and feedback: pay equal attention to girls and boys, state explicitly your similar expectations concerning their abilities in physics, give all students enough time to answer a question, collect several answers to one question, give positive feedback during the lesson and in personal conversations.

- Self-concept of girls: praise girls not only for their diligence and discipline, but also for their ability and talent in physics, avoid any impression that physics is only something for highly gifted people or men, emphasize that girls are neither less 'attractive', nor less 'female', when they are interested in and good at physics.
- Contents of physics instruction: pay attention to the different experiences of girls and boys and to the context of physics instruction, create relations between physics and people whenever possible.
- Atmosphere and methods of learning: arrange conversations and discussions as often as possible; form single-sex groups for group-discussions and practicals; support co-operation and suppress open competition and make your physics classroom more comfortable.[4]

In addition, teachers introduced more everyday physics, project-learning, student presentations, and hands-on activities geared toward topics of student background and interest. This group showed major changes in student attitude, as both women's and men's expectations of future physics courses rose significantly from that of the control group. The integration of preconceptions/areas of interest and expectations of the students at the end of the intervention correlated as $r = 0.45$, $p < 0.001$[5] and the inclusion of everyday physics correlated with student expectations as $r = 0.15$, $p < 0.001$. The only other variables showing correlations of this magnitude were parents' knowledge of physics and their physics-related expectations for their children. Further studies[6,7,8] validate the same conclusion that abundant feedback, integration of the different everyday experiences and interests relevant to all students in the construction of new knowledge are important techniques in reducing the gender gap in interest in physics.

The next technique – cooperative learning – is similarly well-verified in the literature[9]. Over 500 distinct studies support the conclusion that cooperative learning benefits students across different disciplines, ages, genders, races, socioeconomic classes, abilities, and ethnicities.[10] One meta-analysis by Robert E. Slavin reviewed 64 cooperative learning studies in elementary and secondary schools. Nearly 80% of the studies found significant positive effects on student achievement. None found significant negative effects.[11] Slavin also found that the particular form of cooperative learning – the means of accountability, for example – can vary and students will still tend to benefit from this type of teaching and learning strategy.[12]

One such variation could be the amount of structured lecture that takes place during class, as compared to student discussion. Michael Gurian, an expert on education and gender, traces the impact of neurological sex differences:

> Because boys' brains have more cortical areas dedicated to spatial-mechanical functioning, males use, on average, half the brain space that females use for verbal-emotive functioning. The cortical trend toward spatial-mechanical functioning makes many boys want to move objects through space, like balls, model airplanes, or just their arms and legs… The male brain is better suited for symbols, abstractions, diagrams, pictures, and objects moving through space than for the monotony of words. These typical "boy" qualities in the brain help illustrate why boys generally learn higher math and physics more easily than most girls do when those subjects are taught abstractly on the chalkboard.[13]

In contrast, typical 'girl' qualities – such as increased oxytocin, a chemical linked to human interaction; better listening skills; better discrimination among various tones of voice; and more cortical spaces geared toward verbal and emotive functioning – lend themselves to classrooms with increased group discussion. While gender difference results must be cautiously considered as not all students will fit in the suggested binary, such findings are valuable for the insight the provide into how some men and women react differently to pedagogy.

A recent two-year program at the University of Missouri-Kansas City that taught teachers about these particular gender differences achieved impressive results. After developing lessons and classrooms that balanced both discussion and visual/abstract elements, one school doubled or tripled the number of students in top achievement levels.[14] Gender-specific treatment in Beaumont Middle School in Lexington, Kentucky, correlated with a significant rise in Scholastic Reading Inventory (SRI) scores.[15] Other researchers agree:[16] if co-ed classrooms are to continue, educators must embrace sex differences, as well as individual differences within students, with a combination of group discussion and structured lecture.

An Israeli study led by Anat Zohar and David Sela sheds light on two more pedagogical lessons: the impact of competitiveness in the classroom and the important difference between connection-based student understanding and equation-based rote-learning.[17] After finding significant evidence of a physics testing gender gap in a 400 high school Ministry of Education database study, the researchers conducted semi-constructed clinical interviews to gain understanding about how students viewed various issues regarding their physics studies. Two issues emerged as especially unfavorable to many women: excessive competitiveness and lack of teaching for true understanding.

In these interviews, more women than men saw competitiveness as a part of their physics class ($p < 0.05$), and many of the women explicitly noted that it makes them feel uncomfortable. One girl described her experience:

> It [the competition] is annoying. It ruins your desire to study. . . . It goes on in several classes, but in physics it's really bad . . . because it is an extremely competitive class . . . They constantly try to break in. Each sentence [the teacher] says, ten of them are trying to complete it for him. They are always breaking in and they vigorously fight each other trying to reply . . . It annoys me. I can't stand all that competition . . . I hate it.[18]

At the same time, women tended to find physics very interesting when they perceived a focus on true deep understanding of the material, as opposed to rote-learning. One student shared her excitement:

> [I enjoy] when they let us [go through] a thinking process . . . because they don't just give us formulas, exercises and that's it, now go take the matriculation exams. I know that in some schools that is the way they learn. This is how it is with most school subjects. That's a problem. But I like the way it is here [in physics class.] They don't just give you the formula . . . They often show you all the way from the beginning, how the person who discovered it was thinking. They show you an experiment and how he discovered it . . . You have the place where you have to think about how it will go on from here.[19]

In contrast, female students expressed severe disappointment when denied the chance for such learning. One girl described her physics experience as "turning into a nightmare" when the class became "formulas without any meaning."[20] One pinpointed the moment she lost interest in physics as when she realized there was no need to read the textbook in order to understand the full theory. She found that she did better when she practiced using the equations without understanding.[21] With regard to this lack of teaching for understanding, both the number of students and the degree of distress and frustration with which they expressed dissatisfaction were much larger for women than men. With other studies showing widespread support for these conclusions,[22,23,24,25] instructors who hope to bridge the gender gap in physics must make an effort to reduce competitiveness and foster true student understanding.

A hidden issue lies within this idea of 'true' student understanding. As exposed in the interviews above, many women perceive 'understanding' as based on connections and broader, personal, contexts. Through detailed study of taped introductory physics lab sessions, researchers at the Institute for Theoretical Physics at the University of Vienna constructed a framework for how men and women think of understanding physics differently.[26] Boys tend to work more abstractly, leading some to find satisfaction in understanding physics in and of itself. For example, consider the following excerpt from a class discussion on chaos (emphasis added):

> Boy: …when a star explodes, then the gravitation is changing and this influences the curve of the planets. Another example: if one is skiing downhill on a route full of humps, if one is falling down then, one does not know in which way one will fall…
> Girl: If now *you* are falling down a staircase, you cannot predict where you will fall.[27]

As in the Labudde findings on gendered areas of past background and interest, women tend to focus more on connecting the material with the personal and the natural. Boys, in contrast, are less likely to need broad contexts and connections. While instructors should take a balanced approach that includes abstract discussions of the concepts, students should be given ample opportunity to work with broader worldviews. For example, the Vienna group recommends allowing students "to formulate their ideas in everyday language and to use (personal) analogies and anthropomorphisms" throughout the learning process.[28]

These eight above strategies – integrating everyday experiences and interests relevant to both genders; tying-in student's prior knowledge and interests; providing frequent feedback; increasing cooperation and communication, amongst students as well as between students and instructors; including a combination of group discussion and structured lecture; decreasing competitiveness; emphasizing 'true' understanding that can apply concepts to different situations; and highlighting the role of physics within a broad worldview – inspired the Harvard research group of Lorenzo, Crouch, and Mazur to begin a large-scale study of the gender gap in their introductory mechanics physics courses. The researchers introduced interactive engagement (IE) methods in the form of peer instruction, *Tutorials in Introductory Physics*,[29] and cooperative quantitative problem-solving activities. On average, 202 students enrolled in the calculus-based course, which consisted of 1.5 hours of instruction twice per week in a large lecture hall and 1 to 2 hours of 15-20 student small sections per week.

In 1990, all lectures and sections took place in a traditional lecture format. The researchers refer to these students as the *T* group. From 1991-1995 (except 1992, when the researchers did not take data), the lecture changed to a 'Peer Instruction' model. This format separates the 90 minute class into 10-15 minute mini-lectures broken up by periods of small student-led group discussion addressing conceptual questions and difficulties. Instructors expect students to read the textbook material on the day's topic before class in preparation for these discussions, and students completed multiple-choice reading quizzes or small written assignments to ensure accountability. The instructors call these students the *IE1* group because of their course's increase in interactivity over the traditional *T* group. In 1996 and 1997, the researchers added a change in the structure of the small sections, using the *Tutorials* program developed at the University of Washington[30] and their own cooperative problem solving activities,[31] forming the fully interactive *IE2* group. The *Tutorials* program focuses on students' conceptual understanding and ability to apply newly learned physics formalisms to situations other than those expressly taught. To do this, the program walks students through the reasoning necessary to construct concepts and apply them in real-world situations while providing practice using formulas, graphs, diagrams, and verbal descriptions.[32]

To measure student learning, the researchers compared student improvement on the Force Concept Inventory (FCI), a widely known and validated multiple-choice test of conceptual mechanics understanding.[33] Specifically, instructors measured the class average normalized gain scores $\langle g \rangle$,

$$\langle g \rangle = \frac{\langle S_f \rangle - \langle S_i \rangle}{100 - \langle S_i \rangle}, \tag{1}$$

where $\langle S_i \rangle$ is the average score out of 100 on the FCI before instruction and $\langle S_f \rangle$ is the average score after the semester's instruction is complete. By breaking the gain scores down by gender and type of instruction, figure 2.2 best represents the study's results:

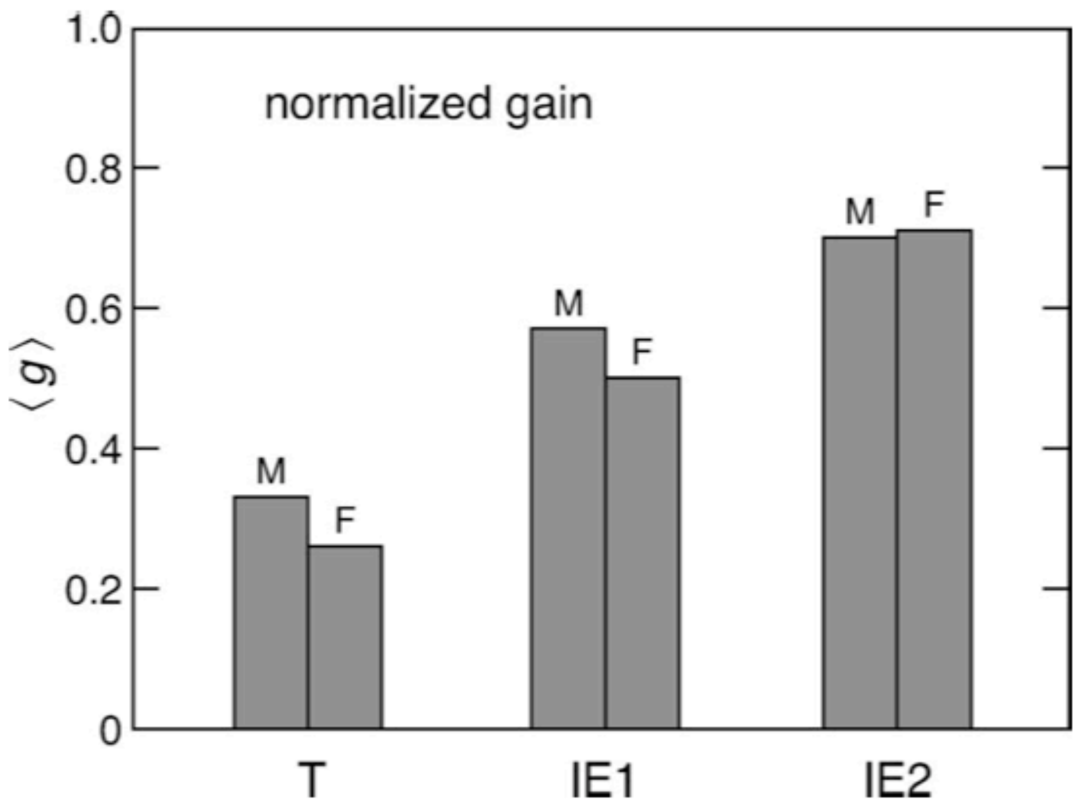

Figure 2.2: Results from Lorenzo et al.[34]

These results show that $\langle g \rangle$ increases significantly for both genders from the *T* to *IE1* to *IE2* instructional approaches – student learning increases as the level of interactive engagement increases. In addition, while gender gaps from *T* and *IE1* were statistically significant (with $p = 0.0004$ for *T* and $p < 0.0001$ for *IE1*), women's normalized gain scores actually surpassed men's in *IE2*, resulting in no significant gender gap ($p > 0.05$).[35]

After thorough analysis found no significant variation among instructors, the researchers concluded that the elimination of the gender gap is the result of changes in their pedagogical approach:

> We attribute the observed reduction of the gender gap to the use of Peer Instruction, the *Tutorials*, and cooperative problem-solving activities. These instructional methods give students opportunities to interact and explain their ideas during both lecture and section [while] providing frequent feedback to students on their understanding through the conceptual questions and tutorials, alternating between structured teaching and peer discussion, emphasizing conceptual reasoning, promoting collaboration among peers, and creating a less competitive classroom culture.[36]

Such lessons from previous gender gap research provide useful ideas for the formation of a quantum mechanics course geared toward bridging the gender gap. All instructors should heed the particular conclusions – increase in-class interaction, reduce competition, foster collaboration, and emphasize conceptual understanding – in order to combat the pressing gender gap in physics.

NOTES:

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[1] M. Lorenzo, C. H. Crouch, and E Mazur, “Reducing the Gender Gap in the Physics Classroom.” *American Journal of Physics* 74 (2006): 118-122.
[2] P. Labudde, W. Herzog, M. P. Neuenschwander, E. Violi, and C. Gerber, “Girls and physics: Teaching and learning strategies tested by classroom interventions in grade,” Int. J. Sci. Educ. **22**(2), 143-157 (2000).
[3] *Ibid.*, p. 149.
[4] *Ibid.*, p. 148.
[5] For an explanation and discussion of *p-values*, see chapter 5.
[6] L. McCullough, “A gender context for the Force Concept Inventory,” Paper presented at the winter meeting of the American Association of Physics Teachers, San Diego, CA, 2001 (unpublished).
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[9] L. Danzl-Tauer, “The relationship between intervention, equity, and excellence in rural high school biology classrooms,” Ph.D. dissertation, Purdue University, 1990. Results described in J. B. Kahle and J. Meece, “Research on gender issues in the classroom,” in *Handbook of Research on Science Teaching and Learning*, edited by D. L. Gabel (Macmillan, New York, 1994), pp. 542-557.
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[12] R. E. Slavin, “Research on Cooperative Learning and Achievement: What We Know, What We Need to Know.” Contemporary Educational Psychology **21,** 43–69 (1996).
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[15] *Ibid.*
[16] A. Kitchenham, “Vive la difference: Gender, motivation, and achievement,” School Libraries in Canad **22**(2), 34-37, 44 (2002); **22**, 44 (2002).
[17] A. Zohar and D. Sela, “Her physics, his physics: Gender issues in Israeli advanced placement physics classes,” Int. J. Sci. Educ. **68**(2), 63-89 (1984).
[18] *Ibid.*, p. 257.
[19] *Ibid.*, p. 259.
[20] *Ibid.*, p. 260.
[21] *Ibid.*, p. 260.
[22] P. Laws, P. Rosborough, and F. Poodry, “Women’s responses to an activity-based introductory physics program,” Am. J. Phys. **67**(7), S32-S37 (1999).

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[25] G. M. Hilderbrand, “Redefining achievement,” in *Equity in the Classroom: Towards Effective Pedagogy for Girls and Boys*, edited by P. F. Murphy and C. V. Gipps (Falmer and UNESCO, Washington, DC, 1996), p. 149-171.
[26] H. Stadler, R. Duit, and G. Benke, “Do boys and girls understand physics differently?,” Phys. Educ. **35**(6), 417-422 (2000).
[27] *Ibid.,* p. 420, italics in original.
[28] *Ibid.*, p. 422.
[29] L. C. McDermott, P. S. Schaffer, and the University of Washington PERG, *Tutorials in Introductory Physics* (Prentice Hall, Upper Saddle River, NJ, 1998).
[30] *Ibid*.
[31] M. Lorenzo, Table I.
[32] “Tutorials in Introductory Physics.” University of Washington Department of Physics. <http://www.phys.washington.edu/groups/peg/tut.html> Retrieved April 5, 2008.
[33] D. Hestenes, M. Wells, and G. Swackhamer, “Force Concept Inventory.” Am. J. Phys. **30**(3), 141-151 (1992). Revised in 1995 by I. Halloun, R. R. Hake, E. Mosca, and D. Hestenes.
[34] M. Lorenzo, Figure 2.
[35] *Ibid.*, p. 120.
[36] *Ibid.*, p. 121.

Chapter 3: Agential Realism

Agential Realism, a feminist approach to teaching quantum mechanics created by Karen Barad, proposes significant pedagogical changes in physics. Barad draws primarily on the scientific philosophy of Neils Bohr, disagreeing with those who believe that science describes some objective, independent world. Instead, she ascribes science the role of describing 'the between' – the interactions (or, "intra-actions", in her terminology) of objects and humans, participants and observers. She combines a feminist science perspective with the view that reality is comprised of 'intra-actions' between objects and 'agencies of observation,' such as the involved apparatus and observers. In critiquing the dominant culture in physics education, Barad calls for a shift away from a complacent 'relax and enjoy it, the instructor will tell you how the world works' mentality. In its place, education should emphasize the role of the students as scientists in an ongoing process of understanding and constructing theory as well as in the reality described by the theory itself. In doing so, she highlights the impact of scientists' particular social positions within this depiction of science. She pushes away from a stark, clean, neat, 'objective' view of science and draws on quantum mechanical truths to replace it with a focus on the very personal. She emphasizes the impact of "cultural and ideological specificities (e.g., political, historical, linguistic, racial, religious)" on science.[1]

To understand agential realism, one must first consider the quantum mechanical truths that inspired Bohr's epistemology. Bohr reacts primarily to six discoveries that challenge a deterministic, mechanics-based description of the universe as a collection of independent, objective objects: the issue of wave-particle duality, the nature of collapsing superpositions, the uncertainty principle, the interaction of knowledge and behavior, the concept of entanglement, the peculiarity of measurement within quantum mechanical systems.

Wave-particle duality is evident in even the most cursory descriptions of quantum-scale matter. Experimental phenomena such as the photoelectric effect and bubble chamber particle tracks demonstrate the particle-like behavior of photons, electrons, and the like. At the same time, these so-called particles act like waves, diffracting and interfering in two-slit experiments. In a quantum-mechanical framework, the de Broglie relation and a probability density model can help to unify these apparently incongruous behaviors, but a difference from a macroscopic understanding of matter remains. Scientists must accept that these objects – best called quantons so as not to show bias toward either particles or waves[2] – demonstrate both wave and particle-like attributes.

Quantons continue to demonstrate surprising abilities in the realm of superpositions. Possible measurements, such as the spin of an electron or the polarization of light, correspond to operators, for whom a given set of eigenstates describes the potential outcomes. The most common example refers to measuring the spin of a quanton along a particular axis, where the possible outcomes are exclusively up, $|\uparrow\rangle$, or down, $|\downarrow\rangle$. Experiments with Stern-Gerlach devices[3] reveal the peculiar truth that a group of identically prepared quantons, while only measurable in either $|\uparrow\rangle$ or $|\downarrow\rangle$ for this experimental set-up, can sometimes be found in $|\uparrow\rangle$ and sometimes in $|\downarrow\rangle$. Quantum mechanics refers then to this quanton as a superposition of the states $|\uparrow\rangle$ and $|\downarrow\rangle$. The quanton has probabilities of being measured as one eigenstate or another as determined by the coefficients of superposition, but until measured the spin is not necessarily one direction or the other. Determinate values only exist when an appropriate apparatus for measuring that value acts on the quanton.

Attempting to obtain full information about a given state raises the next issue, the uncertainty principle first introduced by Heisenberg. After measuring the quanton's spin along one axis, then along another axis orthogonal to the original, repeating the initial measurement does not give the same result. 50% of the time the quanton's spin will come up as $|\uparrow\rangle$ and 50% of the time as $|\downarrow\rangle$. It is once again in a superposition of states $|\uparrow\rangle$ and $|\downarrow\rangle$. Introducing some other apparatus designed to determine a different value returns the original value to a superposition. In this way, uncertainty may be a misleading term, as the case really is one of indeterminacy. It is not a matter of observer limitations in measurement that prevent knowing the exact values of the spins along each axis – such knowledge is unattainable.

The canonical two-slit experiment goes even further in emphasizing that the amount of observer knowledge actually affects the system. The fact that sending quantons through one at a time produces an interference pattern is best explained by describing the quantons in a superposition of having gone through both slits. Placing 'which-way' detectors at the slits that announce through which slit a quanton just passed destroys the interference pattern. This 'which-slit' knowledge is a measurement that collapses the superposition of paths taken, without which there cannot be an interference pattern. In this way, the measurement/collapsing of wavefunctions link knowledge with the behavior of the system.

The idea of entanglement can in many ways be thought of as the extension of superpositions to two quantons. If two quantons are prepared in an entangled state such that measuring a particular value for one determines that value for both, the entangled state of the two quantons must be understood as a single entity.[4] In a similar way to how measuring a quanton affects its superposition and thus its other potentially measurable values, measuring the entangled value in one quanton affects the other.

This moment of measurement is particularly interesting. In some macroscopically unfamiliar way, the state transitions suddenly and completely during the process of measurement. For example, in the well-known thought experiment of Schrödinger's cat, opening the box takes the cat out of its superposition of $|\text{alive}\rangle$ and $|\text{dead}\rangle$, collapsing the 'aliveness' value of the cat into one of these states. The particular nature of this transition eludes any macroscopic-like description.

In this issue one finds a relatively accessible entrance to Bohr's epistemology. One common thread in his philosophical writings is the idea of a specific 'cut' enacted between the objects and the agencies of observation. In the place of a world composed of individual objects with individually determinate boundaries and properties, he describes a nature in which "the nature of the observed phenomenon changes with corresponding changes in the apparatus."[5] Wave-particle duality is not a logical inconsistency because of the complementary nature of apparatuses/situations that measure for either wave-like behavior or particle-like behavior.

To Bohr, wave-particle duality, superpositions, the uncertainty principle, the interaction of knowledge and behavior, entanglement, and the peculiarity of measurement all point toward a "'quantum wholeness,' or the lack of an inherent […] distinction between the 'object' and the 'agencies of observation.'"[6] Every complete description of reality or elements within must include the observer and apparatus. Both are central to its very nature, as the universe is comprised of intra-actions between these 'objects' and 'agencies of observation' at the quantum scale.

To form the backbone of agential realism, Barad couples Bohr's philosophy-physics with more than two decades of feminist sciences studies research, particularly Sandra Harding's "standpoint theory."[7] These feminist scholars concentrate on the interaction between scientific knowledge and gender, race, sexuality, and class ideologies. Standpoint theory, for example, focuses on 'strong' objectivity, in which scientists best describe the world through the inclusion, not omission, of identity.

Scientists produce socially situated knowledge by recognizing how their past experiences, biases, culture, and expectations influence the models they use and/or question. Historical examples are commonplace – look to the difference between medieval and contemporary astronomy models of orbits derived from the same data, for example.[8] Even using the same data, scientists gravitate toward theories and ideas about theories based on their identity. Gender plays an important, but often undervalued role – consider the delay in the discovery of an all-female species of lizard. Might scientists more aware of gender interactions be better prepared for such a finding?

Standpoint theory stands in contrast to a view of science as a process whose subject can speak absolute truth about the universe from no particular social location or human perspective at all.[9] While the timed swings of a pendulum will not change based on the gender of the observer doing the timing, the models one might propose or choose to adhere to/challenge are a function of the scientist's identity. As put by Harding,

> Scientists can never study the trees, rocks, planetary orbits, or electrons that are 'out there' and untouched by human concerns. Instead, they are destined to study something different (but hopefully systematically related to what is 'out there'): *nature as an object of knowledge*. Trees, rocks, planetary orbits, and electrons always appear to natural scientists only as they are already socially constituted in some of the ways that humans and their social groups are already socially constituted for the social scientist.[10]

According to standpoint theory, scientist must recognize the impact of their identities on how they attempt to perceive the world around them.

Barad draws on the precedent set by these authors to demand a shift away from the dominant culture 'Physics is Phun' approach, a mindset counter to true student understanding. 'Physics is Phun' pushes student towards equations and numbers and away from the conceptual struggles necessary in understanding quantum mechanics. In doing so, it also separates physics from the real and the personal. Consider a Richard Feynman quote that epitomizes this 'Physics is Phun' perspective:

> On the other hand, I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you really have to understand in terms of some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. If you simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing.[11]

Not only does Feynman encourage his students to "just relax and enjoy it" instead of struggling to understand the material, but he fails to encourage any critical questioning of the material presented, instead treating it as "[this] is what nature behaves like." Implicit in such a presentation of physics is a removal of the historical and personal differences, struggles, disagreements, and uncertainties that went into the formation of this theory. The continuing denial of such a process discourages students from fully taking part in the scientific questioning and learning process, particularly amongst traditionally underrepresented groups in physics who may lack scientific role models who share their background. Adrienne Rich, one such feminist scholar, describes the effect: "When someone with the authority of a teacher, say, describes the world and you are not in it, there is a moment of psychic disequilibrium, as if you looked into a mirror and saw nothing."[12] Students will lose interest in an approach that excludes them for two reasons. First of all, this world lacks relevancy – if they do not see themselves, this model either does not apply to them or they do not/cannot take part. Secondly, a model of the world that fails to include its observers must be incomplete. A feminist approach to science demands the active inclusion and participation of all students – they must see themselves as part of the world being described, and they must be able to claim some agency in the process of description.

The impact of the "do not take the lecture too seriously, feeling that you really have to understand" approach cannot be minimized, either. As explored in chapter 2, a failure to focus on true understanding may be a major contributor to the gender gap. Instead of fastforwarding through conceptually difficult material in order to focus on working with equations and numbers with which students might be more comfortable, educators must allow students to struggle with quantum mechanics. In fact, recent work by the Mazur Physics Education Research Group indicates that students who express confusion with challenging material may be more likely to correctly understand the concepts.[13] Confusion is not something to be avoided at all costs, but is instead an integral component of the learning process.

Synthesizing standpoint theory and this pursuit of true student understanding with Bohr's philosophy-physics, the theory of agential realism doubly highlights the role of the scientist-student. As per Bohr, no scientific theory is complete without incorporating the observer and apparatus. In Bohr's "quantum wholeness," the student-scientist's exact situation – her biases, her background, her equipment, and what she seeks to measure – are what interact with the object of study to determine the value under investigation. Moreover, this is the nature of reality – every aspect of every moment is the result of these intra-actions.

Within this framework, pedagogy should move toward a more sophisticated, nuanced treatment of difficult principles that increasingly brings up important historical and philosophical issues. It must encourage students to struggle with difficult concepts and reflect on the process of science by emphasizing the existence of disagreement and misunderstanding on the part of past physicists.[14] It must foster true student understanding, not rush toward numbers and equations. Just as Bohr broke away from the ideas of an independent, objective reality, physics should depart from "an extreme culture of objectivity: a culture of no culture, which longs passionately for a world without loose ends, without temperament, gender, nationalism, or other sources of disorder – for a world outside human space and time."[15] Agential realism demands that students engage with the challenging concepts of quantum mechanics in a context that recognizes quantum as real, relevant, and continually under discussion. Educators must strive to ensure that students see themselves as active participants in that dialogue as well as in the nature it describes.

NOTES:

[1] K. Barad, "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995), p. 70.
[2] This idea came from T. Moore, *Six Ideas That Shaped Physics, Unit Q: Particles Behave Like Waves*. New York: McGraw-Hill Higher Education (2003), p. 78.
[3] For a good description, see *Ibid.*, pp. 85-114.
[4] This assertion forms a large part of Bohr's response to the EPR challenge to quantum mechanics, and is also affirmed by tests of Bell's inequality. Barad offers a much more in-depth discussion in *Meeting the Universe Halfway*, pp. 269-274, including how Bohr's response is more than just a challenge to locality.
[5] K. Barad, *Meeting the Universe Halfway*. London: Duke University Press (2007), p. 106.
[6] *Ibid*., p. 118.
[7] For a thorough introduction, see S. Harding, Ed. *The Feminist Standpoint Theory Reader: Intellectual and Political Controversies*. New York: Routledge, 2004.
[8] S. Harding *Whose Science? Whose Knowledge? Thinking From Women's Lives*. Ithaca, New York: Cornell University Press, 1991, pp. 145-146.
[9] D. Haraway, "Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective." *The Feminist Standpoint Theory Reader: Intellectual and Political Controversies*. Ed. Sandra Harding. New York: Routledge, 2004, p. 81.
[10] S. Harding, "Rethinking Standpoint Epistemology: What is 'Strong Objectivity?'" *The Feminist Standpoint Theory Reader: Intellectual and Political Controversies*. Ed. Sandra Harding. New York: Routledge, 2004, p. 133, italics in original.
[11] R. Feynman, *The Character of Physical Law*, Cambridge, MA: MIT Press (1965) from K. Barad, "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995), p. 43.
[12] A. Rich, "Invisibility in Academe" in *Blood, Bread, and Poetry: Selected Prose 1979-1986*. New York: Norton (1986) from K. Barad, "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995), p. 45.
[13]E. Mazur, "The scientific approach to teaching: Research as a basis for course design", presented at Teaching and Learning Committee Lunch Talk at Pomona College in Claremont, CA on 14 April 2008. Talk available online at <http://mazur-www.harvard.edu/talks.php>.
[14] K. Barad, "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995), p. 47.
[15] S. Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists*. New York: McGraw-Hill (1988). From K. Barad, "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995), p. 46.

Chapter 4: Creating a Better Quantum Class

Given the suggested pedagogical improvements of chapters 2 and 3, the focus now shifts toward the implementation of these gender-gap reducing strategies in two quantum mechanics classes in the introductory physics course of Pomona College. While the first session draws particularly on past mechanics-based pedagogical research, the other focuses on presenting the 'agential realist' approach to quantum mechanics. The class session chosen covered chapter 4 and sections 1-4 of chapter 5 in the text *Six Ideas That Shaped Physics Unit Q: Particles Behave Like Waves*,[1] which introduces wave-particle duality, the de Broglie hypothesis, and the two-slit interference experiment.

As self-identified on the response forms, the first class had only 7 students, 6 males and 1 female,. The second had 20 students, 10 male and 10 female. The larger class was paired with the agential realist teaching approach in order to lend more weight to the findings on this less established pedagogy. Separate lesson plans, available in appendix A, were prepared for each class in cooperation with Prof. Thomas Moore, who was chosen as an unbiased instructor. Students completed questionnaires both before and after each class measuring student interest in quantum mechanics and science using a simple Likert scale. In addition, the questionnaires contained a straightforward free-response question to measure student understanding of wave-particle duality. Each class was observed and videotaped, and neither experienced any significant deviation from the lesson plan. Final preparations included changes to the physical space of the classroom – while the first class sat in different tables of two or three facing forward, the second sat at tables arranged in a large circle to encourage an open atmosphere for discussion.

As is customary in most sessions of Pomona's introductory physics courses, students completed reading and a small problem set on the day's material before class. After reviewing the students' responses in order to gauge student understanding of the reading, the instructor explored some of the more conceptually difficult material from an experimentalist perspective, keeping students involved with a variety of probing questions. Consider the following interaction:

> Instructor: "To get to the conundrum that's being presented in these chapters, what's the evidence that light is a wave?"
> Student: "It makes interference patterns…"
> Instructor: "Yeah, you saw these in class with your own eyes [using a laser] that light is a wave. …What's the evidence that light is a particle -- that is, can be described usefully as photons?"
> Student: "The Photoelectric effect."
> Instructor: "Right. Good. The chapter even discusses how you can actually count photons one-by-one. What about the evidence that an electron, say, to take an example, is a particle?"
> Student: "We've always treated it as a particle."
> Instructor: "Yeah, why?"
> Student: "Because we can measure its mass."
> Instructor: "Right. Which means ultimately, somehow, we figure there are individual electrons." [Instructor goes on to describe the Millikan oil drop experiment and the resulting conclusions about the quantization of charge].

In his lecture on the chapter's material, the instructor consistently grounded each concept in its experimental origins, many of which students had seen as demonstrations or laboratory exercises. Moreover, he sought to highlight the story and people behind the experiments:

> Instructor: It's really kind of a cool story about how [Davisson and Germer] broke their apparatus and tried to fix it and couldn't put it back together to make it work. They were supposed to be doing something else entirely. And then they noticed this weird behavior and they discovered this whole thing [electrons making interference patterns] by accident. It was very good of them to not just say, "Well, looks like we screwed that up" and throw it away and actually say, "This is odd – why should it

> behave like this?" and try to figure out what was going on. And that was a very important moment.

After reviewing these basic concepts, the instructor moved to a more theoretical discussion, deriving the de Broglie hypothesis formula as a way of interrelating the concepts of wavelength, momentum, and Planck's constant as well as describing wave behavior. About 15 minutes into class, he shifted gears away from lecture to do an example problem in small groups, allowing the students a couple of minutes to work with one another at their tables to answer the following question:

> (Q4T.3) Imagine that in a Davisson-Germer type of experiment we shine a beam of electrons on a nickel crystal perpendicular to the crystal face and find the we get enhanced scattering at an angle of 50 degrees. If we double the kinetic energy of the electron beam, the angle of enhanced scattering will (A) increase or (B) decrease by a factor of:
>
> A. A bit less than $\sqrt{2}$
> B. Exactly $\sqrt{2}$
> C. A bit more than $\sqrt{2}$
> D. A bit less than 2
> E. Exactly 2
> F. More than 2
> G. Some other number (explain)

This question focuses on conceptual student understanding: it connects theoretical concepts to experimental phenomena; forces students to think abstractly about the relationships between scattering angle, electrons, kinetic energy, and wavelength; and uses proportionality to key students in on the these relationships instead of simply plugging into an equation. Students did not compete to answer first, but rather helped each other and answered simultaneously by showing their answer to the teacher visually.

After discussing the sample problem, the class shifted into a technology-based interactive activity using the *Interference* program developed by Jason Evans and Prof. David Tanebaum (Pomona College).[2] This program allows students to see the one-quanton-at-a-time build-up of an interference pattern. The program also features the ability to modify the slit and separation size and add detectors with variable accuracy that collapse the two-slit interference pattern. After the instructor introduced the program and demonstrated the two-slit experiment, the class discussed how each quanton "interferes with itself" to create the two-slit pattern. Students then collaborated together to the following question from the text, in which they matched different experimental set-ups with the resulting interference patterns:

Q5T.2 Figure Q5.8 displays a sample interference pattern and five interference patterns labeled A through E. Each row of the table below describes a set of parameters that will create one of the displayed patterns (the first row shows the parameters that display the "Sample" pattern). The table rows are organized so that each set of parameters differs from the previous one by a change in only one value. The Detectors column refers to whether there are proximity detectors operating at the slits. Your task is to write the appropriate letter in the rightmost column of the table. You might use some of the letters more than once. (Thanks to David Tanenbaum and Jason Evans for developing this exercise.)

Case	Wavelength	Slit Width	Slit Separation	Detectors?	Pattern
Sample	5 nm	3 μm	10 μm	No	Sample
(a)	5 nm	6 μm	10 μm	No	______
(b)	5 nm	6 μm	20 μm	No	______
(c)	10 nm	6 μm	20 μm	No	______
(d)	10 nm	6 μm	20 μm	Yes	______
(e)	10 nm	6 μm	10 μm	Yes	______

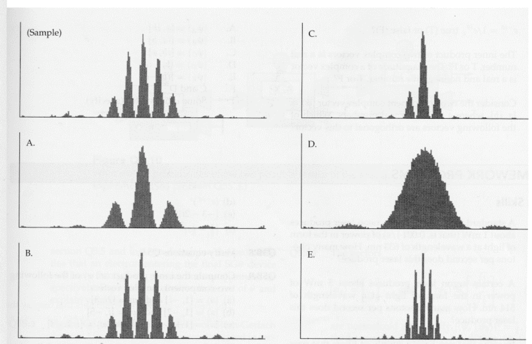

Figure Q5.8 (see problem Q5T.2).

Figure 4.2: Student Activity for use with the *Interference* program.[3]

By having students first predict the answers without the use of the program, this problem accesses past student knowledge about the relationship between wavelength and 2-slit interference patterns to explore the wave-like properties of quantons. At the same time, students get to apply their new knowledge that adding detectors creates a 1-slit interference pattern. Using the program, students get to see the pattern build up statistically as the result of many thousands of quantons and validate or correct their predictions. Figure 4.1 shows students at work on this activity:

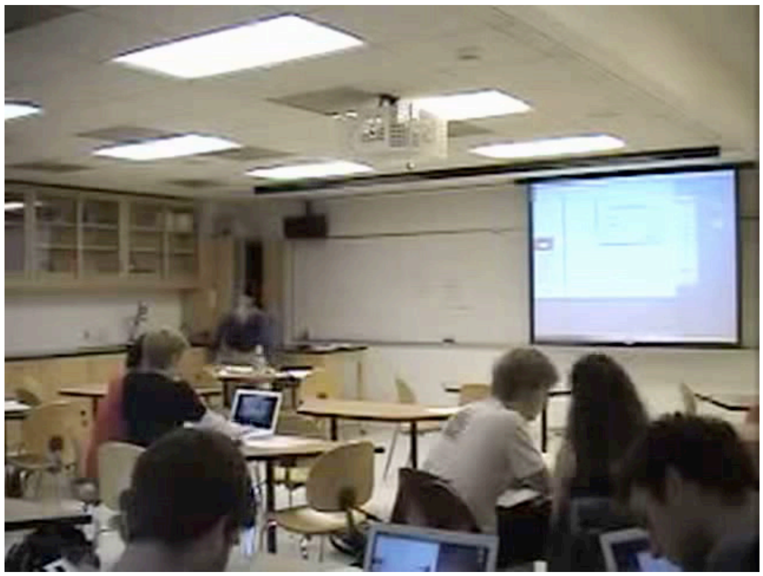

Figure 4.1: Students at Work Together in the Mechanics-Based Pedagogy Class

After predicting the pairings, students then checked their logic using the *Interference* program. This extended computer-based student activity took students until the end of class.

Recall that mechanics-based gender-gap research called for the first session to focus on integrating everyday experiences and interests relevant to both genders; incorporating student's prior knowledge and interests; providing frequent feedback; increasing cooperation and communication, amongst students as well as between students and instructors; balancing student interactive activities and structured lecture; decreasing competitiveness; emphasizing 'true' understanding that can apply concepts to different situations; and highlighting that physics is part of a broader context. Through its combination of broad context, experiment-based lecture and non-competitive, collaborative student activities, this session succeeded in adopting these strategies.

Consider the exchange between the instructor and students in the first section, as they use the *Interference* program model of quantum behavior to understand the two-slit experiment:

> Instructor: Now here's the part that's really freaky about this. What happens if I try and figure out which slit the particle went through? …You can put detectors by each slit – see the detectors? -- and do one particle at a time. See? Then, Ah! That one went through the lower slit. And I do another particle. Ah! That one went through the upper slit. And I do more particles… what's going to happen if I do thousands?
> Student: About half of them should go through each slit.
> Instructor: You think so? Yeah, they'll be pretty closely equal, because it's random. What kind of pattern will be formed?
> Student: You'll get a lot in the middle [of the screen], but not the double-slit pattern.
> Instructor: Right! [There are actually] two single slit patterns, slightly displaced from each other… When you try to find out what slit the quanton went through, you destroy the double slit pattern. [Instructor explains the idea of each quanton interfering with itself to create the pattern]. Now, if you don't find that disturbing, that reality should behave this way, then you're not really understanding it! [Laughter]. …It's not explainable in any classical way. This is about simply knowing, or even having the possibility of knowing, which slit the electron went through.
> Student: Are there still people working on this now, trying to figure out why this works?
> Instructor: Yes, oh yes! And it's resisted solution for 70 years or so!

Students grappled with the concepts interactively, working with one another and with a model that they got to control, working toward true understanding. The student's last reaction demonstrates the non-exclusivity of the two approaches, as recognizing the relevance and continual discovery of quantum mechanics is a major goal of the agential realist approach, as well. Finally, notice the effect of the hands-on model – the experimental phenomena become personal: the instructor gets to say "*you* can put detectors" and students begin their explanation with "*you'll* get…". Students were able to grapple with concepts within a personal framework in a highly engaging, collaborating, and non-competitive environment.

The second class session covered the same material (Q4-Q5.4), but students also read supplementary material in preparation of a discussion about the implications of wave-particle duality. Appendix B contains the first part of these materials: a two page reader presenting Bohr's philosophy-physics and comparing it with Heisenberg, Einstein and Barad's perspectives.[4] In addition, students read pages 186-191 from Brian Greene's physics for non-physicists volume *The Fabric of the Cosmos*.[5] These readings met the desired criteria: they provided interesting material that would elicit student discussion relevant to the topic of quantum mechanics; be appropriately leveled for current student knowledge; raise the issue of how identity-related assumptions interact with science; be relatively brief; and not just describe quantum phenomena, but rather begin to ask critical questions about how quantum mechanics might change one's perceptions of reality. Students were asked to bring a 1-2 paragraph typed or hand-written response to class answering any of the discussion questions interspersed throughout the reading or on a topic of their choice that they wished to explore.

Class began in much the same way, exploring some of the more conceptually difficult material from an experimentalist perspective, though without the benefit of the students completing any problems before class. After the 15-minute lecture on wave-particle duality and the de Broglie hypothesis, the instructor moved into the *Interference* program demonstration and a shortened version of the related student activity. 30 minutes into the class, the instructor sat down and began prompting student discussion of the reading material.

Initially, students reacted poorly to the change in class structure. Despite each completing a brief reading response, nobody spoke in response to the instructor's first questions, even after more than twenty seconds of silence. After the instructor asked more specific questions, students began to engage with one another as hoped for:

> Student 1: "I think that as powerful as the mind is, it can't create things from nothing. So I feel like there has to be an objective reality, whether or not we know if we can fully understand it. I feel like there has to be something there in order for us to perceive it. I can't perceive nothing." […]
> Student 2: "I would disagree and say that we can't perceive passively. The whole idea that I got from this article is that it's just impossible to even look at something or imagine something or do anything passively. It's always active. So, since the act of doing that changes it, how can you say that there was something before? Even trying to look at the thing before would change it. You can never get something that won't be changed by observing it."

Though conversation only briefly touched on the intersection of identity and science, students thoroughly debated the issue of whether or not science describes an independent reality. While students recognized the impact of quantum ideas about the role of the observer, they also discussed how science "works":

> Student: "Science, or rationality, is one of the most valid forms of truth. Even though we can't access the exact nature of something in and of itself, we have access to the perception of an object. And, with that perception, we can observe its properties and deduce these actual physical laws that correlate to that experience… and it's valid, to a certain degree."

Figure 4.2 shows the class in the midst of the discussion:

Figure 4.2: Students in the Agential Realist Section

The discussion definitely provided a sophisticated and nuanced treatment of the difficult concepts of quantum mechanics, particularly as they relate to students' perceptions of the world around them. In this way, the second session did well to introduce quantum mechanics using agential realist pedagogy: students recognized the existence of past and ongoing disagreements between scientists about these issues; the class focused on exploring conceptual difficulties, not rushing toward numeric descriptors or telling students to "just relax and enjoy it"; and students became active participants in a discussion of real and relevant quantum mechanics.

Written student responses also confirm that students began to engage in the challenging philosophical and conceptual issues. Consider some excerpts from these responses:

> I suppose that the realist opinion resonates best with me, probably because if you expand the non-realist view as Einstein did, to the extent of the moon disappearing or completely changing its behavior when our backs re turned – why, then the non-realist view seems like some sort of non-falsifiable paranoia. If I'm watching the moon, and it doesn't deviate from its normal behavior whether or not I'm the only one watching, or whether one or five or ten thousand of my friends decide to watch it with me, then I think that the moon won't alter.
>
> The realist understanding of science stems from our everyday experience of the world through our senses and also from historical and philosophical expectations. The reductionist approach to science *began* by dividing macroscopic objects into component parts in order to fully understand [them, leading to] the discovery of atoms and sub-atomic particles (which is of course where the trouble starts).

As sought by the agential realist approach, students applied the readings to their lives, their perceptions of the world, and their understanding of science. Consider one student's reaction:

> I definitely liked [the agential realist class]. It was more engaging. Sometimes I feel like I could just sleep through physics class and get the same grade. [The discussion] made it more real… and we were in charge. Sometimes, in quantum in particular, there's a disconnect. [The discussion] made it matter.[6]

The question that remains is how, quantitatively, did the sections affect the gender gap and student interest? Chapter 5 provides the informative and potentially surprising answer.

NOTES:

[1] T. Moore, *Six Ideas That Shaped Physics, Unit Q: Particles Behave Like Waves*. New York: McGraw-Hill Higher Education (2003).
[2] This BASIC program is available online through the Pomona College Physics Department website "Programs" for the introductory class, 51, at <http://www.physics.pomona.edu/sixideas/sicpr.html>. It was created by Jason Evans and Prof. David Tanenbaum (Pomona College) and modified for use by Prof. Thomas Moore (Pomona College) over the summer of 2007. The program is freeware, and may be freely distributed, used, and/or modified, subject to the terms of the GNU General Public License, version 2 or higher (http://www.opensource.org/licenses/gpl-license.php).
[3] Problem Q5T.2 from T. Moore, *Six Ideas That Shaped Physics, Unit Q: Particles Behave Like Waves*. New York: McGraw-Hill Higher Education (2003), pp. 92-93.
[4] G. Stecklein "A Companion Reader for an Introduction to Quantum Mechanics." Created for Pomona College Physics Department Senior Exercise *Bridging the Gender Gap*, 2008.
[5] B. Greene, *The Fabric of the Cosmos*. New York: Vintage Books, 2004, pp. 186-191.
[6] Informal interview with participant, Pomona College, 19 April 2008.

Chapter 5: Results and Analysis

This section focuses on the quantitative results of the two approaches to bridging the gender gap – first, pedagogy inspired by past gender gap work in mechanics courses, and second, the agential realist approach described in chapter 3. Both classes received pre and post-session questionnaires consisting of one free-response question to measure student understanding of wave-particle duality and 6-8 Likert-scale questions on interest in science marked on a scale of 1 to 5. Students were made aware that their answers would not be seen by their instructor nor affect their course grade in any way. The pre-class questionnaire asked:

1. Describe what a physicist might mean by "wave-particle duality." [free response]
2. How well do you feel you understand quantum mechanics (from 1 = not well at all to 5 = very well)?
3. How would you rate your interest in physics before taking this course? (from 1 = no interest to 5 = much interest)?
4. How would you rate your interest in quantum mechanics before this course?
5. How would you rate your interest in physics now?
6. How would you rate your interest in quantum mechanics now?
7. To what extent are you considering a future career as a physical scientist (e.g. physicist, geologist, chemist, astronomer, but *not* life sciences or medicine)?
8. How "good" do you think you are at physics (from 1 = not good at all to 5 = very good)?
9. How well do you feel this class embraces your personal learning style?

The post-class questionnaire asked:

1. Describe what a physicist might mean by "wave-particle duality." [free response]
2. How well do you feel you understand quantum mechanics (from 1 = not well at all to 5 = very well)?
3. How would you rate your interest in physics now (particularly in light of the most recent class session, from 1 = no interest to 5 = much interest)?
4. How would you rate your interest in quantum mechanics now (particularly in light of the most recent class session)?

5. If more sessions were like this most recent class session (today's), how do you think your interest in a future career related to physics might change (from 1 = strongly decrease to 5 = strongly increase, with 3 = no change)?
6. If more sessions were like this most recent class session (today's), how do you think your perception of how "good" you are at physics might change (from 1 = strongly decrease to 5 = strongly increase, with 3 = no change)?
7. How well do you feel the most recent class session (today's) embraced your personal learning style?

Student responses to the free response question were graded, with the identities of the students concealed, out of 3 using the following rubric: 1 point for on-topic effort shown, 1 point for recognizing this duality applies to all quantons (light, electrons, etc.), and 1 point for acknowledging that the particular experimental context determines which behavior the quantons demonstrate. Example of responses earning a score of 3 include "Quantons can be perceived as waves or particles, depending on how they react to different tests (and, in the case of the beam-splitter experiment described in the text, whether or not you observe their path)" and "All light and matter exhibits wave-like and particle-like behavior depending on the situation involved."

After calculating the average question 1 score for students in each session before and after the class, the normalized gains can be compared, where for pre score average s_1, post score average s_2, and maximum possible score *S*, the normalized gain is given by

$$\langle g \rangle = \frac{s_2 - s_1}{S - s_1}. \tag{1}$$

This gain score provides a measurement of student learning.[1] To measure the difference between normalized gains, this statistical analysis uses *p-values*. These values represent how consistent this difference is with zero. In particular, the calculation uses the Gaussian approximations of the standardized deviation-based uncertainties to calculate the probability that a given measurements within the distribution of each gain score would not have a positive difference. By convention *p-values* of 0.05 or less, that is a 5% or smaller probability, are considered significant.[2]

Table 5.1 shows the results of question 1 for the two classes, where each average or gain is listed with its uncertainty in parenthesis, as propagated from the standard deviation of the mean for the average scores.[3] Unfortunately, the presence of only one woman in the first section rendered gender differences statistically meaningless in that class, data are broken down by gender for the second section only.

Class:	Pre Avg.	Post Avg.	Normalized Gain
Mechanics-based pedagogy	1.79 (0.21)	2.43 (0.20)	0.53 (0.19)
Agential realist approach	1.31 (0.20)	2.19 (0.25)	0.52 (0.16)
Male	1.14 (0.14)	1.86 (0.40)	0.38 (0.22)
Female	1.44 (0.34)	2.44 (0.29)	0.64 (0.20)

Table 5.1: Student Gains in Understanding of Wave-Particle Duality

This study found no statistically significant difference in students' gains in understanding of wave-particle duality between the two approaches. In addition, there was *no significant difference in the gains between genders* ($p > 0.05$). The agential realist approach erased the gender gap in students' learning of wave-particle duality.

For purposes of context, consider figure 5.1, which compares these normalized gains to those from Lorenzo et al:

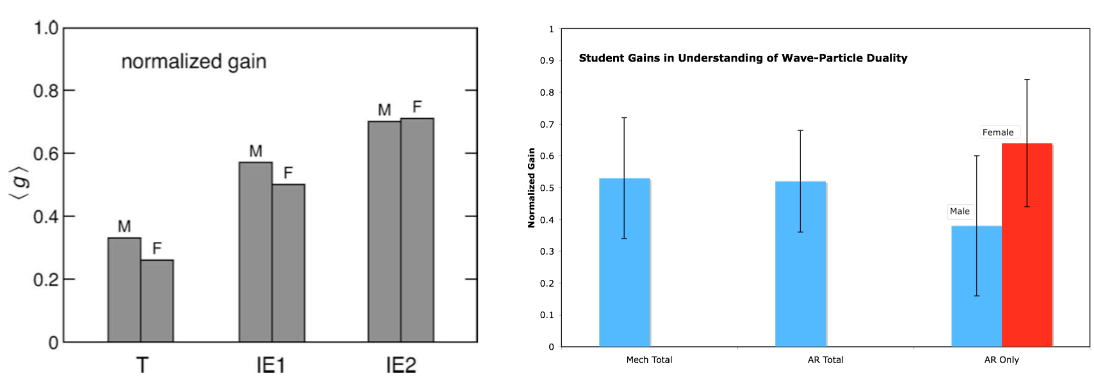

Figure 5.1: A Context for Student Gains in Understanding of Wave-Particle Duality[4]

The gains experienced by both classes as a whole are quite comparable to the IE1 group, whose gender gap was also not statistically significant. According to Hake's normalized gain classification,[5] these qualify as medium gains: $0.3 \le \langle g \rangle < 0.7$.

Students' *perceived* understanding of quantum mechanics, while lower than the actual gains, also showed no significant difference between the two sections. Table 5.2 and Figure 5.2 display how students responded to the question "How well do you feel you understand quantum mechanics (from 1 = not well at all to 5 = very well)?", again with uncertainties in parenthesis:

Class:	Pre Avg.	Post Avg.	Normalized Gain
Mechanics-based pedagogy	2.86 (0.46)	3.43 (0.30)	0.27 (0.21)
Agential realist approach	2.63 (0.20)	3.13 (0.13)	0.21 (0.09)
Male	2.71 (0.42)	3.00 (0.22)	0.13 (0.19)
Female	2.56 (0.18)	3.25 (0.15)	0.28 (0.08)

Table 5.2: Gain in Students' Perceived Understanding of Quantum Mechanics

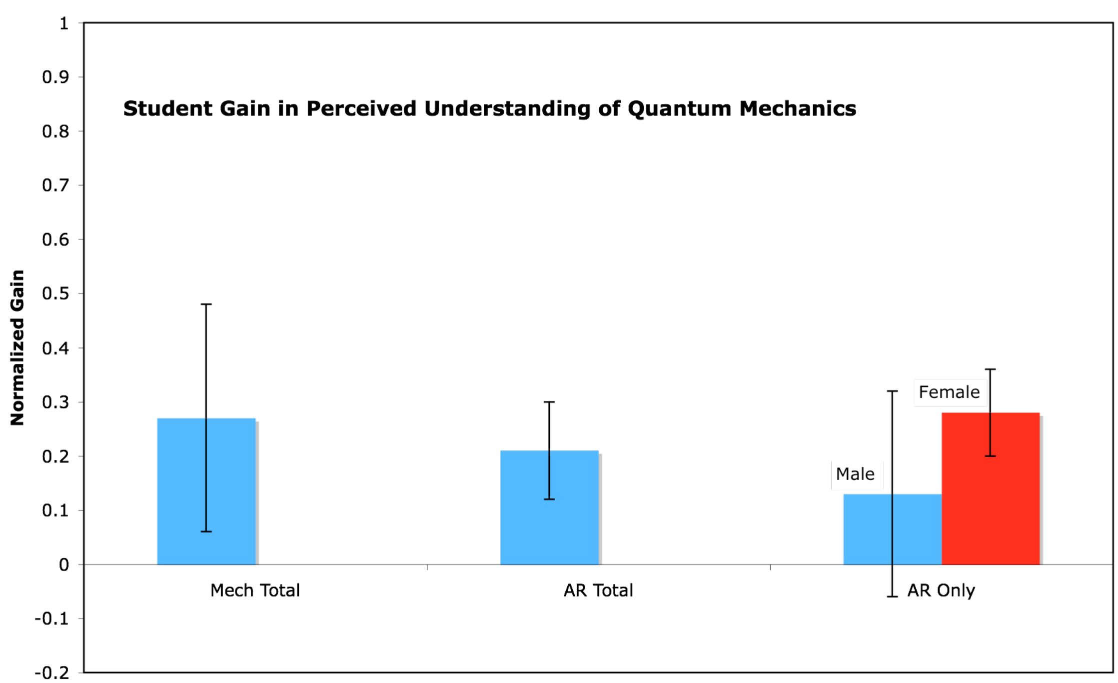

Figure 5.2: Gain in Students' Perceived Understanding of Quantum Mechanics

While both sections showed increases in perceived understanding of quantum mechanics, there were no significant differences between the sections or between genders.

Measuring changes in student interest in physics, however, reveals interesting differences between the teaching approaches. Table 5.3 and Figure 5.3 compare student responses to the question "How would you rate your interest in physics now (particularly in light of the most recent class session)?" with their interest in physics as reported on the pre-questionnaire.

Class:	Pre Avg.	Post Avg.	Normalized Gain
Mechanics-based pedagogy	2.71 (0.42)	3.57 (0.43)	0.38 (0.22)
Agential realist approach	3.34 (0.28)	3.47 (0.29)	0.08 (0.23)
Male	3.86 (0.34)	3.86 (0.40)	0.00 (0.46)
Female	2.94 (0.39)	3.17 (0.39)	0.11 (0.26)

Table 5.3: Student Gain in Interest in Physics

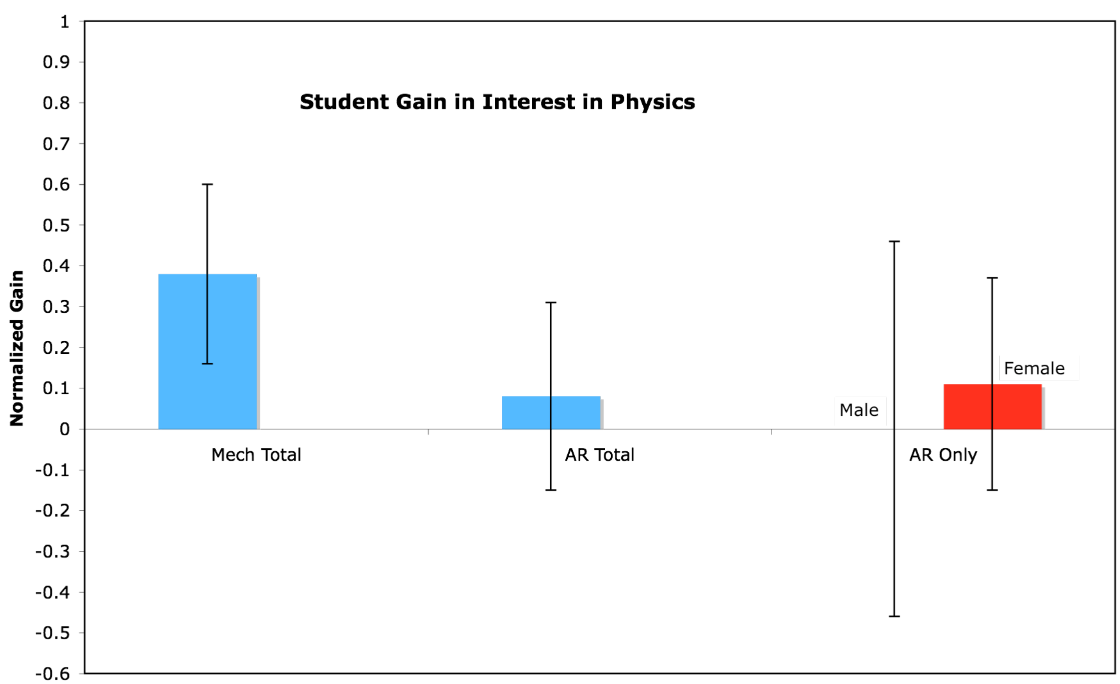

Figure 5.3: Student Gain in Interest in Physics

While the mechanics-based pedagogy class showed a statistically significant increase in student interest in physics ($p < 0.05$), the agential realist class did not. Though measurements of normalized gain in interest in physics showed no significant gender differences, measurements support the idea that this class combated the gender gap. Males began with a much higher interest in physics – 3.86 as compared to 2.94 ($p < 0.05$) – in accordance with chapter 1 research on the gender gap. After the session, however, there was no longer a statistically significant gap in interest in physics (3.86 vs. 3.17, $p \approx 0.10$), as seen in figure 5.4.

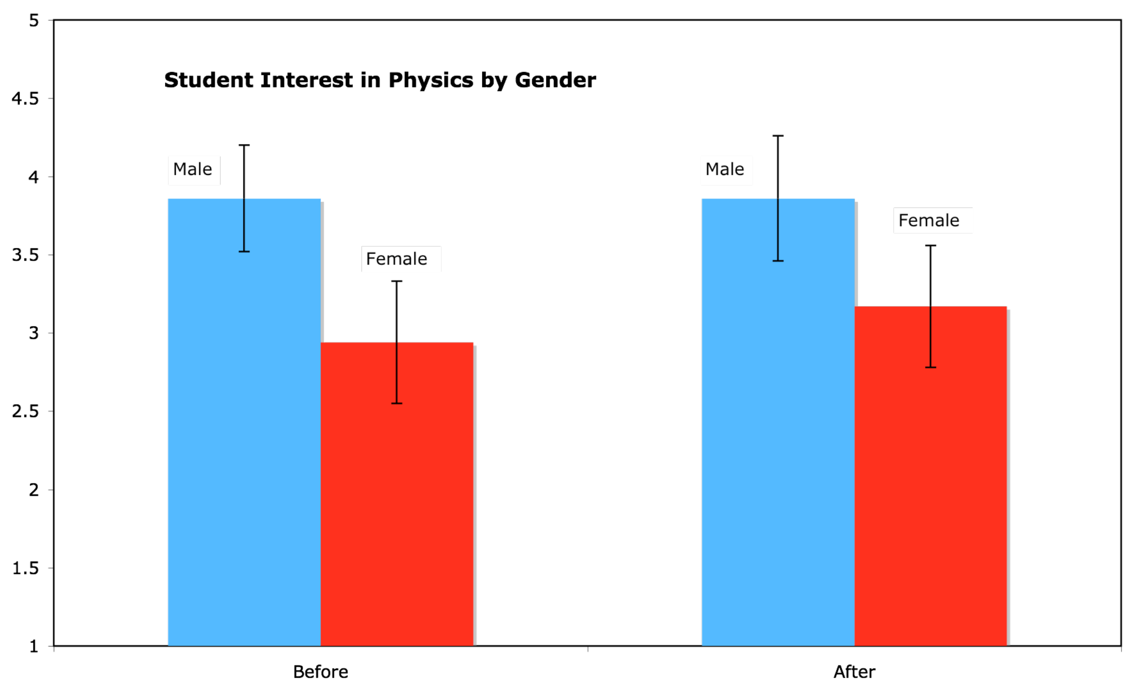

Figure 5.4: Student Interest in Physics by Gender in the Agential Realist Section

In order to explore the possibility that the agential realist class was only effective for students historically unselected for by traditional physics courses (as suggested by later findings, particularly those seen in figure 5.8 and 5.9), table 5.4 and figure 5.5

compare interests in physics before and after the agential realist class for those students with low initial interest in physics (those who put a 1 or 2 on the pre-questionnaire).

Class:	Pre Avg.	Post Avg.	Normalized Gain
Mechanics-based pedagogy	1.67 (0.33)	3.00 (0.58)	0.40 (0.18)
Agential realist approach	1.67 (0.33)	2.00 (0.58)	0.10 (0.20)

Table 5.4: Interest in Physics for Students with Low Initial Interest in Physics

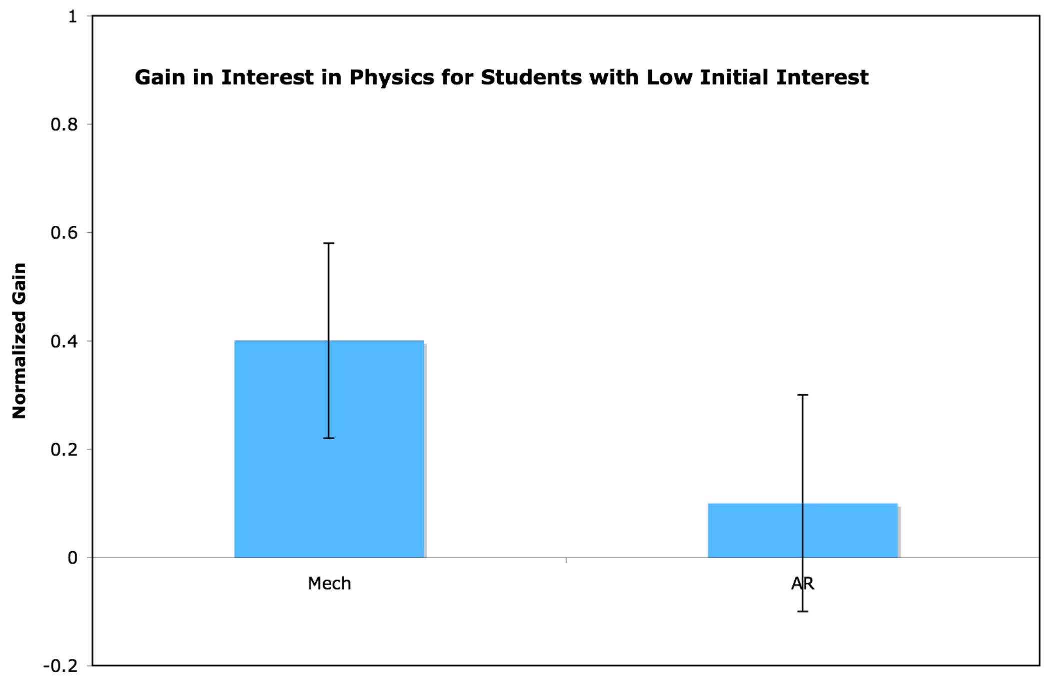

Figure 5.5: Gain in Interest in Physics for Students with Low Initial Interest

Differences still exist between the classes, as this initially low-interest group showed a statistically significant increase in interest ($p < 0.05$) after the mechanics-based section, but not the agential realist section.

Measuring change in student interest in quantum mechanics found different results. Table 5.5 and Figure 5.6 compare student responses to the question “How would you rate your interest in quantum mechanics now (particularly in light of the most recent class session)?" with their interest in quantum mechanics as reported on the pre-questionnaire.

Class:	Pre Avg.	Post Avg.	Normalized Gain
Mechanics-based pedagogy	3.29 (0.29)	4.00 (0.31)	0.42 (0.21)
Agential realist approach	3.03 (0.30)	3.75 (0.31)	0.37 (0.18)
Male	3.57 (0.43)	4.00 (0.44)	0.30 (0.37)
Female	2.61 (0.39)	3.56 (0.44)	0.40 (0.21)

Table 5.5: Student Gain in Interest in Quantum Mechanics

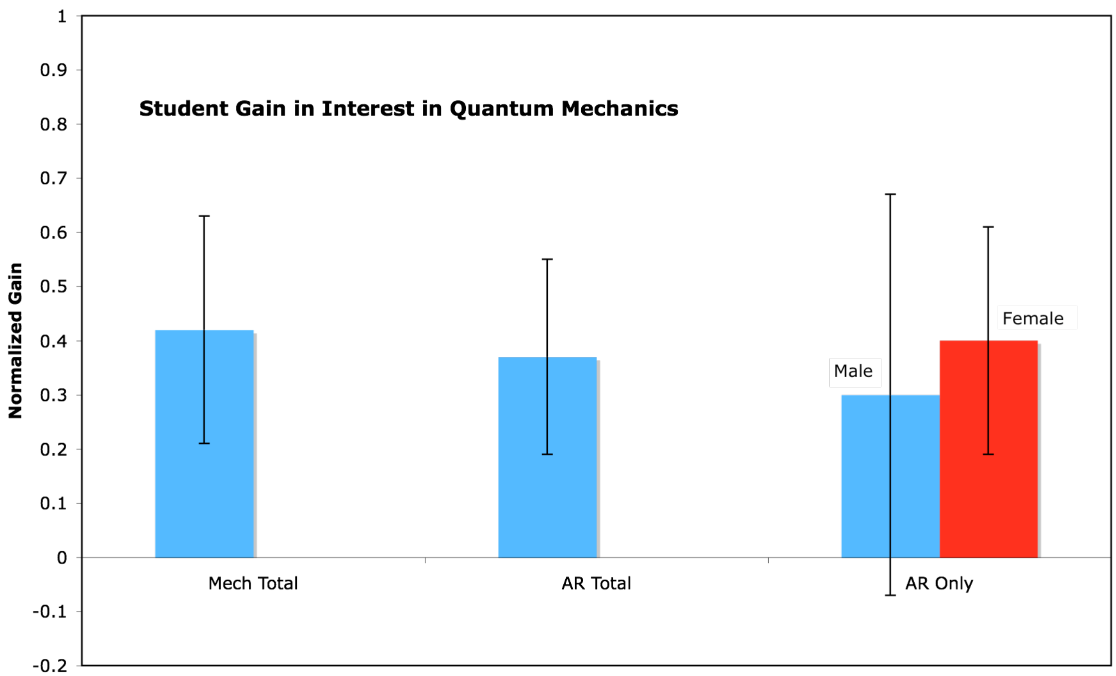

Figure 5.6: Student Gain in Interest in Quantum Mechanics

Both sections showed a statistically significant increase in student interest in quantum mechanics ($p < 0.05$ in both classes). Again, the statistically significant difference in interest present initially ($p < 0.05$) no longer remained after the class, as seen in figure 5.7.

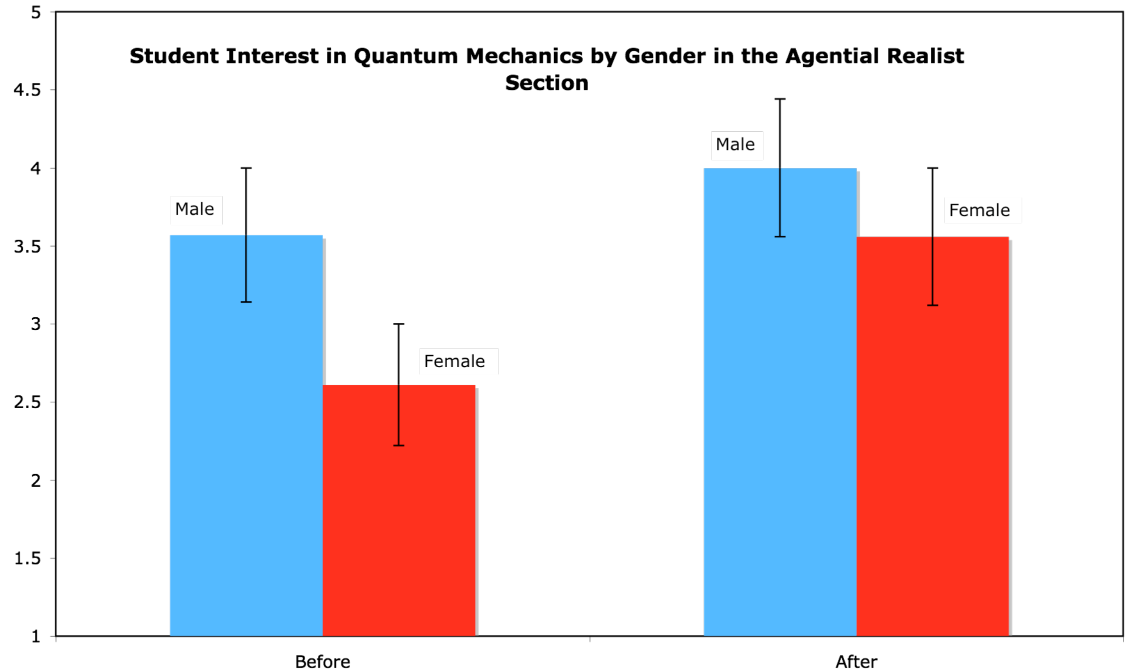

Figure 5.6: Student Interest in Quantum Mechanics by Gender

Despite this finding, data continued to reveal possible weaknesses of the agential realist approach. Consider student's predictions of how more classes like the test class would impact how "good" they are at physics, as seen in table 5.6 and figure 5.8.

Class:	Initial Perceived Ability	Predicted change (from 1 = strongly decrease to 5 = strongly increase, with 3 = no change)
Mechanics-based pedagogy	3.14 (0.46)	3.71 (0.29)
Agential realist approach	3.25 (0.27)	3.03 (0.23)
Male	3.29 (0.36)	3.00 (0.38)
Female	3.22 (0.40)	3.06 (0.29)

Table 5.6: Perception of and Predicted Change in Perception of Physics Ability

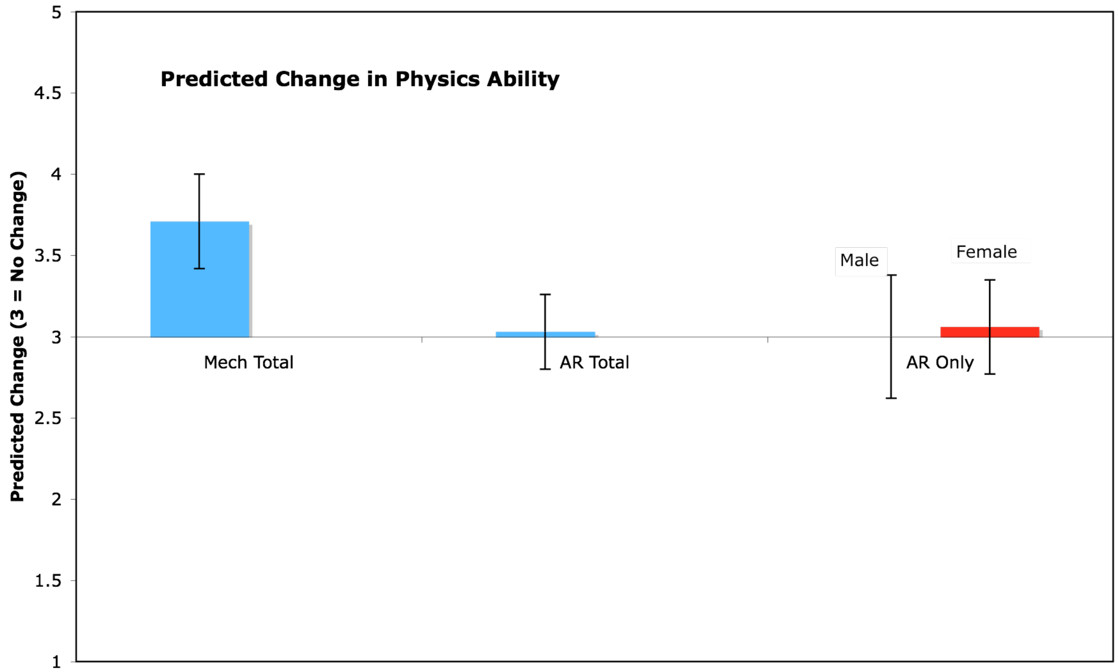

Figure 5.8: Predicted Change in Perception of Physics Ability

On average, students in the mechanics-based pedagogy section predicted that their ability at physics would increase as a result of more classes of that type with a high statistical significance ($p < 0.01$). Average student response in the agential realist approach classroom predicted no change in physics ability.

When examined more closely, however, interesting trends emerge. Although there was no significant gender difference in response, breaking predicted changes down by initial perceived ability yields insightful information. Consider table 5.7 and figure 5.9, which consider the above data for those students who initially reported a 4 or 5 (out of 5) for their physics ability.

Class:	Predicted Change (from 1 = strongly decrease to 5 = strongly increase, with 3 = no change)
Mechanics-based pedagogy	3.75 (0.48)
Agential realist approach	2.50 (0.22)

Table 5.7: Predicted Change in Physics Ability for Students with Perceived High Abilities (Reported 4 or above)

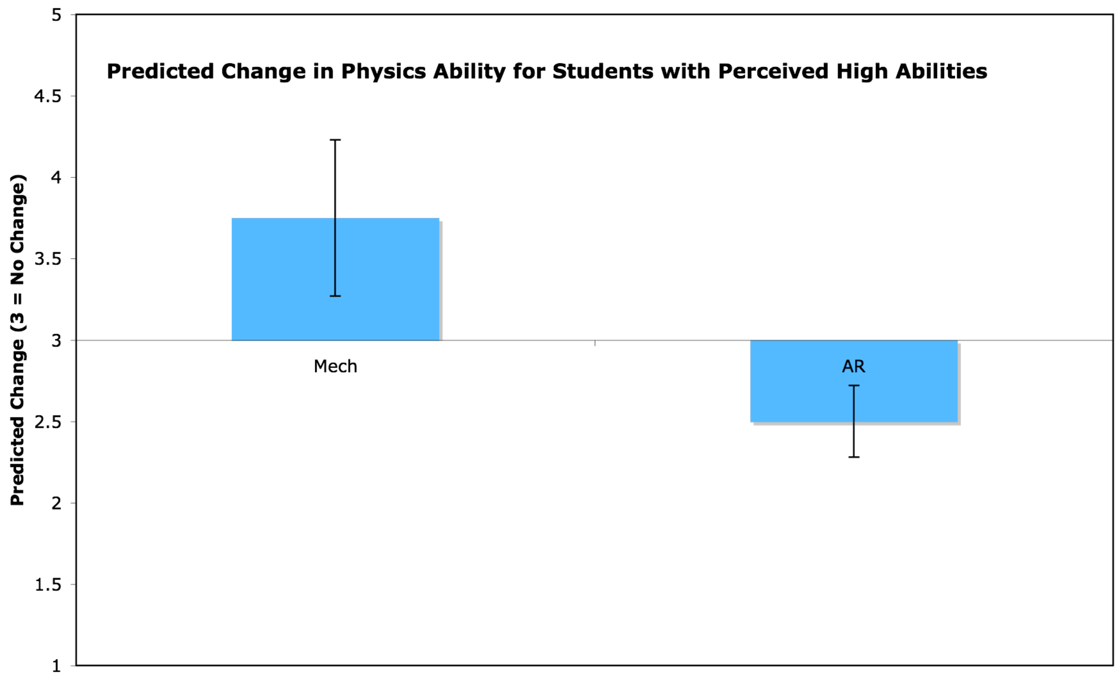

Figure 5.9: Predicted Change in Physics Ability for Students with Perceived High Abilities

While students in the mechanics-based pedagogy section continued to predict an improvement in their physics abilities, students with perceived high-abilities predicted that agential realist-type classes would *negatively impact* how good they are at physics ($p < 0.05$). This is not just the effect of a select few students, either – every student in this group predicted that more sessions like the agential realist class would decrease or not change how "good" they think they are at physics. Interestingly, this did not correlate to gender differences, as male and female students reported no significant difference in initial perception of physics ability.

In contrast, table 5.8 and figure 5.10 show the predicted change in physics ability for students with perceived low or medium abilities (those who scored themselves a 3 or lower on how "good" they were at physics initially):

Class:	Predicted Change (from 1 = strongly decrease to 5 = strongly increase, with 3 = no change)
Mechanics-based pedagogy	3.67 (0.33)
Agential realist approach	3.35 (0.30)

Table 5.8: Predicted Change in Physics Ability for Students with Perceived Low or Medium Abilities (Reported 3 or below)

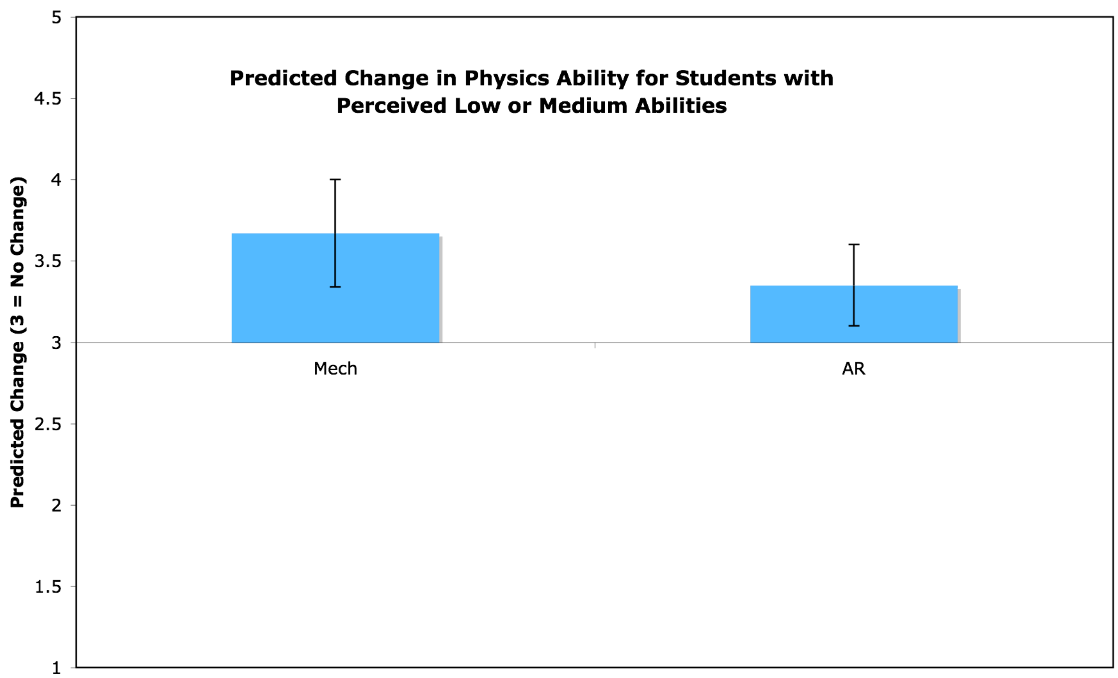

Figure 5.10: Predicted Change in Physics Ability for Students with Perceived Low or Medium Abilities

Unlike the perceived high-ability students in the agential realist section, neither group of these perceived low-ability students did not predict that more classes like the modified sessions would negatively affect how "good" they were at physics. As before, the group of these students in the mechanics-based pedagogy section in fact predicted a statistically significant increase in physics ability ($p < 0.05$).

The complexity of student response to these classes continued to be revealed in student responses to the questions “How well do you feel this class embraces / the most recent class session (today’s) embraced your personal learning style?”, as shown in table 5.9 and figure 5.11.

Class:	Course in General	This Session
Mechanics-based pedagogy	2.36 (0.54)	3.71 (0.29)
Agential realist approach	2.72 (0.21)	3.06 (0.35)

Table 5.9: Fit of Personal Learning Style with Course in General vs. Modified Session

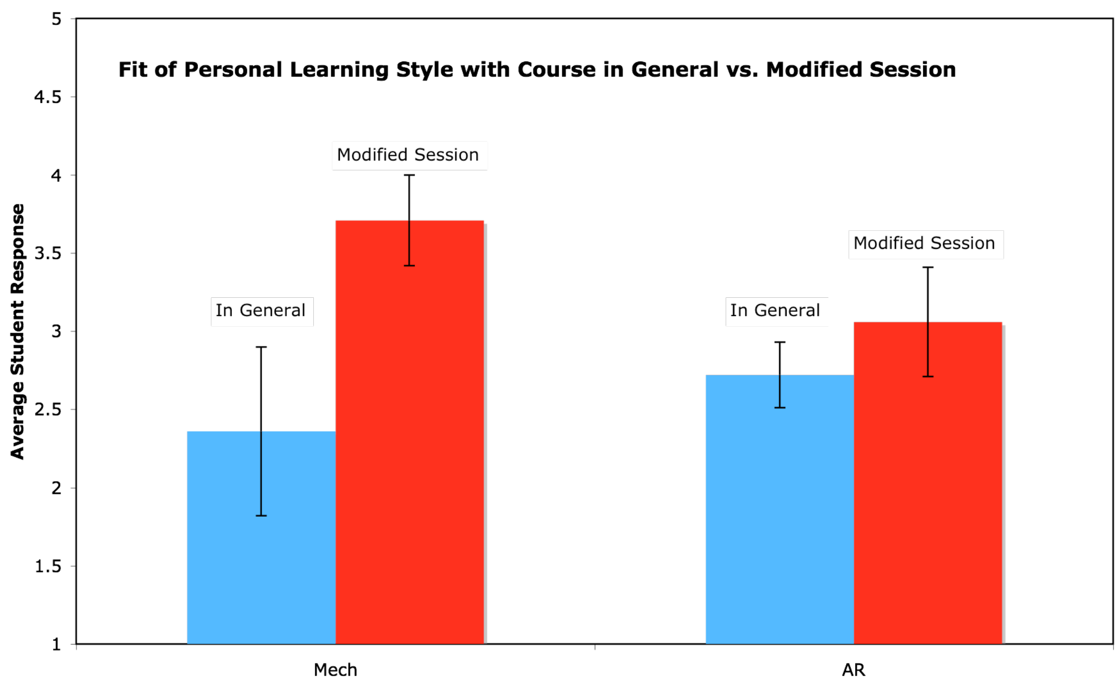

Figure 5.11: Fit of Personal Learning Style with Course in General vs. Modified Session

The first section showed a statistically significant improvement from their perception of the affinity with the class in general to that with the modified session ($p < 0.05$), but the second did not. Attempting to break these results down further were inconclusive, as seen in tables 5.9-5.10 and figures 5.12-5.13.

Agential realist approach	Course in General	This Session	Difference
Male	2.71 (0.36)	3.14 (0.55)	0.43 (0.66)
Female	2.72 (0.28)	3.00 (0.47)	0.28 (0.55)

Table 5.9: Fit of Personal Learning Style with Course in General vs. Modified Session by Gender in the Agential Realist Class

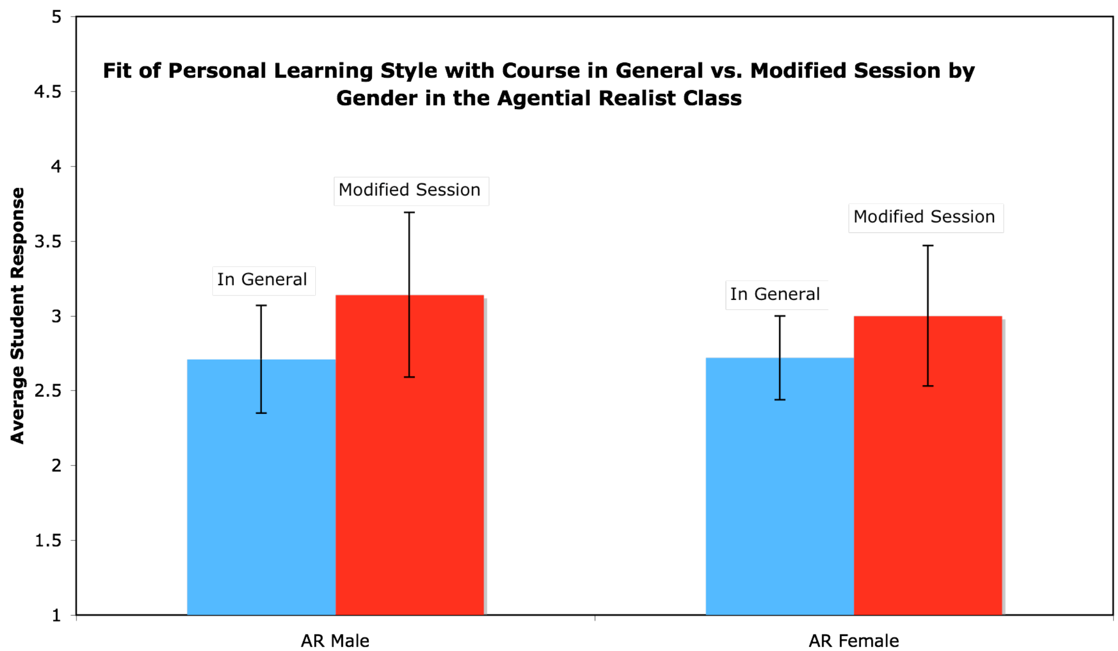

Figure 5.12: Fit of Personal Learning Style with Course in General vs. Modified Session by Gender in the Agential Realist Class

No gender differences emerged, as students continued to feel similarly about both the course in general and the modified session.

Class:	Course in General	This Session	Difference
Mechanics-based pedagogy	1.25 (0.25)	3.25 (0.25)	2.00 (0.35)
Agential realist approach	1.83 (0.17)	2.83 (0.60)	1.00 (0.62)

Table 5.10: Fit of Personal Learning Style with Course in General vs. Modified Session for Students with Low Reported Affinity with Class Style (Reported a 1 or 2)

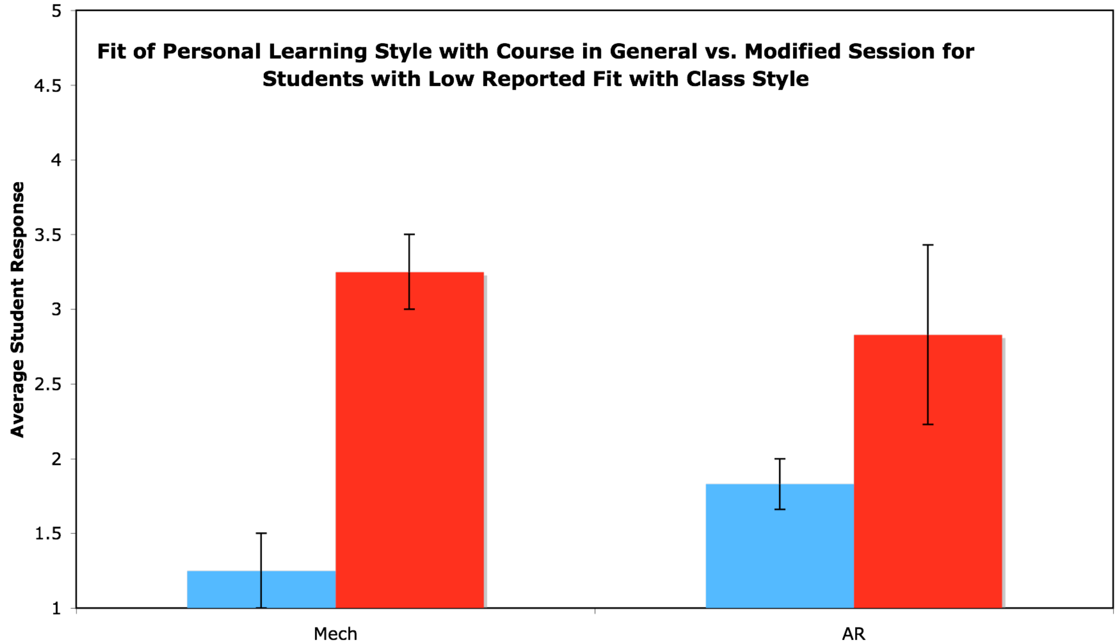

Figure 5.13: Fit of Personal Learning Style with Course in General vs. Modified Session for Students with Low Reported Affinity with Course Style

Those students from the agential realism class who initially reported a low affinity with the course style, responded like the other section's students that their affinity with the modified class session was significantly higher than with the course in general ($p = 0.05$).

Finally, attempts to investigate how these pedagogies might impact post-college plans proved inconclusive. Consider students' predictions of how more classes like the test class would impact their interest in future physics-related careers, as seen in table 5.11 and figure 5.14.

Class:	Initial Interest	Predicted change (from 1 = strongly decrease to 5 = strongly increase, with 3 = no change)
Mechanics-based pedagogy	3.57 (0.53)	3.29 (0.18)
Agential realist approach	2.63 (0.38)	2.97 (0.26)
Male	3.29 (0.61)	2.86 (0.46)
Female	2.11 (0.42)	3.06 (0.32)

Table 5.11: Interest and Predicted Change in Interest in Future Physics-Related Careers

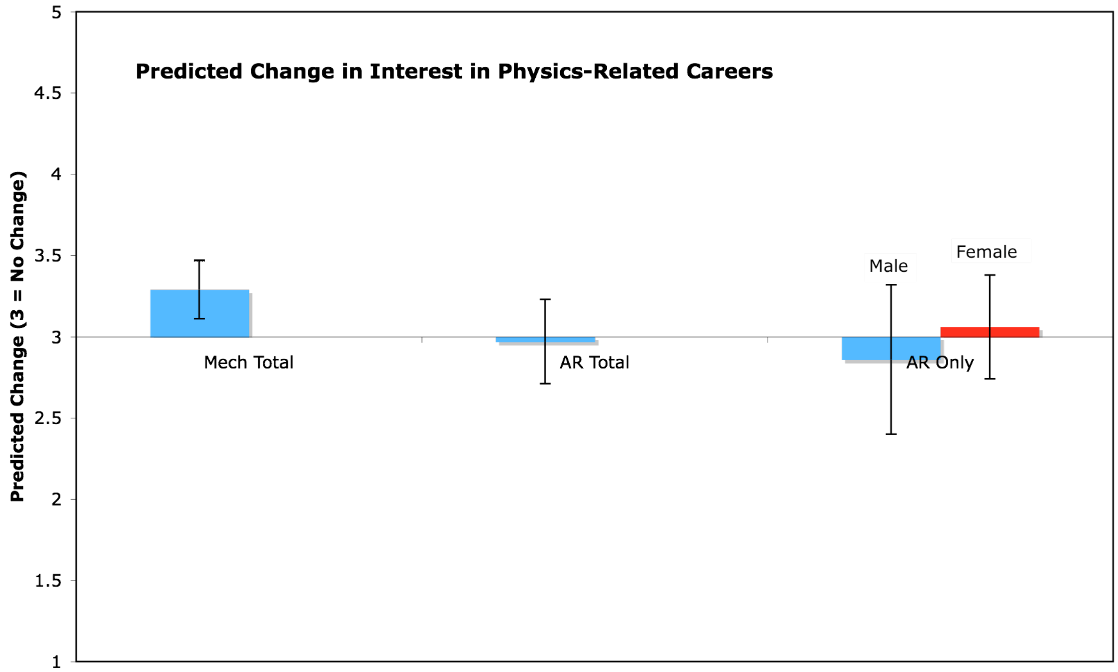

Figure 5.14: Predicted Change in Interest in Future Physics-Related Careers

Neither class predicted an increase in interest in physics-related careers ($p > 0.05$ in both cases). No subsections (including male, female, and low and high-initial interest in physics-related careers) reported a significantly different prediction than "no change."

In summary, both classes appear to offer promise. Both show a statistically significant increase in student understanding of wave-particle duality and interest in quantum mechanics. Within the agential realist approach, women's understanding increased as much as men's, implying that the gender gap was successfully erased. Also, gender differences in interest in physics in general and quantum mechanics disappeared after the class session. Although the lack of gender diversity in the mechanics-based pedagogy class made measuring that section's impact on the gender gap impossible, results suggested many possible advantages over the agential realist approach. General interest in physics increased in the mechanics-based pedagogy section, but not the agential realist section. Students in the mechanics-based pedagogy section predicted that their ability at physics would increase as a result of more classes of that type, while average student response in the second section predicted no change in physics ability. Finally, only in the first classroom did students express that the modified session did a better job of fitting their personal learning styles than the course in general (the initial 'fit with course in general' scores were not statistically different).

Further analyses shed some light on these possible weaknesses of the agential realist approach. The average student response in the agential realist class indicated no predicted increase in physics ability primarily because students with *perceived high-abilities* predicted that agential realist-type classes would negatively impact how good they are at physics. It appears possible that the agential realist approach is off-putting to students who have succeeded in traditional frameworks. This approach might be particularly effective only for students historically unselected for by traditional physics approaches (e.g. women, students who have 'learned' they are not good at physics). Consider the additional support of the data on how students felt the course in general and the modified session "fit" with their personal learning style. Students from the agential realism class who initially reported a low affinity with the course felt that the modified class session fit their learning style significantly better. With the rest of the class included, there was no significant preference for the modified session over the way the class is usually taught.

At the same time, some data challenge this hypothesis. Students with low initial interest in physics did not show an increased interest after the agential realist class, for example, even though this group would by definition include students historically 'turned-off' by traditional physics approaches. Moreover, all students in the mechanics-based pedagogy section did show an increased interest. This section also saw improvements in all students' perceptions of physics ability and sense of 'fit' with the modified session over the class in general. These findings suggest the possibility that progressive pedagogy can work for everyone – historically selected and unselected students alike.

NOTES:

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[1] The author chose to use normalized gain in order to best compare with Lorenzo, et al. Debate exists, however, on whether this is the best measurement of student learning, as seen in A. F. Heckler, "Measuring Student Learning by Pre and Post Testing: Absolute Gain vs. Normalized Gain." Submitted to AJP June 2004, available from <http://link.aip.org/link/?AJPIAS/74/917/1>.

[2] See J. R. Taylor *Introduction to Error Analysis*. Sausolito, CA: University Science, 1997, p. 237. Particular thanks are owed to Prof. Adam Edwards (Pomona College) for his help in the calculation of these significance values, which are derived according to the following method: Take the difference of the two measurements. To determine how "consistent" that difference is with zero, assuming that the errors on these two measurements are not correlated, use the standard linear error propagation formula to calculate the error on the difference (add the errors in quadrature). This is the Gaussian error on the difference. Calculate how large the difference is relative to this error. This is how many standard deviations away the difference is from zero. Using J. R. Taylor Appendix B, p. 288, determine how likely it is to have this many standard deviations or more. This is the *p* value: the probability that, if the true values of both measured quantities stay the same, repeated measurements would find a larger difference between the two.

[3] As per *Ibid.*, p. 147. The specific propagation of the student score uncertainties into the gain uncertainties was done as follows. For an average pre-score of $a \pm \partial a$ and post-score of $b \pm \partial b$, the uncertainty of the normalized gain, $g = (b-a)/(N-a)$), is

$$\partial g = \sqrt{\left(\frac{\partial b}{(N-a)}\right)^2 + \left(\partial a \cdot \left(\frac{b}{(N-a)^2} - \frac{1}{N-a} - \frac{a}{(N-a)^2}\right)\right)^2}\,. \qquad (2)$$

[4] M. Lorenzo, Catherine H. Crouch, and Eric Mazur. "Reducing the Gender Gap in the Physics Classroom." *American Journal of Physics* 74 (2006).

[5] R. R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," Am. J. Phys. **66**(1), 64-74 (1998).

Chapter 6: Conclusions

With its mixed findings and limited scope, this study strongly makes the case for work on the gender gap in physics education, particularly in quantum mechanics. Both approaches considered – one based primarily on lessons from gender gap research in mechanics-based physics classes, and the other drawing on a combination of feminist theory and Bohr's philosophy-physics – were successfully implemented and tested. Both yielded promising results, but also raised challenging questions. Researchers must begin further studies, particularly with larger sets of students, while seeking the participation of sociologists, education theorists, and gender theorists in order to combat the severe and pressing problem of the gender gap in physics.

The study successfully implemented and measured the impact of two approaches to combating the gender gap. The first attempted to integrate pedagogy based on past mechanics classes geared toward eliminating the gender gap, particularly the work by Lorenzo et al.[1] The second presented the agential realist approach, as created and championed by Karen Barad, a heretofore untested model with an emphasis on connecting quantum mechanics to students' lives, identities, and conceptions of the world.[2] Both classes covered the same material: chapter 4 and sections 1-4 of chapter 5 in the text *Six Ideas That Shaped Physics Unit Q: Particles Behave Like Waves*,[3] which introduces wave-particle duality, the de Broglie hypothesis, and the two-slit interference experiment.

The first section set out to increase in-class interaction, reduce competition, foster student collaboration, and focus on conceptual understanding. To meet these goals, the class combined instructor-led lecture, group work, and a collaborative, hands-on activity using technology to model quantum behavior. The instructor encouraged student engagement throughout the course and explained difficult concepts by connecting the ideas involved to experimental phenomenon, particularly those seen or completed by the students. Students worked together at their tables on the example problem, which required students to think abstractly about a real experimental situation and the relationships between measurables, not simply plug into an equation. Continuing to work in these groups, students engaged in an interactive activity geared toward true student understanding.[4] To avoid competition, the instructor encouraged all students to help one another and to answer at the same time, with no impact on student grades.

The second session sought to engage students in a context that recognized quantum as continually under discussion and offering a vastly different picture of interactions between humans and the world. At the same time, the agential realist class drew on feminist standpoint theory, which calls for science courses to focus on the intersection of identity and science. In this framework, pedagogy must embrace students as full participants both in science and the world science describes. In response to these objectives, the class included pre-readings geared toward recognizing disagreement within the history of physics and encouraging students to grapple with the challenging conceptual and philosophical issues raised about reality. Students brought in 1-2 paragraph written responses to the reading. In addition to a brief lecture with many of the same features as the first section, this section also included a shortened version of the same collaborative activity. For the last twenty minutes of class, students engaged in a discussion on the implications of quantum mechanics. Student responses and observation of the discussion indicate that the class successfully engaged students to take on the issues as hoped.

Pre and post-questionnaires measured the impact of these two classes with a free-response question on wave-particle duality and simple Likert-scale questions. The results of both sections were promising, as each showed registered a statistically significant increase in student understanding of wave-particle duality and interest in quantum mechanics. Due to class size/diversity restrictions, gender data were only available for the agential realism section, but within the agential realist approach, the gender gap was successfully erased. Not only did women's understanding of wave-particle duality increased as much as men's, but gender differences in interest in physics in general and quantum mechanics disappeared after the class session.

At the same time, some results suggested advantages of the mechanics-based pedagogy over the agential realist approach. General interest in physics increased in the first section, but not in agential realist class. Students in the mechanics-based pedagogy section predicted that their ability at physics would increase as a result of more classes of that type, while average student response in the second section predicted no change in physics ability. When asked about the fit of the course in general with their personal learning styles, scores between the classes were not statistically different, but when compared to the fit of the modified session with their personal learning style, only the mechanics-based pedagogy section showed an improvement.

Further analysis revealed divisions within the student response that suggests an explanation for these differences between the two styles of teaching. Unlike the mechanics-based section, the students with perceived high-abilities in the agential realist section predicted that agential realist-type classes would negatively impact how good they are at physics. These findings suggest that the agential realist approach is off-putting to students who have succeeded in traditional frameworks, an idea supported by the data on student affinity with the courses'/modified sessions' teaching styles. Students from the agential realism class who initially reported a low affinity with the course felt that the modified class session fit their learning style significantly better, but, with the rest of the class included, there was no significant difference in preference for the modified session over the class as usual. Agential realism, as an alternative approach to teaching that challenges students' assumptions about how physics should be taught, is likely to find resistance from the students who have done well in traditional classrooms.

This idea faces some challenges, however. Most importantly, the mechanics-based pedagogy approach seemed to benefit all students, critiquing the concept of a trade-off between those who traditionally have done well and those who have not. This section saw an increased interest in physics, predicted perceptions of physics ability, and sense of 'fit' with the modified session among *all* groups of students. However, this class adhered more closely to student expectations and previous experiences in physics classes. Past education research at Pomona has suggested that challenging student expectations may negatively affect student interest and satisfaction.[5] The class may also have been some influence from the instructor, who, though chosen to be as objective as possible, told the first group that they were part of a pedagogical experiment in which they might be receiving an experimental form of education. The psychological effects of this statement might have increased students' satisfaction with this session.[6]

To continue along these lines of research, the next step would be to conduct a similar experiment with a larger set of students so that gender differences could be measured within the mechanics-based pedagogy group. If this section shows the same gender-gap reduction seen in the agential realism group, the exact implementation of the agential realist framework should be reconsidered. Although students, especially those with positive experiences from traditional physics programs, may always be wary of change, perhaps a longer exposure could isolate the initial shock and rejection from the true effects of this new pedagogy. Going forth, what matters is continuous dedication to bridging the gender gap. By raising awareness, seeking out new pedagogies, supporting and engaging in educational research, and talking about the issue, this systematic inequality can and must be stopped.

NOTES:

[1] M. Lorenzo, C. H. Crouch, and E Mazur, “Reducing the Gender Gap in the Physics Classroom.” *American Journal of Physics* 74 (2006): 118-122.
[2] K. Barad, “Feminist Approach to Teaching Quantum Physics” in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press (1995), p. 70.
[3] T. Moore, *Six Ideas That Shaped Physics, Unit Q: Particles Behave Like Waves*. New York: McGraw-Hill Higher Education (2003).
[4] The activity was based on the simple program *Interference* created by Jason Evans and Prof. David Tanenbaum (Pomona College) and modified by Prof. Thomas Moore (Pomona College) for the course, and used problem Q5T.2 from T. Moore, *Six Ideas That Shaped Physics, Unit Q: Particles Behave Like Waves*. New York: McGraw-Hill Higher Education (2003), pp. 92-93.
[5] Informal interview with Prof. Thomas Moore, Pomona Collge, 23 April 2008.
[6] Known as the Hawthorne Effect, many publications verify the potentially major consequences of such a situation, including S. W. Draper “The Hawthorne, Pygmalion, Placebo and Other Effects of Expectation.” <http://www.psy.gla.ac.uk/~steve/hawth.html#Hawthorne%20overall> 22 April 2008.

Appendix A: Lesson Plans

To incorporate:
Lessons from Harvard group (focus of session #1)

- Integrate everyday experiences and interests of both genders
- Incorporate student's prior knowledge and interests
- Provide frequent feedback
- Increase collaboration and communication
- Maintain a balance of lecture and interactive approaches
- Avoid competition
- Emphasize true understanding: experimental context, avoid 'formula only'
- Highlight how physics is part of a broader context

Agential Realism (focus of session #2)

- Talk about "real-ness" of quantum mechanics
- Talk about discovery and implications, stressing agential/dynamic aspects
- Allow students to be confused and to struggle with the difficulty of quantum
- Avoid rushing to the math at the expense of understanding the concepts.

Focus on change in structure (can't just add material on top of an already full class).
Importance of never compromising the quality of education (instructor must seek out and answer student questions to the best of his/her ability in both classrooms).

To break away from:

- "extreme culture of objectivity: a culture of no culture, which longs passionately for a world without loose ends, without temperament, gender, nationalism, or other sources of disorder – for a world outside human space and time" (Barad 46)
- removing real agency (for example, by subscribing to a model of a world, separate from its discoverers, waiting to be understood 'objectively').
- mindset of "either give in to the mysticism or leave" or 'give in to the mysticism so that you can start using equations, whose numerical results prove their correctness and validate the model.'

Class Session #1 on Quantum Mechanics (10:00-10:50am, March 14)

Goal: Facilitate student interest in and understanding of chapters Q4 ("The Wave Nature of Matter") and Q5.1-5.4 ("The Quantum Facts of Life", up to but not including spin).

Pre-reading: Q4, Q5.1-5.4.

Pre-class questions: Q4T.4, Q4B.4, Q4S.5

10:00-10:02 Classroom management.
10:02-10:10 Review three-minute questions.
10:10-10:20 Instructor response to student questions from the reading, example problems.

- Review evidence of wave and particle behavior for photon, then quantons.
- Define "quanton" and review the idea of an interference pattern.
- Introduce formula Q4.4b as a way of interrelating the concepts of wavelength, momentum, and Planck's constant as well as describing wave behavior.

10:20-10:25 Example problem Q4T.3

- Students work in groups, report answer visually by pointing to the back of books.

10:25-10:45 Instructor-led exercise and then student experimentation with the interference pattern computer program.

- Describe situation of Q5T.2
- What happens if one particle at a time? (Interference pattern will build up…).
- Interactive demonstration of the program.
- Make distinction between envelope (slit width) and interference pattern (slit separation).
- Students fill out Q5T.2 table using program in their small groups.
- Students experiment with different inputs as appropriate for remaining time.

10:45-10:50 Students fill out questionnaires.

If possible (Q4, Q5.1-5.4 material):

- Begin with experimental phenonmenon (Millikan oil drop/particle tracks, slit experiments) before moving to theoretical/equation-based discussion of particle/wave duality.
- Highlight the story/people behind the Davisson-Germer experiment (pp. 66-67).
- Refer to light-interference experiments to give context for de Broglie hypothesis.

Class Session #2 on Quantum Mechanics (9:00-9:50am, March 24)

Goal: Student interest in and understanding of chapters Q4 ("The Wave Nature of Matter") and Q5.1-5.4 ("The Quantum Facts of Life", up to but not including spin).

Pre-reading: Q4, Q5.1-5.4, Implications of quantum reading (Greene 186-191; handout).

Three-minute questions: Included in handout. Note that these are response questions to be written out (at least 1-2 paragraphs) and brought to class.

9:00-9:02 Classroom management.
9:02-9:15 Instructor example/response to student questions from the reading.

- Define "quanton" and review the idea of an interference pattern.
- Introduce formula Q4.4b as a way of interrelating the concepts of wavelength, momentum, and Planck's constant as well as describing wave behavior.

9:15-9:30 Instructor-led computer interference-pattern activity.

- Describe situation of Q5T.2
- What happens if one particle at a time? (Interference pattern will build up…).
- Interactive demonstration of the program.
- Cut in half: do (a) as the sample, then students do (c) and (d).
- Make distinction between envelope (slit width) and interference pattern (slit separation).

9:30-9:45 Student discussion on possible implications of wave-particle duality.
9:45-9:50 Students fill out questionnaires.

Prompts for student-led discussion:

- (See reading; start with boldfaced questions – students should have answered at least one of these in their responses)
- What implications do these experiments have on your understanding of the world? How is this world 'weird' (i.e. differs from our macro experience?
- What role do equations, in general, play in helping you understand quantum physics? How about the equations introduced in today's readings?
- How might the Enlightenment idea that science reveals one true reality interact with the idea of wave-particle duality?
- Are there other situations in science in which our terminology can be misleading (other than that addressed by the introduction of "quanton")?
- How might these ideas fit into broader discussions of science (e.g. science and philosophy, science and religion, etc.)?
- Explore the term "observations." How is it similar to and different from "interactions?" Why are such terms important to this discussion?
- Difference between a separate reality 'from humans' and separate from interactions (regardless of humans)?
- What parallels might be seen to some issues in general relativity?

Appendix B: A Companion Reader for an Introduction to Quantum Mechanics

(To be read in addition to chapter 4 and sections 1-4 of chapter 5 in the text *Six Ideas That Shaped Physics Unit Q: Particles Behave Like Waves*[1] and pages 186-191 from Brian Greene's physics for non-physicists volume *The Fabric of the Cosmos*[2]).

Please bring a 1-2 paragraph typed or hand-written response to class answering any of the bold-faced questions. Or, if there is some other question about this material that you wish to explore in your response, please feel free to do so.

In light of the experiments described in today's texts, many people begin to believe that quantum mechanics paints a different picture of the universe than that offered by Newtonian mechanics and our everyday experiences. Many debates surround such differences and their implications for our understanding of the world, particularly in light of wave-particle duality, two-slit experiments, and the role of the observer (e.g. detectors at the slits). Consider some competing claims made about the implications:

> "The idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them…is impossible." –Heisenberg[3]

In this quote, Heisenberg extrapolates from the experimentally determined fact that quantons' behaviors change when observed to ask questions about their 'true reality.' When nobody is looking, are they like waves or particles? Heisenberg posits that this question cannot be answered. He takes issue with the very idea of a 'true reality.'

> The facts [of quantum mechanics] not only set a limit to the extent of the information obtainable by measurements, but they also set a limit on the meaning which we may attribute to such information. We meet here in a new light the old truth that in our description of nature the purpose is not to disclose the real essence of [physical objects] but only to track down, so far as it is possible, relations between the manifold aspects of our experience." –Bohr[4]

Here Bohr expounds on Heisenberg's basic idea. Like Heisenberg, Bohr subscribes to a worldview in which physics cannot describe a 'real' universe separate of observers, but rather must focus on the connections between observations. Instead of describing whether a quanton is like a particle or wave, he suggests that the focus should be on the way in which quantons interact with other parts of the world.

> "[One interpretation of quantum mechanics is that its] laws make no claim to describe physical reality itself, but only probabilities of the occurrence of a physical reality that we have in view… I cannot but confess that I attach only a transitory importance to this interpretation." –Einstein[5]

Einstein reacts negatively to Bohr and Heisenberg's interpretations. He believes that it is possible to describe a 'real' physical reality, and that this is the heart of physics. Such perspectives are commonly referred to as 'realist.' Moreover, he extends Bohr's philosophy to the absurd, famously asking "whether the moon exists only when one looks at it."[6] Like Einstein, many scientists oppose non-realist perspectives.

Which of the different opinions mentioned here resonate with you? Why? Where might this 'realist' understanding of science originate? What problems does such a view of science face when applied to quantum mechanics?

Karen Barad, a feminist scientific philosopher, seeks to answer some of these questions:

> Scientific theories do not tell us about objects as they exist independently of us human beings; they are partial and located knowledges. …Why would we be interested in such a thing as an independent reality anyway? We don't live in such a world.[7]
>
> [T]he sciences are marked by the cultural and ideological specificities (e.g., political, historical, linguistic, racial, religious) of their creators… reproducibility, not some abstract notion of objectivity, characterizes a post-Newtonian understanding of Western science.[8]

In these passages Barad suggests that science as a process is never 'objective' to begin with, which further critiques any idea of describing an 'objective' reality. Instead, she focuses on the idea that science works by verifying models, the entire process of which is influenced by our particular culture, upbringing, and historical context.

> [T]he usefulness of science is parasitic on the intra-actions of science and society, contrary to the Enlightenment insistence that its justification and reliability depend precisely on a strict division between the two.[9]

Here Barad continues to point out how the socio-cultural-historical context affects how people understand and react to scientific discoveries. She refers specifically to the Enlightenment-era assumption that scientific concepts characterize an independent reality very similar to our everyday experience. Like Bohr and Heisenberg, she takes issue with this assumption of an 'independent reality,' but recognizes that it is an idea with which most people are raised. We have experience with both particles and waves, but never something that is both. She suggests that if physics is supposed to describe a separate reality similar to our experience, people will struggle with quantum theory because they can't imagine something that behaves like both a wave <u>and</u> a particle. She suggests that challenging some of our assumptions may be key to dealing with these struggles.

What historical and cultural factors affect how you think about science? What is the role of science in Barad's framework? How is her point of view similar to and different from the others described here?

Take some time and try to formulate your own ideas about the implications of quantum mechanics as you understand so far. **What do you think?**

NOTES:

[1] T. Moore, *Six Ideas That Shaped Physics, Unit Q: Particles Behave Like Waves*. New York: McGraw-Hill Higher Education (2003).
[2] B. Greene, *The Fabric of the Cosmos*. New York: Vintage Books, 2004, pp. 186-191.
[3] Heisenberg, Werner. *Physics and Philosophy*. New York: HarperCollins, 1958, p. 129.
[4] N. Bohr, *Essays 1958-1962 on Atomic Physics and Human Knowledge (A)*. New York: Interscience, 1963, p. 18.
[5] "On Truth & Reality." January 20, 2008. <http://www.spaceandmotion.com/Albert-Einstein-Quotes.htm>.
[6] A. Pais *Reviews of Modern Physics*, **51**, 863 (1979): 907.
[7] Barad, Karen. "Feminist Approach to Teaching Quantum Physics" in *Teaching the Majority*. Ed.: Rosser, Sue V. New York: Teachers College Press, 1995, p. 67.
[8] *Ibid*., p. 70.
[9] *Ibid*., p. 70.

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