PHYS 213: Electrodynamics and Classical Field Theory

Syllabus Spring 2009

CRN 46932, section 10

Teacher: Dr. Harald W. Griesshammer, Samson Hall 317, 202-994-3849, hgrie@gwu.edu.

Lectures: ***Monday/Wednesday 12:20 to 14:00 in Samson Hall 311*** (100 min each, for 4 credits).
No lectures: ***6 April***. Thus, there will probably be a makeup lecture on ***30 April***.

Surgery hours: ***Wednesdays at 10:00 in Samson Hall 209*** to discuss the problem sheets and for questions, discussions and suggestions; *duration:* till all questions are answered.
More office hours by appointment weekdays after 3pm in my office. Best email what and when to discuss to make sure I have time and am prepared.

Web-site: ***http://home.gwu.edu/˜hgrie/lectures/edyn09/edyn09.html*** for up-to-date course information, .pdf-files of Problem Sheets, a manuscript, suggested reading, corrections, etc.

Prerequisites: Undergraduate Electrodynamics on the level of Griffith: *Introduction to Electrodynamics*, Chaps. 1-6; advanced undergraduate mathematical methods; undergraduate Quantum Mechanics.
The graduate courses in Autumn, in particular *PHYS 209: Mathematical Methods of Theoretical Physics* and the chapters on Lagrangean Mechanics and on Relativity in *PHYS 211: Classical Mechanics*, are indispensable. See the first two paragraphs in the *Questions to Check Your Progress.*
Coordinated with *PHYS 221: Quantum Mechanics I* (Haberzettl).
Co-requisite: *PHYS 282: Computational Physics II* (Haberzettl/Griesshammer).

Goals: Introduction into the theoretical concepts and mathematical methods of Classical Electrodynamics as example of a relativistic Field Theory. Focus on skill-building, symmetry principles, controlled approximations, and concepts at the fore-front of research.

Outline of Contents in thematic order only; duration is estimated only.

1. The Fundamental Equations of Electrodynamics (1 lecture)

   Recap: vector analysis (incl. Gauß', Stokes', Helmholtz' theorems), fields, interpretation of Maxwell's equations

2. Electrodynamics as Relativistic Field Theory (4 lectures)

   Recap Special Relativity and action for point particles – Lagrange mechanics of continua, fields and Electrodynamics – gauge fields and gauges – conserved currents – energy, momentum and stress

3. Electrostatics (4 lectures)

   Poisson equation – Recap Green's functions, boundary value problems, spherical harmonics and other complete orthonormal sets of functions – Cartesian and spherical multipole moments

4. Magnetostatics (1 lectures)

   Law of Biot-Savart – magnetic dipole

5. Radiation and Radiating Systems (6 lectures)

   Wave equation – plain waves – polarisation – retarded potentials — antennae and radiation multipoles – radiation from a moving charge – Bremsstrahlung – synchrotron radiation – radiation loss and Larmor's formula – emergence of geometrical optics

6. Scattering Theory (3 lectures)

   boundary conditions – cross-sections – Lorentz oscillator model and its limits

7. Electrodynamics in Matter (8 lectures)

   Polarisability – energy-dependent dielectric constant and magnetic susceptibility – free fields in matter – reflection and refraction – dispersion relations

8. Advanced Topics (time permitting)

   Quantum Mechanics with the classical electromagnetic field – superconductivity and topology – non-perturbative phenomena in classical field theory – solitons – a dash into field quantisation

Style: ***"Commenting lecture with strong student participation"***, i.e. focus on central points to guide and assist you in exploring relevant literature. *The home-page lists strongly suggested reading to efficiently prepare and in particular follow-up on course material.* Most important is the link to a manuscript of the lecture in my (illegible) hand-writing, see p. 4. Read over the manuscript before class and grasp the essential points. *I will assume that you have read this material before each lecture and that you will familiarise yourself with its formal aspects after each lecture.* The better prepared you are, the more we can focus on discussing your questions, problems, observations. The class becomes more interactive and thus more fun – and therefore you learn more. Study details of the manuscript after the lecture, as starting point for your own literature research using good books like those recommended for particular subjects in the "Suggested Reading" column below. Some people prefer to have a print-out of the manuscript in class, so that they do not have to write down all details but can highlight and annotate important points.
We will *not* repeat in class the contents of textbooks, but add different perspectives and seek a deeper understanding of the underlying concepts. I present you not the entirety of Electrodynamics – that would be impossible –, but provide an introductory overview with a personal selection of topics which are frequently used in modern research. Some topics are *not covered thoroughly enough* in class, some may be hard to find in textbooks (see notes on the bibliography), and others are only addressed in the homework. From time to time, we will only briefly review the concepts and concentrate on solving as a group a problem which has been distributed to you in advance. You are strongly encouraged to think about the problem before class.
The "lectures" are only a first guide to study Electrodynamics in books, e.g. in those listed below. You should ask yourselves the type of questions that lead to developing and understanding the key physical concepts and the skills of scientific reasoning. I as teacher can assist, guide, motivate, trigger and speed up your studies, but learning is an active process which takes place within you more than in the lecture hall. Its difference to research is mostly that when doing research, you learn what is not yet found in textbooks.

I encourage you strongly to ask questions and initiate discussions in class and during Surgery hours at all times. Think of lectures rather as "tutorial" or "studio" than a fixed set of hours in which I talk and you listen. If I cannot give you a satisfactory answer right away, I will come back to you, and you should continue asking until you are satisfied. If you have no questions, I will assume that you get bored, encouraging me to speed up. If you find discussion in class or Surgery hard to follow, see me instantly!

Grading policy: In order to foster collaboration and cooperation among you, the course will be graded on an absolute scale. The final grade is a sum of:

- Exercises/Homework (40% of total): weekly, see below for details;
- Mid-Term Exam (30% of total): **Friday, 27 March at 10:00 in Samson Hall 311**, 2.0 hours;
- Final Exam (30% of total): **Monday, 11 May at 10:00 in Samson Hall 311**, 2.5 hours.

In order to pass, you need at least 60% of all points *and* at least 50% of the points available in each of the three components *separately.* In particular, you need at least 50% of all points in all Problem sheets together (not per sheet!). 80% is an excellent score, and 90% has not been achieved yet. I do not post scores on the web. If you have questions or comments on your grade or your overall score, please see me.

For your protection, the exams are closed-book. A sheet with some possibly relevant mathematical formulae will be provided by me, several days before the exam. I will assume that you have memorised the most fundamental Physics formulae, like Maxwell's equations. If you have understood the Physics contents of formulae and practised enough examples, you will not even bother to consciously memorise anything.

Exercises/Homework: distributed Wednesdays in class and on the web, **due the following Tuesday at 12:00 noon** in my pigeon-hole for paper-submissions or by fax (202-994-3001) or electronically to my email (.pdf-file only). **Handwritten solutions must be on 5x5 quadrille ruled paper** (I recommend a composition book or the like). *Late homework is graded as zero points. No exceptions.*
Graded solutions are **returned and discussed during Surgery hour on Wednesday**. Typically, problem sheets contain a mix of detailed and only outlined questions, with up to 30 points per sheet. Some problems require numerics or graphics programmes (Maple, Mathematica, Fortran, Assembler, C(++), etc.). It is a fact of life that if you score more than 60% of the homework points, you will most likely perform well in exams and the qualifying. Some exam questions will almost certainly be based on homework solutions.
While it is necessary to have the correct answer for full credit, it is not sufficient. Indeed, it may serve you only one point. What you hand in should be a tidy and efficiently short presentation of your results and how they come about, which can be understood and reproduced by your peers. Imagine it is not homework, but a research problem whose solution you are asked to explain to your peers. I neither encourage nor discourage you to submit solutions electronically. But if you do so, submit in .pdf format only and work with a good drawing programme like xfig or gimp (freeware) for sketches. Electronic submission is no excuse for leaving out sketches or figures.
I reserve the right to award zero points for any illegible, chaotic or irreproducible section of your homework.
I encourage you to form study groups to discuss the reading and attack Problem sheets as team. Nothing helps you understand better than interacting with your peers. However, practise additional problems alone to make sure that you do not become dependent on the others.
You can best study and check your progress if you present results and problems with selected exercises in the seminar-style Surgery hours. Your discussion of solutions, problems and comments shape them. As integral part of the lecture, I encourage you to attend them regularly. There is no better preparation for the exams. Surgery is my prime tool to gauge our progress and revisit material which is not fully digested yet.
Some projects of *PHYS 282: Computational Physics II* will be chosen from material in this course, and hence will need some "real" programming. These do not count towards your grade in this course; see separate announcement of *PHYS 282: Computational Physics II* (Dr. Haberzettl), and later in the course.
Typical workload for this course: 10 to 12 hours per week, in addition to lectures and surgery hours.

A note on academic integrity: You like Physics, or you would not be here. Thus, it is trivial that you will abide by the GW Code of Academic Integrity (*http://www.gwu.edu/˜ntegrity/code.html*) in all graded work. You are encouraged to collaborate on your homework and even be inspired by a good textbook, but make sure you have understood what you hand in as your solution. Do *not* offend your own (and my) intelligence by copying other people's work (especially without referencing). The web-site, all problems and solutions are for your personal use only. Please do not pass solutions or problems on to any student who has not taken the course (yet). Noncompliance with these rules is a breach of integrity and will be dealt with accordingly. If you have any questions about what constitutes academic dishonesty, ask me.

Absences and Excuses follow standard GW policy. It is your own responsibility to make sure you fulfil the criteria for passing, in particular that you get at least 50% of all the points available in all Problem sheets together (not per sheet). The only way around this criterion is to submit in writing documentation that you were unable to perform homework for more than half the semester due to reasons out of your control, as outlined in the GW policy on absences and excuses.
There will be no make-up exams. A missed exam will be dealt with case-by-case. Bring any potential conflicts or difficulties to my attention *before* the exam. If you miss an exam for some unexpected reason, it is your responsibility to notify me in writing *within 24 hours* of the missed exam, or the grade will be zero for

the missed exam. Absence for medical reasons must have formal, written documentation from the medical office providing care. DC traffic is no excuse, and no additional time will be provided for late-comers.
If you see a conflict between religious observances and the class and exam schedule, you will bring them to my attention in advance, as soon as possible at the beginning of the semester.

Lecture Manuscript

A scanned version of a chapter-by-chapter manuscript can be found by following the links of chapter headings in the Class Schedule and Contents Section on the web-site.
Caveat: Warning and Disclaimer These are my notes for preparing the class, in my handwriting. While considerable effort has been invested to ensure the accuracy of the Physics presented, this script bears only witness of my limited understanding of the subject. I am most grateful to every reader who can point out typos, errors, omissions or misconceptions. Maybe over the years, with lots of student participation, this can grow into something remotely useful.
The script only intends to ease the pain of preparing and following the lecture, and does not replace the thorough study of textbooks (see note above on the Style of the Lecture, p. 2). The script is not intended to be comprehensible, comprehensive – or even useful. It is certainly not legible. Your mileage will vary. This script is not useful or relevant for exams of any kind.

Some Suggested Reading

There is *no required reading* for this course. You will not be able to find all aspects of the lecture explained well in only one textbook. Moreover, it is an essential part of the learning process to view the same topic from different angles, i.e. using different textbooks. Here is a list of those which I found most useful. If you discover others, tell me. *The web-site lists recommended readings for each lecture.*
An asterisk * indicates titles on Course Reserve at Gelman Library, with max. 3 days for loan. Be social.

[M] G.B. Arfken and H.J. Weber: Mathematical Methods for Physicists; 4th edition, Academic Press, ca. 78$. While not optimal (as we saw last semester), it is a reasonable tool to refresh and study the necessary math.

[Brau] * Ch.A. Brau: Modern Problems in Classical Electrodynamics; Oxford University Press; ca. 98$. A "new kid on the block" which I find an excellent compromise between [Jack] and [Lan2/8], arguing beautiful Physics. While most closely reflecting the philosophy of the lecture, some topics are not or insufficiently covered. May be too weak on explaining mathematical details.

[Jack] * J.D. Jackson: Classical Electrodynamics; 3rd ed., John Wiley, ca. 100$. The classic text/bible of researchers. Covers all aspects, but too focused on mathematical details. Chaotic treatment of media.

[Lan2] * L.D. Landau and E.M. Lifshitz: The Classical Theory of Fields [Course of Theoretical Physics Series, Vol. 2]; 4th ed., Butterworth-Heinemann; ca. 45$. Indispensable for theorists, concise, dismissing mathematical details as trivial, and hence maybe sometimes hard to swallow. Electrodynamics in matter is found in [Lan8]; includes General Relativity.

[Lan8] * L.D. Landau, E.M. Lifshitz and L.P. Pitaevskii: Electrodynamics of Continuous Media [Course of Theoretical Physics Series, Vol. 8]; 2nd ed., Butterworth-Heinemann; ca. 45$. Good presentation, but slightly outdated, very detailed and maybe sometimes hard to swallow. Covers what [Lan2] leaves out.

[Low] * F.E. Low: Classical Field Theory – Electromagnetism and Gravitation; John Wiley; ca. 99$. Pricey but concise book which focuses on concepts. Good compromise between [Jack] and [Lan2, Lan8]. Despite its title, Gravitation is only a short addendum. Only marginal coverage of media.

[Schw] J. Schwinger, L.L. DeRaad, K.A. Milton, W. Tsai: Classical Electrodynamics; Perseus Books; ca. 62$. Unconventional approach, from a master of the field.

[Grif] D.J. Griffith: Introduction to Electrodynamics; 3rd ed., Prentice Hall; ca. 102$. Undergraduate text.

[Schwa] M. Schwartz: Principles of Electrodynamics; Dover; ca. 12$. Undergraduate text.

The University Counseling Center (UCC) assists you in addressing personal, social, career, and study problems that can interfere with your academic progress and success.
Services for students include:
– **Crisis Consultations at 202-994-5300** open day and night, not only for emergency.
– Academic Support and Peer Tutoring Services: *http://gwired.gwu.edu/counsel/AcademicSupport*
– Podcasts and Self-Help: *gwired.gwu.edu/counsel/PodCast, gwired.gwu.edu/counsel/OutreachSelfHelp*

They are also very good when you need to review your habits, like learning and exam strategies.
It's never too early to get help.

Conventions

I define and normalise special functions (like Legendre Polynomials $P_l(z)$, spherical harmonics $Y_{lm}(\vartheta, \varphi)$ etc.) as in [Brau] = [Jack] = [M] = Gradshteyn/Ryzhik: *Table of Integrals, Series and Products.*

Einstein's summation convention: sum over all indices which appear exactly once as subscript and exactly once as superscript, except if stated otherwise.

"east-coast" metric	$g_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$	contra-variant 4-vectors	$V^\mu = (V^0, \vec{V})$
space-time indices	$\mu, \nu, \rho, \dots = 0, \dots, 3$	spatial indices	$i, j, k, \dots = 1, 2, 3$
function of 3-dim. vector	$f(\vec{r})$	function of 4-dim. vector	$f(x^\mu) \equiv f(x)$
3-dim. scalar product	$a_i b^i \equiv a^i b_i \equiv \vec{a} \circ \vec{b} \equiv \vec{a}^T \vec{b}$	4-dim. scalar product	$a \cdot b \equiv a_\mu b^\mu \equiv a^\mu b_\mu$
Green's function of linear, d-dimensional differential operator D			$D\, G(\vec{r}, \vec{r}') = \delta^{(d)}(\vec{r} - \vec{r}')$

Systems of Electromagnetic Units are not a glorious chapter of metrology: There exist five "major" systems, and several variants which are used next to each other or even simultaneously within the same branch of Physics. I use the **Gaussian (cgs) System**, which knows only three fundamental units (centimetres, grams and seconds) and shortens formulae (no ϵ_0 or μ_0, hardly any 4π etc.). The standard system of everyday life is SI, with the familiar basic units m, kg, s, A, K, rad and cd. While the Physics contents of an equation is of course independent of the system used, one is in applications obviously interested in questions like "at which current is this resistor blasted". [Lan2/8, Low, Schw] and [Jack, Chap. 1-9] use cgs; [Brau, Grif, Schwa] and [Jack, Chap. 10-16] use SI.

You can choose whichever system you want, but I expect your solutions to be consistent!

Fortunately, the system used is uniquely determined by any two of the fundamental equations which contain $\vec{E}$ and a combination of $\vec{E}$ and $\vec{B}$. You find below a table with two equations and conversion factors from Gaussian to SI units. More on systems, units and dimensions e.g. in the appendices of [Jack] and [Brau].

Unit	**Gaussian cgs System**	**Syst. Internat. d'Unitès SI**
el. field strength of point charge Q	$\frac{Q}{r^2}$	$\frac{1}{4\pi\epsilon_0}\,\frac{Q}{r^2}$
Lorentz force $\vec{F}$	$Q\,(\vec{E} + \frac{1}{c}\,\vec{v} \times \vec{B})$	$Q\,(\vec{E} + \vec{v} \times \vec{B})$
Gauss' law (Maxwell I)	$\vec{\nabla} \cdot \vec{E} = 4\pi\,\rho$	$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_0}\,\rho$
Faraday's law of induction (Maxwell II)	$\vec{\nabla} \times \vec{E} + \frac{1}{c}\,\dot{\vec{B}} = 0$	$\vec{\nabla} \times \vec{E} + \dot{\vec{B}} = 0$
elementary charge q	$1.6022 \times 10^{-20}\,\tilde{c}\,\underbrace{\mathrm{g}^{\frac{1}{2}}\,\mathrm{cm}^{\frac{3}{2}}\,\mathrm{s}^{-1}}_{\text{electrostatic units (esu)}}$	1.6022×10^{-19} Coulomb (C)
dielectric constant of the vacuum ϵ_0	1 (no dimensions)	$\frac{10^7}{4\pi c^2}\,\frac{\mathrm{A}^2\,\mathrm{s}^2}{\mathrm{kg\ m}} = \frac{1}{\mu_0 c^2}$
permeability of the vacuum μ_0	1 (no dimensions)	$4\pi \times 10^{-7}\,\frac{\mathrm{kg\ m}}{\mathrm{A}^2\,\mathrm{s}^2}$
unit potential $(\Phi, \vec{A})$	$\frac{10^8}{\tilde{c}}\;\underbrace{\mathrm{g}^{\frac{1}{2}}\,\mathrm{cm}^{\frac{1}{2}}\,\mathrm{s}^{-1}}_{\text{statvolt=erg esu}}$	$= 1$ Volt (V)
unit el. field strength $\vec{E}$	$\frac{10^6}{\tilde{c}}\;\underbrace{\mathrm{g}^{\frac{1}{2}}\,\mathrm{cm}^{-\frac{1}{2}}\,\mathrm{s}^{-1}}_{\text{statvolt cm}^{-1}\text{=dyn esu}}$	$= 1\,\frac{\mathrm{V}}{\mathrm{m}}$
unit mag. induction $\vec{B}$	$10^4\;\underbrace{\mathrm{g}^{\frac{1}{2}}\,\mathrm{cm}^{-\frac{1}{2}}\,\mathrm{s}^{-1}}_{\text{Gauß (G)}}$	$= 1$ Tesla (T)

$c := 2.997\,924\,58 \times 10^8\ \mathrm{m\,s}^{-1}$: velocity of light in vacuum;

$\tilde{c} = 2.997\,924\,58 \times 10^{10}$: num. conversion factor: velocity of light in vacuum in Gaussian units [cm s^{-1}].

Some Essential Numbers which you should know by heart when woken up at night: Because formulae are nice, but we also want to explain natural phenomena quantitatively.
Units are arbitrary: Some calculate in metres, grams and Celsius, while others prefer feet, pounds and Fahrenheit. Still, some systems facilitate conversions and calculations more than others. A very efficient system is the **Natural System of Units** in which as many fundamental constants as possible have as simple a value as possible. It is particularly popular in Nuclear and High-Energy Physics.

Set the speed of light and Planck's quantum (more accurately: $\hbar = h/(2\pi)$) to $c = \hbar = 1$. This expresses velocities in units of c, and actions and angular momenta in units of $\hbar$. There is then only one fundamental unit, namely either an energy- or a length-scale. Time-scales have the same units as length-scales. When one sets on top of that Boltzmann's constant $k_\mathrm{B} = 1$, energy and temperature have the same units. This is particularly nice because one only has to memorise a handful of really relevant numbers for quick estimates. In this system, "matching units" between different parts of an equation becomes very easy: $E = m$ instead of $E = mc^2$, etc. This example also shows how to "restore" the SI answer from an answer in "natural units": Throw in enough powers of $c\,[\mathrm{m/s}]$ and $\hbar\,[\mathrm{kg\,m^2/s}]$ till you match the proper SI units. In the example, you have to convert $\mathrm{kg\,m^2/s^2}$ into kg, i.e. add two powers of m/s, which shows you have to multiply with c^2.
[As a last step, one could set Newton's gravitational constant $G_N = 1$, which eliminates *any* dimension-ful unit – but that is done only by String Theorists.]

Here some numbers which will appear regularly in the course. The list is not exhaustive, not meant to be relevant and may not be useful. Your mileage may vary. It's better to know too much than not enough. You should check these values and understand how they come about.
$\approx$: number rounded for easier memorising – it suffices to know the first significant digit.
$\widehat{=}$, $\widehat{\approx}$: correspondences are correct only in the natural system of units.

Quantity	**Value**
speed of light in vacuum	$c \approx 3 \times 10^8$ m s^{-1}
energy electron gains when accelerated by 1 V	1 electron Volt (eV) $\approx 1.6 \times 10^{-19}$ Joule $= 1\frac{q}{[\mathrm{C}]}$ J
typ. length-scale in Atomic Physics (size of H-atom, atom-spacing in solid)	1 Ångstrom (Å) $= 10^{-10}$ m $= 0.1$ nm
typ. length-scale in Sub-Atomic Physics (size of proton, neutron)	1 fermi (femtometre, fm) $= 10^{-15}$ m
conversion factor energy-length	$\hbar c \mathrel{\widehat{=}} 1 \approx 200$ MeV fm $\approx 2 \times 10^{-7}$ eV m ≈ 2 keV Å
$\Longrightarrow$ conversion factor distance-time (nat. units) (time for light to travel a typ. distance-scale)	1 fm $\mathrel{\widehat{\approx}} \frac{1}{3} \times 10^{-23}$ s; 1 Å $\mathrel{\widehat{\approx}} \frac{1}{3} \times 10^{-18}$ s
conversion factor energy-temperature: $E = k_\mathrm{B} T$	1 eV $\mathrel{\widehat{\approx}}$ 11 600 Kelvin
fine-structure constant/measure of el. strength	$\alpha = \left.\frac{q^2}{\hbar c}\right\vert_{\text{Gauß}} = \left.\frac{q^2}{4\pi\varepsilon_0 \hbar c}\right\vert_{\text{SI}} \approx \frac{1}{137}$ (no units!)
electron mass	$m_\mathrm{e} \approx 511$ keV
nucleon (proton, neutron) mass	$m_\mathrm{N} \approx 940$ MeV $\approx 1800\, m_\mathrm{e}$
energy levels of the Hydrogen-atom	$E_n = -\frac{\alpha^2 m_e c^2}{2n^2} \approx -\frac{13.6\text{ eV}}{n^2}$, $n = 1, 2, 3, \dots$
Bohr-radius of the Hydrogen-atom	$a_\mathrm{B} = \frac{\hbar}{\alpha m_e c} \approx 0.5$ Å
typ. energy & wave-length of visible light	$E_\text{vis} \approx [2; 3]\,\text{eV}$, $\lambda_\text{vis} \approx [400; 700]\,\text{nm} \approx [4000; 7000]\,$Å
Avogadro's number of particles per mol	$N_\mathrm{A} \approx 6 \times 10^{23}$ mol^{-1} (atoms in 12 g of pure ^{12}C)
volume of 1 mol ideal gas at STP (1 bar, 273 K)	22.4 litres (l) mol^{-1}

Some Hints for a Successful Graduate Life

This is by no means a complete list, but it helps me in my teaching and research. Use your own judgement!

Take Dr. Haberzettl's hand-out "How To Write Homework – and Related Questions" seriously. You do not have to type your Electrodynamics homework, but he has some very good advise how to avoid errors and which cross-checks are very valuable.

Attack your homework early. Don't postpone it to the last few days or even minutes.

Make a plan of attack. First think what solution you expect from your physical intuition. Then ponder over a good way to find the solution. This can take even an hour. Then take a deep breath. Then think again about the problem. Then solve. The time spent on first thinking about the solution is much shorter than the time wasted with abandoned attempts when you instantly start scribbling. In particular in exams.

Form teams (see above). Nothing helps one to understand better than discussing homework and lectures with peers. But practise additional problems alone in order not to become dependent on others.

Put craftsmanship before ingenuity. You will be outstanding soon enough, but for now, continuous, solid work is more reliable than occasional sparks of brilliance.

Don't get nailed-down. Nobody requires you to find the *best/most elegant/fastest* solution. *Any* solution will do for a start. Once you have one, you can always look for a better one – if you have the time. When stuck, discuss with your peers (and consult the lecture and books). If you get very stuck, do another problem first. It's no use to get no problem done because you wasted all your resources on the first one.

Practise sketching and plotting. Discussions, sketches and plots are a must! Not only because the homework is full of these words, and you will loose a lot of points if you do not discuss, sketch and plot. But human beings are visual beings: We understand and recollect much better when we see a figure.

Scrutinise your homework when it is returned to you and reproduce a correct solution. Clean up your notes. What did you not understand? What did you miss? Was there a faster way? Where are your strengthes and weaknesses? You should spend at least a hour on that, as soon as possible. It will help you with the next homework set.

Work through each lecture on the day it is delivered. If you miss that, you will have a very hard time to understand the next lecture. In that context, "Tomorrow will be another day" is a very bad motto.

"Fill in the gaps" of the lecture. Spell out the details of a proof, make sure the signs and factors are correct, etc. That already gives you a lot of free practise in math, and makes sure your thinking and notes are up-to-date and correct. And you have a set of notes you understand when you come back after weeks or months or years, for exams or research.

Consult books (plural!) after you have reviewed the lecture. It will clarify things further, show you new and different perspectives, and deepen your understanding. I usually excerpt information which I found interesting in a book, in addition to lecture notes.

Look at the Physics behind a formula. Does it make "sense" from your physical intuition? Do you understand what it means? What are its limits, i.e. regimes where it becomes particularly simple to understand? What are its limitations, i.e. where does it not work? Explain it and its underlying principle to a peer or to an undergraduate, using no math. You will believe your most beautiful mathematical proof only if you can also give a good intuitive argument why the formula should be right.

Ask yourself: What is the hidden agenda behind this topic in the lecture, homework, etc.? What can I learn that goes beyond the straightforward application? Is there a greater principle involved which I can use in different contexts? Why is e.g. a proof presented this way? In which other fields could I use similar techniques/reasoning, outside electrodynamics?

Talk with your lecturers. We post out office hours not out of courtesy, and we don't bite. If you don't come to me with your problems, how can I help you? I – for one – love discussing. Have no fear to overburden me. I will tell you when I have had enough.

Have a life outside Physics.