South African Institute of Physics

Benchmark Statement for Physics in South Africa

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Preface

Society expects that public training programmes should be of relevance to its needs, lead to employment, prepare for citizenship, be recognised by academia and be sufficiently transparent and comparable to facilitate mobility and recognition. Furthermore, these training programmes should be understood and valued by and appeal to significant numbers of good students.

There is an over-emphasis on passing examinations as opposed to meaningful learning. Graduates often lack the skill to integrate knowledge, and are consequently unable to demonstrate the required understanding by applying the disciplinary knowledge appropriately and effectively.

Business and industry markets are increasingly demanding practical (useful) skills, a development that excludes many graduates. The prospects of South Africa increasing its service and manufacturing development and exporting such services and products to earn a significant fraction of the multi-billion-dollar industry are limited. A study by Griesel and Parker (Graduate Tributes: A baseline study on South African graduates from the perspective of employers, 2009) reported that South African companies have identified task-directed engagement and the application of knowledge to be the key skills which new recruits are lacking. Companies are finding it increasingly difficult to identify individuals with the required specialised skills and are thus spending considerable resources on in-house training and sponsoring staff to attend courses offered externally. In addition, employers often argue that disciplinary expertise is only one of a much larger set of components that determine whether an individual will operate successfully on entering a profession.

In 2008 the heads of physics departments expressed their concerns about the under- preparedness of students entering first-year physics and the inadequate competence of graduates in physics when completing their first degree at university. In response to these concerns, the Council of the South African Institute of Physics launched a project: Review of Physics Training in South Africa. The objectives of this project are the following:

- To develop a set of standards for physics training in South Africa;
- To assess the levels of commonality and diversity of the physics programmes;
- To assess the range, scope and effectiveness of current teaching and learning practices in physics at universities; and
- To develop a set of recommendations which would improve the effectiveness of physics teaching at universities.

This project should provide a foundation for quality enhancement of physics training. Quality in programme design and delivery would enhance the achievement of the declared aims of the programme and would guarantee the suitability of meeting the expectations of students, academic staff, employers and the public. The development of a benchmark statement which comprises a set of standards for physics in South Africa is an essential component of the project.

A benchmark is a standard or point of reference against which programmes may be compared or assessed. Benchmarking is a strategic process often used to evaluate and measure performance in relation to best practices of the particular sector towards improving one's own performance. Benchmarks are usually broad in nature as they reflect the consensus of all the participating organisations or institutions on the desired performance for improving the quality of their operations or outputs.

Where benchmarks are formulated by a group comprising participants who are representative of the sector, they have to take a broad approach to integrate concerns at regional and national levels. After consultation with physicists on a regional basis, a Benchmark Statement Task Team (consisting of seven members) was constituted, representing the 17 physics departments in the country. The Task Team has now completed this first version of the benchmark statement, which will be updated from time to time through consultations with the South African physics community.

The framework provided by the benchmark is a tool for planning training programmes. In order to facilitate the monitoring and evaluating of progress against the benchmarks and the analysing of existing gaps, it is necessary to break down the benchmark into its corresponding standards and indicators that spell out the best practices implicitly understood in the benchmark. While it is ideal to have indicators, which are as specific as possible to make them measurable, they usually remain somewhat generic. Such a framework of standards will facilitate the assessment of the range, scope and effectiveness of current teaching and learning practices in physics at universities.

It is up to each institution to formulate the precise and measurable indicators that apply to its situation in the context of various national policies, including the Higher Education Qualifications Framework, Level Indicators, and the generic Qualification Standard for the Bachelor of Science degree, as well as the respective university rules.

1. Introduction

1.1. This benchmark statement characterises the skills and achievements that graduates of physics-based degrees should attain. These degrees are BSc and BSc Honours: service courses are not included. Throughout this statement references to physics should be considered as encompassing all branches of experimental (or observational), computational and theoretical, unless otherwise stated.

1.2. Advances in physics are at the core of the development of our world. Physics is a basic science that is important in any education system as knowledge of physics is required by most science and engineering professions. Furthermore, physics research and the physics principles involved in many advanced technological devices make a physics establishment vital for any advanced economy. In South Africa, there is a long tradition of physics research at universities and national laboratories. There is a general acceptance that there is a need for more research and development in the South African economy in which physicists have a vital role to play. The desperate need for qualified science teachers is another area where there is a specific South African need. Furthermore, physics is not simply a discipline for the training of scientific personnel, [continue here]

but lies at the core of our intellectual understanding of all aspects of nature and the foundation of many of the sciences.

1.3. Physics is a demanding discipline. A deep understanding of the frontiers of physics often requires advanced knowledge, which is usually acquired during postgraduate studies (MSc and PhD). This benchmark statement focuses on the BSc and BSc Honours degrees.

1.4. Physics degrees will continue to evolve in response to developments in the subject and to influence and reflect changes in the school curriculum. The significant differences in the quality of schools in South Africa and the various programmes to address these, such as extended degree programmes, make an entrance requirement for the BSC programmes in physics problematic. Universities usually have admission requirements which are informed by the level of the school curriculum and its assessment in relation to the challenges which the university programme presents to the students.

1.5. This benchmark statement concentrates on general graduate outcomes and does not specify or prescribe a physics curriculum. A core curriculum for physics at BSc and BSc Hons level is suggested in a separate document attached hereto. The physics curricula at the various universities obviously vary and include many more topics than are suggested in the core curriculum.

2. Nature and extent of physics

2.1. Physics is concerned with the observation, understanding and prediction of natural phenomena and the behaviour of systems. It deals with profound questions about the nature of the universe and with some of the most important practical, environmental and technological issues of our time. Its scope is broad and involves mathematics and theory, experiments and observations, computing, technology, materials, and information theory. Ideas and techniques from physics also enable developments in related disciplines, including chemistry, computing, engineering, materials science, mathematics, medicine, biophysics and the life sciences, meteorology, and statistics.

2.2. Physics is both a theoretical and a practical discipline that continually evolves. It is characterised by the idea that systems can be understood by identifying a few key quantities, such as energy and momentum, and the universal principles that govern [Please continue here]
them. Part of the appeal of the subject is that there are relatively few such principles and that these apply throughout science and not only in physics. The laws of mechanics are a good example: deduced by Newton after studying observations of planetary motion, they govern systems familiar in everyday life as well as many of the phenomena observed in the movement of stars and galaxies.

2.3. In order to make quantitative predictions, physics uses mathematical models. The types of approximation used to find satisfactory models of experimental observations turn out to be very similar whether the underlying laws are those of classical physics, statistical mechanics or quantum theory. Typically, an idealised model of some phenomenon is established, the equations for the model are solved (often with further approximations) and the results related back to what is observed experimentally. Sometimes a model turns out to be appropriate in very different circumstances. For example, the same model describes the behaviour of electrons in metals and in white dwarf stars.

2.4. Physics is an empirical science. The skills and methods used to make measurements are an integral part of physics. The final test of the validity of any theory is whether it agrees with experiment. Many important discoveries are made as the result of the development of some new experimental technique. Instruments developed originally in physics can find applications in other branches of science; for example, the accelerators which were originally developed to study the nucleus are now used for studying thin films in material science and for carbon dating.

2.5. Progress in physics requires imagination and creativity. It is often the result of collaboration between physicists from different backgrounds and can involve the exchange of ideas and techniques with people from outside the discipline. Within physics there are three broad categories of activity: experimental (or observational); computational; and theoretical, although many physicists span these categories.

2.6. Studying physics brings benefits that last a lifetime, as well as knowledge and skills that are valuable outside physics. Such benefits include a practical approach to problem solving, often using mathematical formulation and solution; the ability to reason clearly and to communicate complex ideas; information and communication technologies (ICT); and self-study skills, along with the pleasure and satisfaction that comes from being able to understand the latest discoveries in science. [After graduation, physicists work in a wide variety of employment, including research, development and education, industry, government and academia, and increasingly in areas such as business and finance, where they are sought after for their pragmatic and analytical approaches to the solution of problems.]

3. Subject knowledge and understanding

3.1. The BSc and BSc Honours degree programmes in physics address the more general and fundamental topics of physics, provide a selection of more advanced topics, and develop investigative, experimental, mathematical, computational, modelling and other generic skills. The various programmes emphasise different areas. For example, theoretical physics programmes normally include significantly more mathematical and computational skills, usually replacing much or possibly all conventional laboratory work.

3.2. Undergraduate physics curricula need to cater for students planning to move on to research (in industry or academia), as well as for students looking for a broad physics-based education which will make them numerate, articulate and eminently employable. Curricula usually distinguish between fundamental ideas and the description and modelling of phenomena. The fundamentals, which all students need to cover to some extent, include electromagnetism, quantum and classical mechanics, statistical physics and thermodynamics, wave phenomena, and the properties of matter. Students should also study the application of the fundamental principles to particular areas. These may include (but need not be limited to) atomic physics, nuclear and particle physics, condensed matter physics, materials, optics, plasmas, and fluids. Astrophysics and astronomy programmes should normally include the application of physical principles to cosmology; the structure, formation and evolution of stars and galaxies; planetary systems; and high-energy phenomena in the universe. [Medical physics programmes are already specified by the accreditation board.] In addition, the curricula should help students to develop some understanding of applications in everyday life as well as some qualitative understanding of current developments at the frontiers of the subject.

3.3. Students should learn that physics is a quantitative subject and should appreciate the use and power of mathematics for modelling the physical world and solving problems. Mathematics is an essential part of a physics degree.

3.4. Physics curricula should give students the experience of the practical nature of physics. They should provide students with the skills necessary to plan investigations and collect and analyse data, including estimation of inherent uncertainties. All graduates in physics should have some appreciation of natural phenomena in an experimental context. Except perhaps for theoretical physics degrees where the skills identified here are gained in other clearly specified ways, practical work should thus be a vital and challenging part of a physics degree. Students should also become proficient in presenting experimental results or theoretical conclusions and in the writing of reports. Open-ended project work should be used to facilitate the development of students' skills in research and planning (through the use of databases and published literature) and their ability to critically assess the link between theoretical results and experimental observation. Project work could also play an important role in providing an opportunity for students to integrate knowledge from different parts of the physics curriculum.

4. Subject-based skills, generic skills and qualities

In addition to acquiring insights into the working of the physical world, BSc and BSc Honours degrees in physics develop a wide range of competence in generic and subject-specific skills of which the following are particularly relevant:

4.1. Physics skills

Students should learn:

- how to formulate and tackle problems in physics. For example, they should learn how to identify the appropriate physical principles, how to use special and limiting cases and order-of-magnitude estimates to guide their thinking about a problem and how to present the solution, making their assumptions and approximations explicit;
- how to use mathematics to describe the physical world. They should have an understanding

of mathematical modelling and of the role of approximation;

- how to plan, execute and report the results of an experiment or investigation. They should be able to use appropriate methods to analyse their data and to evaluate the level of its uncertainty. They should also be able to relate any conclusions they make to current theories of the physics involved; and
- to compare critically the results of model calculations with those from experiment and observation.

4.2. Generic skills

A physics degree should enhance the following types of skills:

- Problem-solving skills - physics degree programmes involve students in solving problems with well-defined solutions. They should also gain experience in tackling open-ended problems. Students should develop their ability to formulate problems in precise terms and to identify key issues. They should develop the confidence to try different approaches in order to make progress on challenging problems;
- Investigative skills - students will have opportunities to develop their skills of independent investigation. Students will generally have experience of using textbooks and other available literature, of searching databases and the Internet, and of interacting with colleagues to derive important information;
- Communication skills - physics and the mathematics used in physics deal with unexpected ideas and difficult concepts; good communication is essential. A physics degree should develop a student's ability to listen carefully, to read demanding texts, and to present complex information in a clear and concise manner;
- Analytical skills - physics helps students appreciate the need to pay attention to detail and to develop their ability to manipulate precise and intricate ideas, to construct logical and reasoned arguments, and to use technical language correctly;
- ICT skills - during their studies, students will develop their computing and ICT skills in a variety of ways, including their ability to use appropriate software such as programming languages and analysis packages; and
- Personal skills - students should develop their ability to work independently, to use their initiative and to organise themselves to meet deadlines. They should gain experience of group work and be able to interact constructively.

4.3. Ethical behaviour

Students should appreciate that to fabricate, falsify or misrepresent data or to commit plagiarism constitute unethical scientific behaviour. They should be objective, unbiased and truthful in all aspects of their work and recognise the limits of their knowledge.

5. Teaching, learning and assessment

5.1. Physics is a hierarchical discipline that lends itself to systematic exposition and the ordered and structured acquisition of knowledge. It is also an empirical subject. Practical skills, including an appreciation of the link between theory and experiment, should be developed. This leads to teaching methods that may typically include the following:

- lectures supported by problem classes and group tutorial work,
- practical work,
- the use of textbooks, electronic resources and other self-study materials,
- open-ended project work, some of which may be team-based, and
- activities devoted to generic and subject-specific skills development.

5.2. The balance between these may vary between institutions, programmes and modules, and will evolve with time owing to advances in information technology and pedagogical thinking.

5.3. Approaches to skills development should encompass both generic and subject-specific skills. It may well be more appropriate to develop both within the physics context. Development between levels of study should be evident: for example, laboratory work may become open-ended with more demanding reporting criteria at the higher levels. Computer skills should normally include the basics of programming, but it is increasingly the case that the use of programs for simulation, for computer algebra and for data analysis is more appropriate for the physicist. Skills may also be developed in the use of computers for the control of experiments and the acquisition of data.

5.4. A variety of assessment methods are appropriate within a physics programme, some of which are more suitable for formative assessment. Evidence of the standards achieved could be obtained from many of the following:

- time-constrained examinations
- closed-book and open-book tests
- problem-based assignments
- laboratory books and reports
- observation of practical skills
- individual project reports (including placement or case study reports)

- team project reports
- oral and/or poster presentations; possibly including seminar presentations
- interviews
- essays
- project artefacts such as computer programs or electronic circuits
- electronic media
- peer and self-assessment.

5.5. The performance of individual students may vary significantly between modules and the students' marks in some modules may not be commensurate with their overall performance: this variability should be taken into account during the assessment.

5.6. At the end of the three- or four-year programme, students could be required to sit for a comprehensive examination to test their mastery of the fundamental concepts of physics and their ability to integrate the various elements of physics. The examination should cover the full range of the curriculum, should emphasise deeper understanding rather than rote problem-solving skills, and should require the student to synthesise concepts learned in different modules at different levels.

6. Benchmark standards

6.1. All students graduating with BSc and BSc Honours degrees in physics are expected to demonstrate that they have acquired knowledge, abilities and skills in the areas identified in the previous sections, but there will inevitably be significant differences in their level of attainment. In particular, there will be differences between the level of attainment demonstrated by a typical student graduating from the BSc degree programme and a typical student graduating from the BSc Honours programme.

6.2. In discussing the range of knowledge and levels of attainment in this section, the topics to be covered are those outlined in Section Three.

6.3. It is the learning outcomes contained within a programme specification that are assessed and it is the responsibility of institutions to ensure that their regulations and procedures guarantee the integrity of their awards.

Physics major in a BSc degree

Typical level for BSc (Physics)

6.4. The BSc degree structure varies from university to university. Some of the institutions require that students should offer two major subjects while other universities require a single major. Several students would take physics up to first- or second-year level only. This benchmark statement refers only to the learning outcomes in physics at the final level (third year) of the BSc degree.

6.5. BSc degrees with a major in physics should be awarded to students who have demonstrated the following:

- a basic knowledge and understanding of physical laws and principles, and some application of these principles;
- an ability to identify relevant principles and laws when dealing with problems;
- the ability to execute and analyse the results of an experiment or investigation. Students should be able to evaluate the level of uncertainty in their results and compare these results with expected outcomes, theoretical predictions or published data and hence assess their significance;
- a familiarity with basic laboratory apparatus if on an experimental programme;
- competent use of appropriate ICT packages/systems for the analysis of data and the retrieval of appropriate information;
- an ability in numerical manipulation and the ability to present and interpret information graphically;
- an ability to communicate scientific information, in particular through scientific reports; and
- an ability to manage their own learning and to make use of appropriate texts and learning materials.

The above is the typical level for a BSc degree. For admission to a BSc Honours programme, a student is expected to demonstrate potential to be able to reach the typical BSc Honours level as outlined below.

Typical level BSc Hons (Physics)

6.6. Typical holders of a BSc Honours degree in physics will have demonstrated the following:

- a knowledge and understanding of most fundamental physical laws and principles, and competence in the application of these principles to diverse areas of physics;
- an ability to solve problems in physics using appropriate mathematical tools. Students should be able to identify the relevant physical principles and make approximations necessary to obtain solutions;
- the ability to execute and analyse critically the results of an experiment or investigation and draw valid conclusions. Students should be able to evaluate the level of uncertainty in their results and compare these results with expected outcomes, theoretical predictions or with published data. They should be able to evaluate the significance of their results in this context;
- a familiarity with advanced laboratory apparatus and techniques if on experimental programmes;
- effective use of appropriate ICT packages/systems or programming languages for the analysis of data and the retrieval of appropriate information;
- an ability in numerical manipulation and the ability to present and interpret information graphically;
- an ability to use mathematical techniques and analysis to model physical behaviour;
- an ability to communicate scientific information. In particular, students should be able to produce clear and accurate scientific reports; and
- an ability to manage their own learning and to make use of appropriate texts, research-based materials or other learning resources.

Appendix A: CORE PHYSICS CURRICULUM

In this section, a core curriculum for physics at BSc Hons level is suggested. It is not implied that these topics should be covered during the BSc Hons year, but rather that these topics should have been covered during the four years of study, including the BSc Hons year. The physics curricula at the various universities obviously vary and include many more topics than are suggested in the core curriculum.

Mathematics for Physicists

- Trigonometric and hyperbolic functions; complex numbers
- Series expansions, limits and convergence
- Calculus to the level of multiple integrals; solution of linear ordinary and partial differential equations
- Vectors to the level of div, grad and curl; divergence theorem and Stokes' theorem
- Matrices to the level of eigenvalues and eigenvectors
- Fourier series and transforms including the convolution theorem
- Probability distributions

Mechanics and Relativity

Classical Mechanics to include:

- Newton's laws and conservation laws, including rotation
- Newtonian gravitation to the level of Kepler's laws

Special relativity to the level of:

- Lorentz transformations and the energy-momentum relationship

Quantum Physics

Background to quantum mechanics to include:

- Black body radiation
- Photoelectric effect
- Wave-particle duality
- Heisenberg's uncertainty principle

Schrödinger wave equation to include:

- Wave function and its interpretation
- Standard solutions and quantum numbers to the level of the hydrogen atom
- Tunnelling
- First order time independent perturbation theory

Atomic, nuclear and particle physics to include:

- Quantum structure and spectra of simple atoms
- Nuclear masses and binding energies
- Radioactive decay, fission and fusion
- Pauli exclusion principle, fermions and bosons and elementary particles
- Fundamental forces and the Standard Model

Condensed Matter Physics

- Mechanical properties of matter to include elasticity and thermal expansion
- Inter-atomic forces and bonding
- Phonons and heat capacity
- Crystal structure and Bragg scattering
- Electron theory of solids to the level of simple band structure
- Semiconductors and doping
- Magnetic properties of matter

Oscillations and Waves

- Free, damped, forced and coupled oscillations to include resonance and normal modes
- Waves in linear media to the level of group velocity
- Waves on strings, sound waves and electromagnetic waves

Electromagnetism

- Electrostatics and magnetostatics
- DC and AC circuit analysis to the level of complex impedance, transients and resonance
- Gauss, Faraday, Ampère, Lenz and Lorentz laws to the level of their vector expression
- Maxwell's equations and plane electromagnetic wave solution; Poynting vector
- Electromagnetic spectrum
- Polarisation of waves and behaviour at plane interfaces

Optics

- Geometrical optics to the level of simple optical systems
- Interference and diffraction
- Dispersion

Thermodynamics and Statistical Physics

Zeroth, first and second laws of thermodynamics to include:

- Temperature scales, work, internal energy and heat capacity
- Entropy, free energies and the Carnot cycle
- Changes of state

Statistical mechanics to include:

- Kinetic theory of gases and the gas laws to the level of Van der Waals equation
- Statistical basis of entropy
- Maxwell-Boltzmann distribution
- Bose-Einstein and Fermi-Dirac distributions
- Density of states and partition function