1.anonymize authors

2.CCSXML

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A Domain Analysis of Data Structure and Algorithm Explanations in the Wild

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ABSTRACT

Explanations of data structures and algorithms are complex interactions of several notations, including natural language, mathematics, pseudocode, and diagrams. Currently, such explanations are created ad hoc using a variety of tools, and the resulting artifacts are static, reducing explanatory value. We envision a domain-specific language for developing rich, interactive explanations of data structures and algorithms. In this paper, we analyze this domain to sketch requirements for our language. We perform a grounded theory analysis, to generate a qualitative coding system for explanation artifacts collected online. We show that grounded theory provides a robust methodology for analyzing qualitative objects and that the resultant coding system forms the skeleton of a domain-specific language. This work is part of our effort to develop the paradigm of explanation-oriented programming, which shifts the focus of programming from computing results to producing rich explanations of how those results were computed. **4.I want to say something here about using formal qualitative methods to expand the reach of computer science 5.do we mention explanation trees in the abstract and pre-order traversals?**

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability;

KEYWORDS

ACM proceedings, LaTeX, text tagging

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1 INTRODUCTION

Data structures and algorithms are at the heart of computer science and must be explained to each new generation of students. A pressing question is: How can we do this effectively?

In this paper, we focus on the *artifacts* that constitute or support explanations of data structures and algorithms (hereafter just "algorithms"), which can be shared and reused. For verbal explanations, such as a lecture, the supporting artifact might be the associated slides. For written explanations, the artifact is the explanation as a whole, including the text and any supporting figures. Explanation artifacts associated with algorithms are interesting because they typically present a complex interaction among many different notations, including natural language, mathematics, pseudocode, executable code, various kinds of diagrams, animations, and more.

Currently, explanation artifacts for algorithms are created ad hoc using a variety of tools and techniques, and the resulting explanations tend to be static, reducing their explanatory value. Although there has been a substantial amount of work on algorithm visualization [7–11, 14], and tools exist for creating these kinds of supporting artifacts, there is no good solution for creating integrated, multi-notational explanations as a whole. Similarly, although some algorithm visualization tools provide a means for the student to tweak the parameters or inputs to an algorithm to generate new visualizations, they do not support creating cohesive interactive explanations that correspondingly modify the surrounding explanation or that allow the student to respond to or query the explanation in other ways. To fill this gap, we envision a *domain-specific language* (DSL) that supports the creation of rich, interactive, multi-notational artifacts for explaining algorithms. The development of this DSL is part of a larger effort to explore the new paradigm of *explanation-oriented programming*, briefly described in Section 2.1.

The intended users of the envisioned DSL are CS educators who want to create *interactive artifacts* to support the explanation of algorithms. These users are experts on the corresponding algorithms, and also trained and skilled programmers. The produced explanation artifacts might supplement a lecture or be posted to a web page as a self-contained (textual and graphical) explanation. The DSL should support pedagogical methods directly through built-in abstractions and language constructs. It should also support a variety of forms of student interaction. For example, teachers should be able to define equivalence relations enabling users to automatically generate variant explanations [6], to build in specific responses to anticipated questions, and to provide explanations at multiple levels of abstraction.

This paper represents a formative step toward this vision. We conduct a *qualitative analysis* of our domain in order to determine the form and content of the explanation artifacts that educators are already creating. We base our analysis on an established qualitative research method called *grounded theory* in order to better understand how well existing artifacts explain complex topics

More specifically, we collect 15 explanation artifacts from the internet, consisting of only lecture notes that explain two algorithms and one data structure commonly covered in undergraduate computer science courses: Dijkstra's shortest path algorithm [12,

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pp. 137–142], merge sort [12, 210–214], and AVL trees [13, pp. 458–475]. We analyze these artifacts through the application of grounded theory, 6.cite Strauss and Corbin on first grounded theory paper a formal method for analyzing qualitative data that originated in sociological research. Through the application of grounded theory, we develop a coding system that captures the structure of explanation for each document. An overview of the coding system is given in Section7.create grounded theory overview section.

This paper makes the following contributions:

C1. We provide a case study on analyzing *qualitative data* through the application of a formal research method *grounded theory*, that is not part of the computer science parlance.
C2. We provide a coded qualitative data set of explanation artifacts, using the system defined in C3 applied to our sample of 15 collected explanation artifacts (Section **??**).
C3. 8.decide if we need to split this contribution up We provide a coding system for analyzing *explanation artifacts* in the form of lecture notes, and we show that through the application of the coding system, each such artifact forms a tree structure, which we have termed a *explanation tree*.
C4. We describe how a coding system grounded in data can directly provide a semantics basis for a DSL and argue for the advantages of such an approach (Section **??**).

2 BACKGROUND

In this section, we put the present work into context by the describing the paradigm of *explanation-oriented programming* in Section 2.1, the exploration of which is an underlying motivation of our work, and by introducing the methodology of grounded theory [15] in Section **??**, which is the theoretical foundation of our coding system.

2.1 Explanation-oriented programming

Explanation-oriented programming (XOP) is a new programming paradigm where the primary output of a program is not a set of computed values, but an *explanation of how* those values were computed [3–6, 16]. A high-level goal of this work is to further develop the paradigm of XOP through the development of a specific DSL.

Programming languages for XOP should not merely produce explanations as a byproduct, but should provide abstractions and features specific to the creation of interactive explanation artifacts. For example, they should provide facilities for creating application-specific notations and visualizations (which are widespread in explanations of algorithms), and for describing alternative explanations produced in response to user input, for example, at different levels of abstraction, by parameterization, or generated by explanation equivalence laws [6]. Additionally, languages for XOP should help guide the programmer toward the creation of *good* explanations.

The need for interactive explanation artifacts is motivated by the observation that there is a trade-off between personal explanations and traditional explanation artifacts, which can be partially bridged by XOP programs viewed as rich, interactive explanation artifacts. A good *personal explanation* is useful because the explainer can *respond* to the student, adjusting the pace and strategy as necessary. For example, the teacher can answer questions, rephrase parts of an explanation, and provide additional examples as needed. Unfortunately, good personal explanations are a scarce resource. First, there are limited number of people who can provide high quality personal explanations on a topic. Second, a personal explanation is usually ephemeral and so cannot be directly shared or reused. Since personal explanations are hard to come by, many students learn from *impersonal explanation artifacts*, such as recorded lectures, textbooks and online written nd graphical resources. These impersonal explanations lack the interaction and adaptability of personal explanations, but have the advantage of being easy to massively share and reuse via libraries and the internet.

In-person lectures, such as those covering algorithms in most undergraduate computer science programs, exist at a midway point between impersonal and personal explanations, perhaps closer to the personal end of the spectrum. These *classroom explanations* are adaptable—students can ask questions in class, the teacher can respond, and explanations can be adapted on the fly if students are confused—but they are not as adaptable as personal explanations since the teacher must accommodate many students at once. Classroom explanations are more efficient than personal explanations since they are shared amongst many students, but not as efficient as impersonal explanations since they are still ephemeral and therefore difficult to reuse.

We target another midway point, a bit closer to the impersonal end of the spectrum, of *interactive explanation artifacts* that provide as much of the responsiveness and adaptability of personal explanations as possible, but which can still be massively shared and reused online. Such an explanation artifact would be quite expensive to produce with current tools since an *explanation designer* must not only construct a high quality initial explanation and corresponding visualizations, but also anticipate and explicitly program in responses to queries by the student. We expected that DSLs for XOP can help alleviate this burden.

2.2 Grounded Theory

In this section we present an overview of the research method known as grounded theory. This section is meant to help orient the reader to understand the process by which the coding system was formed, in addition to providing a summary of a qualitative research method that has seen little use inside computer science.

2.2.1 Main Idea. Grounded theory was discovered by sociology researchers, Glaser and Strauss in the late sixties. Its central idea is to generate, or discover theory, inductively, *based on data* rather than to use data to evince a hypothesis of a theory. Grounded theory is rooted in a *pragmatist* view of theory i.e. that theory should be purposed and suited towards its intended uses vis-a-viz logico-deductive theories which are concerned with what can be expressed by the theory [15]. As Glaser and Strauss state: 9.fix this quotation

"A grounded theory is one that is inductively derived from the study of the phenomena it represents".

2.2.2 How to do grounded theory. Like any methodology, grounded theory employs a specific vocabulary to refer to stages and practices

of research. This section will introduce grounded theory terminology in concert with an operational example that will show how one may actually perform a grounded theory analysis.

Imagine a researcher who is attempting to find out why factory workers are leaving within a year of being hired from a given manufacturing center. The first task for a grounded theorist would be to collect data from the subject they wish to study. In our example this data would most likely be in the form of interviews with the people who work there, their work schedule, perhaps an organization chart. Once some data has been collected the researching will enter a phase called *coding*, coding is the act of taking some qualitative data e.g lecture notes, an interview, personal letters and assigning tags that describes the data.

The act of coding consists of three stages[1]: First, a researcher performs what is known as *open coding*. In open coding, one writes down *any* term or terms that describes the data. This first set of tags is often varied, numerous, and will typically consist of many concepts that are expressed in duplicate, or related tags. In our operational example these tags could be things such as the names of a worker's position, nicknames that people call one another, things about an interviewees life or family. Open coding should make use of *in vivo* terms, these are terms that people in the culture use. For example, a computer scientist may discuss the" "recurrence relation", while a factory worker may use the term" "floor boss" to mean the floor manager.

The second stage of coding is called *Axial Coding*, in axial coding the researcher tries to identify the relationships between the tags that were developed in open coding. The goal of this step is to develop a *coding paradigm*, which is a theoretical model that visually displays the inter-relationship between codes [2]. These codes should provide some answer to the question "What are the connections between codes?". An axial code for our operational example may coalesce sets of open codes to several axial codes. For example, if one had the open codes "tired, exhausted, not enough time with family, called in on days off", these might inform the axial code "burn out".

Selective Coding is the last and final stage of coding, in this stage the researcher tries to identify one or two central tags that forms the basis for their theory. After identifying these core tags the researcher then seeks to relate the core tags to the remaining tags. In our operational example, we might have the axial codes "burn out, little vacation time, worried about retirement, and struggling to make ends meet" and conclude that the selective code would be "poor benefits".

Grounded theory and coding proceed in parallel to data collection and analysis. That is to say that the research in our example will be simultaneously collecting data, coding, forming their theory from the data, and moving back and forth between each activity. This is a marked departure from quantitative methods which seek to restrict access to the data and analysis of the data, until all of it has been collected[1].

Through the use of coding, the researcher interacts with their data. But how does that researcher know when to stop coding? Or how much data to code? Such questions are the motivation for three central tenets in grounded theory.

The first tenet is called *Constant Comparison*, constant comparison is a technique in which researchers compare tags that they are currently applying to previous uses of that tag. The central idea is that during coding, the researcher must think back and ask themselves if they are being consistent. Researchers should perform this check at every stage of coding, it is pivotal to the validity of the method[15].

The second tenet is the concept of *theoretical sampling*, theoretical sampling, as opposed to representative sampling, focuses on filling in the perceived gaps in data based on the current theory. To put this into context, if the researcher in our example were a quantitative researcher they would determine the total population at the plant, and then use statistics to generate a representative data set. The grounded theory researcher, would look at their data and determine that they do not have any interviews from the night shift, thus they will go and collect more data to fill the gap *based on their current results*.

The last tenet describes how to reach an end point in coding; grounded theorists call it *Saturation*. Saturation occurs when new data is added to the researcher's data set and no new tags or modifications to the coding system are required. This represents a point in the research when the researcher's system is able to express data that was *not* used to generate it. The requisite number of data to reach this point may vary drastically based on factors such as researcher, topic, and motivating research questions. For this study, we reached saturation at 11 documents.

In this study, grounded theory was employed to generate a *coding paradigm* about explanation artifacts. Our resultant theory is that explanation artifacts correspond to a pre-order traversal of a *explanation tree*. Such trees, expressed in the coding system, distill the essence of a given explanation artifact. **10.Eric's thoughts on flowery language**

2.3 Experimental Setup

In this section we describe how the data was collected, any preprocessing the data may have undergone, and the system used to apply tags to the data.

We restrict the scope of data collection to include only objects that provide an explanation of common computer science algorithms from computer science departments at accredited universities. Restricting the scope of objects in this manner provides two benefits: 1) All explanatory objects have a stated, intrinsic goal to communicate the mechanics, application, or implementation of some common computer science algorithm. 2) There are bountiful and varied examples of different approaches to explain *the same* algorithm, and numerous examples of *like* approaches to explain different algorithms. All data collected was either in pdf file format, or an html file that was converted to pdf using libreoffice **11.references references references**. No powerpoint lecture notes were considered because we feared that such documents would be information scarce i.e. powerpoints are used to structure a lecture and thus should be considered with the concomitant lecture.

All data was coded by hand with the aid of Atlast.ti software **12.reference for software here** by a single researcher. The use of the Atlast.ti software was primarily for organizational and representational benefit, such as generating the code list, and performing constant comparison. This analysis, and any other grounded theory analysis, could be performed without such an aid. If a document

drifted substantially into a different algorithm then that section was not considered. For example, if a document explaining Dijkstra's algorithm, discussed shortest-path problems, then this was considered as it is directly relevant to Dijkstra's algorithm, but if that document included a section on Bellman-Ford's algorithm, then this section was not considered.

Explanatory objects were indexed according to the algorithm that was to be explained, and a simple counter. For example, the first document regarding AVL Trees would be named "AVT001" while the sixth would be "AVT006" and so on. All of the data in this paper was collected and analyzed by a single researcher.

We made no attempt to restrict the size of the data collected, in order to collect a diverse set of data. The smallest document collected had only a page and a half of relevant material while the longest consist of eighteen pages. All data can be found the projects github repository **13.move stuff to github**.

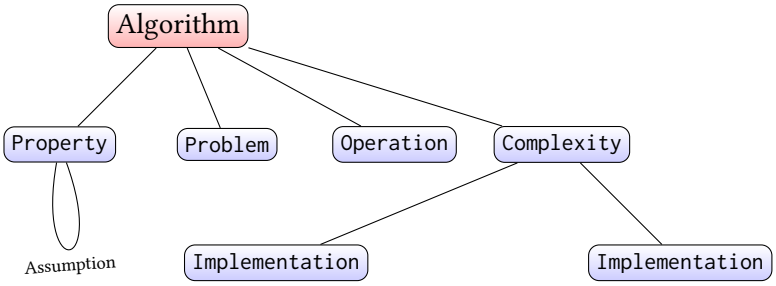
3 RESULTS

3.1 The Coding System

3.2 Explanation Trees

4 DISCUSSION OF RESULTS

In this section we summarize and interpret the results presented above. To ensure transparency and openness, the reader may find all raw data, and any post-processing scripts published online https://github.com/lambda-land/XOPTypology_Paper



14.Fix this caption, and figure, this was just proof of concept

Figure 1: Explanation Tree for Dijkstra's 009

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