A Three-layered Conceptual Framework of Data Mining

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Summary. The study of the foundations of data mining may be viewed as a scientific inquiry into the nature of data mining and the scope of data mining methods. There is not enough attention paid to the study of the nature of data mining, or its philosophical foundations. It is evident that conceptual studies of data mining as a scientific fields, instead of a collection of isolated algorithms, are needed for the further development of the field. A three-layered conceptual framework is thus proposed, consisting of the philosophy layer, the technique layer and the application layer. Each layer focuses on different types of fundamental questions regarding data mining, and jointly they form a complete characterization of the field. To complement the extensive technique layer and application layer studies, we discuss in detail the main issues of the philosophy layer study.

1 Introduction

With the development and success of data mining, many researchers became interested in a fundamental issue, namely, the foundations of data mining [1, 7, 8, 22]. Although three dedicated international workshops have been held [7, 8, 9], there still do not exist well-accepted and non-controversial answers to many basic questions, such as what is the foundations of data mining? What is the scope of the foundations of data mining? What are the differences, if any, between existing research and research on the foundations of data mining? The study of the foundations of data mining may be started by answering these questions.

The study of the foundations of data mining should be viewed as a scientific inquiry into the *nature* of data mining and the scope of data mining *methods*. This simple view separates two important issues. The study of the nature of data mining concerns the philosophical, theoretical, and mathematical foundations of data mining as a subject of study; while the study of data mining methods concerns its technological foundations by focusing on the algorithms and tools. A review of the existing studies show that not enough attention has been paid to the study of the nature of data mining, more specifically, to the philosophical foundations of data mining [22].

The following quote from Salthe [16] about studies of ecosystem is equally applicable to the studies of data mining:

> "The question typically is not what is an ecosystem, but how do we measure certain relationships between populations, how do some variables correlate with other variables, and how can we use this knowledge to extend our domain. The question is not what is mitochondrion, but what processes tend to be restricted to certain region of a cell."[page 3]

In the context of data mining, one is more interested in the algorithms for finding "knowledge", but not what is knowledge and what is the knowledge structure. One is more interested in a more implementation oriented view or framework of data mining, rather than a conceptual framework for the understanding of the nature of data mining.

There are many reasons accounting for such unbalanced research efforts. The problems of data mining are first raised by very practical needs for finding useful knowledge. One is inevitably focused on detailed algorithms and tools, without carefully considering the problem itself. A workable program or software is more easily acceptable by, and at the same time is more concrete and more easily achievable by, many computer scientists than an in-depth understanding of the problem itself. Furthermore, the fundamental questions regarding the nature of the field, the inherent structure of the field and its related fields, are normally not asked at its formation stage. This is especially true when the studies produce useful results.

The study of the foundations of data mining therefore needs to adjust the current unbalanced research efforts. We need to focus more on the understanding of the nature of data mining as field instead of a collection of algorithms. We need to define precisely the basic notions, concepts, principles, and their interaction in an integrated whole. Results from the studies of cognitive science and education are relevant to such a purpose. Posner suggested that, according to the cognitive science approach, to learn a new field is to build appropriate cognitive structures and to learn to perform computations that will transform what is known into what is not yet known [14]. Reif and Heller showed that knowledge structure of a domain is very relevant to problem solving[15]. In particular, knowledge about a domain, such as mechanics, specifies descriptive concepts and relations described at various levels of abstraction, is organized hierarchically, and is accompanied by explicit guidelines specify when and how knowledge is to be applied [15]. The knowledge hierarchy is used by Simpson for the study of the foundations of mathematics [18]. It follows that the study of the foundations of data mining should focus on the basic concepts and knowledge of data mining, as well as their inherent connections, at multi-level of abstractions. Without such an understanding of data mining, one may fail to make further progress.

In order to study the foundations of data mining, we need to move beyond the existing studies. More specifically, we need to introduce a conceptual framework, to be complementary to the existing implementation and process oriented views. The main objective this paper is therefore to introduce such a framework.

The rest of the paper is organized as follows. In Section 2, we re-examine the existing studies of data mining. Based on the examination, we can observe several problems and see that needs for the study of the foundations of data mining. More specifically, there is a need for a frawework within which to study the basic concepts and principles of data mining, and the conceptual structures and chararacterization of data mining. For this purpose, in Section 3, a three-layered conceptual framework of data mining is proposed, consisting of the philosophy layer, the technique layer, and the application layer. The relationships among the three layers are discussed. The mains issues of the philosophy layer are discussed in Section 4.

2 Overview of the existing data mining studies and the problems

Data mining, as a relatively new branch of computer science, has received much attention. It is motivated by our desire of obtaining knowledge from huge datasets. Many data mining methods, based on the extensions, combinations, and adaptation of machine learning algorithms, statistical methods, relational database concepts, and other data analysis techniques, have been proposed and studied for knowledge extraction and abstraction.

2.1 Existing data mining studies

The vast existing studies of data mining can be classify roughly into three views.

The function-oriented view

The function-oriented view can be described by a well-accepted definition of data mining, which defines it as *"the non-trivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns from data"* [2]. A pattern is an expression in a language that describes data, and has a representation simpler than the data. The functionalities of the discovered patterns are emphasized in this definition. The function-oriented approaches put forth efforts on searching, mining and utilizing the functionalities of different patterns embedded in various databases. For example, frequent itemsets, association rules and correlations, as well as clusters of the data points, are common classes of patterns. They are extensively studied in data mining domain regards to their descriptive, predictive functionalities.

The theory-oriented view

The theory-oriented approaches fix the attention on the theoretical aspects of data mining, and also the related disciplines. Many models and processes of data mining are critically investigated and examined from the theory-oriented point of view [2, 11, 21, 25]. In the mean time, the study of data mining is not in the vacuum, it has many relationships with the other existing studies. It should ingest and has ingested nutritious from the context, as general as scientific research methodologies, and as specific as the concepts and theories of statistics, machine learning, databases, pattern recognition, and pattern visualization. For example, some efforts have been made to bring the rough sets and fuzzy logic, utility and measurement theory, concept lattice and knowledge structure, and the other mathematical and logical models into the data mining models.

The procedure/process-oriented view

From the procedure-oriented view, the prime advantage of data mining is its computer-aid techniques, which can make the "non-trivial" processes of mining become effective and efficient. Extensive studies in the field have been focused on algorithms and methodologies for mining different types of knowledge, speeding up existing algorithms, and evaluation of discovered knowledge [2]. The objective of procedure-oriented approaches is same as the one of function-oriented approaches, though, the function-oriented approaches dedicate to the discovery of patterns in various knowledge systems with attractive and useful functionalities, and the procedure-oriented approaches work on the technique development and innovation, which may boost the discovery process and produce new types of knowledge.

2.2 Problems and potential solutions

Unbalanced with the maturity of data mining algorithms and techniques, the foundations of data mining is still questionable. A foundation is the basis on which a thing is founded, or is supported. The foundations of data mining should deal with fundamental questions of the field itself, but not only the processes that tend to be restricted to certain region, the method to measure relationships between certain populations, or the applications of using certain knowledge.

It is arguable that the foundations of data mining should not be sole mathematics or logic, or any other individual fundamental disciplines. Based on the multiform databases, the diversity of patterns, the ever changing techniques and algorithms, and the different views we discussed above, there is no such a theory or model can possibly found, support and enclose all of them into a whole. Instead, a framework is urgently needed. According to the dictionary, a framework is *a structure for supporting or enclosing something else, especially a skeletal support used as the basis for something being constructed.* Our understanding of the foundations of data mining is based on the following principle: A layered framework that formed in a conceptual scheme can possibly hold different foundations of data mining together, bring the disciplines of data mining into a complete understanding, and further, determine the methods of cognition, of action, of survival and development.

3 A three-layered conceptual framework

A three-layered conceptual framework is proposed by Yao in [22], consisting of the philosophy layer, the technique layer, and the application layer. The layered framework represents the understanding, discovery, and utilization of knowledge, and is illustrated in Figure 1.

3.1 The philosophy layer

The philosophy layer investigates the essentials of knowledge. One attempts to answer the fundamental question, namely, what is knowledge? There are many related issues to this question, such as the representation of knowledge, the expression and communication of knowledge in languages, the relationship between knowledge in the mind and in the external real world, and the classification and organization of knowledge [19]. Philosophical study of data mining services as a precursor to technology and application, it generates knowledge and the understanding of our world, with or without establish the operational boundaries of knowledge.

3.2 The technique layer

The technique layer is the study of knowledge discovery in machine. One attempts to answer the question, how to discover knowledge? In the context of computer science, there are many issues related to this question, such as the implementation of human knowledge discovery methods by programming languages, which involves coding, storage and retrieval issues in a computer, and the innovation and evolution of techniques and algorithms in intelligent systems. The main stream of research in machine learning, data mining, and knowledge discovery has concentrated on the technique layer. Logical analysis and mathematical modelling are considered to be the foundation of technique layer study of data mining.

3.3 The application layer

The ultimate goal of knowledge discovery is to effectively use discovered knowledge. The application layer therefore should focus on the notions of "usefulness" and "meaningfulness" of discovered knowledge for the specific domain. These notions can not be discussed in total isolation with applications, as knowledge in general is domain specific.

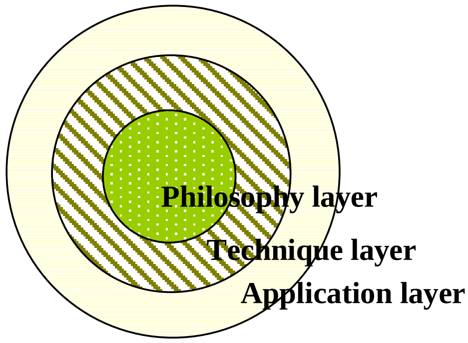

Fig. 1. The three-layered conceptual framework of data mining.

3.4 The relationships among the three layers

Two points need to be emphasized about the three-layered conceptual framework. First, the three layers are different and self-contained. This point can be demonstrated by three facts:

(1.)The philosophical study does not depend on the availability of specific techniques and applications. In other words, no matter knowledge is discovered or not, utilized or not, even if the knowledge structure and expression are recognized or not, it exists. Furthermore, all human knowledge is conceptual and forms an integrated whole [13]. The output of philosophical study can be expressed as theories, principles, concepts or other knowledge structures. Either knowledge structure is built by connecting new bits of information to the old. The essential study of knowledge at philosophical layer has important implications for the human society, even if it is not discovered or utilized yet, even if it is simply providing a general understanding how we human fit into the cosmos. For example, the modern Periodic Chart proposed by Mendelyeev provides a fundamental knowledge structure for classifying and organizing all the atomic. Some of the atomic are still not discovered till now, let alone being used.

(2.)The technical study can carry out part of the philosophic study results but not all, and it is not constrained by applications. Whereas the philosophy layer describes a very generalized conceptual scheme, the current techniques, including hardware and software are hardly to bring all of it into reality. On the other hand, the existence of a technique/algorithm does not necessarily imply that discovered knowledge is meaningful and useful. The output of technical study can be expressed by algorithms, flow charts, mathematical models, and intelligent systems. The technology can be commercialized. There are many successful story in data mining domain. The benefits of technological implementation and innovation tend to move the study of technical layer to be more and more profit-driven.

(3.)The applications of data mining is materialized knowledge in specific domains. The application layer study of data mining can be isolated to be another relative separate aspect. Think about the evaluation of discovered knowledge, the explanation and interpretation of discovered knowledge, using discovered knowledge as raw materials for a wide variety of derivative products, further, distributing, marketing and managing the knowledge outputs, all of these can be extended to the corresponding new research fields, and realistically applied to distinct domains and systems. Comparing to philosophical and technological studies, the applications have more explicit targets and schedules.

Second, the three layers mutually function on each other. We also explain this point by three facts:

(1.)It is expected that the results from philosophy layer will provide guideline and set the stage for the technique and application layers. It provides the conceptual guidance of knowledge structures, which serves as a pilot lamp for the further research work. It is quite normal that, the more rigidly one declares that certain type of knowledge is "valid, novel, useful and/or understandable" , the more efficiently the mining techniques will be proposed, the more effectively mined knowledged will be utilized and explained, and sometime, the more possible suspicions and supports will be raised.

(2.)The technique layer is the systematic pursuit of computer science activities of the framework. The technology development and innovation cannot go far without the conceptual guidance. Notwithstanding, the philosophical study cannot leave the technology either. The requirement of technology development promotes the philosophical study, while the technology development provides the necessary means for conceptual investigation and organization. At the mean time, technique layer is the bridge between philosophical view of knowledge and the application of knowledge. Technical support is the necessary condition to make the dream come true, and achieve the commercial benefit after all.

(3.)The applications of philosophical and technical outcomes give an impetus for the re-examination of philosophical and technical studies too. The application outputs are required an immediate evaluation and assessment. These feedbacks come from the users and the customers necessitate the researchers work on the other two layers to make respond, either to complete or modify the knowledge structure, the methodology, or innovate the existing technology.

Three layers of the conceptual framework are tightly integrated, namely, they are mutually connected, supported, promoted, facilitated, conditioned and restricted. The division between the three layers is not clear cut, and may overlap and interweave with each other. Any of them is indispensable in the study of intelligence and intelligent systems. They must be considered together in a common framework through multi-disciplinary studies, rather than in isolation.

Since the technique layer and application layer are extensively studied, in this paper, we only emphasize on the philosophy layer study of data mining. In the following section, we study the main issues related to this layer in detail.

4 Main issues of philosophy layer study

The philosophy layer is the study of knowledge. In this section, we discuss the concept formation, knowledge representation, evaluation, classification and explanation. We use concept as an example to illustrate most of the ideas.

4.1 Concept formation and learning

Concept is a special form of knowledge. Concepts present a profound development and consciousness of percepts, and enable human to know and understand facts that far outstrip our limited observations [13]. Concept formation and learning is under the light of cognitive science, which studies the intelligence and its computational processes in mind, in machine and in the abstract.

In the process of concept formation and learning, there are two basic issues known as aggregation and characterization [3]. Aggregation aims at the identification of a group of objects so that they form the extension of a concept. Characterization attempts to describe the derived set of objects in order to obtain the intension of the concept [3].

For aggregation, one considers two main processes called differentiation and integration [13]. Differentiation enables us to grasp the differences between elements, so that we can separate one or more elements from other elements. Integration is the process of generalizing the features of similar elements, then putting together elements into an inseparable whole. In general, the elements we mentioned above can be either objects or attributes in an information table.

As the final step in concept formation, characterization provides a definition of a concept, condenses the inseparable whole into a brief, retainable statement, tells what distinguishes the units and from what they are being distinguished. This, in Ayn Rand's words, is "to distinguish a concept from all other concepts and thus to keep its units differentiated from all other existents [13]." Please refer to [23] for more detail issues about concept formation and learning.

4.2 Knowledge representation

One needs to define and formulate the knowledge representation clearly and concisely. This step demands that one has full philosophical understanding and its underlying mathematical concepts.

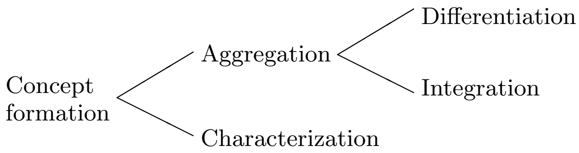

Fig. 2. Concept formation and learning.

A virtual space that can hold knowledge as concepts is called a concept space, namely, it refers to the set or class of the concepts. If we consider the data mining process as a searching for concepts in a particular concept space, we need to study different kind of concept spaces first. Inside the concept space, the concept can be represented and discovered. Generally enough, a concept space S can hold all the concepts, including the ones that can be defined as a formula, and the ones that cannot. A definable concept space DS is a sub-space of the concept space S. There are many definable concept spaces in different forms. In most situations, one is only interested in the concepts in a certain form. Consider the class of conjunctive concepts, that formula constructed from atomic formula by only logic connective $\wedge$. A concept space CDS is then referred to as the conjunctively definable space, which is a sub-space of the definable space DS. Similarly, a concept space is referred to as a disjunctively definable space if the atomic formulas are connected by logic disjunctive $\vee$.

The relationship among the above mentioned concept spaces is illustrated in Figure 3. A particular computational model is normally based on one or some philosophical assumptions and may not be able to cover all.

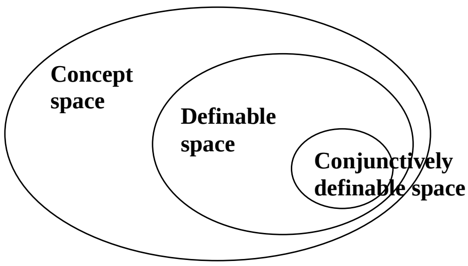

Fig. 3. Some concept spaces.

4.3 Knowledge evaluation

Concept formation and knowledge representation do not have to concern the quantity. Though, the quantity evaluation of the concept relations is also important. Many measures have been proposed and studied to quantify the usefulness or interestingness of concepts and concept relations [10, 17, 24]. The results lead to an in-depth understanding of different aspects of knowledge.

Generally, measures can be classified into two categories consisting of objective measures and subjective measures [17]. Objective measures depend on the structure of rules and underlying data used in the discovered process. Subjective measures depend on the user who examines the rules. While most of the measures are objectively defined by mathematical properties, Yao *et al.* proposed a subjective framework for rule interestingness evaluation based on the user preference [24].

With respect to a certain knowledge representation, for example, a concept, and a certain evaluation measure, one may have many different semantic meanings, and they stand for different kinds of knowledge. For example, an association is considered interesting if the support of it is high and the confidence of it is also high, it is so called a frequent itemset. If the support of it is low but the confidence of it is high, it is also considered as interesting as a peculiar.

4.4 Knowledge classification and organization

Partitions and coverings are two simple and commonly used knowledge classifications of the universe. A partition of a finite universe is a collection of non-empty, and pairwisely disjoint subsets whose union is the universe. A covering of a finite universe is a collection of non-empty and possibly overlapped subsets whose union is the universe. Partitions are a special case of coverings.

Knowledge is organized in a tower (hierarchy) or a partial ordering. Based on the above discussion, we have partition-based hierarchy and covering-based hierarchy. Hierarchy means that the base or minimal elements of the ordering are the most fundamental concepts and higher-level concepts depend on lower-level concepts [18]. Partial ordering means that the concepts in the hierarchy are reflexive, anti-symmetric and transitive. The first-level concept is formed directly from the perceptual data [13]. The higher-level concepts, representing a relatively advanced state of knowledge, are formed by a process of abstracting from abstractions [13]. On the other hand, the series of lower-level concepts, on it the higher-level concept is formed, is not necessarily unique in content. Within the requisite overall structure, there may be many alternatives in detail [13].

The nature process of knowledge cognitive follows the hierarchy from lower-level concepts to higher-level according to the intellectual dependency. The revise process does exist because of impatience, anti-effort, or simple error. Peikoff analyzes that the attempt to function on the higher levels of complex structure without having established the requisite base will build confusion on confusion, instead of knowledge on knowledge. In such minds, the chain relating higher-level content to perceptual reality is broken [13].

4.5 Knowledge explanation

Scientific research and data mining have much in common in terms of their goals, tasks, processes and methodologies. Scientific research is affected by the perceptions and the purposes of science. Martella *et al.* summarized the main purposes of science, namely, to describe and predict, to improve or manipulate the world around us, and to explain our world [12]. The results of the scientific research process provide a description of an event or a phenomenon. The knowledge obtained from research this helps us to make predictions about what will happen in the future. Research findings are a useful tool for making an improvement in the subject matter. Research findings also can be used to determine the best or the most effective ways of bringing about desirable changes. Finally, scientists develop models and theories to explain why a phenomenon occurs. Goals similar to those of scientific research have been discussed by many researchers in data mining. As Guergachi recently stated, the goal of data mining is what science is and has been all about: discovering and identifying relationships among the observations we gather, making sense out of these observations, developing scientific principles, building universal laws from observations and empirical data [5]. For example, Fayyad *et al.* identified two high-level goals of data mining as prediction and description [2]. Ling et al. studied the issue of manipulation and action based on the discovered knowledge [8]. Yao *et al.* introduced the notion of explanation-oriented data mining, which focuses on constructing models for the explanation of data mining results [25].

The consequence after the immediate comparison is that an explanation construction and evaluation task is added to the existing data mining process. Explanation-oriented data mining uses the background knowledge to infer features that can possibly explain and interprets knowledge discovered from data. The constructed explanations give some evidence about under what conditions (within background knowledge) the discovered pattern is most likely to happen, or how the background knowledge is related to the pattern.

5 Conclusion

A three-layered conceptual framework of data mining is proposed in this paper consisting of the philosophy layer, the technique layer and the application layer. The philosophy layer deals with the formation, representation, evaluation, classification and organization, and explanation of knowledge; the technique layer deals with the technique development and innovation; the application layer emphasizes on the application, utility and explanation of mined knowledge. The layered framework focuses on the data mining questions and issues in different abstract levels, and thus, offers us opportunities and challenges to reconsider many issues in the established fields.

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