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A EUROPEAN SPECIFICATION FOR PHYSICS BACHELOR STUDIES

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A EUROPEAN SPECIFICATION FOR PHYSICS BACHELOR STUDIES

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PREFACE

The **European Physical Society** (EPS) is a Europe-wide professional association with 41 national member societies. The EPS supports the Bologna Process and provides with a series of *specifications* a means to describe the characteristics of the physics study programmes in a European dimension. This series covers (a) the bachelor or first-cycle or EQF level 6, (b) master or second-cycle or EQF level 7 and (c) doctorate or third-cycle level or EQF level 8, which together constitute one of the three priorities of the *Bologna Process* [EC09a]. The specifications also describe general expectations about the standards for the award of qualifications at the given level and articulate the attributes and capabilities - *i.e.* the learning outcomes - that those possessing such qualifications should be able to demonstrate. These qualifications are in agreement with the *European Qualifications Framework* (EQF) [EC09b]. National statements and guidelines [MS04, KF05, IM07, LM07 and QA08] have already been established in some countries, and have been very influential in designing these specifications. The European bachelor level or EQF level 6 corresponds to the UNESCO level ISCED 5A [UN06]

This present EPS *specification* refers to the physics *bachelor* degree in a European perspective. **Specifications are used for a variety of purposes**. Primarily, they are an important external source of reference for higher education institutions (HEIs) when new programmes are being designed and developed. They provide general guidance for articulating the learning outcomes associated with the programme but are not detailed descriptions of a core or model curriculum. Specifications provide for variety and flexibility in the design of programmes and encourage innovation within an agreed overall national, regional or institutional framework.

Specifications also provide support to institutions in pursuit of **internal quality assurance**. They enable the learning outcomes specified for a particular programme to be reviewed and evaluated against agreed general expectations.

Finally, specifications are among a variety of **external reference points** that may be drawn upon for the purpose of external review. Reviewers should not use specifications as a crude checklist for these purposes however. Rather, they should consider them in conjunction with the relevant programme descriptions, the institutions' own internal evaluation documentation, in order to arrive at a rounded judgment based on a broad range of evidence.

This present physics bachelor specification has been undertaken by a **European group of physics higher education specialists** (see Annex 1). The group's work has been funded with support from the European Commission [EC07] and was facilitated by the European Physical Society, which publishes and distributes these documents. The present document went through a full consultation and validation process with the wider European academic community and the stakeholder groups.

In due course the specification will be **revised** to reflect developments in physics (and astronomy) and the experiences of institutions and others who are working with it. The EPS will initiate revision and will make arrangements for any necessary modifications to the document in collaboration with the European physics community.

A **Glossary** of key terms in higher education can be found in [EU09a] & [Vl07].

In Annex 2 a common European **Benchmark** framework for Bachelor degrees in Physics is added.
It was kindly provided by the Working Group 1 in the **STEPS** (*Stakeholders Tune European Physics Studies*) **TWO** network. It is aimed at the level of an indicative listing, which broadly specifies the common programme which can be found in most physics degrees across Europe. Also this document went through a full consultation and validation process with the wider European academic community and the stakeholder groups.

PHYSICS BACHELOR STUDIES

1 - Introduction

1.1 The present *specification for physics bachelor programmes* characterises a European-wide view of the competences and achievements that graduates of physics bachelor degrees should have acquired through their studies and training. There exists a wide range of programmes delivering such degrees reflecting the varying aspects of physics and different national perspectives, traditions and educational policy imperatives. However, there is wide agreement across Europe of what constitutes the basics of physics and the essentials of what should be included in a first degree in physics. This specification relates to the physics components of programmes delivering degrees where **physics (including astronomy) and mathematics represents a significant proportion - at least 70% - of the programme**. In a large number of European countries bachelor degrees are a fairly recent development inspired by the Bologna Process. Physics departments and national physical societies might welcome some guidance on what such degrees should try to achieve and the topics they should aim to cover. This document builds on extensive work carried out over recent years by the physics group in the *TUNING* project [TU09a] and over a longer period by the *EUPEN* group of physics departments [Fe05] both of which have done a great deal to establish European-wide consensus on the essentials of physics degree programmes. While this work has been vital in order to establish a European wide consensus, several parts of the present text rely very much on the Physics Benchmark produced by the QAA in the UK [QA08] from which they have been directly taken.

1.2 Physics is a *major discipline* in the European Higher Education Area (EHEA) with over 100 000 full-time equivalent students registered on undergraduate HE programmes. Physics graduates play a major role in the EU economy. However, physics is not only a discipline which is required for scientific and technical professionals, it is also an essential part of our understanding of all aspects of nature and the principles and methods which allow us to understand the universe. As such it has wide and deep cultural dimensions and its study is of universal value. It forms the foundation of many of the sciences and their applications. Physics is also an important backbone for new advances in technology, which constitutes an important factor in the development and economy of our society.

1.3 Physics is a maturing and demanding discipline. An understanding of the frontiers of physics often requires *advanced knowledge*, which cannot necessarily be acquired during a bachelor degree programme. The present specification has taken this into account in interpreting the generic competences of the qualification framework for bachelor or first-cycle level physics degree programmes.

1.4 Physics degrees will continue to evolve in response to developments in the discipline and changes in the (secondary) school curriculum. Hence the present specification concentrates on general learning outcomes and does *not specify a model or a core physics curriculum*.

2 - Programme structure and delivery

2.1 Physics is a *hierarchical* discipline that requires systematic exposure and ordered as well as structured acquisition of knowledge. It is a subject which relies on experiment and observation as the source of our knowledge of the physical universe but which complements this with theoretical constructs based on a fairly small number of all embracing principles and laws often expressed and developed using mathematics. Practical skills have to be developed as also does an appreciation of the link between theory and experiment.

'This leads to teaching methods that may typically include [QA08]:

- lectures supported by problem classes and group tutorial work;
- laboratory work;
- the use of textbooks and other self-study materials;
- open-ended project work, some of which may be team-based;
- activities devoted to physics-specific and generic competence development'.

In the *TUNING* methodology [TU09a], the use of learning outcomes and competences is necessary in order to make study programmes and their course units or modules student-centred and output-oriented. This approach requires that the key knowledge and skills that a student needs to achieve during the learning process determine the content of the study programme. *Modularisation* of the study programmes is explained in [We09, Ke09].The balance between the above teaching methods may vary between institutions, programmes and modules, and will evolve with time due to advances in information technology and pedagogical thinking [Fe05, Ke09].

2.2 'Approaches to skills development should encompass both *physics-specific* and *generic competences* [TU09b], developed 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 include the basics of programming. Acquiring familiarity with programs for simulation, computer algebra and data analysis has gained increasing relevance for the physicist. Skills may also be developed in the use of computers for the control of experiments and the acquisition of data'.

2.3 '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 some or all of the following [QA08]:

- time-constrained examinations;
- closed-book and open-book tests;
- problem based assignments;
- laboratory reports;
- observation of practical skills;
- individual project reports (including placement or case-study reports);
- team project reports;
- oral and/or poster presentations, including seminar presentation;
- oral examinations & viva voce interviews;
- essays;
- project outcomes such as computer programs or electronic circuits;
- electronic media;
- peer and self assessment'.

2.4 'Examination and test questions should be graded to assess a *student's understanding of concepts* and ability to develop, apply and test mathematical models, to perform calculations, to solve new problems, to communicate physical arguments and to assess critically results in their context. Time-constrained work has its place in testing the student's capacity to organise work as well as to think and to communicate under pressure. Such assessments should be augmented by others, such as presentations and project reports, which allow students to demonstrate what they can achieve under less severe time constraints. Skills such as project-planning and execution, research competences, application of IT and report writing, are best assessed in this way' [QA08].

2.5 In 2004 the *Joint Quality Initiative* [JQ04] developed the following descriptors, known as the *Dublin Descriptors* (based on Bloom's [Bl56] Taxonomy), to determine when students in their learning process would have attained the bachelor level:
"Qualifications that signify completion of the first cycle are awarded to students who:

- have demonstrated knowledge and understanding in a field of study that builds upon their general secondary education, and is typically at a level that, whilst supported by advanced textbooks, includes some aspects that will be informed by knowledge of the forefront of their field of study;
- can apply their knowledge and understanding in a manner that indicates a professional approach to their work or vocation, and have competences typically demonstrated through devising and sustaining arguments and solving problems within their field of study;
- have the ability to gather and interpret relevant data (usually within their field of study) to inform judgments that include reflection on relevant social, scientific or ethical issues;
- can communicate information, ideas, problems and solutions to both specialist and non-specialist audiences;
- have developed those learning skills that are necessary for them to continue to undertake further study with a high degree of autonomy."

In their 2007 London Summit the 'Bologna' ministers insisted on the use of learning outcomes in curriculum design and student-centred pedagogy (see also [TU09a]).

2.6 Institutions which apply the *European Credit Transfer and Accumulation System* (ECTS) [EC09c] publish their course catalogues on the web, including detailed descriptions of study programmes, units of learning, university regulations and student services [Ke09]. Course descriptions contain learning outcomes (what students are expected to know, understand and be able to do) and workload (the time students typically need to achieve the learning outcomes), expressed in terms of credits. In most cases, student workload ranges from 1,500 to 1,800 hours for *an academic year of 60 ECTS*, and one credit corresponds to 25-30 hours of work. Credit transfer and accumulation are helped by the use of the ECTS key documents (course catalogue, learning agreement, and transcript of records) as well as the *Diploma Supplement* [DS09].

2.7 In a recent study [Ke09] it was concluded that the **vast majority** (almost 90%) of the 155 investigated physics bachelor programmes from 24 countries have a duration of *three years or 180 ECTS* credits. Only in exceptional cases [*e.g.* Ph09] is the duration two years. Four-year bachelor programmes (240 ECTS) can be found in Greece, Ireland, Spain, Lithuania, Macedonia and Scotland.

2.8 *Physics bachelor degree programmes* address the more general and fundamental topics of physics, provide a selection of more advanced topics, and encourage the development of investigative, experimental, mathematical, computational, modelling and other generic competences. The various programmes will emphasise different areas. Engineering physics courses might emphasise experimentation and provide a focus to the curriculum that is more geared towards industrial applications.

2.9 *Bachelor physics curricula* need to cater both for students planning to move on to research in industry or academia (if the student choose for 70+ % of physics and mathematics modules) - and obtain a subsequent physics master degree and/or a doctorate degree - as well as for students looking for a broad physics-based education which will provide them with a firm base of generic skills and make them eminently employable. The latter kinds of curricula have a long tradition in the UK and Ireland, while in almost all continental countries such programmes are rather new and will require both employers and graduates to develop a better understanding of the careers and job opportunities they provide. A recent inquiry [Eu09b] by the Eurydice network of the E.C. concludes: '*Whatever their practice, all countries face serious challenges in adapting to fast-changing societal demands, and ensuring that qualifications – in particular those of the first cycle – give access to the labour market*'.

3 - Physics

3.1 'Physics is concerned with the quantitative observation, understanding and prediction of *natural phenomena and the behaviour of human-made 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, measurement, *i.e.* quantitative experimentation and observations, computing, technology, materials and information theory. Concepts and techniques from physics also drive developments in related disciplines including chemistry, computing, engineering, materials science, mathematics, medicine and the life sciences, meteorology and statistics' [QA08].

3.2 'Physics is both *an experimental and a theoretical* discipline that is continuously evolving. It is deeply rooted in the idea that even complex systems can be understood by identifying a few key quantities such as energy and momentum, and the universal principles that govern them. Part of the appeal of physics is that there are relatively few such principles and that these apply throughout science and not just in physics. The laws of mechanics are a good example; deduced by Newton after studying observations of planetary motion, they govern systems familiar from everyday life as well as many of the phenomena observed in the movement of stars and galaxies' [QA08].

3.3 Physics as an *experimental 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 a result of the development of some new experimental technique. For example, techniques developed to liquefy helium subsequently led to the totally unexpected discovery of superconductivity, superfluidity and the whole field of low temperature physics. Instruments developed originally in physics frequently find applications in other branches of science; for example, electromagnetic radiation emitted by electron accelerators, which were originally designed to study elementary particles, is now used to study the properties of materials in engineering, biology and medicine' [QA08]. Moreover, devices such as transistors and lasers, which were developed within basic physics research programmes, have revolutionised technology.

3.4 '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 describing the model in mathematical terms are solved (often with further approximations) and the results compared with experimental observation. Sometimes a model is applicable to very different circumstances. For example, the same statistical model that describes the behaviour of electrons in metals is equally applicable to white dwarf stars' [QA08].

3.5 'Progress in physics requires *imagination and creativity*. It is often the result of collaboration between physicists with different backgrounds and increasingly involves exchange of ideas and techniques with people from other disciplines. Within physics, there are three broad categories of activity: experimental (or observational), computational and theoretical, although many physicists span these categories' [QA08].

3.6 'Studying physics at a university brings *benefits that last a lifetime* and knowledge and skills that are valuable outside the field of 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, IT and self-study skills, along with the pleasure and satisfaction that comes from being able to understand the latest discoveries in physics or natural science. After graduation, physicists work in a wide variety of employment, including research, development and education, in industry and academia and increasingly in areas such as business and finance, where they are sought for their analytical and synthetical approaches to the solution of problems' [QA08].

4 - Physics bachelor discipline competences

4.1 Curricula will usually distinguish between fundamental ideas and the description and modelling of phenomena.

The *fundamentals*, which all students need to cover to some extent, include:

- (classical) mechanics
- electromagnetism
- quantum physics
- thermodynamics
- statistical physics
- wave phenomena
- optics
- properties of matter: their elementary constituents and interactions.

Bachelor students should also familiarise themselves at the introductory level with the application of the fundamental principles to particular areas:

- atomic physics
- nuclear and particle physics
- condensed matter physics
- physics of materials
- plasmas
- physics of fluids.

In case *astrophysics and astronomy* courses are part of the programme, these may include the application of physical principles to:

- cosmology
- structure, formation and evolution of stars and galaxies
- planetary systems
- high-energy phenomena in the universe.

In addition, the curricula should help students to achieve some qualitative understanding of current developments at the frontiers of the physics discipline.

4.2 Students should learn that physics is a quantitative field of study and appreciate the use and power of mathematics for *modelling* the physical world and *solving problems*. Mathematical competence is an essential part of a physics degree.

4.3 Physics curricula should expose students to the *experience of the practical* nature of physics [IU08]. They should provide students with the skills necessary to plan investigations and collect and analyse data (including estimation of inherent uncertainties). These skills may be acquired as part of a course in a laboratory or by a range of alternatives including computer simulations. These experimental competences could also be acquired by providing opportunities for student internship in national or multinational laboratories or industrial research and development centres. Practical work should thus be a vital and challenging part of a physics degree, and all undergraduates in physics should have an appreciation of natural phenomena in an experimental context. Students should also become proficient in presenting experimental results or theoretical conclusions and in the writing of scientific reports. Independent project work should be used to facilitate the development of students' skills in research and planning (by use of data bases and published literature) and to enhance their ability to assess critically the link between theoretical results and experimental observation.

4.4 Physics bachelor graduates should be able:

- to formulate and tackle problems in physics. For example, they should be able to identify the appropriate physical principles, to use special and limiting cases and order-of-magnitude estimates to guide

their thinking about a problem and to present a solution by making their assumptions and approximations explicit;
- to plan and execute an experiment or investigation and to report the results. They should be able to use appropriate methods to analyse their data and to evaluate the level of uncertainty. They should also be able to relate any conclusions they make to current theories of the physics involved;
- to use mathematics to describe the physical world. They should have an understanding of mathematical modelling and the role of approximation. They should be able to compare critically the results of model calculations with those from experiment and observation. They should also be able to make error and statistical analysis of experimental data to ensure the validity and significance of results.

5 - Physics bachelor generic competences

A physics bachelor degree should enhance the following generic competences [TU09b & Fe05] (most of the following text is taken directly from [QA08]):

▶ Problem-solving

Physics degree programmes engage students in solving problems with well-defined solutions. They will 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 confidence in pursuing different approaches in order to make progress on challenging or non-standard problems.

▶ Analytical

Physics helps students learn the need to pay attention to detail and to develop their ability to manipulate precise and intricate ideas, to construct logical arguments and to use technical language correctly.

▶ Investigative

Students will have opportunities to develop their skills of independent investigation. Generally, students will have experience with extracting important information from textbooks and other literature, with searching databases and with interacting with colleagues.

▶ Communication

Physics and the mathematics used in physics deal with surprising ideas and difficult concepts; good communication is essential. A physics degree should develop students' ability to listen carefully, to read demanding texts, and to present difficult ideas and complex information in a clear and concise manner.

▶ Information Technology

During their studies, students will develop their computing and IT skills in a variety of ways, including their ability to use appropriate software such as programming languages and software packages.

▶ Personal

Students should develop their ability to work independently, to use their initiative, to organise their activities to meet deadlines, and to interact constructively with other people.

▶ Language

Since a mobile labour force with language competences is crucial for economic growth and better jobs, enabling European enterprises to compete effectively in the global marketplace, multilingualism contributes to personal development and reinforces social cohesion. Students should **at least** develop an oral and written knowledge of English, the *lingua franca* of physics.

Ethical behaviour

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

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ANNEXES

1 - Membership of the bachelor specification group

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2 - European Benchmark for Physics Bachelor Degree

Summary

This is a proposal to produce a common European Benchmark framework for bachelor degrees in Physics. The purpose is to help implement the common European Higher Education Area (EHEA) and to facilitate co-operation and student exchange between European Universities. It is aimed at the level of an indicative listing, which broadly specifies the common programme which can be found in most physics degrees across Europe. It also aims to represent the level of physics knowledge and skills physics departments across Europe generally consider sufficient to admit graduates of other universities to their master programmes without supplementary requirements, except possibly for minor adaptations that do not lead to a net increase in the workload. It is not intended to either provide a fixed and detailed physics syllabus or to replace the national quality assurance systems in force in various countries.

1 - Introduction

Most European countries have introduced a bachelor degree in response to the Bologna agreement and have introduced, or are in the process of introducing masters programmes. In parallel to this countries are either introducing or strengthening national (in some cases cross-border or regional) quality assurance mechanisms which are external to the university.

Major changes to the structure of Physics degrees are associated with:

- The Bologna agreement
- The introduction of the bachelor/master system
- External quality assurance mechanisms on a national or regional level
- National degree benchmarks for subject areas

Quality agencies are mainly concerned with generic competences (*e.g.* teamwork, communication skills) and the general organisation of university studies. They are not usually prescriptive at the level of detailed curricula. Indeed most national frameworks for physics degrees only provide a very general idea of the content and are not sufficiently detailed for our purpose. Examples of this are the German [1] (English version) and UK [2] national frameworks for Physics degrees. In the main document an EPS working group issued such a framework intended to be valid Europe wide [3].

There have been extensive studies of physics curricula by the EUPEN [4] (*EUropean Physics Eucation Network*), and its continuation the STEPS (*Stakeholders Tune European Physics Studies*) and STEPS TWO [5] projects. In addition the TUNING project has looked in detail at physics degrees and produced *Reference Points for the Design and Delivery of Degree Programmes in Physics* [6]. Similar publications have been produced by the German Conference of Physics Departments [7] (in German) and the IOP (Institute of Physics) in the UK [8]. While there are many similar documents, the German and UK documents span the full spectrum of approaches to physics, from the more rigorously mathematical "*Continental European*" approach to the less theoretically intensive "*Anglo-Saxon*" one.

This is an attempt to provide a more detailed common physics syllabus but without specifying the content in too much detail as many different approaches are possible to teach the same content and skills. The level of detail involved lies between the general learning outcomes for a degree course and those for particular modules/course units.

2 - Rationale

The rationale for this project is to provide a general reference point for Physics degrees*, to aid the implementation of the Bologna changes and facilitate co-operation and student exchange between physics departments across Europe. The aims are as follows:

- Provide a Europe wide reference set of benchmarks
- Not to be overly prescriptive, allowing for variations in teaching approaches
- Concentrating on physics content, not general competences, which are well covered in other documents
- Specify the physics knowledge required for a masters level course in physics
- Provide a "quality mark" for Physics degrees
- Help mobility both within bachelor degrees (Socrates/Erasmus type mobility) and between bachelor and master degrees (Bologna type mobility).
- Provide a useful reference point especially for smaller countries and less well known universities, or for bachelor students planning to enrol in a master programme elsewhere.

Clearly if this is going to be a useful document it needs to be sufficiently detailed to be useful without imposing a rigid curriculum. All the following detailed structure needs to be approached from a flexible perspective and not applied in an inflexible manner. General competences should also be addressed explicitly in the programme, either as an integrated part of some of the content oriented courses or in separate courses.

3 - Overall structure

On the basis of the EUPEN and TUNING studies, six broad areas of study or themes have been identified. Five of these are essential for a physics degree and clearly compulsory and the sixth is provided for optional minor specialisations. The sixth theme can be a minor subject (or subjects) either related to Physics or totally unrelated. Examples of this are foreign language skills, Chemistry, Electronics, Medical Physics, Astronomy & Astrophysics and Geophysics; it may also contain courses on general or teaching skills. Another alternative is a placement period in an outside organisation. This stream may also be omitted and the credits reassigned to other streams.

This structure is based on a 3 year bachelor degree, but it could equally cover the first 3 years of an integrated degree or even a 4 year bachelor. In the case of a 4 year bachelor degree, it is possible that the credit allocations would be larger in some streams. Credit allocations are indicative not precise values. Most

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* The programmes concerned may have a different formal title. In many countries programmes called "Technical Physics" or "Physics and …" (e.g., "Astronomy") are offered that satisfy these benchmarks, either in full or with only minor exceptions; other programmes with such titles may not do so, however.

modules/course units on a degree programme should be allocated to one area based on their content, even if they also cover part of another stream. However occasionally they may need to be split between areas.

The streams are indicated in the following table. Overall at least 140 of the normally 180 ECTS credits would have to be in physics and maths; that is in the first 5 streams. Notional credit values for each stream are in the range 20-40, with the exception of the optional stream which is 0-40. The tables are not intended to specify a temporal order of the subjects or a grouping in modules or other units.

Physics Bachelor degree

At least 140 out of 180 ECTS credits in physics & maths

Mechanics & Thermodynamics (20-40 credits)
Classical mechanics, Thermodynamics and kinetic theory, Special relativity, Advanced classical mechanics, Background to quantum mechanics.

Optics & Electromagnetism (20-40 credits)
Oscillations & waves, Basic optics, Electromagnetism, Advanced Electrodynamics and Optics.

Quantum Physics (20-40 credits)
Quantum mechanics, Statistical mechanics, Solid state physics, Atomic, nuclear and particle physics.

Experimental/laboratory (20-40 credits)
Laboratory work, Project work.

Mathematics & computing (20-40 credits)
Mathematics, IT skills & Modelling.

Optional subjects (0-40 credits)
A minor subject (or subjects) either related to Physics or totally unrelated.

A more detailed structure for the benchmarks is given in the table on the following two pages. In order to keep this table to a reasonable size the topics have been given as headings which should be understandable to physicists. It has become usual to specify learning outcomes for particular modules, this is not done in this case to save space and avoid repetition. Each of the items contained in this listing will refer to several learning outcomes. The table should be considered as a core content; programmes will contain additional subjects or treat some subjects in more depth than indicated in the table. So, if a student changes university after the bachelor to pursue a master elsewhere, he or she will often have less knowledge and skills in some subjects than students who completed their bachelor at their new university, but more in some other subjects. Such students may then be advised or sometimes even required to supplement their existing knowledge in some subjects, but this should be possible by substitution for courses already covered in his or her own bachelor programme or by restricting the choice of electives, and not lead to a net increase of the overall workload.

In addition to general physics bachelor programmes, departments may offer interdisciplinary or specialised bachelor programmes (*e.g.* aimed at future teachers of physics, often combined with another subject, or at other professional fields). Such programmes are not primarily designed to prepare for a general physics master and may not contain all the subjects listed in this document, or treat them in the breadth and/or depth envisaged here. In general, there will be arrangements to grant graduates of such programmes access to physics master programmes as well; such arrangements may involve restrictions on the electives chosen, but sometimes also “bridging courses” to be covered before or during the master programme that amount to additional credit requirements.

4 - Detailed structure

The following table relies heavily on the IOP document [8], from which most subject descriptions have been adopted.

Mechanics and Thermodynamics

20-40 ECTS credits

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

Thermodynamics and kinetic theory of gases
Zeroth, first and second laws of thermodynamics to include:
- Temperature scales, work, internal energy and heat capacity
- Entropy, free energies and the Carnot cycle
- Kinetic theory of gases and
the gas laws to the level of the van der Waals equation
- The Maxwell-Boltzmann distribution
- Statistical basis of entropy
- Changes of state

Special relativity
- to the level of Lorentz transformations and the energy-momentum relationship

Advanced classical mechanics Basic
Lagrangian and Hamiltonian mechanics.

Background to quantum mechanics
- Black body radiation
- Photoelectric effect
- Wave-particle duality
- Heisenberg's Uncertainty Principle

Optics & Electromagnetism

20-40 ECTS credits

Oscillations & 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
- Doppler effect

Basic optics
- Geometrical optics to the level of simple optical systems
- The electromagnetic spectrum
- Interference and diffraction at single and multiple apertures
- Dispersion by prisms and diffraction gratings
- Optical cavities and laser action

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

Advanced Electrodynamics and Optics
- Maxwell's equations and plane electromagnetic wave solution; Poynting vector
- Polarisation of waves and
behaviour at plane interfaces

Quantum Physics

20-40 ECTS credits

Quantum mechanics
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

Statistical mechanics
- Bose-Einstein and Fermi-Dirac distributions
- Density of states and partition function

Atomic, nuclear and particle physics
- 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

Solid state 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

Experimental & laboratory work

20-40 ECTS credits

Laboratory work
- plan an experimental investigation;
- use apparatus to acquire experimental data;
- analyse data using appropriate techniques;
- determine and interpret the measurement uncertainties (both systematic and random) in a measurement or observation;
- report the results of an investigation and
- Understand how regulatory issues such as health and safety influence scientific experimentation and observation.

Project work
The objectives of such project work will include most of the following:
- investigation of a physics-based or physics-related problem
- planning, management and operation of an investigation to test a hypothesis
- development of information retrieval skills
- carrying out a health and safety assessment
- establishment of co-operative working practices with colleagues
- design, assembly and testing of equipment or software
generation and informed analysis of data and a critical assessment of experimental (or other) uncertainties

Mathematics & computing

20-40 ECTS credits

Mathematics
- 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
- Three-dimensional trigonometry
- Vectors to the level of div, grad and curl/rot; divergence theorem and Stokes' theorem
- Matrices to the level of eigenvalues and eigenvectors
- Fourier series and transforms including the convolution theorem
- Probability distributions

IT skills & Modelling
- Word processing packages
- Data analysis and manipulation packages
- Data calculation & presentation
- Information searching
- (A) Programming language(s)
- Modelling of physical systems

Optional subjects

0-40 ECTS credits

A minor subject (or subjects) either related to Physics or totally unrelated. This stream may also be omitted and the credits reassigned to other streams.

Examples include:
- Chemistry
- Electronics
- Astronomy & Astrophysics
- Medical Physics
- Geophysics
- Biophysics
- Meteorology
- Foreign language skills

This theme may also include courses on generic and/ or teaching skills

Industrial Placement
Some degree programmes may include a placement in industry or other external organisation for up to one semester.

5 - Implementation

The present scheme has some analogies with the *Eurobachelor®* [9] model of the *European Association of Chemical and Molecular Sciences*. However, we do not propose to follow their procedure in all particulars. We suggest physics departments self-certify their programmes as being consistent with these benchmarks or not, and if not give their reasons. When some subjects cannot be accommodated within the obligatory courses, they might be offered as electives. When a student satisfies the benchmarks by choosing such electives, or by taking voluntary courses, the fulfilment of the benchmarks may be certified individually, *e.g.*, in the diploma supplement. These statements could be monitored in the course of existing quality assurance procedures. Similarly, we suggest departments use these benchmarks to specify the knowledge and skills they require for admission to their masters programmes; they may deviate from them, but should then point out explicitly where their requirements for some or all of their master programmes differ from those specified above.

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The **European Physical Society** (EPS) is a not-for-profit representative organization whose purpose is to promote physics and physicists in Europe. Created in 1968, the EPS provides an international forum to discuss science and policy issues of interest to its members.

NOTES

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