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RESEARCH ARTICLE

Reasoning about interruption of biological processes

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Abstract
Humans are able to apply abstract reasoning patterns to learned knowledge and principles, and infer correct results. Our work is motivated by the vision of automated asking and answering of questions related to a biology textbook—a capability which requires application of abstract reasoning patterns. For example, biological processes such as cellular respiration have an intricate structure that defines the ordering among different steps and the participants in each step. A person who understands the process is expected to be able to reason with how the process is affected if one or more steps are interrupted. In this article we analyze a family of questions about process interruption, and present reasoning patterns that an automated reasoning system can use to answer them. Our reasoning patterns rely on the order of steps of the process and the participants of those steps. We suggest that this approach leads to more intuitive and simpler reasoning than an approach of based on theory of intentions, or an approach that relies on qualitative simulation. Our work is a step toward a system that can discuss answers to questions and assist human learners of biology.

Introduction

Learning a scientific discipline such as biology is a challenge to many people. In a typical advanced high school or introductory university-level biology course, a student is expected to learn about 5000 new concepts and several hundred thousand new relationships among them (Chaudhri et al., 2013). Science textbooks are difficult to digest and yet there are few alternative resources for students. Our work is motivated by the vision of automated answering of biology questions, as embodied in a system called *AURA* for representing knowledge in a textbook (Gunning et al., 2010). Our work is a step toward a

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system that can discuss questions and assist human learners of biology.

Humans are able to apply abstract reasoning patterns to learned knowledge and principles, and infer correct results. Biological processes such as cellular respiration and fermentation feature an intricate structure of steps and sub-steps, and intimate connections with related processes within the larger biological setting. A person who understands a biological process—for example, having digested the contents of a textbook—is expected to reason with how the process is affected if one or more steps are interrupted. Indeed, this reasoning can be seen as a form of story understanding, which Winston argues is central to a computational account of human intelligence (Winston, 2012). The challenge for AURA, however, is not so much to develop a cognitive approach that emulates such human reasoning in this regard, but to develop a system capable of automated reasoning over biology textbook questions. This article addresses a form of explanatory reasoning (Hiatt, Khemlani, & Trafton, 2012) concerning one type of human-level inference in this domain: interruption of biological processes.

As concrete examples, recall high school biology (Reece et al., 2013) and consider the following questions:

1. In the absence of oxygen, yeast cells can obtain energy by which process?
2. What happens if rubisco production is blocked in plant cells?
3. The rate of reaction of the electron transport chain that functions in oxidative phosphorylation can be reduced by removing what substance?

We characterize the above questions as examples of *process interruption* questions because they ask about the behavior of the process if we introduce some form of interruption: remove normally available raw material to the process, stop some related process, or wish to change the behavior of the process.

To answer the first question, we would need to know what part of cellular respiration in a yeast cell could continue and produce energy without oxygen—or what alternative processes in a cell could produce energy without oxygen. To answer the second question, we would need to know what processes use as raw material the output from rubisco production which they could not obtain from elsewhere. To answer the third question, we would need to know removal of what substance would slow down the reaction of the electron transport chain reaction.

We argue that answering the above family of process interruption questions can be done by *process description analysis*: that is, reasoning among the ordering of the steps and the entities that participate in those steps. This process description corresponds to a flow chart that describes a process. We give examples of such reasoning for the above three sample questions, and from there, induce an abstract algorithmic approach that could be applied to a variety of process interruption reasoning questions. We evaluate our approach on a suite of over 100 process interruption reasoning questions to illustrate that the approach is general, tractable, and scales beyond the above three examples.

The article is structured as follows. Section 'Representation of process structure' describes how processes are modeled in the AURA knowledge base. Section 'Examples of process interruption reasoning' gives examples of process interruption reasoning. Section 'A generic template for reasoning' provides a computational approach to such reasoning. Section 'Question formulation in the AURA system' describes how process interruption questions are interpreted by AURA such that reasoning can be applied. Section 'Comparison with related work' contrasts our approach with two proposed alternatives, and finally, Section 'Conclusion' concludes the paper.

Representation of process structure

Our work is in the context of the AURA system for representing knowledge in textbook and answering questions by deductive reasoning (Chaudhri et al., 2013; Gunning et al., 2010). The AURA knowledge base (Chaudhri, Clark, Overholtzer, & Spaulding, 2014, Chaudhri, Elenius, Hinojoza, & Wessel, 2014) consists of a set of hierarchically organized classes and relations. The key relations that are of interest for representing process structure are as follows:

A subevent B	B is a step of process A
A first-event B	B is the first step of process A
A next-event B	Process B follows process A
A raw-material B	Process A uses B as input
A result B	Process A produces B as result
A has-function B	Process B is a function of entity A
A agent B	Entity B is the agent of process A
A site B	Entity B is location of process A

In addition to the relations listed above, we support the standard relations from qualitative process theory: positive influence, negative influence, directly proportional and inversely proportional (Forbus, 1984).

As a concrete example, we show in Fig. 1 a portion of the representation of Glycolysis in the AURA knowledge base (KB), and give below its representation in first order logic.