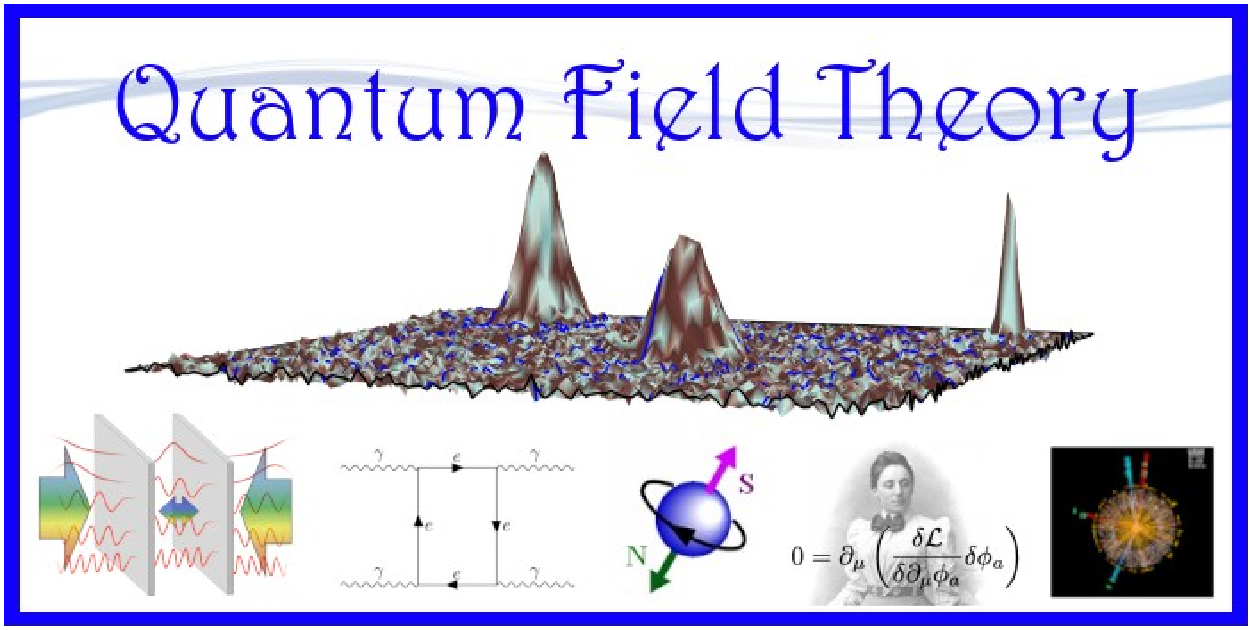

Applications of Quantum Theory (PHYS 451)

Spring Semester, 2022

Instructor:

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General Course Information

Quantum field theory provides the theoretical foundation for particle physics and for much of condensed-matter physics, and this semester's "Applications of Quantum Theory" course will serve as an introduction to the subject. In your PHYS 351 course ("Quantum Theory"), you studied how non-relativistic particles described by quantum-mechanical wavefunctions behave in the presence of external potentials or fields – potentials or fields which are treated classically. In this course, we shall move beyond this simplified picture of quantum mechanics in two ways. First, we shall modify our fundamental equation of motion in non-relativistic quantum mechanics, the Schrödinger equation, in order to make it compatible with Einstein's special theory of relativity. This modification alone can account for a number of puzzling phenomena we observe in nature, including spin and the existence of antiparticles. Second, we shall develop a conceptual framework for treating quantum systems in a fully quantum-mechanical way. Within this framework, particles can be viewed as excitations of *quantum fields* – excitations that can be created or annihilated. We shall see how fundamental symmetries of nature dictate how these quantum fields interact with one another and develop the tools for making quantitative predictions about these interactions.

By the time this semester concludes, you can look forward to being able to do all of the following:

- You will understand and be able to use **Einstein notation** for describing quantities in spacetime.
- You'll be able to apply the **Klein-Gordon and Dirac equations** in order to analyze the motion of relativistic particles.
- You'll understand and be able to explain the difference between **first quantization** and **second quantization**.
- You will be able to characterize how different quantities perform under **symmetry transformations** and be able to perform those transformations.
- You'll be able to analyze and construct **Field Lagrangians** for different theories based on on the symmetry properties of the fields they contain.
- You'll understand how to interpret **Feynman Diagrams** at a quantitative level and be able to apply this understanding in order to calculate physical quantities like scattering and decay rates.

The requirements for this course include PHYS 351 ("Quantum Theory"), as well as an understanding of multi-variable calculus, linear algebra, and the strategies for solving differential equations at the level of MATH 264. While a familiarity with special relativity at the level of PHYS 130 ("Relativity, Spacetime, and Contemporary Physics") will be extremely helpful, this course is not a prerequisite for PHYS 451. Thus, we will review the relevant aspects of special relativity during the first week of class.

Components of the Course

The course will consist of class meetings, reading assignments in the text, problem sets, and three sets of "checkpoint activities." These are described more fully below.

Class Meetings:

Class meetings will be held from **11:00 AM – 11:50 AM Eastern Time** in Hugel 017 each Monday, Wednesday, and Friday during the semester. Regular attendance at these class meetings is expected. A schedule of topics to be covered each day is listed on the course web page. Much of the material covered in this course is quite challenging. It is therefore important that you come to class prepared to ask questions and to engage in discussions. You should be aware that class meetings will involve not only my lecturing to you about the material covered in the readings (which is not necessarily the best way for me to help you learn the material), but a variety of other activities as well – the benefit you get out of which is directly proportional to the effort you put in.

Textbook:

The one required textbook for this course is

- Tom Lancaster and Stephen J. Blundell, *Quantum Field Theory for the Gifted Amateur* (Oxford University Press, 2014).

In addition to this textbook, I will occasionally assign supplementary readings from the following text in order to highlight the particle-physics applications of the material we will be studying in this class:

- David Griffiths, *Introduction to Elementary Particles*, 2nd Ed. (Wiley-VCH, 2008).

These supplementary readings will be provided for you on the course Moodle. Of course, there also exist a number of well-written graduate-level quantum-field-theory texts, which include the following:

- Michael E. Peskin and Daniel V. Schroeder, *An Introduction To Quantum Field Theory* (Perseus Books, 1995).
- Matthew D. Schwartz, *Quantum Field Theory and the Standard Model* (Cambridge University Press, 2014).
- Ta-Pei Cheng and Fong Li, *Gauge Theory of Elementary Particle Physics* Revised Ed. (Oxford University Press, 1984).

However, I caution that each of these these texts presumes a far greater amount of prior knowledge on the part of the reader than Lancaster and Blundell's book. Approach these at your own risk!

Finally, given the mathematical nature of the subject material and the variety of special functions we will encounter over the course of the semester, you may want to have a good reference volume on mathematical methods in physics on hand. For this, I recommend the following:

- Mary L. Boas, *Mathematical Methods in the Physical Sciences*, 3rd Ed. (Wiley, 2005).
- George B. Arfken, Hans J. Weber, and Frank E. Harris, *Mathematical Methods for Physicists*, 7th Ed. (Academic Press, 2012).

<u>Homework Assignments</u>:

There's no way of truly understanding quantum field theory – or indeed any topic in physics – without delving in and working through problems. For this reason, I will be assigning a number of homework problems each week which I feel provide practice with the most crucial aspects of the material we're covering in the course. A list of the problems included in each problem set will be provided on the course Moodle.

Each homework assignment is due at **5:00 PM Eastern Time** on the day indicated on the course web page (usually a Friday). Your work should be submitted in PDF format using the appropriate upload link on the course Moodle page. However, you do not need to typeset your homework in a fancy way. Writing your work out by hand on paper, scanning or photographing the pages, and converting the images to PDF format is perfectly acceptable. You may still turn in late homework for reduced credit (a 10% penalty for every 24 hours it is overdue) up until the beginning of the next class meeting. However, because we will frequently discuss homework problems during this class meeting, late homework will not be accepted after that time.

I strongly encourage you to work together on homework problems with other students in the class. This can be a very productive way of expanding your own knowledge, and working with other people to solve problems is a big part of how science is really done. However, the work that you upload and turn in to me must be your own: it should reflect your own understanding and should be written up independently after all discussion between you and your peers is complete.

Checkpoints**:**

The material in this course is organized into three units of roughly equal duration, each of which has a different physics focus. At the end of each unit, there will be a "checkpoint period" within which you will complete a set of three activities designed to demonstrate, check, and solidify your understanding of the material we've been covering in this course and to reflect on how this material connects to other things you've learned. Taken together, these checkpoint activities play the same role that an exam plays in many other courses. In particular, during each checkpoint period, you will do the following.

- You will complete a set of short, more **conceptually-focused problems** related to the material we have covered. Although you will complete these problems outside of class, you will complete them individually and do so within a specified length of time (which will not exceed 1.5 hours).
- You will solve one or two **calculationally-focused** problems similar in scope to the more involved problems that might appear on a problem set. There is no time limit on these problems (beyond the duration of the checkpoint period itself), and you are permitted to work collaboratively with your classmates on them. However, each member of the class must submit their own work.
- You will compose a **short written exposition** about a topic of your choosing that relates to the material we've been covering in this course. By "short," I mean that your exposition should contain around 350 – 400 words and should not under any circumstances exceed a page in length, even when whatever pictures, figures, and/or equations you include (and I strongly recommend including at least one or two) are taken into account. Your exposition will be shared on the Moodle with other members of the class, and you'll have the opportunity to summarize it orally for the class as well.

Each of these checkpoint activities contributes equally to your grade. The first checkpoint period will span from **Feb. 25th – Mar. 4th**. The second will span from **Apr. 8th – Apr. 15th**. The third will begin on **May 6th**, the last day of the semester (whereupon your written summary will be due), and extend through **May 13th**, which is the Friday during finals week (wherein, in compliance with Lafayette College policies, the first two activities will be construed to constitute a take-home final). As with homework assignments, you will turn in your work on all of these checkpoint exercises in PDF format via a designated set of upload links on the course Moodle page.

Office Hours:

My official office hours this semester will be held on **Tuesdays and Thursdays from 11:00 AM – 12:00 noon Eastern**, and on **Fridays from 1:00 – 2:00 PM and 4:00 – 5:00 PM Eastern** unless otherwise noted on the course web page. In order to minimize the risk of COVID-19 transmission, my office hours this semester will be held not in my office, but rather in Hugel 117, which is a better ventilated room equipped with a HEPA filter. Alternatively, if you feel more comfortable attending office hours virtually, I will also have a Zoom meeting open during each of the time windows specified above. The link for this office-hours Zoom meeting is

- https://lafayette.zoom.us/j/99772595796

The password is provided on the course Moodle. If I am meeting with another student – either in person or virtually – at the time you join this Zoom meeting, you may be placed in the waiting room for a bit before I am able to meet with you. However, if you and other students in the course have the same question, you can certainly meet with me as a group – and this applies to in-person office-hours meetings as well.

If you are unable to make it to these official office hours either virtually or in person, you may also email me to make an appointment to meet at some other time. However, I recommend that you do this as far in advance as possible in order to ensure that we can find a time to meet.

Grading and the Honor Code

Course Grade:

Your grade in the course will be determined by the following criteria:

Homework	37%
Checkpoint 1 (Relativistic Quantum Mechanics)	21%
Checkpoint 2 (Propagation and Interaction)	21%
Checkpoint 3 (Symmetries and Model-Building)	21%

Intellectual Honesty:

When studying, working on homework problems, or working on the calculationally-focused problems that you need to complete during each checkpoint period, I encourage you to work with other students. However, you may not consult a solutions manual or any other source for answers to the problems, and the final problem write-ups should be your own work. You are not permitted to work together on the set of conceptually-focused problems that you need to complete during each checkpoint period or to consult with anyone else about them until that checkpoint period is over. However, while working on any portion of the checkpoint activities, you may freely refer to the textbook (Lancaster & Blundell's *Quantum Field Theory for the Gifted Amateur*), your notes, all handouts and other materials distributed in class, and a table of integrals. You may also use a graphing calculator and a copy of Wolfram Mathematica.

As always, you are expected to abide by the principles of intellectual honesty and academic integrity outlined in the Lafayette Student Handbook, which can be found at

- https://conduct.lafayette.edu/student-handbook/

<u>Other Useful Information</u>

Student Academic Resources Site:

This is a centralized website for Lafayette students which contains resources related to college-transition support, accessibility services, tutoring, health and well-being, advising and registration, technology help, library services, student funds, and more. A link to the site is provided below

https://spaces.lafayette.edu/enrol/index.php?id=1276

You are encouraged to self-enroll in this site and to bookmark it for future reference.

Accessibility Services:

In compliance with Lafayette College policy and equal access laws, I am available to discuss appropriate academic accommodations that you may require as a student with a disability. If you are requesting accommodations, you must register with the Accessibility Services Office (administered by the Academic Resource Hub) for disability verification and for the determination of reasonable academic accommodations. Accessibility Services will then provide me with a document which outlines what those accommodations are. I cannot provide accommodations until I receive such a letter. Requests for academic accommodations must be made within the first two weeks of the semester, except in unusual circumstances, so that suitable arrangements can be made in a timely manner.

Informal Surveys:

As the semester progresses, I want to hear from you how you feel the course is going, what you like, what you don't like, what your concerns are, and how you think the course could be improved. Therefore, throughout the semester, you'll have the opportunity to fill out short surveys and informal evaluations on the course Moodle so I can get your feedback.

Course Communication:

This syllabus, a list of assigned readings and problem sets, and other course materials will be posted on the course web page, which can be found at

- https://workbench.lafayette.edu/~thomasbd/Phys451-AppsQTheory-Spring-2022/Phys451-AppsQTheory-Spring-2022.html

In addition to the course web page, there is also a Moodle page for this course which I will frequently use in distributing course materials, communicating with the class, etc. The Moodle page can be found at

- https://moodle.lafayette.edu/course/view.php?id=22407

Occasionally, it may be necessary for me to communicate additional information (scheduling changes, clarifications about homework problems, etc.) to the class as a whole.

When I do so, I will use your official Lafayette email addresses for all course-related correspondence, so make sure to check your Lafayette email regularly.

COVID-19 Protocols:

In order to minimize the risk of COVID-19 transmission during class meetings, strict protocols will be followed. These requirements apply throughout the semester, regardless of what campus protocols happen to be in force at any given time. Any person present in the classroom during class meetings is **required to wear a mask at all times**, beginning from the moment that person enters the classroom. That mask must fit the wearer's face tightly and **cover the wearer's nose and mouth**. If your mask does not fit these criteria, you will be instructed to the classroom until you have acquired a mask that does. I urge all members of the class to wear a tightly fitting N95 or KN95 respirator rather than a cloth mask or surgical mask in class meetings whenever possible. A cloth mask provides only limited protection, and a surgical mask provides only marginally better protection than a cloth mask. By contrast, an N95 respirator, when worn properly, provides a significant degree of protection both to you and others around you. I will be wearing an N95 mask in the classroom at all times. In accord with these precautions, eating and drinking will not be allowed during class meetings.

If you are experiencing COVID-19 symptoms and there is not a compelling alternative explanation for those symptoms (e.g., you feel fatigued because you stayed up all night working on a problem set), do not come to class meeting. Instead, inform me of the situation by email and get a COVID-19 test as soon as possible. If the test result is negative, you may attend subsequent class meetings. If the test results is positive, you are required by Lafayette protocols to isolate and may not attend class meetings until the isolation period is over. If this should occur, inform me immediately so that we can discuss how you will keep up with your work in this class during the isolation period. If you are experiencing COVID-19 symptoms and have not yet received your test result, or if you are isolation, you may attend office hours virtually, but not in person.

In the event that any member of the class adamantly refuses to abide by these safety protocols during any class meeting, class will be canceled effective immediately. The Dean of Students will be notified and all members of the class will receive instructions by email as to how and when we will make up for the rest of that class meeting.

Contingency Procedures for Virtual Class Meetings:

The default expectation is that all class meetings this semester will be held in person in Hugel 017. However, under certain circumstances, we may temporarily be compelled to move those meetings online. Those circumstances include the following:

- Your instructor is quarantining or in isolation
- A substantial fraction of the class is quarantining or in isolation
- There is a winter-weather emergency

I will notify all members of the class by email as far in advance as possible if we need to switch to a virtual classroom environment at any point during the semester. This may not be an infrequent occurrence, so please check your email regularly. The Zoom link that we will use for remote class meetings is

- https://lafayette.zoom.us/j/92619386242

The password is provided on the course Moodle. The assumption is that whenever this occurs, we will return to an in-person learning environment as soon as circumstances permit.

If we are ever temporarily forced to move to a virtual format, I would like us to be able to simulate the atmosphere of a physical classroom to whatever extent we can. For this reason, I would like to ask that you have your camera on during any virtual class meetings we end up having and to use the "gallery view" option on Zoom so that we can all see each other and respond to each other's visual cues. I will do the same. That said, if there are extenuating circumstances which would make having your camera on an issue for you, please reach out to me and we will work out an equitable solution. Please mute yourself when you are not speaking in order to reduce background noise. Please raise your actual hand in order to take part in the discussion. If I do not see your actual hand, please raise your "digital hand."

Privacy Statement Concerning Course Materials and Classroom Recordings:

At Lafayette College, all course materials are proprietary and for class purposes only. This includes posted recordings of lectures, worksheets, discussion prompts, and other course items. Reposting such materials or distributing them through any means is prohibited. Such materials should not be reposted or distributed through any means. You must request my permission prior to creating your own recordings of class materials, and any recordings are not to be shared or posted online even when permission is granted to record. Permission will be granted only when sanctioned as an academic accommodation in an official letter from the Accessibility Services Office. If you have any questions about proper usage of course materials please ask me. Please also be in contact with me if you have any concerns with being recorded during the course.

Online discussions in Moodle occurring during synchronous class sessions should also remain private and not be shared outside of the course. Courses using Moodle will make student information visible to other students in this class. Student information in courses is protected by the Family Educational Right to Privacy Act (FERPA). Disclosure of student information to unauthorized parties violates federal privacy laws and it must not be shared with anyone outside the class. Questions can be referred to the Registrar's Office.

Mandatory Credit-Hour Statement:

The student work in this course is in full compliance with the federal definition of a four-credit-hour course. The full policy and practice statement can be found on the Registrar's Office website at

- http://registrar.lafayette.edu/additional-resources/cep-course-proposal/

In Closing

On a final note, I want to make it clear that I'm aware of how challenging learning can be in such difficult and unpredictable times. I will do my best to be flexible in light of the difficult situations that you may encounter over the course of the semester, and I ask that you be open with me about these situations and alert me to any issues that arise. I will likewise let you know if my own circumstances change and will do my best to communicate any changes to the course schedule, the mode of instruction, etc., to all of you in a timely manner.

Despite these uncertainties, we have a rewarding semester ahead of us. Quantum field theory is a beautiful subject. It provides us not only with the conceptual tools with which to compute scattering and decay rates, but also with a deeper understanding of *why* the fundamental particles we observe in nature behave as they do.

Course Schedule

The full, up-to-date schedule for the course, including due date for all assignments is available on the course web page.

Week	Topics and Readings	Due Dates
Week 1 1/24 – 1/28	**Special Relativity Redux** Lancaster 0.4; Griffiths 3.1 – 3.5	
Week 2 1/31 – 2/4	**Representing Transformations** Lancaster 0.6 – 1.3, Griffiths 7.4	HW1 (Due 2/4)
Week 3 2/7 – 2/11	**Least Action** Lancaster 1.4 – 2.3, 5.1 – 5.4	HW2 (Due 2/11)
Week 4 2/14 – 2/18	**Field Quanta** Lancaster 2.4 – 4.2	HW3 (Due 2/18)
Week 5 2/21 – 2/25	**Relativistic Quantum Mechanics** Lancaster 6.1 – 6.4, 36.4 – 36.5; Griffiths 7.1 – 7.2	HW4 (Due 2/25)
Week 6 2/28 – 3/4	**Field Lagrangians** Lancaster 7.1 – 8.2, Appendix B	Checkpoint 1
Week 7 3/7 – 3/11	**Symmetries and Noether's Theorem** Lancaster 9.1 – 11.3	HW5 (Due 3/11)
Week 8 3/14 – 3/18	**Spring Break** (No classes)	
Week 9 3/21 – 3/25	**Canonical Quantiztion** Lancaster 11.4 – 12.3; 16.1 – 16.4	HW 6 (Due 3/25)
Week 10 3/28 – 4/1	**Propagators and Vertices** Lancaster 17.1 – 18.3; 38.1 – 38.2	HW7 (Due 4/1)
Week 11 4/4 – 4/8	**Feynman Diagrams** Lancaster 18.4 – 19.6	HW8 (Due 4/8)
Week 12 4/11 – 4/15	**From Squiggles to Observables** Lancaster 20.1 – 20.4; Griffiths 6.1 – 6.2	Checkpoint 2
Week 13 4/18 – 4/22	**The Fundamental Forces** Lancaster 14.1 – 15.4, 46.1 – 46.2; Griffiths 8.3 – 8.4	HW 9 (Due 4/22)
Week 14 4/25 – 4/29	**Loops and Renormalization** Lancaster 26.1 – 26.3, 32.1 – 32.6;	HW10 (Due 4/29)
Week 15 5/2 – 5/6	**The Standard Model and Beyond** Lancaster 26.4 – 26.5, Griffiths 10.8 – 10.9	HW 11 (Due 5/6)
Final Exam Week		Checkpoint 3