Creating Synthetic Datasets via Evolution for Neural Program Synthesis

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Abstract
Program synthesis is the task of automatically generating a program consistent with a given specification. A natural way to specify programs is to provide examples of desired input-output behavior, and many current program synthesis approaches have achieved impressive results after training on randomly generated input-output examples. However, recent work has discovered that some of these approaches generalize poorly to data distributions different from that of the randomly generated examples. We show that this problem applies to other state-of-the-art approaches as well and that current methods to counteract this problem are insufficient. We then propose a new, adversarial approach to control the bias of synthetic data distributions and show that it outperforms current approaches.

1. Introduction
Program synthesis has long been a key goal of AI research. In particular, researchers have become increasingly interested in the task of programming by example (PBE), where the goal is to generate a program consistent with a given set of input-output (I/O) pairs. Recent studies have achieved impressive results, capable of solving PBE problems that humans would find difficult (e.g., Sharma et al., 2017; Zohar & Wolf, 2018; Ellis et al., 2019). However these studies have a concerning weakness: since large, naturally occurring datasets of program synthesis problems do not exist, these studies train and test their models on synthetic datasets of randomly generated programs and I/O pairs. The justification for using these synthetic datasets is that if a model can correctly predict programs for arbitrary PBE problems, then it has likely learned the semantics of the programming language and can generalize to problems outside the synthetic data distribution (Devlin et al., 2017).

While this justification is plausible, a model might also perform well because it has learned specific aspects of the synthetic data distribution, and recent studies have found this to be the case for several state-of-the-art models (Shin et al., 2019; Clymo et al., 2019). These studies find that current PBE models often perform poorly on distributions different from that of the training data, and they propose methods to mitigate this issue by generating synthetic data with more varied distributions. The idea behind these methods is that a model trained on more varied synthetic data should generalize to a wider variety of distributions, hopefully including those of real-world PBE problems.

Nevertheless, we find that these methods are often insufficient. Previous studies differ on what constitutes a “varied distribution” of synthetic data, creating definitions based on problem-specific heuristics. While generating training data based on these heuristics does help models generalize to certain distributions, we find that models trained using these methods still fail to generalize to many other distributions, including those resembling distributions of real-world PBE problems.

Moreover, different methods fail to generalize to different distributions, raising the question of how one should construct test sets to evaluate these methods. While previous studies have arbitrarily picked test sets that they believe present a reasonable challenge for state-of-the-art methods, this approach may lead to overly optimistic evaluations. A study may report that a method performed well because the researchers failed to find those distributions on which the method performs poorly.

In this paper, we propose an adversarial method to generate a training set. Our adversarial approach builds a training set iteratively, finding data distributions on which a given model performs poorly and adding data drawn from those distributions to the training set on each iteration. We test this method by using it to generate training data for the PCCoder model from Zohar et al. (2018), and we show that models trained using our method generalize to a variety of distributions better than previously proposed methods.
Moreover, we propose using a variation of our adversarial approach to generate test sets to evaluate PBE methods. We create test sets for different versions of PCCoder using this approach and show that these test sets reveal weaknesses in models that are not obvious when using other test sets.

This paper makes the following key contributions:

1. We propose a new, adversarial method to generate desirable distributions on which to train models for PBE.

2. We show that models trained using our method generalize to a variety of datasets better than models trained using previously proposed methods.

3. We show that our adversarial approach may also be used to generate test sets that are less likely to overestimate the performance of a model.

2. Related Work

Most studies on PBE methods generate I/O pairs using random sampling schemes, filtering out invalid I/O pairs for each program by constraining the sample space and rejecting sets of I/O pairs that do not meet these constraints. Balog et al. (2016) construct a dataset of PBE problems for DeepCoder by enumerating programs up to a given length and removing programs with easily detectable issues (e.g., redundant variables). For each program generated, they then create I/O pairs by sampling inputs uniformly from a restricted range of values guaranteed to yield valid outputs for the given program. Feng et al. (2018) and Zohar et al. (2018) also create datasets using the DeepCoder DSL (domain-specific language) in a similar manner.

Bunel et al. (2018) generate PBE problems for Karel (Pattis, 1981) by randomly sampling programs from the Karel DSL and removing programs with obvious problems, similar to Balog et al. They then generate I/O pairs for each program by sampling random inputs and running the program to obtain the corresponding outputs. However, Bunel et al. do not specify what sampling distributions are used for the programs and I/O pairs.

Parisotto et al. (2016) create a dataset for the Flashfill domain (Gulwani et al., 2012) by enumerating programs up to 13 expressions long and then randomly sampling inputs to create I/O pairs. They report that while their model achieves 97% accuracy on their synthetic data, they achieve only 38% accuracy on a small dataset of 238 real-world problems. Devlin et al. (2017) use a data generation approach similar to Parisotto et al. but with an improved model and are more successful, achieving 92% accuracy on the same real-world dataset used by Parisotto et al.

All of the papers above focus on advancing models for PBE, but they do so largely using synthetic data to train those models. Shin et al. (2019) report that even minor differences between the synthetic data distributions used for training and evaluation can drastically decrease a model’s performance. To solve this problem, they propose a data generation method to improve a model’s ability to generalize to other data distributions. They first choose a set of “salient variables” for the domain, defined as a mapping from I/O pairs in the synthetic dataset to a finite, discrete set. They then sample I/O pairs such that the salient variables will be approximately uniformly distributed in the resulting dataset. Shin et al. find that the model proposed by Bunel et al. (2018) better generalizes to a variety of distributions when trained with data generated with this method. However, this method has two major disadvantages. First, it requires the user to determine the correct salient variables, which may be difficult for complex domains. Second, if the domain of valid I/O pairs is highly dependent on the program, it is often prohibitively complex to enforce uniformity across salient variables.

Recently, Clymo et al. (2019) proposed a method to generate PBE problems using a SMT solver. They impose constraints on the I/O pairs to ensure that pairs selected for the dataset are not too similar to each other and then select I/O pairs that satisfy these constraints using a SMT solver. However, when testing an implementation of this method on the DeepCoder domain, the reported improvement of the constraint-based methods over simpler sampling methods is marginal, with the best constraint-based method performing only 2.4% better than the best sampling method. Moreover, many of their constraints are highly specific to the DeepCoder domain, and Clymo et al. do not offer a way to adapt their method to other problem spaces. Nevertheless, they present a method that does not require the salient variables of Shin et al. (2019), and they show that their approach can be applied to domains such as DeepCoder, for which it is difficult to enforce uniformity across salient variables.

3. Methodology

We propose an iterative, adversarial approach to build a synthetic dataset of PBE problems. Given a PBE model trained on a given dataset, we use an evolutionary algorithm to find a data distribution on which this model performs poorly. We then add PBE problems drawn from that distribution to the dataset and train a new model on the new, larger dataset. We then repeat the steps above using the new model and new dataset. Algorithm 1 provides pseudocode for this process.

The evolutionary algorithm works as follows. Let \( \Phi \) be the space of programs in our DSL, and let \( I \times O \) be the space of I/O pairs. Suppose we have a model \( M : I \times O \rightarrow \Phi \), and we select a family of data distributions of the form \( D(\bar{\mu}) : \)
One might be concerned that our evolutionary algorithm could return distributions on which a given model performs poorly due to ambiguity rather than overfitting. For example, a model given I/O pairs of all zeros likely will not return the underlying program, since many programs could potentially create those I/O pairs. However, it is important to note that in the DeepCoder domain, as well as other program synthesis domains, a model given a problem \((\phi, i, o)\), where \(\phi(i) = o\), need not return \(\phi\). To solve the problem, the model may return any program that maps \(i\) to \(o\), making ambiguous I/O pairs, such as those containing only zeros, easy to solve. Therefore, we are confident that distributions returned by our algorithm will be those for which the model performs poorly due to overfitting on synthetic data rather than ambiguity of examples.

An obvious disadvantage to our approach is that one must choose the space of distributions to be explored by the evolutionary algorithm. Nevertheless, we believe the task of choosing a space of distributions to be less difficult than the tasks of choosing salient variables (Shin et al., 2019) or SMT constraints (Clymo et al., 2019) necessary for previously proposed methods. Whereas the correct choice of salient variables or SMT constraints may not be intuitive, we argue that the guidelines for choosing a space of distributions for our approach are relatively simple: one should choose the largest space of distributions that can feasibly be searched by the evolutionary algorithm. A larger space of distributions will allow our algorithm to generate more varied training data at the cost of being more difficult to search.

**Algorithm 1** Adversarial algorithm

**Input:** model \(M\), dataset \(X\), evolutionary algorithm \(E\), iterations \(N\), episodes \(e\), population size \(n\), elites size \(m\), num probs \(c\)

**for** \(i = 0\) to \(N - 1\) **do**

- \(\text{params} = E(M, e, n, m)\)
- Randomly generate \(c\) programs \(\subset \Phi\)
- Draw \(c\) inputs \(\subset I\) from distribution \(D(\text{params})\)
- \(\text{outputs} = [\text{programs}[j][\text{inputs}[j]], 0 \leq j < c]\)
- \(\text{problems} = \text{zip}(\text{outputs}, \text{inputs}, \text{outputs})\)
- Add problems to \(X\)
- Train \(M\) on \(X\)

**end for**

**Algorithm 2** Evolutionary algorithm

**Input:** model \(M\), episodes \(e\), population size \(n\), elites size \(m\)

**Randomly initialize** \(\text{params} = [\phi^i, 0 < i < n]\).

**for** \(i = 0\) to \(e - 1\) **do**

- Randomly generate problems \(S = [S_j, 0 \leq j < n]\).
- \(\text{Calculate fitnessScores} = [F(S_j), 0 \leq j < n]\)
- Sort \(\text{fitnessScores}\) in descending order of \(f_{\text{fitnessScores}}\)
- \(\text{newParams} = \text{params}[\cdot]: m\)
- **for** \(j = 0\) to \(m - 1\) **do**
  - **for** \(k = 0\) to \(n/m - 1\) **do**
    - Append \(\text{newParams}[j] + \epsilon\) to \(\text{newParams}\)
  **end for**
- \(\text{params} = \text{newParams}\)

**end for**

4. Experiments

The DeepCoder DSL (Balog et al., 2016) is a language for manipulating lists of integers, capable of expressing complex behaviors such as branching and looping. To evaluate our approach, we generate synthetic data to train PCCoder (Zohar & Wolf, 2018), which solves PBE problems from the DeepCoder domain using a beam search guided by a neural network. In this section, we first discuss the implementation of our adversarial method for the DeepCoder domain and then test this implementation against previously proposed methods. Code and data will be made available.

4.1. Evolutionary Algorithm

To implement our evolutionary algorithm, we need to define the space of data distributions our algorithm will explore. The DeepCoder DSL uses integers between -256 and 255 and lists of integers with lengths between 1 and 20. Therefore, we can define a simple data distribution with four parameters: a lower and upper bound for integers \((a, b : -256 \leq a \leq b \leq 255)\) and a lower
and upper bound for list lengths \((c, d : 1 \leq c \leq d \leq 20)\). For any integer input, we then draw an integer from \(\text{discrete uniform}(a, b)\). For any list input, we draw a list length \(l\) from \(\text{discrete uniform}(c, d)\) and then draw \(l\) integers from \(\text{discrete uniform}(a, b)\) to fill the list. Our evolutionary algorithm will explore the space of all such distributions.

To calculate the fitness function for a distribution, we draw 100 problems of program length 5 from the distribution and run our model on each problem with a timeout of 60 seconds. When evaluating models in our experiments, we use test sets with program lengths of 5, 8, 10, 12, and 14, and we use a timeout of 300 seconds. However, running models on programs longer than 5 lines with a timeout of 300 seconds would cause our evolutionary algorithm to take prohibitively long to run, so we use shorter programs and timeouts to estimate fitness of distributions.

Next, we define the random variables we will use to mutate our distributions. We mutate integer bounds by adding values drawn from \(U\left((-250/2^i, 250/2^i)\right)\), where \(i \in [0, 5]\) is the index of the current iteration of the evolutionary algorithm (starting at 0). We mutate list length bounds by adding values drawn from \(U\left((-20/2^i, 20/2^i)\right)\). Since the bounds of these distributions decrease on each iteration, our evolutionary algorithm is able to explore a wide variety of distributions in earlier iterations and then make smaller adjustments during later iterations.

Finally, we describe how we initialize our population of distributions. As observed by Clymo et al. (2019), smaller input values are valid for more programs in the DeepCoder DSL. Therefore, to speed up training, we initialize \(a\) and \(b\) from \(N(0, 10)\) rather than \(U(-256, 255)\) to make it more likely that initial distributions will generate valid I/O pairs. While one may worry that using \(N(0, 10)\) will prevent our algorithm from exploring larger values of \(a\) and \(b\), recall that we initially mutate our distributions with a random variable uniformly distributed between −250 and 250. This allows our algorithm to explore the entire space of available distributions.

4.2. Baselines

We compare our approach to three previously suggested approaches. First, we use the approach used by Balog et al. (2016), Feng et al. (2018), and Zohar et al. (2018) to generate data for DeepCoder, which we call Restricted Domain. This approach imposes a set of program-dependent constraints on inputs that ensure the corresponding outputs are valid. While this approach removes all invalid I/O pairs when generating examples, the constraints are overly strict and remove many valid I/O pairs as well.

Second, we use the approach proposed by Shin et al. (2019), in which we choose a set of what they call “salient variables” and then try to ensure a uniform distribution of those variables in our dataset. We describe Shin et al.’s algorithm to ensure uniformity of salient variables in Appendix A. For our salient variables, we use the same variables that define distributions selected by our evolutionary approach: the minimum and maximum integers of the inputs and the minimum and maximum list lengths of the inputs. Note that since valid ranges of inputs vary greatly from program to program in the DeepCoder domain, it is prohibitively complex to ensure that these variables are uniformly distributed. Nevertheless, Shin et al.’s method still increases the uniformity of salient variables: KL divergence from the uniform distribution decreases by 10.7% from 3.27 to 2.92 when using Shin et al.’s method instead of Restricted Domain. Since Shin et al. were able to see noticeable improvements in their study of the Calculator domain with just a 13% improvement in KL divergence, we believe it is worth including this method in our baselines. We call this the Salient Variables approach.

Finally, we use an approach called Non-Uniform Sampling proposed by Clymo et al. (2019). For a given program, we generate a value \(r\) from an exponential distribution. The input values for I/O pairs are then selected uniformly at random with replacement from the range \([-r, r]\). The intuition behind this approach is that smaller input values are valid for more programs in the DeepCoder DSL, so sampling with a bias toward smaller values increases the probability that suitable inputs will be found for all programs. Clymo et al. report that they choose a rate parameter of 0.001 for their exponential distribution. However, an exponential distribution with a rate parameter of 0.001 has a mean of 1000, well above the maximum valid value in the DeepCoder DSL of 255. Therefore, we pick of rate parameter of 0.01 for our experiments.

Clymo et al. also propose an approach they call Semantic Variation. In this approach they constrain input and output values using constraints that help ensure that I/O pairs selected will be varied. They then use a SMT solver to generate I/O pairs that satisfy these constraints. While we would like to use this approach as a baseline, Clymo et al. do not specify how they encode the constraints that for input \(i\) and output \(o\) selected for program \(\phi\), \(\phi(i) = o\) and \(i \neq \phi(i)\). This missing detail is important, since Clymo et al. also report that the DeepCoder DSL is too complex to encode such constraints for certain programs \(\phi\) and therefore resort to an unspecified approximation of those constraints. However, Clymo et al. report that semantic variation performed only 2.4% better than Non-Uniform Sampling when comparing area under top-\(k\) curves, so we believe the inclusion of Non-Uniform Sampling to be sufficient for our experiments.
To compare the above approaches with our own, we generate datasets using each approach and then train the PC-Coder model using each dataset, creating four differently trained PC-Coder models (three trained using the baselines and one trained using our approach). Each dataset contains 300,000 PBE problems. To create our adversarial dataset, we first train PC-Coder on 140,000 problems generated using Restricted Domain as Zohar et al. (2018) did for the original version of PC-Coder. Using this model for the first iteration, we then add 160,000 problems generated using 20 iterations of the adversarial algorithm.

We test our four models on five test sets: three test sets generated using the baselines and two test sets generated from distributions we believe would be common among human-generated examples. We generate the test sets to have the same size and program lengths as Zohar et al. (2018): each test set contains 2500 programs of lengths 5, 8, 10, 12, and 14 (with 500 programs of each length).

To create the two test sets generated from “human-like” distributions, we first observe that while no large-scale dataset of human-generated examples exists for the DeepCoder domain, Balog et al. (2016) and Zohar et al. (2018) provide several human-created examples of DeepCoder problems in their figures. An immediately noticeable discrepancy between the human-created I/O pairs in the appendices and the synthetic I/O pairs used in those studies is that the human-created I/O pairs use small, positive integers far more frequently than the synthetic data. Moreover, positive integers are more common than negative numbers in the human-created data, regardless of the absolute values of the integers. Based on these observations, we create two “human-like” test sets:

1. **1-to-10**: We generate synthetic data using the constraints from Balog et al. (2016), but we change the valid range for all integers from \([-256, 255]\) to \([1, 10]\).

2. **Small Integers**: We generate synthetic data using the constraints that integer variables must be between 1 and 10 but integers within lists may be between 1 and 255. We remove the constraints of Balog et al. (2016), since these constraints limited the variety of examples in these particular test sets.

When running our models, we set PC-Coder’s memory size to 11 and its timeout to 300 seconds. We performed all experiments on Intel Xeon 2.30GHz CPUs.

### 4.3. Results

Tables 1-4 show the percentage of problems solved by each approach. While some of the baselines slightly outperform our adversarial approach on certain test sets—in particular, each baseline unsurprisingly outperforms on its own test sets—the adversarial approach generalizes to all of the baseline test sets reasonably well. Whereas the performance of each baseline approach sometimes drops drastically when evaluated on test sets from other baselines, as shown by the bolded accuracies in tables 1-4, the adversarial approach performs decently on test sets from all baselines. Moreover, on the human-like test sets, the adversarial approach outperforms all baseline approaches by a significant margin.

It is promising to see that the adversarial approach outperforms the baselines on the small integers dataset in particular. The small integers distribution is outside the space of distributions available to our evolutionary algorithm, so in theory, training data generated by our adversarial approach might not improve performance on this distribution. However, our results show that our adversarial approach was able to generate data drawn from distributions similar enough to the small integers distribution to improve performance.

Another interesting observation is that all models find the 1-to-10 test sets particularly difficult. This may be because small, positive integers are valid inputs for a disproportionately large number of programs in the DeepCoder DSL. I/O pairs in the 1-to-10 test sets can specify a wide variety of

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### Table 1. Performance of PC-Coder trained using Restricted Domain. The worst accuracy for each program length is bolded.

| LENGTH | DATASET                  | % SOLVED |
|--------|--------------------------|----------|
| 5      | RESTRICTED DOMAIN        | 94.6%    |
|        | NON-UNIFORM SAMPLING     | 18.8%    |
| 8      | SALIENT VARIABLES        | 95.8%    |
|        | 1-TO-10                  | 60.4%    |
|        | SMALL INTEGERS           | 60.2%    |
| 10     | RESTRICTED DOMAIN        | 60.4%    |
|        | NON-UNIFORM SAMPLING     | 17.2%    |
| 12     | SALIENT VARIABLES        | 72.4%    |
|        | 1-TO-10                  | 31.4%    |
|        | SMALL INTEGERS           | 47.6%    |
| 14     | RESTRICTED DOMAIN        | 48.8%    |
|        | NON-UNIFORM SAMPLING     | **16.4%**|
|        | SMALL INTEGERS           | 40.6%    |
|        | **RESTRICTED DOMAIN**    | 36.8%    |
|        | **NON-UNIFORM SAMPLING** | **6.8%** |
|        | SMALL INTEGERS           | 37.2%    |
|        | **RESTRICTED DOMAIN**    | 25.0%    |
|        | **NON-UNIFORM SAMPLING** | **8.4%** |
|        | SMALL INTEGERS           | 32.8%    |
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Table 2. Performance of PCCoder trained using salient variables. The worst accuracy for each program length is bolded.

| LENGTH | DATASET               | % SOLVED |
|--------|-----------------------|----------|
| 5      | RESTRICTED DOMAIN     | 95.4%    |
|        | Non-Uniform Sampling  | 21.8%    |
|        | Salient Variables     | 97.6%    |
|        | 1-to-10               | 62.0%    |
|        | SMALL INTEGERS        | 60.2%    |
| 8      | RESTRICTED DOMAIN     | 72.6%    |
|        | Non-Uniform Sampling  | 17.8%    |
|        | Salient Variables     | 69.8%    |
|        | 1-to-10               | 37.4%    |
|        | SMALL INTEGERS        | 48.4%    |
| 10     | RESTRICTED DOMAIN     | 57.8%    |
|        | Non-Uniform Sampling  | 16.4%    |
|        | Salient Variables     | 53.2%    |
|        | 1-to-10               | 28.0%    |
|        | SMALL INTEGERS        | 40.2%    |
| 12     | RESTRICTED DOMAIN     | 40.2%    |
|        | Non-Uniform Sampling  | 8.6%     |
|        | Salient Variables     | 40.6%    |
|        | 1-to-10               | 21.2%    |
|        | SMALL INTEGERS        | 39.6%    |
| 14     | RESTRICTED DOMAIN     | 30.2%    |
|        | Non-Uniform Sampling  | 9.4%     |
|        | Salient Variables     | 32.2%    |
|        | 1-to-10               | 17.0%    |
|        | SMALL INTEGERS        | 34.8%    |

Table 3. Performance of PCCoder trained using Non-Uniform Sampling. The worst accuracy for each program length is bolded.

| LENGTH | DATASET               | % SOLVED |
|--------|-----------------------|----------|
| 5      | RESTRICTED DOMAIN     | 51.8%    |
|        | Non-Uniform Sampling  | 97.4%    |
|        | Salient Variables     | 49.8%    |
|        | 1-to-10               | 44.0%    |
|        | SMALL INTEGERS        | 55.8%    |
| 8      | RESTRICTED DOMAIN     | 20.8%    |
|        | Non-Uniform Sampling  | 82.4%    |
|        | Salient Variables     | 21.4%    |
|        | 1-to-10               | 21.8%    |
|        | SMALL INTEGERS        | 42.6%    |
| 10     | RESTRICTED DOMAIN     | 15.2%    |
|        | Non-Uniform Sampling  | 64.8%    |
|        | Salient Variables     | 11.6%    |
|        | 1-to-10               | 15.8%    |
|        | SMALL INTEGERS        | 35.2%    |
| 12     | RESTRICTED DOMAIN     | 8.0%     |
|        | Non-Uniform Sampling  | 48.0%    |
|        | Salient Variables     | 9.0%     |
|        | 1-to-10               | 12.8%    |
|        | SMALL INTEGERS        | 34.4%    |
| 14     | RESTRICTED DOMAIN     | 8.6%     |
|        | Non-Uniform Sampling  | 37.0%    |
|        | Salient Variables     | 10.0%    |
|        | 1-to-10               | 10.6%    |
|        | SMALL INTEGERS        | 30.2%    |

programs with a small set of numbers, which may make it difficult for a model (or even a human) to differentiate programs based on I/O pairs. If humans providing I/O pairs do in fact gravitate toward small, positive integers, this is potentially a large concern for PBE research.

4.4. Using the algorithm to measure performance

Previous PBE studies have often evaluated the performance of their models using test sets drawn from the same distribution as the training set. However, this approach risks overestimating a model’s performance, since a model may perform well on a test set because it has learned features of the synthetic data distribution rather than the semantics of the programming language. Therefore, we argue that a PBE model should be evaluated on a test set drawn from a different distribution than the training set. Naturally, this raises the question of what distribution we should use for the test set. In this section, we propose using our adversarial algorithm to generate test data from those distributions on which the model performs worst. The intuition behind this approach is that adversarially generated test data should come from a distribution as different as possible from the training data by design. If a model can perform well on adversarially generated test data, it has likely learned the semantics of the DSL and is not relying on features specific to the training data.

We use this method to evaluate our four versions of PCCoder. For each version of PCCoder, we use Algorithm 2 to generate a dataset of 100 examples with program length 5. Table 5 shows that our adversarial approach significantly outperforms the 3 baselines. We can also see that there exist distributions on which our models perform far worse than would be suggested by Tables 1-4. For example, while the Salient Variables method achieves an accuracy of at least 20% on all test sets of length 5 in our previous experiments, our evolutionary algorithm finds a distribution for which this method has an accuracy of just 9%.

This approach also allows us to better evaluate Non-Uniform Sampling. Looking at tables 1-4, one might think that Non-Uniform Sampling performs worst out of the four methods, as it is outperformed by the other methods on all test sets except for those generated using Non-Uniform Sampling. However, table 5 shows that PCCoder trained using Non-Uniform Sampling achieves 51% accuracy on the most difficult distribution our evolutionary algorithm can find, easily outperforming the other two baselines. Based on these results, one might conclude that the model trained using Non-Uniform Sampling actually performs better than
that we may not find the worst distribution possible in these cases, mainly because the 1-to-10 distribution is not within the space of distributions searched by our algorithm. Therefore, our algorithm can only find distributions that are similar to the 1-to-10 distribution in nature.

Nevertheless, this evaluation method is far less likely to overestimate performance than those of other studies, which tend to use test sets drawn from the same distribution as the training set or otherwise drawn from arbitrary distributions that the researchers believe will be sufficiently challenging. By testing on arbitrarily chosen distributions, a study may overestimate a model’s performance because it overlooked distributions on which the model generalized poorly. However, our approach finds the most difficult distribution for a model within a given search space, providing a more systematic way to test a model’s ability to generalize to different distributions.

### 5. Discussion and Future Work

Researchers often train PBE models using randomly generated problems, the idea being that a model that can correctly predict programs for arbitrary inputs has likely learned the semantics of its DSL and can therefore generalize to problems outside the synthetic data distribution. However, recent studies have demonstrated that these models often overfit on their synthetic training sets and often generalize poorly to data from even slightly different distributions. We present a new method to generate synthetic data for program synthesis models that mitigates this issue. We show that a model trained with data generated using this method is able to outperform models trained with previously proposed methods on a variety of baselines.

Moreover, we show that our method can be adapted to generate test sets. Previous studies have chosen distributions for synthetic test sets either by reusing the distribution of the training data or by arbitrarily picking distributions believed to provide a sufficient challenge for their models. We use an evolutionary algorithm to generate test data from distributions that are intentionally as different as possible from the training distribution. These test sets allow for a more conservative evaluation of program synthesis models and
allow us to better evaluate a model’s ability to generalize to different distributions.

It would be interesting to see whether using a more expressive model, such as a generative adversarial network, to generate PBE problems could improve our ability to find distributions on which models perform poorly. In this study, we use a simple yet effective evolutionary algorithm to find such distributions and then randomly generate PBE problems from those distributions. However, another idea might be to generate problems using a neural network, which is trained to generate problems on which a given PBE model will fail. This neural network could potentially generate problems from a wider variety of distributions than our evolutionary algorithm can. Thus exploring other adversarial methods to generate synthetic data remains a promising area for future work.

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A. The Salient Variables Method

Here we give a more detailed description of the Salient Variables method of Shin et al. (2019) introduced as a baseline in Section 4.2. Let $I$ be the space of inputs, which is originally sampled from a distribution $q: I \rightarrow [0,1]$. Let $X$ be the discrete, finite space of a salient variable, which is calculated by $v: I \rightarrow X$. We would like to sample a dataset $D$ from $I$ such that $v$ has a uniform distribution throughout $D$. To do this, we sample $i \sim q$ and calculate $x = v(i)$. We then add $i$ to $D$ with probability $g(i)$, where

$$g(i) = (P_q[v(i) = x] + \epsilon)^{-1} \left( \min_{x' \in X} P_q[v(i) = x'] + \epsilon \right)$$

with $P_q[v(i)]$, the probabilities induced over $v(i)$ via $q$, calculated empirically based on counts computed with past samples drawn from $q$. $\epsilon \in \mathbb{R}^+$ is a hyperparameter that allows the algorithm a tolerance for non-uniformity. Increasing $\epsilon$ increases the algorithm’s speed at the cost of allowing the distribution of $v(i)$ to diverge further from the uniform in $D$. We repeat the above until $D$ is of a desired size. Note that $X$ can be a space of tuples, allowing us to ensure that the joint distribution of multiple salient variables is uniform, as we do in Section 4. Algorithm 3 provides pseudocode for this method.

For our implementation in Section 4, we divide our salient variables by 10 and truncate the result. For example, if the minimum integer of an input is -256, we place -26 into our dictionary of counts in algorithm 3. This way, we have far fewer elements in our dictionary of counts so that $p_{min}$ in algorithm 3 will become greater than 0 after a reasonable amount of time.

Algorithm 3 Salient Variables algorithm

**Input:** distribution $q$, salient variable $v$, tolerance $\epsilon$, dataset size $n$

Create dictionary of counts $C = \{x : 0, x \in X\}$

$D = []$

$t = 0$

while $|D| < n$ do

Sample $i \sim q$

$C[v(i)] = C[v(i)] + 1$

$t = t + 1$

$p_{min} = \min_{x \in X} C[x]$

$p_{curr} = \frac{C[v(i)]}{t}$

$g = \frac{p_{min} + \epsilon}{p_{curr} + \epsilon}$

Sample $h \sim \text{Bernoulli}(g)$

if $h$ then

Add $i$ to $D$

end if

end while