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Front Matter

Konstantin Likharev
SUNY Stony Brook, konstantin.likharev@stonybrook.edu

Konstantin K. Likharev

Essential Graduate Physics

Lecture Notes and Problems

Beta version

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Preface

This is a series of lecture notes and problems on "Essential Graduate Physics", consisting of the following four parts:

CM: *Classical Mechanics* (for a 1-semester course),
EM: *Classical Electrodynamics* (2 semesters),
QM: *Quantum Mechanics* (2 semesters), and
SM: *Statistical Mechanics* (1 semester).

The parts share a teaching style, structure, and (with few exceptions) notation, and are interlinked by extensive cross-referencing. I believe that due to this unity, the notes may be used for teaching these courses not only in the (preferred) sequence shown above, but in almost any order – or in parallel.

Each part is a two-component package consisting of:

(i) *Lecture Notes* chapter texts,[2] with a list of exercise problems in the end of each chapter, and
(ii) *Exercise and Test Problems with Model Solutions* files.

The series also includes two brief reference appendices, *MA: Selected Mathematical Formulas* (16 pp.) and *CA: Selected Physics Constants* (2 pp), and a list of references.

The series is a by-product of the so-called *core physics* courses I taught at Stony Brook University from 1991 to 2013. Reportedly, most physics departments require their graduate students to either take a set of similar courses or pass comprehensive exams based on an approximately similar body of knowledge. This is why I hope that my notes may be useful for both instructors and students of such courses, as well as for individual learners.

The motivation for composing the lecture notes (which had to be typeset because of my horrible handwriting) for Stony Brook students was my desperation to find textbooks I could actually use for teaching. First of all, the textbooks I could find, including the most influential *Theoretical Physics* series by L. Landau and E. Lifshitz, did not match my classes, which included experiment-oriented students, some PhD candidates from other departments, US college graduates with insufficient undergraduate background, and a few advanced undergraduates. Second, for the rigid time restrictions imposed on the core physics courses, most available textbooks are way too long, and using them would mean hopping from one topic to another, picking up a chapter here and a section there, at a high risk of losing the necessary background material and logical connections between course components - and students' interest with them. On the other hand, many textbooks lack even brief discussions of several traditional and modern topics that I believe are necessary parts of *every* professional physicist's education.[3,4]

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[2] The texts are saved as separate .pdf files of each chapter, optimized for two-page viewing and double-side printing; merged files for each part and the series as a whole, convenient for search purposes, are also provided.

[3] To list just a few: statics and dynamics of elastic and fluid continua, basic notions of physical kinetics, turbulence and deterministic chaos, physics of reversible and quantum computation, energy relaxation and dephasing in open quantum systems, the Rotating-Wave Approximation (RWA) in classical and quantum mechanics, physics of electrons and holes in semiconductors, weak-potential and tight-binding approximations of the energy band theory, optical fiber electrodynamics, macroscopic quantum effects in Bose-Einstein condensates,

The main goal of my courses was to make students familiar with the basic notions and ideas of physics (hence the series' title), and my main effort was to organize the material in a logical sequence the students could readily follow and enjoy, at each new step understanding why exactly they need to swallow the next knowledge pill. As a back side of such a minimalistic goal, I believe that my texts may be used by advanced undergraduate physics students as well. Moreover, I hope that selected parts of the series may be useful for graduate students of other disciplines, including astronomy, chemistry, mechanical engineering, electrical, computer and electronic engineering, and material science.

At least since Confucius and Sophocles, i.e. for the last 2,500 years, teachers have known that students can master a new concept or method only if they have seen its application to at least a few particular problems. This is why in my notes, the range of theoretical physics methods is limited to the approaches that are indeed necessary for solution of the problems I had time to discuss, and the introduction of every new technique is always accompanied by an application example or two. Additional exercise problems are listed in the end of each chapter of the lecture notes, and may be used for homeworks. Individual readers are strongly encouraged to solve as many of these problems as possible.[5]

Detailed model solutions of the exercise problems (some with additional expansion of the lecture material), and several shorter problems suitable for tests (also with model solutions), are gathered in 6 separate files - one per semester. These files are available for both university instructors and individual readers – free of charge, but in return for a signed commitment to avoid unlimited distribution of the solutions (see p. vii below). For instructors, these files are available not only in the Adobe Systems' Portable Document Format (*.pdf), but also in the Microsoft Office 1997-2003 format (*.doc) free of macros, so that the problem assignments and solutions may be readily grouped, edited, etc., before their distribution to students, using either virtually any version of Microsoft Word or independent software tools - e.g., the public-domain OpenOffice.org.

I know that that my texts are far from perfection. In particular, some sacrifices made at the topic selection, always very subjective, were extremely painful. (Most regretfully, I could not find time for even a brief introduction to the general relativity.[6]) Moreover, it is very probable that despite all my effort and the great help from SBU students and teaching assistants, not all typos/errors have been weeded out. This is why all remarks (however candid) and suggestions by the readers would be highly appreciated. All significant contributions will be gratefully acknowledged – both online and in possible future edition(s) of the series.

Bloch oscillations and Landau-Zener tunneling, cavity QED, and the Density Functional Theory (DFT). All these topics are discussed, if only concisely, in these notes.

[4] Recently several high-quality, graduate-level teaching materials became freely available online, including R. Fitzpatrick's text on *Classical Electromagnetism* (farside.ph.utexas.edu/teaching/jk1/Electromagnetism.pdf), B. Simons' "lecture shrunks" on *Advanced Quantum Mechanics* (www.tcm.phy.cam.ac.uk/~bds10/aqp.html), and D. Tong's lecture notes on several topics (www.damtp.cam.ac.uk/user/tong/teaching.html).

[5] The problems that require either more bulky calculations, or more creative approaches (or both :-), are marked by stars.

[6] For an introduction to the subject, I can recommend either a review by S. Carroll, *Spacetime and Geometry*, Addison-Wesley, 2003, or a longer text by A. Zee, *Einstein Gravity in a Nutshell*, Princeton U. Press, 2013.

Disclaimer

Since these materials are available free of charge, it is hard to imagine that somebody would blame their author for deceiving "customers" for his commercial gain. Still, I would like to go a little bit beyond the usual litigation-avoiding claims,[7] and offer a word of caution to the potential reader, in order to preempt his or her possible later disappointment.

This is NOT a course of theoretical physics – at least in the contemporary sense of the term

Though much of the included material is similar to that in textbooks on "theoretical physics" (most notably from the famous series by L. Landau and E. Lifshitz), this lecture note series is different from them by its emphasis on the basic concepts and ideas of physics, their relation to experimental data, and most important applications - rather than on sophisticated theoretical techniques. Indeed, the set of theoretical methods discussed in the notes is limited to the minimum necessary for quantitative understanding of the key notions of physics and solving a few (or rather about a thousand :-) core problems. Moreover, because of the notes' shortness, I have not been able to cover some key fields of theoretical physics, most notably the general relativity and quantum field theory - beyond some introductory elements of quantum electrodynamics in QM Chapter 9. If you want to work in modern theoretical physics, you need to know much more than these lectures!

Moreover, this is NOT a textbook – at least not the usual one

A usual textbook tries (though most commonly fails) to cover virtually all aspects of the field. As a result, it is typically way too long for being fully read and understood by students during the time allocated for the corresponding course, so that the instructors are forced to pick up selected chapters and sections, frequently loosing narrative's logic lines. In contrast, these notes are much shorter (about 200 pages per semester), enabling their thorough reading – perhaps with just a few later sections dropped, depending on reader's interests. I have tried to mitigate the losses due to this minimalistic approach by providing extensive further reading recommendations on the topics I had no time to cover. The reader is highly encouraged to use these sources (and/or the corresponding chapters of more detailed textbooks) on any topic(s) of his or her special interest.

Then, what these notes ARE and why you may like to use them (I think)

By tradition, graduate physics education consists of two main components: research experience and advanced physics courses. Unfortunately, the latter component is currently under pressure in many physics departments, apparently because of two reasons. On one hand, the average knowledge level of students entering graduate school is not improving, so that bringing them up to the level of contemporary research becomes increasingly difficult. On the other hand, the research itself is becoming more fragmented, so that the students frequently do not feel an immediate need for a broad physics

[7] Yes Virginia, these notes represent only my personal opinions, not necessarily those of the Department of Physics and Astronomy of Stony Brook University, the SBU at large, the SUNY system, the Empire State of New York, the federal agencies and private companies that funded my group's research, etc. No dear, I cannot be hold responsible for any harm, either bodily or mental, their reading may (?) cause.

knowledge base for their PhD project success. Some thesis advisors, trying to maximize the time they could use students as a cheap laboratory workforce, do not help.

I believe that this trend toward the reduction of a broad physics education in graduate school is irresponsible. Experience shows that during his or her future research career, a typical current student will change research fields several times. Starting from scratch in a new field is hard - terribly hard in an advanced age (believe me :-). However, physics is fortunate to have a *hard core* of knowledge, that many other sciences lack. With this knowledge, the student will always feel in physics at home, while without it, he or she may not be able even to understand research literature in the new field, and would risk being reduced to auxiliary work roles – if any.

I have seen the main objective of my Stony Brook courses to give an introduction to this hard core of physics knowledge, at the same time trying to convey my own enchantment by the unparalleled beauty of the concepts and ideas of this science, and the remarkable logic of their fusion into a wonderful single construct. Let me hope that these notes relay not only the knowledge as such, but also at least a part of my enchantment.

Versions and Acknowledgements

This is a preliminary ("Beta") version of the series. My plans are to publish, in a few years, its final version. Until that has happened, I commit to keeping the Beta stable. The only changes still to be made in it will be corrections of the typos noticed by the readers and myself, and minor stylistic edits.

I am extremely grateful to my faculty colleagues and other readers who commented on certain sections of the notes; here is their list (in the alphabetic order):[8]

A. Abanov, P. Allen, D. Averin, S. Berkovich, P.-T. de Boer, M. Fernandez-Serra, R. F. Hernandez, T. Konstantinova, A. Korotkov, V. Semenov, F. Sheldon, X. Wang.

(Evidently, these kind people are not responsible for the remaining deficiencies.)

The Department of Physics and Astronomy of the Stony Brook University was very responsive to my requests of certain time ordering of my teaching assignments, that was beneficial for note writing and editing. The department, and the university as the whole, also provided a very friendly general environment for my work during the past 25 years.

A large part of my scientific background and experience, reflected in these materials, came from my education (and then research work) in the Department of Physics of Moscow State University.

And last but not least, I would like to thank my wife Lioudmila for several good advices on aesthetic aspects of note typesetting, and for all her love, care, and patience – without them, this project would be impossible.

Konstantin.Likharev@StonyBrook.edu

[8] I am very much sorry that I have not kept proper records from the beginning of my lectures at Stony Brook, so I cannot list all the numerous students and TAs who had kindly attracted my attention to typos in earlier versions of these notes. Needless to say, I am very grateful to them all as well.

Problem Solution Request Templates

Requests should be sent to *konstantin.likharev@stonybrook.edu* in either of the following forms:

- an e-mail from a valid university address,
- a scanned copy of a signed letter – as an e-mail attachment.

Approximate contents:

A. Request from a Prospective Instructor

Dear Dr. Likharev,

My plans are to use your lecture notes and/or problems of the *Essential Graduate Physics* series, part <select: CM, EM, QM, SM>, in my course <title> during <semester, year> in the <department, university>. I would appreciate sending me file *Exercise and Test Problems with Model Solutions* of that part of the series in the <select: .pdf, both .doc and .pdf> format(s).

I will avoid unlimited distribution of the solutions, in particular their posting on externally searchable Web sites. If I distribute the solutions among my students, I will ask them to adhere to the same restraint.

I will let you know of any significant typos / deficiencies I may find.

Sincerely, <signature, full name, university position, work phone number>

B. Request from an Individual Learner

Dear Dr. Likharev,

My plans are to use your lecture notes and problems of the *Essential Graduate Physics* series, part(s) <select: CM, EM, QM, SM>, for my personal education. I would appreciate sending me file(s) *Exercise and Test Problems with Model Solutions* of that part(s) of the series.

I will not share the material with anyone, and will not use it for passing courses that are officially based on your series.

I will let you know of any significant typos / deficiencies I may find.

Sincerely, <signature, full name, present home address (in English), acting phone number>

Notation

Abbreviations

Eq. any formula (e.g., equation)

Fig. figure

Sec. section

Fonts

F, $\mathcal{F}$ scalar variables

$\mathbf{F}$, $\boldsymbol{\mathcal{F}}$ vector variables

$\hat{F}, \hat{\mathcal{F}}$ scalar operators

$\hat{\mathbf{F}}, \hat{\boldsymbol{\mathcal{F}}}$ vector operators

F matrix

$F_{jj'}$ matrix element

Symbols

$\dot{}$ time differentiation operator (d/dt)

∇ spatial differentiation vector (*del*)

$\approx$ approximately equal to

$\sim$ of the same order as

$\propto$ proportional to

$\equiv$ equal to by definition (or evidently)

$\cdot$ scalar ("dot-") product

$\times$ vector ("cross-") product

$\overline{}$ time averaging

$\langle\ \ \rangle$ statistical averaging

[,] commutator

{ , } anticommutator

Parts of the series

CM: Classical Mechanics

EM: Classical Electrodynamics

QM: Quantum Mechanics

SM: Statistical Mechanics

Appendices

MA: Selected Mathematical Formulas

CA: Selected Physical Constants

Formulas

The most general and/or important formulas are highlighted with blue frames and short titles on the margins.

Numbering

Chapter numbers are dropped in all references to formulas, figures, footnotes, and problems within the same chapter.

General Table of Contents

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