Classical Electromagnetism (ICTS Course for Int.PhD.)

Instructor : R. Loganayagam.
Tutor : Chandan Jana

Time : Jan-May 2018 (starting Jan 3rd Evening 4:30 PM)

Course Philosophy :

I think of the theoretical physics graduate course curriculum as being divided into two halves : first, an 'un-compromisable' core minimum of five subjects in which a student should have a thorough critical and analytic skills. These are

1. Classical mechanics (at the level of the standard textbook by Goldstein or Landau-Lifshitz Vol. 1)
2. Quantum mechanics (at the level of the standard textbook "Modern Quantum Mechanics" by Sakurai)
3. Statistical mechanics (at the level of the standard textbook by M. Kardar or R. K. Pathria)
4. Mathematical Physics (at the level of the standard textbook by K. F. Riley, M. P. Hobson and S. J. Bence)
5. Classical electrodynamics (at the level of standard textbooks mentioned below)

I feel that it is very difficult to go very far in theoretical physics without a deep and thorough understanding of these subjects. To work on a research problem, this needs to be supplemented by 3 to 4 courses in the appropriate research area.

My reason for this opinion is as follows : each of these core subjects introduce a particular worldview which has been very successful in our understanding of physical reality. And these viewpoints recur again and again in theoretical physics (in fact, I would define a theoretical physics problem as one where this happens). So, let me begin by describing the worldview of classical electrodynamics.

First some history. It is often said that electrodynamics was historically born out of unification of two forces - electric and magnetic. In fact, I think a more precise statement is that it combine *six* different phenomena noted by our ancestors :

1. **Magnets**, magnetic compass and magnetism of the earth.
2. **Lightning** and atmospheric phenomena like Aurora Borealis.
3. Motion of biological organisms. e.g., forces applied by humans via their **nerves and tissues**.

4. The forces born out of materials and chemicals including the forces behind **chemical reactions**.

5. **Electrostatic** forces obtained by rubbing various materials against each other.

6. Phenomena associated with **light** and optics in general.

In a remarkable turn of history filled with a long array of accidental experimental discoveries, these forces and energies were understood to be one and the same. This is perhaps the first lesson of electrodynamics : *much of the physical reality we see around us have common origins.*

What are the other lessons of electrodynamics ? They include

- Convenient description of reality is in terms of **fields**. These fields have a physical reality of their own, e.g., they carry energy and momentum. The fields evolve according to certain **partial differential equations** with appropriate **initial conditions/boundary conditions**.

- The microscopic forces except gravity are all described in fact by a pair of **electric** and **magnetic** fields acting between **charges** and **currents**. The charges produce fields and the fields in turn affect charges.

- Often, fields leave the charges to travel far in terms of **waves**. These waves can undergo **reflection, refraction, interference and diffraction** in various media.

- In vacuum, these waves can travel very fast (in fact, with the maximum possible speed) and are thus **relativistic**.

- In media, the **collective behaviour** of charges leads to an **effective/averaged description** whereby the forces are screened/enhanced/modified into something entirely new. The waves **disperse** in a frequency dependent way and their **effective speed of propagation** also becomes frequency dependent.

- At temperatures much below their frequencies, these waves start behaving like particles thus leading to **quantum behaviour**.

- When the reverse effect of particles behaving like waves is taken into account, one then forms **stable bound states/novel phases** (like atoms, molecules, solids, liquids etc.).

The reader will notice that these highlighted ideas are absolutely fundamental to how a physicist (especially theoretical physicist) views the world. It is a way of thinking, analysing and arguing about physical phenomena and one of the primary aims of an electrodynamics course is to train a student to do that.

It also serves as a stepping stone towards more advanced courses of the graduate curriculum. To name a few : quantum and statistical field theory, astrophysics (via plasma physics), condensed matter physics, General relativity, particle physics (more generally high energy theory including string theory). In reality, it is almost impossible to find something in physics where the tools and viewpoint of electromagnetism are not employed at least indirectly. To summarise, this is a **very important** course.

Prerequisites:

I am assuming you are familiar with the following topics which are standard during a first course in electromagnetism :

- Vector analysis: gradient, divergence, curl, divergence theorem, Stokes' theorem.
- Electrostatics : Poisson equation, Boundary value problems, image problems, multipole expansion.
- Electric field and potential in matter, polarisation.
- Magnetostatics.
- magnetic field in matter, magnetisation.
- Electrodynamics: Faraday's law of induction, Maxwell?s equation in free space and in matter.
- Electromagnetic waves in free space and in dielectrics.

There will be one examination (take home) on 8th January so that I can have an idea of where the class stands regarding these topics.

The basic texts that cover these pre-requisites are

- Introduction to electrodynamics by David J.Griffiths
- Electricity and magnetism by Edward M.Purcell and David M.Morin
- Feynman Lectures on Physics Vol 2 by Feynman, Leighton and Sands
- Classical Electrodynamics by Greiner

If you feel that in a particular topic, you are underprepared I will strongly recommend to look at the relevant chapters in these books. You should be roughly be able to read and comprehend first 75% of these books. Let me know if that is not the case.

Apart from these, it is good to revise various things from previous courses

- Classical mechanics : Lagrangian, Hamiltonian, Canonical transformation, Noether theorem
- Quantum mechanics : Rotations, spherical harmonics
- Statistical mechanics : Basic kinetic theory, Boltzmann weight etc.
- Mathematical methods : PDEs (especially second order PDEs like wave equation, Poisson equation, Heat equation), variable separation, Bessel functions, Legendre polynomials etc.

Especially for the last set of topics, I like to refer to

- R. Courant and D. Hilbert. Methods of Mathematical Physics (2 Vols.).
- P.M. Morse and H. Feshbach, Methods of Theoretical Physics (2 Vols.).
- K. F. Riley, M. P. Hobson and S.J. Bence, Mathematical Methods for Physics and Engineering: A Comprehensive Guide

Course contents:

The traditional topics in a course of this type include

- Intro to Special Relativity, Covariant formulation of electrodynamics
- Symmetries, Conservation laws, Lagrangian and Hamiltonian formalism in electrodynamics
- Radiation theory, multipole expansion methods and basics of scattering
- Static boundary value problems : Green functions, multipole methods in electrostatics/magnetostatics

If done in full detail (say as done in any of the main textbooks below), this is a lot of material for a semester course ! The main texts which cover this material are

- Classical Electrodynamics by J.D. Jackson
- Modern electrodynamics by A. Zangwill
- Classical Electrodynamics by J. Schwinger, L. L. DeRaad, Jr., K. A. Milton, and W-y. Tsai.

But I will not rigorously follow any of these textbooks and I will supplement it with my own notes/other books. Nevertheless, I encourage you try to finish reading most parts of these three books by end of the semester.

There will be a drop test testing on these topics on Jan 20th 2018. I will require all of you to take it. If you do well, you do not have to credit the course.

Other interesting books at this level includes

- Classical Electromagnetic Theory by J. Vanderlinde
- Classical Electricity and Magnetism by Wolfgang K.H. Panofsky and Melba Phillips
- L.D. Landau, E.M. Lifshitz and L.P. Pitaevskii
  - Vol 2 : Classical theory of Fields
  - Vol 8 : Electrodynamics of Continuous Media
- Electromagnetic processes in dispersive media by D.B.Melrose and R.C.McPhedran
- Static And Dynamic Electricity by William R. Smythe

Some more modern aspects which I hope to at least touch upon briefly :

- Mathematical aspects of Gauge invariance, Charged fields, Superconductivity, Josephson junctions
- Materials with electromagnetic response beyond the dielectric-magnet-conductor triad (piezoelectrics, Hall insulators, topological insulators etc.), emergent abelian gauge fields
- Plasma physics, MHD, atmospheric/geophysical/astrophysical electric and magnetic fields
- Electrokinetics, Nernst-Planck equation, ion transport electric double layers and electric fields in Biology (in nerves, heart, brain etc.)

Basic Info :

- **Instructor name :** R.Loganayagam,
- **Tutor name :** Chandan Jana,
- **Class hours :** Tuesday/Thursday mornings 10:30 AM - 12 PM(1.5 to 2 hrs), Emmy Noether room ,
- **First few Classes:**
  - First class on Jan 3rd Wednesday Evening 4:30 PM.
  - There will be a two week long break after that till 18th Jan, i.e., till the end of 'ICTS At Ten' meeting and Kavli Asian Winter School (except for the Griffiths level exam on 8th).
  - We will have to arrange a series of makeup classes to compensate on mutually agreeable time.
- **Tutorial time :** Friday afternoon 2:30 PM - 4 PM(1.5 to 2 hrs) , Emmy Noether room
- **Office hours of the Instuctor :** office no. A-103 from 2:30 p.m.- 3:30 p.m. (preferably) on Tuesday.
- **Tutor Office hours :** office no. H-102 from 2:30 p.m.- 3:30 p.m. (preferably) on Wednesday.
- **Tutorial structure :** Two students will be called to board to solve two problems from the assignment on the day of tutorial. The tutorial will be an interactive session where the problems can be discussed among students as well as the tutor.
- **Assignment Policy :**
  - Frequency : There will be an assignment roughly every week.
  - Submission : Please ensure to submit the assignments by the next tutorial.
  - Plagiarism: You all are encouraged to collaborate with others in the class. But do not copy from others.
- **Student Evaluation :**
  - The evaluation part of the course has three components : assignments exams and term paper presentation.
  - Refer above for the assigment policy.
  - There will be a mid-semester and an end-semester exam apart from various quizes. The end-sem exam will be waived for those who present a term paper.
  - The grading policy will be based on the following weightage :
    * Quiz : 10%
    * Assignments : 20%
    * Mid term Exam : 30%
    * End term Exam (or Term paper) : 40%