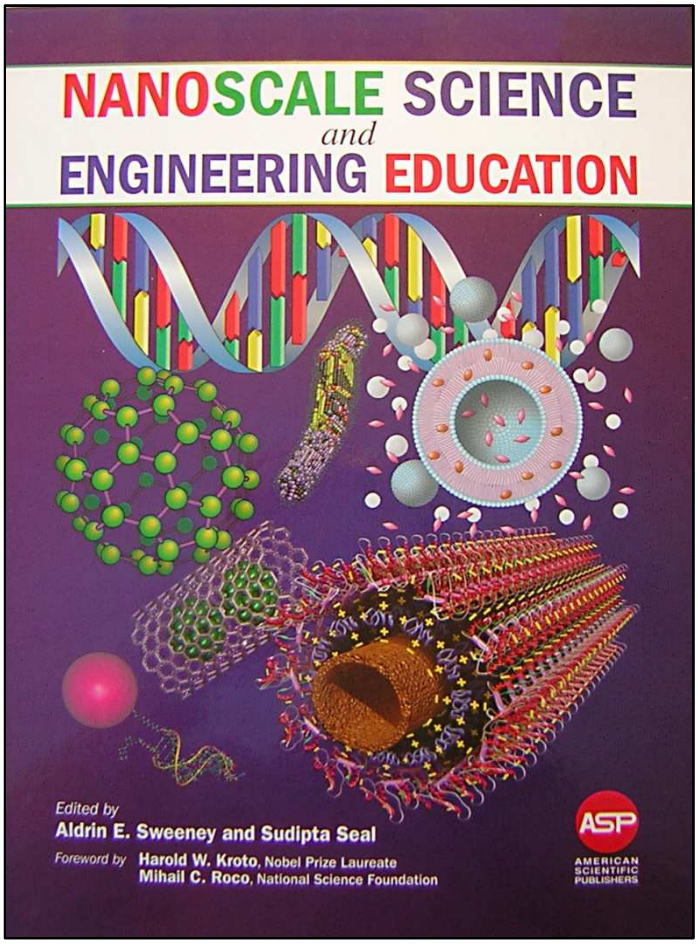
Engineering Nanoscience: A curriculum to Satisfy the Future Needs of Industry

Book Chapter

Knut Deppert, Rune Kullberg, and Lars Samuelsson



Engineering Nanoscience: A curriculum to Satisfy the Future Needs of Industry

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1. Introduction

Driven by seemingly limitless applications, nanoscience and nanotechnology will revolutionize industry. A major bottleneck in making this revolution happen to its full potential is people. We will not be able to realize this revolution unless we can supply industry with highly qualified nanoengineers who are able to design novel devices in widely varying areas of application. The new character and interdisciplinary nature of nanotechnology makes designing educational programs a challenge. Although university-level education in this field is expanding rapidly, most universities offer only specialized courses, and do not offer entire programs. In 2003, Lund University in Sweden launched *Engineering Nanoscience*, a novel educational program. This five year curriculum is one of the few complete degree programs in nanoscience that starts at university entrance level and leads to a Master's degree. The curriculum is a unique symbiosis of education and research. Teaching is driven by high-level research activities in the field, and research will benefit from the highly qualified graduates leaving the program. In this chapter, which is based on a shorter paper by Deppert and Samuelson [1], the architects of this curriculum discuss the philosophy behind the program, provide an overview of its components, and also describe how the challenges associated with establishing such a program were addressed.

2. The Need for an Interdisciplinary Approach

The field of nanoscience and nanotechnology is one of the most dramatically developing areas of science and technology today. Nanoscience is the study of the fundamental principles of structures and devices having at least one dimension that is between 1 and 100 nm (10^{-9} m and 10^{-7} m). The essence of nanotechnology is the understanding and application of phenomena and functionality at the atomic level, to design functional materials bottom-up, and to create complex structures with fundamentally new and optimized structures and properties. Compared to the behavior of isolated molecules (containing a few atoms and with sizes of about 1 nm), or that of bulk materials (containing at least 10^{20} atoms and of dimensions larger than a millimeter), the behavior of structural features on the nanoscale exhibits important differences. This is the regime where a typical dimension is 10 nm, which is one ten thousandth of the diameter of a human hair. This field is concerned with materials and systems whose structures and components exhibit novel and significantly improved properties. At the nanoscale, most of the traditional disciplines of science meet, allowing, for instance, quantum physics to be implemented in devices and systems. Nanoengineering tools make it possible to manipulate, address, and detect individual biomolecules. The interplay between these disciplines is one of the greatest strengths of nanoscience.

However, because nanotechnology embraces all the traditional scientific disciplines and fields of engineering, it also poses one of the greatest challenges in teaching. The enormous progress in science over the past centuries has prevented the emergence of universal scientists and engineers of the type represented by Leonardo da Vinci. Today, science and technology are divided into a multitude of different sub-fields, and many researchers are trained to deal only with their specialized area. This situation limits, and is a threat to, cooperation across disciplines. There is extensive knowledge in each field, and each has its own scientific terms and language. Teaching in the specialized fields and bridging language barriers both represent considerable challenges in teaching nanoscience and nanotechnology. Or as Mihail Roco, one of the main architects of the U.S. National Nanotechnology Initiative, expressed it [2]: "A key challenge for converging technologies development is the education and training of a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress of the new technologies. Interdisciplinary connections reflecting unity in material and information worlds need to be promoted." Thus, nanoscience education should produce a highly educated generalist with a basis in nanoscience and -technology, a kind of renaissance nanoengineer, who may understand medicine as chemistry on the single-molecule level, and may use quantum mechanics as a primary design tool in electrical engineering.

3. Meeting the Challenge

3.1 Finding a strategy

Why would anyone want to tackle this huge challenge? Those working in nanotechnology have discovered that they often lack the specialized knowledge of colleagues from other fields with whom they are collaborating. It can be very frustrating for both parties when the physicist asks the biologist, who wants help with the investigation of an enzyme, "What is an enzyme?" or the biologist asks the physicist "What is a transistor?" The development of nanotechnology and the future growth of related industry are strongly dependent on highly qualified scientists and engineers who are knowledgeable in several traditional disciplines. In 2002, Mihail Roco underlined this need when stating that the preparation of the nanotechnology workforce for the next decade is a major challenge to the progress of the new technology [3].

Traditional university education is often represented as a straight line or as a sequential vertical progression from basic to specialized courses in a particular discipline. In contrast, two different strategies can be seen for university education in nanoscience and nanotechnology. One emphasizes interdisciplinary specialization, and the other a coherent curriculum. For simplicity they can be referred to as the "T" and the "Inverted-T" approach (Figure 1).

The first strategy, the T strategy, is a modification of existing educational programs. Conventional undergraduate courses in a traditional science or engineering discipline are followed by interdisciplinary specialized courses. The latter part of such a program may include specialized courses or courses in other disciplines, a certain major or double majors, special seminars, and involvement in real research on nanoscience or nanotechnology topics. The design of such a program seems to be rather simple and such programs have, indeed, been offered by our university and others for a long time. Normally,

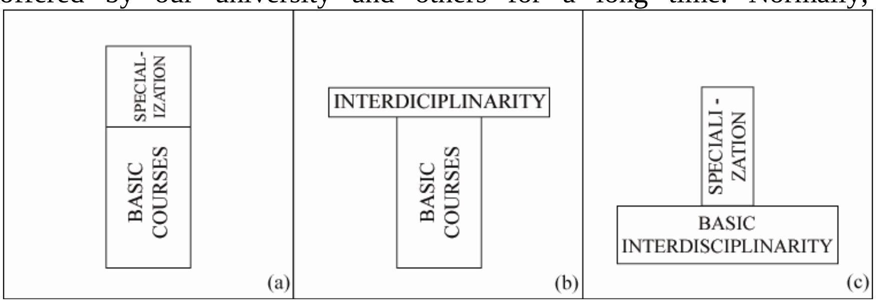

Figure 1: Schematic of university education: (a) traditional scientific/engineering subjects, (b) interdisciplinary specialization (“T”), and (c) coherent curriculum (“Inverted-T”).

specialized courses are developed based on individual (or collective) faculty research interests, and the need for graduate students to assist in such research. Typically, such courses evolve over the years in a research environment designed for students who may enter a Ph.D. program. With a sufficient number of such courses available at different colleges, faculties or departments, all the university has to do is to create a frame or theme and call it "nano".

The T strategy seems to be the strategy favored by many universities, and represents only limited changes to the traditional approach. Most universities have adapted this strategy in creating "nano"-education programs, at least in the U.S.A. [4]. This strategy offers two main advantages: it is easy to develop, and it minimizes the administrative effort required. Even small universities can create this type of nano-program, although with a limited degree of interdisciplinarity. Organizational efforts are minimal since one has only to deal with part of a complete educational program within an existing curriculum. An advantage is that accreditation of such a program is usually obtained fairly readily. Larger universities with a high degree of established interdisciplinary research and education could also benefit from this “low-effort” strategy. However, the essence of nanotechnology is more than just providing an engineer or biologist with extra knowledge. It is a way of thinking and seeing possibilities and we believe that it is difficult to accomplish a deep understanding of nanoscience by employing the T strategy.

A clear alternative is the Inverted-T strategy where the students are introduced to the essence and interdisciplinarity of nanoscience and nanotechnology from the very first day. Using this strategy, freshmen are taught the unifying concepts of matter and biological systems. This prepares them to apply these unifying concepts from one field to another. A synergistic view of the potential applications of nanoscience and -technology in various areas of relevance would be the natural outcome of this approach. By reversing the sequence of learning we can train engineers to take a coherent view of nanoscience and we can motivate students to learn the necessary basics in the traditional fields of science and engineering [2]. Naturally, this approach must be combined with the teaching of basic knowledge and skills in physics, mathematics, chemistry, electronics, biology, physiology, materials science, engineering at the nanoscale (nanotechnology), and engineering science, in order to allow the student to grasp the concepts of nanoscience in the different fields. Thus, real interdisciplinarity is accomplished from the very beginning of the program combining the breadth of nanoscience with the depth of each of the disciplines involved [5]. We advocate this strategy in teaching nanoscience and -technology at university level. It is also a good way of overcoming the dangerous dis-integration seen by Rustum Roy, who observed that every discipline and department realizes the added value when claiming to convey interdisciplinary work albeit within the discipline [6].

The general argument against the implementation of this strategy is that it may create engineers and scientists with little knowledge in many fields; a workforce with broad but insufficient knowledge and skills. Certainly, this risk is a real one, but we will describe three methods of addressing these concerns. The first method is *extension*, i.e. teaching each discipline in depth. By offering four years of studies in physics, chemistry, biology, etc. the student will gain a deep understanding in the disciplines, but may not find the time or need to use all this knowledge and related skills. The second method is *specialization*; the student specializes in one discipline towards the end of a period of interdisciplinary studies. After students have grasped the essence of nanoscience and fundamental interdisciplinary skills, they then delve more deeply into their specific field of interest. This includes an extension of their basic knowledge and skills by attending further courses in that discipline. The third method is *concerted action*, in which all courses in the interdisciplinary block interact and redundant teaching is avoided. This method is a rather complicated one and requires meticulous organization of the curriculum. Using this method, allows the total time taken to complete a degree program to be shortened, however, it may not assure depth of knowledge in the requisite disciplines. Thus, we suggest a combination of the concerted action and specialization approaches in order to ensure that graduates have the necessary depth of knowledge and skills for industry or for related research in academia or industry. It should be mentioned here that neither the T nor the Inverted-T strategy can, within the same period of time, supply the student with the same detailed knowledge and skills in one discipline as a traditional approach, a fact that is depicted in Figure 1 by the different heights of the components. However, the abilities of students completing the Inverted-T program may be better suited to modern science and technology.

Another argument against the Inverted-T strategy in nanoscience and –technology education comes from industry. In a survey conducted by the European NanoBusiness Association in spring 2005, only 10% of the respondents considered a first degree in nanotechnology to be the best choice (see Figure 2) [7]. Here, responses were received from a total of 142 participants, 79% from Europe, covering different kinds of activities, such as manufacturing, transportation, financing, and healthcare. However, industry has not had any comprehensive experience of graduates with a first degree in nanotechnology, and may thus lack an

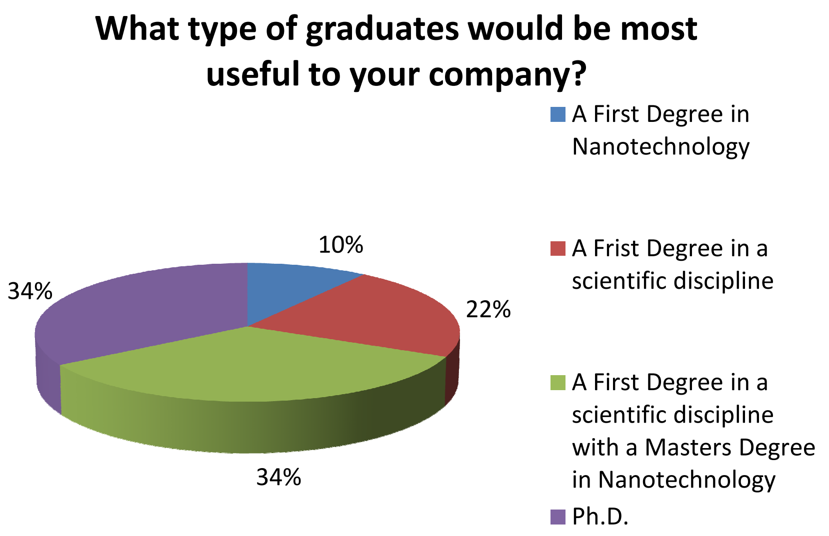

Figure 2: Outcome of the 2005 European NanoBusiness Survey [7].

understanding of the potential of engineers with this profile. We know from our personal contacts with industry that this type of engineer is highly regarded, as has also been seen by representatives of the nano-curriculum at Aarhus University in Denmark [8].

Interestingly, our current Ph.D. students who have graduated from traditional science or engineering programs express their conviction that the Inverted-T undergraduate nano-curriculum would have been the right choice for them and are rather jealous. Further, the outcome of a survey conducted by Nanoforum between August and October 2004 clearly illustrates the need for nanotechnology engineers with a broad basic background (see Figure 3) [9]. The education of the workforce should not

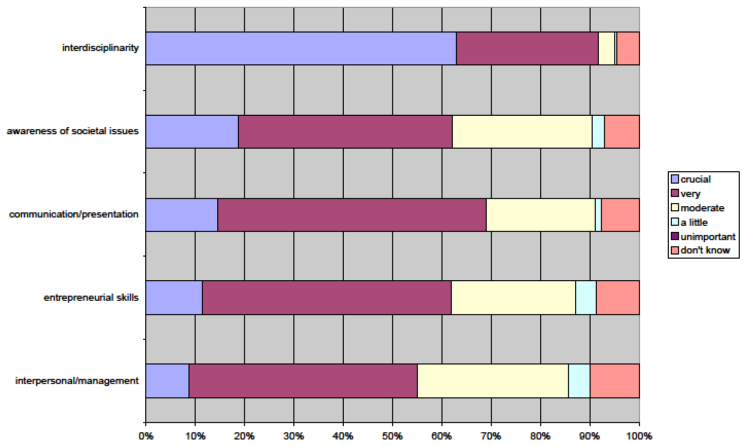

Figure 3: Ranking of skills important for nanotechnology personnel according to all respondents in the European Nanotechnology Gateway Open Consultation on the European Strategy for Nanotechnology conducted by Nanoforum [9].

be limited to natural science or engineering, and interdisciplinarity is by far considered the most important skill. Almost two thirds of the respondents ranked interdisciplinarity as crucial and more than one in four as very important.

The creation of such a curriculum imposes a high administrative and organizational burden on those involved. In our opinion, however, it is worth the effort, and we see the clear advantage over any other alternative in being able to educate a workforce with a coherent view of nanoscience and thorough basic knowledge. It is also the only university education strategy today that is able to fulfill the mission of liberal education, i.e. producing students who are critical thinkers, and who are capable of participating in intelligent debates about how society should be transformed. With this type of curriculum, we have the chance to create an informed and highly educated citizen, able to steer the direction of nanotechnology in beneficial ways [10]. With our nanoengineers we might be able to move toward a 'universal information domain of exchange' for ideas, models, and cultures [2].

To our knowledge, only a few universities worldwide have adopted this strategy, and the reason may lie in the organizational and administrative effort associated with it, and some degree of skepticism on the part of industry. In Europe, three such curriculums have been established in Denmark, one at Aarhus University [11] and two at Copenhagen, one at the Technical University of Denmark [12] and one at Copenhagen University [13] (See also the corresponding chapter in this book by Danielsen & Bjornholm). All have been in operation since fall 2002. Besides the geographical nearness to Lund University, competition is minimal since all four universities focus on their area in nanoscience and only Lund offers an engineering program. Two other such curricula have been available at Basel University in Switzerland [14] and at University of Kassel in Germany since 2003 [15]. Two new curricula started in 2006, one at University of Duisburg-Essen in Germany [16] and one at the Norwegian University of Science and Technology at Trondheim [17]. The University of Würzburg in Germany offers a program called "Nanotechnik", which is designed according to a more traditional system [18]. In September 2003, Lund University launched

Engineering Nanoscience [19], a sophisticated Inverted-T program, and below we will describe it in detail and discuss how some of the challenges associated with the establishment of the program were mastered.

Before that, a few words about Lund and its university. Lund is situated in the southern part of Sweden, in the province of Scania, and around 100,000 persons call Lund their home. Although young at heart, Lund is one of the oldest cities in Sweden. It was founded as a Danish city towards the end of the 10th century. During the 12th century it became an archiepiscopal seat, serving as a leading religious, academic, and cultural center in Denmark and all of Scandinavia. Denmark lost Scania to Sweden in 1658, and the university was founded in 1666 as part of the Swedification of the region. Lund University [20] is the largest in Scandinavia today with 100 educational programs, some 100 subjects and more than 1,000 single-subject courses. The University has more than 42,000 students and 6,000 employees. Annually, 1,600 exchange students are received. Lund University has eight faculties (American universities call their faculties “colleges”), with the Faculty of Engineering, which is called "Lunds Tekniska Högskola" (LTH) in Swedish, being one of the largest [21]. LTH is one of few complete engineering faculties in Sweden. Here, you can find all the traditional engineering Masters programs together with newer ones. There are Bachelor programs and architecture as well as industrial design. The Faculty of Engineering has 8,000 students and about 1,400 employees.

3.2 Creating a Curriculum

Once one is convinced that the Inverted-T strategy is the most suitable organizational structure for nanoeducation, one faces the next challenge: How do we realize it? The first requirement is scientists working in the field. Because nanotechnology is interdisciplinary, it also requires faculties with various specialties. Thus, to create a complete program, it is necessary to be based at a large university that has all the necessary faculties. The university leaders, as well as the deans of the faculties and all the specialists, must be committed to the common goal. For almost 20 years, nanoscience and -technology research at Lund University has been conducted within the Nanometer Structure Consortium, one of the first European nanocenters. The consortium is the main Swedish center for materials technology, nanoscale physics, nanoelectronics, and applications of nanometer structures [22]. Research ranges from growth, characterization, and basic studies of materials, to the implementation of nanostructures in nanoelectronics and photonics, and biomedical studies. It was in this research environment that the need to create a new educational program became obvious to us, as the doctoral students and their supervisors found that they needed skills from other departments and disciplines. They also recognized that they needed a common language and platform on which to interact.

We had the opportunity to bring together the most enthusiastic researchers and teachers. A core group was created that prepared the first outline of an educational program. As discussed above, we chose a structure with a broad general compulsory curriculum followed by in-depth specialization according to the Inverted-T strategy. From an organizational point of view, it was decided at an early stage that the program would best be administered within the Faculty of Engineering (LTH), but with active involvement and with courses given by experts from the Faculties of Science and Medicine at Lund University. Next, this core group made use of their connections in the academic system and engaged different departments of the university in the project, allowing for the creation of the program.

An advisory group was formed consisting of representatives from both academia and industry to ensure that the planned areas of specialization were those of interest to industry. Industrial representatives were from Lund and its close neighbor Malmö, as well as from Stockholm and from smaller enterprises, as well as from research divisions of multinational companies. Based on the requirements for the degree of "Civilingenjör" (Master of Science in Engineering, M.Sc. Eng.) as laid out in the Swedish Ordinance for Higher Education ("Högskoleverket", HSV) [23], the group drew up a list of specifications for the new program. The most important issue was interdisciplinarity and the ability to lead and conduct projects in groups, which may even be comprised of people from different cultures. Especially the industrial representatives demanded a broad education in order to cover the different areas of nanoscience. Another important objective of the program was the education and training of engineers who can develop new technology and enhance the knowledge base.

Based on the recommendations of the advisory group, the core group laid the foundation by determining the knowledge and skills necessary. Here, we could refer to the experience of existing programs such as those at the universities of Aarhus, Basel, and Copenhagen. An initial structure was outlined based on the existing educational system in Sweden and on existing courses given at Lund University. The preferable alternative would have been to take our "wish list" and create courses accordingly. However, the expense would have been too high bearing in mind the number of students anticipated. Thus, a compromise was reached by combining existing courses with modified and new ones.

It should be mentioned that there is no national Swedish program to promote nanoscience and nanotechnology, nor governmental support to promote higher education in this field. Thus, the design, establishment, and maintenance of the curriculum are entirely financed by Lund University. In contrast, in the U.S.A., the main part of the funding under the National Nanotechnology Initiative (NNI) is intended for university-based research with the clear demand to help meet the growing need for graduates with nanoscale science and engineering skills [5]. The 2008 budget for the agencies participating in the National Nanotechnology Initiative is nearly $1.5 billion [24]. It was hoped that education in nanoscience in Europe would be supported by the European Union. In June 2005, the Commission of the European Communities adopted the Action Plan "Nanosciences and nanotechnologies: An action plan for Europe 2005-2009" [25] (See chapter in this book by Baraton et al). In the action plan, the Commission urged the promotion of networking and dissemination of best practices for education and training in the field. However, no provision was made for direct financial support of education. Apart from the limited support in starting up the program by Lund University, the only financial support available for the departments involved in the program is an honorarium to the lecturers after they have taught the courses. This amounts to approximately $28,000 for a course of 7.5 credits with 40 students, and this pays for the salaries of the teachers, the costs of equipment, hiring the lecture halls, and overhead costs. The total annual cost of the program, when finalized, will be on the order of $1.8 million.

4. The Structure of the Program

4.1 The General Structure

The program is divided into two main blocks (see Figure 4): the first includes basic and interdisciplinary knowledge and skills, while the second is directed toward a specialized area. The first block extends over three years and includes basic mathematics, physics, chemistry, biology, electronics, and medicine, as well as applications in electronic and functional materials, device technology, analysis, and sensors. The students are trained in the fabrication and characterization of nanostructures. It should be noted that the program is influenced by the research centered at the Department of Physics. The first block is equivalent to an undergraduate (Bachelor's) program; however, in the Swedish higher education system the first degree awarded is a Master's degree for this type of engineering program.

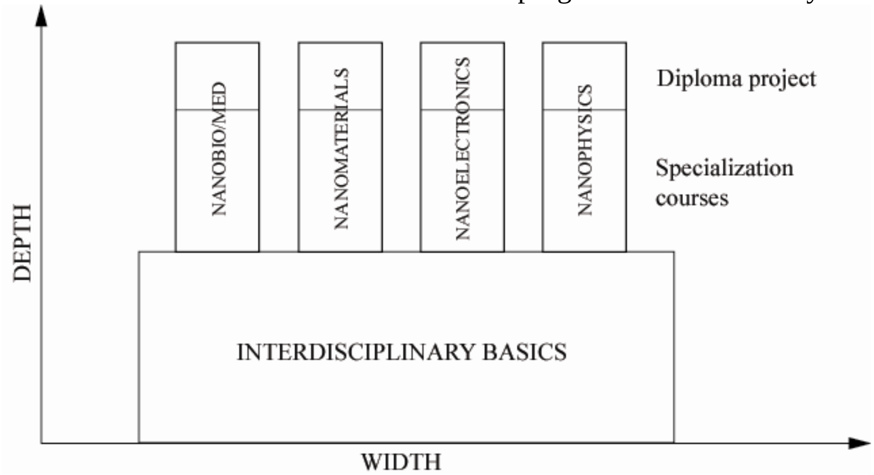

Figure 4: Schematic of the structure of the Engineering Nanoscience curriculum at Lund University illustrating the depth and breadth of the program.

In Sweden, implementation of the Bologna system is in operation since 1 July 2007, the essence being that students should be able to move freely between universities in Europe. The Bologna system has led to some changes in the Swedish higher education system. The latest step in this process was taken when ministers responsible for higher education of 45 European countries met in Norway in May 2005 [26].

Before we can explain the detailed structure of the curriculum, we should explain the structure of the education system at the Faculty of Engineering at Lund University. The academic year is divided into two semesters, a fall and a spring semester. The fall semester starts around 1 September and ends just before Christmas. The spring semester starts around 15 January and ends around 1 June. Both semesters are divided into two teaching periods, each period containing seven weeks of teaching and about one week of exams. Most courses are given within one teaching period, some run over two periods and, in exceptional cases, a course can run over four teaching periods. Courses can consist of lectures, seminars, problem-solving exercises, laboratory work, and independent studies. For each course passed, the student obtains credits (or points). With the implementation of the Bologna system, one week of study, that is, 40 working hours, corresponds to 1.5 credits. One academic year thus consists of 60 credits, evenly distributed over the two semesters. A Master of Science in Engineering degree ("civilingenjör") is equivalent to 300 credits, that is, 5 years of study.

Course Description

DEVICE PROCESSING AND TECHNOLOGY FFF110
Process- och komponentteknologi
University credits: 7.5 Grading scale: TH Level: G2 (Senior Undergraduate)
Language of Instruction: The course might be given in English
Course Coordinator: Dr. Jonas Johansson E-mail: jonas.johansson@ftf.lth.se
Compulsory for: N3 Optional for: E4, F4
Prerequisites: FFF100 Thermodynamics and Electronic Materials or ESS030 Physics of Devices or FFF010 Solid State Physics, Basic Course
Assessment: Written examination and compulsory laboratory exercises
Home Page: http://www.teknisknanovetenskap.lth.se
Term: Fall, Study Period 1

Aim

The purpose of this course is to provide fundamental knowledge about fabrication and characterization of semiconductor devices on the nanometer scale. The focus is set on modern materials and processing techniques with nanotechnology as a main theme. Most of the processes are general and are applied in traditional Si based IC technology as well as in advanced III-V technology and MEMS/NEMS fabrication.

Required Knowledge and Understanding

To successfully pass the course the student must be able to:
- describe fabrication processes based on diffusion, deposition and surface patterning
- explain how the above-mentioned processes can be applied to the nanometer scale systems
- analyze a specific device and determine which process steps that are needed for its fabrication
- explain the dependence of device performance on processing capabilities and limitations.

Practical Requirements

To successfully pass the course the student must:
- carry out basic processing in a clean room
- write well-structured technical reports about semiconductor device processing.

Contents

Materials properties of semiconductors. Device fabrication: process overview, comparison between Si and III/V. Processes: Epitaxy, doping, ion implantation, diffusion, etching, lithography. Recent methods as e.g. surface functionalization and nanoimprint lithography will also be treated. Metal-semiconductor interfaces, which are of significant importance in a number of applications will be covered. Fabrication and applications of p-n junction diodes and characterization and modeling of their electronic and optoelectronic properties. Fabrication and properties of heterostructures will be taught and exemplified by the transistors HBT and HFET. Fabrication and principles for MEMS/NEMS (micro/nano-electromechanical systems) will also be treated. In a number of laboratory exercises, some of the covered process steps will be applied in order to make working devices. Since it is highly important that semiconductor processing is carried out in a clean and dust free environment, strong emphasis will be put on clean room work methods. Finally, some advanced semiconductor structures and their properties will be demonstrated.

Literature

May, G.S., Sze, S.M., Fundamentals of Semiconductor Fabrication, Wiley, 2004 or Sze, S.M., Semiconductor Devices Physics and Technology, Wiley, 2002 and copied material.

Figure 5: Example of a course plan of one of the compulsory courses within the curriculum. "Grading TH" means that grades of 5, 4, 3 or failed are given.

	tp 1	tp 2	tp 3	tp 4
Year 1	MATHEMATICS 5c Calculus in one variable I	MATHEMATICS 6c Linear algebra	MATHEMATICS 5c Calculus in one variable II	MATHEMATICS 5c Calculus in one variable III
Year 1	PHYSICS 12c Waves, atoms and thermodynamics		CHEMISTRY 7.5c General and inorganic chemistry	CHEMISTRY 5c Organic chemistry
Year 1	NANO 4c Interdisciplinary introduction	NANO 3c Project and symposium	PROGRAMMING 7.5c Basics	
Year 2	MATHEMATICS 6c Calculus in several variables	PHYSICS/NANO 9c Quantum physics and nanotechnology, incl. software tools	MATHEMATICS/NANO 7.5c Mathematical tools for nanoscience	CHEMISTRY/NANO 7.5c Functional materials
Year 2	BIOLOGY 7.5c Biology of the cell	MEDICINE 7.5c Human physiology	PHYSICS/ELECTRONICS 7.5c Electronic materials	ELECTRONICS 7.5c Electricity and electronics
Year 3	NANO/ENGINEERING 7.5c Processing and device technology	NANO 7.5c Materials analysis at the nanoscale	NANO/ENGINEERING 7.5c Sensors	Free choice/selected courses within specialization 15c
Year 3	MATHEMATICS 7.5c Mathematical statistics	ENGINEERING 7.5c Systems controlling	NANO/ENGINEERING 7.5c Project: Engineering at the nanoscale	
Year 4	Selected compulsory courses within specialization			
Year 4	Free choice of courses			
Year 5	Courses within specialization			
Year 5	Diploma project			

Figure 6: Outline of the courses in the Engineering Nanoscience curriculum. Each course is represented by a box, stating the subject, the name of the course and the number of Swedish credits (c). The four annual teaching periods are denoted tp1-tp4.

A variety of methods is used to assess student-learning outcomes. The type of examination may vary between courses. A traditional written exam is sometimes set at the end of the course, often with a time limit of five hours, while other lecturers prefer oral exams. Continuous assessment is employed in a few courses and other teachers judge the students via written reports. Students receive a grade for each course passed. The grading system varies, for some courses grades of pass/fail are given whereas in others a scale of 5/4/3/0, i.e., excellent/good/adequate/fail is used. In courses given by lecturers from the Faculty of Science the grades are good/adequate/fail. Students who fail an exam have the opportunity to repeat it during their period of study. Some students use this opportunity to improve their grade by repeating the exam. Each course has a written and approved course plan that describes all the compulsory components, the outline, and the content of the course, as well as other useful information, such as the e-mail address of the lecturer responsible for the course and the grading system used (Figure 5). A course can be given by one lecturer alone or by two or more lectures. All courses are categorized in three different levels: G1, freshmen and sophomores, G2, senior undergraduate, and A, advanced. G-level courses are normally within the basic block and A-level courses within the specialization.

The configuration of the courses varies between the different faculties. While most courses at the Faculty of Engineering are worth 7.5 credits, i.e. occupying the time of students for half a teaching period, courses at the Faculties of Science and Medicine often are worth 15 credits, i.e. occupying a whole teaching period. Several 7.5-credit courses are usually given in parallel. If courses of 15 credits run over one teaching period, which is often the case, no other course may be planned in parallel. Sometimes, however, exceptional students can pass courses equivalent to more than 15 credits in one teaching period. The organization of an interdisciplinary curriculum involving courses from different faculties, with different sizes and lengths poses considerable challenges. It should be mentioned that apart from the structuring of the curriculum, the credit system also fulfills another function. Sweden has a financial support system comprising a stipend and loans to students. The National Board of Student Aid (Centrala studiestödsnämnden, CSN) administers student financing [27]. If a student fails to gain a minimum of credits during the academic year, financing is withdrawn and she or he may be forced to terminate their studies. Although we have highly motivated students in the Engineering Nanoscience Program at Lund University, this check provides extra motivation for some students. To summarize this excursion into the university education system, one year of studies is made up of different courses equivalent to 60 credits. We will now explain the structure of the compulsory interdisciplinary course block depicted in Figure 6.

How is the Inverted-T strategy executed in this curriculum? As can be seen from the diagram, the spirit of nanoscience is present right from the beginning and continues throughout the compulsory basic block. In addition, all disciplines of relevance to nanoscience are included as well as basic mathematics. Special engineering courses on device processing, analysis tools and nanoengineering are integrated. It is also clear that this is not a complete curriculum of physics, chemistry or biology. However, the most relevant basics from each of these disciplines are taught in the basic block. It can also be seen that other traditional engineering disciplines, like mechanics, are not included in the interdisciplinary block as individual courses. The basics of such disciplines are incorporated into other courses due to the limited time available. Thus, elements of mechanics are included in the basic physics course, the course on software tools and the course on sensors. Again, this puts extra pressure on the program management and the teachers involved. Additionally, a course on mechanics is included in two areas of specialization.

4.2 The Courses in the Basic Block

After describing the outline of the curriculum we will continue with a short description of the compulsory courses in the basic block. Two of the courses, the introductory course in the first year and the engineering course in year 3, will be described in more detail below.

In the first year the curriculum starts with the introductory course on Nanoscience. This course defines the quintessence or soul of the curriculum and presents an overview of the field. One third of the first year is dedicated to the mathematics necessary to understand the basic concepts of the disciplines involved. The course on basic physics runs parallel with the introductory course and the first two mathematics courses. The physics course includes mechanical oscillations and waves, followed by atomic physics, some quantum mechanics, their applications to lasers, and basic thermodynamics. Because the mathematical skills of the students are still rudimentary, the physics course is more of a descriptive nature aimed at motivating the students to delve deeper into math. With knowledge of the atomic structure, students then take the two courses in basic chemistry. These courses, constituting 20% of the first year, cover the basics of inorganic and organic chemistry and give the students a deeper understanding of the structure and formation of molecules up to proteins and DNA. The course in basic programming runs in parallel with the chemistry courses. This course is intended to provide basic engineering skills in programming, but also to inspire students to structure their thinking. Although the mathematics courses and the course in programming are common courses given by the Faculty of Engineering for students in several programs, the introductory course and the courses in physics and chemistry are designed explicitly for the nanoengineering curriculum.

The second year starts with a course in biology, where the knowledge gained from the chemistry course in terms of macromolecules is used to teach students the biology of the cell. A further mathematics course runs in parallel. A physics course that introduces quantum mechanics, illustrated with nanostructures and nanoelectronics, follows. In addition, the students are provided with an engineering tool to solve complex problems since the course also includes the basics of MatLab®, while the parallel course on human physiology provides the basics of the human body. A special course, given by physicists, provides the mathematical tools required for nanoscientists. Here, mathematical methods are motivated by and applied to central problems within nanoscience. The basics of electronic materials, solid-state physics, and electronic components are taught in the parallel course, which is followed by a course on basic electronics. In a parallel course, chemists teach the design and properties of functional materials, such as optical and magnetic inorganic materials and polymers.

Year 3 starts with a course on the fabrication and characterization of micrometer, nanometer, and semiconductor structures, with hands-on laboratory exercises in which the students fabricate devices such as light-emitting diodes. Skills in the characterization of nanostructures are improved in the next course on materials analysis. The tools required to use and construct models of statistical processes are taught in the course on mathematical statistics. A course on system engineering follows, which covers the basics of the use of system analysis and dynamic models of feedback systems. At the end of the compulsory block are two courses on engineering topics. The course on sensors gives an overview of the fabrication and design of sensors, especially biomedical sensors. The engineering course is intended to enhance the overall engineering abilities of the students.

4.3 The Introductory Course

The basic block is framed by two special courses, both devoted to nanoscience and –technology, an introductory course and an engineering course. The very first lecture that the students attend is that in the introductory course, an outline of which is given in Table 1. This course is of utmost importance for the whole program. The course first provides an overview of the entire field, and the students are introduced to many aspects of nanoscience. After completing the course, students will have comprehensive general knowledge of nanoscience and -technology. An important aspect of this introductory course is that it highlights interdisciplinary and important research results in the field over the past 5-10 years. The course focuses on results that have led to important breakthroughs in the four fields that are represented by the four specialization profiles at the end of the Engineering Nanoscience Program, especially with regard to life sciences (biology and medicine). This offers the students an opportunity to envision what they will learn in the next four years, and what the job opportunities can be. It also gives them the chance to reflect once more on whether they have chosen the right program.

This illustrates the second objective of the course, to identify the students that may not perform well in the Engineering Nanoscience Program. For those students a counseling service is offered, as explained below. Although the students actively chose this curriculum, most of them have only rudimentary knowledge of nanoscience and technology. They may even have entered the curriculum with misconceptions about nanoscience and -technology. We know from our early questionnaires that some students may have quite the wrong idea about some topics or disciplines. For instance, some students stated at the beginning of the curriculum that they loved physics but disliked modern electronics, an indication that they did not know what electronics means. We were not

Study week	Course element	Subject
Week 1	Lecture 1	Overview “nano”
	Seminar 1	Some physics behind “nano”
	Lecture 2	Energy concepts: From atoms to semiconductor
	Seminar 2	More physics behind “nano”
	Lecture 3	Quantum physics at the nanoscale
Week 2	Lecture 4	Nanostructures: Materials and instruments
	Lecture 5	Nanoscience and biomedicine
	Lecture 6	The nerve system, natural sensors I
Week 3	Lecture 7	The nerve system, natural sensors II
	Lecture 8	Nanoscience: Biomedical applications
	Lecture 9	Conducting projects and presentation technique
Week 4	Laboratory exercise	Trip to four different research labs
Week 5	Lecture 10	Ethics of nanoscience
	Lecture 11	Information and literature search
Week 6	Information	Presentation of list of projects
	Lecture 13	Commercialization of nanotechnology
	Industry visit	Visit to companies
Week 7	Q & A	Q & A in preparation for the exam
	Kick-off	Start of the project
Week 8	Oral exam	Individual, 15 min. each
Week 9-12	Work on project	
Week 12	Deadline	Deadline for project report
Week 13	Symposium	
Week 14	Evaluation	Individual evaluation of the presenting performance of the groups

Table 1: Outline of the introductory course.

too surprised over this comment since we know that electronics is rarely taught at high schools in Sweden, and when it is, it is often taught badly.

The third objective of the course is to convey the “soul”, or underlying philosophy, of the curriculum to the students. We want the students to feel that they are a special group studying a special subject and that they are stimulated and inspired for further studies. Further, we want the students to develop a feeling of kinship to the course and the group, and understand the value of collaboration within science and technology. The fourth course objective is for the students to obtain their first insight into the nature of projects and the way in which a project is carried out. During the course, the students attend a lecture on the theory of conducting projects and will conduct a project themselves. Each student chooses a project area within the entire field of nanoscience and then focuses on one dedicated aspect of nanoscience and -technology, such as functional nanomaterials. The project is conducted in small groups of three or four students, and consists mainly of literature studies and gathering research information, but with the supervision of and interaction with researchers active in the field chosen. The project culminates in a symposium at which the students present their results in articles, as posters, and in talks. At this first scientific conference, at which invited keynote speakers from industry or academia introduce each of the main nanoscience areas, the students enjoy an enthusiastic atmosphere in which their own work is featured. Apart from gaining deeper knowledge in one specific area of nanoscience, the students also increase their knowledge in other areas, as the symposium acts as a forum

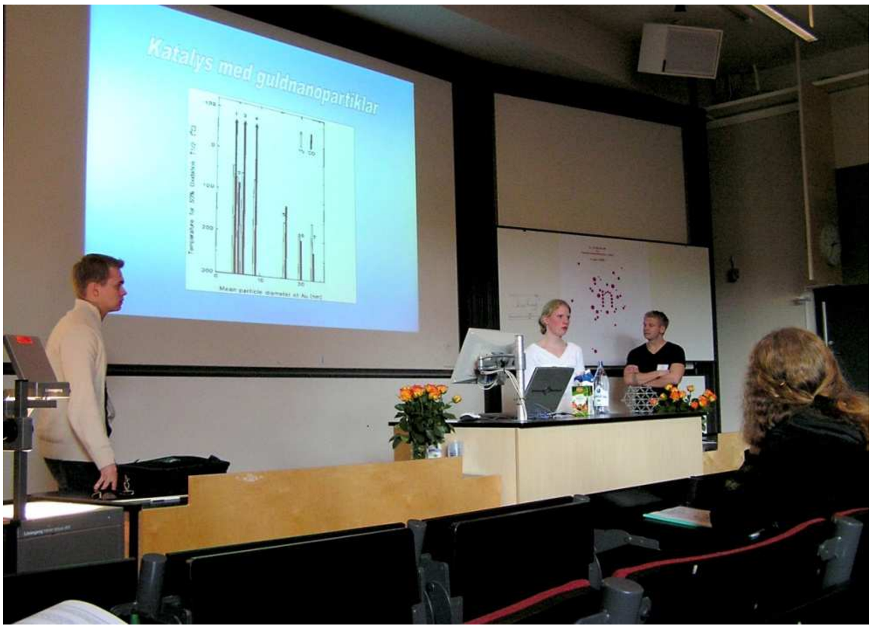

Figure 7: A student group presenting the results of their project on catalysis with gold nanoparticles during the symposium.

for teaching and learning. Through the projects and the subsequent presentations, students obtain training in using scientific literature and writing reports, both subjects they have had lectures on, and become acquainted with oral and poster presentations, skills they will need in their future careers.

The symposium not only serves the requirements of the course in training and examination of the students, but also fulfills the goals of nanoscience outreach and recruitment. Teachers and students from local high schools are invited to attend the symposium free of charge. Our students are instructed to keep their project reports and presentations on a level that is comprehensible to senior year high-school students. Every year, about fifty students and a dozen teachers used this opportunity to learn more about nanoscience and nanotechnology. In this way we can introduce nanoscience into high schools. Although we do not envisage introducing concepts of nanoscience and –technology at the elementary-school level, as advocated by Mihail Roco [2], we have found that our outreach activities are particularly successful at high-school level. This is also of importance for recruitment of future undergraduate students into the Engineering Nanoscience Program. The symposium is held before the deadline for application to university in Sweden. Thus, among the high-school students attending there will be some who may have considered our curriculum and they will have the chance to see the level of skills and knowledge they could gain within one year. During scheduled breaks in the symposium activities, there is ample time for high-school students to meet with the undergraduate students or university lecturers and to ask them about the program. We have found that our enthusiastic students are the very best promoters of the program.

The fifth objective of the introductory course is for students to come into close contact with research environments and top-of-the-line projects. This happens both during dedicated visits to research labs where the students can see state-of-the-art experiments, as well as during their projects. Since the visits to the research labs are at different faculties, the students are confronted with different scientific approaches and are able, from the very beginning of the program, to establish a large number of contacts with researchers and lecturers. The introductory course also mediates knowledge of the close interplay between technology and science. This sixth objective is accomplished by visits to research departments of companies and by a special lecture on the commercialization of nanotechnology. The seventh objective is that of encouraging students to actively discuss and reflect on all aspects of nanoscience and -technology. During the course special attention is paid to reflection on ethical issues. In a special lecture, initiated by one of Europe's most prominent expert in nanoethics, Göran Hermerén (Superintendent of the Department of Medical Ethics at Lund University and President of the European Group on Ethics in Science and New Technologies), the students are introduced to the philosophy behind ethics and the tools used to discuss ethical aspects. The students then discuss the development and use of nanotechnology from a Developing-World perspective and for military purposes.

Even an introductory course such as we have created for our curriculum needs written material in order to facilitate effective learning. We searched for a textbook that covered the entire field of nanoscience in a way easy enough for freshmen to understand. The book by Booker and Boysen [29] came closest to our requirements. It has the advantage that the language in the book is rather easy and does not use overly technical terminology, and thus is appropriate for young Swedish students. Most people in Sweden are comfortable with the English language; however, there is a difference between learning in that language and watching Hollywood movies. Thus, with this textbook we can even guide the students towards reading modern scientific literature and communicating in English. At this point a word about language is appropriate. The first two years of the basic block are taught in the Swedish language since it is always easier to learn in your mother tongue, especially complex concepts. This, however, does not mean that all textbooks are in Swedish. About half of the textbooks used in the courses in the basic block are in English. Sweden is too small a country for all textbooks to be written in Swedish or for all non-Swedish textbooks to be translated. The result is that our students are rather good at reading and understanding English scientific texts after completing the compulsory courses, while still being able to communicate in Swedish about nanoscience and -technology. After the first two years, the teacher is free to choose English or Swedish as the course language. The choice is influenced by the lecturer, who may not have Swedish as a first language, and also exchange students taking the course, who may not have Swedish as their first language.

It is particularly important that such an important course be taught by lecturers who are knowledgeable and enthusiastic, and who can communicate well with students. Lars Samuelson, the scientific leader of the Nanometer Structure Consortium, is responsible for the course and gives most of the lectures. Other lectures, in life sciences, are given by a professor from the area of cell biology. At the beginning of the course, the teacher in charge of the basic physics course, which is taught in parallel, is involved to ensure "positive overlap". Further, a number of specialists, e.g., a librarian and industrial representatives, as well as other Consortium researchers, are involved in the course. The director of the Engineering Nanoscience Program (Knut Deppert) is involved in order to assure that the underlying educational philosophy of the curriculum is conveyed to the students.

4.4 The course Engineering on the Nanoscale

The second special course, which together with the introductory course forms the frame around the basic block, is the final one of the compulsory block. It is an engineering course in which the students really experience the close interplay between technology and science at the nanoscale. The basic concept of the course is to explore whether an idea that has emerged from the study of nanoscience could be protected by a patent and/or commercialized. One student alone, or two students together, develop a concept, preferably their own, of an application of nanotechnology and analyze the possibility of filing a patent and bringing this concept to market. The student, or the small group, works independently but with various forms of support. The lecturer who is responsible for the course has successfully converted ideas into products and companies. This academic plays an important role in mediating her/his experience to the students, and can describe both the opportunities and the limitations. A number of specialized lectures and seminars provide support to students as they develop their ideas. These lectures and seminars will be given by experts in the field and will deal with: (a) intellectual property rights, (b) economics of small companies, (c) starting a company, (d) product design, (e) ethical and environmental problems, and (f) marketing. Thus, the students will come into contact with the engineer's way of thinking, as well as with economists, patent engineers, and that of potential customers. The third kind of support is based on the network that exists within the University for the commercialization of ideas. Students can benefit from this network, which includes the first Swedish science park, Ideon [30], as well as organizations such as LUInnovation [31]. The various projects will be presented at a symposium, both successful and unsuccessful projects. In the very best case, a limited number of small companies may even result from the course. However, this has not happened yet.

4.5 Concerted Action: Positive Overlap between Courses

As mentioned above, the third method of ensuring depth in the curriculum, despite the short time available, is *concerted action*. All courses in the interdisciplinary block interact in a specific manner, and overlapping or redundant teaching is largely avoided. This method is a rather complicated one and requires careful organization of the curriculum. Even when there are two teachers giving one course, one teacher may not know exactly what the other has taught the students. This is an even more challenging task when courses are taught by teachers from different faculties. It should also be borne in mind that some overlap between courses, or even lectures, can have a positive effect on learning, and should be encouraged rather than avoided. An example of intended overlap is the teaching of the basics of thermodynamics, which is done in the chemistry course by chemists and by physicists in a course in the second year.

Here, we will describe the implementation of this method, i.e. the building of "knowledge chains", in our curriculum. When discussing the introductory course, we mentioned briefly the involvement of the physics teacher at the beginning of this course. This is the first positive overlap between courses. The introductory course presents the foundations of nanoscience, e.g. quantum physics, which it is hoped will motivate the students to learn the fundamental physics and mathematics necessary to understand nanoscience. While introducing the basic concepts of nanoscience, the students may need to repeat some physics background which is accomplished in the physics course. Further, the physics course deals with the areas of physics that are essential to understand nanoscience, such as atomic physics and waves. All other parts such as astronomy and subatomic physics are excluded. The knowledge on atoms that the students gain here forms the basis for the chemistry courses that follows. The chemistry teachers can then directly start to teach the students how molecules are formed and time can be saved on the explanation of the periodic table. At the end of the chemistry courses, the students know the composition of the molecules in living organisms, forming the basis for the subsequent biology course. With this knowledge, the course in cell biology continues until the students have learned all the relevant basics of the cells in an organism. This provides the starting point for the study of physiology, where the cells are combined into function-specific organs in the human body. Here, we concentrate on the human body since some of the more dramatic impact of nanotechnology is to be expected in the field of medicine, such as new drugs, drug delivery systems or sensing devices [32]. This is also clearly expressed in the findings of the 2005 European NanoBusiness Survey (see Figure 8) [7].

The examples described above are not the only positive overlaps between courses that were needed in order to create the curriculum. Another example is the sequence of mathematical courses that runs

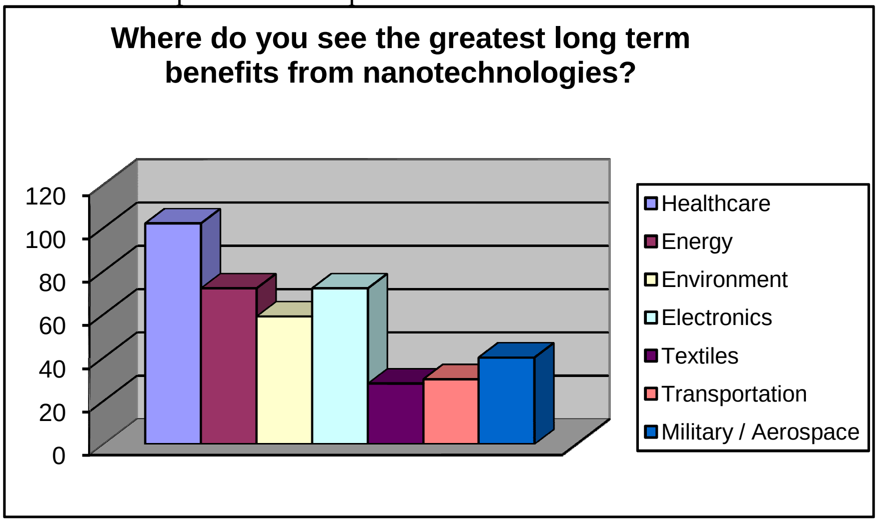

Figure 8: Outcome of the 2005 European NanoBusiness Survey [7].

parallel to other courses in the first year of study. This sequence, established by the Department of Mathematics at Lund University, begins with a review of advanced high-school mathematics and successively builds up the knowledge and skills necessary to cope with the basics of quantum mechanics. In the *Engineering Nanoscience* curriculum, that sequence is extended to include a short course that introduces software tools and a detailed course on mathematical tools for nanoscientists. The students are now able to handle Fourier integrals, Laplace transforms, and partial differential equations. The mathematics is taught in terms of applicability to phenomena in physics and not in pure mathematical terms. Thus, students acquire the skills required to use the appropriate mathematical tools when necessary. At the end of this sequence in the basic block is the course on electronics. This course utilizes the students' mathematical knowledge, starting from Maxwell's equations and finishing with the modeling of real circuits.

A further interaction occurs between the above-mentioned short course on software tools and the parallel-running course on quantum phenomena and nanotechnology. In the latter the students need the software tools for the laboratory and calculation exercises and the tools are introduced with simple examples from quantum physics and mechanics. An additional positive overlap occurs in the sharing of teaching of the basics of thermodynamics between chemistry and physics in year 1. Here, we have the further advantage that the students learn parts of the basics from both sides, thus becoming familiar with the similarity between the lowest unoccupied molecular orbital (LUMO) in molecular chemistry and the conduction band edge in semiconductor physics.

This positive overlap may seem to be natural at a university, and this may be the case for a traditional curriculum that has run over many years with considerable involvement of, and interaction between, the same teachers. Here, it is the result of hard work. Most of all, it requires the goodwill and enthusiasm of all those involved: the program management needs to coordinate the lecturers responsible for each course, the teachers need to adjust the courses, and the time schedules have to be coordinated. In the end, a functioning chain of learning is created, and even the students recognize the positive overlap after some time. We estimate the time saved to be on the order of two lectures, including the appropriate study time, for each of the ten courses with positive overlap. Counting the number of teaching hours saved, the total saving for the whole basic block is about 8 of the 165 credits, i.e. almost 5%. With much greater effort, it would be possible to reach 10%. However, we would then lose some of the teaching overlap that enhances the learning of the students. Together with the following specialization courses, the 5% saving is sufficient for a curriculum that creates highly qualified nanoengineers. The most elegant way to increase positive overlap would be to run the curriculum first for all involved teachers, before opening it to students. However, we doubt that any university in the world would have the time and resources required to do this.

4.6 Areas of Specialization

The specialization area that follows the basic block is an essential component of the curriculum. During the specialization block, courses are chosen such that the depth (or height) of knowledge is guaranteed, and, for students intending to continue into research, this part will effectively prepare them for Ph.D. studies in their chosen area of specialization. The two years of specialization also prepares students for continuation in high-tech and research-based industry, where the breadth and depth of their skills in engineering nanoscience will be highly appreciated. During these two years, the students delve more deeply into their field of interest, choosing between nanobiomedicine, nanomaterials, nanoelectronics, and nanophysics. As mentioned above, this specialization does not mean that the students only attend courses that deal specifically with one of these nanofields, e.g. nanophysics. Some courses are specific to the separate fields, but most of the specialized courses are at an advanced level in the main discipline, in the above case, physics.

All four areas of specialization (i.e. nanobiomedicine, nanomaterials, nanoelectronics, and nanophysics) are a continuation of the knowledge and skills gained in the first three years of the program. Specialization starts with compulsory area-specific courses that give deeper knowledge of, and skills required for, the direction chosen, and finishes with practical research-related education and training. During this period, students will carry out Master's projects while taking courses at the relevant departments. For each area of specialization a basket of courses has been chosen that consists mainly of existing courses in order to minimize the cost since, on average, less than ten students will choose the same area of specialization. Further, several courses are included in two or more specialization baskets. This is possible due to the interdisciplinarity of nanoscience. It also aids program economy. In addition to the course basket, the students must read one course on sustainability. Below, we briefly describe the main courses in each of the four areas of specialization.

For the specialization in *nanobiomedicine*, the compulsory course is a 15-credit course on biochemistry since we see that the students do not reach a sufficient level in this subject. Thereafter, we envisage three different foci within this specialization. The first is on pharmaceuticals, with courses in human physiology, immunology, toxicology, and pharmacology. The second is on biomedical analysis with courses in bioanalysis, microfluidics, genetics, colloidal chemistry, optical techniques, and microsensors. The third focus area includes courses on biomedical materials, courses in biophysics, mechanics, virology, biomechanics, and colloidal chemistry.

For the specialization in *nanomaterials*, there are two compulsory courses, one in materials chemistry and the other in materials analysis. While the first one builds on the students' knowledge in chemistry, the second is a hands-on course to enable students to perform advanced analysis of nanomaterials with several types of microscopes. Thereafter, three different foci have been outlined. One is on materials synthesis with courses in colloid chemistry, crystal growth, polymer chemistry, powder technology, and mechanics. The second is on functional materials with courses on polymer chemistry, chemistry of nanostructures, and biomechanics. Third, materials analysis will include courses on analytical chemistry, surface physics, and atomic and molecular spectroscopy.

Regarding the area of specialization in nanoelectronics, one course is compulsory: a newly developed 7.5-credit course in nanoelectronics. This course deals with the applications of nanoelectronics in a number of areas and it will give knowledge about how devices may be realized and modeled. Thereafter, two foci are envisaged, one in high-frequency electronics and one in medical electronics. The first includes courses in semiconductor physics, high-speed electronics, quantum mechanics, and advanced electronic design. The second includes courses in microfluidics, analog electronics, system technology, and microsensors.

Also in the area of specialization in nanophysics there is only one compulsory course, a 7.5-credit course on physics of low-dimensional structures and quantum devices. This course concerns artificial materials with substructure on the nanometer scale such that the electronic motion is restricted to two, one or zero dimensions. The emphasis is on semiconductor heterostructures but also other low-dimensional systems will be discussed. The concepts and the underlying theory are introduced based on quantum mechanics and extended by the application to heterostructures. Our aim is again to improve the students' skills in the use of advanced mathematical tools and to deepen the knowledge in physics. Two foci are envisaged, one on theoretical and one on experimental nanophysics. The first includes courses on solid-state theory, theoretical biophysics, semiconductor physics, and quantum mechanics. The second includes courses in crystal growth, mechanics, microfluidics, surface physics, and system technology. Apart from the courses mentioned above in the four different areas of specialization, students can choose between a number of additional courses offered by the departments involved.

Apart from the four designated specializations, nanobiomedicine, nanomaterials, nanoelectronics, and nanophysics, students may create their own individual area of specialization. This specialization must fulfill three requirements: the courses chosen must amount to at least 45 credits, of which at least are from A-level courses, it must contain a course on sustainability and must be approved by the Program Board in advance. This means that in a discussion about the courses that should be included in the individual specialization, the program director and the student agree on the focus and the importance of the area chosen. This leads to interesting discussions. One student is contemplating moving into the world of finance, dealing with stocks and technology funds, and realizes that stockbrokers lack knowledge about the emerging field of nanotechnology. Thus, he sees a clear possibility to pursue a career by using his in-depth knowledge of the field as a consultant, not only on the stock market but also perhaps for venture capital companies. In his case, we have discussed a selection of advanced nanotechnology courses and some courses in economics and financing. Another student has the ambition of becoming a journalist, a specialization that we feel is of special importance, as the public should be informed about all aspects of nanotechnology, although there seems to be no clear responsibility established for this purpose (see Figure 9). We believe that those of our

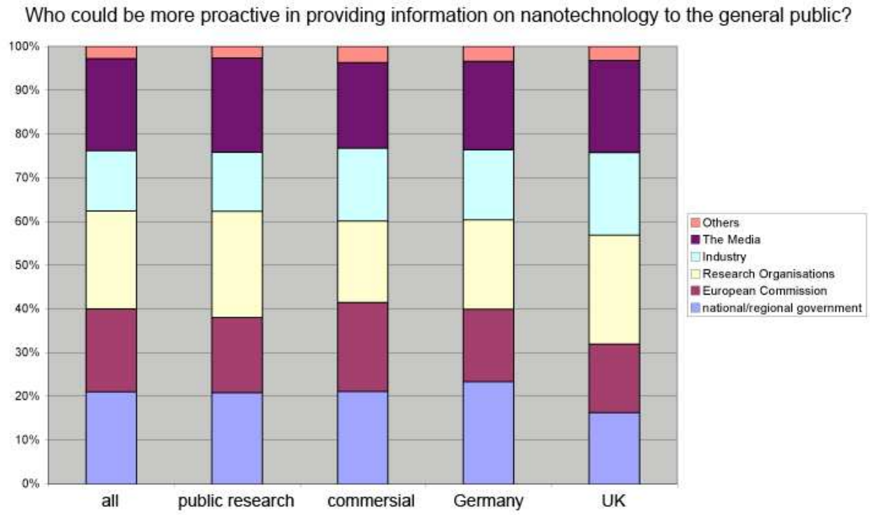

Figure 9: Responsibility for informing the public about nanotechnology according to all respondents in the European Nanotechnology Gateway Open Consultation on the European Strategy for Nanotechnology [9].

students who can communicate well are perfectly qualified to become science reporters because they have broad knowledge about many fields of science and technology, more than graduates can gain in traditional university programs.

The way in which the curriculum is organized provides the opportunity for our students to study abroad for a semester, one year, or even two years. We encourage our students to make use of this opportunity to enhance their language skills (not necessarily English) and to broaden their horizons. Students are exposed to other cultures, gain insight into life outside of Sweden, and acquire a better understanding of the issues that are important to people in other countries. This certainly enhances their interdisciplinarity, since working with people from different scientific disciplines is often like moving between different cultures. The fourth year of the curriculum, with its specialization courses, is naturally suited for studies at other institutions, since advanced courses on basic sciences, e.g. in chemistry or physics, are available in almost every country. Our students can benefit here from the extensive network of Lund University, which, together with special contracts with the Faculty of Engineering, gives them the possibility to take courses free of charge at more than 600 universities worldwide.

Upon successful completion of the specialization block, students are awarded a Master of Science degree in Engineering Nanoscience. The specialization block is also arranged so as to be a freestanding Master's course for students from other disciplines, such as physics, chemistry, or biology, or for exchange students. Here, special courses that deal with advanced nanoscience and -technology are to be chosen. However, in most cases, it is required that they take key courses from the first three years of the program.

5. Management of the Curriculum

The curriculum is managed by a team; the work is governed by a Program Board (in Swedish: programledningen). The director of the program, the deputy, an administrator, a counselor, a representative of the teachers and six students constitute the Program Board. The director together with the support of a deputy and the administrative personnel constitute the executive management and work with the curriculum on a daily basis; the teacher and the student representatives are involved in more general and strategic issues. The director and the deputy are both experienced teachers, and successful researchers within the field of nanoscience and -technology. Officially, 30% of the scheduled working time of the director is devoted to this task; in practice, directing the curriculum occupies about 20-25 working hours per week. The main responsibilities of the director include: (a) organization of the interplay between courses, (b) budget of the program, (c) contact with the teachers, (d) contact with the students, (e) keeping track of the students' progress, (f) course evaluation, (g) developing the program, (h) coordinating students' studies abroad, and (i) advertising the program. The deputy devotes 15% of her/his time while both the administrator and the counselor work half-time for the Engineering Nanoscience Program and half-time for another engineering program. The counselor (in Swedish: studievägledare) provides assistance in the many student-related tasks that the director has to deal with and the administrator (in Swedish: programplanerare) acts as the secretary for the program and ensures that the budget is not exceeded.

The work of the Program Board is regulated by an Educational Board (in Swedish: utbildningsnämnd) that discusses and defines policies regarding several programs, with one of the authors of this book chapter (Rune Kullberg) who is the head of the Board. Teachers, students, representatives from industry, and administrative personnel constitute the Board. The main concern of the Board is to maintain the high quality of the curriculums. Emphasis is therefore placed on maintaining high pedagogical quality in each course. The Board does not advocate one pedagogical model, since variations in teaching methods and methods of assessment are encouraged within the curriculum, which requires open dialog between students and teachers in order to establish the rules of the game. Mutual respect between teachers and students is necessary if everybody is to accept the use of certain methods, even if this is not the preferred method of each individual.

The Educational Board encourages pedagogical development of the teachers and the courses, and stimulates discussions on pedagogical problems, e.g., by organizing pedagogical seminars. Teachers are encouraged to improve their pedagogical knowledge and skills and reflect on different teaching and examination methods. Methods that improve the dialog between students and teachers are supported. The competence of the teachers is judged according to the following criteria:

- scientific competence,
- pedagogical skills and the ability to reflect on them,
- comprehensive understanding of, and attention to, the learning process;
- communicative skills, and
- the ability to lead, organize, and plan.

The Board uses several methods to assess the competence of teachers; active student involvement being one of the most important. We are very fortunate to have a large number of enthusiastic students who want to get the most out of the program, can voice their criticisms, and have good ideas about how improvements can be made. There is an established system of evaluation, during, as well as after, each course. One or two student representatives are elected by their peers to convey the comments and criticisms of the entire class to the teachers and the program director. In the middle of each teaching period, the lecturer responsible for the course, the student representatives, and the program director meet and discuss the course. Some changes may be made directly, if necessary. At the end of each course, the students' impressions are collected using a questionnaire. The results of this are discussed by the same group that met in the middle of the teaching period and are reported to the Educational Board. The results of these evaluations show that most criteria regarding the teachers are fulfilled. For example, criterion 1, scientific competence, was never in question, but for a very limited number of courses, concern was articulated concerning criteria 3 and 4. We plan to focus our ongoing development of the curriculum on these areas.

It should be mentioned that the Program Board organizes other activities besides the courses, all in close cooperation with the students. The first is the introductory week for freshmen. In the week that precedes the start of the program, new students are introduced to the university, the faculty, and to life as a student. They are organized in groups of about eight with a student from the second or third year as a mentor. These groups include students from the programs in Engineering Physics [33] and Engineering Mathematics [34] due to the close relations with these programs. The Program Boards cooperate closely, several courses are given together, and the students from these programs are all organized in one students' union. The freshmen are given a thorough introduction to the program by the program director and we describe what we expect of them. Two introductory lectures are given, one in mathematics and one in physics in order to assess the level of knowledge among the newcomers and to level the playing field. Additionally, one day of experimental physics is included in this week, posing a task that requires imagination and basic knowledge. Older students introduce the newcomers to appropriate methods of learning, and small groups often form that continue throughout the program in which the students help each other. The sophomores guide the freshmen around the campus, organize an excursion into the countryside around Lund, and arrange a party for them.

The students are offered counseling by the guidance and careers counselor who is part of the Program Board. This service enables the students to obtain specified and detailed information on how to plan their studies in general, as well as on different learning techniques and how to deal with administrative matters. Career support is of course a natural service and students often ask questions on future careers, although the students are still far from finishing their Master's degree. The mere knowledge that they have the opportunity to talk to someone about problems that may arise during their time at university gives many of the students a sense of "being seen and taken care of". Besides the counselor working within the program, additional counseling service is provided by the faculty and the university.

For selected courses, the program management offers Supplemental Instruction (SI) [35]. The purpose of SI is to assist freshmen with their studies through the support of older students. Sophomores are trained to act as group leaders and function as moderators to help organize study routines as well as illustrate different strategies to resolve problems. SI leaders do not provide knowledge concerning the subject of the course, instead they stimulate and facilitate the understanding of the course material. The freshmen benefit from more efficient method of studying and improved chances of attaining better results.

The Program Board also arranges three or four evening meetings, called *Nano Nights*, at which students can discuss nanoscience in industry, nanotechnology in the region, the possibility of studying abroad, or other issues of interest with invited guests.

6. The Need for Nanoengineers

As mentioned above, there is extremely interesting research in nanoscience and -technology in the Lund area, centered around the Nanometer Structure Consortium [22]. Research is also being conducted at other locations in Sweden in this field, the main centers being at Stockholm, Göteborg, and Uppsala [36]. In addition, several spin-off companies in the field of nanotechnology have recently been established e.g. QuNano AB [37]. Regarding the number of patents in the field, Sweden was among the top 15 countries in the world in 2003 [38]. Thus, we can identify a clear need for skilled engineers in nanoscience and -technology in our region.

In the 2005 European NanoBusiness Survey, a major problem was identified in finding highly skilled personnel. As 62% of respondents indicated that it was "difficult" to find personnel with the desired skills, this suggests a serious problem, with little difference between academic institutions, multinational and small- and medium-sized companies (SMEs) (see Figure 10) [7].

The need for trained personnel seems to be of the highest importance for SMEs and start-up companies. This was revealed by the questionnaire

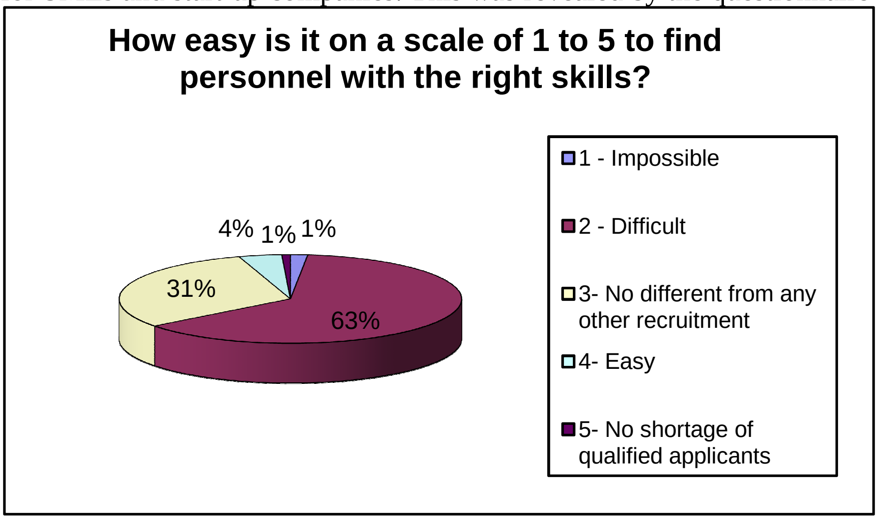

Figure 10: Outcome of the 2005 European NanoBusiness Survey [7].

on the European Strategy for Nanotechnology, where the lack of highly skilled personnel was identified as the most serious problem (see Figure 11) [9].

When is the best time to launch a university program in nanoscience and -technology? In our opinion, the best time is when it is clearly seen that graduates educated in this field will be needed. We must also remember that education programs aim at responding to anticipated needs. At present, job opportunities for nanoengineers are not that numerous, in Sweden or in other parts of the world. In 2002, a U.S.

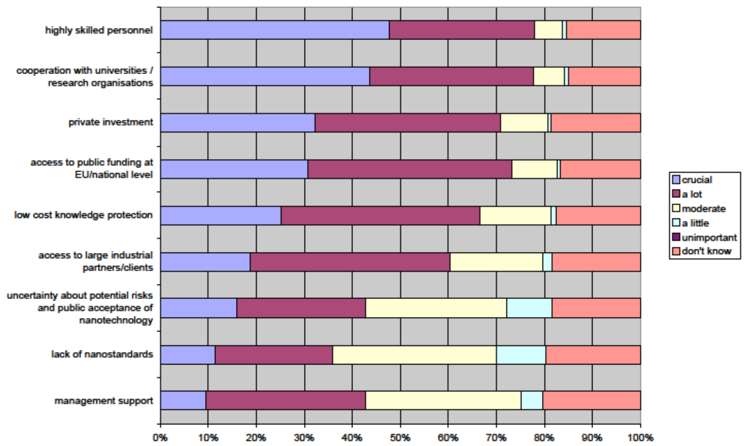

Figure 11: Rating of the importance of the main difficulties that are faced by SMEs and start-up companies according to the respondents to the European Nanotechnology Gateway Consultation on the European Strategy for Nanotechnology.

National Science Foundation workshop on nanotechnology education stated that the demand for qualified scientists and engineers with nanofabrication skills is expanding rapidly. The development of interdisciplinary education programs that engage the interest of students of all ages, especially at undergraduate level, is crucial to development in the area of nanotechnology [39]. Further, based on the exponential development of the field, we anticipate a considerable need in the near future. According to Roco, it is estimated that about 2 million nanoengineers will be needed worldwide in 5-10 years from now [40].

A similar demand was recognized by the Open Consultation on European Strategy in 2004 [9]. Almost one-half of the respondents to this questionnaire foresaw a shortage of qualified personnel within 5 years, and another quarter in 5-10 years, with no significant difference between respondents from public research organizations and commercial organizations (see Figure 12). Based on the results of this questionnaire,

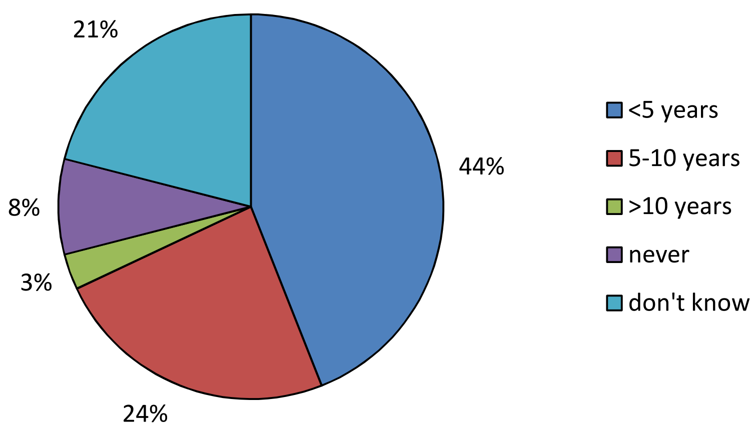

Figure 12: Expected occurrence of a shortage of personnel trained in nanotechnology according to all respondents in the European Nanotechnology Gateway Open Consultation on the European strategy for Nanotechnology.

we started our program at just the right time, since the first nanoengineers graduated from our university with a Master's degree in Engineering Nanoscience in 2007.

An additional time constant is built into the academic system. It may take years to obtain the necessary authorization to establish such a program and additional years to overcome all the administrative problems on the intra-university level. We began preparations in the 2001–2002 academic year and launched the program in 2003. The universities of

Copenhagen and Aarhus launched their programs a year earlier, and others will probably follow. There is thus great potential for providing the engineers needed for the development of nanotechnology.

7. Our Curriculum as a Magnet for Students

The Engineering Nanoscience Program at Lund University was originally intended to accommodate 40 students. While other programs in science and engineering suffer from decreasing numbers of students, the Engineering Nanoscience Program received a high number of applications. As can be seen from Table 2, to date, we have consistently received more than two primary applicants per place. When applying to university in Sweden, applicants can apply to several programs and places. Although we observed a drop in 2006 and 2007, we foresee an increase in the number of applicants to the program in the future as knowledge of the program becomes more widespread through our students, who advocate for it, and as information on nanotechnology spreads even more in the public arena.

Year	Number of 1st choice applicants	Total number of applications	Number of 1st choice applicants per place
2003	85	362	2.1
2004	112	437	2.8
2005	118	431	3.0
2006	89	309	2.2
2007	81	321	2.0

It should be noted that admission to the program is limited to students having studied science at high school. Those who have chosen arts and social science, and occupational subjects are not eligible. Further, not all students who have studied science at high school will be directly eligible, as some high schools do not offer courses in all disciplines, and some subjects, such as biology or electronics, may not have been available. Bearing this in mind, there are no demands on biology and electronics but some emphasis is placed on mathematics, physics, and chemistry.

Despite efforts to admit only those students considered suitable and motivated for the program, some drop out (see Table 3). Two main reasons were identified for dropping out: (i) wrong subject and (ii) personal reasons. "Wrong subject" may mean that the student has realized that he or she would prefer to pursue a pure science career rather than an engineering career, or that nanotechnology is not what they expected. It can also mean that the program is too demanding. Personal reasons are usually related to family matters. It is in theory possible to interview all applicants, which would help minimize the number of students dropping out because they have chosen the "wrong" subject. However, this would have needed the permission of the Swedish higher education authorities, apart from requiring extra administrative and financial resources. Although interviewing applicants is common in some countries, the prognosis as to the success of the student may be questioned. We are currently investigating offering applicants a web-based self-assessment, which would supply prospective students with additional information in the process of choosing the right university program. A comprehensive example of such self-assessment is that offered by the Electrical Engineering Program at RWTH in Aachen, Germany [41].

We are very pleased that the proportion of female students is more than 25% (see Table 3), as many engineering programs attract only a small number of female students. Having a reasonable proportion of women in the class appears to improve the atmosphere. We know from statistics on student performance within the Faculty of Engineering at

Lund University that the best results are obtained when the minority gender in a class lies between 30 and 50%, with the minimum number of students of this gender being 10 [42]. One of the main reasons why the number of female students is rather high lies in the attraction that stems from the unique combination of life sciences, physics, mathematics, and engineering.

Year	1st year		2nd year		3rd year		4th year	
	Total	Female	Total	Female	Total	Female	Total	Female
2003	47	10	-	-	-	-	-	-
2004	57	18	41	9	-	-	-	-
2005	54	11	41	13	34	11	-	-
2006	48	11	44	10	41	13	34	11

Table 3: Number of students in the Engineering Nanoscience Program on September 1 of each year. Note some students entered the program in Years 2 or 3.

Which students choose our curriculum? Geographically, recruitment is rather local. Almost 60% of all students on the program are from the province of Scania, in which Lund is located. Of these, 15% are from Lund itself. The majority of the remaining students are from neighboring provinces, and only a few are from the Stockholm area or further north. Although the Engineering Nanoscience Program at Lund is the only one of its kind in Sweden, its geographical outreach thus appears rather limited. However, this is not unique for our program, as most young Swedes attend the university closest to their home, or where they went to high school. Regarding the age of the students, two thirds enter the program at an age of 18 or 19. This means that they mainly come directly from high school, and have rather limited work experience. Swedish students leave high school at the age of 18 (school age 7 years + 9 years compulsory education + 3 years high school). The remaining students have either studied another university program for one or two years, worked for a few years in industry or as teachers, or improved their high-school grades at evening classes.

We have already described how we use the symposium at the end of the introductory course in the first year for the recruitment of final year high-school students. High-school teachers are also invited to attend this symposium. We plan to extend our drive aimed at high schools through a new course on the basics of nanoscience and –technology, similar to the introductory course, which will be available to high-school teachers. At time of writing, this course is under development in cooperation with the National Centre for Education in Physics [43], which is based at Lund University, and has a number of highly experienced educationalists at its disposal.

8. Summary

We have created a unique university program in nanoscience and nanotechnology at Lund University: *Engineering Nanoscience*. The curriculum is based on a broad basic education that covers all the areas of science and technology relevant to nanoscience. We believe this curriculum will enable us to educate nanoengineers with a coherent view on nanoscience and thorough basic knowledge. Through this type of curriculum, we have the chance to create informed and highly-educated individuals, able to influence the direction of nanotechnology in beneficial ways. Our program will be able to fulfill the mission of liberal education that turns students into critical thinkers who are capable of participating in intelligent debates about how societies ought to be transformed. The program is well oversubscribed and we are pleased that almost 30% are female students. Our students are highly motivated, enthusiastic and like the broad education - they see themselves as *renaissance nanoengineers*. The curriculum will naturally undergo adjustments as and when required, and the Bologna model will be fully implemented in 2007.

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