

# When More Data Hurts: A Troubling Quirk in Developing Broad-Coverage Natural Language Understanding Systems

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## Abstract

In natural language understanding (NLU) production systems, users’ evolving needs necessitate the addition of new features over time, indexed by new symbols added to the meaning representation space. This requires additional training data and results in ever-growing datasets. We present the first systematic investigation into this *incremental symbol learning* scenario. Our analyses reveal a troubling quirk in building (broad-coverage) NLU systems: *as the training dataset grows, more data is needed to learn new symbols, forming a vicious cycle*. We show that this trend holds for multiple mainstream models on two common NLU tasks: intent recognition and semantic parsing. Rejecting class imbalance as the sole culprit, we reveal that the trend is closely associated with an effect we call *source signal dilution*, where strong lexical cues for the new symbol become diluted as the training dataset grows. Selectively dropping training examples to prevent dilution often reverses the trend, showing the over-reliance of mainstream neural NLU models on simple lexical cues and their lack of contextual understanding.<sup>1</sup>

## 1 Introduction

Broad-coverage natural language understanding (NLU) systems that simultaneously support a wide range of user requests are critical for developing general-purpose natural language interfaces. Such systems are already being deployed and reach millions of users worldwide: As of 2021, Amazon Alexa contains more than 80,000 skills (Vailshery, 2021), and Microsoft has deployed a new conversational interface for Outlook that uses over 300 composable functions to represent fine-grained semantics in task-oriented user-agent dialogues (Semantic Machines et al., 2020; Burrage, 2021).

\*Work done as an intern at Microsoft Semantic Machines.

<sup>1</sup>Code, models, and data will be available at <https://aka.ms/nlu-incremental-symbol-learning>.

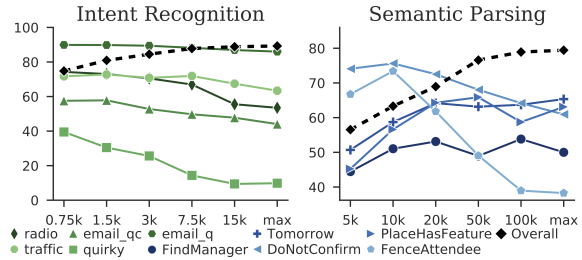


Figure 1: Overall and per-symbol test accuracy for learning a new symbol from a fixed number of training examples (30 for intent, 100 for SMCaFlow) when the overall training dataset grows (x-axis). Each line represents fixing a different symbol. As training data size increases, overall accuracy (averaged across symbols) increases but new symbol accuracy often decreases.

These broad-coverage NLU systems do not acquire their full capability on day one: new features (e.g., intents or functions), and the new training examples for learning them, are added incrementally. However, there has been little research on the data and learning dynamics during such incremental development. The wide deployment and high cost of such systems make this research critical, and we aim to call attention to this important problem.

We consider two prototypical NLU tasks: intent recognition and semantic parsing. NLU is generally concerned with mapping utterances into symbolic meaning representations (e.g., intent labels for intent recognition and sequences of functions/arguments for semantic parsing). We consider the following *incremental symbol learning* scenario: given a set of existing symbols and their training data, we want to learn a new symbol, which entails adding new labeled data for the symbol. As the system supports more and more symbols, its training data size continually increases. This relates more broadly to domain adaptation (Ben-David et al., 2010) if we consider the new symbols to be a new domain with a very small number of examples, and differs from continual learning (Madotto et al., 2021), which learns a new domain using only training data for the new domain (with replay of

limited data from previous domains). We instead train models from scratch on all the existing data and the new symbol data simultaneously, which is typical in practice to guarantee accuracy on both old and new features.

At first blush, dataset growth may seem positive, in holding with a common assumption of supervised learning: *more data is generally better* (Kearns et al., 1994). However, our analyses reveal a troubling quirk: *as the training data size increases, the performance on the new symbol decreases*. To investigate this, we simulate the incremental symbol learning scenario by trying to learn a new symbol from a fixed number of new training examples when the overall training data size gradually increases. We examine an English intent recognition dataset (Liu et al., 2019a) and an English semantic parsing dataset (Semantic Machines et al., 2020), testing 5 symbols per dataset.

Fig. 1 shows the overall test accuracy of our best models (cf. §2) as well as the accuracy on examples containing the new symbol. As the dataset grows, the average test accuracy across all symbols increases monotonically. However, the accuracy on the new symbol’s examples generally decreases. This decrease could lead to a *vicious cycle*, where an increasing number of training examples would need to be collected to achieve adequate accuracy for each new symbol, accelerating the dataset’s growth and thereby further increasing the demand for data for future (and also existing) symbols as they become a smaller percentage of the data.

Class imbalance is one obvious candidate explanation for the performance decrease: as the number of examples  $N$  in the dataset grows and the number of examples for the new symbol  $\hat{y}$  stays fixed, the prior probability of the new symbol  $p(\hat{y}) \sim \frac{\text{count}(\hat{y})}{N}$  in the training data decreases. If this were true, simply upsampling the new symbol’s annotations should revert the decrease. With a view to addressing class imbalance, we explore two common solutions: upsampling and group distributionally robust optimization (DRO) (Sagawa et al., 2019, 2020). However, neither of them fully attenuates the accuracy drop nor delivers a satisfactory solution.

The failure of these solutions leads us to identify a different force associated with the performance decrease, *source signal dilution*, whereby the reliability of the signal coming from indicative tokens in the user utterances for the new symbol is increasingly diminished in larger datasets. This force is

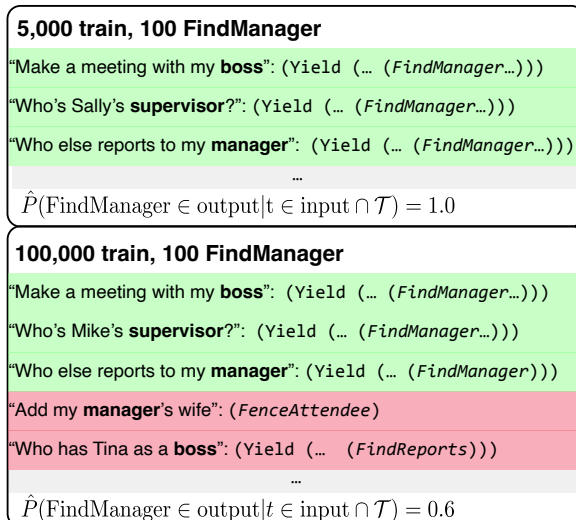


Figure 2: Source signal dilution in the training set: as the dataset grows, the set of cues  $t$  (in bold) associated with FindManager becomes less predictive of it.

illustrated in Fig. 2. At low data settings, some tokens are highly correlated with the FindManager symbol, but as the dataset grows, the correlation with these tokens is diluted by competing examples that, often by coincidence, contain the same tokens. We show that when diluting examples (shown in red) are removed, the accuracy drop largely disappears, indicating that our state-of-the-art neural NLU models are overly-reliant on simple lexical cues for learning the new symbol instead of contextual understanding of the input as a whole. Thus, when such lexical cues become less reliable in larger datasets, the models struggle to learn the new symbol. We later argue that while the removal of diluting examples may address the symptoms expressed under increasing dataset sizes, it falls short of an adequate or scalable solution.

Our main contributions are threefold:

- We identify a troubling quirk in developing broad-coverage NLU systems that challenges the common assumption that more data typically entails better performance.
- Based on our observations, we identify plausible forces leading to the decreased accuracy seen in Fig. 1, foremost among them the dilution of the source signal (cf. Fig. 2). A deeper understanding of this force may guide systematic solutions to this problem.
- Finally, we release our code and models, including a model for the SMCaIFlow dataset (Semantic Machines et al., 2020) that sets a new state of the art. We hope it will serve as a useful baseline for future development on this challenging dataset.

## 2 Datasets and Models

Intent recognition and task-oriented semantic parsing share multiple common features. They both translate user utterances to symbols in a certain meaning representation and they are both commonly used in production NLU systems. This makes them ideal testbeds for exploring the dynamics in incremental symbol learning.

### 2.1 Intent Recognition

Intent recognition involves classifying utterances into a given set of *intents* (Lorenc et al., 2021). Intents often index into a set of pre-defined templates (e.g., the intent `play_music` might index into a template with slots “song name,” “song artist” etc.) and are central to many digital assistant technologies. New intents may be added to the agent incrementally during the development process as needs for new capabilities arise. For example, an agent capable of cooking tasks may be extended to other household tasks, requiring it to understand the associated intents.

We use the *NLU evaluation* data provided by Liu et al. (2019a), containing 25,715 utterances for 68 intents across 18 scenarios. 2,571 and 5,144 utterances are reserved for validation and testing, respectively. When examining each new intent, we fix the number of examples for the new intent at 30, chosen to represent a low-resource intent, and vary the size of the training set  $N \in \{750, 1,500, 3,000, 7,500, 15,000, 18,000\}$  where 18,000 is the *max* in Fig. 1. We examine 5 intents:

- `play_radio` is primarily triggered when users ask for radio stations to be played.
- `email_query` is for email-related queries.
- `email_querycontact` is triggered by questions about contacts in an address book.
- `general_quirky` is a catch-all category for trivia-style questions and pleasantries.
- `transport_traffic` is triggered by traffic-related questions and commands.

Some of the intents (e.g., `play_radio`) have a set of easily-identifiable trigger tokens (e.g., “radio” and “fm”) while others (e.g., `general_quirky`) have very diverse inputs. Example utterances for each intent can be found in Appendix A.1.

To model this task, we apply a linear classification layer to the [CLS] token of BERT base (Devlin et al., 2019), finetuning the whole contextualized encoder at training time. This model was trained to convergence with the Adam optimizer using a learning rate of  $1e-5$ .

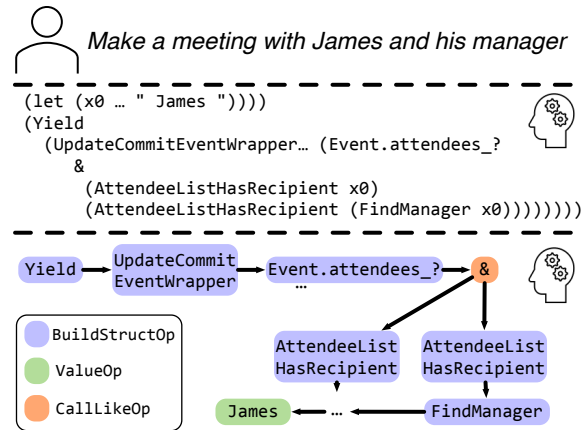


Figure 3: Example of an SMCaFlow program; it can be represented as a Lisp expression (middle) or as a DAG (bottom).

### 2.2 Semantic Parsing

While providing a good environment for experimentation, the intent recognition task lacks the complexity of a full real-world production environment. We therefore seek to expand our experiments and analyses to a production-level task and dataset. To that end, we use the SMCaFlow dataset (Semantic Machines et al., 2020; Burrage, 2021), which offers a task-oriented semantic parsing challenge, where a user iteratively creates a dataflow graph in a dialogue with an agent (cf. Fig. 3). The dataset has 41,517 dialogues with 338 function types, yielding 121,024 training user turns in the full setting. Following prior work (Semantic Machines et al., 2020), the input to our parsing model is the previous user utterance, the corresponding agent response, and the current user utterance, all concatenated. The model is tasked with learning to generate a typed Lisp program; see Fig. 3 for an example, (further examples in Appendix Table 4).

We explore both a sequence-to-sequence (seq2seq) model and a sequence-to-graph (seq2graph) model, using the MISO framework (Zhang et al., 2019b; Stengel-Eskin et al., 2021), which is built on top of AllenNLP (Gardner et al., 2018). The former directly predicts the Lisp string, while the latter produces a DAG as seen at the bottom of Fig. 3. Details follow.

**LSTM seq2seq** Our baseline model is an LSTM-based seq2seq model similar to that used by Dong and Lapata (2016) and Semantic Machines et al. (2020). It consists of a BiLSTM encoder and an LSTM decoder with attention over the encoder states and a source copy operation to copy entity spans from the source text; its embedding layer

is initialized with GloVe embeddings (Pennington et al., 2014). See Appendix B.1 for more details.

**Transformer-based transductive** A more competitive approach follows the transductive parsing paradigm (Zhang et al., 2019a), which aims to directly produce the underlying DAG instead of the surface form, generating graph nodes as well as edges. We implement a transformer-based transductive model based on the architecture and code from Stengel-Eskin et al. (2021). The model directly generates the linearized DAG (cf. Fig. 3) underlying the SMCaFlow Lisp expression; the nodes of the DAG (functions and arguments) are generated in a sequence-to-sequence fashion, with graph edges and edge types being assigned during decoding via a biaffine parser (Dozat and Manning, 2017). Following past work, the input features for this model are a concatenation of BERT (Devlin et al., 2019), GloVe, and character CNN features. We also experiment with RoBERTa (Liu et al., 2019b) and ALBERT (Lan et al., 2019) as the encoder in Appendix C, which show qualitatively similar behavior. Therefore, we report BERT results in the remaining experiments. We give additional details on the transductive transformer model in Appendix B.2.

**Data** As SMCaFlow’s test set is not publicly available, we first split the validation data in half to obtain a held-out test set. We then construct training splits by selecting 100 examples for each new symbol and varying  $N \in \{5,000, 10,000, 20,000, 50,000, 100,000, max\}$ , where *max* is the maximum amount of data that can be taken from the 121,024 training examples while excluding all but 100 examples for the new symbol. This number is typically slightly under 120,000. We describe the symbols examined; Appendix A.2 has further examples.

- FindManager is invoked when a user queries for a person’s manager.
- Tomorrow returns tomorrow’s date.
- DoNotConfirm is applied when a user wants to cancel a proposed action (e.g., confirming the creation of an event) by the agent.
- FenceAttendee is invoked when a user tries to create an event with a person without using their proper name (e.g., “mom” or “my dentist”).
- PlaceHasFeature is used when a user asks whether a place has certain amenities (e.g., outdoor seating) or offers certain services.

These vary in compositionality: FindManager and PlaceHasFeature take arguments, but Tomorrow does not, and FenceAttendee and DoNotConfirm are complete programs in themselves. FindManager and Tomorrow have strong input cues, but DoNotConfirm and FenceAttendee come from very diverse inputs.

### 3 Experiments

**Baseline** The first experimental setting is the baseline setting, as presented in Fig. 1. Here, we vary the size of the training data while holding the number of examples for each new symbol fixed. We train each model with three random seeds for all experiments, reporting the average. Note that we train each model on *all* of the training data (for new and old symbols) simultaneously, which is the typical setting for production systems.

**Upsampling** In our upsampling experiments, we increase the number of examples for a new symbol by duplicating training examples for that symbol. While this addresses the class imbalance problem, it does not increase the diversity of inputs. We explore two ways of setting the number of times we duplicate the existing examples: *adaptive* and *fixed*. For adaptive upsampling, we upsample the new symbol examples so that the ratio of new symbol examples to total training size (i.e.,  $\frac{\text{count}(\hat{y})}{N}$  where  $\text{count}(\hat{y})$  is the number of examples for the new symbol  $\hat{y}$  after upsampling) remains constant as  $N$  increases. For example, the ratio for intent recognition is 30 new symbol examples in 750 total examples (0.04) so at 15,000 total examples we would have 600 new symbol examples, upsampled from the original 30. Note that although this strategy gives us a more comprehensive picture as it keeps class imbalance constant, it is unrealistic in practice: whenever we add new training data for a symbol (often, daily in deployed systems) we would have to proportionally increase the ratio for all other symbols, rapidly expanding the training set. Thus, we also examine a fixed strategy, where we upsample by the same ratio as  $N$  increases. After exploring ratios in  $\{2, 4, 8, 16, 32, 64\}$ , we selected 32 based on validation performance; i.e., each example for the new symbol is copied 32 times in the training set. Upsampling eliminates (adaptive) or alleviates (fixed) class imbalance, while also improving the reliability of trigger tokens for the new symbol (e.g., “manager” for FindManager) to some degree.



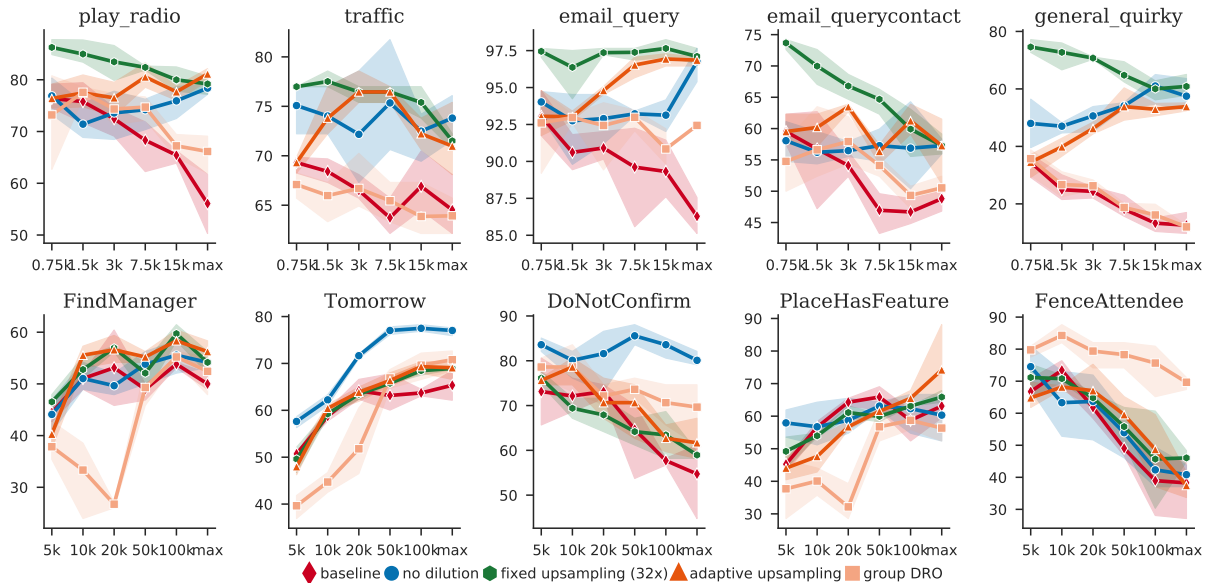


Figure 4: Per-symbol accuracy on intent recognition and semantic parsing as the size of the training set increases. Shaded regions represent 95% bootstrap confidence intervals.

**Group DRO** has been proposed as a method for robust generalization under severe class imbalances (Sagawa et al., 2019). Rather than optimizing by minimizing the average loss across a training batch, group DRO seeks to minimize the loss for the worst-performing group in each batch. More formally, given a set of groups  $\mathcal{G}$ , a parameter space  $\Theta$ , a model  $f(x; \theta)$ , a loss  $l$ , and a per-group training distribution  $P_g$ , the group DRO objective is:

$$\theta^* = \arg \min_{\theta \in \Theta} \left( \max_{g \in \mathcal{G}} \mathbb{E}_{(x,y) \sim P_g} [l(f(x; \theta), y)] \right)$$

We apply this objective to our intent recognition model, treating each intent as a separate group. As long as the worst-performing group is the new intent (e.g., play\_radio), the model will be optimized solely for that intent. For the SMCaFlow setting, applying group DRO is more challenging, as the output is a program containing multiple functions rather than a single class. We apply group DRO to SMCaFlow by defining two groups: programs with the new symbol, and those without it.

## 4 Results and Analysis

### 4.1 Overall Model Performance

We first evaluate model performance using the original data splits of the two datasets. The purpose is to verify that our chosen models are competitive on these datasets and can serve as a solid foundation for subsequent studies on incremental symbol learning. For intent recognition, the BERT-based

Model	Dev EM	Test EM
LSTM (ours)	66.9%	52.4%
TFMR +BERT (ours)	79.3%	74.5%
Platanios et al. (2021)	–	75.3%
TFMR +BERT, tuned (ours)	80.3%	75.5%
TFMR +RoBERTa, tuned (ours)	80.8%	<b>75.7%</b>

Table 1: Exact-match (EM) accuracy on SMCaFlow official test set when trained on the full dataset. The transformer (TFMR) transductive model with encoder tuning sets a new state of the art.

classifier trained on the full dataset obtains 90.5% test accuracy, indicating that it is suited to the task. Table 1 shows the performance of the semantic parsing models on the full SMCaFlow validation and test splits. Here, the test split is the held-out split used in the official SMCaFlow leaderboard. To further increase the seq2graph model’s performance, we follow Stengel-Eskin et al. (2020) and unfreeze the top 8 layers of the encoder (e.g. BERT, RoBERTa). These tuned models outperform Platanios et al. (2021), setting a new state of the art for SMCaFlow. To reduce computation we use models with frozen encoders for the following sections.

### 4.2 More Data Can Hurt Performance

**Intent Recognition** Fig. 1 and Fig. 4 show the overall and per-symbol accuracy of a model when the number of examples for a new intent is fixed at 30. As the size of the training set increases, the overall accuracy of the model, averaged across all intents, improves. However, the accuracy on the new intent decreases.

**Semantic Parsing** When the number of examples for a symbol is fixed at 100, and the number of other training examples increases, Fig. 1 and Fig. 4 show that the accuracy on new symbols is highly non-monotonic. Fig. 5 shows that the non-monotonic accuracy is not just a quirk of transductive parsing but is also seen in a commonly-used LSTM-based seq2seq baseline model. In Appendix C we include results for RoBERTa (base and large) and ALBERT, which indicate that the non-monotonic and often-decreasing SMCaFlow trends are not due solely to the architecture or the encoder. While intent recognition displays largely decreasing performance curves, some curves for SMCaFlow symbols (e.g., FindManager) increase and decrease at different settings. This may be attributed to competing forces: additional data may increase the seq2seq or seq2graph model’s fluency in producing syntactically correct outputs, but it also increases the class imbalance and source signal dilution, with different settings having different balances of these forces.

### 4.3 Addressing Class Imbalance

Assuming the number of examples for the new symbol stays fixed, then as the size of the dataset grows, the new symbol represents a smaller and smaller minority as compared to all other symbols combined; i.e., class imbalance increases. If the growing class imbalance were the culprit behind the decrease in accuracy observed in Fig. 1, then we would expect a robust optimization technique that prioritizes minority classes, such as group DRO, to ameliorate the problem. DRO was designed for optimization that is robust to distribution shifts in the group priors between the training and test data. In other words, DRO optimizes the model for performance on both majority and minority classes, so that if the minority classes become more prevalent at test time, the overall performance does not suffer. In our setting, the test distribution remains fixed, while the training distribution changes as more data is added, with the new symbol becoming less probable, increasing the distribution shift between training and test data. If the growing class imbalance (i.e., the growing shift between the training and test distributions) were the cause for the decreasing accuracy, DRO would help the model overcome the shift and improve the performance.

The group DRO curves in Fig. 4 show that, while the accuracy on the new symbol is often

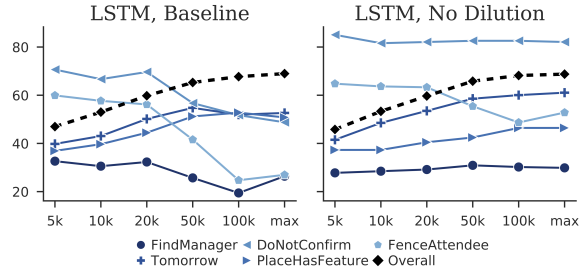


Figure 5: LSTM performance on the new symbol decreases as the total training size increases, but removing source signal dilution largely fixes it.

raised above the baseline (e.g., FenceAttendee, email\_query), it generally still decreases as the training set grows. Additionally, applying group DRO often results in an accuracy lower than the baseline for many training data sizes (e.g., PlaceHasFeature, FindManager, and traffic). Thus, while group DRO may improve the results on the new symbol for a given setting, it does not alleviate the core problem: a larger dataset leads to lower accuracy than what could have been obtained with a smaller dataset. This suggests that the underlying problem goes beyond the distribution shift induced by class imbalance.

The upsampling curves for both strategies (fixed and adaptive) in Fig. 4 show a similar trend: upsampling can improve overall accuracy and can reduce the rate at which the accuracy decreases, but often fails to remove the decrease. In some cases (e.g., email\_query, PlaceHasFeature) fixed upsampling does lead to monotonically-improving accuracy; however, these improvements are inconsistent across symbols, suggesting that there may be other forces at play.

### 4.4 Addressing Source Signal Dilution

The failure of group DRO and upsampling to solve the problem suggests that it may not be due purely to the increased class imbalance. We propose another contributing factor: a decrease in the reliability of the source signal when additional data is added. For many symbols, there is often a set of tokens  $\mathcal{T}$  that can be found in most of the utterances for that symbol. For example, for the play\_radio intent, at least one of the tokens in  $\mathcal{T} = \{\text{radio, fm, play}\}$  is found in 78.04% of the corresponding utterances in the full training data. Thus, the set  $\mathcal{T}$  is a strong signal for predicting play\_radio. However, as more data is added, elements in  $\mathcal{T}$  will happen to appear more in the inputs for other intents, reducing their strength as a

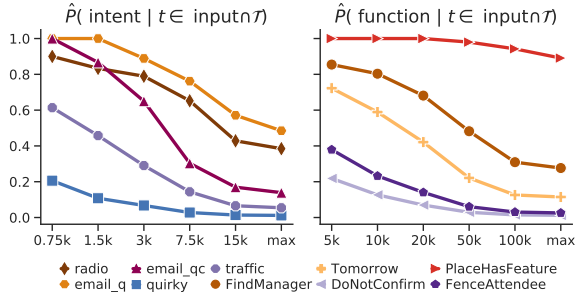


Figure 6: As dataset size increases, the source signal strength of the trigger tokens to each symbol decreases.

signal for predicting `play_radio`. More formally, we define the *source signal strength* of a trigger token set  $\mathcal{T}$  to a symbol  $\hat{y}$  as  $\hat{P}(\hat{y} \in \text{output} \mid \exists t \in \mathcal{T}, t \in \text{input})$ , i.e., among the training examples that contain at least one of the trigger tokens in the input, what percentage of those have  $\hat{y}$  in the output. *Source signal dilution* then refers to the decrease of the source signal strength of  $\mathcal{T}$  to  $\hat{y}$  when the overall training data grows, and the trigger tokens become less predictive of the symbol  $\hat{y}$ .

Fig. 6 shows the source signal strength for each of the examined symbols. The set of trigger tokens for each symbol were determined manually and given in Appendix A.3. Across symbols, as the size of the dataset increases, the source signal strength decreases, with more examples for other symbols containing the same tokens in their inputs, diluting the signal. Note that the different starting points of these lines indicate that different symbols start with a higher or lower source signal strength. For example, even at the most concentrated setting (750 total examples to 30 `general_quirky` examples), `general_quirky` has no trigger tokens that are strongly correlated, while `play_radio` has a small set of trigger tokens that are perfectly correlated with it. Taken together with Fig. 1, Fig. 6 shows that source signal dilution has a positive correlation with the decreasing performance on that symbol.

To further investigate the impact of source signal dilution and see if there is any causal link, we conduct an intervention and experiment with removing the diluting examples (e.g., the ones in red in Fig. 2) from the training data. In the “no dilution” setting of Fig. 4, we remove the diluting examples for each new symbol and fill in with other training examples to keep the class imbalance unchanged,<sup>2</sup> but we ensure that the new examples do not contain

<sup>2</sup>This holds except for the max setting, where the max amount of data is reduced since more examples are discarded.

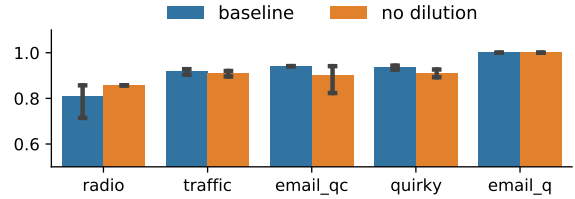


Figure 7: Test accuracy on examples that contain any of the trigger tokens associated with the new intent, but whose label is some other intent.

any of the trigger tokens for the new symbol. For example, in Fig. 2, at 100,000 training examples, we would not add the two examples highlighted in red. They would be replaced by examples that do not contain “manager,” “boss,” and “supervisor” in the input. In other words, we change the datasets such that the curves in Fig. 6 remain flat.

Here, we see that the decrease is in fact often attenuated at larger training datasets, and the accuracy even increases for several intents and functions. Considering that the “no dilution” setting has exactly the same amount of class imbalance as the baseline setting, this confirms that *source signal dilution is a distinct factor from class imbalance that contributes to the challenges in incremental symbol learning*. This result is not unique to BERT-based models: when we remove the same examples for the GloVe-based LSTM SMCaFlow parser, we see similar trends (cf. Fig. 5).

#### 4.5 Impact on Competing Examples

The increase in performance on the new symbol that results from removing diluting examples, as seen in Fig. 4, might come at a cost. Specifically, since we are removing examples containing trigger tokens associated with the new symbol (e.g., examples containing “manager” in the input but not `FindManager` in the output), we run the risk of losing performance on those examples in the test set. Fig. 7 shows the intent recognition performance on such test examples (i.e., examples that would have been excluded from the training set), for the maximum number of total training examples (18000).<sup>3</sup> The accuracy decreases when we remove diluting examples, sometimes substantially; i.e., the improvement on the new symbol from removing diluting examples comes at a cost to exactly the type of examples we are removing.

<sup>3</sup>SMCaFlow lacks enough examples with source-side competition for other symbols in the test set to perform a similar quantitative evaluation.

While this is unsurprising, it is unfortunate, as it indicates that the strengthening of the source signal through removal, while perhaps addressing the symptoms of the problem seen in Fig. 1, falls short of presenting a satisfactory cure.

## 5 Discussion

Firstly, our results show that, as the training dataset grows, the performance on a new symbol with a fixed number of examples often decreases, suggesting that an increasing amount of data for the new symbol will be required as the dataset expands. The longer the life-span of a system, the more new symbols may be added to it—our results suggest that as an NLU system extends its coverage, the data annotation cost may spiral up. Simple solutions like upsampling and group DRO do not suffice in this case: even with these in place, the performance remains decreasing or non-monotonic. Our results demonstrate that removing diluting examples does largely remove the performance decrease.

However, treating the removal of diluting examples as a solution is unsatisfying in three ways. First, we now face a new challenge as we iterate the addition of new symbols. Perhaps for the first symbol added, we can successfully remove offending examples from the training set; but as we iterate this process, we may find ourselves removing increasing percentages of our training data, with increasingly disparate subsets of annotations for each symbol. This makes removal an unattractive solution. Secondly, while we can intervene on the training distribution, we cannot control the user distribution. Fig. 7 shows that the performance on test examples containing trigger tokens but labeled with other intents does decrease after removal. This suggests that the model’s ability to capture the full range of user utterances may be reduced on some axes after removal, even if the accuracy on the new symbol is increased. Finally, treating removal of diluting examples as a solution means accepting that our models are largely failing to compositionally and contextually analyze the inputs. Despite the fact that our models leverage the power of recurrence and often use large pre-trained contextualized encoders, their reliance on simple non-contextual lexical cues is reminiscent of simpler non-contextual models like Naive Bayes classifiers. We would ideally hope that a contextualized representation would be sensitive to the difference between, for example, “Who is my manager?” and

“Invite my manager’s wife.” However, it seems that, despite their contextualized inputs, the models may be overly sensitive to the presence or absence of individual tokens.

Despite these unsatisfying observations, the removal of diluting examples also leads to a more promising conclusion, namely that the models we investigate seem to be able to handle a high degree of class imbalance, provided that the source signal is strong enough for the minority class. In the “no dilution” setting, the class imbalance remains exactly the same as for the baseline and group DRO settings. The strong performance under the “no dilution” setting suggests that the models can cope with large class imbalances (e.g., 100,000 total examples to 100 new symbol examples) provided that the lexical cues for the minority class in the training data are strong. Both the intent classifier and the transductive parser are capable of handling extremely large class imbalance ratios if the source-target mapping is reliable. This helps explain why the models’ performance can improve even as the class imbalance increases.

## 6 Related Work

Our learning setting relates closely to work on learning with imbalanced data as well as analyses of spurious correlations. [Sagawa et al. \(2020\)](#) find that over-parameterized networks display a similar trend to our trends on the worst-performing group as model capacity is increased: minority-group performance decreases as overall performance increases. They conclude that large models tend to memorize minority-class data and rely on spurious correlations, leading to worsening accuracy. Our work examines the accuracy on specific symbols as the size of the *dataset* (rather than of the model) grows. Different solutions have been proposed to improve generalization on minority data, such as distributionally robust optimization (DRO; [Oren et al., 2019](#); [Sagawa et al., 2019](#); [Zhou et al., 2021](#)) as well as other training and re-weighting strategies ([Liu et al., 2021](#); [Ye et al., 2021](#)). These solutions are typically applied to image classification tasks; in a space more closely related to NLU, [Li and Nenkova \(2014\)](#) explore several upsampling and re-weighting strategies for discourse relation classification with imbalanced data, and [Larson et al. \(2019\)](#) investigate the effect of imbalanced data for detecting out-of-scope intents. [Gardner et al. \(2021\)](#) argue that simple lexical features, such as the ones we highlight, represent spurious corre-



lations in the data; on this account, the models investigated here are prone to over-reliance on such spurious correlations, with the removal of diluting examples strengthening them. In a similar vein, McCoy et al. (2019) present evidence that natural language interface models rely upon spuriously-correlated features, and present a challenge dataset with such correlations mitigated. Yaghoobzadeh et al. (2021) connect a model forgetting an example during training (i.e., the example was correctly classified, and then became incorrectly classified) with spurious correlations and propose a two-stage fine-tuning solution for improving model robustness.

This past work in learning with spurious correlations and imbalanced data has focused on single-label multi-class classification problems; we follow this trend in our experiments with intent recognition. However, we go beyond the single-label setting in our semantic parsing experiments, where we investigate class imbalance in a highly structured multi-label multi-class output space.

The challenging setting we present differs also from never-ending learning (Mitchell et al., 2015) and domain adaptation/continued training in that for each iteration of the dataset, a new model is trained, rather than continued training on a single model. Li et al. (2021a) investigate few-shot learning for semantic parsing via continued training, where a trained model is exposed to a small set of annotations for a new predicate. While we also attempt to learn from relatively few annotations, we do not adapt learned models, instead simulating the common production setting where models are re-trained on datasets as a whole.

Previous parsing approaches for SMCaFlow have followed both modeling paradigms used here: Semantic Machines et al. (2020) present a seq2seq baseline for SMCaFlow, following previous work in seq2seq semantic parsing (Vinyals et al., 2015; Dong and Lapata, 2016; Jia and Liang, 2016). Platanios et al. (2021) outperform that baseline with a transductive seq2graph model using explicit type constraints. Treating semantic parsing as a seq2graph transduction problem has proved to be a strong paradigm for parsing Abstract Meaning Representations (Banarescu et al., 2013; Zhang et al., 2019a,b), Semantic Dependencies (Oepen et al., 2014, 2016; Zhang et al., 2019b), Universal Conceptual Cognitive Annotation (Abend and Rappoport, 2013; Zhang et al., 2019b), Universal Decompositional Semantics (White et al., 2020;

Stengel-Eskin et al., 2020, 2021), and GQA (Hudson and Manning, 2019; Li et al., 2021b).

## 7 Conclusion

We examined the effect of a growing dataset on the ease of learning new symbols for NLU, finding that it often becomes harder to learn a new symbol as more data is collected. This trend holds across models and settings, and could pose significant problems as NLU systems increase in lifespan and coverage. We found that the weakening of simple lexical associations as the datasets grow is closely tied to the decrease in performance, indicating that the neural models tested in this study may be overly reliant on simple lexical cues. We end by encouraging others to examine these effects in the problems tested here and also in similar problems, where similar effects are likely to be found.

## 8 Limitations

In our work, we have examined intent recognition and semantic parsing; while these tasks are prototypical NLU tasks, they represent a subset of natural language processing tasks in which the challenges associated with incremental symbol learning might appear. Furthermore, we consider two datasets from these tasks, which we deem to be good representatives but which we acknowledge are not exhaustive. Importantly, as we state in Section 1, all datasets examined here are in English—while we expect the results to hold for other languages, this remains to be verified empirically. Specifically, our investigation relies heavily on *tokens* to measure source signal dilution; this may need to be modified for languages that have more or less semantic content per token than English.

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## References

- Omri Abend and Ari Rappoport. 2013. *Universal Conceptual Cognitive Annotation (UCCA)*. In *Proceedings of the 51st Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 228–238, Sofia, Bulgaria. Association for Computational Linguistics.
- Laura Banarescu, Claire Bonial, Shu Cai, Madalina Georgescu, Kira Griffitt, Ulf Hermjakob, Kevin

- Knight, Philipp Koehn, Martha Palmer, and Nathan Schneider. 2013. [Abstract Meaning Representation for sembanking](#). In *Proceedings of the 7th Linguistic Annotation Workshop and Interoperability with Discourse*, pages 178–186, Sofia, Bulgaria. Association for Computational Linguistics.
- Shai Ben-David, John Blitzer, Koby Crammer, Alex Kulesza, Fernando Pereira, and Jennifer Wortman Vaughan. 2010. A theory of learning from different domains. *Machine learning*, 79(1):151–175.
- Eugenie Burrage. 2021. [Start a conversation with your personal productivity assistant in Outlook with Cortana](#).
- Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. 2019. [BERT: Pre-training of deep bidirectional transformers for language understanding](#). In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, pages 4171–4186, Minneapolis, Minnesota. Association for Computational Linguistics.
- Li Dong and Mirella Lapata. 2016. [Language to logical form with neural attention](#). In *Proceedings of the 54th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 33–43, Berlin, Germany. Association for Computational Linguistics.
- Timothy Dozat and Christopher D. Manning. 2017. [Deep biaffine attention for neural dependency parsing](#). In *5th International Conference on Learning Representations, ICLR 2017, Toulon, France, April 24-26, 2017, Conference Track Proceedings*. OpenReview.net.
- Matt Gardner, Joel Grus, Mark Neumann, Oyvind Tafjord, Pradeep Dasigi, Nelson F. Liu, Matthew Peters, Michael Schmitz, and Luke Zettlemoyer. 2018. [AllenNLP: A deep semantic natural language processing platform](#). In *Proceedings of Workshop for NLP Open Source Software (NLP-OSS)*, pages 1–6, Melbourne, Australia. Association for Computational Linguistics.
- Matt Gardner, William Merrill, Jesse Dodge, Matthew E Peters, Alexis Ross, Sameer Singh, and Noah Smith. 2021. [Competency problems: On finding and removing artifacts in language data](#). *ArXiv preprint*, abs/2104.08646.
- Drew A Hudson and Christopher D Manning. 2019. [Gqa: A new dataset for real-world visual reasoning and compositional question answering](#). In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pages 6700–6709.
- Robin Jia and Percy Liang. 2016. [Data recombination for neural semantic parsing](#). In *Proceedings of the 54th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 12–22, Berlin, Germany. Association for Computational Linguistics.
- Michael J Kearns, Umesh Virkumar Vazirani, and Umesh Vazirani. 1994. *An introduction to computational learning theory*. MIT press.
- Zhenzhong Lan, Mingda Chen, Sebastian Goodman, Kevin Gimpel, Piyush Sharma, and Radu Soricut. 2019. [Albert: A lite bert for self-supervised learning of language representations](#). In *International Conference on Learning Representations*.
- Stefan Larson, Anish Mahendran, Joseph J. Peper, Christopher Clarke, Andrew Lee, Parker Hill, Jonathan K. Kummerfeld, Kevin Leach, Michael A. Laurenzano, Lingjia Tang, and Jason Mars. 2019. [An evaluation dataset for intent classification and out-of-scope prediction](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 1311–1316, Hong Kong, China. Association for Computational Linguistics.
- Junyi Jessy Li and Ani Nenkova. 2014. [Addressing class imbalance for improved recognition of implicit discourse relations](#). In *Proceedings of the 15th Annual Meeting of the Special Interest Group on Discourse and Dialogue (SIGDIAL)*, pages 142–150, Philadelphia, PA, U.S.A. Association for Computational Linguistics.
- Zhuang Li, Lizhen Qu, Shuo Huang, and Gholamreza Haffari. 2021a. [Few-shot semantic parsing for new predicates](#). In *Proceedings of the 16th Conference of the European Chapter of the Association for Computational Linguistics: Main Volume*, pages 1281–1291, Online. Association for Computational Linguistics.
- Zhuowan Li, Elias Stengel-Eskin, Yixiao Zhang, Cihang Xie, Quan Hung Tran, Benjamin Van Durme, and Alan Yuille. 2021b. [Calibrating concepts and operations: Towards symbolic reasoning on real images](#). In *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV)*, pages 14910–14919.
- Evan Zheran Liu, Behzad Haghgoo, Annie S. Chen, Aditi Raghunathan, Pang Wei Koh, Shiori Sagawa, Percy Liang, and Chelsea Finn. 2021. [Just train twice: Improving group robustness without training group information](#). In *Proceedings of the 38th International Conference on Machine Learning, ICML 2021, 18-24 July 2021, Virtual Event*, volume 139 of *Proceedings of Machine Learning Research*, pages 6781–6792. PMLR.
- Xingkun Liu, Arash Eshghi, Pawel Swietojanski, and Verena Rieser. 2019a. [Benchmarking natural language understanding services for building conversational agents](#). In *Proceedings of the Tenth International Workshop on Spoken Dialogue Systems Technology (IWSDS)*, pages xxx–xxx, Ortigia, Siracusa (SR), Italy. Springer.

- Yinhan Liu, Myle Ott, Naman Goyal, Jingfei Du, Mandar Joshi, Danqi Chen, Omer Levy, Mike Lewis, Luke Zettlemoyer, and Veselin Stoyanov. 2019b. Roberta: A robustly optimized bert pretraining approach. *arXiv preprint arXiv:1907.11692*.
- Petr Lorenc, Petr Marek, Jan Pichl, Jakub Konrád, and Jan Šedivý. 2021. Benchmark of public intent recognition services. *Language Resources and Evaluation*, pages 1–19.
- Andrea Madotto, Zhaojiang Lin, Zhenpeng Zhou, Seungwhan Moon, Paul Crook, Bing Liu, Zhou Yu, Eunjoon Cho, Pascale Fung, and Zhiguang Wang. 2021. [Continual learning in task-oriented dialogue systems](#). In *Proceedings of the 2021 Conference on Empirical Methods in Natural Language Processing*, pages 7452–7467, Online and Punta Cana, Dominican Republic. Association for Computational Linguistics.
- Tom McCoy, Ellie Pavlick, and Tal Linzen. 2019. [Right for the wrong reasons: Diagnosing syntactic heuristics in natural language inference](#). In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*, pages 3428–3448, Florence, Italy. Association for Computational Linguistics.
- Tom M. Mitchell, William W. Cohen, Estevam R. Hruschka Jr., Partha Pratim Talukdar, Justin Betteridge, Andrew Carlson, Bhavana Dalvi Mishra, Matthew Gardner, Bryan Kisiel, Jayant Krishnamurthy, Ni Lao, Kathryn Mazaitis, Thahir Mohamed, Ndapandula Nakashole, Emmanouil A. Platanios, Alan Ritter, Mehdi Samadi, Burr Settles, Richard C. Wang, Derry Wijaya, Abhinav Gupta, Xinlei Chen, Abulhair Saparov, Malcolm Greaves, and Joel Welling. 2015. [Never-ending learning](#). In *Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence, January 25-30, 2015, Austin, Texas, USA*, pages 2302–2310. AAAI Press.
- Toan Q Nguyen and Julian Salazar. 2019. [Transformers without tears: Improving the normalization of self-attention](#). *ArXiv preprint*, abs/1910.05895.
- Stephan Oepen, Marco Kuhlmann, Yusuke Miyao, Daniel Zeman, Silvie Cinková, Dan Flickinger, Jan Hajič, Angelina Ivanova, and Zdeňka Urešová. 2016. [Towards comparability of linguistic graph Banks for semantic parsing](#). In *Proceedings of the Tenth International Conference on Language Resources and Evaluation (LREC'16)*, pages 3991–3995, Portorož, Slovenia. European Language Resources Association (ELRA).
- Stephan Oepen, Marco Kuhlmann, Yusuke Miyao, Daniel Zeman, Dan Flickinger, Jan Hajič, Angelina Ivanova, and Yi Zhang. 2014. [SemEval 2014 task 8: Broad-coverage semantic dependency parsing](#). In *Proceedings of the 8th International Workshop on Semantic Evaluation (SemEval 2014)*, pages 63–72, Dublin, Ireland. Association for Computational Linguistics.
- Yonatan Oren, Shiori Sagawa, Tatsunori B. Hashimoto, and Percy Liang. 2019. [Distributionally robust language modeling](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 4227–4237, Hong Kong, China. Association for Computational Linguistics.
- Jeffrey Pennington, Richard Socher, and Christopher Manning. 2014. [GloVe: Global vectors for word representation](#). In *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*, pages 1532–1543, Doha, Qatar. Association for Computational Linguistics.
- Emmanouil Antonios Platanios, Adam Pauls, Subhro Roy, Yuchen Zhang, Alexander Kyte, Alan Guo, Sam Thomson, Jayant Krishnamurthy, Jason Wolfe, Jacob Andreas, and Dan Klein. 2021. [Value-agnostic conversational semantic parsing](#). In *Proceedings of the 59th Annual Meeting of the Association for Computational Linguistics and the 11th International Joint Conference on Natural Language Processing (Volume 1: Long Papers)*, pages 3666–3681, Online. Association for Computational Linguistics.
- Shiori Sagawa, Pang Wei Koh, Tatsunori B Hashimoto, and Percy Liang. 2019. [Distributionally robust neural networks for group shifts: On the importance of regularization for worst-case generalization](#). *ArXiv preprint*, abs/1911.08731.
- Shiori Sagawa, Aditi Raghunathan, Pang Wei Koh, and Percy Liang. 2020. [An investigation of why overparameterization exacerbates spurious correlations](#). In *Proceedings of the 37th International Conference on Machine Learning, ICML 2020, 13-18 July 2020, Virtual Event*, volume 119 of *Proceedings of Machine Learning Research*, pages 8346–8356. PMLR.
- Abigail See, Peter J. Liu, and Christopher D. Manning. 2017. [Get to the point: Summarization with pointer-generator networks](#). In *Proceedings of the 55th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 1073–1083, Vancouver, Canada. Association for Computational Linguistics.
- Semantic Machines, Jacob Andreas, John Bufe, David Burkett, Charles Chen, Josh Clausman, Jean Crawford, Kate Crim, Jordan DeLoach, Leah Dorner, Jason Eisner, Hao Fang, Alan Guo, David Hall, Kristin Hayes, Kellie Hill, Diana Ho, Wendy Iwaszuk, Smriti Jha, Dan Klein, Jayant Krishnamurthy, Theo Lanman, Percy Liang, Christopher H. Lin, Ilya Lintsbakh, Andy McGovern, Aleksandr Nisnevich, Adam Pauls, Dmitrij Petters, Brent Read, Dan Roth, Subhro Roy, Jesse Rusak, Beth Short, Div Slomin, Ben Snyder, Stephon Striplin, Yu Su, Zachary Tellman, Sam Thomson, Andrei Vorobev, Izabela Witoszko, Jason Wolfe, Abby Wray, Yuchen Zhang, and Alexander Zotov. 2020. [Task-oriented dialogue](#)

- as dataflow synthesis. *Transactions of the Association for Computational Linguistics*, 8:556–571.
- Elias Stengel-Eskin, Kenton Murray, Sheng Zhang, Aaron Steven White, and Benjamin Van Durme. 2021. [Joint Universal Syntactic and Semantic Parsing](#). *Transactions of the Association for Computational Linguistics*, 9:756–773.
- Elias Stengel-Eskin, Aaron Steven White, Sheng Zhang, and Benjamin Van Durme. 2020. [Universal decompositional semantic parsing](#). In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pages 8427–8439, Online. Association for Computational Linguistics.
- Lionel Sujay Vailshery. 2021. [Total number of Amazon Alexa skills in selected countries as of January 2021](#).
- Oriol Vinyals, Lukasz Kaiser, Terry Koo, Slav Petrov, Ilya Sutskever, and Geoffrey E. Hinton. 2015. [Grammar as a foreign language](#). In *Advances in Neural Information Processing Systems 28: Annual Conference on Neural Information Processing Systems 2015, December 7-12, 2015, Montreal, Quebec, Canada*, pages 2773–2781.
- Aaron Steven White, Elias Stengel-Eskin, Siddharth Vashishtha, Venkata Subrahmanyam Govindarajan, Dee Ann Reisinger, Tim Vieira, Keisuke Sakaguchi, Sheng Zhang, Francis Ferraro, Rachel Rudinger, Kyle Rawlins, and Benjamin Van Durme. 2020. [The universal decompositional semantics dataset and decomp toolkit](#). In *Proceedings of the 12th Language Resources and Evaluation Conference*, pages 5698–5707, Marseille, France. European Language Resources Association.
- Yadollah Yaghoobzadeh, Soroush Mehri, Remi Tachet des Combes, T. J. Hazen, and Alessandro Sordani. 2021. [Increasing robustness to spurious correlations using forgettable examples](#). In *Proceedings of the 16th Conference of the European Chapter of the Association for Computational Linguistics: Main Volume*, pages 3319–3332, Online. Association for Computational Linguistics.
- Han-Jia Ye, De-Chuan Zhan, and Wei-Lun Chao. 2021. [Procrustean training for imbalanced deep learning](#). *ArXiv preprint*, abs/2104.01769.
- Sheng Zhang, Xutai Ma, Kevin Duh, and Benjamin Van Durme. 2019a. [AMR parsing as sequence-to-graph transduction](#). In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*, pages 80–94, Florence, Italy. Association for Computational Linguistics.
- Sheng Zhang, Xutai Ma, Kevin Duh, and Benjamin Van Durme. 2019b. [Broad-coverage semantic parsing as transduction](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 3786–3798, Hong Kong, China. Association for Computational Linguistics.
- Chunting Zhou, Xuezhe Ma, Paul Michel, and Graham Neubig. 2021. [Examining and combating spurious features under distribution shift](#). In *Proceedings of the 38th International Conference on Machine Learning, ICML 2021, 18-24 July 2021, Virtual Event*, volume 139 of *Proceedings of Machine Learning Research*, pages 12857–12867. PMLR.



## A Data

### A.1 Intent recognition

Table 2 contains example utterances for each intent.

### A.2 Semantic parsing

The SMCaFlow data consists of user-agent dialogues, where the agent produces executable Lisp programs based on user commands. Variable binding can be performed in Lisp to refer to a value multiple times in a program in a parsimonious way. Underlyingly, the variable binding procedure corresponds to re-entrancy in the DAG encoding the program graph. Thus, the SMCaFlow parsing task can be tackled either at the level of the Lisp string (sequence-to-sequence) or at the level of the DAG (sequence-to-graph), with the latter approach demanding a method for handling re-entrant nodes in a graph. Table 4 shows examples for each SMCaFlow function considered.

### A.3 Trigger Tokens

Table 3 has the trigger tokens per symbol. These were determined manually by examining tokens which yielded high  $\hat{P}(\hat{y} \in \text{output} \mid \exists t \in \mathcal{T}, t \in \text{input})$  at the lowest data setting.

## B Models

### B.1 LSTM

The LSTM model takes as input the previous user utterance, the produced agent utterance (if these are available) and the current user utterance, all separated by special tokens. These are tokenized and embedded using an embedding layer initialized with 300-dimensional GloVe embeddings (Pennington et al., 2014). Note that there is no contextualized encoder used here. The encoder is a 2 layer stacked BiLSTM, with a hidden size of 192 and dropout of  $p = 0.5$  between cells. The decoder embeddings are initialized randomly and are also 300-dimensional. The decoder also has 2 layers with a hidden size of 384, and recurrent dropout of  $p = 0.5$ . The source attention is implemented as an MLP with hidden size 64. Batches are bucketed by length during training, and a patience threshold of 20 epochs without improvement is set. The LSTM models are trained with ADAM using a learn rate of  $1e - 3$  and weight decay of  $3e - 9$ . Note that for SMCaFlow this paradigm is fairly weak due to its tendency to produce malformed Lisp expressions

at lower data regimes and the handling of variable binding through let expressions.

### B.2 Transformer

For the transductive model, the DAG for a program (cf. Fig. 3) is first transformed into a tree by copying and co-indexing re-entrant nodes. The tree is then linearized into a sequence of nodes, edge heads, edge types, and node indices. At test time, the model produces these sequences, which can be deterministically reconstructed into a DAG by merging co-indexed nodes. The generation component of the model maintains a dynamic output vocabulary over three operations: generation from a fixed vocabulary, source copying from the input, and target copying from previously generated tokens. The target copy operation allows the model to handle re-entrant nodes, which appear more than once in the linearized tree. This operation allows us to later recover node indices and thus re-build a DAG by merging copied nodes. The edge heads and labels are parsed by a biaffine parser (Dozat and Manning, 2017). This allows the model to handle functions, arguments, and types separately via typed edges. Each operation type (ValueOp, BuildStructOp, CallLikeOp) corresponds to a different edge type; the edge types for arguments are also indexed to allow for explicit argument ordering (e.g. arg0, arg1, etc.).

The input to the model is the same as for the LSTM: the concatenation of the previous two dialogue turns, followed by the current user utterance. These are tokenized and embedded with 300-D GloVe embeddings as well as 100-D character CNN features. There is embedding dropout with  $p = 0.33$  to prevent overfitting. The input text is also passed through bert-base-cased, with each subword receiving a 768-D representation. These are max-pooled across subword tokens to align with the token-level embeddings. The encoder hidden size is 512, with a 8 heads and a feed-forward dimension of 2048. The layer-norm and feedforward layers are swapped, and the weight initialization is downscaled by a factor of 512, following Nguyen and Salazar (2019). The encoder has dropout  $p = 0.2$ .

For the transformer, the decoder embeddings are also initialized with GloVe and character CNN features. The decoder also has 8 layers with the same dimensions and dropout as the encoder. As in the LSTM model, source attention is implemented as

Intent	Utterance
play_radio	play radio mirchi for me
play_radio	go to channel one hundred and six point nine
play_radio	i want to hear morning edition on npr
play_radio	are you set radio on my favorite radio station
email_query	open email for unread mails
email_query	what is the subject of latest email i got and who sent it
email_query	has dad sent any emails recently
email_query	new email from mom
email_querycontact	find all the contacts named john
email_querycontact	what is mary s.'s birthday
email_querycontact	what information do you have on file in my information about bill
email_querycontact	give me charles telephone number
general_quirky	nice to talk to you
general_quirky	ask me an arithmetic question
general_quirky	i would like it to help with coding debugging
general_quirky	i like my robot to talk to me like a friend
transit_traffic	what is the traffic situation right in broadway street
transit_traffic	what is the traffic like today
transit_traffic	is there traffic right now in maiden lane
transit_traffic	let me know about current traffic in carmen drive

Table 2: Examples of intent recognition data.

Symbol	Tokens
email_query	emails, inbox
email_querycontact	contact, phone, number
general_quirky	day, today, tell, can
play_radio	channel, radio, fm, point, station, tune
transport_traffic	traffic
FindManager	boss, manager, supervisor
PlaceHasFeature	takeout, casual, waiter
Tomorrow	tomorrow
FenceAttendee	meet, mom
DoNotConfirm	cancel, n't, no

Table 3: Triggers for each symbol. Triggers were chosen manually by inspecting the list of tokens that yielded high  $\hat{P}(\text{symbol}|t \in \text{input} \cap \mathcal{T})$  the lowest data setting for each function.

an MLP, here with a hidden dimension of 512. The target attention (for target-side copy) is identical. Source attention uses coverage (See et al., 2017). The biaffine parser projects the transformer representations to 512 and has dropout  $p = 0.2$ . We train transformer models with a patience of 20, using Adam with a linear learning rate warmup stage, followed by exponential learning rate decay. We set the number of warmup steps to 8000.

## C Other Encoders

Fig. 8 shows that the trends seen in Fig. 1 also apply also to other encoders, namely ALBERT and RoBERTa (large and base). Here, we see that the trends almost exactly mimic the trends seen when using BERT in Fig. 1.

The decreasing and often non-monotonic performance as well as the strong similarity of the trends

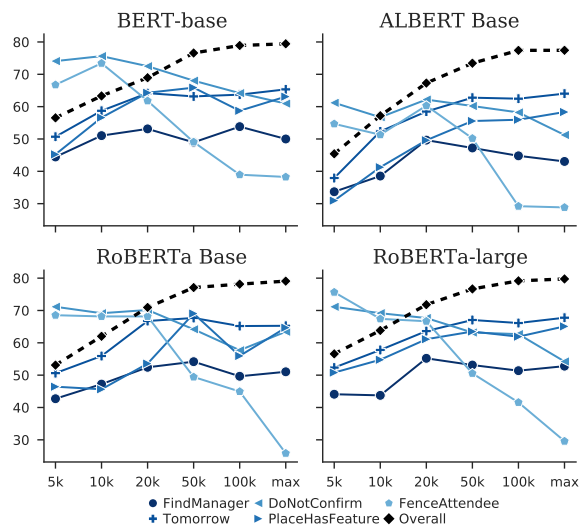


Figure 8: Parsers with RoBERTa and ALBERT features show similar trends as with BERT features.

Function	Dialogue Context	Current User Utterance
FindManager	N/A	Make an event with Abby and her boss
FindManager	<b>User:</b> Who are Jake’s reports, <b>Agent:</b> Jake Cobb has no direct reports.	Who does he report to?
FindManager	<b>User:</b> Add an event called presentation with Jamal and his supervisor for Friday at 11. <b>Agent:</b> Is this good?	Add Igor and his supervisor to this as well.
Tomorrow	N/A	Find an event for tomorrow after 4 pm.
Tomorrow	N/A	Schedule lunch with Nick tomorrow at noon
Tomorrow	<b>User:</b> What time will the sun rise in seattle tomorrow <b>Agent:</b> Sunrise will be at 12 : 00 AM tomorrow.	what time will the sun set in seattle tomorrow
DoNotConfirm	<b>User:</b> Can you change the time to 4 instead? <b>Agent:</b> How about now?	No, I don’t like either of those.
DoNotConfirm	<b>User:</b> No I need it to be in the afternoon, <b>Agent:</b> Does one of these work?	No they don’t
DoNotConfirm	<b>User:</b> Schedule a dentist appointment tomorrow afternoon, <b>Agent:</b> Does one of these work?	No
FenceAttendee	N/A	Create lunch with mom on sunday
FenceAttendee	<b>User:</b> What events do I have tomorrow, <b>Agent:</b> I found 2 events tomorrow.	Add my sister, brother, and Daniel
FenceAttendee	N/A	Can you tell me if I meet with our repair rep this week or next week?
PlaceHasFeature	<b>User:</b> What cuisine do they serve? <b>Agent:</b> Sorry, I can’t handle that yet.	Does the Black Bottle restaurant have a full service bar?
PlaceHasFeature	<b>User:</b> Find me Round Table Pizza in Truckee, <b>Agent:</b> I found one option.	Could I bring a party of people there?
PlaceHasFeature	N/A	Is Bamonte’s in Brooklyn capable for large parties?

Table 4: Example data for SMCalf flow semantic parsing.

suggests that the source signal dilution problem is not unique only to BERT or to LSTMs.

## D Licensing

All code is released under an MIT license.

## E Artifacts

All pre-existing artifacts were used in accordance with their original purpose. The artifacts produced by this paper (code, models) are intended to be used for intent recognition and semantic parsing.