A Unified Approach to Nanotechnology Education

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Abstract

We present an educational strategy intended to unify nanotechnology education not only as part of university curricula, but also for broader audiences. The implementation of this strategy includes the use of five primary content "blocks," or modules, to teach the core principles of nanotechnology to audiences with varying levels of understanding. In a university setting, freshman in science and engineering disciplines take a departure course in which these blocks are introduced. They continue working toward majors in their own departments before returning for a design and synthesis course at the senior and graduate student levels. This course, developed at the University of Nevada, Reno, is entitled "Nanotechnology System Design and Synthesis." It is an integrated microtechnology/ nanotechnology course in which the five blocks are reinforced and expanded upon, drawing on students' new knowledge in their respective disciplines, while at the same time challenging them to apply their knowledge to a real-world nanotechnology system design. The senior-level course serves as the capstone experience course for a newly created nanotechnology minor, and a graduate version of the course serves as the departure point for graduate students. It uses a microcantilever transducer to bridge the micro- and nano-domains and provide a system-level understanding of nanotechnology. Outside a university setting, course material blocks can be adapted to serve the general public, K-12 students, and members of industry.

1.0 Introduction: Training for Tomorrow's Technology

In December of 2003, President Bush signed the 21st Century Nanotechnology Research and Development Act.[1] The bill puts into law the Presidential National Nanotechnology Initiative started under President Clinton and allocates \$3.7 billion over the coming four years for research and development programs, including new research centers, education and training efforts, research into the societal and ethical consequences of nanotechnology, and technology transfer programs to move nanotechnology out of research institutions and into the workplace.[2] The National Science and Technology Council (NSTC) has stated: "The impact of nanotechnology on the health, wealth, and lives of people could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century."[3] The NanoBusiness Alliance recently released a survey[4] projecting the global market for the nanotechnology industry will reach \$700 billion by 2008.

Here we define nanotechnology as research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1 - 100 nanometers, where engineers create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.

The national impact of recent legislation, especially the acceleration of technical progress in nanotechnology it should catalyze, warrants a carefully considered educational strategy. An organized approach to the training of both university students and the general public can help ensure a more productive and efficient transition into a future in which this new discipline will undoubtedly play a role. Future economic trends are likely to depend on the ability of universities to prepare the employees and entrepreneurs of tomorrow's micro- and nanotechnology industries.

However, microtechnology—a topic that links the academic disciplines of physics, chemistry, biology and engineering for devices and phenomena in the scale of millionths of a meter—faces the challenge of teaching students with backgrounds in different knowledge domains (especially since traditional curricula do not leave room for such varied study). Nanotechnology, which deals with matter on an even smaller scale than microtechnology, faces the same challenge since it is even more multidisciplinary; in fact, it is difficult to find one scientific or engineering discipline that does not contribute to nanotechnology. Micro- and nanotechnologies share similar backgrounds and converge where devices are fabricated to interact with matter at the nanoscale and where nanoscale matter is organized to create larger systems. This convergence is inclusive of the one area and part of the other and is commonly called nanotechnology.

Here we describe a unified nanotechnology educational strategy, which includes an innovative microtechnology/nanotechnology course for undergraduate and graduate students. The course, "Nanotechnology System Design and Synthesis (NSDS)," was developed at the University of Nevada, Reno and provides a forum for synthesis of concepts from numerous scientific and engineering programs with a focus on nanotechnology. The course also implements the novel strategy of presenting a microcantilever transducer as the "bridge" linking the micro- and nano-domains. Ongoing research in atomic force microscopy, as well as biological and chemical sensing, is integrated into course material and laboratory experiences. The course in this way provides an example of an effective, highly pertinent small system.

More detail about the course will be presented later, but we will first focus on the broader educational strategy to which it belongs.

2.0 Unifying Educational Strategy: Mapping Content to All Audiences

The material developed for the NSDS course is intended to have multiple uses. The overall approach to nanotechnology education based on this content is depicted in Figure 1.

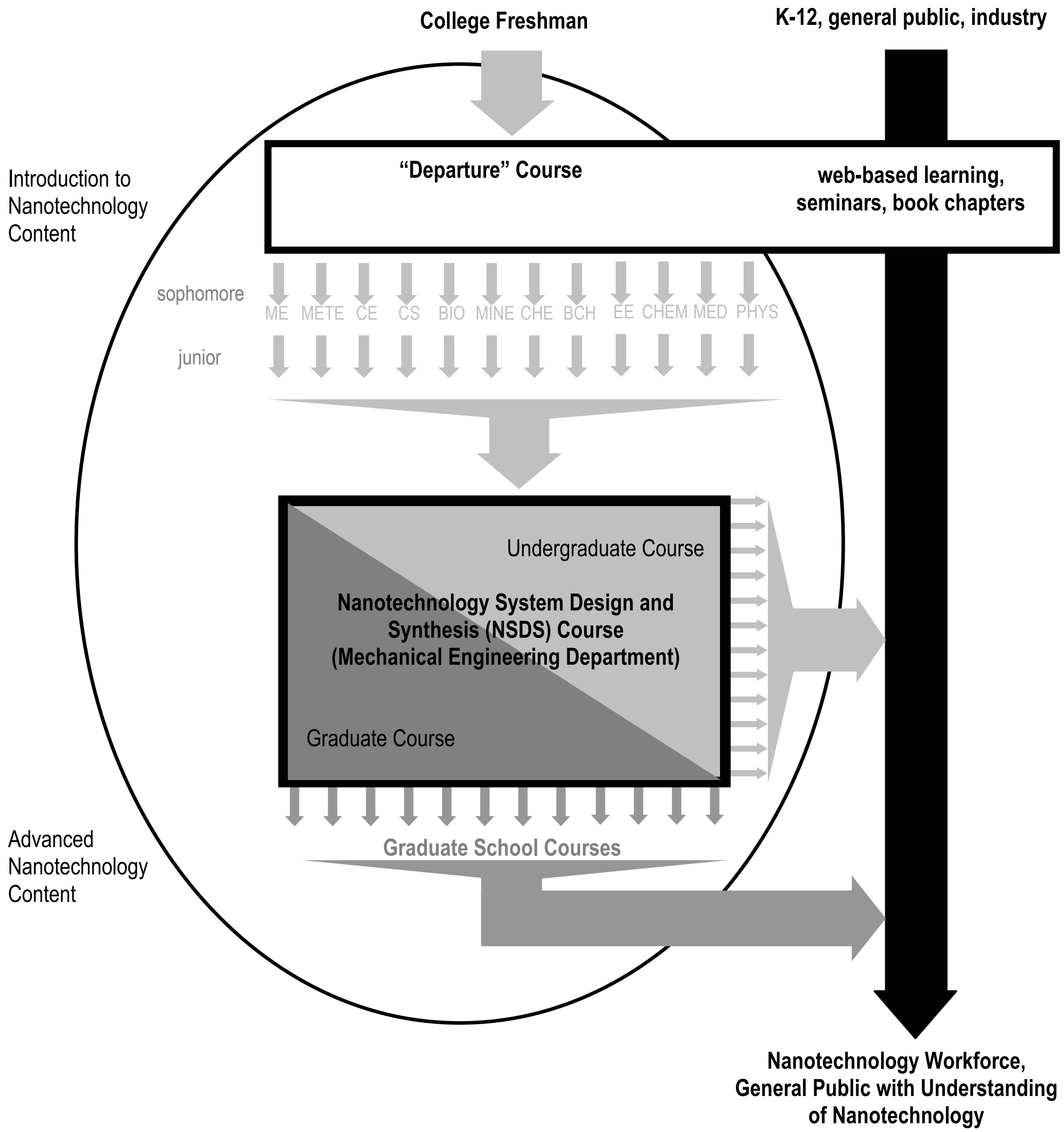

Figure 1: Flow chart depicting the use of two sets of nanotechnology educational content—introductory and advanced—to train and educate diverse audiences in nanotechnology. The freshmen level departure course material can be used for general audiences and the NSDS course material is used for both undergraduate and graduate students.

Stan Williams, renowned researcher and Director of Quantum Science Research at Hewlett Packard, has said that the role universities should play as part of the National Nanotechnology Initiative is to train students in a specialty field, while providing them with the ability to communicate well with others, "I want people who are very deep in their discipline and can talk to each other."[5] This statement supports the strategy we have adopted, with the addition that the students will not only be able to communicate well in general, but will have an appreciation and broad understanding of disciplines other than their own.

As shown, college freshman in science and engineering degree programs are initially familiarized with the concepts of nanotechnology in a “departure course.” This course will be implemented in the Fall 2004 semester as a modified version of the freshman-level Introduction to Engineering course (E100A) that has already been developed at UNR. The objective of the course is to teach students about engineering and design. Nanotechnology content will be added to this course in the Fall of 2004. The definitions of both engineering and technology include “the application of science.” Therefore, nanotechnology is in many respects nano-engineering, and the best place to introduce nanotechnology to students from all disciplines appears to be in a course that introduces both engineering and nanotechnology as connected disciplines. Designated as a college of engineering course, E100A will combine students from civil, mechanical and electrical departments as well as interested students from all other engineering and scientific disciplines. The “departure” nanotechnology course material consists of five 1-hour lectures given each week for five weeks, several demonstrations and two lab tours. (The Genomics Center and the Nanofabrication Facility) In addition, content from the five lectures could be used by introductory science instructors for implementation in their own courses.

The NSDS course then serves a capstone role, funneling undergraduates from diverse disciplines into a synthesis course. After study in their respective majors, students are provided a forum where they can see the connections of “nano” for the first time if they didn't attend the “departure” course, or be refreshed if they did. It is also their chance to apply their knowledge individually or in teams to a real nanotechnology system. They can make a sensor, a self-assembled monolayer based device, a DNA/in-organic material system, etc.—but a system nonetheless. NSDS is a 400/600 level course which serves both undergraduate and graduate students.

The outcome of this approach is a workforce and a general public better familiarized with nanotechnology. As shown in Figure 2, the five main blocks of lecture content from the NSDS course can easily be adapted to serve a younger, K-12 audience, the general public or as a primer for members of industry. For seniors and graduate students, each one of the five blocks contains two 75-minute lectures; for the freshman, each block represents a 1-hour lecture given each week for five weeks. Each lecture incorporates an exciting demo wherein a specific concept is portrayed. By further reducing these lectures to the most enticing demos, a one-hour presentation for K-12 lectures and assemblies can be produced; interested schools can then request the five-session program if desired. For presentations to the general public or industry, the first freshman lecture can be used or all five blocks can be distilled down to a 1-hour overview. Detail about the content of each block is provided in Section 3.1.

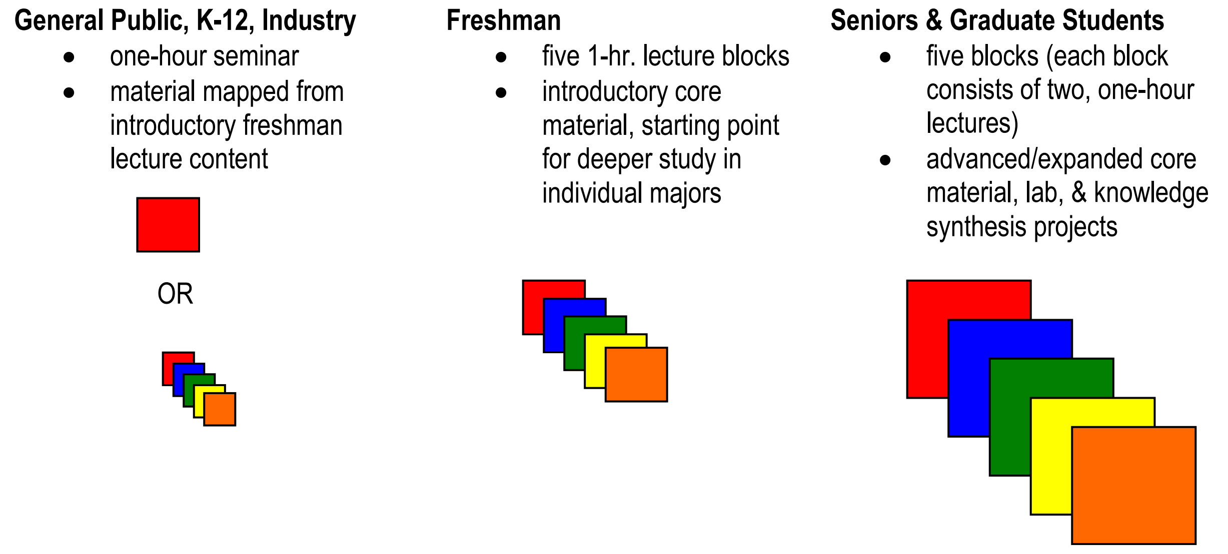

Figure 2: The five-lectures of core content are applied to three main audiences: the public, college freshman and college seniors/graduate students. The synthesis course content reinforces and builds upon material introduced to the students as freshman. While graduate students have more stringent requirements, the core content themes are consistent. Presentations to the general public can consist of either the first freshman lecture or a one-hour overview version of all five freshman blocks. See Section 3.1 for block content details.

2.1 Creation of a Nanotechnology Minor

The NSDS course described here is designed to serve as the capstone course for a newly developed nanotechnology minor program at UNR. The UNR Interdisciplinary Nanotechnology Education Program will be a cohesive and comprehensive interdisciplinary undergraduate degree minor offered to students enrolled in degree majors in engineering and the sciences. The governing philosophy of the program is that rather than producing graduates with a "major" in nanotechnology, it is more valuable to produce a workforce that is trained in the "traditional" fields of science and technology, but with an emphasis on nanotechnology, i.e., a degree minor. This minor will provide undergraduates with broad, interdisciplinary training in nanotechnology.

Objectives of the program include support of faculty for the development of courses and curricular materials that support the nanotechnology program; opportunities for undergraduate students to participate in research activities in nanotechnology; and preparation of students for future employment and/or graduate school.

2.2 Mechanical Engineering: A Logical Home for Nanotech Synthesis

The NSDS course is housed in the Mechanical Engineering department because nanotechnology design and synthesis activities are by their nature very much mechanical engineering activities. The discipline of mechanical engineering is one of the broadest traditional engineering disciplines and encompasses everything from the generation and application of heat and mechanical power, to the design, production, and use of machines, tools, and systems that integrate mechanical, electrical and even biological components. At the fundamental level, mechanical engineering is where the mechanical properties of matter are applied to the creation of structures, machines and systems.

This is not to say that other disciplines do not play a major part in nanotechnology; this could not be further from the truth. Most courses required to gain an understanding of nanotechnology are found in the biology, chemistry, physics, materials engineering, chemical engineering, and electrical engineering departments. It is the synthesis of nanoscale knowledge and the design and control of systems that fits squarely in mechanical engineering. It is these strengths that mechanical engineering can bring to the universal effort of nanotechnology education.

The way the NSDS course is set up, it should challenge both a mechanical engineering student and a biology student to apply what they know, while being reasonable for both students. Both will learn a new common set of technical information, conveyed at a common level. The wide subject spectrum of prerequisite classes taken by NSDS students prior to the course is accounted for in the course's approach. While a deeper understanding of a subject like biology can enable a student to discover more connections and applications during the discussion of organic nanotechnology, the section about microcantilever physics will not leave them behind. Material from a particular student's major will be reinforced and melded to other fields of study; material from outside their major will be comprehensible and demanding, but will not necessitate a mastery of the subject. Engineering content is conveyed at a freshman/sophomore level, making it graspable by a biology student and refreshing or new for an engineering student; meanwhile, both students broaden their perspectives. The course facilitates a team design and synthesis experience where each student must apply what they know and serve a team's resident "expert" in one field. Still, because of the broad design and system-level thinking and control, the course retains its "mechanical" distinction.

3.0 Educational Approach: The Microcantilever as the "Bridge" to Nanomechanics

Nanotechnology research and development includes controlled manipulation of nanoscale structures and their integration into larger material components, systems and architectures. This requires the ability to apply various scientific principles to system-level design and analysis. Nanomechanics is a large subset of nanotechnology and is defined as the design, fabrication, and use of structures and devices, both organic and inorganic, with motion or dimensions measured in nanometers.

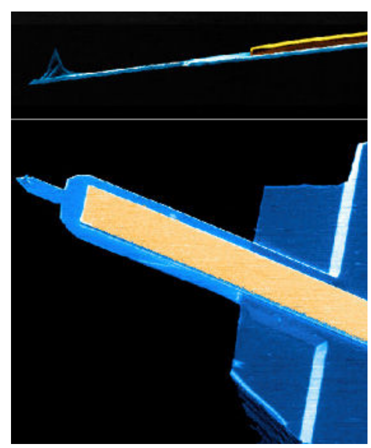

Figure 3: The Active Probe (Veeco, Inc.) is an example of a microcantilever used in micro- and nanotechnology.

As such, the specific focus of lecture content in the course is on the nanomechanics of microcantilevers since they are fabricated on the micro-scale, move and measure motion and have interactions with matter on the nanoscale, and operate as part of a controlled system. Used in scanning probe microscopy, lithography and myriad chemical and biological sensing applications, the microcantilever is a unique tool that links the two otherwise distinct topics of MEMS and nanoscience. Though not the course's sole focus, the microcantilever serves well as a tie binding the material.

An example microcantilever device is the Scanning Probe Microscope (SPM), which is fabricated with micro-technology and used in nanotechnology to investigate and manipulate matter. One such SPM cantilever is shown in Figure 3.

The SPM takes several forms; one instance, the Atomic Force Microscope (AFM), is one of the most important tools for imaging and manipulating matter at the nanoscale. As noted in the National Nanotechnology Initiative (NNI) Implementation Plan[6]: "These instruments, including scanning tunneling microscopes, atomic force microscopes, and near-field microscopes, provide the 'eyes' and 'fingers' required for nanostructure measurement and manipulation." As a critical component in the development of nanotechnology, knowledge about SPM application and operation will continue to be an important pillar on which many future findings will rest.

Another example device examined in the course is the microcantilever-based chemical and biological sensor. An advantage to employing course material relating to the SPM and microcantilever-based chemical and biological sensors is that it naturally creates multidisciplinary material in both micro- and nanotechnology systems. This focus links the material, and these real life, state-of-the-art applications enhance student interest and provide the motivation to investigate, design, build and test similar or unrelated nanotechnology systems in the project portion of the course.

3.1 Nanotechnology System Design and Synthesis (NSDS)

NSDS is a 3-credit, senior and graduate level course. It stresses the history, principles, application, and design of microtechnology and nanotechnology systems and consists of a combination of lectures and project work where students from different backgrounds can apply their knowledge to the design of a nanotechnology system. The prerequisite is "senior standing" in a student's respective major. The syllabus is as follows:

Section 1: Microtechnology

1. **History**
2. **Fabrication Processes**
   a. Fabrication Tools and Safety
   b. Surface Processes
   c. Bulk Processes
3. **Device principles and operation**
   a. Mechanical Design and Principles—cover issues of bending, vibration, thermodynamics, fluid mechanics, heat conduction, scaling laws, materials, microactuation
   b. Electrical Design and Principles—simple amplifier circuit theory and design, piezoelectric and capacitive sensing principles, semiconductor operation, electrochemistry, electrostatics
   c. Devices—applications in health care, aerospace, industrial, consumer, telecommunications, other sensors and actuators

Section 2: Microcantilever Nanomechanics

2. **Microcantilever fabrication and system design**

Section 3: Nanotechnology

1. **Big picture of the principles in a small world**
   a. Biology
   b. Chemistry
   c. Materials
   d. Quantum Physics
2. **Microcantilever Application in Dry Nanotechnology**—Inorganic Nanotechnology
3. **Microcantilever Application in Wet Nanotechnology**—Organic Nanotechnology
4. **Other Nanotechnologies**

The course is broken down into five main blocks, each block consisting of two, one-hour lectures. These lectures are given every week for five weeks. The lectures are the starting point for deeper discussions with seniors and graduate students. The rest of the course is devoted to hands-on application and reporting where students work in the lab and report on their findings.

The lectures, or blocks, are derived from the syllabus. The titles of the blocks and the sections of the syllabus from which they draw are as follows:

- **Block 1:** Introduction to Micro- and Nanotechnology (1.1, 2.1, 3.1)
- **Block 2:** Microfabrication, Device Principles and Operation (1.2, 1.3)
- **Block 3:** Microcantilever Nanomechanics (2.2)
- **Block 4:** Microcantilever Nanotechnology Applications (3.2, 3.3)
- **Block 5:** Other Nanotechnologies (3.4)

Prior versions of this course have been taught at UNR before,[7] and similar work by the authors is available elsewhere.[8,9,10] The course was especially effective in minimizing technology transfer time. For example, the students understood the basic operation and construction of one of the most advanced SPMs in the world before the initial results were published. While most work completed to date centered on developing course material and not on formal assessment, the end-of-semester student evaluations compared favorably to other courses taught by the department, as well as to other courses taught by the professor. In addition, the prototype course was well received by both the College of Engineering and the College of Arts and Science.

The NSDS course is based on the rapid technology knowledge transfer of the latest laboratory advances directly into the classroom. In addition to the value of this approach, the value of active learning has been well documented,[11] and many studies have shown that engineering students need more practice applying theoretical knowledge to practical tasks.[12] In addition educators have stated that research universities need to provide their undergraduate students with "a research experience that is genuine and meaningful." [13] However, the difficulty is to put engineering students, "as much as possible, in the shoes of the engineer," [14] when the technology is as new as the need to teach it, and there is a short supply of both engineers and engineering tools in the new technology.

To address this concern, laboratory space and equipment are available to allow a central focus of this course to be real design and synthesis projects. The project work satisfies the important aspect of hands-on training and also provides an opportunity for students from different backgrounds to apply their knowledge to the design of a real nanotechnology system. Example projects include characterization and optimization of a clean room instrument such as a plasma etcher or sputtering system, development and implementation of a growth procedure for a specific type of nanotube, modeling and testing of experimental designs of microcantilever sensors, and testing of a prototype DNA sensor. Since the class has access to research programs and staff working in nanotechnology, their projects can be selected so as to strike a balance between benefiting a specific ongoing research effort and the students' educational development.

Graduate students are expected to achieve a deeper understanding of the material presented to the combined undergraduate/graduate enrollment in NSDS and are therefore required to complete an advanced semester design project involving more laboratory work, device fabrication, analysis and a final report and presentation. They meet with the instructor for one hour each week during an extra, all-graduate student discussion.

Graduate students' homework assignments also include extra and more complex problems. They conduct additional literature surveys which are discussed in the all-graduate class session, and their projects require a greater level of work and detail. The more involved design project and weekly sections provide knowledge synthesis opportunities for the graduate students. In addition, graduate students are given more access to the professor in order to organize and carry out their design project. This access takes the form of extra graduate class time. To enhance their integration into a research setting, they are given access to members of the professor's research staff for help with their design project.

4.0 Conclusion

The course described here represents a crucial component of an overall educational strategy. Nanotechnology is unique in its diversity: that is, the sheer size of the knowledge base necessary to fully grasp the subject of nanotechnology makes teaching it difficult. By creating two tiers of similar content – one of introductory material, another of advanced concept application – it is possible to both entice and synthesize nanotechnology understanding. In the university setting, this entails teaching an introductory nanotechnology course and providing students the opportunity to explore their own fields of study before returning in their senior year to a design and synthesis course like that described in this article. It should also be noted that the blocks of material developed for these courses can be adapted and used to educate the general public, K-12 students and industry.

Acknowledgement

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Biographical Information

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