Quantum Physics III (8.06) — Spring 2016

Term Paper

1 Project Summary

Everyone in 8.06 will be expected to research, write and "publish" a short paper on a topic related to the content of 8.05 or 8.06. The paper can explain a physical effect or further explicate ideas or problems covered in the courses. It can be based on the student's own calculations and/or library research. The paper should be written in the style and format of a brief journal article and should aim at an audience of 8.06 students.

Writing, editing, revising and "publishing" skills are an integral part of the project. Each of you will ask another student to edit your draft and will then prepare a final draft on the basis of the suggestions of your "peer editor". We will supply templates for the RevTeX version of LaTeX (used by the journal Physical Review) so that you can prepare your paper in a finished, publishable, form. In there is sufficient demand, we can also arrange a LaTeX tutorial.

You will submit your first draft marked up with editorial comments by your peer editor. This first draft will then be critiqued by a "writing assistant" (see below) and returned to you. Two weeks after the first draft is due, you will submit your final draft. Your papers will be graded on the intellectual quality of your work, the effectiveness of your presentation and the success of your prose style. A part of your grade will also be determined by how carefully and constructively you edited the draft of the paper for which you were the peer editor. The grade you earn for your paper will count 25% towards your final grade in 8.06.

Because 8.06 is a CI-M Subject, in order to pass 8.06 you must obtain a grade of C or better on your term paper. If you do not succeed in this, you will get a grade of Incomplete until you revise your term paper sufficiently to earn at least a C, and only at that time you will be assigned a final grade, again with your term paper grade counting 25%.

When a practicing physicist writes a research paper, s/he often asks a few colleagues to comment on a first draft. The final draft is then reviewed anonymously by one or several peers before it is accepted by a journal like the Physical Review. The goal of this informal and formal peer review process is to push authors to write papers which successfully communicate ideas among a community of peers. Your goal is to write a paper which presents a phenomenon or problem in quantum physics in a way which communicates your ideas clearly and effectively to your fellow 8.06 students, namely to *your* peers. If your peers cannot understand what you write, you have not succeeded. Note that writing for your peers is a much higher standard than writing for the faculty. Presenting a topic sufficiently clearly and logically that one of your peers new to this topic can learn about it requires clarity of thought and depth of understanding. These are the prerequisites for an effective written (or, for that matter, verbal) presentation.

We have obtained resources to support five "writing assistants" who can help you with writing, editing and preparing the paper. Each of you will be contacted by email by one of the writing assistants in class during lecture 13. (See the schedule below.) You should arrange to meet soon thereafter, and should seek their assistance from then on as you need it. They will critique the proposal and outline for your paper, and will also critique the first draft which you submit after it has been peer edited. In between, you may also ask them to help you with parts of your paper as you write them. Think of your writing assistant as a coach. They are there to help you, and are good at it. If you wish to get their help earlier than Tuesday, March 29, 2016, please submit your paper proposal and the name of your peer editor earlier, and one of the writing assistants will be assigned to help you.

By the time you turn in your final paper, it will have been edited by one of your peers and you will also have had time to implement the suggestions of one of the writing assistants. Past 8.06 students have found that their papers improve enormously through this process. Based on experience from previous years, by the time you turn in your finished paper, very many of you will have produced an account of a piece of physics written to a very high standard. It would be a shame if these papers were not "published". We shall have as our goal the "publication" of a journal consisting of all your papers. Note that for publication it is important that you submit your paper electronically, using the LaTeX template provided. Subject to these caveats, we hope to produce a compilation of all of your papers. We will circulate this "journal" to all of you, so that you can in the end read the work of all your peers, and not just of the one person whose work you edited.

2 Schedule and Due Dates for the Paper

You should use the first part of the term to consider possible topics and to choose a peer editor. Your peer editor must be an 8.06 student, and must be someone whose own 8.06 paper topic is unrelated to yours. A list of suggested topics is given below, but you are free to choose topics not on this list upon first obtaining Prof. Harrow's approval.

Your **proposal** is due in class during lecture 13. This must consist of: a title, a one paragraph description of what you plan to write about, an outline of your proposed paper, a list of several references you plan to use, the name of your peer editor, and your name and email address.

You will then be contacted by one of the writing assistants. They may either accept your proposal, or request that you revise it in response to their suggestions. You should arrange to meet with them as soon as possible (even if they accept your proposal). Anyone who has not met with their writing assistant at least once before submitting their first draft will be penalized.

There is a **peer editing session** between lectures 17 and 18. At that time, you and your peer reviewer will exchange drafts and make constructive, written comments on each other's work. We will cancel recitation on that day in order to make time for the peer editing session. The quality of the term papers improve dramatically from peer comments, so it is recommended that you implement their suggestions before submitting your first draft. To demonstrate that you participated in the peer editing session, you should submit a copy of your peer editing comments in the PSET bin on that day for grading.

Your **first draft** is due the day after lecture 18.

A hard copy of your **final, polished paper**, printed using the RevTeX *final, twocolumn* options is due by midnight after Lecture 21, when a pdf version should be submitted electronically. Think of this as submitting your paper to the 8.06 Physical Review, and our "publisher" Charles Suggs will assemble the pdf files into a bound document. You will all get a copy of the 2016 8.06 Physical Review in the last lecture.

After you turn in your final draft, you will have one more paper-related assignment. On the last pset, you will be asked to edit or create an article on wikipedia preferably relating to your paper. This can be a very small change, e.g. changing a few sentences or 1-2 equations, but it should be substantive (i.e. more than just grammar). While writing your paper, you should remember any shortcomings in the wikipedia articles that you come across. More details of this assignment will be in pset 9.

3 Nature of the Paper

The aim of this project is to give a clear and pedagogical presentation of a "problem" or "phenomenon" in quantum mechanics.

- A "problem" could be similar to but more elaborate than the type of problems that appear on problem sets. For example, *squeezed states* were introduced briefly in the context of the harmonic oscillator in 8.05. A student might delve deeper into the squeezed state formalism, describe the properties of squeezed states, explain the types of problems where they are useful, and give some examples of their applications. Such a paper would resemble a short chapter in some hypothetical text book for 8.05. The principal references for a paper like this could be existing quantum mechanics texts and the references to the original literature to be found in them.

- A paper focused on a "phenomenon" would introduce the phenonomenon and explain its origins in terms of the concepts and language of 8.06. For example, in studying the properties of atoms, we will briefly mention phenomena such as line-width, Thomas precession, and the Lamb shift. To write a paper about atomic line-widths, for example, a student might find out what some of the dominant types of line broadening are, when and how one can reduce them, and might talk about experiments that have managed to do so. Once again the principal references would likely be texts, perhaps modern physics texts in this case, histories of quantum physics, and the original literature.

Papers on "problems" might be based at least in part on your own calculations. Papers on "phenomena" might involve some library research. In either case reference must be given for any material taken from other sources. Do not plagiarize. Anyone who contemplates borrowing material directly from mainstream texts should consider how difficult it is to find a text that presents quantum physics at the level appropriate to 8.06.

We encourage students to write papers which expand upon a problem or phenomenon which was already introduced in either 8.05 or 8.06 lectures. If you do this, you should begin at the level of whatever we have already covered and then go farther. Students may also choose topics which have not appeared at all in class, but whose quantum mechanical explanation can be understood based upon what we have learned in 8.05 and 8.06.

Please do not try to choose subjects which are obscure, difficult, or controversial. Misguided attempts like this to gain the respect of the faculty inevitably have the opposite effect. There are plenty of deep, interesting, and challenging subjects in the mainstream of quantum mechanics.

Papers can range between 3.5 and 7 pages in length (in the RevTeX *final, twocolumn* format) including references and figures. These limits are firm.

Students are encouraged to use equations and figures to aid their presentation, much as they are used in articles and textbooks.

Ingredients of a good term paper Ideally a term paper should contain some calculation and some context (historical, mathematical, physical, engineering, etc.). The sample paper on reflectionless potentials does a good job of showing what level of calculations is right: enough detail for an 8.06 student to follow, but not an excessive amount. However, there are a few ways that your own papers should differ. First, this paper shows more originality than you need to: it gives a solution to a problem that has not previously been published (even if it had been "folklore" before), which is not reasonable to ask of you. On the other hand, it would be better if it gave more of a connection to a real-world scenario. Given the topic, this would be difficult, but the discussion section still gives an idea of the type of material that is good to include.

4 Possible Topics

Students are welcome to suggest topics of their own. You should do this by sending Prof. Harrow a brief paragraph by email, summarizing the topic. There is no separate deadline by which you must do this, but note that your complete proposal is due in class during lecture 13.

At the time you submit your proposal, you should already know that Prof. Harrow has approved your choice of topic. (Note that your writing assistant may nevertheless require you to revise your proposal.)

Here is a list of possible topics. In some cases, either Prof. Harrow or Prof. Stewart will have ideas for where to begin reading about these topics. Not in all cases, however. The library sessions with Barbara Williams (see above) are designed to help you find appropriate source material.

1. Coherent/squeezed/Gaussian states.

2. The allotropic forms (ortho/para) of hydrogen.

3. Nuclear Magnetic Resonance. Since we have spent some time on this in class, you should go beyond it. Some possibilities are dynamic nuclear polarization, nuclear quadrupole resonance, composite pulses, spin-echo, liquid vs solid-state NMR, relaxation mechanisms, or its application in particular experimental/medical contexts.

4. Magnetic monopoles, gauge invariance, and the Dirac quantization condition for the magnetic charge of a magnetic monopole.

5. Scattering off a magnetic flux tube.

6. Bell's theorem and its variants. Again since we have seen this in 8.05, you will need to go beyond it. Some possibilites are the Tsirelson bound, the question of loopholes and/or various experimental tests or a discussion of other nonlocal games.

7. Neutrino oscillations in vacuum.

8. Oscillation phenomena involving kaons and/or B mesons.

9. The solar neutrino problem.

10. Levinson's theorem — how the scattering phase shift is related to the number of bound states in a potential.

11. The shell model of nuclear structure.

12. Application of random matrix theory to nuclear physics.

13. The properties of the deuteron.

14. The α-decay of ^{238}U.

15. The rotational and vibrational spectrum of diatomic molecules.

16. Dynamical $SU(n)$ symmetry of the harmonic oscillator in n dimensions.

17. Supersymmetric quantum mechanics, beyond what we did in 8.05.

18. The Zeeman effect in weak, intermediate and strong magnetic fields.

19. The Lamb shift in hydrogen — evidence that relativistic quantum mechanics must be replaced by quantum field theory. (This is an example of a topic where you will not be able to give a complete derivation of the effect, but where those of you interested in the history of physics could write a paper which explains the quantum physics more qualitatively while at the same time describing the experiments and the history in full.)

20. The non-relativistic quark model of the proton, neutron and related particles.

21. Isospin — a quantum symmetry of elementary particles.

22. The 21 cm line of hydrogen and its role in astrophysics.

23. The Casimir effect.

24. Feynman's path integral approach to quantum mechanics, and its application to several problems of your choice which we have previously analyzed using other methods. (If you choose a formal topic like this, about a method rather than a phenomenon or problem, you must take it far enough to show how the method is applied to a phenomenon or problem.)

25. The van der Waals force between hydrogen atoms in excited states.

26. Quantum computing. This is too broad a topic for a paper, but you might discuss a proposal for building quantum computers, some particular algorithm (not Grover, Simon or Shor, since those may appear in lecture), or some other topic such as quantum error correction.

27. Quantum cryptography.

28. Bose-Einstein condensation.

29. Integer and/or Fractional Quantum Hall Effect.

30. Photonic Crystals.

31. Quantum Dots.

32. Crystallographic defects, e.g. NV centers in diamond.

33. The deHaas van Alphen effect as a tool for measuring the shapes of Fermi surfaces in metals.

34. Periodic potentials and band structure in 3-d.

35. Graphene and pseudo-spin.

36. Some topic within quantum statistical mechanics. Possibilities include the quantum Ising model, quantum Monte Carlo, quantum phase transitions, von Neumann entropy or the spectrum of black body radiation. (You could also include an account of how Planck was led to discover quantum mechanics in the first place, or of how the spectrum of black body radiation appears in the cosmic three-degree background radiation.)

37. Decoherence in some physical system.

38. Optical pumping, masers, lasers.

39. Masers in astrophysics.

40. Interesting applications of the semiclassical approximation.

41. The Ramsauer-Townsend effect.

42. The Josephson effect.

43. The Wigner-Eckart theorem.
44. Fractional statistics in two dimensions.
45. Wigner functions and applications.
46. Tunneling, beyond the discussion in class. The Euclidean approach; effects of nonzero temperature.
47. The microscopic origin and effects of quantum dissipation, for example on tunneling.
48. Inverse scattering method and its application to solitons.
49. The Dirac equation and its application to hydrogen.
50. ... and so on.

5 Writing Tips

Here are some tips that you may find useful.

5.1 Structure

- Identify a well-defined topic area as early as possible. Changing your focus is fine, but you may find that it requires substantial rewriting to keep things clear.
- Work through and understand the physics before writing. You should do this over Spring Break. This will ensure that you have a well-defined topic before you start writing. You will find that this will make structuring the paper infinitely easier.
- Make sure the main points of your paper are clearly indicated. This is especially important for scientific writing, since the reader can easily get bogged down in details. Your main points should be highlighted by the structure of the paper as well as mentioned in the introduction and/or abstract.
- Write the abstract and, possibly, the introduction last.
- After you have your outline ready, don't be afraid to draft later sections before earlier sections. If you understand the last half of your argument better than the first, start by writing the last half. Doing so will help you think through how to understand and explain the first half.

5.2 Style

- In thinking about both style and structure, remember that you are writing a scientific paper and not a work of literature. The writing in great works of literature typically has multiple meanings, and can be understood in many ways, at different levels. It can be read differently by readers at different times or with different backgrounds. It often makes veiled allusions to other great literature. Over the years, great literature takes on meanings that go beyond those intended consciously by its author. In contrast, the central purpose of a scientific paper is the clear communication of your ideas to your readers, with no ambiguity, multiple meanings or veiled allusions. Your goal is to ensure that every one of your readers, who may indeed have varying backgrounds, understands your ideas in precisely the way that you intend. This means that clarity and precision are your paramount goals. You should seek to ensure that no reader can misunderstand what you intend to communicate in any sentence that you write, even should they willfully try to misunderstand you. To this end, write in simple, declarative sentences, avoid contorted constructions and always aim for clarity.

- Feel free to use whichever voice you are most comfortable with. "I will show," "we will show" or "it will be shown" are all fine. For unknown reasons, some students seem to think that personal pronouns are banned and the passive voice is required. Nothing could be further from the truth. Good scientific writing should be animated and compelling. Your paper should "tell a physics story". I find the overuse of the passive voice to be deadening. Don't be dull. Clarity and precision come first, but don't fall into the trap of thinking that this can only be accomplished via boring your reader to tears. Not true.

- Short sentences often are more effective. If you must, for whatever reason, use a long sentence, especially one with many asides, clauses and qualifications—and these sometimes cannot be avoided in technical prose—try at least to start the sentence with something related to its main point, rather than meandering into it at the end. If a sentence would work just as well by deleting a word, you should usually delete that word.

- Try to lead your reader along, motivating their interest, building up the physics ground work you need them to understand, drawing them into the story you are telling, and working up to a compelling conclusion.

- All the advice I've given you about style is just as important when, later in life, you find yourself preparing a lecture or a seminar.

5.3 Some Details

- Be rigorously consistent in your notation, even at the risk of being repetitive.

- Clearly define every quantity that you introduce. It is acceptable to do this immediately either before the quantity is used, or immediately after. An example of this is: "The hydrogen atom has potential

$$V = -\frac{e^2}{r},$$

where e is the electron charge and r is the distance between the electron and the proton."

- Avoid ambiguous references, such as "this shows". Instead, use references like "Eq. 4.1 shows." The LaTeX commands \label and \ref are useful here.

6 More on Peer Editing

As described in the project summary, each of you will act as an editor for one of your peers. (Note: if you cannot find someone to act as your editor, ask Prof. Harrow. He will pair people up as he gets such requests. You must list the name of your peer editor as part of your proposal, due in class during lecture 13. Between lectures 17 and 18 you and your peer editor will exchange drafts and make constructive comments, which will help improve the quality of your paper before the first draft deadline the day after lecture 18.

As you are editing the work of one of your peers, you should start by praising what the document does well. If the author has made specific requests (i.e. "please see if my argument in this section makes sense to you") then spend much of your time responding to these specific requests. Do not focus on spelling and the mechanics of writing, unless asked by the author to do so, or unless you have very general comments. (Of course, note problems of this sort which you happen to spot, but this is not your main goal and the author should in general not rely on you for this sort of editorial review.) Instead, focus on helping the author to revise content, organization and logic. Do not just criticize. Make suggestions on how to solve the problems you notice in the paper.

As you edit the work of your peer, here are some of the questions which you should be thinking about:

- What is the paper's main argument?
- How interesting is it? Is the importance of the topic explained?
- How specific is the argument? Would it benefit from being made more general or complete? Would it, in contrast, benefit from being made more focussed?
- Is the paper divided into sections and subsections in a way which makes following its logic easy? Does each section flow logically from the preceding one? Do ideas flow smoothly from one paragraph to the next?
- Early in the text, is there a clear road map of the entire document?
- Are all outside sources documented? If, as will be the case for almost all 8.06 papers, the paper contains ideas which are not the results of calculations done by the author and are not ideas we have all seen in lecture, can you see from which source the author learned each such idea?

- Are all technical terms which are new to you defined clearly, and used consistently?
- If the paper presents the solution to a problem, what are the arguments on which the solution rests? Do you understand each argument and the solution as a whole? Is each part of each argument substantiated? (Either by calculation presented in the paper, or by reference to 8.05 and 8.06 material which you can see substantiates the argument.) Is there anything missing, which would help complete an argument?
- If the paper describes a phenomenon, do you understand the description? Is the nature of the phenomenon clearly described? Are the reasons why the phenomenon is of interest clear? Do you understand the quantum mechanical explanation of the phenomenon presented by the author? What do you wish the author had included that would have given you a better understanding of the phenomenon?

You may also want to

7 The LaTeX Templates

LaTeX (and its ancestor TeX) are widely used in academic and technical publishing. They are "mark-up" languages, like HTML, that tell a processor how to construct mathematical expressions that look like typeset text. One of the objectives of this assignment is to give you an experience preparing a physics paper for "publication". When practicing physicists submit papers to the Physical Review, they do so by emailing a LaTeX file, and perhaps some postscript figures, to the editorial office. Since your paper will be published in the 8.06 Physical Review, you will do essentially the same, except our "publisher" Charles Suggs prefers to your submitted paper to be in final pdf format.

Although many 8.06 students have had previous exposure to LaTeX, some have not. To facilitate writing and publication of your finished papers, we have put a template for an article in the ReVTeX format used by Physical Review on the web for you to download. LaTeX itself is already available as standard Athena software, and if ReVTeX is not installed on your machine, you can download it from `http://journals.aps.org/revtex/`.

To get started, you need only download the templates, open them in your favorite editor (such as *emacs*), and notice the way the LaTeX template deals with title pages, footnotes, references, equations, mathematical symbols in text and set off from text, equation labels, tabs, and so forth. You can construct your paper by cutting the text out of the template text and inserting your own.

You should begin by downloading the template and making sure that you can LaTeX it successfully to produce output that looks like the hard copy of the template paper posted on the course web page.

In order to do this in unix, you will need the commands:

- `pdflatex filename.tex` or `pdflatex filename` will run the LaTeX typesetting program to produce typeset output from your input file. If there are errors in your LaTeX file, the file `filename.log` will contain error messages that are usually helpful. (Note that you will need to run LaTeX twice on the file, in order for all the references to bibliographic items and equation numbers to come out right.)

- `bibtex filename` will optionally process a separate `bib` file if you choose to use this for your bibliography. If you do this, you will need to run `pdflatex` once before running `bibtex` and twice afterwards.

- `latexmk --pdf filename` will run `pdflatex` and `bibtex` as many times as necessary to update the `pdf` file. Why not always use this program? When there are compiling errors, it can be more annoying to use.

- `latex filename.tex` and `dvips filename.dvi -o` will create first a `dvi` file and then a `ps` file. `ps2pdf filename.ps` can then optionally create a `pdf` file. This more old-fashioned approach may be preferable when printing on athena, but usually you will want to go straight to pdf using `pdflatex`.

Figures can be included in `jpg`, `png`, `pdf` or `eps` formats. If includegraphics is used without an extension, latex/pdflatex will search for a valid extension. The one catch is that `eps` formats are not automatically supported by `pdflatex`. However, the template provided uses the package `epstopdf` so that when includegraphics encounters an eps file it will automatically convert it to pdf. If you know how to produce illustrations in one of these formats, the template will illustrate how to incorporate them into your paper. Most graphics packages can generate eps or pdf output. The advantage of these formats over the more common jpg or png formats is that vector graphics resize more gracefully than bitmaps.

We strongly urge people who are new at LaTeX to communicate with classmates. Likewise we strongly encourage LaTeX wizards to help the less experienced with the nuances of the language.

For Mac OS X users, the program TeXShop (available as part of the MacTex package at https://www.tug.org/mactex/) can be a good alternative to the command line. TeXShop combines a text editor with a TeX compiler, and has the feature that Cmd-clicking on one window will jump to the corresponding point in the other window. For Windows users, LaTeX can be downloaded from http://miktex.org/ and this includes a program TeXworks (also available on other platforms) with similar features to TexShop. On any platform, emacs has extensive LaTeX support, including a semi-WYSIWYG ability to preview equations within the editor.