Scallop: A Language for Neurosymbolic Programming

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We present Scallop, a language which combines the benefits of deep learning and logical reasoning. Scallop enables users to write a wide range of neurosymbolic applications and train them in a data- and compute-efficient manner. It achieves these goals through three key features: 1) a flexible symbolic representation that is based on the relational data model; 2) a declarative logic programming language that is based on Datalog and supports recursion, aggregation, and negation; and 3) a framework for automatic and efficient differentiable reasoning that is based on the theory of provenance semirings. We evaluate Scallop on a suite of eight neurosymbolic applications from the literature. Our evaluation demonstrates that Scallop is capable of expressing algorithmic reasoning in diverse and challenging AI tasks, provides a succinct interface for machine learning programmers to integrate logical domain knowledge, and yields solutions that are comparable or superior to state-of-the-art models in terms of accuracy. Furthermore, Scallop’s solutions outperform these models in aspects such as runtime and data efficiency, interpretability, and generalizability.

CCS Concepts:
• Software and its engineering → Domain specific languages;
• Computing methodologies → Learning paradigms; Probabilistic reasoning; Logical and relational learning.

Additional Key Words and Phrases: Neurosymbolic methods, Differentiable reasoning

ACM Reference Format:

1 INTRODUCTION

Classical algorithms and deep learning embody two prevalent paradigms of modern programming. Classical algorithms are well suited for exactly-defined tasks, such as sorting a list of numbers or finding a shortest path in a graph. Deep learning, on the other hand, is well suited for tasks that are not tractable or feasible to perform using classical algorithms, such as detecting objects in an image or parsing natural language text. These tasks are typically specified using a set of input-output training data, and solving them involves learning the parameters of a deep neural network to fit the data using gradient-based methods.

The two paradigms are complementary in nature. For instance, a classical algorithm such as the logic program $P$ depicted in Figure 1a is interpretable but operates on limited (e.g., structured) input $r$. In contrast, a deep neural network such as $M_0$ depicted in Figure 1b can operate on rich (e.g., unstructured) input $x$ but is not interpretable. Modern applications demand the capabilities of both paradigms. Examples include question answering [Rajpurkar et al. 2016], code completion [Chen et al. 2021b], and mathematical problem solving [Lewkowycz et al. 2022], among many others.

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For instance, code completion requires deep learning to comprehend programmer intent from the code context, and classical algorithms to ensure that the generated code is correct. A natural and fundamental question then is how to program such applications by integrating the two paradigms.

Neurosymbolic programming is an emerging paradigm that aims to fulfill this goal [Chaudhuri et al. 2021]. It seeks to integrate symbolic knowledge and reasoning with neural architectures for better efficiency, interpretability, and generalizability than the neural or symbolic counterparts alone. Consider the task of handwritten formula evaluation [Li et al. 2020], which takes as input a formula as an image, and outputs a number corresponding to the result of evaluating it. An input-output example for this task is \( \langle x = 1 + \frac{3}{5}, y = 1.6 \rangle \). A neurosymbolic program for this task, such as the one depicted in Figure 1c, might first apply a convolutional neural network to the input image to obtain a structured intermediate form as a sequence of symbols ['1', '+', '3', '/', '5'], followed by a classical algorithm to parse the sequence, evaluate the parsed formula, and output the final result 1.6.

Despite significant strides in individual neurosymbolic applications [Chen et al. 2020; Li et al. 2020; Mao et al. 2019; Minervini et al. 2020; Wang et al. 2019; Yi et al. 2018], there is a lack of a language with compiler support to make the benefits of the neurosymbolic paradigm more widely accessible. We set out to develop such a language and identified five key criteria that it should satisfy in order to be practical. These criteria, annotated by the components of the neurosymbolic program in Figure 1c, are as follows:

1. A symbolic data representation for \( r \) that supports diverse kinds of data, such as image, video, natural language text, tabular data, and their combinations.
2. A symbolic reasoning language for \( P \) that allows to express common reasoning patterns such as recursion, negation, and aggregation.
3. An automatic and efficient differentiable reasoning engine for learning \( \frac{\partial y}{\partial \theta} \) under algorithmic supervision, i.e., supervision on observable input-output data \( (x, y) \) but not \( r \).
4. The ability to tailor learning \( \frac{\partial y}{\partial \theta} \) to individual applications’ characteristics, since non-continuous loss landscapes of logic programs hinder learning using a one-size-fits-all method.
5. A mechanism to leverage and integrate with existing training pipelines \( \frac{\partial y}{\partial \theta} \), implementations of neural architectures and models \( M_{\theta} \), and hardware (e.g., GPU) optimizations.

In this paper, we present Scallop, a language which satisfies the above criteria. The key insight underlying Scallop is its choice of three inter-dependent design decisions: a relational model for symbolic data representation, a declarative language for symbolic reasoning, and a provenance framework for differentiable reasoning. We elaborate upon each of these decisions.

Relations can represent arbitrary graphs and are therefore well suited for representing symbolic data in Scallop applications. For instance, they can represent scene graphs, a canonical symbolic representation of images [Johnson et al. 2015], or abstract syntax trees, a symbolic representation of natural language text. Further, they can be combined in a relational database to represent multimodal data. Relations are also a natural fit for probabilistic reasoning [Dries et al. 2015], which is necessary since symbols in \( r \) produced by neural model \( M_{\theta} \) can have associated probabilities.
Next, the symbolic reasoning program $P$ in Scallop is specified in a declarative logic programming language. The language extends Datalog [Abiteboul et al. 1995] and is expressive enough for programmers to specify complex domain knowledge patterns that the neural model $M_\theta$ would struggle with. Datalog implementations can take advantage of optimizations from the literature on relational database systems. This in turn enables efficient inference and learning since the logical domain knowledge specifications of the task at hand help reduce the burden of $M_\theta$, whose responsibilities are now less complex and more modular. Finally, Datalog is rule-based, which makes programs easier to write, debug, and verify. It also facilitates inferring them by leveraging techniques from program synthesis [Gulwani et al. 2017] and ILP [Cropper and Dumančić 2022].

While symbolic reasoning offers many aforementioned benefits, it poses a fundamental challenge for learning parameter $\theta$. Deep learning relies on gradient-based methods, enabled by the differentiable nature of the low-level activation functions that comprise $M_\theta$, to obtain $\frac{\partial w}{\partial \theta}$. The key challenge then concerns how to support automatic and efficient differentiation of the high-level logic program $P$ to obtain $\frac{\partial P}{\partial \theta}$, which can be used in conjunction with $\frac{\partial w}{\partial \theta}$ to compute $\frac{\partial w}{\partial \theta}$. Scallop addresses this problem by leveraging the framework of provenance semirings [Green et al. 2007]. The framework proposes a common algebraic structure for applications that define annotations (i.e., tags) for tuples and propagate the annotations from inputs to outputs of relational algebra (RA) queries. One of our primary contributions is a novel adaptation of the framework for differentiable reasoning for an extended fragment of RA that includes recursion, negation, and aggregation. Scallop implements an extensible library of provenance structures including the extended max-min semiring and the top-k proofs semiring [Huang et al. 2021]. We further demonstrate that different provenance structures enable different heuristics for the gradient calculations, providing an effective mechanism to tailor the learning process to individual applications’ characteristics.

We have implemented a comprehensive and open-source toolchain for Scallop in 45K LoC of Rust. It includes a compiler, an interpreter, and PyTorch bindings to integrate Scallop programs with existing machine learning pipelines. We evaluate Scallop using a suite of eight neurosymbolic applications that span the domains of image and video processing, natural language processing, planning, and knowledge graph querying, in a variety of learning settings such as supervised learning, reinforcement learning, rule learning, and contrastive learning. Our evaluation demonstrates that Scallop is expressive and yields solutions of comparable, and often times superior, accuracy than state-of-the-art models. We show additional benefits of Scallop’s solutions in terms of runtime and data efficiency, interpretability, and generalizability.

Any programming language treatise would be remiss without acknowledging the language’s lineage. TensorLog [Cohen et al. 2017] and DeepProbLog (DPL) [Manhaeve et al. 2021] pioneered the idea of extending probabilistic logic programming languages (e.g., ProbLog [Dries et al. 2015]) with differentiable reasoning. Scallop was originally proposed in [Huang et al. 2021] to improve the scalability of DPL by using Datalog instead of Prolog and relaxing its exact probabilistic semantics. We build upon [Huang et al. 2021] by extending its expressiveness, formalizing the semantics, developing a customizable provenance framework, and providing a practical toolchain.

The rest of the paper is organized as follows. Section 2 presents an illustrative overview of Scallop. Section 3 describes Scallop’s language for symbolic reasoning. Section 4 presents the differentiable reasoning framework. Section 5 describes our implementation of Scallop. Section 6 empirically evaluates Scallop on a benchmark suite. Section 7 surveys related work and Section 8 concludes.

2 ILLUSTRATIVE OVERVIEW

We illustrate Scallop using an reinforcement learning (RL) based planning application which we call PacMan-Maze. The application, depicted in Fig. 2a, concerns an intelligent agent realizing a sequence of actions in a simplified version of the PacMan maze game. The maze is an implicit 5 × 5
grid of cells. Each cell is either empty or has an entity, which can be either the actor (PacMan), the goal (flag), or an enemy (ghost). At each step, the agent moves the actor in one of four directions: up, down, right, or left. The game ends when the actor reaches the goal or hits an enemy. The maze is provided to the agent as a raw image that is updated at each step, requiring the agent to process sensory inputs, extract relevant features, and logically plan the path to take. Additionally, each session of the game has randomized initial positions of the actor, the goal, and the enemies.

Concretely, the game is modeled as a sequence of interactions between the agent and an environment, as depicted in Fig. 2b. The game state \( s_i \in S \) at step \( i \) is a \( 200 \times 200 \) colored image \( (S = \mathbb{R}^{200 \times 200 \times 3}) \). The agent proposes an action \( a_i \in A = \{\text{up}, \text{down}, \text{right}, \text{left}\} \) to the environment, which generates a new image \( s_{i+1} \) as the next state. The environment also returns a reward \( r_i \) to the agent: 1 upon reaching the goal, and 0 otherwise. This procedure repeats until the game ends or reaches a predefined limit on the number of steps.

A popular RL method to realize our application is Q-Learning. Its goal is to learn a function \( Q: S \times A \rightarrow \mathbb{R} \) that returns the expected reward of taking action \( a_i \) in state \( s_i \). Since the game states are images, we employ Deep Q-Learning [Mnih et al. 2015], which approximates the \( Q \) function using a convolutional neural network (CNN) model with learned parameter \( \theta \). An end-to-end deep learning based approach for our application involves training the model to predict the \( Q \)-value of each action for a given game state. This approach takes 50K training episodes to achieve a 84.9% test success rate, where a single episode is one gameplay session from start to end.

In contrast, a neurosymbolic solution using Scallop only needs 50 training episodes to attain a 99.4% test success rate. Scallop enables to realize these benefits of the neurosymbolic paradigm by decomposing the agent’s task into separate neural and symbolic components, as shown in Fig. 2b. These components perform sub-tasks that are ideally suited for their respective paradigms: the neural component perceives pixels of individual cells of the image at each step to identify the entities in them, while the symbolic component reasons about enemy-free paths from the actor...
// File path_planner.scl

// Type declarations

const UP = 0, DOWN = 1, RIGHT = 2, LEFT = 3

rel safe_cell(x, y) = range(0, 5, x), range(0, 5, y), not enemy(x, y)

rel edge(x, y, x, yp, UP) = safe_cell(x, y), safe_cell(x, yp), yp == y + 1

// Rules for DOWN, RIGHT, and LEFT edges are omitted...

rel next_pos(p, q, a) = actor(x, y), edge(x, y, p, q, a)

rel path(x, y, x, y) = next_pos(x, y, _)

rel path(x1, y1, x3, y3) = path(x1, y1, x2, y2), edge(x2, y2, x3, y3, _)

rel next_action(a) = next_pos(p, q, a), path(p, q, r, s), goal(r, s)

Fig. 3. The logic program of the PacMan-Maze application in Scallop.

to the goal to determine the optimal next action. Fig. 2c shows an outline of this architecture’s implementation using the popular PyTorch framework.

Concretely, the neural component is still a CNN, but it now takes the pixels of a single cell in the input image at a time, and classifies the entity in it. The implementation of the neural component (EntityExtractor) is standard and elided for brevity. It is invoked on lines 14-15 with input game_state_image, a tensor in \( \mathbb{R}^{200\times200\times3} \), and returns three \( \mathbb{R}^{5\times5} \) tensors of entities. For example, actor is an \( \mathbb{R}^{5\times5} \) tensor and \( \text{actor}(2,3) \) is the probability of the actor being in cell (2,3). Likewise, since there are four possible actions, the output of the symbolic component is represented by a unary relation next_action.

Symbols extracted from unstructured inputs by neural networks have associated probabilities, such as the \( \mathbb{R}^{5\times5} \) tensor actor produced by the neural component in our example (line 14 of Fig. 2c). Scallop therefore allows to associate tuples with probabilities, e.g. 0.96 :: actor(2,3), to indicate that the actor is in cell (2,3) with probability 0.96. More generally, Scallop enables the conversion of tensors in the neural component to and from relations in the symbolic component via input-output mappings (lines 9-11 in Fig. 2c), allowing the two components to exchange information seamlessly.

**Declarative Language.** Another key consideration in a neurosymbolic language concerns what constructs to provide for symbolic reasoning. Scallop uses a declarative language based on Datalog, which we present in Section 3 and illustrate here using the program in Fig. 3. The program realizes the symbolic component of our example using a set of logic rules. Following Datalog syntax, they are “if-then” rules, read right to left, with commas denoting conjunction.

Recall that we wish to determine an action \( a \) (up, down, right, or left) to a cell \( (p, q) \) that is adjacent to the actor’s cell \( (x, y) \) such that there is an enemy-free path from \( (p, q) \) to the goal’s cell \( (r, s) \). The nine depicted rules succinctly compute this sophisticated reasoning pattern by building successively complex relations, with the final rule (on line 14) computing all such actions.

---

2 We elide showing an auxiliary relation of all grid cells tagged with probability 0.99 which serves as the penalty for taking a step. Thus, longer paths are penalized more, driving the symbolic program to prioritize moving closer to the goal.

The arguably most complex concept is the path relation which is recursively defined (on lines 10-11). Recursion allows to define the pattern succinctly, enables the trained application to generalize to grids arbitrarily larger than $5 \times 5$ unlike the purely neural version, and makes the pattern more amenable to synthesis from input-output examples. Besides recursion, Scallop also supports negation and aggregation; together, these features render the language adequate for specifying common high-level reasoning patterns in practice.

**Differentiable Reasoning.** With the neural and symbolic components defined, the last major consideration concerns how to train the neural component using only end-to-end supervision. In our example, supervision is provided in the form of a reward of 1 or 0 per gameplay session, depending upon whether or not the sequence of actions by the agent successfully led the actor to the goal without hitting any enemy. This form of supervision, called algorithmic or weak supervision, alleviates the need to label intermediate relations at the interface of the neural and symbolic components, such as the actor, goal, and enemy relations. However, this also makes it challenging to learn the gradients for the tensors of these relations, which in turn are needed to train the neural component using gradient-descent techniques.

The key insight in Scallop is to exploit the structure of the logic program to guide the gradient calculations. The best heuristic for such calculations depends on several application characteristics such as the amount of available data, reasoning patterns, and the learning setup. Scallop provides a convenient interface for the user to select from a library of built-in heuristics. Furthermore, since all of these heuristics follow the structure of the logic program, Scallop implements them uniformly as instances of a general and extensible provenance framework, described in Section 4. For our example, line 8 in Fig. 2c specifies diff-top-k-proofs with $k=1$ as the heuristic to use, which is the default in Scallop that works best for many applications, as we demonstrate in Section 6.

3 LANGUAGE

We provide an overview of Scallop’s language for symbolic reasoning which we previously illustrated in the program shown in Fig. 3. Here, we illustrate each of the key constructs using examples of inferring kinship relations.

3.1 Data Types

The fundamental data type in Scallop is set-valued relations comprising tuples of statically-typed primitive values. The primitive data types include signed and unsigned integers of various sizes (e.g. i32, usize), single- and double-precision floating point numbers (f32, f64), boolean (bool), character (char), and string (String). The following example declares two binary relations, mother and father:

```plaintext
type mother(c: String, m: String), father(c: String, f: String)
```

Values of relations can be specified via individual tuples or a set of tuples of constant literals:

```plaintext
rel mother("Bob", "Christine") // Christine is Bob’s mother
def father = {("Alice", "Bob"), ("John", "Bob")} // Bob is father of two kids
```

As a shorthand, primitive values can be named and used as constant variables:

```plaintext
cnst FATHER = 0, MOTHER = 1, GRANDMOTHER = 2, ... // other relationships
def composition(FATHER, MOTHER, GRANDMOTHER) // father’s mother is grandmother
```

Type declarations are optional since Scallop supports type inference. The type of the composition relation is inferred as (usize, usize, usize) since the default type of unsigned integers is usize.
3.2 (Horn) Rules
Since Scallop’s language is based on Datalog, it supports “if-then” rule-like Horn clauses. Each rule is composed of a head atom and a body, connected by the symbol \(-\) or \(\rightarrow\). The following code shows two rules defining the \texttt{grandmother} relation. Conjunction is specified using “,”-separated atoms within the rule body whereas disjunction is specified by multiple rules with the same head predicate. Each variable appearing in the head must also appear in some positive atom in the body (we introduce negative atoms below).

\begin{verbatim}
rel grandmother(a, c) :- father(a, b), mother(b, c) // father's mother
rel grandmother(a, c) :- mother(a, b), mother(b, c) // mother's mother
\end{verbatim}

Conjunctions and disjunctions can also be expressed using logical connectives like \& and \lor. For instance, the following rule is equivalent to the above two rules combined.

\begin{verbatim}
rel grandmother(a, c) = (mother(a, b) \lor father(a, b)) \& mother(b, c)
\end{verbatim}

Scallop supports value creation by means of foreign functions (FFs). FFs are polymorphic and include arithmetic operators such as \(+\) and \(-\), comparison operators such as \(!=\) and \(\geq\), type conversions such as \([\text{i32}]\) as \text{String}, and built-in functions like \$hash and \$string_concat. They only operate on primitive values but not relational tuples or atoms. The following example shows how strings are concatenated together using FF, producing the result \texttt{full_name("Alice Lee")}.

\begin{verbatim}
rel first_name("Alice"), last_name("Lee")
rel full_name($string_concat(x, "␣", y)) = first_name(x), last_name(y)
\end{verbatim}

Note that FFs can fail due to runtime errors such as division-by-zero and integer overflow, in which case the computation for that single fact is omitted. In the example below, when dividing 6 by denominator, the result is not computed for denominator 0 since it causes a FF failure:

\begin{verbatim}
rel denominator = \{0, 1, 2\} // there are 3 denominators
rel result(6 / x) = denominator(x) // results contain only integers 3 and 6
\end{verbatim}

The purpose of this semantics is to support probabilistic extensions (Section 3.3) rather than silent suppression of runtime errors. When dealing with floating-point numbers, tuples with NaN (not-a-number) are also discarded.

Recursion. A relation \texttt{r} is dependent on \texttt{s} if an atom \texttt{s} appears in the body of a rule with head atom \texttt{r}. A recursive relation is one that depends on itself, directly or transitively. The following rule derives additional kinship facts by composing existing kinship facts using \texttt{composition} relation.

\begin{verbatim}
rel kinship(r3,a,c) = kinship(r1,a,b), kinship(r2,b,c), composition(r1,r2,r3)
\end{verbatim}

Negation. Scallop supports stratified negation using the \texttt{not} operator on atoms in the rule body. The following example shows a rule defining the \texttt{has_no_children} relation as any person \texttt{p} who is neither a father nor a mother. Note that we need to bound \texttt{p} by a positive atom \texttt{person} in order for the rule to be well-formed.

\begin{verbatim}
rel person = \{"Alice", "Bob", "Christine"\} // can omit () since arity is 1
rel has_no_children(p) = person(p) \&\& not father(_, p) \&\& not mother(_, p)
\end{verbatim}

A relation \texttt{r} is negatively dependent on \texttt{s} if a negated atom \texttt{s} appears in the body of a rule with head atom \texttt{r}. In the above example, \texttt{has_no_children} negatively depends on \texttt{father}. A relation cannot be negatively dependent on itself, directly or transitively, as Scallop supports only stratified negation. The following rule is rejected by the compiler, as the negation is not stratified:

\begin{verbatim}
rel something_is_true() = not something_is_true() // compilation error!
\end{verbatim}
Aggregation. Scallop also supports stratified aggregation. The set of built-in aggregators include common ones such as count, sum, max, and first-order quantifiers forall and exists. Besides the operator, the aggregation specifies the binding variables, the aggregation body to bound those variables, and the result variable(s) to assign the result. The aggregation in the example below reads, “variable n is assigned the count of p, such that p is a person”:

```
rel num_people(n) = n := count(p: person(p))
```

In the rule, p is the binding variable and n is the result variable. Depending on the aggregator, there could be multiple binding variables or multiple result variables. Further, Scallop supports SQL-style group-by using a where clause in the aggregation. In the following example, we compute the number of children of each person p, which serves as the group-by variable.

```
rel parent(a, b) = father(a, b) or mother(a, b)
rel num_child(p, n) = n := count(c: parent(c, p) where p: person(p))
```

Finally, quantifier aggregators such as forall and exists return one boolean variable. For instance, in the aggregation below, variable sat is assigned the truthfulness (true or false) of the following statement: “for all a and b, if b is a’s father, then a is b’s son or daughter”.

```
rel integrity_constraint(sat) = sat := forall(a, b: father(a, b) implies (son(b, a) or daughter(b, a)))
```

There are a couple of syntactic checks on aggregations. First, similar to negation, aggregation also needs to be stratified—a relation cannot be dependent on itself through an aggregation. Second, the binding variables must be bounded by a positive atom in the body of the aggregation.

### 3.3 Probabilistic Extensions

Although Scallop is designed primarily for neurosymbolic programming, its syntax also supports probabilistic programming. This is especially useful when debugging Scallop code before integrating it with a neural network. Consider a machine learning programmer who wishes to extract structured relations from a natural language sentence “Bob takes his daughter Alice to the beach”. The programmer could imitate a neural network producing a probability distribution of kinship relations between Alice (A) and Bob (B) as follows:

```
rel kinship = {0.95::(FATHER, A, B); 0.01::(MOTHER, A, B); ... }
```

Here, we list out all possible kinship relations between Alice and Bob. For each of them, we use the syntax [PROB]::[TUPLE] to tag the kinship tuples with probabilities. The semicolon “;” separating them specifies that they are mutually exclusive—Bob cannot be both the mother and father of Alice.

Scallop also supports operators to sample from probability distributions. They share the same surface syntax as aggregations, allowing sampling with group-by. The following rule deterministically picks the most likely kinship relation between a given pair of people a and b, which are implicit group-by variables in this aggregation. As the end, only one fact, 0.95::top_1_kinship(FATHER, A, B), will be derived according to the above probabilities.

```
rel top_1_kinship(r, a, b) = r := top<1>(rp: kinship(rp, a, b))
```

Other types of sampling are also supported, including categorical sampling (categorical<K>) and uniform sampling (uniform<K>), where a static constant K denotes the number of trials.

Finally, rules can also be tagged by probabilities which can reflect their confidence. The following rule states that a grandmother’s daughter is one’s mother with 90% confidence.

```
rel 0.9::mother(a, c) = grandmother(a, b) and daughter(b, c)
```

Probabilistic rules are syntactic sugar. They are implemented by introducing in the rule’s body an auxiliary 0-ary (i.e., boolean) fact that is regarded true with the tagged probability.
4 REASONING FRAMEWORK

The preceding section presented Scallop’s surface language for use by programmers to express discrete reasoning. However, the language must also support differentiable reasoning to enable end-to-end training. In this section, we formally define the semantics of the language by means of a provenance framework. We show how Scallop uniformly supports different reasoning modes—discrete, probabilistic, and differentiable—simply by defining different provenances.

We start by presenting the basics of our provenance framework (Section 4.1). We then present a low-level representation SclRam, its operational semantics, and its interface to the rest of a Scallop application (Sections 4.2-4.4). We next present differentiation and three different provenances for differentiable reasoning (Section 4.5). Lastly, we discuss practical considerations (Section 4.6).

4.1 Provenance Framework

Scallop’s provenance framework enables to tag and propagate additional information alongside relational tuples in the logic program’s execution. The framework is based on the theory of provenance semirings [Green et al. 2007]. Fig. 4 defines Scallop’s algebraic interface for provenance. We call the additional information a tag t from a tag space T. There are two distinguished tags, 0 and 1, representing unconditionally false and true tags. Tags are propagated through operations of binary disjunction ⊕, binary conjunction ⊗, and unary negation ⊖ resembling logical or, and, and not. Lastly, a saturation check ⋈ serves as a customizable stopping mechanism for fixed-point iteration.

All of the above components combined form a 7-tuple (T, 0, 1, ⊕, ⊗, ⊖, ⋈) which we call a provenance T. Scallop provides a built-in library of provenances and users can add custom provenances simply by implementing this interface.

Example 4.1. max−min−prob (mmp) ≜ ([0, 1], 0, 1, max, min, λx. (1 − x), =), is a built-in probabilistic provenance, where tags are numbers between 0 and 1 that are propagated with max and min. The tags do not represent true probabilities but are merely an approximation. We discuss richer provenances for more accurate probability calculations later in this section.

A provenance must satisfy a few properties. First, the 5-tuple (T, 0, 1, ⊕, ⊗) should form a semiring. That is, 0 is the additive identity and annihilates under multiplication, 1 is the multiplicative identity, ⊕ and ⊗ are associative and commutative, and ⊗ distributes over ⊕. To guarantee the existence of fixed points (which are discussed in Section 4.3), it must also be absorptive, i.e., t₁ ⊕ (t₁ ⊗ t₂) = t₁ [Dannert et al. 2021]. Moreover, we need ⊖ 0 = 1, ⊖ 1 = 0, 0 ⊗ 1 = 0 ⊗ 0, and 1 ⊕ 1. A provenance which violates an individual property (e.g. absorptive) is still useful to applications that do not use the affected features (e.g. recursion) or if the user simply wishes to bypass the restrictions.

4.2 SclRam Intermediate Language

Scallop programs are compiled to a low-level representation called SclRam. Fig. 5 shows the abstract syntax of a core fragment of SclRam. Expressions resemble queries in an extended relational algebra. They operate over relational predicates (p) using unary operations for aggregation (∫

Fig. 4. Algebraic interface for provenance. Fig. 5. Abstract syntax of core fragment of SclRam.
We now present the operational semantics for our core fragment of SclRam.

Fig. 6. Semantic domains for SclRam.

with aggregator \( g \), projection \( \pi_\alpha \) with mapping \( \alpha \), and selection \( \sigma_\beta \) with condition \( \beta \), and binary operations union (\( \cup \)), product (\( \times \)), and difference (\( \setminus \)).

A rule \( r \) in SclRam is denoted \( p \leftarrow e \), where predicate \( p \) is the rule head and expression \( e \) is the rule body. An unordered set of rules combined form a stratum \( s \), and a sequence of strata \( s_1; \ldots; s_n \) constitutes a SclRam program. Rules in the same stratum have distinct head predicates. Denoting the set of head predicates in stratum \( s \) by \( P_s \), we also require \( P_{s_i} \cap P_{s_j} = \emptyset \) for all \( i \neq j \) in a program. Stratified negation and aggregation from the surface language is enforced as syntax restrictions in SclRam: within a rule in stratum \( s_i \), if a relational predicate \( p \) is used under aggregation (\( \gamma \)) or right-hand-side of difference (\( \setminus \)), that predicate \( p \) cannot appear in \( P_{s_j} \) if \( j \geq i \).

We next define the semantic domains in Fig. 6 which are used subsequently to define the semantics of SclRam. A tuple \( u \) is either a constant or a sequence of tuples. A fact \( p(u) \in F \) is a tuple \( u \) named under a relational predicate \( p \). Tuples and facts can be tagged, forming tagged tuples (\( t :: u \)) and tagged facts (\( t :: p(u) \)). Given a set of tagged tuples \( U_T \), we say \( U_T \uplus u \) iff there exists a \( t \) such that \( t :: u \in U_T \). A set of tagged facts form a database \( F_T \). We use bracket notation \( F_T[p] \) to denote the set of tagged facts in \( F_T \) under predicate \( p \).

4.3 Operational Semantics of SclRam

We now present the operational semantics for our core fragment of SclRam in Fig. 7. A SclRam program \( \bar{s} \) takes as input an extensional database (EDB) \( F_T \), and returns an intentional database (IDB) \( F'_T = \llbracket \bar{s} \rrbracket (F_T) \). The semantics is conditioned on the underlying provenance \( T \). We call this tagged semantics, as opposed to the untagged semantics found in traditional Datalog.

Basic Relational Algebra. Evaluating an expression in SclRam yields a set of tagged tuples according to the rules defined at the top of Fig. 7. A predicate \( p \) evaluates to all facts under that predicate in the database. Selection filters tuples that satisfy condition \( \beta \), and projection transforms tuples according to mapping \( \alpha \). The mapping function \( \alpha \) is partial: it may fail since it can apply foreign functions to values. A tuple in a union \( e_1 \cup e_2 \) can come from either \( e_1 \) or \( e_2 \). In (cartesian) product, each pair of incoming tuples combine and we use \( \otimes \) to compute the tag conjunction.

Difference and Negation. To evaluate a difference expression \( e_1 \setminus e_2 \), there are two cases depending on whether a tuple \( u \) evaluated from \( e_1 \) appears in the result of \( e_2 \). If it does not, we simply propagate the tuple and its tag to the result (DIFF-1); otherwise, we get \( t_1 :: u \) from \( e_1 \) and \( t_2 :: u \) from \( e_2 \). Instead of erasing the tuple \( u \) from the result as in untagged semantics, we propagate a tag \( t_1 \otimes (\ominus t_2) \) with \( u \) (DIFF-2). In this manner, information is not lost during negation. Fig. 8 compares the evaluations of an example difference expression under different semantics. While the tuple \((2,3)\) is removed in the outcome with untagged semantics, it remains with the tagged semantics.

Aggregation. Aggregators in SclRam are discrete functions \( g \) operating on set of (untagged) tuples \( U \in \mathcal{U} \). They return a set of aggregated tuples to account for aggregators like \( \arg\max \) which can produce multiple outcomes. For example, we have \( \text{count}(U) = \{|U|\} \). However, in the probabilistic domain, discrete symbols do not suffice. Given \( n \) tagged tuples to aggregate over, each tagged tuple can be turned on or off, resulting in \( 2^n \) distinct worlds. Each world is a partition of the input set \( U_T (|U_T| = n) \). Denoting the positive part as \( X_T \) and the negative part as \( \bar{X}_T = U_T - X_T \), the tag associated with this world is a conjunction of tags in \( X_T \) and negated tags in \( \bar{X}_T \). Aggregating on
Expression semantics
\[ \begin{align*}
\alpha : \mathbb{U} &\rightarrow \mathbb{U}, & \beta : \mathbb{U} &\rightarrow \text{Bool}, & g : \mathbb{U} &\rightarrow \mathbb{U}, & \llbracket e \rrbracket : \mathcal{F}_{T} &\rightarrow \mathcal{U}_{T} \\
\end{align*} \]

\[
\begin{align*}
& t : p(u) \in \mathcal{F}_{T} \quad \text{(PREDICATE)} \quad t : u \in \llbracket e \rrbracket (\mathcal{F}_{T}) \\
& t : u \in [p](\mathcal{F}_{T}) \quad t : u \in [\sigma_{\beta}(e)](\mathcal{F}_{T}) \quad (\beta(u) = \text{true}) \quad (\text{SELECT}) \quad t : u \in \llbracket e \rrbracket (\mathcal{F}_{T}) \quad u' = \alpha(u) \quad (\text{PROJECT}) \\
& t : u \in [e_{1}](\mathcal{F}_{T}) \cup [e_{2}](\mathcal{F}_{T}) \quad (\text{UNION}) \quad t : u \in [e_{1} \cap e_{2}](\mathcal{F}_{T}) \\
& t : u \in [e_{1}](\mathcal{F}_{T}) \quad (\text{DIFF-1}) \quad t : u \in [e_{1} \cap e_{2}](\mathcal{F}_{T}) \quad (\text{DIFF-2}) \\
& t : u \in [\llbracket e \rrbracket (\mathcal{F}_{T}) \setminus u] \quad (\text{AGGREGATE}) \\
\end{align*} \]

Rule semantics
\[
\begin{align*}
\text{(NORMALIZE)} \\
& \llbracket \bigcup_{i=1}^{n} t_{i} \rrbracket : u \quad \text{if } t_{1} : u, \ldots, t_{n} : u \text{ are all tagged-tuples in } \mathcal{U}_{T} \text{ with the same tuple } u \\
& r_{\text{old}} : p(u) \in [p](\mathcal{F}_{T}) \quad (\text{RULE-1}) \quad t_{\text{new}} : u \in \llbracket e \rrbracket (\mathcal{F}_{T}) \quad [p](\mathcal{F}_{T}) \not\equiv u \quad (\text{RULE-2}) \\
& (r_{\text{old}} \oplus t_{\text{new}}) \cdot p(u) \in [p \leftarrow e](\mathcal{F}_{T}) \quad (\text{RULE-3}) \\
\end{align*} \]

Stratum and Program semantics
\[
\begin{align*}
& \text{IFP}^{\text{old}} : (\mathcal{F}_{T} \rightarrow \mathcal{F}_{T}) \rightarrow (\mathcal{F}_{T} \rightarrow \mathcal{F}_{T}), \quad [\mathcal{S}] : \mathcal{F}_{T} \rightarrow \mathcal{F}_{T} \\
& \text{IFP}^{\text{old}} (h) = h \circ \cdots \circ h = h^{n} \text{ if there exists a minimum } n > 0, \text{ such that } h^{n}(\mathcal{F}_{T}) = h^{n+1}(\mathcal{F}_{T}) \\
& \text{IFP}^{\text{new}} (\mathcal{F}_{T}) = \mathcal{F}_{T} \cup \{ \bigcup_{p \in \mathcal{F}_{T}} [p] \} \\
& \text{IFP}^{\text{old}} \oplus \text{IFP}^{\text{new}} : \mathcal{F}_{T} \rightarrow \mathcal{F}_{T} \text{ such that } r_{\text{old}} \oplus t_{\text{new}} \\
\end{align*} \]

Fig. 7. Operational semantics of core fragment of ScRLam.

\[
\begin{align*}
\text{rel safe-cell} (x, y) = \text{grid-cell} (x, y), \quad \text{not enemy} (x, y) \quad \rightarrow \quad \text{safe-cell } \leftarrow \text{grid-cell } - \text{enemy} \\
\end{align*} \]

(a) Untagged semantics (b) ScRLam tagged semantics (c) ScRLam with max-min-prob

Fig. 8. An example rule adapted from Section 2 is compiled into a ScRLam rule with difference. g and e are abbreviated relation names. The graphs illustrate the evaluation of expression \( g - e \) under different semantics.

The world then involves applying aggregator \( g \) on tuples in the positive part \( X_{T} \). This is inherently exponential if we enumerate all worlds. However, we can optimize over each aggregator and each provenance to achieve better performance. For instance, counting over max-min-prob tagged tuples can be implemented by an \( O(n \log(n)) \) algorithm, much faster than exponential. Fig. 9 demonstrates a running example and an evaluation of a counting expression under max-min-prob provenance. The resulting count can be 0-9, each derivable by multiple worlds.

Rules and Fixed-Point Iteration. Evaluating a rule \( p \leftarrow e \) on database \( F_{T} \) concerns evaluating the expression \( e \) and merging the result with the existing facts under predicate \( p \) in \( F_{T} \). The result of

Recursion in \( SclRam \) means evaluating all the rules in \( lfp \) on the set to join (\( \oplus \)) the distinct tags. From here, there are three cases to merge the newly derived tuples (union, projection, or aggregation). Therefore, we perform normalization on the set to join (\( \oplus \)) the distinct tags. For instance, all tags such as \( \llbracket \cdot \rrbracket \) represents a world corresponding to our arena (\( \blacksquare \): enemy; \( \square \): no enemy). A world is a conjunction of 9 tags, e.g., \( \llbracket \cdot \rrbracket = t_A3 \odot (\ominus t_A2) \odot \cdots \odot (\ominus t_C1) \). We mark the correct world \( \blacksquare \) which yields the answer 2.

Recursion in \( SclRam \) is realized similar to least fixed point iteration in Datalog [Abiteboul et al. 1995]. The iteration happens on a per-stratum basis to enforce stratified negation and aggregation. Evaluating a single step of stratum \( s \) means evaluating all the rules in \( s \) and returning the updated database. Note that we define a specialized least fixed point operator \( lfp^\circ \), which stops the iteration once the whole database is saturated. Fig. 10 illustrates an evaluation involving recursion and database saturation. The whole database saturates on the 7th iteration, and finds the tag representing the optimal path for the PacMan to reach the goal. Termination is not universally guaranteed in \( SclRam \) due to the presence features such as value creation. But its existence can be proven in a per-provenance basis. For example, it is easy to show that if a program terminates under untagged semantics, then it terminates under tagged semantics with max-min-prob provenance.

### 4.4 External Interface and Execution Pipeline

Thus far, we have only illustrated the max-min-prob provenance, in which the tags are approximated probabilities. There are other probabilistic provenances with more complex tags such as proof trees or boolean formulae. We therefore introduce, for each provenance \( T \), an input tag space \( I \), an output tag space \( O \), a tagging function \( \tau : I \rightarrow T \), and a recover function \( \rho : T \rightarrow O \). For instance, all probabilistic provenances share the same input and output tag spaces \( I = O = [0, 1] \) for a unified interface, while the internal tag spaces \( T \) could be different. We call the 4-tuple \( (I, O, \tau, \rho) \) the external interface for a provenance \( T \). The whole execution pipeline is then illustrated below:

\[
\begin{aligned}
F_{\text{option}} \xrightarrow{\tau} F_T \xrightarrow{\text{SclRam program, } \bar{x}} F'_T \xrightarrow{\rho} F_O
\end{aligned}
\]

In the context of a Scallop application, an EDB is provided in the form \( F_{\text{option}} \). During the tagging phase, \( \tau \) is applied to each input tag to obtain \( F_T \), following which the SclRam program operates on \( F_T \). For convenience, not all input facts need to be tagged—untagged input facts are simply
### 4.5 Differentiable Reasoning with Provenance

We now elucidate how provenance also supports differentiable reasoning. Let all the probabilities in the EDB form a vector $\vec{r} \in \mathbb{R}^n$, and the probabilities in the resulting IDB form a vector $\vec{y} \in \mathbb{R}^m$. Differentiation concerns deriving output probabilities $\vec{y}$ as well as the derivative $\nabla \vec{y} = \frac{\partial \vec{y}}{\partial \vec{r}} \in \mathbb{R}^{m \times n}$.

In Scallop, one can obtain these using a *differentiable provenance (DP)*. DPs share the same external interface—let the input tag space $I = [0, 1]$ and output tag space $O$ be the space of *dual-numbers* $\mathbb{D}$ (Fig. 12). Now, each input tag $r_i \in [0, 1]$ is a probability, and each output tag $y_j = (y_j, \nabla y_j)$ encapsulates the output probability $y_j$ and its derivative w.r.t. inputs, $\nabla y_j$. From here, we can obtain our expected output $\hat{y}$ and $\nabla \hat{y}$ by stacking together $y_j$-s and $\nabla y_j$-s respectively.

Scallop provides 8 configurable built-in DPs with different empirical advantages in terms of runtime efficiency, reasoning granularity, and performance. In this section, we elaborate upon 3 simple but versatile DPs, whose definitions are shown in Fig. 11. In the following discussion, we use $r_i$ to denote the $i$-th element of $\vec{r}$, where $i$ is called a *variable* (ID). Vector $\vec{e}_i \in \mathbb{R}^n$ is the standard basis vector where all entries are 0 except the $i$-th entry.

#### 4.5.1 diff-max-min-prob (dmmp)

This provenance is the differentiable version of mmp. When obtaining $r_i$ from an input tag, we transform it into a dual-number by attaching $\vec{e}_i$ as its derivative. Note that throughout the execution, the derivative will always have at most one entry being non-zero and, specifically, 1 or $-1$. The saturation check is based on equality of the probability part only, so that the derivative does not affect termination. All of its operations can be implemented by algorithms with time complexity $O(1)$, making it extremely runtime-efficient.

#### 4.5.2 diff-add-mult-prob (damp)

This provenance has the same internal tag space, tagging function, and recover function as dmmp. As suggested by its name, its disjunction and conjunction operations are just $+$ and $\cdot$ for dual-numbers. When performing disjunction, we clamp the real part of the dual-number obtained from performing $+$, while keeping the derivative the same. The saturation function for damp is designed to always returns true to avoid non-termination. But this decision makes it less suitable for complex recursive programs. The time complexity of operations in damp is $O(n)$, which is slower than dmmp but is still very efficient in practice.
4.6 Practical Considerations

We finally discuss some practical aspects concerning SCLRAM extensions and provenance selection. Additional Features. We only presented the syntax and semantics of the core fragment of SCLRAM. SCLRAM additionally supports the following useful features: 1) sampling operations, and the provenance extension supporting them, 2) group-by aggregations, 3) tag-based early removal and its extension in provenance, and 4) mutually exclusive tags in dtkp.

Provenance Selection. A natural question is how to select a differentiable provenance for a given Scallop application. Based on our empirical evaluation in Section 6, dtkp is often the best performing one, and setting \( k = 3 \) is usually a good choice for both runtime efficiency and learning performance. This suggests that a user can start with dtkp as the default. In general, the provenance selection process is similar to the process of hyperparameter tuning common in machine learning.

5 IMPLEMENTATION
We implemented the core Scallop system in 45K LoC of Rust. The LoC of individual modules is shown in Table 1. Within the compiler, there are two levels of intermediate representations, front-IR and back-IR, between the surface language and the ScLRAM language. In front-IR, we perform analyses such as type inference and transformations such as desugaring. In back-IR, we generate query plans and apply optimizations. The runtime operates directly on ScLRAM and is based on semi-naive evaluation specialized for tagged semantics. There are dynamic and static runtimes for interpreted and compiled ScLRAM programs.
Currently, all computation is on CPU only, but can be parallelized per-batch for machine learning.

Scallop can be used through different interfaces such as interpreter, compiler, and interactive terminal. It also provides language bindings such as scallopy for Python and scallop-wasm for WebAssembly and JavaScript. With scallopy, Scallop can be seamlessly integrated with machine learning frameworks such as PyTorch, wherein the scallopy module is treated just like any other PyTorch module. When jit is specified in scallopy, Scallop programs can be just-in-time (JIT) compiled to Rust, turned into binaries, and dynamically loaded into the Python environment.

Scallop provides 18 built-in provenances (4 for discrete reasoning, 6 for probabilistic, and 8 for differentiable). The WMC algorithm is implemented using sentential decision diagram (SDD) [Darwiche 2011] with naive bottom-up compilation. We allow each provenance to provide its own implementation for operations such as aggregation and sampling. This gives substantial freedom and enables optimizations for complex operations. Our provenance framework is also interfaced with scallopy, allowing to quickly create and test new provenances in Python.

6 EVALUATION
We evaluate the Scallop language and framework on a benchmark suite comprising eight neuro-symbolic applications. Our evaluation aims to answer the following research questions:

RQ1 How expressive is Scallop for solving diverse neuro-symbolic tasks?
RQ2 How do Scallop’s solutions compare to state-of-the-art baselines in terms of accuracy?
RQ3 Is the differentiable reasoning module of Scallop runtime-efficient?
RQ4 Is Scallop effective at improving generalizability, interpretability, and data-efficiency?
RQ5 What are the failure modes of Scallop solutions and how can we mitigate them?

In the following sections, we first introduce the benchmark tasks and the chosen baselines for each task (Section 6.1). Then, we answer RQ1 to RQ5 in Section 6.2 to Section 6.6 respectively. All Scallop related and runtime related experiments were conducted on a machine with two 20-core Intel Xeon CPUs, four GeForce RTX 2080 Ti GPUs, and 768 GB RAM.

6.1 Benchmarks and Baselines
We present an overview of our benchmarks in Fig. 14. They cover a wide spectrum of tasks involving perception and reasoning. The input data modality ranges from images and videos to natural language texts and knowledge bases (KB). The size of the training dataset is also presented in the figure. We next elaborate on the benchmark tasks and their corresponding baselines.

**MNIST-R**: A Synthetic MNIST Test Suite. This benchmark is designed to test various features of Scallop such as negation and aggregation. Each task takes as input one or more images of handwritten digits from the MNIST dataset [Lecun et al. 1998] and performs simple arithmetic (sum2, sum3, sum4), comparison (less-than), negation (not-3-or-4), or counting (count-3, count-3-or-4) over the depicted digits. For count-3 and count-3-or-4, we count digits from a set of 8 images. For
this test suite, we use a CNN-based model, DeepProbLog (DPL) [Manhaeve et al. 2021], and our prior work [Huang et al. 2021] (Prior) as the baselines.

**HWF.** : *Hand-Written Formula Parsing and Evaluation.* HWF, proposed in [Li et al. 2020], concerns parsing and evaluating hand-written formulas. The formula is provided in the form of a sequence of images, where each image represents either a digit (0–9) or an arithmetic symbol (+, −, ×, ÷). Formulas are well-formed according to a grammar and do not divide by zero. The size of the formulas ranges from 1 to 7 and is indicated as part of the input. The goal is to evaluate the formula to obtain a rational number as the result. We choose from [Li et al. 2020] the baselines NGS-m-BS, NGS-RS, and NGS-MAPPO, which are *neurosymbolic methods* designed specifically for this task.

**Pathfinder.** : *Image Classification with Long-Range Dependency.* In this task from [Tay et al. 2020], the input is an image containing two dots that are possibly connected by curved and dashed lines. The goal is to tell whether the dots are connected. There are two subtasks, Path and Path-X, where Path contains $32 \times 32$ images and Path-X contains $128 \times 128$ ones. We pick as baselines standard CNN and Transformer based models, as well as the state-of-the-art neural models S4 [Gu et al. 2021], S4* [Gu et al. 2022], and SGConv [Li et al. 2022].

**PacMan-Maze.** : *Playing PacMan Maze Game.* As presented in Section 2, this task tests an agent’s ability to recognize entities in an image and plan the path for the PacMan to reach the goal. An RL environment provides the game state image as input and the agent must plan the optimal action {up, down, left, right} to take at each step. There is no “training dataset” as the environment is randomized for every session. We pick as baseline a CNN based Deep-Q-Network (DQN). Unlike other tasks, we use the “success rate” metric for evaluation, i.e., among 1000 game sessions, we measure the number of times the PacMan reaches the goal within a certain time-budget.

**CLUTRR.** : *Kinship Reasoning from Natural Language Context.* In this task from [Sinha et al. 2019], the input contains a natural language (NL) passage about a set of characters. Each sentence in the passage hints at kinship relations. The goal is to infer the relationship between a given pair of characters. The target relation is not stated explicitly in the passage and it must be deduced through a reasoning chain. Our baseline models include RoBERTa [Liu et al. 2019], BiLSTM [Graves et al. 2013], GPT-3-FT (fine-tuned), GPT-3-ZS (zero-shot), and GPT-3-DS (5-shot) [Brown et al. 2020]. In an alternative setup, CLUTRR-G, instead of the NL passage, the structured kinship graph
corresponding to the NL passage is provided, making it a Knowledge Graph Reasoning problem. For CLUTRR-G, we pick GAT [Veličković et al. 2017] and CTP [Minervini et al. 2020] as baselines.

**Mugen.** : Video-Text Alignment and Retrieval. Mugen [Hayes et al. 2022] is based on a game called CoinRun [Cobbe et al. 2019]. In the video-text alignment task, the input contains a 3.2 second long video of gameplay footage and a short NL paragraph describing events happening in the video. The goal is to compute a similarity score representing how “aligned” they are. There are two subsequent tasks, Video-to-Text Retrieval (VTR) and Text-to-Video Retrieval (TVR). In TVR, the input is a piece of text and a set of 16 videos, and the goal is to retrieve the video that best aligns with the text. In VTR, the goal is to retrieve text from video. We compare our method with SDSC [Hayes et al. 2022].

**CLEVR.** : Compositional Language and Elementary Visual Reasoning [Johnson et al. 2017]. In this visual question answering (VQA) task, the input contains a rendered image of geometric objects and a NL question that asks about counts, attributes, and relationships of objects. The goal is to answer the question based on the image. We pick as baselines NS-VQA [Yi et al. 2018] and NSCL [Mao et al. 2019], which are neurosymbolic methods designed specifically for this task.

**VQAR.** : Visual-Question-Answering with Common-Sense Reasoning. This task, like CLEVR, also concerns VQA but with three salient differences: it contains real-life images from the GQA dataset [Hudson and Manning 2019]; the queries are in a programmatic form, asking to retrieve objects in the image; and there is an additional input in the form of a common-sense knowledge base (KB) [Gao et al. 2019] containing triplets such as (giraffe, is-a, animal) for common-sense reasoning. The baselines for this task are NMNs [Andreas et al. 2016] and LXMERT [Tan and Bansal 2019].

### 6.2 RQ1: Our Solutions and Expressivity

To answer RQ1, we demonstrate our Scallop solutions to the benchmark tasks (Table 2). For each task, we specify the interface relations which serve as the bridge between the neural and symbolic components. The neural modules process the perceptual input and their outputs are mapped to (probabilistic) facts in the interface relations. Our Scallop programs subsequently take these facts as input and perform the described reasoning to produce the final output. As shown by the features column, our solutions use all of the core features provided by Scallop.

The complete Scallop program for each task is provided in [Li et al. 2023]. These programs are succinct, as indicated by the LoCs in the last column of Table 2. We highlight three tasks, HWF, Mugen, and CLEVR, to demonstrate Scallop’s expressivity. For HWF, the Scallop program consists of a formula parser. It is capable of parsing probabilistic input symbols according to a context free grammar for simple arithmetic expressions. For Mugen, the Scallop program is a temporal specification checker, where the specification is extracted from NL text to match the sequential events excerpted from the video. For CLEVR, the Scallop program is an interpreter for CLEVR-DSL, a domain-specific functional language introduced in the CLEVR dataset [Johnson et al. 2017].

We note that our prior work [Huang et al. 2021], which only supports positive Datalog, cannot express 5 out of the 8 tasks since they need negation and aggregation, as indicated by columns ‘N’ and ‘A’. Moreover, HWF requires floating point support which is also lacking in our prior work.

Besides diverse kinds of perceptual data and reasoning patterns, the Scallop programs are applied in a variety of learning settings. As shown in Section 2, the program for PacMan-Maze is used in an online representation learning setting. For CLUTRR, we write integrity constraints (similar to the one shown in Section 3.2) to derive semantic loss used for constraining the language model outputs. For CLUTRR-G, learnable weights are attached to composition facts such as composition(FATHER, MOTHER, GRANDMOTHER), which enables to learn such facts from data akin to rule learning in ILP.
Table 2. Characteristics of Scallop solutions for each task. Structured input which is not learnt is denoted by \(^*\). Neural models used are RoBERTa [Liu et al. 2019], DistilBERT [Sanh et al. 2019], and BiLSTM [Graves et al. 2013] for natural language (NL), CNN and FastRCNN [Girshick 2015] for images, and S3D [Xie et al. 2018] for video. We show the three key features of Scallop used by each solution: (R)ecursion, (N)egation, and (A)ggregation. †: For MNIST-R, the LoC is 2 for every subtask.

<table>
<thead>
<tr>
<th>Task</th>
<th>Input</th>
<th>Neural Net</th>
<th>Interface Relation(s)</th>
<th>Scallop Program</th>
<th>Features</th>
<th>LoC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNIST-R</td>
<td>Images</td>
<td>CNN</td>
<td>digit(id, digit)</td>
<td>Arithmetic, comparison, negation, and counting.</td>
<td>✔ ✔ ✔</td>
<td>2†</td>
</tr>
<tr>
<td>HWF</td>
<td>Images</td>
<td>CNN</td>
<td>symbol(id, symbol) length(len)</td>
<td>Parses and evaluates formula over recognized symbols.</td>
<td>✔</td>
<td>39</td>
</tr>
<tr>
<td>Pathfinder</td>
<td>Image</td>
<td>CNN</td>
<td>dot(id) dash(from_id, to_id)</td>
<td>Checks if the dots are connected by dashes.</td>
<td>✔</td>
<td>4</td>
</tr>
<tr>
<td>PacMan-Maze</td>
<td>Image</td>
<td>CNN</td>
<td>actor(x, y) enemy(y, x) goal(x, y)</td>
<td>Plans the optimal action by finding an enemy-free path from actor to goal.</td>
<td>✔ ✔ ✔</td>
<td>31</td>
</tr>
<tr>
<td>CLUTTR (-G)</td>
<td>Query</td>
<td>-</td>
<td>question(sub, obj)</td>
<td>Deduces queried relationship by recursively applying learnt composition rules.</td>
<td>✔ ✔ ✔</td>
<td>8</td>
</tr>
<tr>
<td>CLUTTR (+G)</td>
<td>Rule</td>
<td>composition(r1, r2, r3)</td>
<td></td>
<td></td>
<td>✔ ✔ ✔</td>
<td>8</td>
</tr>
<tr>
<td>Mugen</td>
<td>Video</td>
<td>S3D</td>
<td>action(frame, action, mod)</td>
<td>Checks if events specified in NL text match the actions recognized from the video.</td>
<td>✔ ✔ ✔</td>
<td>46</td>
</tr>
<tr>
<td>CLEVR</td>
<td>Image</td>
<td>FastRCNN</td>
<td>obj_attr(obj_id, attr, val) obj_rela(rela, o1, o2)</td>
<td>Interprets CLEVR-DSL program (extracted from question) on scene graph (extracted from image).</td>
<td>✔ ✔ ✔</td>
<td>51</td>
</tr>
<tr>
<td>VQAR</td>
<td>Image</td>
<td>FastRCNN</td>
<td>obj_name(obj_id, name) obj_attr(obj_id, val) obj_rela(rela, o1, o2)</td>
<td>Evaluates query over scene graphs (extracted from image) with the aid of common-sense knowledge base (KB).</td>
<td>✔</td>
<td>42</td>
</tr>
</tbody>
</table>

For Mugen, our program is trained in a contrastive learning setup, since it requires to maximize similarity scores between aligned video-text pairs but minimize that for un-aligned ones.

6.3 RQ2: Performance and Accuracy

To answer RQ2, we evaluate the performance and accuracy of our methods in terms of two aspects: 1) the best performance of our solutions compared to existing baselines, and 2) the performance of our solutions with different provenance structures (\(d_{mmp}, d_{amp}, d_{tkp}\) with different \(k\)).

We start with comparing our solutions against selected baselines on all the benchmark tasks, as shown in Fig. 15, Table 3, and Fig. 17. First, we highlight two applications, PacMan-Maze and CLUTTR, which benefit the most from our solution. For PacMan-Maze, compared to DQN, we obtain a 1,000\% speed-up in terms of training episodes, and a near perfect success rate of 99.4\%. Note that our solution encodes environment dynamics (i.e. game rules) which are unavailable and hard to incorporate in the DQN model. For CLUTTR, we obtain a 25\% improvement over baselines, which includes GPT-3-FT, the state-of-the-art large language model fine-tuned on the CLUTTR dataset. Next, for tasks such as HWF and CLEVR, our solutions attain comparable performance, even compared to neurosymbolic baselines NGS-m-BS, NSCL, and NS-VQA specifically designed for each task. On Path and Path-X, our solution obtains a 4\% accuracy gain over our underlying model CNN and even outperforms a carefully designed transformer based model S4.

The performance of the Scallop solution for each task depends on the chosen provenance structure. As can be seen from Table 3 and Figs. 15–17, although \(d_{tkp}\) is generally the best-performing one, each presented provenance is useful, e.g., \(d_{tkp}\) for PacMan-Maze and VQAR, \(d_{amp}\) for less-than...
Scallop: A Language for Neurosymbolic Programming

6.4 RQ3: Runtime Efficiency

We evaluate the runtime efficiency of Scallop solutions with different provenance structures and compare it against baseline neurosymbolic approaches. As shown in Table 4, Scallop achieves substantial speed-up over DeepProbLog (DPL) on MNIST-R tasks. DPL is a probabilistic programming system based on Prolog using exact probabilistic reasoning. As an example, on sum4, DPL takes 40 days to finish only 4K training samples, showing that it is prohibitively slow to use in practice. On the contrary, Scallop solutions can finish a training epoch (15K samples) in minutes without sacrificing testing accuracy (according to Fig. 15). For HWF, Scallop achieves comparable runtime efficiency, even when compared against the hand-crafted and specialized NGS-\u1D45A-BS method.

Comparing among provenance structures, we see significant runtime blowup when increasing $k$ for dtkp. This is expected as increasing $k$ results in larger boolean formula tags, making the WMC procedure exponentially slower. In practice, we find $k = 3$ for dtkp to be a good balance point between runtime efficiency and reasoning granularity. In fact, dtkp generalizes DPL, as one can set an extremely large $k \geq 2^n$ ($n$ is the total number of input facts) for exact probabilistic reasoning.

6.5 RQ4: Generalizability, Interpretability, and Data-Efficiency

We now consider other important desirable aspects of machine learning models besides accuracy and runtime, such as generalizability on unseen inputs, interpretability of the outputs, and data-efficiency of the training process. For brevity, we focus on a single benchmark task in each case.
Table 4. Runtime efficiency comparison on selected benchmark tasks. Numbers shown are average training time (sec.) per epoch. Our variants attaining the best accuracy are indicated in bold.

<table>
<thead>
<tr>
<th>Task</th>
<th>Scallop</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>dmp</td>
<td>34</td>
<td>88</td>
</tr>
<tr>
<td>damp</td>
<td>34</td>
<td>119</td>
</tr>
<tr>
<td>dtkp-3</td>
<td>34</td>
<td>154</td>
</tr>
<tr>
<td>dtkp-10</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>sum2</td>
<td>34</td>
<td>154</td>
</tr>
<tr>
<td>sum3</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>sum4</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>less-than</td>
<td>37</td>
<td>33</td>
</tr>
<tr>
<td>not-3-or-4</td>
<td>37</td>
<td>33</td>
</tr>
<tr>
<td>HWF</td>
<td>89</td>
<td>107</td>
</tr>
<tr>
<td>CLEVR</td>
<td>1,964</td>
<td>1,618</td>
</tr>
</tbody>
</table>

Fig. 19. The predicted most likely (action, mod) pair for example video segments from Mugen dataset.

We evaluate Scallop’s generalization ability for the CLUTRR task. Each data-point in CLUTRR is annotated with a parameter $k$ denoting the length of the reasoning chain to infer the target kinship relation. To test different solutions’ systematic generalizability, we train them on data-points with $k \in \{2, 3\}$ and test on data-points with $k \in \{2, \ldots, 10\}$. As shown in Fig. 18, the neural baselines suffer a steep drop in accuracy on the more complex unseen instances, whereas the accuracy of Scallop’s solution degrades more slowly, indicating that it is able to generalize better.

Next, we demonstrate Scallop’s interpretability on the Mugen task. Although the goal of the task is to see whether a video-text pair is aligned, the perceptual model in our method extracts interpretable symbols, i.e., the action of the controlled character at a certain frame. Fig. 19 shows that the predicted (action, mod) pairs perfectly match the events in the video. Thus, our solution not only tells whether a video-text pair is aligned, but also why it is aligned.

Lastly, we evaluate Scallop’s data-efficiency on the HWF task, using lesser training data (Table 5). While methods such as NGS-MAPO suffer significantly when trained on less data, Scallop’s testing accuracy decreases slowly, and is comparable to the data-efficiency of the state-of-the-art neurosymbolic NGS-m-BS method. PacMan-Maze task also demonstrates Scallop’s data-efficiency, as it takes much less training episodes than DQN does, while achieving much higher success rate.

6.6 RQ5: Analysis of Failure Modes

Compared to purely neural models, Scallop solutions provide more transparency, allowing programmers to debug effectively. By manually checking the interface relations, we observed that the main source of error lies in inaccurate predictions from the neural components. For example, the RoBERTa model for CLUTRR correctly extracts only 84.69% of kinship relations. There are two potential causes—either the neural component is not powerful enough, or our solution is not providing adequate supervision to train it. The former can be addressed by employing better neural architectures or more data. The latter can be mitigated in different ways, such as tuning the selected provenance or incorporating integrity constraints (discussed in Section 3.2) into training and/or inference. For instance, in PacMan-Maze, the constraint that “there should be no more than one goal in the arena” helps to improve robustness.

Table 5. Testing accuracy of various methods on HWF when trained with only a portion of the data. Numbers are in percentage (%).

<table>
<thead>
<tr>
<th>%Train</th>
<th>Scallop</th>
<th>NGS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dtkp-5</td>
<td>RL</td>
</tr>
<tr>
<td>100%</td>
<td>97.85</td>
<td>3.4</td>
</tr>
<tr>
<td>50%</td>
<td>95.7</td>
<td>3.6</td>
</tr>
<tr>
<td>25%</td>
<td>92.95</td>
<td>3.5</td>
</tr>
</tbody>
</table>
7 RELATED WORK

We survey related work in four different but overlapping domains: provenance reasoning, Datalog and logic programming, probabilistic and differentiable programming, and neurosymbolic methods.

Relational Algebra and Provenance. Relational algebra is extensively studied in databases [Abiteboul et al. 1995], and extended with recursion [Jachiet et al. 2020] in Datalog. The provenance semiring framework [Green et al. 2007] was first proposed for positive relational algebra (RA+) and later extended with difference [Amsterdamer et al. 2011] and fixed-point [Dannert et al. 2021]. It is deployed in variants of Datalog [Khamis et al. 2021] and supports applications such as program synthesis [Si et al. 2019]. Scallop employs an extended provenance semiring framework and demonstrates its application to configurable differentiable reasoning.

Datalog is a declarative logic programming language where rules are logical formulas. Despite being less expressive than Prolog, it is widely studied in both the programming language and database communities for language extensions and optimizations [Khamis et al. 2021]. A variety of Datalog-based systems has been built for program analysis [Scholz et al. 2016] and enterprise databases [Aref et al. 2015]. Scallop is also a Datalog-based system that extends [Huang et al. 2021] with numerous language constructs such as negation and aggregation.

Probabilistic Programming is a paradigm for programmers to model distributions and perform probabilistic sampling and inference. Such systems include ProbLog [Dries et al. 2015], Pyro [Bingham et al. 2018], Turing [Ge et al. 2018], and PPL [van de Meent et al. 2018]. When integrated with modern ML systems, they are well suited for statistical modeling and building generative models. Scallop also supports ProbLog-style exact probabilistic inference as one instantiation of our provenance framework. But advanced statistical sampling and generative modeling is not yet supported and left for future work.

Differentiable Programming (DP) systems seek to enable writing code that is differentiable. Common practices for DP include symbolic differentiation and automatic differentiation (auto-diff) [Baydin et al. 2015], resulting in popular ML frameworks such as PyTorch [Paszke et al. 2019], TensorFlow [Abadi et al. 2015], and JAX [Bradbury et al. 2018]. However, most of these systems are designed for real-valued functions. Scallop is also a differentiable programming system, but with a focus on programming with discrete, logical, and relational symbols.

Neurosymbolic Methods have emerged to incorporate symbolic reasoning into existing learning systems. Their success has been demonstrated in a number of applications [Chen et al. 2020; Li et al. 2020; Mao et al. 2019; Minervini et al. 2020; Wang et al. 2019; Xu et al. 2022; Yi et al. 2018]. Similar to [Li et al. 2020; Mao et al. 2019; Yi et al. 2018], we focus primarily on solutions involving perception followed by symbolic reasoning. Other ways of incorporating symbolic knowledge include semantic loss [Xu et al. 2018, 2022], program synthesis [Chen et al. 2021a; Shah et al. 2020], and invoking large language models (LLMs) [Cheng et al. 2022; Zelikman et al. 2023]. Most aforementioned neurosymbolic methods build their own domain-specific language or specialized reasoning components, many of which are programmable in Scallop and are instantiations of our provenance framework [Chen et al. 2020; Mao et al. 2019; Xu et al. 2018, 2022]. TensorLog [Cohen et al. 2017], DPL [Manhaeve et al. 2021], and [Huang et al. 2021] can be viewed as unified neurosymbolic frameworks of varying expressivity. Scallop is inspired by DPL, and additionally offers a more scalable, customizable, and easy-to-use language and framework.

8 CONCLUSION

We presented Scallop, a neurosymbolic programming language for integrating deep learning and logical reasoning. We introduced a declarative language and a reasoning framework based on provenance computations. We showed that our framework is practical by applying it to a variety of
machine learning tasks. In particular, our experiments show that Scallop solutions are comparable and even supersede many existing baselines.

In the future, we plan to extend Scallop in three aspects: 1) Supporting more machine learning paradigms, such as generative modeling, open domain reasoning, in-context learning, and adversarial learning. 2) Further enhancing the usability, efficiency, and expressiveness of Scallop’s language and framework. We intend to provide bindings to other ML frameworks such as TensorFlow and JAX, leverage hardware such as GPUs to accelerate computation, and support constructs such as algebraic data types. 3) Applying Scallop to real-world and safety-critical domains. For instance, we intend to integrate it with the CARLA driving simulator [Dosovitskiy et al. 2017] to specify soft temporal constraints for autonomous driving systems. We also intend to apply Scallop in the medical domain for explainable disease diagnosis from electronic health records (EHR) data.

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ARTIFACT AVAILABILITY

All software necessary to reproduce the experiments in this paper is available at [Li et al. 2023]. Additionally, the latest source code of Scallop and its documentation is available at https://github.com/scallop-lang/scallop.

REFERENCES


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