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Fostering analogical reasoning and design skills through creating bio-inspired robotic models

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Abstract

This paper proposes an approach in which students are engaged in scientific inquiry of biological systems, and in construction of robotic models of these systems. Analogical reasoning is used as a thread of the proposed approach, tying together learning by scientific inquiry and learning by technological design. The research questions posed in our educational study address: pedagogical characteristics of the proposed approach, patterns of students' analogical reasoning, and students' attitudes towards the learning experience. We developed a learning environment and a curriculum and conducted courses to 118 middle school students involved in outreach activities and to 41 prospective teachers of science and technology. Dozens of robotic models were designed and constructed by our students in this framework. The models featured topics such as plant, animal, and human behaviors. Findings of our study highlight the potential of using robotic models in science-technology education. They show that the exploration of analogies can furnish a synergetic combination of learning-by-inquiry and learning-by-design and foster development of analogical thinking skills.

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1. Introduction

Science-technology education explores possible ways to create an integrated science-technology curriculum [1, 2]. To achieve that, Lewis [1] proposes to study engineering design and scientific inquiry at school in ways that utilize their complementarity and conceptual proximity. One way is to employ design as a vehicle for teaching scientific content, and the other is to harness science as the driving force for prompting design. Lewis suggests design as a bridge between science and technology education towards achieving scientific and technological literacy. He calls to achieve this goal by new interdisciplinary pedagogies "that are integrative in approach, showing fluidity between engineering and science".

Kolodner [3] proposes to integrate the studies of science and technology in middle schools by aligning between learning-by-design and learning-by-inquiry. She analyzes learning-by-design processes, in which the learners, triggered by an explicit design challenge, “mess about,” generate ideas, identify what they need to inquire, collect data, and gradually construct artifacts. Kolodner presents a learning model that combines design and inquiry activities organized in two connected cycles: the "Design\Redesign" cycle answers the "need to do" while the "Investigate & Explore" cycle answers the "need to know". In this context, design of technological artifacts is motivated by the need to understand scientific concepts.

When acting towards integrative teaching of natural science and technology through binding design and inquiry, we need to take into account the different nature of the two domains. Science focuses on natural phenomena, while technology deals with man-made creation [4]. International Technology Education Association [5] defines the relationship between science and technology from the perspective of symbiotic interdependence: "Science is dependent upon technology to develop, test, experiment, verify, and apply many of its natural laws, theories, and principles. Likewise, technology is dependent upon science for its understanding of how the natural world is structured and how it functions".

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From another perspective, one can notice that both science and technology implement solutions borrowed from one another [6]. From one direction, technological artifacts are designed to mimic or even improve solutions existing in nature. Robot design for example, is greatly influenced by the attempt to imitate appearance, functionality and behaviors of nature-made creatures and, in particular, the human being locomotion and intelligence. In the opposite direction, science is trying to understand and explain natural phenomena by exploring existing, or specially developed technological systems. Neuroscience, for example, uses principles of "information processing theory", which explains mental functions by exploring computer operation [7]. This science-technology relationship is explicitly based on analogies between natural and technological systems. Researchers note that exploring such analogies not only facilitates the development of science and technology, but can also make a strong contribution to education [8].

This paper proposes a model of integrative teaching of science and technology through practice which involves the learner in investigation and exploration of a biological system along with the design and construction of its robotic model. Technology educators consider integrative teaching as a way to consolidate knowledge of concepts from different disciplines through applied learning experiences [9]. Following this view, our approach aims to set a common ground for studying reactive behaviors, i.e. behaviors manifesting responses of biological and robotic systems to external events.

2. Learning with robotic models

The idea of learning with digital manipulatives was introduced by Resnick et al. [10]. Accordingly, manipulative materials with embedded capabilities for sensing, computing and communicating open opportunities for creative design and construction of technological systems and foster systems thinking.

A key feature of a digital manipulative is that it can be programmed to demonstrate a reactive behavior. Learner's inspiration to develop a digital manipulative and program its behavior usually comes from the desire to reflect on a phenomenon and imitate its characteristic behaviors. We consider such a digital manipulative to be in essence a robotic model which is both a technological system and a representation of a phenomenon. Learning with a robotic model can occur in two domains: one in which the model is designed, built, operated and evaluated as a technological system, and the other, in which the model is understood and assessed as a representation of a phenomenon [11]

International Technology Education Association [12] considers a model as "a replica of an object in three-dimensional form", created to answer a certain need. From this perspective we designate the robotic model to satisfy the need for a tangible representation by which concepts and processes related to the biological system can be learned, tested and communicated. As such, the robotic model design is directed not only towards technological efficiency. It also represents the designer's perception of the source – a personal expression which is typical for artistic design [12].

To understand the connection of biological inquiry and technological design, there is a need to clarify the meaning and function of the inquiry and design practices in our context. According to National Research Council [13], scientific inquiry is a multifaceted activity that involves, among other things, "making observations; posing questions; examining books and other sources of information to see what is already known". In the context of modeling a biological system, the function of observations, questioning, and information search is to identify and understand the features of the system that are relevant to the model design.

The design practice is defined [12] as a process that includes the following steps: identifying the need, generating ideas, exploring possible solutions, building and testing prototypes, and refining the solution. The robotic model design answers the need for a tangible representation, by which the features of the biological system can be learned, tested and communicated. Therefore, the ideas, solutions and prototypes developed throughout the design steps are verified by matching them with the features of the biological system, revealed by the inquiry.

Based on the discussed view, we developed the course "Control in Technological and Biological Systems" and delivered it to prospective teachers of science and technology, high school and middle school students. The course consisted of 14 weekly meetings of two hours each, and dealt with the following topics:

- Introduction to robotics (2 hours).
- Basics of construction and programming using the PicoCricket kit (4 hours).
- Sensors and control (4 hours).
- DC motors and mechanical transmissions (4 hours).
- Inquiry into a biological system (4 hours).
- Creation of a robotic model (8 hours).
- Presentation and evaluation of the robotic model (2 hours).

3. Robotic modeling projects

The projects were performed using the PicoCricket kit recommended "to combine art and technology, enabling young people to create artistic creations involving not only motion, but also light, sound, and music" [14]. The kit consists of a programmable microcontroller that can operate different actuators and manage input from light, sound, touch and resistance sensors. The microcontroller provides IR communication with a host computer or other PicoCrickets. In addition, data management capabilities are offered, with an opportunity to sample data from the sensors, implement reactive behaviors, and upload the data to a computer for graphical representation. The PicoCricket "specialties", such as preprogrammed animal voices, colorful lights, and craft materials, are useful for building robotic models of animals and other biological systems.

Dozens of robotic models were developed by our students in the framework of teacher training and outreach courses. The models featured topics such as: plant tropism, animal and human behavior, control in biological systems and