Nanoscale Education for Semiconductor Design

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Abstract: Over the last decades, nanotechnology had established itself as the upcoming revolution in science and technology. The ability of manipulating material at the atomic and molecular levels allowed nanotechnology to open an entirely new paradigm of devices and products. In the semiconductor industry several new nanodevices have been proposed to replace the classical CMOS devices that have been used over the last four decades. These new nanodevices have shown significant potential to overcome the fundamental limits of current CMOS devices. However, limited educational resources and processes are available to prepare future nanotechnology engineers and scientists to integrate these promising nanodevices into the main semiconductor manufacturing streams. This paper proposes new learning structures and processes to propagate nanotechnology learning resources over the pervasive Web. The proposed approach is illustrated by a case study centered around the manufacturing of future nanodevices. We adopt standard structures and processes to organize and navigate through digital instructional contents, such as IEEE LOM and IMS LD. In doing so, we aim at streamlining the propagation of reusable repositories across the open Web to facilitate the integration of nanotechnology learning resources into the rising social trend of massively open online courses (or MOOCs).

1 INTRODUCTION

Nanotechnology was formally defined in the 1999 NSF workshop report as “the ability to control and restructure the matter at the atomic and molecular levels in the range of approximately 1–100 nm, and exploiting the distinct properties and phenomena at that scale as compared to those associated with single atoms or molecules or bulk behavior. The aim is to create materials, devices, and systems with fundamentally new properties and functions by engineering their small structure” (Roco et al., 2000). In 2001 Uddin and Chowdhury (Uddin and Chowdhury, 2001) stated that the fundamental objective of nanotechnology is to model, simulate, design and manufacture nanostructures and nanodevices with extraordinary properties and assemble them economically into a working system with revolutionary functional capabilities.

Applications in a wide spectrum of areas ranging from nanomaterials to industry-specific applications in biotechnology, electronics and energy, are creating unique opportunities all over the World. With the latest advancement in nanolithography and optical proximity correction, the semiconductor industry was successfully able to scale the transistor size further to 20nm. This deep scaling into the nanometer range has enabled several new mobile and communication applications including wearable computers, intelligent handheld devices, healthcare implantable devices , and self-powered wireless sensor networks to mention a few. Today, there are more than 1,300 consumer products containing nanotechnology components, while the inventory of products has grown by over 500% in the last five years (Rodgers et al., 2013). Trends suggest that by 2020 there will be a 3 trillion dollar market with 6 million employees in this field (Roco, 2011).

In order to sustain this successful trend, it is essential to have sufficient workforce with an intensive and focused training in nanotechnology. Unfortunately, because of the interdisciplinary nature of the nanotechnology field (Porter and Youtie, 2009), this kind of workforce is hard to develop. A skilled nanotechnology specialist should have good understanding of several other science and engineering fields including math, material and biomedical sciences, chemistry, physics, computer and environmental sciences, among others. Currently, due to the lack of a proper nanotechnology education, nanotechnology nspecialists develop the required knowledge through training courses and on the job learning experience.

Nanotechnology is rapidly growing as a separate

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discipline by itself (McNally, 2013). However, one major challenge asscoiated with the growth of this discipline is the substantial cost required to provide laboratory experiences. These hands-on practices are essential to experience nanoscale matter (atoms and molecules), and to design nanodevices and systems. The associated cost can be reduced significantly by relying on reusable electronic simulations and Web-based repository of concept resources.

Another typical aspect in nanotechnology education, which is not well supported in existing digital instructional approaches, is the “zoom” effect, which hierarchically and gradually reveals the infinitesimal structures of nanomaterial. An alternative “assembly” effect could empower existing digital instruction to get learners exposed to both bottom-up and top-down approaches of nanostructures manufacturing. In this paper, we propose to augment existing learning technology standards for supporting the design and the development of virtual learning environments.

We adopt standard structures to organize digital instructional contents and processes, such as IEEE LOM (Atif et al., 2003) and IMS SCORM (Hsu et al., 2010). In doing so, we aim at streamlining the propagation of reusable repositories across the open Web to facilitate the integration of nanotechnology learning resources into the rising social trend of Massively Open Online Courses (or MOOCs) (Zhang, 2013).

2 BACKGROUND AND RELATED WORKS

There are several challenges facing the integration of nanotechnology into the mainstream of undergraduate engineering curriculum. First, it is important to increase the awareness of high school and the first year engineering students about how the nanotechnology will shape our future. To this extend, Jones et al. (Jones et al., 2003) investigated the feasibility of allowing students in high school classrooms to conduct nanotechnology experiments through controlling remotely scientific equipments over the Web. Students had access to the nanoManipulator tool which gave them the ability to control an atomic force microscope over the Internet. The authors believe that most students were excited about the experience and developed more accurate concepts regarding nanometer scale as well as 2D and 3D virus morphology.

Another study funded by NSF focused on increasing the nanotechnology awareness for both high school and first year engineering students (Rodgers et al., 2013)showed that student had difficulties defining nanotechnology and its scale. This study also highlighted computer graphics, visualized sizing charts, and educational videos as effective techniques for helping students understand nanotechnology. Moreover, the study showed that connecting nanotechnology to various science and engineering fields could serve as a catalyst method for introducing and increasing students’ awareness and understanding of nanotechnology scope.

To reduce the anticipated lab cost, (Sarangan et al., 2013) suggested the use of a computer based nanofab trainer. The proposed trainer would allow students to practice real-life processes and tools as opposed to normal simulators used for predicting physical phenomena. They also proposed a multimedia system to bring live interactive demonstrations from existing nanotechnology laboratories and cleanrooms to the classrooms. Molecular Workbench software is another tool proposed by Xie and Lee (Xie and Lee, 2012) for teaching nanotechnology concepts. The tool provides a virtual laboratory in which simulated nanoscale processes can be examined and manipulated on a computer screen in real time. The authors conducted a pilot study iwhich showed that simulation-based experimentations can be successfully used for undergraduate students to develop an integrated understanding of concepts in nanotechnology at their own pace.

At the same time there are some efforts to incorporate nanotechnology into the mainstream of an undergraduate engineering curriculum. Uddin and Chowdhury (Uddin and Chowdhury, 2001) proposed the content of three fundamental courses to be integrated into an undergraduate engineering curriculum and suggested that the concepts of nanotechnology should be introduced during freshman and sophomore engineering courses. They also suggested modifying the outcomes of junior and senior design courses to include the modeling, simulation, control and optimization of nanodevices and systems.

However, the common factor in the above instructional design approaches is the lack of a standard platform for Web based education to create a space for educators to share experiences and to reach a wide community of learners.

Electronic learning production is multilayered as shown in Figure 1. The core layer is the learning object, which subsumes learning items following a standard vocabulary defined by IEEE LOM specification. Each item, in turn, points to a resource in the resources layer. As illustrated in Figure 1, some resources may reference files or contents outside the packaged contents through a URL.

Learning objects metadata is a standard structure to describe educational objects. The IEEE LOM stan-

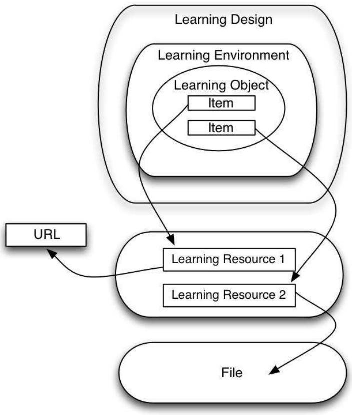

Figure 1: Learning Resource Layers.

dard specifies the vocabulary required to describe a learning object, so it can be used, re-used or referenced in technology supported learning. Learning objects typically incorporate contents to aid learners and education-providers carry out their activities. This content can be in a variety of electronic formats, including (X)HTML, RTF, PDF, or simply a URL. A learning object may be delivered within a specific environment such as a simulated laboratory application. Finally, a learning design may dictate the navigation through a sequence of learning objects. This process obeys a standard specification labeled IMS-LD (IMS Learning Design), which we will further present as part of our proposed framework later in this paper.

A learning object structure includes typical categories following an XML-based specification of LOM standard. This structure recognizes domain-specific requirements, which include a set of functional and non-functional capabilities that are deemed common to learner-assistant software agents. A LOM structure consists of the following elements which we used in our specifications: general, lifecycle, `Technical`, `Educational`, `Rights`, `Relations`. We particularly focus on extending the `Relation` attribute to mimic advocated pedagogical processes in nanoscale education.

3 LEARNING DESIGN FOR NANOSCALE EDUCATION

Current LOM metadata information need to be repurposed to explicitly represent the specification of nanoscale instructional units. This form of instructional units relies on semantic relationships between learning resources to introduce learners to nanomaterials (Manning and Monetti, 2013). Semiconductor design could involve bottom-up or top-down nanofabrication processes, using clusters of nanomaterial elements. This approach to the pyramid of education allows learners to advance through various disciplines that focus on phenomena and methods related to length scales (Roco, 2003). The objective is to provide a progressively comprehensive nanoscale education with connected and integrated knowledge to provide a holistic view, and a deductive understanding to learners.

Table 1: Relationships in Nano-Learning Objects.

Relationship	LOM element
Association	Requires
Aggregation	isBasedOn
Generalization	hasPart

Learning resources in nanoscale education, are structured as nano-learning objects, which describe structural relationships of learning content in order to support association and aggregation connections . These relationships could make use of the `Relation->Kind` element of LOM attributes, as shown in Table 1.

We define three types of relationships. The association relationship guides learners to prerequisite knowledge, whereas the aggregation relationship defines “the degree to which a digital learning resource is made up of other digital learning resources” (National Science Foundation, 2004). Finally, the generalization relationship refers to content assets or subtopics.

Collections of learning objects can be further organized and sequenced to form a learning component, which refers to a lesson or a course. Sequencing learning objects could be modeled through the use of a learning design language, such as the IMS-LD (for Learning Design), developed by IMS in 2003 (Koper et al., 2003). The conceptual structure of learning design is based on a set of concepts or building blocks that support the interaction among roles, activities and environments. In the case of the IMS-LD, each person may be assigned a role (either a learner or staff). Based on the assigned role and the specified learning goal, each person performs an activity within a specific environment. This could be for example a particular experiment in a simulated laboratory environment. The activity may involve both the learner and a remote laboratory staff. Our proposed hierarchical learning processes are based on IMS-LD standard, which sequences learning objects using the aggregation or generalization links for bottom-up or top-down learning designs. Each learning object may further be explored through association links.

Teachers and instruction designers need a specification of nanoscale education to express related learning activities. An IMS-LD compliant specification lends itself to be used by existing graphical authoring tools and engines to play the resulting specifications (Griffiths et al., 2008; McAndrew et al., 2005). To facilitate nanoscale learning developments, we propose ready-made templates that can be further refined to create finished modules (called learning units). These templates guide instructors and content providers to build structured learning contents. We call these templates Nanoscale Learning Design Patterns (NLDPs). They are analogous to Web page templates (e.g. available in Microsoft Front Page) to produce finished Web pages as content and structure are separated. Figure 2 illustrates this IMS-LD based learning design pattern for our nanoscale education model. NLDPs could be implemented using an appropriate editor. The provision of a dedicated high-level nanoscale learning editor supports teachers in the process of creating nanoscale learning units by starting from existing patterns.

The successive levels in the proposed learning design reflect the progressive bottom-up or top-down content coverage. Each levels is supported by a set of activities, which involve either learner or supervising staff. The environment entity indicates the experimental setup to carry out those activities, such as a simulated laboratory as discussed earlier in Figure 1.

4 SEMICONDUCTOR DESIGN INSTRUCTION

College students should get first-hand experience on how to fabricate various types of nanodevices and how to use them to design functional nanosystems. Therefore In additional to the classical CMOS processes, the proposed cyber-infrastructure containers should include learning objects with resources to introduce learners to carbon nano tubes (CNTs) and their unique properties such as their extraordinary strength and thermal conductivity. This learning object also includes resources to explore the electrical properties of CNTs and their usage as field effect transistors (CNTFET). Another learning object embeds motivational resources on the latest developments in semiconductor nanowires and their vast applications as logic devices, photo-detectors, biomedical sensors, thermoelectric generators, and memory devices. Subsequent (optional) learning objects could be used to introduce students to other types of nanodevices such as molecular resonant tunneling devices , single electron transistors , quantum-dot cellular automata devices, or any other future nanodevices as they become more developed and practical. These learning objects form the electronic repository of resources which is structured following the framework presented in Figure 1.

The cognitive navigational process through learning objects and their underlying instructional environments follows the methods used to fabricate the above mentioned nanodevices. These methods and hence the proposed learning path could hierarchically follow bottom-up or top-down approaches. Bottom-up methods are those where the nanodevices are gradually assembled starting from the atom and the molecular levels in an additive fashion until the desired device is built. On the other hand, the top-down methods start from a bulk substrate and use imaging and etching processes to sculpt the device.

The top-down method relies on using several photolithography phases to engrave devices on a substrate and connect them together to realize a specific circuit design. Each photolithography phase usually consists of several steps , which we put together using “`hasPart`” attribute (see Table 1) of LOM’s relation tag.

The photolithography process is very mature as it has been successfully used by the semiconductor industry since 1970s. However the resolution of the photolithography process is limited by the wavelength of the light source used in the process. Current photolithography process uses deep ultraviolet 193 nm laser and liquid immersion techniques along with optical proximity correction to achieve feature length less than 20nm. In order to use the lithography method for future nanodevices, novel processes are needed to reduce the resolution further to few nanometers. Hence, in addition to the classical photolithography, additional learning objects could include scanning, scanning probe, e-beam, soft, nanoprint, nanosphere, and colloidal lithography techniques.

As a result of the massive government and industry investments in nanofabrication research, several bottom-up fabrication processes have matured over the last decade. This suggests an alternative navigation approach of learning objects with relation tag value set to “`isBasedOn`” to aggregate composing learning objects together. These processes and hence the induced instructional navigation can be divided into chemical synthesis and self-assembly ones. Self-assembly processes aggregate learning objects about molecular self-assembly and DNA-scaffolding processes. The chemical synthesis processes, on the other hand, aggregate learning objects on gas-phase and liquid-phase resources to manufacture nanoparticles. The gas-phase subgroup may further aggregate learning objects that illustrate the details of

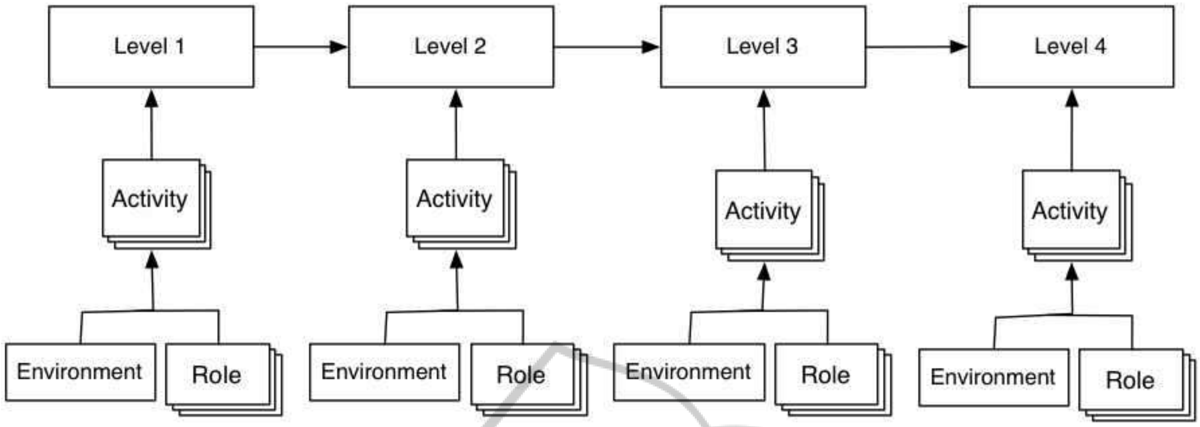

Figure 2: Nanoscale Learning Design.

atomic layer deposition , physical vapor deposition , and chemical vapor deposition processes. Similarly, Sol–gel , and liquid-phase epitaxy learning objects could be included under the liquid-phase subgroup.

It is obvious that the proposed learning objects mentioned above are highly interdisciplinary. The educational material covers a wide range of topics including engineering, chemistry, physics, material science, and biology in case of molecular self-assembly and DNA-scaffolding. Having these learning objects correlated in a bottom-up and top-down approaches following the navigational structure shown in Figure 2 organizes the contributions from instructors and scientists across multiple disciplines. The open Web design structure offers also interaction opportunities and best practice sharing of instructional scenarios among instructors Worldwide. Figure 3 shows the hierarchy of nanofabrication learning objects and their navigational sequence across the proposed cyber-infrastructure design container discussed earlier in Section 3.

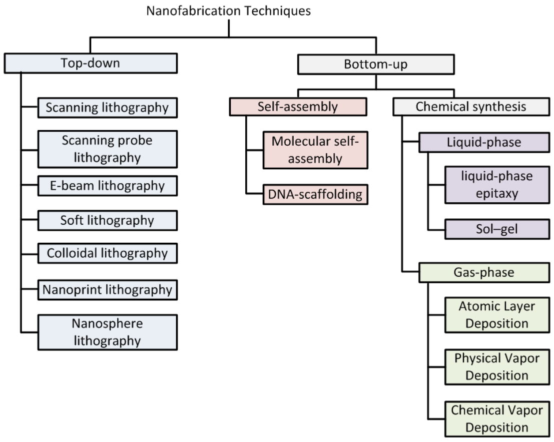

Figure 3: Nanofabrication unites proposed for inclusion in the cyber-infrastructure containers.

In addition to the top-down and bottom-up processes, there are also few other processes such as block copolymer lithography (Bates et al., 2013)that combines the bottom-up self-assembly process with top-down lithographic one, which calls for further customization of the learning design structure shown in Figure 2.

5 CONCLUSION

In view of the current shortage in nanotechnology educational resources, we proposed standard Web-based structures and processes for instructors to share educational material and for learners to personalize their learning experience in nanotechnology. The novel learning structure extends the current LOM metadata to explicitly represent the specifications of nanoscale instructional units based on expanding the standard `Relation` tag of LOM standard with three attributes: `Requires`, `isBasedOn` and `hasPart`. Following this design structure, we also adopted standard learning processes based on IMS-LD information model, that we specifically tailored to accommodate the processes of navigating through nanotechnology instructional material. To illustrate our approaches, we proposed a semiconductor design case study which we mapped on the proposed learning structure and processes to assist instructors sharing and reusing learning resources via the pervasive Web. The aim is to facilitate the integration of nanotechnology learning resources into the rising social trend of massively open online courses (or MOOCs) to benefit a larger community of learners and thus advancing the future of nanoscale developments.

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