ABSTRACT

Learning novel relations from relational databases is an important problem with many applications in database systems and machine learning. Relational learning algorithms leverage the properties of the database schema to find the definition of the target relation in terms of the existing relations in the database. However, the same data set may be represented under different schemas for various reasons, such as efficiency and data quality. Unfortunately, current relational learning algorithms tend to vary quite substantially over the choice of schema, which complicates their off-the-shelf application. We demonstrate Castor, a relational learning system that efficiently learns the same definitions over common schema variations. The results of Castor are more accurate than well-known learning systems over large data.

1. INTRODUCTION

Over the last decade, users’ information needs over relational databases have expanded from answering precise queries to using machine learning in order to discover interesting and novel relations and concepts [5]. For instance, Table 1 shows fragments of the original schema for the UW-CSE database. UW-CSE is a common relational learning benchmark that contains information about students, professors, courses, and publications. Given some examples of known student-advisor pairs, we may want to learn a new relation advisedBy\((\text{stud}, \text{prof})\), which indicates that student \text{stud} is advised by professor \text{prof}, according to available relations in the database. Machine learning algorithms often require to hand-engineer a set of features that capture the essential information required to predict the advisedBy relation, where each feature is the result of a query to the database. We would then compute these features for each example in the training data, store the resulting feature vectors, and run a learning algorithm to learn the relation.

Three challenges arise with the described approach. First, hand-engineering features is not an easy task. It is a slow and tedious process and requires significant expertise. It also restricts the algorithm from identifying patterns that are not reflected in the features or combinations of features. Second, by condensing information into a vector of features, we may lose the relational structure, which translates into the loss of information. Third, the result of the algorithm may be hard to interpret by users.

As opposed to “feature-based approaches”, relational machine learning (also called relational learning or inductive logic programming) attempts to learn concepts directly from a relational database, without requiring the intermediate step of feature engineering [5, 4]. Given a database and training instances of a new target relation, relational learning algorithms attempt to induce (approximate) relational definitions of the target in terms of existing relations. Learned definitions are usually first-order formulas, often restricted to Datalog programs, which are easier to understand by users than the output of typical non-relational learning algorithms. Because the space of possible definitions is enormous, relational learning algorithms must employ heuristics to search for accurate definitions. Unfortunately, such heuristics typically depend on the precise choice of schema for the underlying database, which means that the learning output is schema dependent. As an example, Table 1 shows parts of two schemas for the UW-CSE database. The original schema was designed by relational learning experts and is generally discouraged in the database community as it delivers poor usability and performance in query processing without providing any advantages in terms of data quality [1]. A database designer may use a schema closer to the alternative schema in Table 1, which is in 4th normal form. This would result in a more understandable schema and shorter query execution times, without introducing any redundancy. Note that restructuring the UW-CSE database from the original to alternative schema does not modify the content of the database; it only changes its organization. Let us use the classic relational learning algorithm FOIL [4] to induce a definition of advisedBy\((\text{stud}, \text{prof})\) for both schemas of the UW-CSE database in Table 1. FOIL learns the following definition over the original schema on Table 1:

\[
\text{advisedBy}(A, B) \leftarrow \text{yearsInProgram}(A, 7), \text{publication}(D, A), \text{publication}(D, B).
\]

which covers 5 positive examples and 0 negative examples. On the other hand, FOIL learns the following definition over the alternative schema:

\[
\text{advisedBy}(A, B) \leftarrow \text{student}(A, \text{post\_generals}, 5), \text{professor}(B, \text{faculty}), \text{publication}(C, B), \text{taughtBy}(D, B, E).
\]

which covers 12 positive examples and 10 negative examples. Intuitively, the definition learned over the original schema better expresses the relationship between an advisor and advisee.
2. FRAMEWORK

Relational Learning: An atom is a formula in the form of $R(u_1, \ldots, u_n)$, where $R$ is a relation symbol. A literal is an atom, or the negation of an atom. A Horn clause (clause for short) is a finite set of literals that contains exactly one positive literal. Horn clauses are also called conjunctive queries. A Datalog definition, i.e., union of conjunctive queries, is a set of Horn clauses with the same positive literal. Relational learning algorithms learn Datalog definitions from input relational databases and training data. The learned definitions are called the hypothesis, which is usually restricted to non-recursive Datalog definitions without negation for efficiency reasons. Relational learning can be viewed as a search problem for a hypothesis that deduces the training data.

Decomposition/Composition: Decomposition projects a relation to multiple relations. For example, the transformation from the alternative to original schema in Table 1 decomposes relation student to relations student, inPhase, and yearsInProgram. Decomposition is used in several frequently applied schema normalizations, e.g., 3rd normal form. A decomposition preserves the content of a relation if the original and decomposed relations satisfy certain dependencies, e.g., functional or multivalued dependencies [1]. For example, in Table 1 attribute stud functionally determines phase and years in both original and alternative schemas. These dependencies guarantee that no data item or tuple will be lost during the decomposition and that the original and decomposed databases contain the exact same information. Further, there should be inclusion dependencies, i.e., referential integrity constraints, between the common attributes in the decomposed relations. For instance, in the original schema of Table 1, there are inclusion dependencies between the attributes stud in relations inPhase and yearsInProgram and attribute stud in relation student. Composition joins multiple relations into a single relation. It is the inverse of decomposition. For example, the transformation from original to alternative schema in Table 1 composes relations student, inPhase, and yearsInProgram into relation student. Schema denormalization is an example of composition. During the lifetime of a schema, one may decompose some relations and compose some other relations in the schema. We define a decomposition/composition as a finite set of applications of composition or decomposition to a schema.

Schema Independence: A learning algorithm is schema independent if it learns semantically equivalent definitions over content-preserving transformations of the input database. For instance, for FOIL to be schema independent, it should learn the following definition over the alternative schema of Table 1 for the adviseBy relation as explained in Section 1.

$\text{adviceBy}(A, B) \iff \text{student}(A, C, 7), \text{publication}(D, A), \text{publication}(D, B)$.

This definition is semantically equivalent to the one learned by FOIL over the original schema, which is given in Section 1. Schema independence can be defined on various types of content-preserving schema transformations. In this demonstration, we focus on schema independence over decomposition/composition. The reasons for selecting decomposition/composition are twofold. First, they are used in most normalizations and de-normalizations, which are arguably one of the most frequent schema modifications [1]. We also observe several cases of them in relational learning benchmarks, one of which is shown in Table 1.

3. CASTOR ALGORITHM

As many relational learning algorithms, Castor follows a covering approach. Algorithm 1 depicts Castor’s learning algorithm. It constructs one clause at a time. If the clause satisfies the minimum criterion, Castor adds the clause to the learned definition and discards the positive examples covered by the clause. It stops when all positive examples are covered by the learned definition. Castor
accepts a clause only if its precision and F1-score, i.e., harmonic average of precision and recall, are greater than those of a random classifier. Other algorithms check only for the precision of learned clauses [2]. These algorithms usually overfit to the training data, as they learn clauses that contain too many constants. This happens more often for schemas whose relations have relatively many attributes, e.g., the alternative schema in Table 1. For instance, if an algorithm checks only for precision, it learns the following clause over the alternative schema in Table 1:

\[
\text{advisedBy}(A, B) \leftarrow \text{student}(A, \text{postGenerals}), \text{publication}(C, A), \text{publication}(C, B).\]

On the other hand, Castor, which checks for both precision and F1-score, learns more general clauses, such as

\[
\text{advisedBy}(A, B) \leftarrow \text{student}(A, D, E), \text{publication}(C, A), \text{publication}(C, B).\]

An algorithm that only checks for precision may not overfit over schemas whose relations have relatively small number of attributes, e.g., the original schema in Table 1. For instance, it may learn the following clause over the original schema in Table 1:

\[
\text{advisedBy}(A, B) \leftarrow \text{student}(A), \text{publication}(C, A), \text{publication}(C, B).\]

This means that such algorithm may return different answers over the original and alternative schemas and is not schema independent. However, because Castor checks for both precision and F1-score, it does not suffer from this problem and learns accurate and general clauses over both schemas. Castor follows the bottom-up method for relational learning [2]. First, it constructs the most specific clause that covers a given positive example, relative to the database instance, called bottom clause. Then, it generalizes the bottom clause to cover as most positive and as fewest negative examples as possible.

### 3.1 Bottom Clause Construction

To compute the bottom clause associated with example e and relative to database I, Castor assigns fresh variables to constants in e and maintains this mapping in a hash table. It creates the head of the bottom clause by replacing the constants in e with their assigned variables. The algorithm selects all tuples in the database that contain at least one constant in the hash table. For each tuple, it creates a new literal with the same relation name as the tuple and adds the literal to the body of the bottom clause. If the literal (tuple) has a new constant, the algorithm assigns a fresh variable to the constant and adds the new mapping to the hash table. In each following iteration, the algorithm selects tuples in the database that contain the newly added constants to the hash table and adds their corresponding literals to the clause. This procedure generates very long clauses over a large database after a small number of iterations, which takes a very long time to construct and then generalize. A common method is to restrict the maximum number of literals, called clauseLength, in the body of the bottom clause [2].

For example, assume that we would like to learn relation hardWorking(x), which indicates that a student is hardworking, over the UW-CSE database. Let clauseLength be 2. The bottom clause construction algorithm starts with a positive example, e.g., hardWorking(Mary), assigns a fresh variable v1 to Mary, and adds the literal hardWorking(v1) to the head of the bottom clause. It then finds all tuples that contain constant Mary. Assume that Mary appears only in the student and inPhase relations in the original schema and only in the student relation in the alternative schema introduced in Table 1. Hence, the bottom clause construction adds the corresponding literals to the bottom clause and stops when there are two literals in the bottom clause. Over the original schema, the bottom clause algorithm delivers the clause hardWorking(v1) ← student(v1), inPhase(v1, v2). On the other hand, over the alternative schema it generates the clause hardWorking(v1) ← student(v1, v2, v3).

These two clauses are not semantically equivalent. Hence, the bottom clause construction algorithm may deliver different results for the same example and equivalent instances of schemas representing the same information. More importantly, it may miss some important tuples over some schemas, e.g., yearsInProgram(Mary, 2) over the original schema. To overcome this problem, Castor uses inclusion dependencies to construct bottom clauses. More precisely, after selecting a tuple, Castor applies inclusion dependencies to find other tuples related to the selected tuple and adds them to the bottom clause. For example, after it selects tuple student(Mary) over the database with original schema in our example, it also selects tuples inPhase(Mary, PostPremlns) and year(Mary, 2) as they satisfy inPhase[stud] ⊆ student[stud] and yearsInProgram[stud] ⊆ student[stud], respectively.

### 3.2 Generalization

Castor first creates the bottom clause for a given positive example e. It then generalizes this bottom clause iteratively. Given clause C, Castor randomly picks a subset E+ of positive examples to generalize C. For each example e’ in E+, Castor generates a candidate clause C’, which is more general than C and covers e’. It uses the armg operator [2], which drops literals in the body of C that do not cover e’. Castor then selects the highest scoring candidate clauses and iterates until the clauses cannot be improved. The armg operator may generate non-equivalent clauses from semantically equivalent clauses over a database and its composition/decomposition. For example, given the bottom clauses over the original and alternative schemas in the example in Section 3.1, the literal student(v1) may satisfy example e’, but inPhase(v1, v2) may not. Hence, the algorithm keeps student(v1) and removes inPhase(v1, v2) from the bottom clause generated of the database over the original schema. Because both databases in the example have the same content, literal student(v1, v2, v3) will not satisfy e’ and will be removed by the algorithm from the bottom clause over the alternative schema. To solve this issue, immediately after removing a literal L1 with relation symbol R, Castor also removes literal L2 with relation symbol S such that R[X] ⊆ S[Y] is an inclusion dependency in the schema and L1 and L2 share the same variables and/or constants in attributes X and Y. For example, Castor removes literal student(v2) after removing inPhase(v1, v2) in the example due to the inclusion dependency inPhase[stud] ⊆ student[stud] over the database with original schema. Clauses are further generalized by removing literals that are non-essential.
shown as $Reduce()$ function in Algorithm 1. A literal is non-essential if, after removed from a clause, the number of negative examples covered by the clause does not increase [2]. Castor uses inclusion dependencies to generate equivalent clauses in this step.

4. CASTOR ARCHITECTURE

Castor performs several optimizations to improve the efficiency of the learning algorithm. First, Castor removes redundant literals in bottom clauses. A literal $L$ in clause $C$ is redundant if $C$ is equivalent to $C' = C - \{L\}$. Castor checks clause equivalence by using theta-transformation, which is an approximation of the clause equivalence problem that retains the property of correctness. Second, Castor optimizes the generalization process by reducing the number of coverage tests. If clause $C$ covers example $e$, then clause $C''$, which is more general than $C$, also covers $e$. If Castor knows that $C$ covers $e$, it does not check if $C''$ covers $e$. Third, the bottom clause construction algorithm is implemented inside a stored procedure. We implement Castor on top of the in-memory RDBMS VoltDB. Because stored procedures in VoltDB are pre-compiled, bottom clause construction is very efficient. Figure 1 sketches the high-level architecture of Castor. The first time that Castor is run on a schema, it creates the stored procedure that implements the bottom clause construction algorithm for the given schema. Castor reuses the stored procedure when the algorithm is run again, with either new training data or updated database instance.

Table 2 shows the results of running Castor and two other relational learning algorithms over a subset of the HIV database\(^2\). We learn the relation $hiv\_active(compound)$, which indicates that compound has an anti-HIV activity. We use two schemas, which are a composition/decomposition of each other. The database contains 145M tuples over schema 1 and 7.8M tuples over schema 2. We use the implementation of FOIL and Progol based on the popular relational learning library Aleph\(^3\). We cannot compare our system with QuickFOIL [5], as it is not available for download. We also evaluated ProGolem [2], however it did not terminate after 10 hours. All experiments were run on a 2.6GHz Intel Xeon E5-2640 processor, running CentOS Linux 7.2 with 50GB of main memory.

![Figure 1: High-level architecture of Castor.](image1.png)

![Figure 2: View of Castor output.](image2.png)

![Figure 3: Comparison of Castor to other algorithms.](image3.png)

Table 2: Results of different learning algorithms over HIV data.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Metric</th>
<th>Schema 1</th>
<th>Schema 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOIL</td>
<td>Precision</td>
<td>0.68</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Recall</td>
<td>0.85</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Time (min)</td>
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<td>3</td>
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<tr>
<td>Progol</td>
<td>Precision</td>
<td>0.71</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Recall</td>
<td>0.88</td>
<td>0.94</td>
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<tr>
<td></td>
<td>Time (min)</td>
<td>36.8</td>
<td>16.3</td>
</tr>
<tr>
<td>Castor</td>
<td>Precision</td>
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<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Recall</td>
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<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Time (min)</td>
<td>56</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Table 5. DEMONSTRATION

In our demonstration, we first show examples of different styles of schema design using benchmark databases, such as UW-CSE, and real-world databases, such as HIV and IMDb. Users may select a database and training data, run Castor and observe the graphical view and Datalog of the learned definition, as well as the accuracy of the learned definition as shown in Figure 2. For each database, users will also see a visual representation of the database schema. Users can view a list of prepared composition/decomposition transformations for a database, select their desired transformation, and observe the results of Castor on the original database and its composition/decomposition. Users can also visually explore, decompose/compose the schema of the database, run Castor, and observe the results of Castor on the original and transformed database. In addition to Castor, our prototype has also the implementations of well-known relational learning algorithms: FOIL, Progol, and ProGolem [4, 2]. Users can select one of these algorithms, a database and training data, see the learned definitions of Castor and the selected algorithm over the chosen database, and compare the accuracy and efficiency of the selected algorithms with Castor’s. Further, they can select a composition/decomposition for the chosen database and compare the robustness of the chosen algorithm with Castor as shown in Figure 3.

6. ACKNOWLEDGEMENTS

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7. REFERENCES