

# DeepCoder: Learning to Write Programs

ICLR conference paper by Balog et al., 2017

Presentation by Harry Smith

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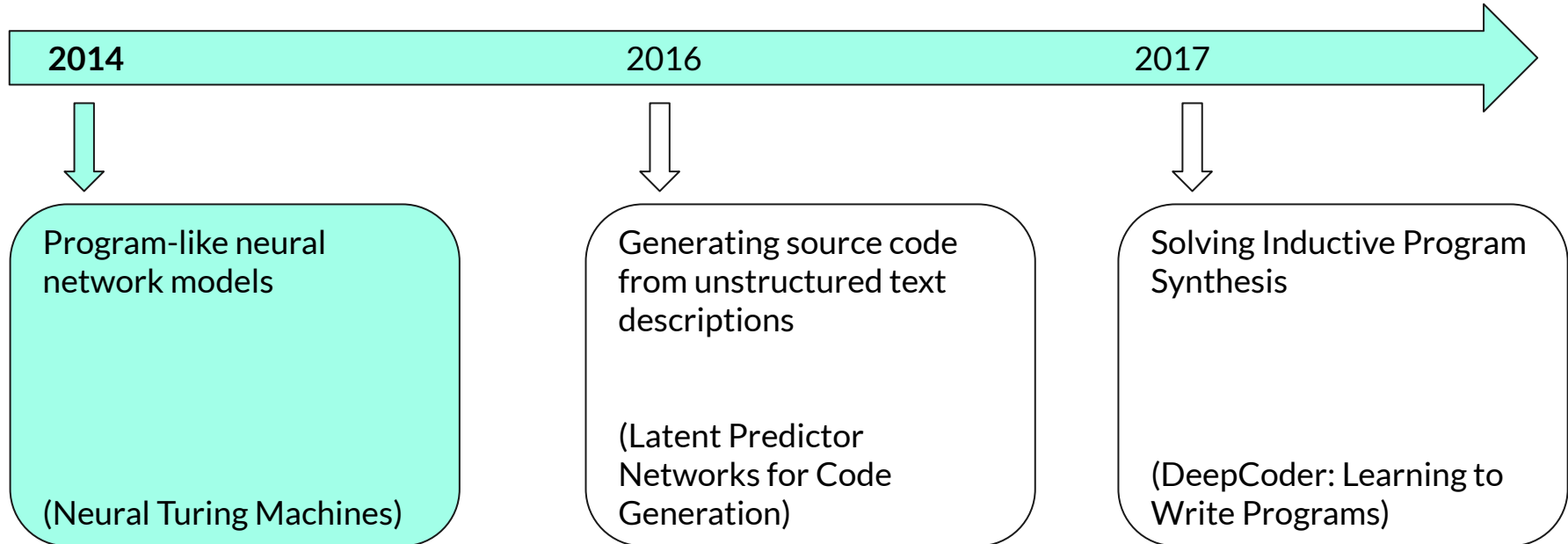
# Background Work & Main Ideas

**“A dream of artificial intelligence is to build systems that can write computer programs”**

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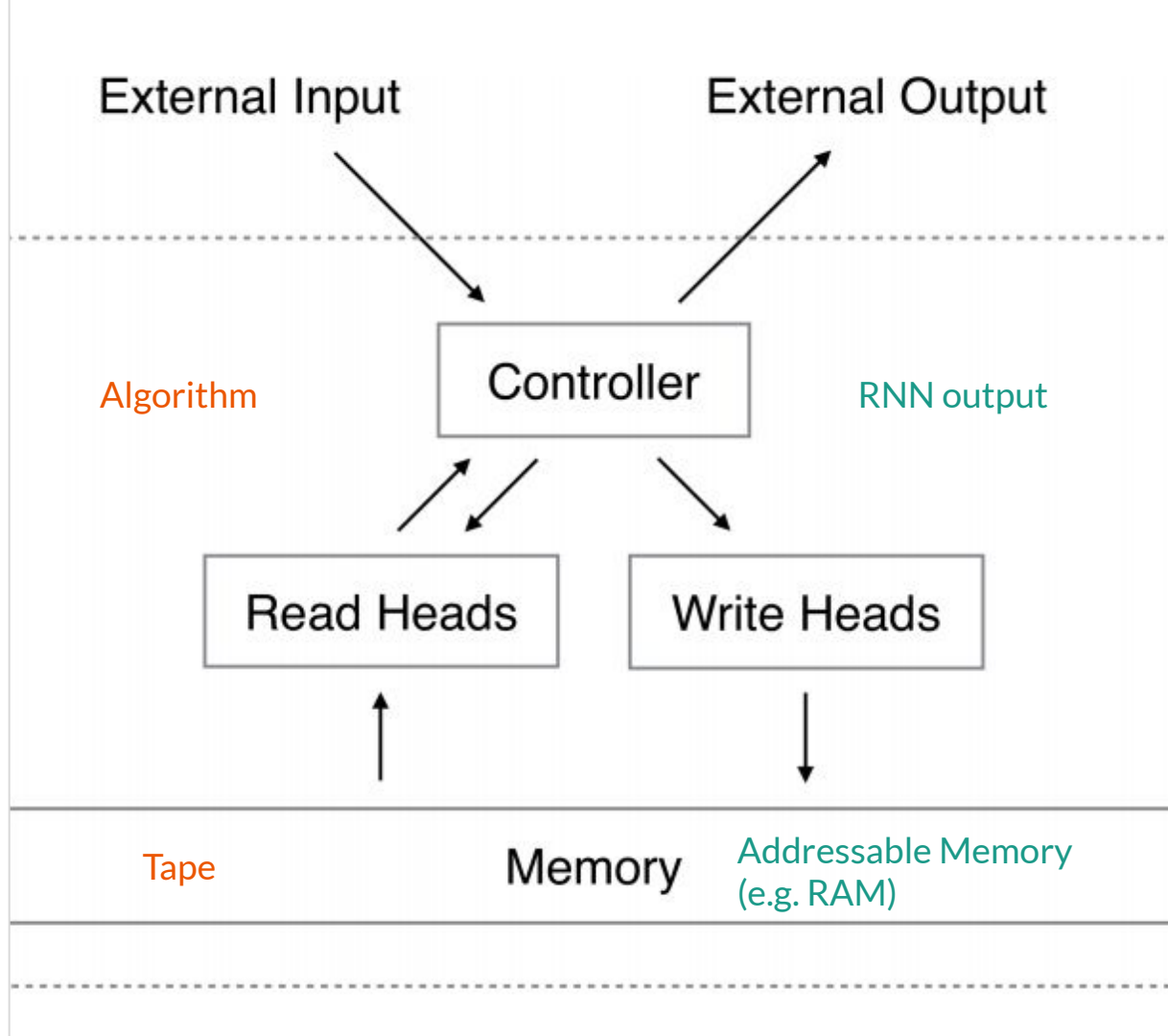
# Working up to AI-Written Computer Programs



# Neural Turing Machines:

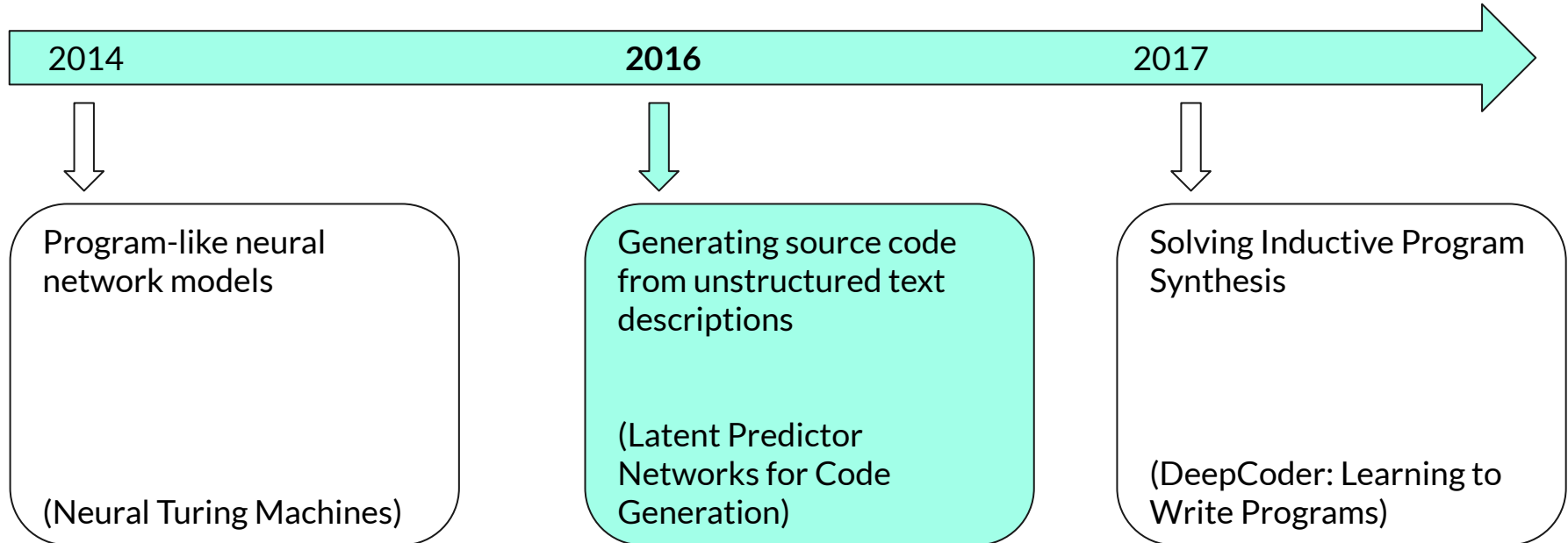
Is it *even possible* to have a machine learning model represent a program?

Graves, A., Wayne, G., & Danihelka, I. (2014). Neural Turing Machines. <https://doi.org/10.3389/neuro.12.006.2007>





# Working up to AI-Written Computer Programs

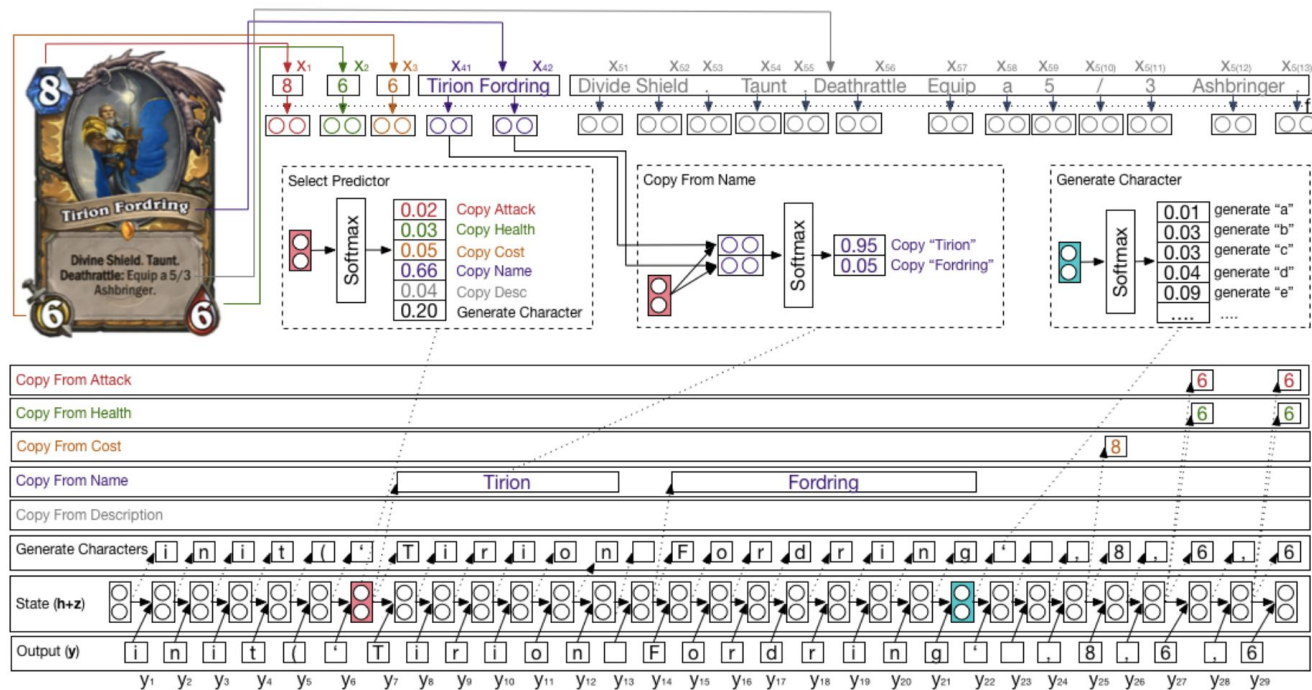


# Latent Predictor Networks for Code Generation



```
class DivineFavor(SpellCard):  
    def __init__(self):  
        super().__init__("Divine Favor", 3,  
                         CHARACTER_CLASS.PALADIN, CARD_RARITY.RARE)  
  
    def use(self, player, game):  
        super().use(player, game)  
        difference = len(game.other_player.hand)  
        - len(player.hand)  
        for i in range(0, difference):  
            player.draw()
```

# Latent Predictor Networks for Code Generation



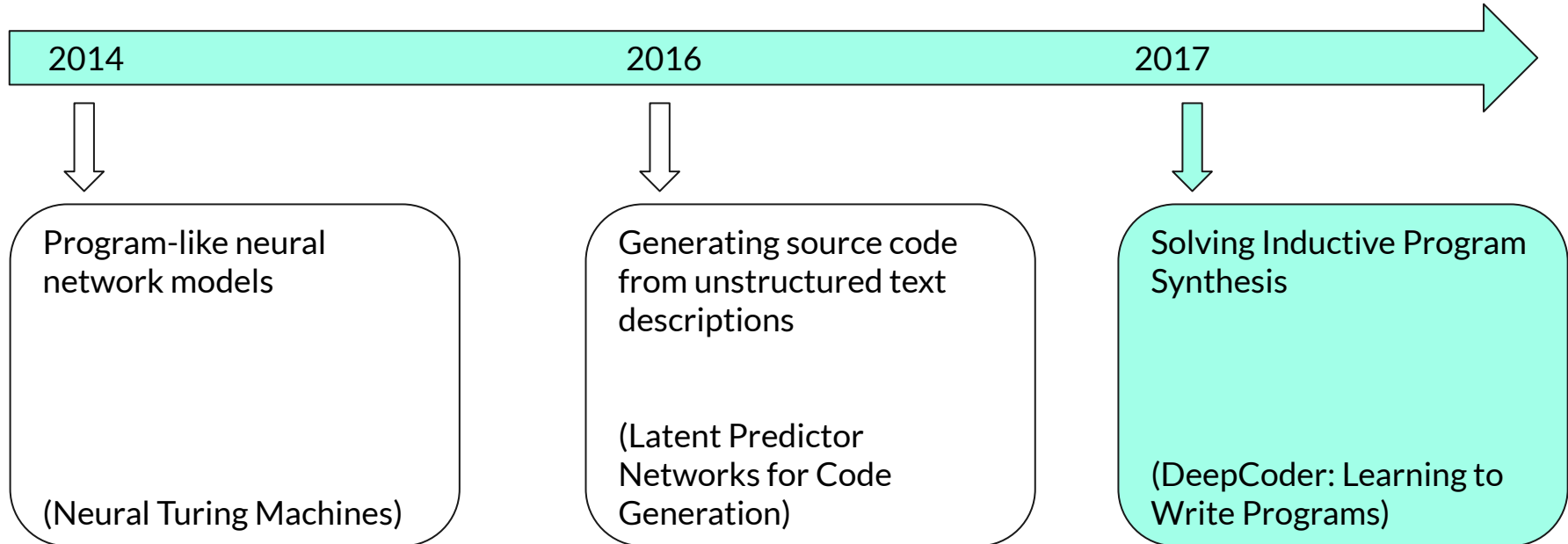
Ling, W., Grefenstette, E., Hermann, K. M., Kočický, T., Senior, A., Wang, F., & Blunsom, P. (2016). Latent Predictor Networks for Code Generation. <https://doi.org/10.1039/c0cc04507a>

Figure 4: Generation process for the code `init('Tirion Fording', 8, 6, 6)` using LPNs.





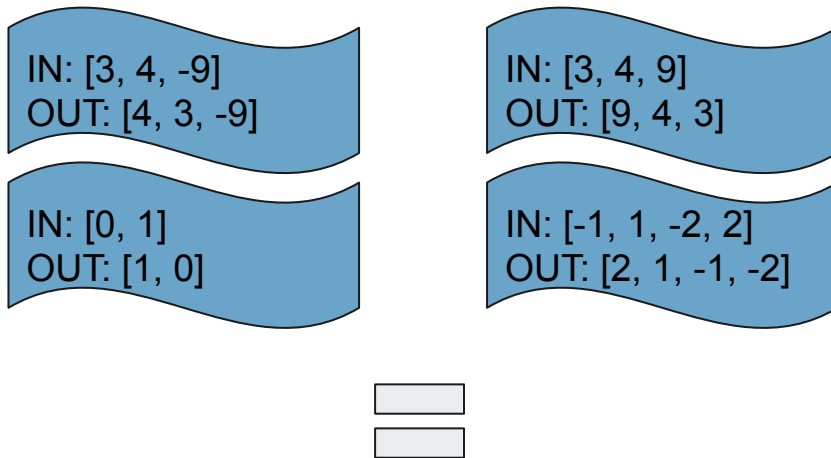
# Working up to AI-Written Computer Programs



# Main Ideas

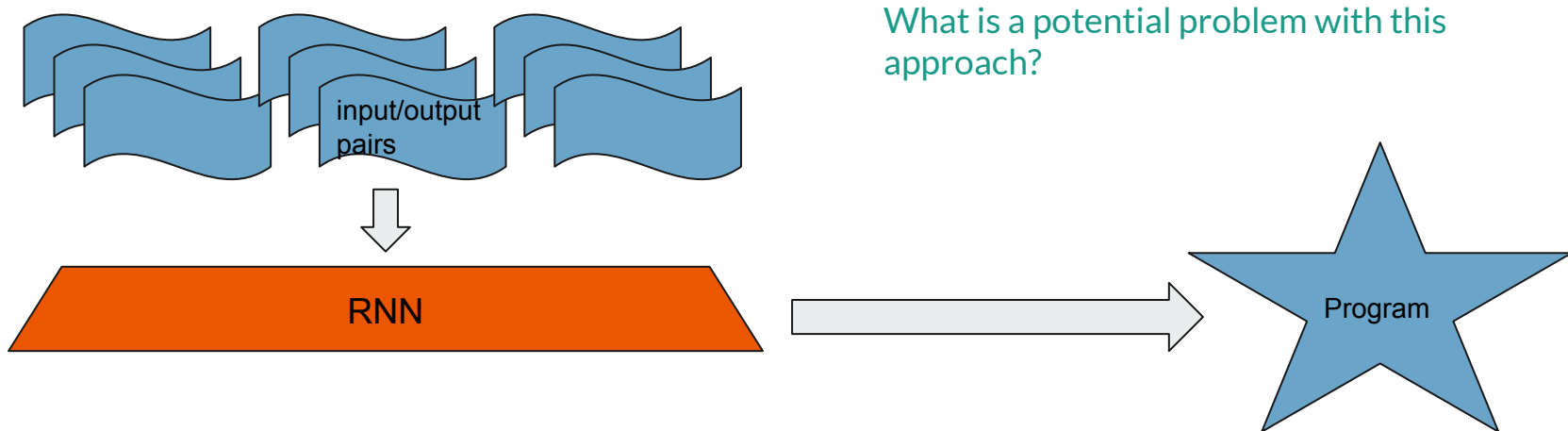
# Main Ideas

- Learn to induce programs
  - Formulated as a **big data problem**:  
going from input-output pairs to code
  - Learn strategies that generalize **across** problems

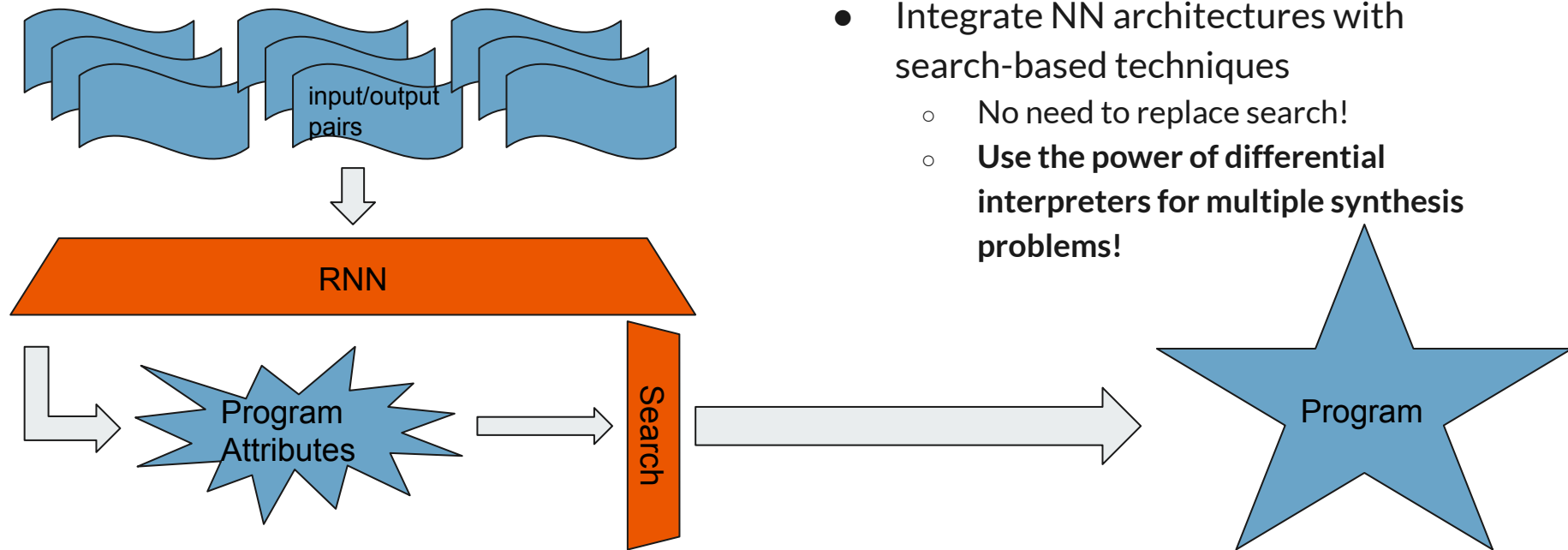


```
def rev_sort(in):  
    return reversed(sorted(in))
```

# The Traditional Differential Interpreter Approach



# Main Ideas



# Main Ideas

- Learn to induce programs
  - Formulated as a **big data problem**
  - Learn strategies that generalize **across** problems
- Integrate NN architectures with search-based techniques
  - No need to replace search!
  - Use the power of differential interpreters

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# Inductive Program Synthesis (IPS)



# The Basics of IPS

*IPS is the problem of taking input-output examples and producing a program that has behavior consistent with the examples.*

- How do we find consistent programs?
- How do we choose the best programs when there are multiple options?





# The Basics of IPS

*IPS is the problem of taking input-output examples and producing a program that has behavior consistent with the examples.*

- How do we find consistent programs?
  - Requires a well defined set of acceptable programs that creates the search space
  - We also need an intelligent search procedure to move through this space
- How do we choose the best programs when there are multiple options?
  - Choose the shortest program?
  - Choose the first program found, with simple normalizations made?

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# Formulating an Approach to IPS: DSLs

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Need to choose a Domain Specific Language (DSL) in which to synthesize problems

- Language should be useful in a certain domain; otherwise, the synthesis is useless.
- Language should be restricted to limit the search space
  - Can't search over all C++ programs!
  - Features like loops or ifs make more solutions consistent

# Formulating an Approach to IPS: DSLs

Balog, M., Gaunt, A. L., Brockschmidt, M., Nowozin, S., & Tarlow, D. (2016). DeepCoder: Learning to Write Programs. Retrieved from <http://arxiv.org/abs/1611.01989>

DeepCoder's solution: an SQL-like query language

- Includes ints, int arrays, and booleans\* as types
- Program is a sequence of function calls storing results in new variable names
- 34 functions are available, including first-order, higher-order, and lambda functions
  - No *explicit* control flow
  - The permissible lambdas are finite and enumerated, e.g. (<0) and (\*4)

```
a ← [int]
b ← FILTER (<0) a
c ← MAP (*4) b
d ← SORT c
e ← REVERSE d
```

## An input-output example:

*Input:*

```
[-17, -3, 4, 11, 0, -5, -9, 13, 6, 6, -8, 11]
```

*Output:*

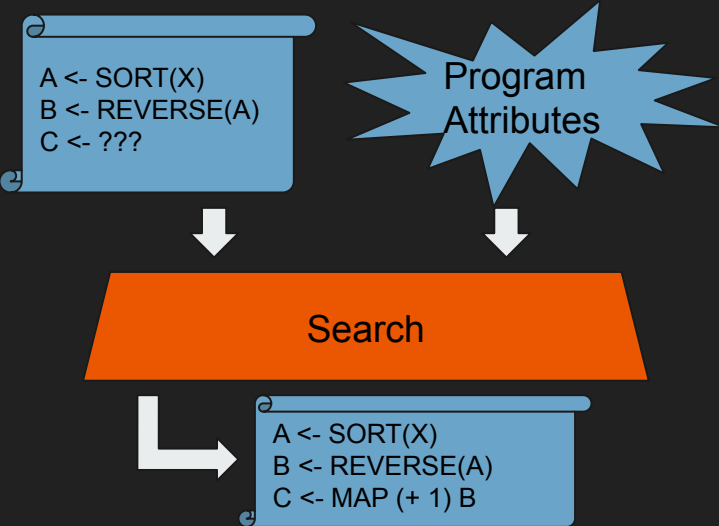
```
[-12, -20, -32, -36, -68]
```

<b>Program 0:</b> $k \leftarrow \text{int}$ $b \leftarrow [\text{int}]$ $c \leftarrow \text{SORT } b$ $d \leftarrow \text{TAKE } k \ c$ $e \leftarrow \text{SUM } d$	<b>Input-output example:</b> <i>Input:</i> 2, [3 5 4 7 5] <i>Output:</i> [7]	<i>Description:</i> A new shop near you is selling $n$ paintings. You have $k < n$ friends and you would like to buy each of your friends a painting from the shop. Return the minimal amount of money you will need to spend.
<b>Program 1:</b> $w \leftarrow [\text{int}]$ $t \leftarrow [\text{int}]$ $c \leftarrow \text{MAP } (*3) \ w$ $d \leftarrow \text{ZIPWITH } (+) \ c \ t$ $e \leftarrow \text{MAXIMUM } d$	<b>Input-output example:</b> <i>Input:</i> [6 2 4 7 9], [5 3 6 1 0] <i>Output:</i> 27	<i>Description:</i> In soccer leagues, match winners are awarded 3 points, losers 0 points, and both teams get 1 point in the case of a tie. Compute the number of points awarded to the winner of a league given two arrays $w, t$ of the same length, where $w[i]$ (resp. $t[i]$ ) is the number of times team $i$ won (resp. tied).
<b>Program 2:</b> $a \leftarrow [\text{int}]$ $b \leftarrow [\text{int}]$ $c \leftarrow \text{ZIPWITH } (-) \ b \ a$ $d \leftarrow \text{COUNT } (>0) \ c$	<b>Input-output example:</b> <i>Input:</i> [6 2 4 7 9], [5 3 2 1 0] <i>Output:</i> 4	<i>Description:</i> Alice and Bob are comparing their results in a recent exam. Given their marks per question as two arrays $a$ and $b$ , count on how many questions Alice got more points than Bob.

Examples of programs written in the DSL, with the natural language descriptions.

Balog, M., Gaunt, A. L., Brockschmidt, M., Nowozin, S., & Tarlow, D. (2016). DeepCoder: Learning to Write Programs. Retrieved from <http://arxiv.org/abs/1611.01989>

# Formulating an Approach to IPS: Search Strategy



Need to solve the problem of how to find the code that satisfies the examples

- The goal of DeepCoder is to interface with an existing solver, using predicted attributes as a guide for search
  - *More on this in a moment...*
- Once a method of predicting attributes of a program is fixed, DeepCoder can interface with the following:
  - **DFS**: Try all programs up to a certain length, and add the estimated most likely function at each step
  - **"Sort and add"**: Try all programs with the estimated most likely  $k$  functions, then on failure try again with the  $k + 1$  most likely, etc.
  - [Sketch: an SMT-based tool](#), which can incorporate program attributes into its own "sort and add" strategy
  - $\lambda^2$ : a tool that enumerates the search space, using deductive pruning. **Designed for small functional programs on data structures!** Also leverages "sort and add" from predicted attributes.



## A word on Sketch and SMT solvers...

Recall that *Satisfiability Modulo Theories* (SMT) solvers are SAT solvers with theories like “algebra” or “inequalities”

$$X < Y; Y < -100$$

For example, an arbitrary search strategy over all integers might take quite some time to find a satisfying  $X, Y$  pair.

An SMT solver with algebra and inequality solves this almost instantly.

## A word on Sketch and SMT solvers...

Sketch models an IPS problem as a hole in a code base that needs to be filled in using a set of available functions. Each function is transformed from its original definition to a mapping from constraints:

```
def plus_one(a):  
    return a + 1
```

Constraint  
mapping

```
plus_one(a_min, a_max, start_inclusive, end_inclusive):  
    return a_min + 1, a_max + 1, start_inclusive, end_inclusive
```

Python definition  
of (+1) lambda

List of output  
constraints given  
input constraints



# A word on Sketch and SMT solvers...

“Constraintified” Sample Program with hole in it

```
A <- int array      all of A in [-10, 10]
B <- ??????        ??????????
C <- map (+1) B     all of C in [-19, 21]
```

Function Library

```
plus_one(a_min, a_max, start_inclusive, end_inclusive):
    return a_min + 1, a_max + 1, start_inclusive, end_inclusive

minus_one(a_min, a_max, start_inclusive, end_inclusive):
    return a_min - 1, a_max - 1, start_inclusive, end_inclusive

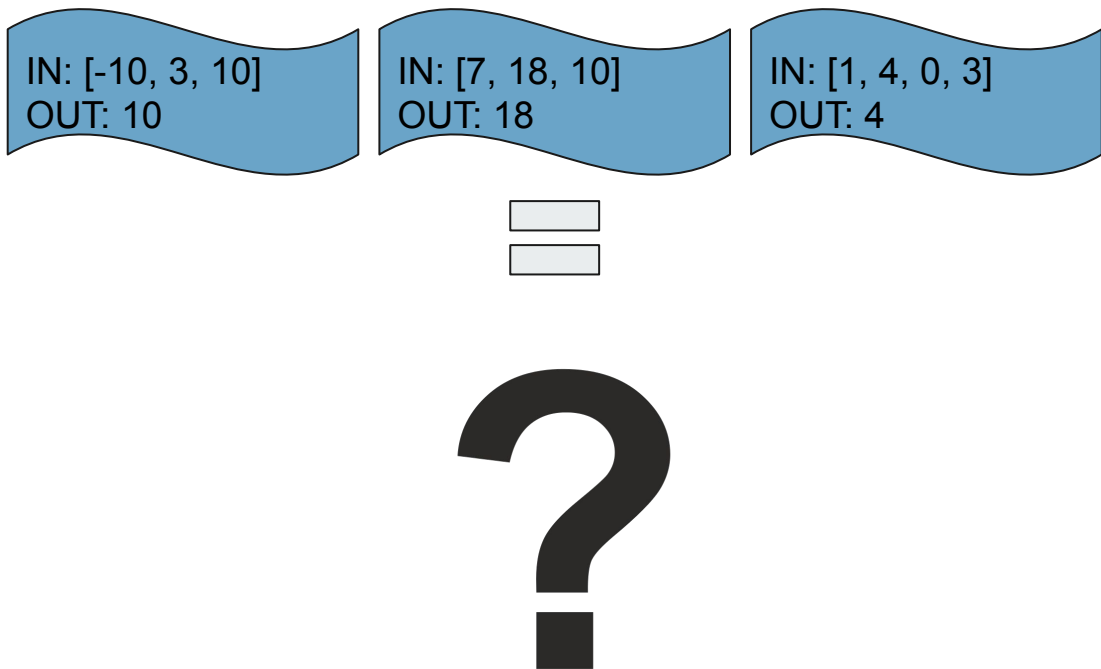
times_two(a_min, a_max, start_inclusive, end_inclusive):
    return a_min * 2, a_max * 2, start_inclusive, end_inclusive
```

Find the function that takes the constraints in step A to the constraints after step C...



# Formulating an Approach to IPS: Ranking

Need to pick the “best solution” of those which are discovered in search



# Formulating an Approach to IPS: Ranking

Need to pick the “best solution” of those which are discovered in search

IN: [4, 3, 10]  
OUT: 10

IN: [7, 18, 10]  
OUT: 18

IN: [1, 4, 0, 3]  
OUT: 4



```
def f(arr): return max(arr)
```

```
def f(arr): return 4 + min(arr) * 2
```

```
def f(arr): return 1 + 1 + 1 + 1 + min(arr) + min(arr)
```

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# Formulating an Approach to IPS: Ranking

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DeepCoder focuses on the search aspect of IPS, and does not define their ranking strategy.

- Possible candidates:
  - Shortest is best
  - Max-margin prediction
    - Assign scores so that ground-truth programs are always scored higher than induced examples.
  - Others?

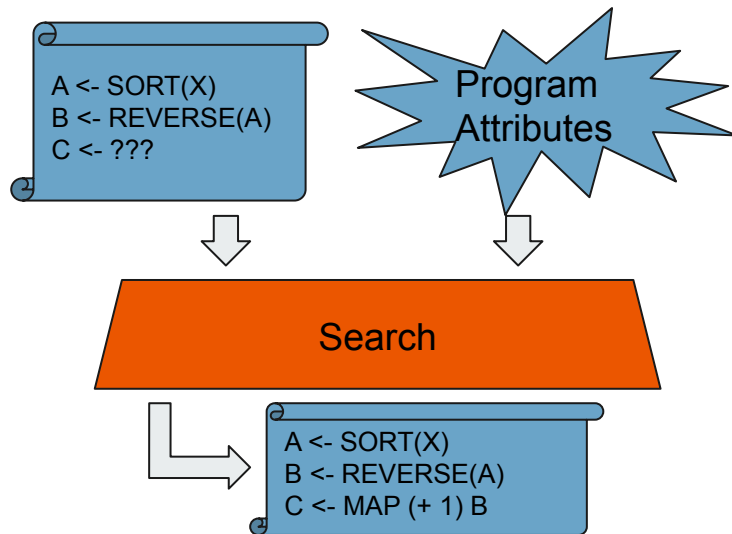
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# Learning Inductive Program Synthesis (LIPS)

# Turning Programs into Attributes

Recall that we need to link machine learning and search to efficiently synthesize programs.

*How do we determine program attributes?*

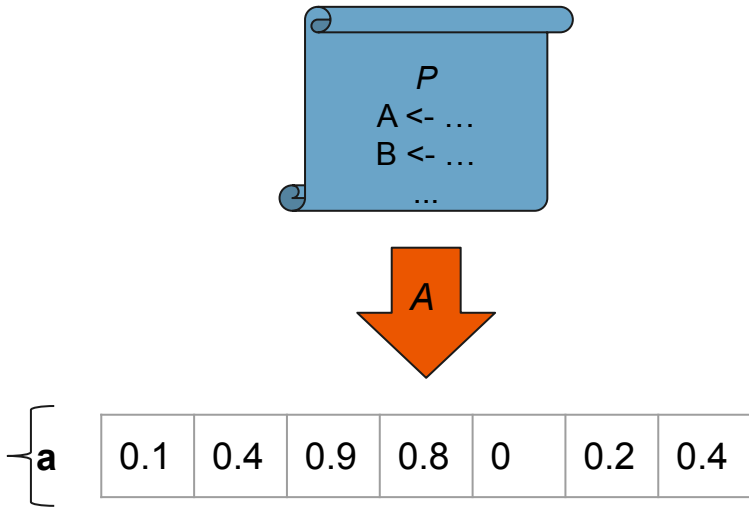


# Turning Programs into Attributes

How do we determine program attributes?

From the input-output pairs!

Formally, we want to define an attribute function  $A$  which maps programs  $P$  into finite attribute vectors  $\mathbf{a}$ :



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# Turning Programs into Attributes

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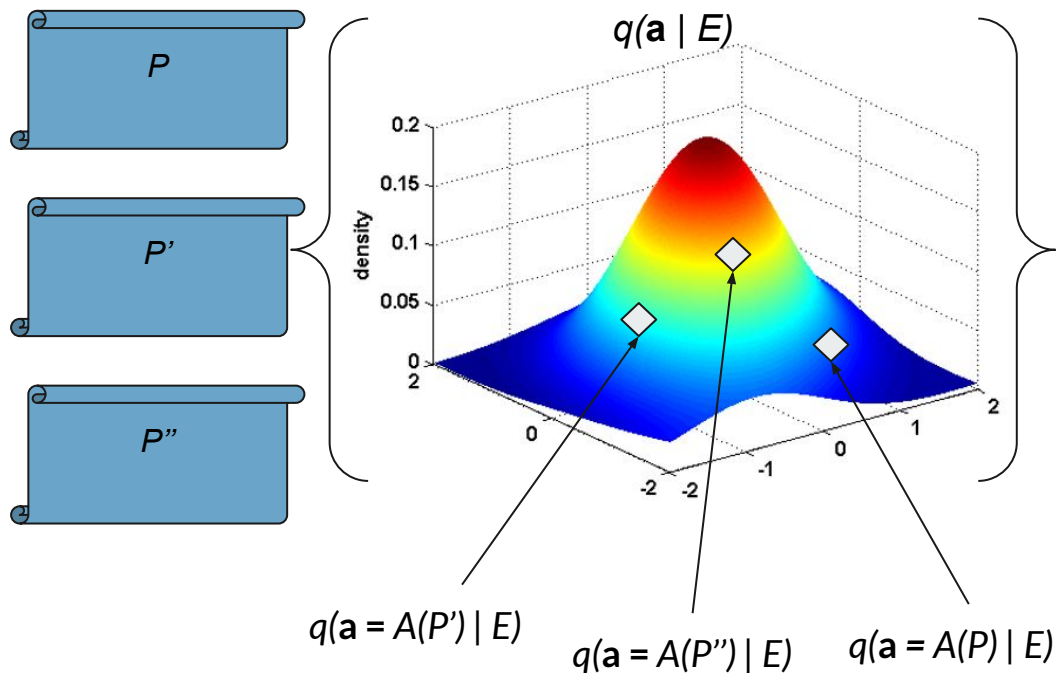
How do we determine program attributes?

From the input-output pairs!

This way, given a set of input-output examples  $E$ , we can compute a distribution  $q(\mathbf{a} \mid E)$ . Then, we search over programs  $P$  ordered by  $q(A(P) \mid E)$ .

# Turning Programs into Attributes

Given a set of input-output examples  $E$ , we can compute a distribution  $q(\mathbf{a} \mid E)$ . Then, we search over programs  $P$  ordered by  $q(A(P) \mid E)$ .





# Turning Programs into Attributes

So what are these attributes?

- The identity function:  $A(P) = P$ ?
- Control Flow Templates?
  - # of loops
  - # of conditionals
- Presence or absence of high-level functions?
  - Does program  $P$  ever use “SORT”?
  - Does program  $P$  end with a call to “MAP”?

```
a ← [int]
b ← FILTER (<0) a
c ← MAP (*4) b
d ← SORT c
e ← REVERSE d
```

**An input-output example:**

*Input:*

`[-17, -3, 4, 11, 0, -5, -9, 13, 6, 6, -8, 11]`

*Output:*

`[-12, -20, -32, -36, -68]`

---

# Turning Programs into Attributes: Data Generation

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How do we formulate this as a big data problem?

- Data Generation procedure:
  - Enumerate programs in the DSL
    - Prune those with redundant variables/instructions
  - Generate valid inputs for a program
    - Enforce constraints on the output value(s)
    - Propagate constraints backwards up to input
  - Select inputs from the valid range and execute the program to get outputs.
    - If the input set is empty, discard the program
  - Read off the attribute vector from the program itself

```
A <- int array  
B <- map (+1) A  
C <- map (*4) B  
D <- C
```

all of A in []

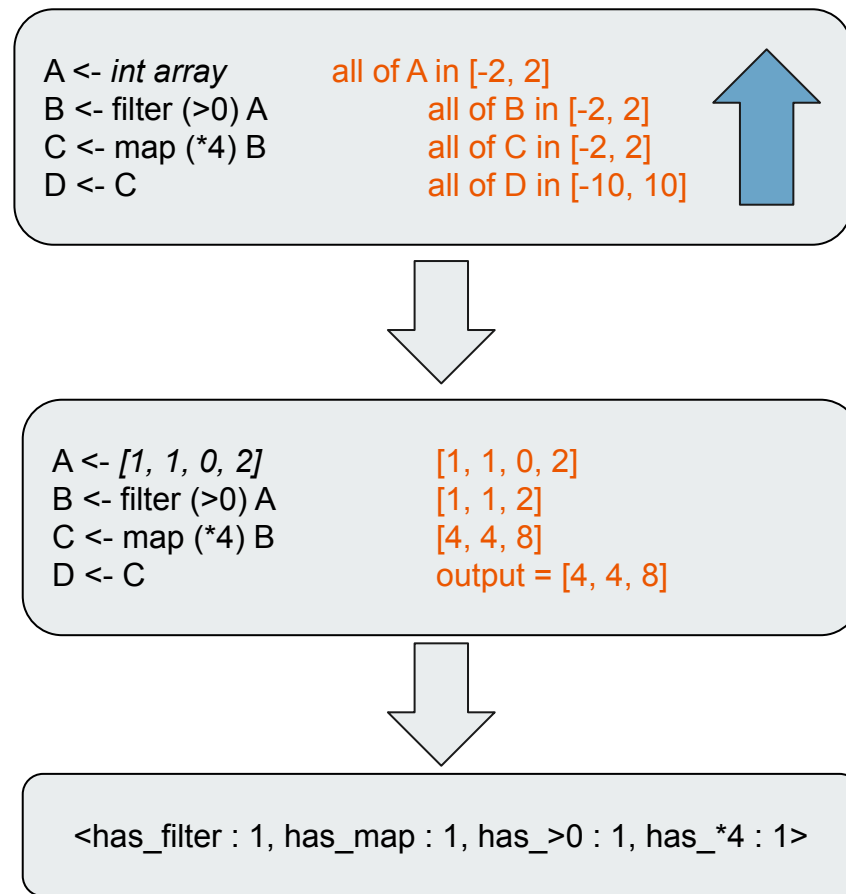
all of B in []

all of C in []

all of D in [1, 3]



Example of Data Generation: Rejecting an example program



Example of Data Generation: Rejecting an example program

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# Turning Programs into Attributes: the learning model

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How are the attributes learned?

- A feed-forward neural network learns the mapping from input-output examples to attributes.
- The FF-NN contains two fundamental components
  - An *encoder*: a differential mapping from  $M$  input-output examples to a latent, real-valued vector
  - A *decoder*: a differential mapping from the latent vector to predictions on the ground truth's attributes



# The Encoder

1. Represent the input/output types (singleton or array) as one-hot vectors
  - // E.g.  $\langle \{0,1\}, \{1,0\} \rangle$  for a function that takes in an array and outputs an integer.
2. Pad all inputs and outputs to a maximum length  $L$  with null value
  - // The array  $[4, 3]$  becomes  $[4, 3, X, X, X]$  when  $L = 5$
3. Map all integers to an  $E = 20$  dimensional embedding
  - // If the input to a problem is a length  $L$  array, the dimensionality of the input becomes  $E \cdot L$
4. For each input-output example...
  - ...concatenate the embeddings of input types, output types, inputs, and outputs into a single vector
  - ...pass this vector through  $H = 3$  hidden layers of  $K = 256$  sigmoid units each
5. Take the arithmetic mean of all output vectors (one for each input-output pair) as the output of the encoder
  - // note that this output vector has dimensionality  $K$

# Embedding of integers

- No justification is given for the choice of  $E = 20$  as the dimension for the embedding of the integers...
  - This is less than the total number of functions available
  - This is four times larger than the length of the programs on which they ran their experiments
  - Perhaps the break between 20 and 21 is where the NN was “no longer simple to train”
- Balog et al. initially experimented with values of  $E = 2$  for programs of length  $T = 1$  and found the result at right:

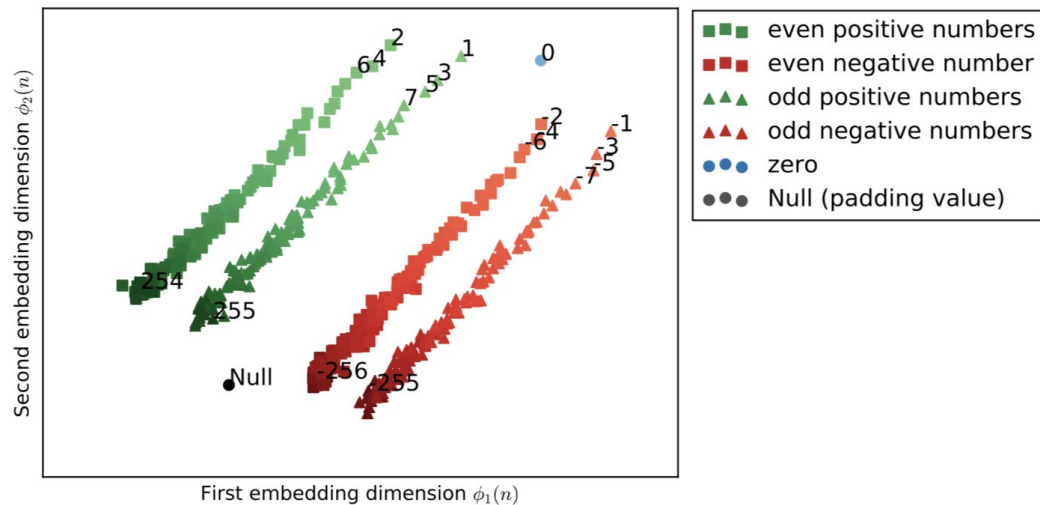


Figure 8: A learned embedding of integers  $\{-256, -255, \dots, -1, 0, 1, \dots, 255\}$  in  $\mathbb{R}^2$ . The color intensity corresponds to the magnitude of the embedded integer.

Balog, M., Gaunt, A. L., Brockschmidt, M., Nowozin, S., & Tarlow, D. (2016). DeepCoder: Learning to Write Programs. Retrieved from <http://arxiv.org/abs/1611.01989>

# The Decoder

1. Pre-multiply the averaged vector ( $K \times 1$ ) by a final “decoding” matrix of dimension  $C \times K$ , where  $C = 34$ , the number of functions in the DSL
2. Interpret the  $C \times 1$  resulting vector as the log-unnormalized probabilities of each function appearing in the source code.



Figure 2: Neural network predicts the probability of each function appearing in the source code.



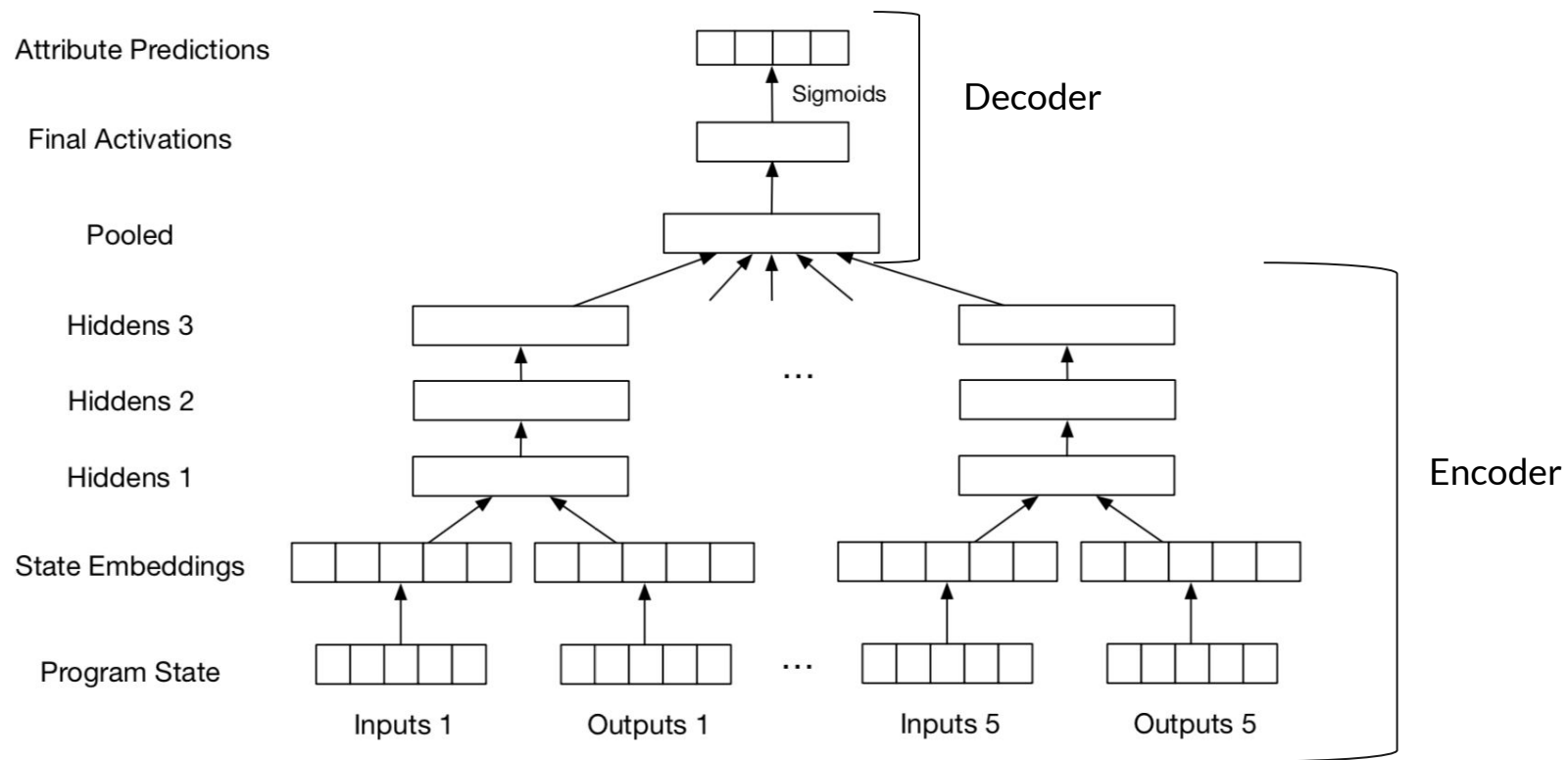


Figure 7: Schematic representation of our feed-forward encoder, and the decoder.

The full architecture

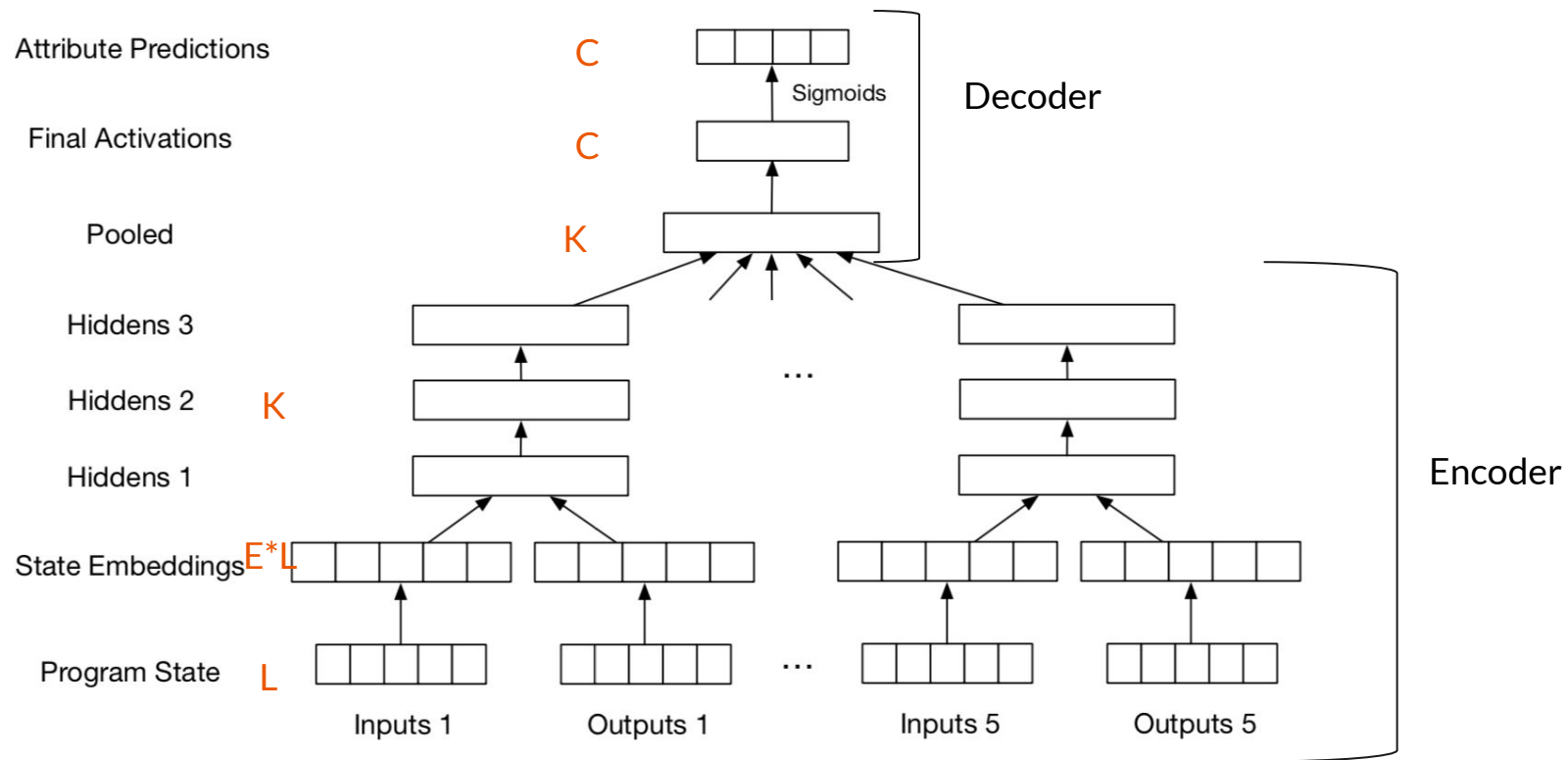


Figure 7: Schematic representation of our feed-forward encoder, and the decoder.

The full architecture (dimensionality tracked in orange)

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# Turning Programs into Attributes: the learning model

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How are the attributes learned?

- The NN is trained using negative cross entropy loss
- The outcome is the joint distribution  $P(\mathbf{a} \mid E)$  of all attributes given the input-output examples
  - The distribution is only over single function presence or absence
  - Likely some power lost by ignoring the correlations among the functions

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# Experimental Results



## Experiment #1.1

1. Train the neural network on programs of length  $T = 3$ .
2. Create a test set of  $P = 500$  programs, each of length  $T$ .
  - a. For each generated program, create 5 input-output examples
  - b. Ensure that each program in the test set is semantically distinct from all other examples
3. Produce attribute vectors for each program using the input-output pairs.
4. Use the attribute vectors with different search strategies to induce programs
  - a. Time the search process
  - b. Timeout after  $10^4$  seconds
  - c. Search space  $\sim 10^6$
5. Compare the speeds of the attribute-guided searches to a baseline
  - a. Baseline strategy is considering the probability of each function appearing to be the overall probability of that function appearing in the dataset



## Experiment #1.1

Table 1: Search speedups on programs of length  $T = 3$  due to using neural network predictions.

Timeout needed	DFS			Enumeration			$\lambda^2$			Sketch		Beam
to solve	20%	40%	60%	20%	40%	60%	20%	40%	60%	20%	40%	20%
Baseline	41ms	126ms	314ms	80ms	335ms	861ms	18.9s	49.6s	84.2s	$>10^3s$	$>10^3s$	$>10^3s$
DeepCoder	2.7ms	33ms	110ms	1.3ms	6.1ms	27ms	0.23s	0.52s	13.5s	2.13s	455s	292s
Speedup	15.2×	3.9×	2.9×	62.2×	54.6×	31.5×	80.4×	94.6×	6.2×	>467×	>2.2×	>3.4×

If the time taken for four programs is 3s, 2s, 1s, 3s, then the timeout needed to solve 50% of problems is 2s.



## Experiment #1.2

1. Train the neural network on programs of length  $T = 4$ .
2. Create a test set of  $P = 100$  programs, each of length  $T = 5$ .
  - a. For each generated program, create 5 input-output examples
  - b. Ensure that each program in the test set is semantically distinct from all other examples
3. Produce attribute vectors for each program using the input-output pairs.
4. Use the attribute vectors with different search strategies to induce programs
  - a. Time the search process
  - b. Timeout after  $10^4$  seconds
  - c. Search space  $\sim 10^6$
5. Compare the speeds of the attribute-guided searches to a baseline
  - a. Baseline strategy is considering the probability of each function appearing to be the overall probability of that function appearing in the dataset



## Experiment #1.1

Timeout needed to solve	DFS			Enumeration			$\lambda^2$
	20%	40%	60%	20%	40%	60%	20%
Baseline	163s	2887s	6832s	8181s	$>10^4s$	$>10^4s$	463s
DeepCoder	24s	514s	2654s	9s	264s	4640s	48s
Speedup	<b>6.8×</b>	<b>5.6×</b>	<b>2.6×</b>	<b>907×</b>	<b>&gt;37×</b>	<b>&gt;2×</b>	<b>9.6×</b>



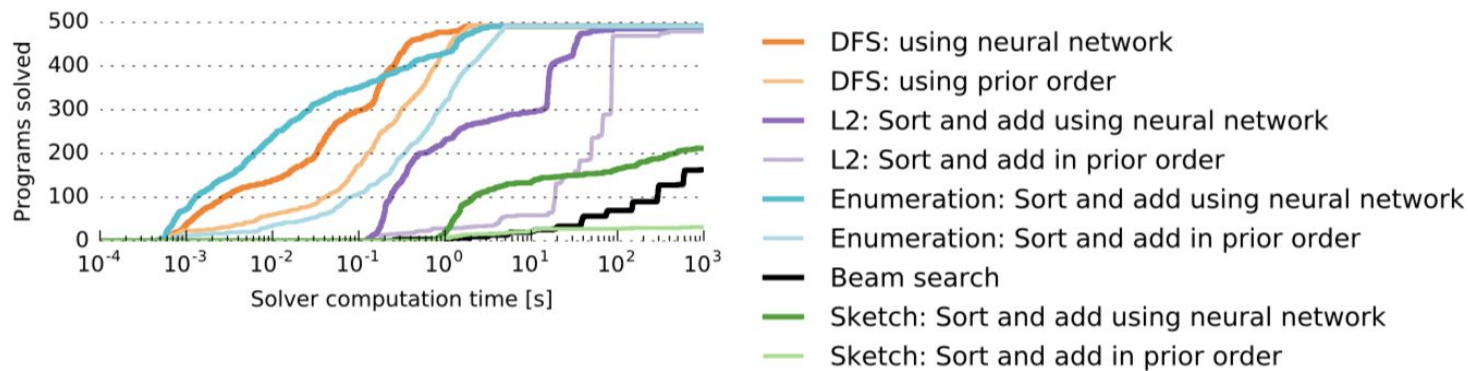
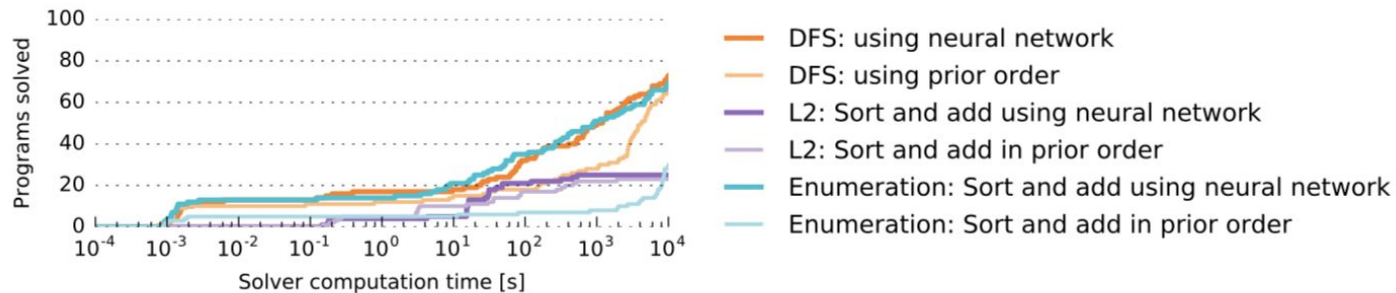


Figure 5: Number of test problems solved versus computation time.





# Experiment #1 Takeaways

- Enumeration enjoys a better speedup than DFS
  - Hypothesized that the attribute vectors are more useful for a sort-and-add strategy than DFS anyway
  - The authors cite other research to suggest that sort-and-add does not lose much or any power from ignoring correlations/positional dependence
  - DFS is penalized quite heavily by making the wrong choice at the beginning, so it matters a lot more which function actually comes first
- The choice of a simple decoder (learned matrix) provides better results than an RNN decoder
  - Authors acknowledge that their strategy for training the RNN was somewhat unsuccessful

“Intuitively, the  $i$ -th row of this matrix shows how the presence of attribute  $i$  confuses the network into incorrectly predicting each other attribute  $j$ .”

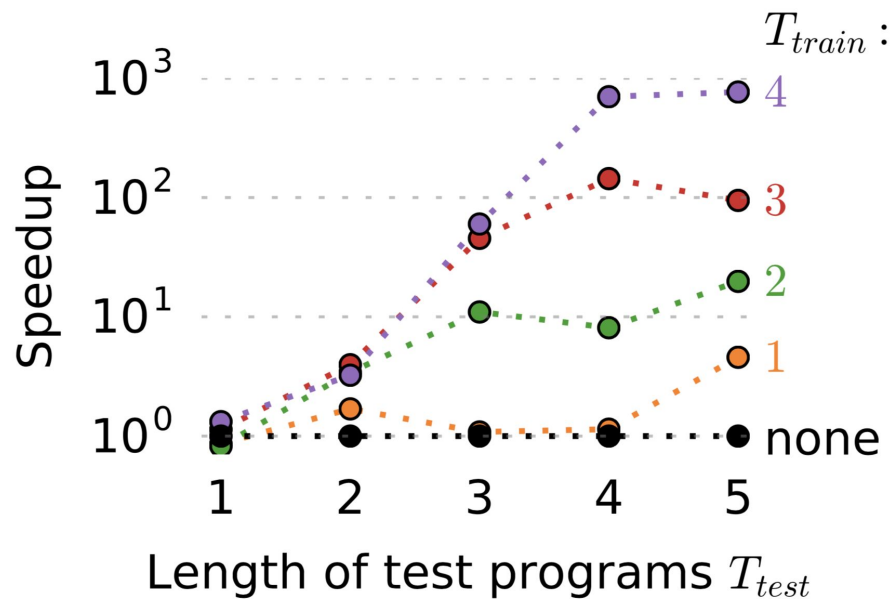
	HEAD	LAST	ACCESS	MINIMUM	MAXIMUM	TAKE	DROP	FILTER	(>0)	(<=0)	(%>=1)	(%>=0)	COUNT	MAP	MIN	MAX	+	*	ZIPWITH	SCANL1	SORT	REVERSE	(*-1)	(**2)	(+1)	(-1)	(+2)	(+3)	(+4)	(/2)	(/3)	(/4)	SUM
HEAD		.17 (15)	.05 (12)	.29 (18)	.09 (6)	.04 (4)	.06 (4)	.12 (14)	.06 (6)	.08 (14)	.07 (17)	.06 (13)	.06 (13)	.16 (24)	.11 (13)	.03 (14)	.06 (14)	.00 (13)	.09 (12)	.05 (13)	.05 (17)	.03 (16)	.03 (17)	.01 (6)	.01 (6)	.02 (5)	.03 (18)	.02 (18)	.00 (9)	.06 (16)	.01 (9)	.02 (18)	.08 (18)
LAST		.34 (18)	.15 (6)	.01 (6)	.05 (4)	.04 (4)	.09 (4)	.04 (6)	.01 (6)	.02 (6)	.11 (6)	.04 (6)	.01 (6)	.04 (6)	.11 (6)	.05 (5)	.11 (16)	.01 (16)	.03 (14)	.06 (15)	.01 (13)	.03 (17)	.03 (16)	.01 (8)	.03 (9)	.01 (9)	.02 (18)	.00 (18)	.00 (9)	.02 (13)	.01 (9)	.02 (18)	
ACCESS		.10 (15)	.19 (18)	.15 (16)	.05 (18)	.16 (16)	.18 (16)	.16 (14)	.03 (14)	.17 (17)	.16 (13)	.12 (13)	.03 (13)	.18 (24)	.06 (13)	.05 (16)	.00 (16)	.02 (17)	.00 (14)	.07 (15)	.02 (17)	.04 (15)	.07 (17)	.02 (17)	.04 (17)	.03 (18)	.02 (18)	.00 (9)	.02 (18)	.02 (18)	.02 (18)	.02 (18)	
MINIMUM		.16 (8)	.22 (9)	.04 (7)	.12 (9)	.18 (7)	.24 (8)	.03 (8)	.16 (8)	.13 (9)	.13 (9)	.06 (7)	.34 (9)	.02 (7)	.25 (8)	.10 (5)	.00 (8)	.01 (8)	.05 (7)	.03 (8)	.06 (7)	.02 (9)	.00 (8)	.02 (9)	.04 (9)	.00 (9)	.02 (10)	.00 (9)	.01 (9)	.04 (8)	.02 (9)	.02 (9)	
MAXIMUM		.25 (16)	.23 (10)	.22 (10)	.05 (10)	.08 (7)	.10 (9)	.09 (10)	.04 (10)	.08 (10)	.06 (10)	.05 (8)	.08 (8)	.00 (8)	.04 (8)	.09 (8)	.08 (10)	.05 (10)	.03 (10)	.02 (10)	.04 (10)	.09 (10)	.01 (10)	.00 (10)	.02 (10)	.02 (10)	.00 (10)	.07 (16)	.01 (16)	.00 (16)	.00 (16)		
TAKE		.05 (40)	.06 (40)	.04 (40)	.06 (40)	.02 (39)	.05 (40)	.12 (40)	.06 (40)	.09 (40)	.05 (40)	.02 (41)	.01 (40)	.05 (40)	.05 (40)	.03 (40)	.00 (42)	.11 (42)	.02 (41)	.03 (40)	.04 (41)	.00 (41)	.03 (41)	.01 (41)	.04 (42)	.02 (41)	.00 (42)	.02 (41)	.03 (41)	.01 (40)	.00 (41)	.00 (41)	
DROP		.04 (44)	.03 (43)	.03 (44)	.03 (43)	.11 (42)	.09 (38)	.06 (44)	.08 (44)	.09 (44)	.05 (39)	.01 (39)	.14 (39)	.06 (40)	.09 (40)	.09 (39)	.00 (38)	.10 (43)	.03 (44)	.05 (44)	.08 (44)	.01 (45)	.01 (44)	.05 (44)	.06 (43)	.02 (44)	.03 (43)	.02 (44)	.01 (44)	.03 (44)	.01 (44)	.00 (44)	
FILTER		.01 (115)	.01 (114)	.02 (114)	.02 (113)	.03 (112)	.06 (109)	.06 (90)	.07 (88)	.08 (61)	.11 (110)	.08 (93)	.11 (91)	.08 (91)	.08 (92)	.09 (92)	.01 (92)	.03 (102)	.03 (102)	.04 (110)	.05 (110)	.02 (115)	.01 (117)	.03 (114)	.04 (116)	.01 (114)	.03 (116)	.01 (113)	.02 (116)	.01 (114)	.03 (116)	.03 (114)	
(>0)		.03 (33)	.02 (34)	.02 (30)	.01 (33)	.02 (32)	.01 (31)	.07 (32)	.13 (33)	.15 (32)	.13 (31)	.06 (24)	.11 (25)	.16 (26)	.11 (29)	.16 (30)	.05 (25)	.06 (29)	.00 (29)	.05 (29)	.02 (31)	.06 (32)	.02 (32)	.03 (34)	.04 (32)	.03 (34)	.00 (32)	.01 (33)	.04 (32)	.00 (33)	.05 (32)	.03 (33)	
(%>=1)		.01 (33)	.01 (33)	.04 (32)	.00 (33)	.06 (32)	.05 (32)	.09 (32)	.11 (31)	.19 (37)	.06 (32)	.12 (32)	.05 (32)	.12 (32)	.05 (32)	.07 (32)	.16 (30)	.02 (32)	.06 (32)	.03 (32)	.06 (32)	.07 (32)	.03 (32)	.00 (32)	.03 (32)	.00 (32)	.03 (32)	.00 (32)	.03 (32)	.03 (32)	.04 (32)	.06 (32)	
(%>=0)		.01 (45)	.01 (43)	.01 (45)	.00 (45)	.02 (42)	.03 (42)	.06 (42)	.05 (42)	.09 (42)	.09 (42)	.17 (42)	.04 (42)	.12 (45)	.05 (42)	.09 (42)	.02 (44)	.04 (42)	.00 (43)	.05 (42)	.05 (42)	.00 (44)	.02 (44)	.00 (44)	.02 (44)	.04 (43)	.02 (44)	.00 (44)	.02 (44)	.06 (43)	.01 (44)	.04 (44)	
COUNT		.04 (32)	.02 (27)	.01 (32)	.01 (32)	.01 (28)	.04 (22)	.14 (24)	.18 (21)	.24 (20)	.20 (20)	.16 (20)	.19 (28)	.15 (29)	.11 (27)	.10 (24)	.14 (28)	.00 (29)	.07 (24)	.09 (26)	.03 (28)	.05 (28)	.02 (32)	.05 (32)	.02 (32)	.03 (32)	.01 (32)	.00 (32)	.01 (31)	.00 (32)	.04 (31)	.06 (32)	
MAP		.01 (246)	.01 (248)	.01 (250)	.02 (249)	.02 (231)	.02 (236)	.02 (220)	.02 (243)	.02 (246)	.02 (240)	.02 (248)	.00 (186)	.04 (188)	.11 (203)	.06 (186)	.05 (188)	.04 (193)	.04 (206)	.04 (246)	.02 (235)	.04 (225)	.03 (231)	.05 (228)	.11 (224)	.01 (228)	.01 (221)	.02 (220)	.06 (218)	.03 (225)	.05 (250)		
MIN		.02 (123)	.02 (122)	.01 (123)	.01 (121)	.01 (121)	.01 (117)	.01 (98)	.01 (115)	.01 (114)	.01 (117)	.01 (120)	.02 (107)	.07 (107)	.08 (104)	.04 (102)	.06 (104)	.00 (103)	.04 (106)	.03 (113)	.03 (111)	.03 (118)	.13 (134)	.09 (118)	.11 (118)	.15 (118)	.01 (116)	.01 (112)	.03 (117)	.06 (116)	.03 (122)		
MAX		.01 (128)	.01 (130)	.01 (129)	.01 (126)	.02 (125)	.02 (125)	.01 (125)	.02 (125)	.02 (124)	.02 (122)	.02 (117)	.15 (125)	.22 (141)	.12 (125)	.08 (83)	.09 (110)	.05 (130)	.03 (178)	.02 (120)	.04 (124)	.03 (125)	.03 (124)	.03 (126)	.03 (125)	.04 (126)	.03 (125)	.01 (124)	.02 (122)	.04 (120)	.04 (122)		
+		.01 (132)	.01 (154)	.01 (152)	.01 (149)	.01 (148)	.01 (128)	.01 (143)	.01 (145)	.01 (150)	.01 (147)	.01 (147)	.00 (132)	.03 (123)	.14 (131)	.07 (119)	.07 (141)	.02 (130)	.01 (146)	.04 (149)	.04 (143)	.02 (149)	.04 (143)	.00 (144)	.04 (144)	.04 (144)	.04 (144)	.04 (144)	.04 (144)	.04 (144)	.04 (144)	.04 (144)	
*		.01 (139)	.01 (141)	.01 (141)	.01 (142)	.01 (132)	.01 (133)	.01 (137)	.01 (135)	.01 (130)	.01 (138)	.01 (138)	.01 (121)	.03 (122)	.10 (107)	.08 (116)	.05 (131)	.04 (138)	.02 (134)	.04 (138)	.03 (134)	.03 (138)	.03 (134)	.03 (138)	.03 (138)	.03 (136)	.03 (132)	.03 (138)	.03 (132)	.03 (138)	.03 (138)	.03 (138)	
ZIPWITH		.01 (423)	.01 (428)	.01 (427)	.01 (425)	.01 (426)	.01 (409)	.01 (437)	.01 (435)	.01 (408)	.01 (403)	.01 (397)	.01 (413)	.01 (319)	.01 (314)	.01 (306)	.01 (259)	.01 (284)	.01 (289)	.02 (327)	.04 (404)	.04 (410)	.04 (414)	.04 (397)	.04 (413)	.04 (399)	.04 (404)	.04 (402)	.04 (406)	.04 (404)	.04 (424)		
SCANL1		.02 (125)	.05 (122)	.03 (124)	.01 (122)	.01 (118)	.02 (109)	.01 (121)	.01 (116)	.01 (119)	.01 (122)	.01 (119)	.01 (179)	.01 (79)	.01 (73)	.01 (69)	.01 (94)	.01 (99)	.01 (21)	.01 (121)	.01 (130)	.01 (119)	.01 (129)	.01 (123)	.01 (122)	.01 (123)	.01 (118)	.01 (119)	.01 (123)	.01 (118)	.01 (123)	.01 (123)	
SORT		.02 (15)	.05 (33)	.00 (31)	.04 (34)	.07 (31)	.05 (34)	.01 (31)	.04 (32)	.01 (33)	.01 (36)	.01 (37)	.18 (27)	.17 (27)	.18 (27)	.02 (27)	.09 (26)	.00 (26)	.02 (29)	.00 (31)	.02 (31)	.09 (31)	.06 (34)	.04 (32)	.07 (33)	.03 (32)	.07 (32)	.03 (32)	.01 (32)	.02 (31)	.03 (31)	.01 (31)	
REVERSE		.00 (39)	.01 (40)	.00 (39)	.00 (40)	.01 (38)	.00 (38)	.02 (38)	.00 (38)	.02 (38)	.01 (38)	.02 (38)	.06 (38)	.21 (38)	.16 (38)	.05 (34)	.01 (32)	.09 (38)	.01 (33)	.02 (38)	.06 (38)	.08 (38)	.03 (39)	.09 (39)	.01 (38)	.06 (37)	.09 (37)	.01 (39)	.00 (37)	.04 (37)	.03 (40)		
(*-1)		.03 (26)	.04 (26)	.01 (25)	.00 (26)	.01 (27)	.02 (26)	.03 (24)	.05 (26)	.03 (26)	.03 (26)	.03 (27)	.03 (27)	.16 (15)	.10 (22)	.06 (22)	.09 (22)	.02 (23)	.06 (22)	.02 (26)	.02 (26)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	
(**2)		.19 (19)	.21 (21)	.00 (21)	.03 (21)	.01 (19)	.01 (21)	.07 (21)	.01 (21)	.04 (21)	.00 (21)	.00 (21)	.00 (21)	.12 (16)	.15 (16)	.06 (16)	.04 (4)	.39 (15)	.09 (15)	.00 (21)	.02 (21)	.00 (21)	.00 (21)	.00 (21)	.04 (20)	.05 (18)	.01 (21)	.05 (21)	.07 (21)	.04 (21)	.01 (21)	.02 (21)	
(+1)		.00 (39)	.01 (39)	.00 (38)	.00 (39)	.01 (34)	.00 (38)	.01 (35)	.00 (39)	.01 (38)	.00 (39)	.01 (36)	.01 (38)	.03 (30)	.35 (35)	.20 (28)	.02 (31)	.05 (33)	.07 (31)	.03 (36)	.03 (31)	.07 (30)	.02 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	
(-1)		.01 (27)	.01 (27)	.01 (27)	.02 (26)	.02 (26)	.02 (24)	.03 (26)	.02 (26)	.01 (27)	.01 (27)	.01 (27)	.01 (27)	.04 (26)	.07 (26)	.12 (26)	.01 (26)	.05 (28)	.08 (26)	.02 (26)	.05 (26)	.01 (27)	.07 (23)	.04 (28)	.00 (28)	.04 (28)	.02 (28)	.03 (28)	.08 (28)	.03 (28)	.04 (28)		
(*2)		.01 (24)	.00 (23)	.00 (24)	.01 (24)	.01 (24)	.01 (22)	.00 (23)	.01 (23)	.01 (23)	.01 (24)	.01 (22)	.01 (19)	.01 (19)	.01 (19)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	.01 (20)	
(*3)		.01 (37)	.01 (37)	.00 (38)	.00 (38)	.00 (34)	.00 (31)	.00 (36)	.00 (37)	.00 (36)	.00 (34)	.00 (36)	.00 (32)	.02 (31)	.02 (31)	.02 (27)	.06 (36)	.01 (36)	.02 (34)	.06 (35)	.06 (36)	.02 (36)	.03 (36)	.03 (37)	.03 (37)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	.03 (36)	
(+2)		.00 (35)	.01 (35)	.00 (35)	.00 (34)	.00 (34)	.00 (33)	.00 (32)	.00 (34)	.00 (34)	.00 (34)	.00 (34)	.00 (34)	.02 (24)	.16 (27)	.05 (27)	.08 (29)	.07 (28)	.08 (35)	.04 (34)	.03 (35)	.02 (34)	.03 (35)	.02 (32)	.03 (32)	.03 (32)	.03 (32)	.03 (32)	.03 (32)	.03 (32)	.03 (32)	.03 (32)	
(/4)		.00 (31)	.00 (32)	.00 (32)	.00 (32)	.00 (29)	.00 (31)	.00 (30)	.00 (32)	.00 (31)	.00 (32)	.00 (31)	.01 (32)	.16 (28)	.03 (25)	.02 (25)	.07 (25)	.03 (25)	.03 (25)	.03 (31)	.02 (32)	.03 (31)	.02 (32)	.03 (31)	.03 (32)	.03 (31)	.03 (32)	.03 (29)	.03 (32)	.03 (32)	.03 (32)	.03 (32)	
(/3)		.02 (33)	.02 (34)	.03 (33)	.01 (31)	.01 (31)	.01 (31)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (27)	.07 (27)	.11 (30)	.04 (30)	.06 (30)	.02 (34)	.01 (34)	.02 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	.01 (34)	
(/4)		.02 (27)	.02 (27)	.02 (27)	.00 (26)	.00 (26)	.00 (26)	.01 (26)	.01 (26)	.00 (26)	.00 (26)	.00 (26)	.00 (27)	.07 (27)	.13 (27)	.10 (27)	.03 (27)	.03 (27)	.03 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	.02 (27)	
SUM		.01 (8)	.07 (8)	.13 (8)	.06 (8)	.10 (8)																											



## Experiment #2

1. Train the neural network on programs of lengths  $T = 1 \dots 4$ .
2. Test the network on test sets where all programs are of length  $1 \dots 5$ 
  - a. N.b. the above two steps lead to 20 train/test pairs
3. Run the sort-and-add enumerative search with all combinations of training and testing data until 20% of programs are solved
  - a. Compare the search with the learned attributes against the baseline priors as before

## Experiment #2





## Experiment #2 Takeaway

- Neural networks are able to generalize beyond programs of the same length that they were trained on
  - This is a result of having a search on top of attribute learning: the search can correct for the bad assumptions of the network.

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# Further Research



# More explicit guiding for LIPS

- Menon et al. (2013) takes a similar approach to this paper, but incorporates explicitly defined “clues” that can be gleaned from input-output examples
  - E.g. input is a permutation of the output
  - Clues cause a reweighting of probabilities
- Domains are slightly off:
  - Smaller training/testing corpus
  - DSL that they chose lends itself towards these clues much more directly

Aditya Krishna Menon, Omer Tamuz, Sumit Gulwani, Butler W Lampson, and Adam Kalai. A machine learning framework for programming by example. In *Proceedings of the International Conference on Machine Learning (ICML)*, 2013.





# Improving the data structures in the DSL

- Li et al. (2016) attempt to predict logical features of the program
  - Instead of presence/absence of certain functions alone
  - Employs a GNN instead of the simpler feed-forward architecture
- Allows the learning to focus on data structure shape and growth instead of simply tracking data changes.

Yujia Li, Daniel Tarlow, Marc Brockschmidt, and Richard S. Zemel. Gated graph sequence neural networks. In *Proceedings of the 4th International Conference on Learning Representations (ICLR)*, 2016.