

Inducing Domain Specific Languages for Bayesian Program Learning

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Abstract

1. Introduction

Automatically inducing programs from examples is a long-standing goal of artificial intelligence. Recent work in program induction show that deep networks can be very successful at learning to write certain kinds of programs (e.g., RobustFill: (Devlin et al., 2017b) and DeepCoder: (Balog et al., 2016)), as can symbolic search techniques (e.g., Metagol: (Muggleton et al., 2015) and FlashFill: (Gulwani, 2011)). However, the success of these approaches – both symbolic and neural – relies crucially upon a hand-engineered *Domain Specific Language* (DSL). The DSL is an inventory of restricted programming primitives, that imparts domain specific knowledge about the space of programs. To what extent can we dispense with hand-engineered DSLs?

This work proposes learning DSLs. We consider the setting where we have a collection of related programming tasks, each specified by a set of input/output examples. Our algorithm, called DREAMHACKER, does two things: it finds programs that solve each of the tasks, and at the same time creates its own DSL by discovering and reusing new domain-specific subroutines. The idea is that induced DSL should distill the commonalities across the programs that solve the tasks, and so can be used to solve other related program learning problems.

Viewed as an inference problem, our goal is to infer the DSL, written \mathcal{D} , along with a program (written p) for each set of inputs/outputs (*tasks*, written x). A DSL \mathcal{D} is a collection of domain specific subroutines. We equip \mathcal{D} with a real-valued weight vector, θ , and together (\mathcal{D}, θ) define a distribution over programs. Figure 1(a) the diagrams this inference problem as a hierarchical Bayesian model.

Inference in the generative model in Figure 1(a) is diffi-

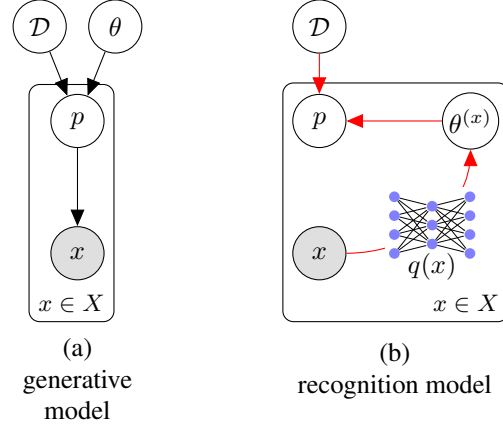


Figure 1: (a) DSL \mathcal{D} generates programs p by sampling DSL primitives with probabilities θ (Algorithm 1). Observe tasks x (program inputs/outputs). (b) neural network $q(\cdot)$, the *recognition model*, regresses from x to a distribution over programs ($\theta^{(x)} = q(x)$). Black arrows correspond to the top-down generative model. Red arrows correspond to the bottom-up recognition model.

cult because the programs are unobserved, and so we must solve a difficult search problem to find any programs at all. To make inference tractable our model learns a bottom-up *recognition model* alongside the top-down generative model (Figure 1b). The recognition model q is a neural network that regresses from observations to a distribution over programs. The neural network q implements an amortized inference/compiled inference scheme (Le et al., 2017; Ritchie et al., 2016) for the generative model.

How should we perform inference for the model in 1(a)? We take the intuitive strategy of exploiting the conditional independence of the programs conditioned on the DSL, and so alternate between estimating the DSL (\mathcal{D}, θ) and estimating a posterior distribution over p by searching for programs written using \mathcal{D} . In practice searching for programs is difficult, so we use the recognition model to learn how to search efficiently.

We apply DREAMHACKER to four domains: building Boolean circuits; symbolic regression; FlashFill-style (Gulwani, 2011) string processing problems; and Lisp-style functions on lists. For each of these we deliberately provide an

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Domain	Part of the learned DSL
Circuits	<code>(nand (nand a a) (nand b b))</code> (an OR gate)
Regression	<code>(+ (* real x) real)</code> (a linear function of x)
Strings	<code>(join '' (split c s))</code> (delete occurrences of c in string s)
Lists	<code>(map (lambda (x) (+ x a)) l)</code> (add a to every element of list l)

Table 1: Examples of structure found in DSLs learned by our algorithm. DREAMHACKER builds a new DSL by discovering and reusing useful fragments of code.

impovertised set of programming primitives, and show that our algorithm discovers its own domain-specific vocabulary for expressing solutions in each of these domains (Table 1).

1.1. Related Work

Our work is far from the first to learn to learn programs, an idea that goes back to Solomonoff (Solomonoff, 1989):

Neural recognition models for program induction: Much recent work in the ML community has focused on engineering neural networks that regress from input/output examples to programs (Devlin et al., 2017b;a; Menon et al., 2013; Balog et al., 2016). This family of work is analogous to a lesioned version of DREAMHACKER where (\mathcal{D}, θ) is held fixed and q is learned.

Predicate Invention in ILP: The Inductive Logic Programming (ILP) community has long worked on the problem of inventing new primitive predicates (Lin et al., 2014; Mugleton et al., 2015), which is analogous to our model with θ held fixed and q ablated.

Inventing new subroutines for program induction: Several program induction algorithms, most prominently the EC algorithm (Dechter et al., 2013), take as their goal to learn new, reusable subroutines that are shared in a multitask setting. We find this work inspiring and motivating, and go beyond it along two dimensions: (1) we propose more sophisticated algorithms for inducing reusable structure, based on a formalism called *Fragment Grammars* (O’Donnell, 2015); and (2) we show how to combine these techniques with bottom-up neural recognition models. Other instances of this related idea are (Liang et al., 2010) and Schmidhuber’s OOPS model (Schmidhuber, 2004).

Our work is an instance of Bayesian Program Learning (BPL; see (Lake et al., 2013; Dechter et al., 2013; Ellis et al., 2016; Liang et al., 2010)). Previous BPL systems have largely assumed a fixed DSL (but see (Liang et al., 2010)), and our contribution here is a general scheme for

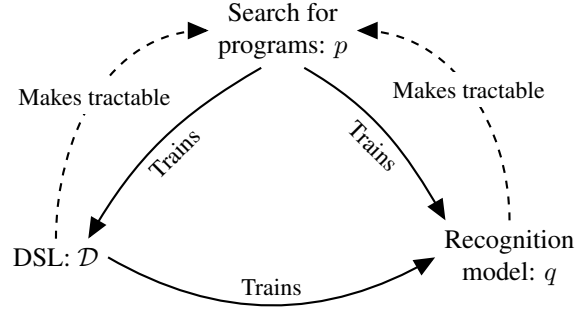


Figure 2: Our algorithm solves for programs, the DSL, and a recognition model. Each of these steps bootstrap off of the others.

getting BPL off the ground with less hand-engineering of the DSL.

2. The DREAMHACKER Algorithm

Our goal is to induce a DSL and find good programs solving each of the tasks. Our strategy is to iterate through three steps: (1) searching for programs that solve the tasks, (2) learning a better neural recognition model – which we use to accelerate the search over programs – and (3) improving the DSL. The key observation here is that each of these three steps can bootstrap off each other:

Searching for programs: Our program search is informed by both the DSL and the recognition model. When these improve we find better programs.

Learning a recognition model: The recognition model is trained both on samples from the DSL and on programs found by the search procedure. As the DSL improves and as search finds more programs, the recognition model gets both more data to train on and better data.

Improving the DSL: We induce a DSL from the programs we have found so far which solve the tasks; as we solve more tasks, we can hone in on richer DSLs that more closely match the domain.

The Helmholtz machine (Dayan et al., 1995) introduced the idea of alternating between learning a generative model and training a recognition model on samples from the generative model. We apply this idea to program induction, motivating why we call our algorithm the DREAMHACKER. Figure 2 diagrams how these three steps feed off of each other.

Section 2.1 frames this 3-step procedure as a means of maximizing a lower bound on the posterior probability of the DSL given the tasks. Section 2.2 explains how we search for programs that solve the tasks; Section 2.3 explains how

we train a neural network to accelerate the search over programs; and Section 2.4 explains how DREAMHACKER induces a DSL from programs.

2.1. Probabilistic Framing

DREAMHACKER takes as input a set of *tasks*, written X , each of which is a program induction problem. It has at its disposal a *likelihood model*, written $\mathbb{P}[x|p]$, which scores the likelihood of a task $x \in X$ given a program p . Its goal is to solve each of the tasks by writing a program, and also to infer a DSL \mathcal{D} .

We frame this problem as maximum a posteriori (MAP) inference in the generative model diagrammed in Figure 1(a). Writing J for the joint probability of (\mathcal{D}, θ) , we want the \mathcal{D}^*, θ^* solving:

$$\begin{aligned} J(\mathcal{D}, \theta) &\triangleq \mathbb{P}[\mathcal{D}]P(\theta) \prod_{x \in X} \sum_p \mathbb{P}[x|p]\mathbb{P}[p|\mathcal{D}, \theta] \\ \mathcal{D}^* &= \arg \max_{\mathcal{D}} \int J(\mathcal{D}, \theta) d\theta \\ \theta^* &= \arg \max_{\theta} J(\mathcal{D}^*, \theta) \end{aligned} \quad (1)$$

The above equations summarize the problem from the point of view of an ideal Bayesian learner. However, Eq. 1 is wildly intractable because evaluating $J(\mathcal{D}, \theta)$ involves summing over the infinite set of all possible programs. In practice we will only ever be able to sum over a finite set of programs. So, for each task, we define a finite set of programs, called a *frontier*, and only marginalize over the frontiers:

Definition. A *frontier* of task x , written \mathcal{F}_x , is a finite set of programs where $\mathbb{P}[x|p] > 0$ for all $p \in \mathcal{F}_x$.

Using the frontiers we define the following intuitive lower bound on the joint probability, which we call \mathcal{L} :

$$J \geq \mathcal{L} \triangleq \mathbb{P}[\mathcal{D}]P(\theta) \prod_{x \in X} \sum_{p \in \mathcal{F}_x} \mathbb{P}[x|p]\mathbb{P}[p|\mathcal{D}, \theta] \quad (2)$$

Mechanistically, DREAMHACKER does approximate MAP inference in the generative model of Figure 1(a) by maximizing this lower bound on the joint probability. We maximize \mathcal{L} by alternatingly maximizing w.r.t. the frontiers and the DSL:

Program Search: Maxing \mathcal{L} w.r.t. the frontiers. Here (\mathcal{D}, θ) is fixed and we want to find new programs to add to the frontiers so that \mathcal{L} increases the most. Adding new programs to the frontiers means searching for new programs p for task x where $\mathbb{P}[x, p|\mathcal{D}, \theta]$ is large.

DSL Induction: Maxing $\int \mathcal{L} d\theta$ w.r.t. the DSL. Here $\{\mathcal{F}_x\}_{x \in X}$ is held fixed so we can evaluate \mathcal{L} . Now the problem is that of searching the discrete space of DSLs and finding one maximizing $\int \mathcal{L} d\theta$. Once we have a DSL \mathcal{D} we can update θ to $\arg \max_{\theta} \mathcal{L}(\mathcal{D}, \theta, \{\mathcal{F}_x\})$.

Searching for programs is hard because of the large combinatorial search space. We ease this difficulty by learning a neural recognition model:

Neural recognition model: tractably maxing \mathcal{L} w.r.t. the frontiers. Here we train a neural network, q , to predict a distribution over programs conditioned on a task. The objective of q is to assign high probability to programs p where $\mathbb{P}[x, p|\mathcal{D}, \theta]$ is large. With q in hand we can find programs for the frontier \mathcal{F}_x by searching for programs that maximize $q(p|x)$. The network q exploits the structure of the DSL \mathcal{D} : rather than directly predicting a distribution over p conditioned on x , it predicts a weight vector, $\theta^{(x)}$, and we define $q(p|x) \triangleq \mathbb{P}[p|\mathcal{D}, \theta = q(x)]$. This taps into the intuition that programming is primarily a top-down activity: as human programmers, we first decide what kind of programming constructs we might need to use, and then we figure out how to assemble them in to the desired program.

Our lower bound \mathcal{L} is unconventional, and one might wonder why we do not instead maximize an ELBO-style bound like in a VAE or in the EM algorithm. For the interested reader, we explain in the supplement that maximizing an ELBO-style bound leads to a pathological behavior that would cause the algorithm to easily become trapped in local optima.

2.2. Searching for Programs

Now our goal is to search for programs that solve the tasks. In this work we use the simple search strategy of enumerating programs from the DSL in decreasing order of their probability, and then checking if an enumerated program p assigns positive probability to a task ($\mathbb{P}[x|p] > 0$); if so, we include p in the frontier \mathcal{F}_x .

To make this concrete we need to define what programs actually are and what form $\mathbb{P}[p|\mathcal{D}, \theta]$ takes. We represent programs as λ -calculus expressions. λ -calculus is a formalism for expressing functional programs that closely resembles the Lisp programming language. λ -calculus includes variables, function application, and the ability to create new functions. Throughout this paper we will write λ -calculus expressions in Lisp syntax. Our programs are all strongly typed. We use the Hindley-Milner polymorphic typing system (Pierce, 2002) which is used in functional languages like OCaml. Variables that range over types are always written using lowercase Greek letters and we write $\alpha \rightarrow \beta$ to mean a function that takes as input type α and returns something of type β . We use the notation $p : \tau$ to mean that the λ -calculus expression p has the type τ . For example, to describe the type of the identity function we would say $(\text{lambda } (x) x) : \alpha \rightarrow \alpha$. We say a type α *unifies* with τ if every expression $p : \alpha$ also satisfies $p : \tau$. Furthermore, the act of *unifying* a type α with τ is to introduce constraints on the type variables of α to ensure that α unifies with τ .

Algorithm 1 Generative model over programs

```

function sampleProgramFromDSL( $\mathcal{D}, \theta, \tau$ ):
    Input: DSL  $\mathcal{D}$ , weight vector  $\theta$ , type  $\tau$ 
    Output: a program whose type unifies with  $\tau$ 
    return sample( $\mathcal{D}, \theta, \emptyset, \tau$ )

function sample( $\mathcal{D}, \theta, \mathcal{E}, \tau$ ):
    Input: DSL  $\mathcal{D}$ , weight vector  $\theta$ , environment  $\mathcal{E}$ , type  $\tau$ 
    Output: a program whose type unifies with  $\tau$ 
    if  $\tau = \alpha \rightarrow \beta$  then
        var  $\leftarrow$  an unused variable name
        body  $\sim$  sample( $\mathcal{D}, \theta, \{\text{var} : \alpha\} \cup \mathcal{E}, \beta$ )
        return (lambda (var) body)
    end if
    primitives  $\leftarrow \{p | p : \tau' \in \mathcal{D} \cup \mathcal{E}$ 
         $\text{if } \tau \text{ can unify with } \text{yield}(\tau')\}$ 
    Draw  $e \sim$  primitives, w.p.  $\propto \theta_e$  if  $e \in \mathcal{D}$ 
        w.p.  $\propto \frac{\theta_{\text{var}}}{|\text{variables}|}$  if  $e \in \mathcal{E}$ 
    Unify  $\tau$  with  $\text{yield}(\tau')$ .
     $\{\alpha_k\}_{k \leq K} \leftarrow \text{argTypes}(\tau')$ 
    for  $k = 1$  to  $K$  do
         $a_k \sim \text{sample}(\mathcal{D}, \theta, \mathcal{E}, \alpha_k)$ 
    end for
    return ( $e \ a_1 \ a_2 \ \dots \ a_K$ )
    where:
     $\text{yield}(\tau) = \begin{cases} \text{yield}(\beta) & \text{if } \tau = \alpha \rightarrow \beta \\ \tau & \text{otherwise.} \end{cases}$ 
     $\text{argTypes}(\tau) = \begin{cases} [\alpha] + \text{argTypes}(\beta) & \text{if } \tau = \alpha \rightarrow \beta \\ \square & \text{otherwise.} \end{cases}$ 

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See Supplement for more detail on program representation. With this notation in hand we can now define DSLs:

Definition. A DSL \mathcal{D} is a set of typed λ -calculus expressions.

Definition. A weight vector θ for a DSL \mathcal{D} is a vector of $|\mathcal{D}| + 1$ real numbers: one number for each DSL primitive $e : \tau \in \mathcal{D}$, written θ_e , and a weight controlling the probability of a variable occurring in a program, written θ_{var} .

Algorithm 1 is a procedure for drawing samples from $\mathbb{P}[p | \mathcal{D}, \theta]$. In practice, we enumerate programs rather than sampling them. Enumeration proceeds by a depth-first search over the random choices made by Algorithm 1; we wrap the depth-first search in iterative deepening to (approximately) build λ -calculus expressions in order of their probability.

Why enumerate, when the program synthesis community has invented many sophisticated algorithms that search for programs? (Solar Lezama, 2008; Schkufza et al., 2013; Feser et al., 2015; Osera & Zdancewic, 2015; Polozov &

Gulwani, 2015). We have two reasons:

- A key point of our work is that learning the DSL, along with a neural recognition model, can make program induction tractable, even if the search algorithm is very simple.
- Enumeration is a general approach that can be applied to any program induction problem. Many of these more sophisticated approaches require special conditions on the space of of programs.

A main drawback of an enumerative search algorithm is that we have no efficient means of solving for arbitrary constants that might occur in the program. In Section 3.2, we will show how to find programs with real-valued constants by automatically differentiating through the program and setting the constants using gradient descent. In Section 3.3 we will show that the bottom-up neural recognition model can learn which discrete constants should be included in a program.

2.3. Learning a Neural Recognition Model

The purpose of the recognition model is to accelerate the search over programs. It does this by learning to predict which programs both assign high likelihood to a task, and at the same time have high prior probability under the prior $\mathbb{P}[\cdot | \mathcal{D}, \theta]$.

The recognition model q is a neural network that predicts, for each task $x \in X$, a weight vector $q(x) = \theta^{(x)} \in \mathbb{R}^{|\mathcal{D}|+1}$. Together with the DSL, this defines a distribution over programs, $\mathbb{P}[p | \mathcal{D}, \theta = q(x)]$. We abbreviate this distribution as $q(p|x)$. The crucial aspect of this framing is that the neural network leverages the structure of the learned DSL, so it is *not* responsible for generating programs wholesale.

We want a recognition model that closely approximates the true posteriors over programs. We formulate this as minimizing the expected KL-divergence:

$$\mathbb{E} [\text{KL} (\mathbb{P}[p|x, \mathcal{D}, \theta] || q(p|x))]$$

which is equivalent to maximizing

$$\mathbb{E} \left[\sum_p \mathbb{P}[p|x, \mathcal{D}, \theta] \log q(p|x) \right]$$

where the expectation is taken over tasks. One could take this expectation over the empirical distribution of the observations, like how an autoencoder is trained (Hinton & Salakhutdinov, 2006); or, one could take this expectation over samples from the generative model, like how a Helmholtz machine is trained (Dayan et al., 1995). We found it useful to maximize both an autoencoder-style objective (written \mathcal{L}_{AE}) and a Helmholtz-style objective (\mathcal{L}_{HM}),

giving the DREAMHACKER objective for a recognition model, \mathcal{L}_{RM} :

$$\mathcal{L}_{\text{RM}} = \mathcal{L}_{\text{AE}} + \mathcal{L}_{\text{HM}} \quad (3)$$

$$\mathcal{L}_{\text{HM}} = \mathbb{E}_{p \sim (\mathcal{D}, \theta)} [\log q(p|x)], \text{ } p \text{ evaluates to } x$$

$$\mathcal{L}_{\text{AE}} = \mathbb{E}_{x \sim X} \left[\sum_{p \in \mathcal{F}_x} \frac{\mathbb{P}[x, p|\mathcal{D}, \theta]}{\sum_{p' \in \mathcal{F}_x} \mathbb{P}[x, p'|\mathcal{D}, \theta]} \log q(p|x) \right]$$

Evaluating \mathcal{L}_{HM} involves sampling programs from the current DSL, running them to get their outputs, and then training q to regress from the outputs to the program. If these programs map inputs to outputs, then we need some way of sampling these inputs as well. Our solution to this problem is to sample the inputs from the empirical observed distribution of inputs in X .

The neural architecture of q depends upon the domain; for domains with sequential structure like strings and lists, we use an RNN, and for domains with a fixed-dimensionality inputs/outputs we use a multilayer perceptron.

2.4. Inducing the DSL from the Frontiers

The purpose of the DSL is to offer a set of abstractions that allow an agent to easily express solutions to the tasks at hand. In the DREAMHACKER algorithm we infer the DSL from a collection of frontiers. Intuitively, we want the algorithm to look at the programs in the frontiers and generalize beyond them; not only so the DSL can better express the current solutions, but also so that the DSL might expose new abstractions which will later be used to discover even better programs.

Recall from Section 2.1 that we want the DSL maximizing $\int \mathcal{L} d\theta$. We replace this marginal with an AIC approximation, giving the following objective for DSL induction:

$$\begin{aligned} \log \mathbb{P}[\mathcal{D}] + \arg \max_{\theta} \sum_{x \in X} \log \sum_{p \in \mathcal{F}_x} \mathbb{P}[x|p] \mathbb{P}[p|\mathcal{D}, \theta] \\ + \log P(\theta|\mathcal{D}) - \|\theta\|_0 \end{aligned} \quad (4)$$

We induce a DSL by searching locally through the space of DSLs, proposing small local changes to \mathcal{D} until Eq. 4 fails to increase. The search moves work by introducing new λ -expressions into the DSL. We propose these new expressions by extracting subexpressions from programs already in the frontier. These extracted subexpressions are fragments of the original programs, and can introduce new variables (Figure 3), which then become new functions in the DSL. The idea of storing and reusing fragments of expressions comes from Fragment Grammars (O'Donnell, 2015) and Tree-Substitution Grammars (Cohn et al., 2010).

We define a prior distribution over DSLs which penalizes the sizes of the λ -calculus expressions in the DSL, and put

Algorithm 2 DSL Induction Algorithm

Input: Set of frontiers $\{\mathcal{F}_x\}$

Hyperparameters: Pseudocounts α , regularization parameter λ

Output: DSL \mathcal{D} , weight vector θ

Define $L(\mathcal{D}, \theta) = \prod_x \sum_{z \in \mathcal{F}_x} \mathbb{P}[z|\mathcal{D}, \theta]$

Define $\theta^*(\mathcal{D}) = \arg \max_{\theta} \text{Dir}(\theta|\alpha) L(\mathcal{D}, \theta)$

Define $\text{score}(\mathcal{D}) = \log \mathbb{P}[\mathcal{D}] + L(\mathcal{D}, \theta^*) - \|\theta\|_0$

$\mathcal{D} \leftarrow$ every primitive in $\{\mathcal{F}_x\}$

while true do

$N \leftarrow \{\mathcal{D} \cup \{s\} | x \in X, z \in \mathcal{F}_x, s \text{ subexpression of } z\}$

$\mathcal{D}' \leftarrow \arg \max_{\mathcal{D}' \in N} \text{score}(\mathcal{D}')$

if $\text{score}(\mathcal{D}') < \text{score}(\mathcal{D})$ **return** $\mathcal{D}, \theta^*(\mathcal{D})$

$\mathcal{D} \leftarrow \mathcal{D}'$

end while

a Dirichlet prior over the weight vector:

$$\mathbb{P}[\mathcal{D}] \propto \exp \left(-\lambda \sum_{p \in \mathcal{D}} \text{size}(p) \right)$$

$$P(\theta|\mathcal{D}) = \text{Dir}(\theta|\alpha)$$

where $\text{size}(p)$ measures the size of the syntax tree of program p , λ is a hyperparameter that acts as a regularizer on the size of the DSL, and α is a concentration parameter controlling the smoothness of the prior over θ . Algorithm 2 specifies the DSL induction algorithm.

To appropriately score each proposed \mathcal{D} we must reestimate the weight vector θ . Although this problem may seem very similar to estimating the parameters of a probabilistic context free grammar (PCFG: see ()), for which we have effective approaches like the Inside/Outside algorithm (Lafferty, 2000), a DSL in DREAMHACKER may be context-sensitive due to the presence of variables in the programs and also due to the polymorphic typing system. In the Appendix we derive a tractable MAP estimator for θ .

2.5. Implementing the DREAMHACKER

Algorithm 3 describes how we combine program search, recognition model training, and DSL induction. We note the following implementation details: (1) on the first iteration, we do *not* train the recognition model on samples from the generative model because a DSL has not yet been learned – we instead train the network to only maximize \mathcal{L}_{AE} . (2) Because the frontiers can grow very large, we only keep around the top 10^4 programs p in each frontier \mathcal{F}_x with the highest likelihood $\mathbb{P}[x, p|\mathcal{D}, \theta]$. (3) During both DSL induction and neural net training, we calculate $\text{score}(\mathcal{D}')$ and \mathcal{L}_{RM} by only summing over the top K programs in \mathcal{F}_x – we found that $K = 2$ sufficed. (4) For added robustness, at each iteration we enumerate programs from both the

Domain	Example programs in frontiers	Example proposed subexpression
Circuits	(lambda x (nand x x)) (lambda x (lambda y (nand x (nand y y))))	(nand z z)
Strings	(lambda s (+ ' ' (index 0 (split ' ' s)))) (lambda s (index 0 (split ' ' s)))	(index 0 (split z s))

Figure 3: The DSL induction algorithm works by proposing subexpressions of programs to add to the DSL. These subexpressions are taken from programs in the frontiers (middle column), and can introduce new variables (z and s in the right column).

Algorithm 3 The DREAMHACKER Algorithm

Input: Initial DSL \mathcal{D} , set of tasks X , iterations I
Hyperparameters: Maximum frontier size F
Output: DSL \mathcal{D} , weight vector θ , recognition model $q(\cdot)$
 Initialize $\theta \leftarrow$ uniform
for $i = 1$ **to** I **do**
 $\mathcal{F}_x^\theta \leftarrow \{p | p \in \text{enumerate}(\mathcal{D}, \theta, F) \text{ if } \mathbb{P}[x|p] > 0\}$
 $q(\cdot) \leftarrow$ train recognition model to maximize \mathcal{L}_{RM}
 $\mathcal{F}_x^q \leftarrow \{p | p \in \text{enumerate}(\mathcal{D}, q(x), F) \text{ if } \mathbb{P}[x|p] > 0\}$
 $\mathcal{D}, \theta \leftarrow \text{induceDSL}(\{\mathcal{F}_x^\theta \cup \mathcal{F}_x^q\}_{x \in X})$
end for
return \mathcal{D}, θ, q

generative model and the recognition model.

3. Experiments

3.1. Boolean circuits

As a toy domain, we consider the problem of learning to build the Boolean circuits out of logic gates. Now, if we equipped our agent with a full repertoire of circuit primitives – XOR gates, multiplexers, etc. – this problem would be easy, and we could use sophisticated symbolic search algorithms like SMT solvers to synthesize circuits. Instead, we gave DREAMHACKER only a NAND gate, and tasked it with building a set of 500 random circuits made out of AND, NOT, and OR gates, as well as 2 or 4 input multiplexers. This experimental setup is an extension of one introduced in the original EC algorithm (Dechter et al., 2013). For this domain our recognition model is a simple multilayer perceptron whose inputs are the input/output examples. Figure 4 shows our algorithm learning to build circuits; Table ??

3.2. Symbolic Regression

We show how to use DREAMHACKER to infer programs containing both discrete structure and continuous parameters. The high-level idea is to synthesize programs with unspecified real-valued parameters, and to fit those parameters by differentiating through the program and optimizing using gradient descent. Concretely, we ask the algorithm

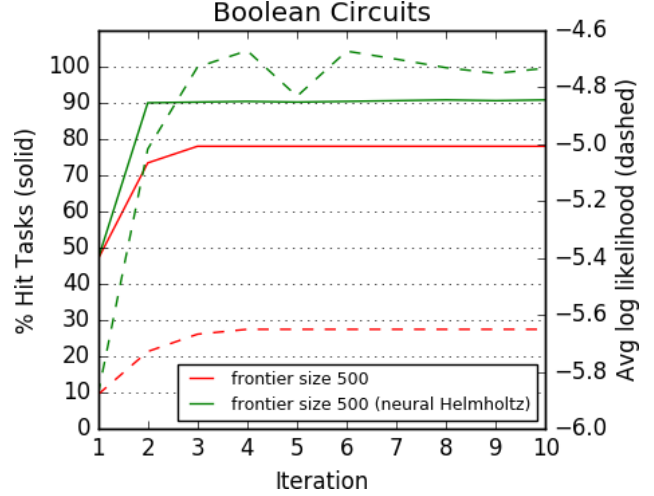


Figure 4: DREAMHACKER learning to build Boolean circuits. We start out with only NAND gates and learn DSL that contains ...

to solve a set of 400 symbolic regression problems, each a polynomial of degree 0 to 4, where our observations x are 10 input/output examples.

We initially give our system only addition and multiplication, along with the possibility of introducing real-valued parameters, which we write as \mathcal{R} . We define the likelihood of an observation x by assuming a Gaussian noise model for the input/output examples, and penalize extra continuous degrees of freedom using the BIC (Bishop, 2006):

What DSL does DREAMHACKER learn? The learned DSL contains templates for polynomials of different orders, which lets the algorithm quickly hone in on the kinds of functions that are most appropriate to this domain (Table 2). Examining the programs themselves, one finds that the algorithm discovers representations for each of the polynomials that minimizes the number of continuous degrees of freedom: for example, it represents the linear function $-x + 2$ with the program $(\ast (\ast (+ x \mathcal{R}) \mathcal{R}) x)$, which has two continuous degrees of freedom – while representing quartic functions using the invented DSL primitive f_6 in

String editing primitives

0,+1,-1
split, join, map, length, slice
append, chr->str, trim, index
lowercase, uppercase, capitalize
", ", ", " ", "<", ">"

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Table 3: Initial set of primitives provided to the system for learning string editing programs

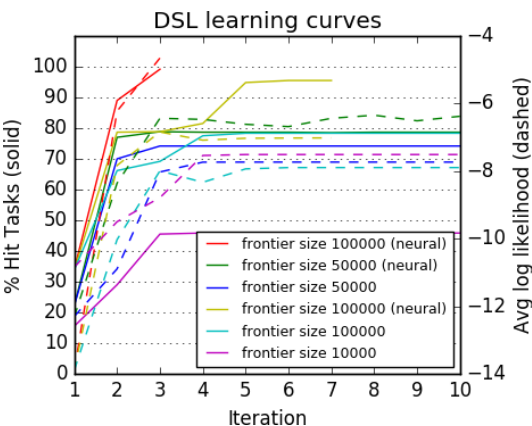


Figure 6: Learning curves for string editing programs

We automatically generated 600 string editing problems, along with input/output examples (Figure 7).

3.4. List functions

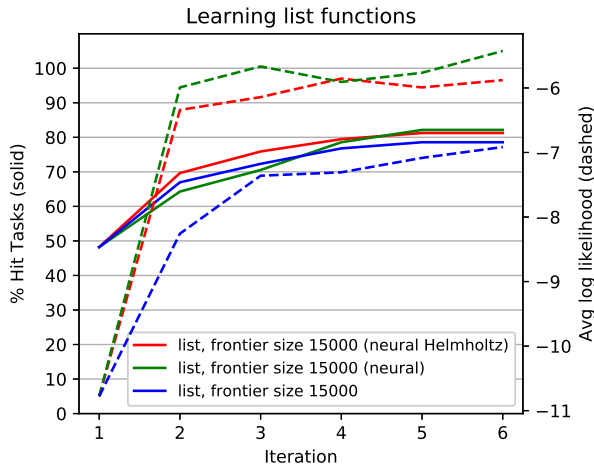
Our list function domain consists of tasks which are solved by functions that take as input an integer or a list of integers, and have as output either a Boolean, an integer, or a list of integers. Examples of these functions are in Table 4. For each function, we create a task x by generating 15 input/output examples used for testing whether a program

Input	Output
kIDY eMSz,zON	eM
KCQ njp,yzhq	nj
zeChf zzZ,dtFP	zz
plbKi fmLCo,ykkOR	fm

Figure 7: Example string edit problem (left) and the program that our system recovers (right)

<i>name</i>	<i>input</i>	<i>output</i>
add-3	[1 2 3 4]	[4 5 6 7]
append-4	[7 0 2]	[7 0 2 4]
len	[3 5 12 1]	4
range	3	[1 2 3]
has-2	[4 5 7 4]	false
has-4	[4 5 7 4]	true
repeat-2	[7 0]	[7 0 7 0]
drop-3	[0 3 8 6 4]	[6 4]

Table 4: Examples from the domain of list functions.



produces the correct output. Supplying many examples reduces ambiguity in the task’s function, ensuring solutions achieve the desired concept.

We supply DREAMHACKER with the DSL outlined in Table 5.

We found that using a less sophisticated but equally-capable DSL made common patterns, such as summation, unlikely and unlearnable in a small enumeration bound.

4. Model

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<i>name</i>	<i>type</i>
empty	$[\alpha]$
singleton	$\alpha \rightarrow [\alpha]$
concat	$[\alpha] \rightarrow [\alpha] \rightarrow [\alpha]$
map	$(\alpha \rightarrow \beta) \rightarrow [\alpha] \rightarrow [\beta]$
reduce	$(\beta \rightarrow \alpha \rightarrow \beta) \rightarrow \beta \rightarrow [\alpha] \rightarrow \beta$
true	bool
not	bool \rightarrow bool
and	bool \rightarrow bool \rightarrow bool
or	bool \rightarrow bool \rightarrow bool
0, ..., 9	int
+	int \rightarrow int \rightarrow int
*	int \rightarrow int \rightarrow int
negate	int \rightarrow int
mod	int \rightarrow int \rightarrow int
eq?	int \rightarrow int \rightarrow bool
gt?	int \rightarrow int \rightarrow bool
is-prime	int \rightarrow bool
is-square	int \rightarrow bool
range	int \rightarrow [int]
sort	[int] \rightarrow [int]
sum	[int] \rightarrow int
reverse	$[\alpha] \rightarrow [\alpha]$
all	$(\alpha \rightarrow \text{bool}) \rightarrow [\alpha] \rightarrow \text{bool}$
any	$(\alpha \rightarrow \text{bool}) \rightarrow [\alpha] \rightarrow \text{bool}$
index	int \rightarrow $[\alpha] \rightarrow \alpha$
filter	$(\alpha \rightarrow \text{bool}) \rightarrow [\alpha] \rightarrow [\alpha]$
slice	int \rightarrow int \rightarrow $[\alpha] \rightarrow [\alpha]$

Table 5: DSL for the domain of list function.

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