Program Synthesis

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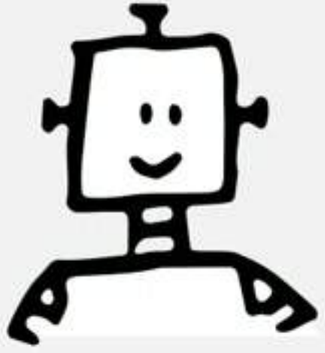
Program Synthesis: "The Golden Dream of CS"

(circa 1950-1960)

Sort

Given: $A[1..n]$

Produce: $B[1..n]$ **ensuring** $B_1 \leq \cdots \leq B_n$ **and** B is a permutation of A



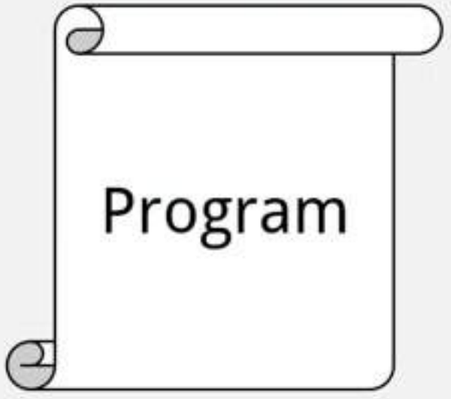
```
void bubblesort(int *array, int length)
{
    int i, j;
    for (i = 0; i < length - 1; ++i)
    {

        for (j = 0; j < length - i - 1; ++j)
        {
            if (array[j] > array[j + 1])
            {
                int tmp = array[j];
                array[j] = array[j + 1];
                array[j + 1] = tmp;
            }
        }
    }
}
```

Modern Program Synthesis

- Input-output examples
- Natural language

- Programming language
- Domain-specific language



- Enumerative/deductive search
- Neural networks

Application: Question answering

Natural language question

Command interpretations
+ query plans

Application: Data wrangling

Input-output examples

String → String data transforms

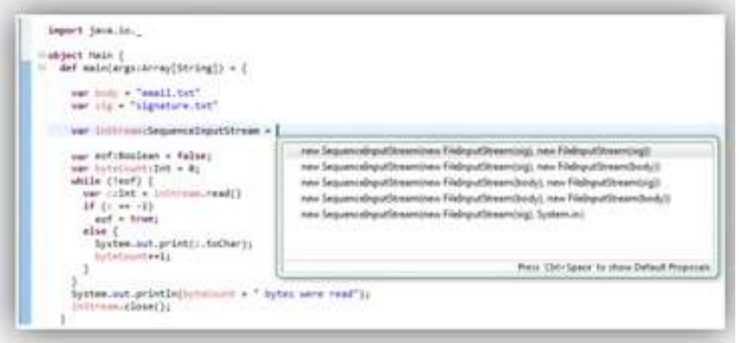
	A	B	C	D	E
1	First Name	Middle Name	Last Name	Combined Name	
2	Mary	Kristy	Mills	Mills, Mary K.	
3	Craig	John	Garland	Garland, Craig J.	
4	Andrew		Simpson		
5	Rupert	L	Richards	Richards, Rupert L.	
6	Joe		Bryant		
7	Jane		Hart		
8	Bob	JD	Bond	Bond, Bob JD.	
9					
10					

Flash Fill

Application: Code generation

Program context/template

Programming language



Outline

- Introduction
- Programming by Examples
- Neural-Guided Program Search
- Neural Program Synthesis

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Flash Fill

[Gulwani, 2011]

	A	B	C	D	E
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```
Concat(input[2], Const(", "), input[0], Const(" "),
    let v = input[1] in Substring(v, AbsPos(v, 0), RegexPos(v, UpperCase, '', -1)),
    Const("."))
```

Flash Fill

[Gulwani, 2011]

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```
if (input[1] == '') then Concat(input[2], Const(", "), input[0], Const(".")) else
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from the beginning till the last uppercase character

Flash Fill

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		L	Richards	Richards,	
			Bryant	Bryant, J.	
			Hart	Hart, J.	
		JD	Bond	Bond, Bob	

Domain-Specific Language (DSL)

Programming by Examples (PBE)

```
if (input[1] == '') then Concat(input[2], Const(", "), input[0], Const(".")) else
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    let v = input[1] in Substring(v, AbsPos(v, 0), RegexPos(v, UpperCase, '', -1)),
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from the beginning till the last uppercase character

PBE Challenges

1. The synthesized program *must* satisfy the examples.
2. Examples are severely ambiguous.
   - Should learn the *intended* program, not just one that satisfies the examples
   - How do we know when to stop?
3. Interactive UX requires quick turnaround.
4. The DSL must be expressive but concise.

Flash Fill DSL (excerpt)

```
@input string[] inputs;

@start string transform := atom | Concat(atom, transform);

string atom := Const(s)
             | let v = std.Kth(inputs, k) in
                 Substring(v, std.Pair(pos, pos));

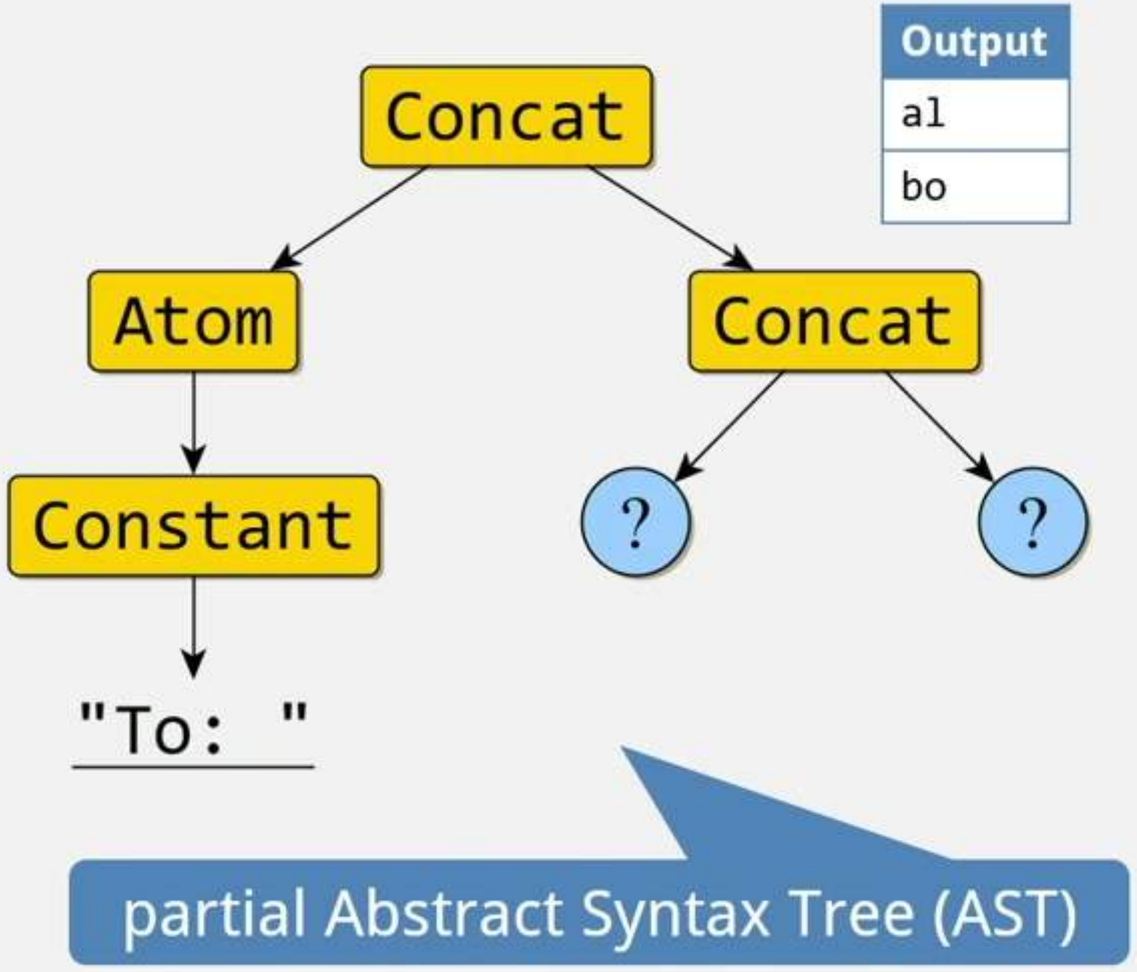
uint? pos := AbsPos(v, k)
           | RegexPos(v, std.Pair(r, r), k);

        string s;          Regex r;          int k;
```

Deductive Search in PBE

[Polozov & Gulwani, 2015]

Input x	Output y
`alice liddell`	`To: al`
`bob o'reilly`	`To: bo`



1. Select a hole (initially root).
2. Select a DSL operator to insert in the hole.

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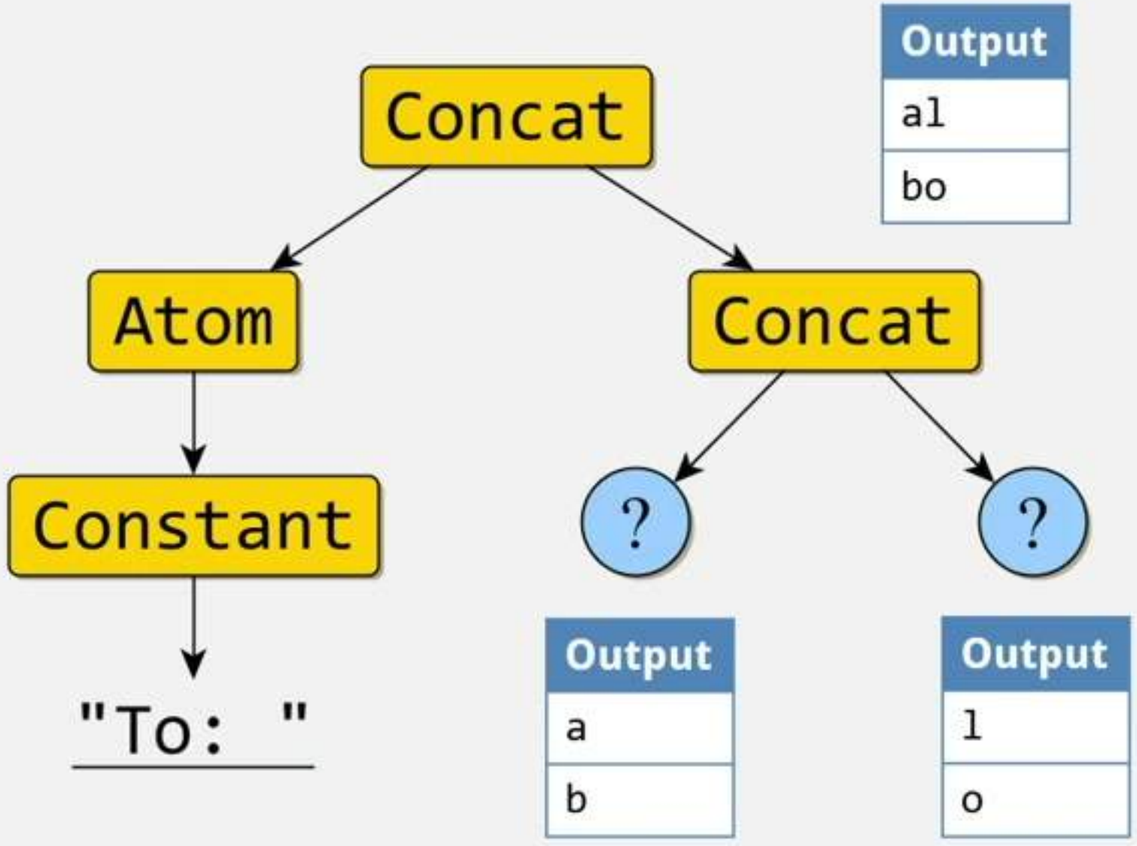

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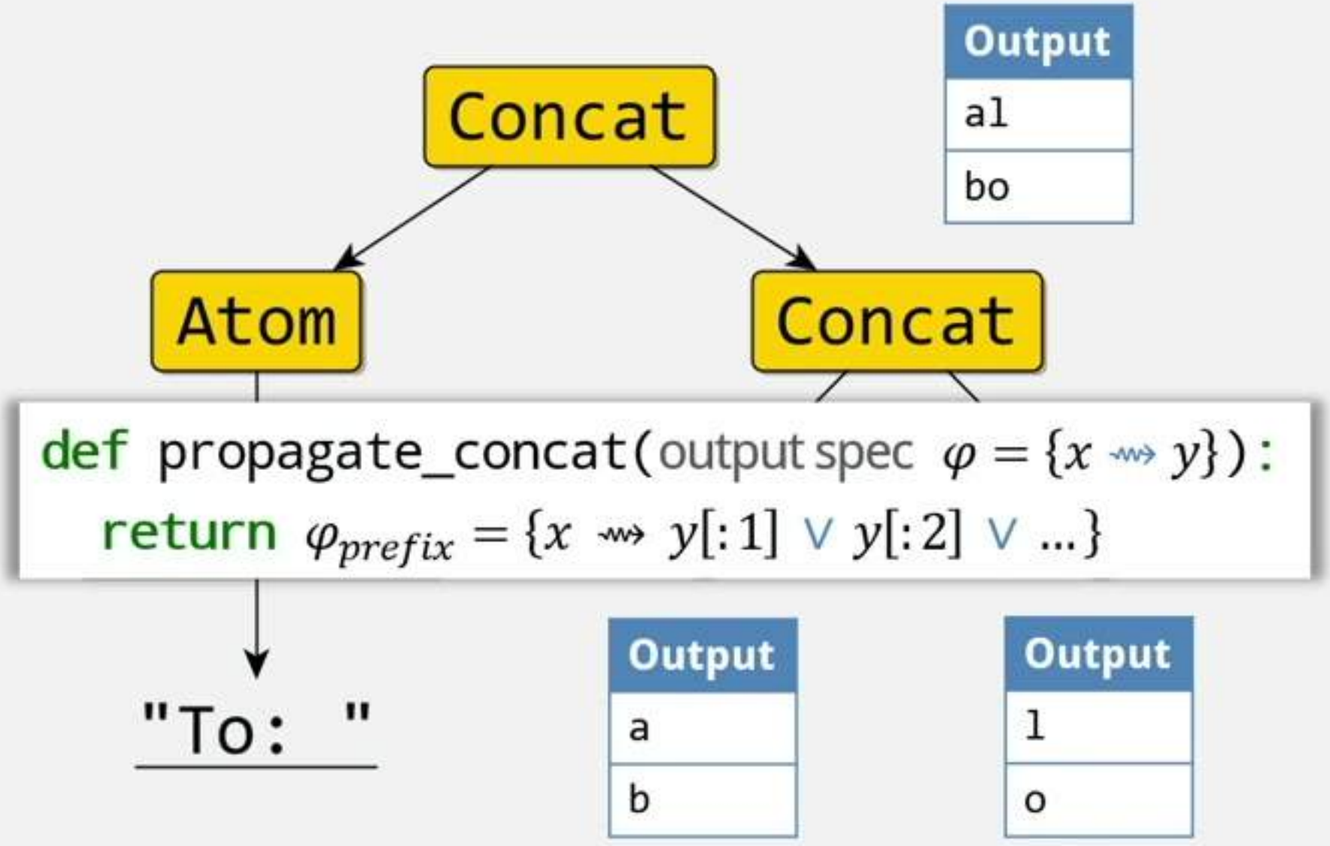

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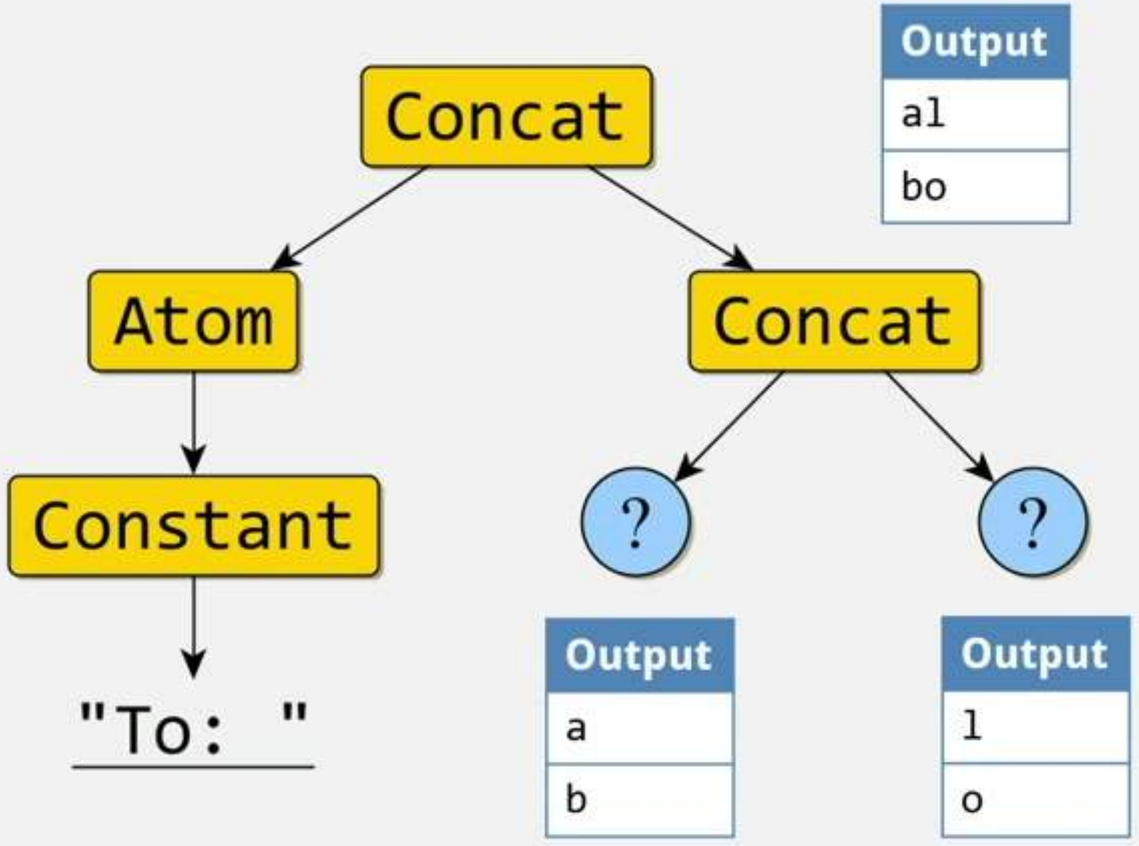

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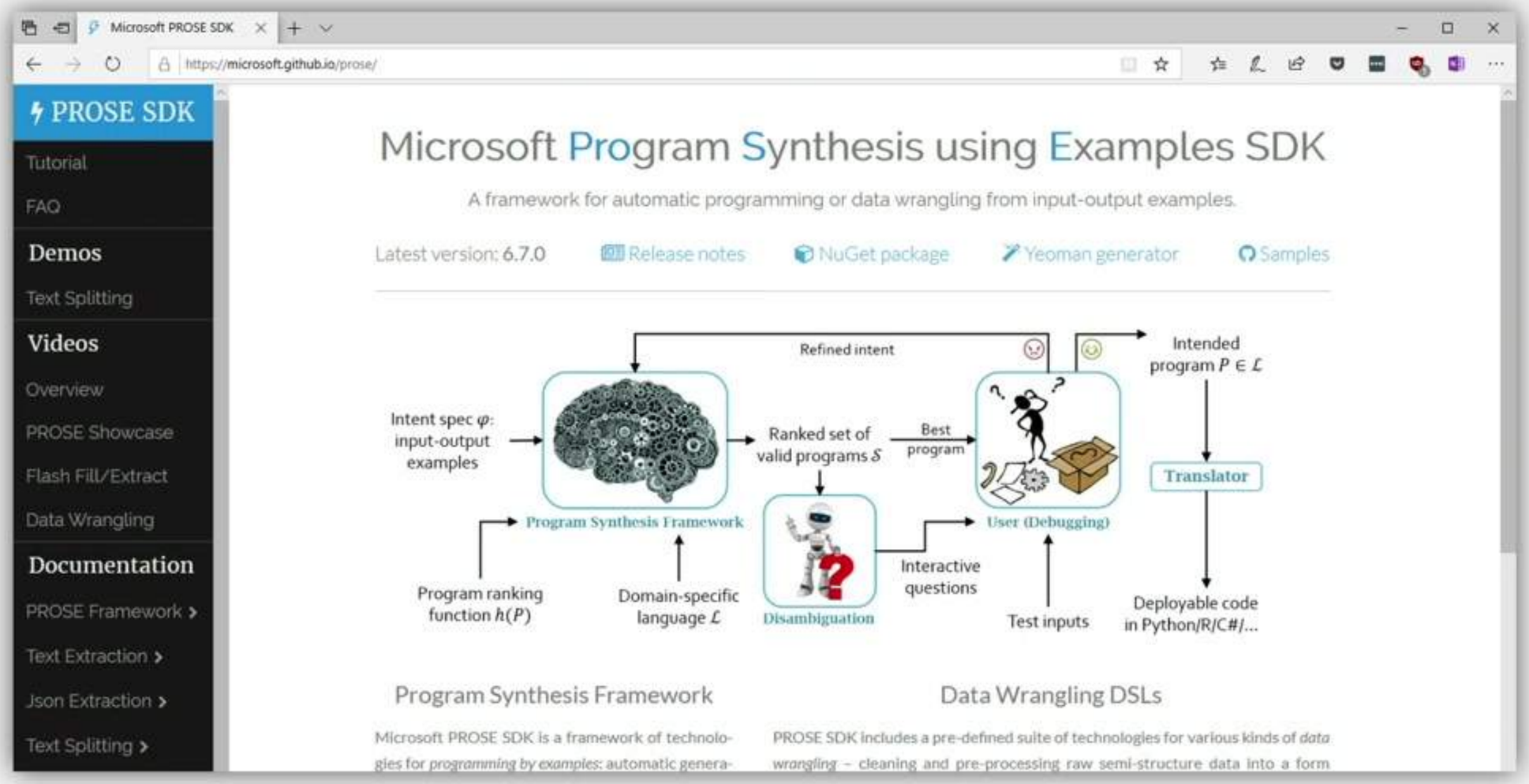
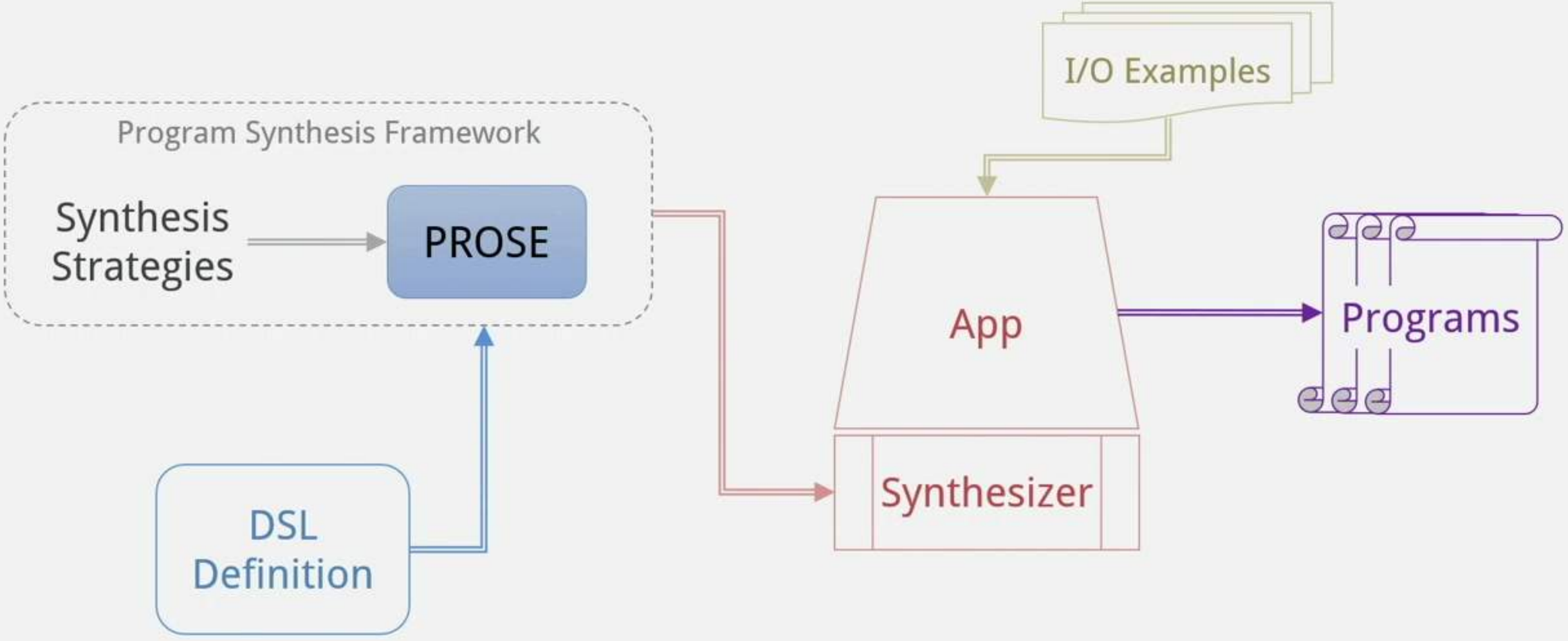
- ✓ Correct by construction
- ✓ Can incorporate program ranking
- ✓ Example propagation easy to write for many operations & domains

Microsoft PROSE SDK

https://microsoft.github.io/prose



Microsoft PROSE SDK



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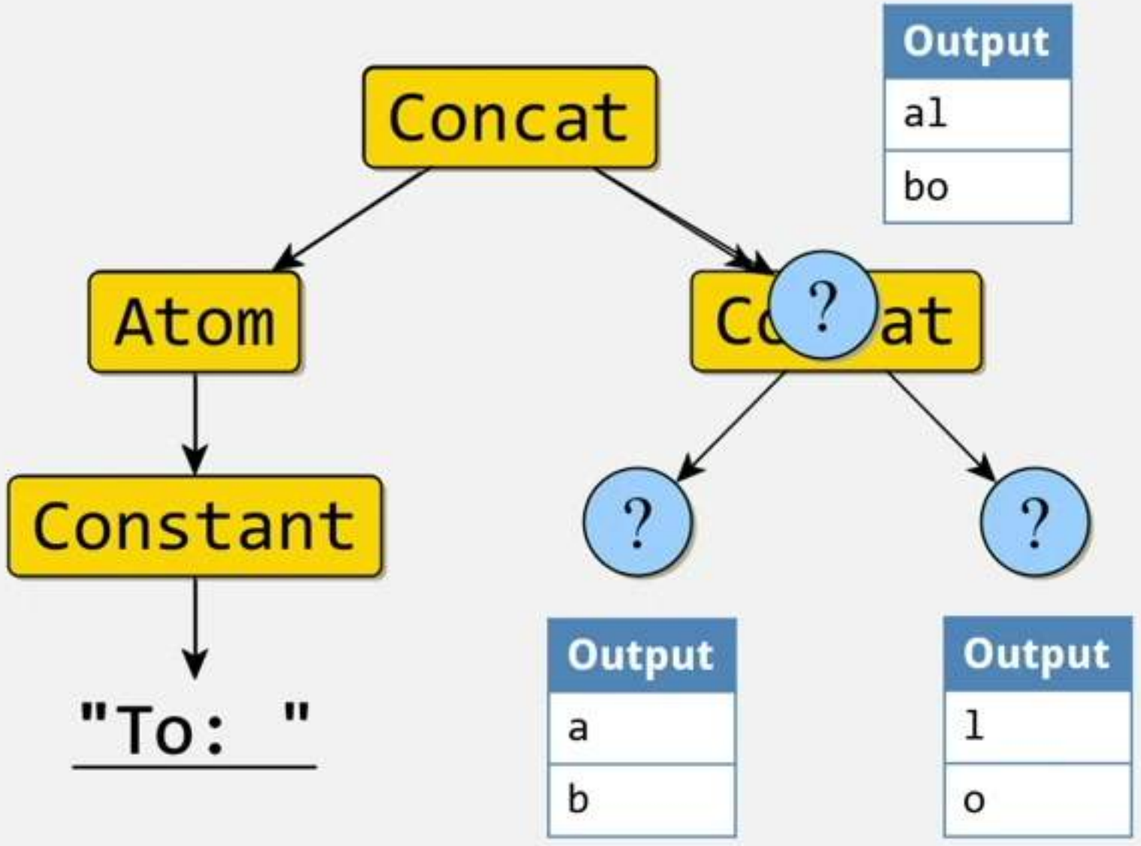

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Deductive Search

Why so slow? Explores the entire search space
(unless deduction prunes some of it)

Machine-learned insights

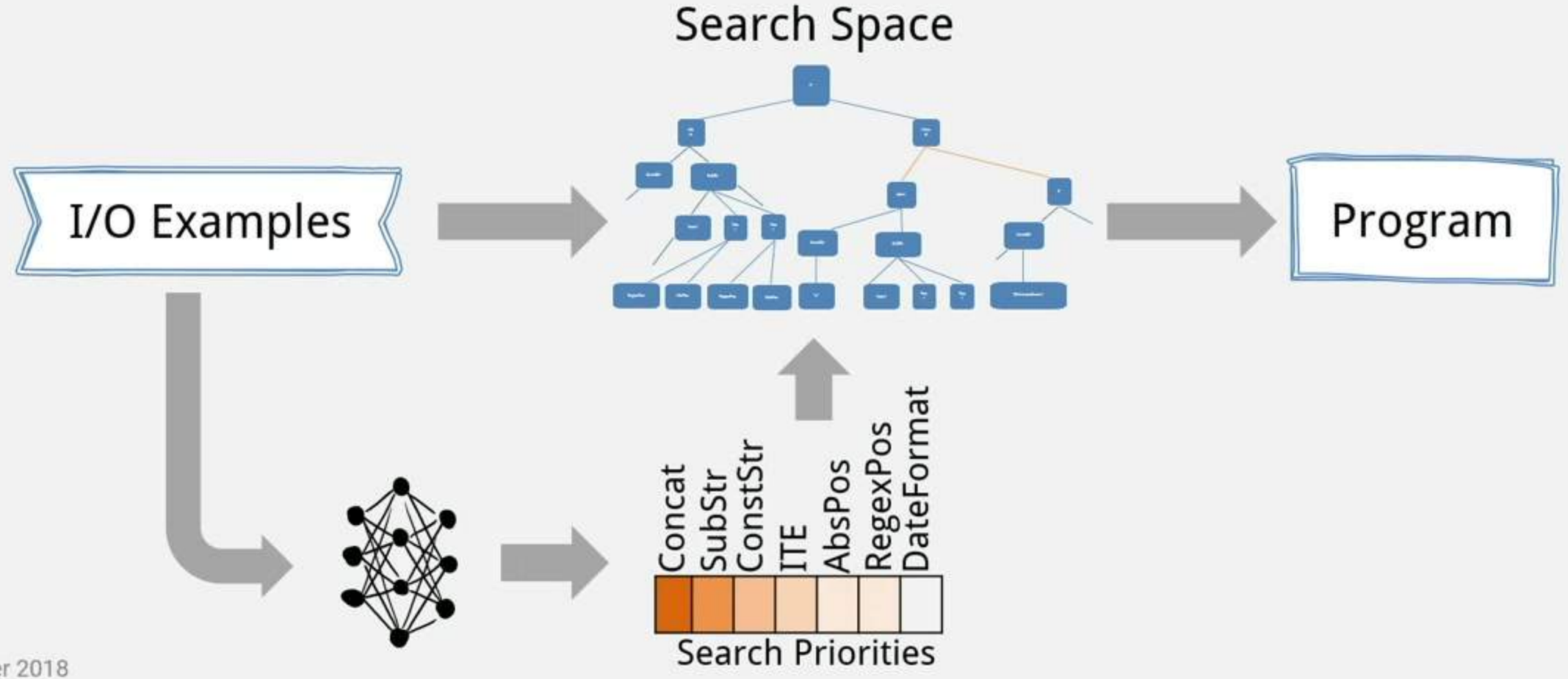
Input	Output
`alice liddell`	`To: al`
`bob o'reilly`	`To: bo`

Can't be a substring, requires concatenation

DeepCoder: Learning to Write Programs

[Balog et al., 2017]

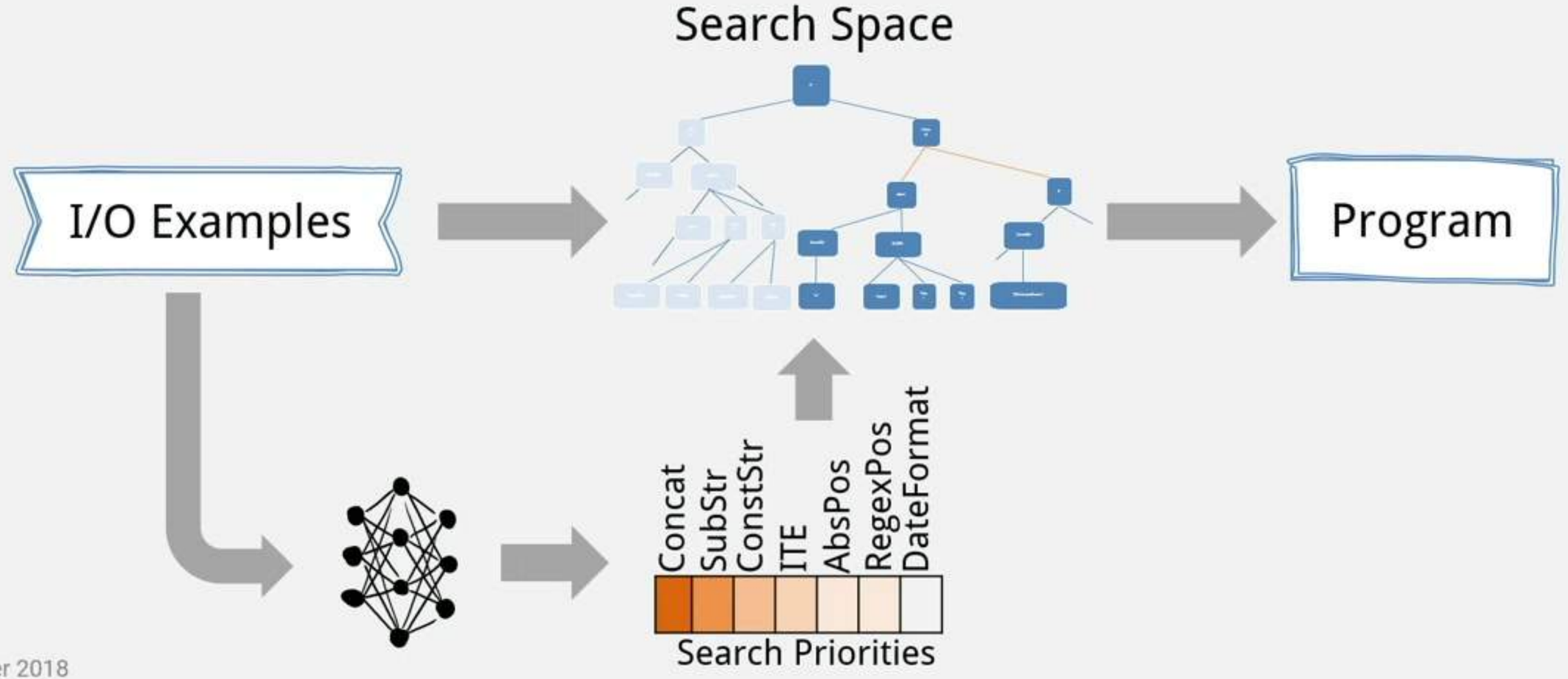
Idea: Order the search space based on a priority list from DNN *before starting*



Neural-Guided Deductive Search

[Kalyan et al., 2018]

Idea: Order the search space based on a priority list from DNN *at each step*



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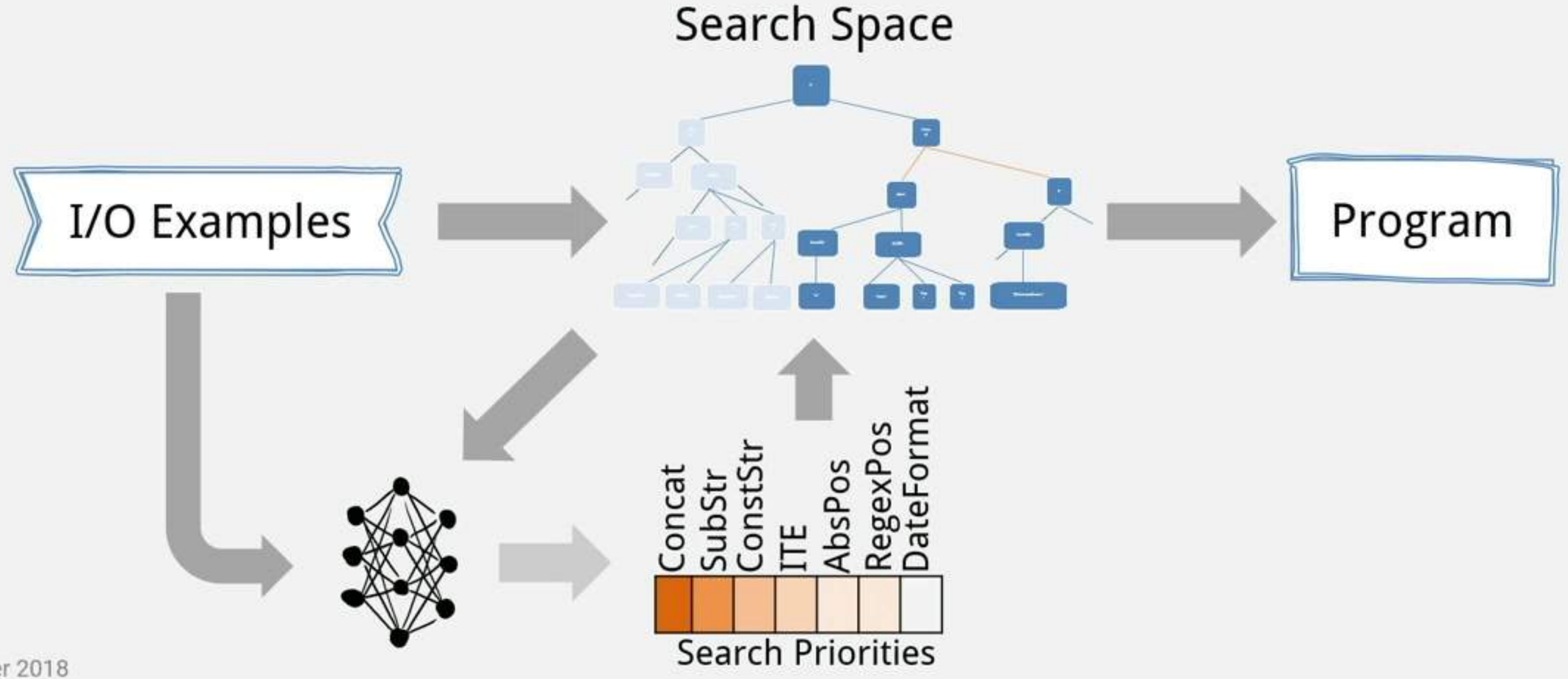

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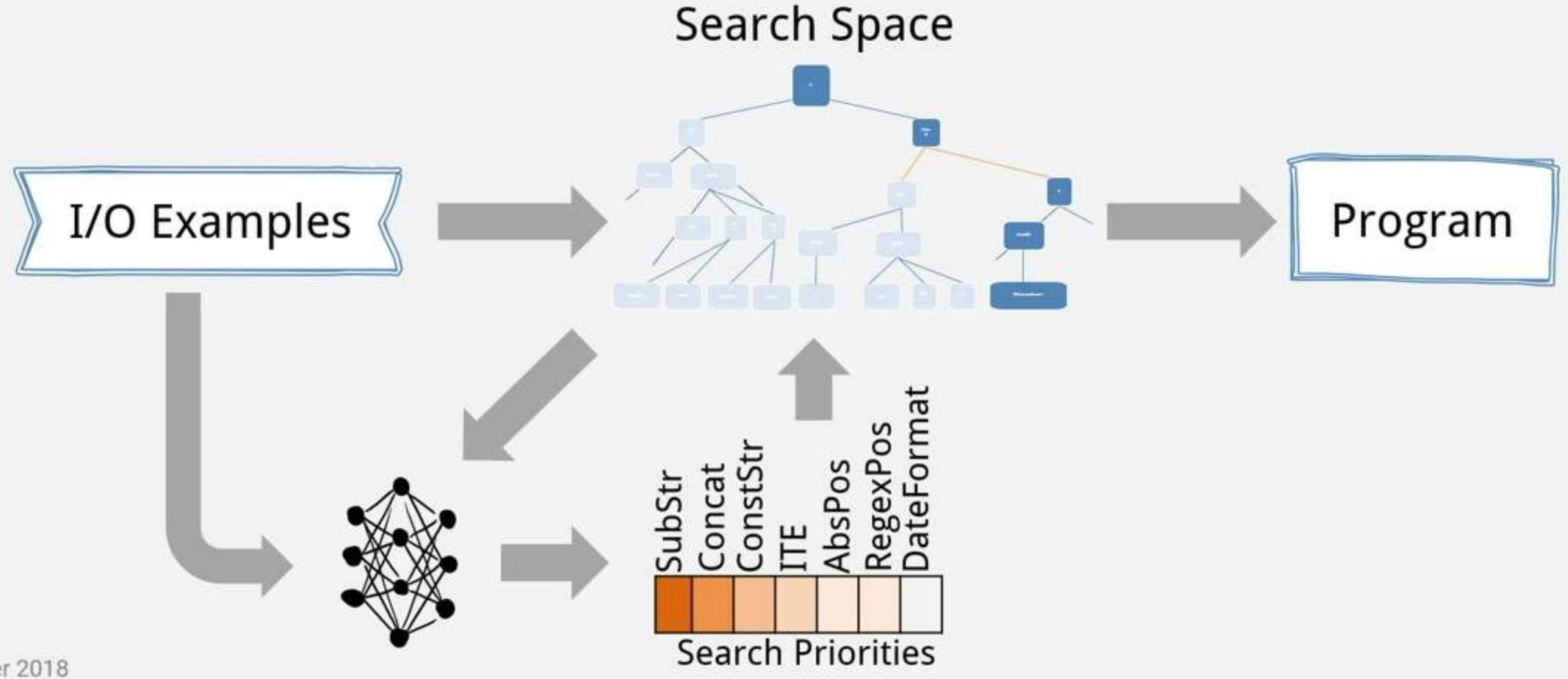


Search branch prediction

- Collect a complete dataset of intermediate search results:

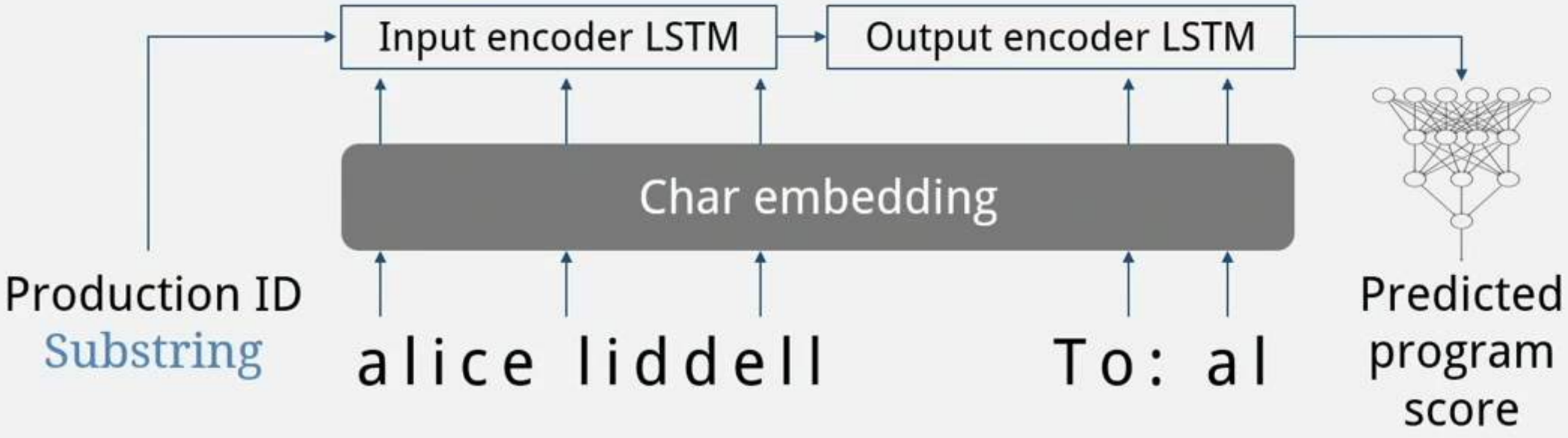
at a search branch $N := F_1(\dots) \mid F_2(\dots) \mid \cdots \mid F_k(\dots)$
given a spec $\varphi = \{x \rightsquigarrow y\}$
produced programs $P_1, \dots, P_k$ with scores $h(P_1, \varphi), \dots, h(P_k, \varphi)$

- Learn a predictive model f s.t. $f(F_j, \varphi) \approx h(P_j, \varphi)$

- Train using squared-error loss over program scores:

$$\mathcal{L}(f;\ F_j, \varphi) = \left[f(F_j, \varphi) - h(P_j, \varphi)\right]^2$$

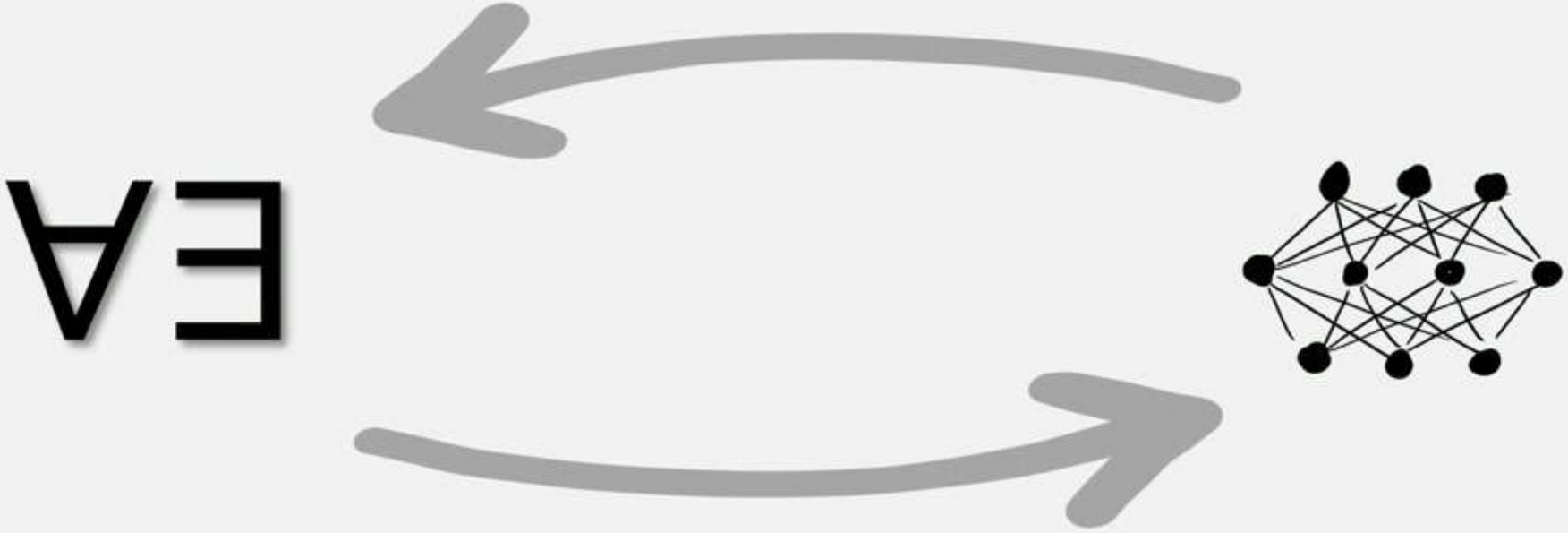
Model



- Guides the search toward higher-quality programs
- Eliminates unproductive search branches
- Balances performance vs. generalization using branch-and-bound

“Neuro-Symbolic” Architectures

Guiding a symbolic search



Verifying neutrally generated programs
Adding semantic structure to data

Natural Language → SQL

Year	City	Country	Nations
1896	Athens	Greece	14
1900	Paris	France	24
1904	St. Louis	USA	12
...	...	...	...
2004	Athens	Greece	201
2008	Beijing	China	204
2012	London	UK	204

Q: When did Greece hold its last Summer Olympics?

```
SELECT MAX(Year) FROM SummerOlympics WHERE Country='Greece';
```

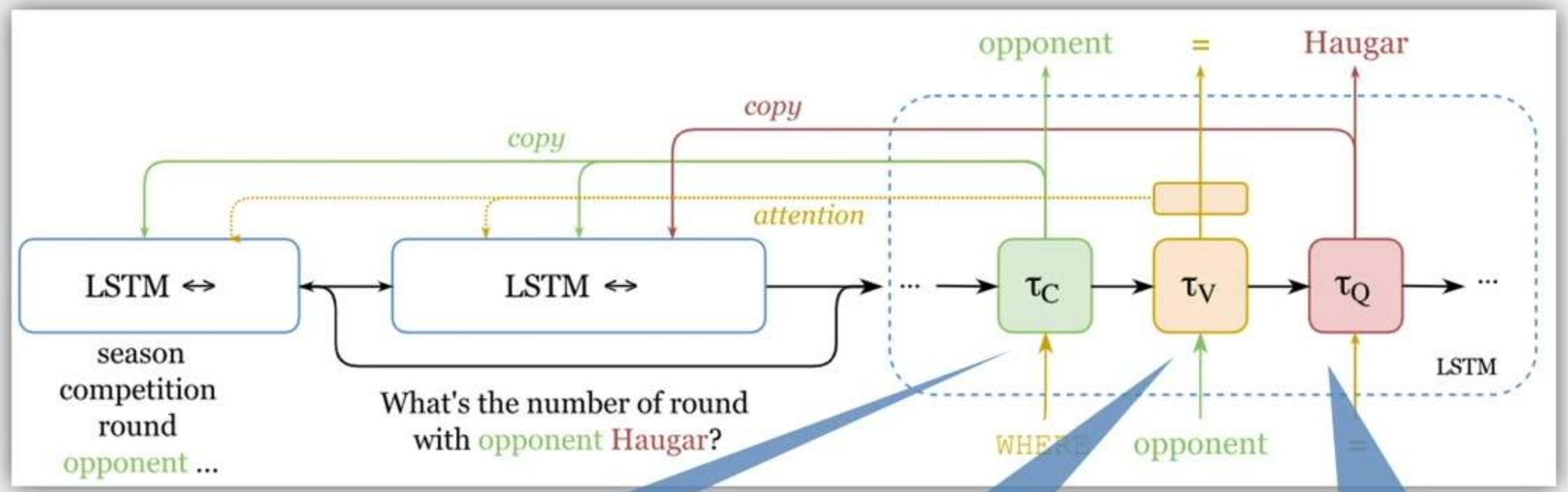
A: 2004

Relevant Information:

1. Column names
2. Column data types
3. Matches between table data and question

Pointer-SQL

[Wang et al., 2017]



Copying mechanism for column names

Constant token

Copying mechanism for words/values

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Execution Guidance during inference:

1. Backtrack if partial query has type error
2. Backtrack if "... `WHERE COND`" is empty
3. Constrain the decoder using grammar types
4. Nondeterministic oracles during training

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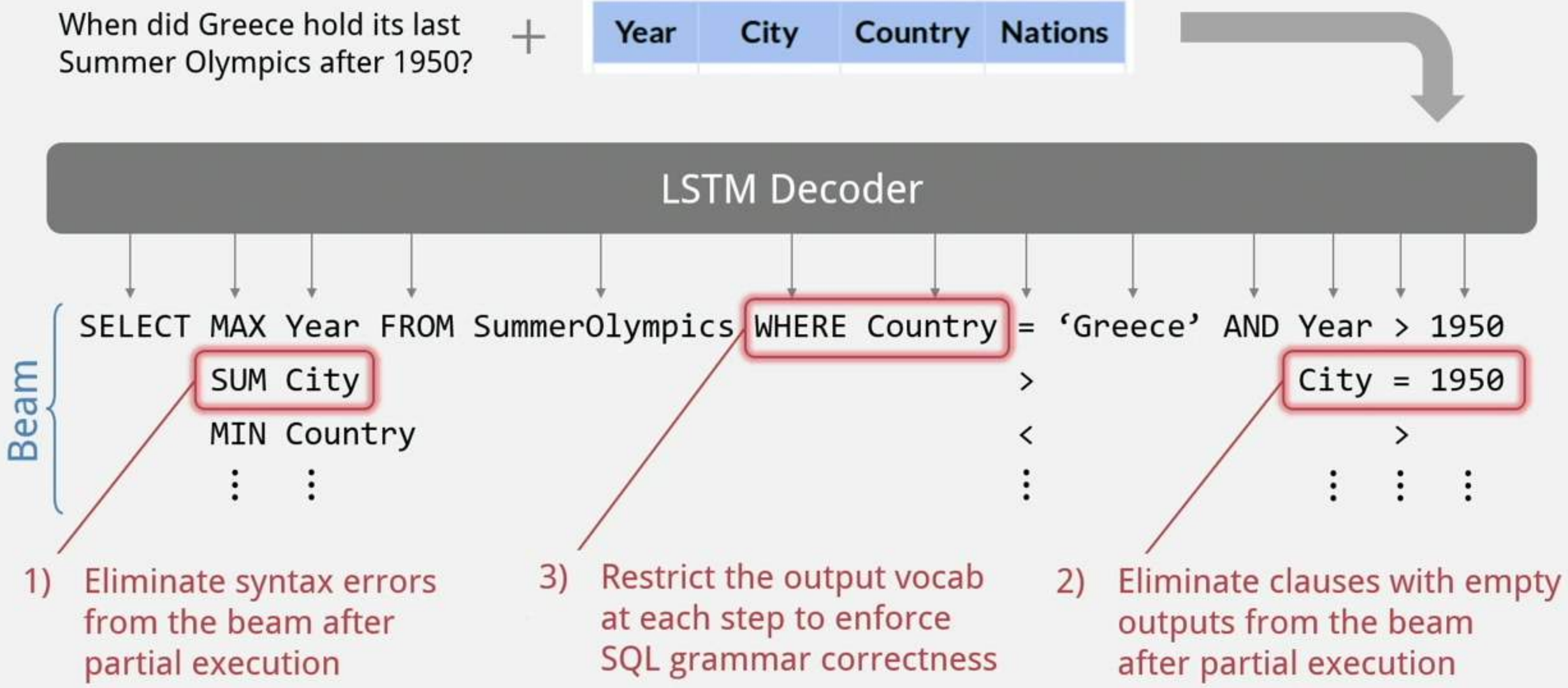
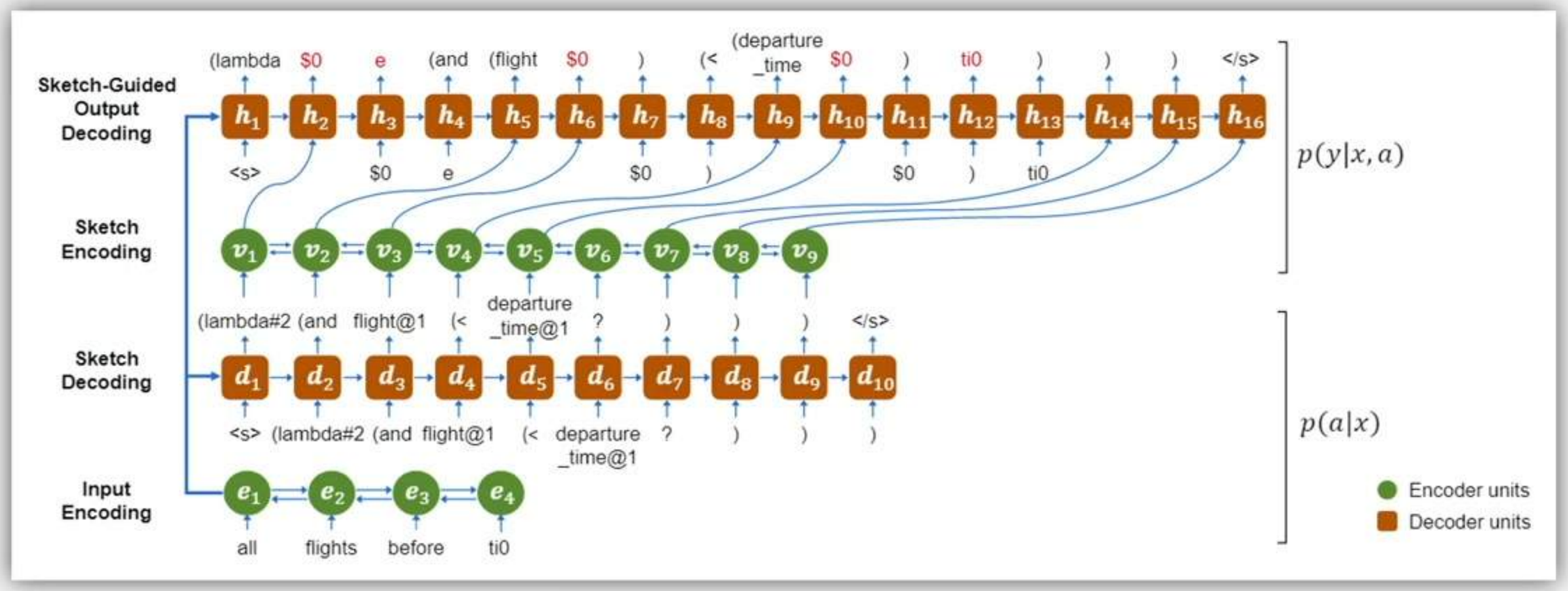
Execution Guidance [Wang et al., 2018]



Coarse→Fine sketch generation

[Solar-Lezama, 2006] [Murali et al., 2018] [Dong & Lapata, 2018]



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Programs: the ML Perspective

Approach 1: Sequence of Words (re-using NLP ideas)

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Programs are different from natural language:

- Semantics for keywords already known
- Many words (APIs, local methods) only used seldomly
- Long-distance dependencies common

Programs: the ML Perspective

Approach 1.1: Sequence/tree of words (re-using NLP ideas)

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Approach 2: Graphs

- Nodes labelled by semantic information
- Edges for semantic relationships

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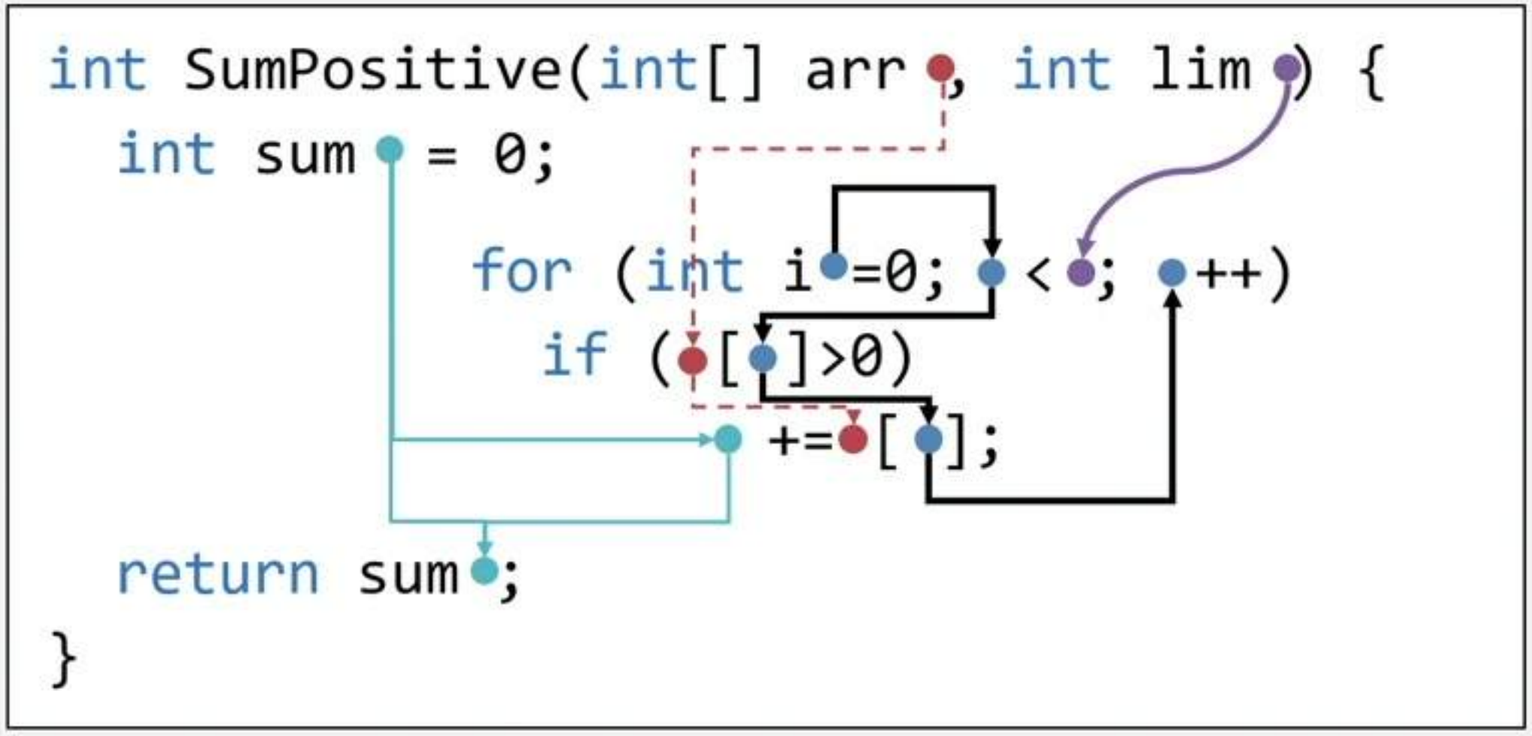
} From Static Analysis

Programs as Graphs: Key Idea

```
int SumPositive(int[] arr, int lim) {
  int sum = 0;
  for (int i = 0; i < lim; i++)
    if (arr[i] > 0)
        sum += arr[i];

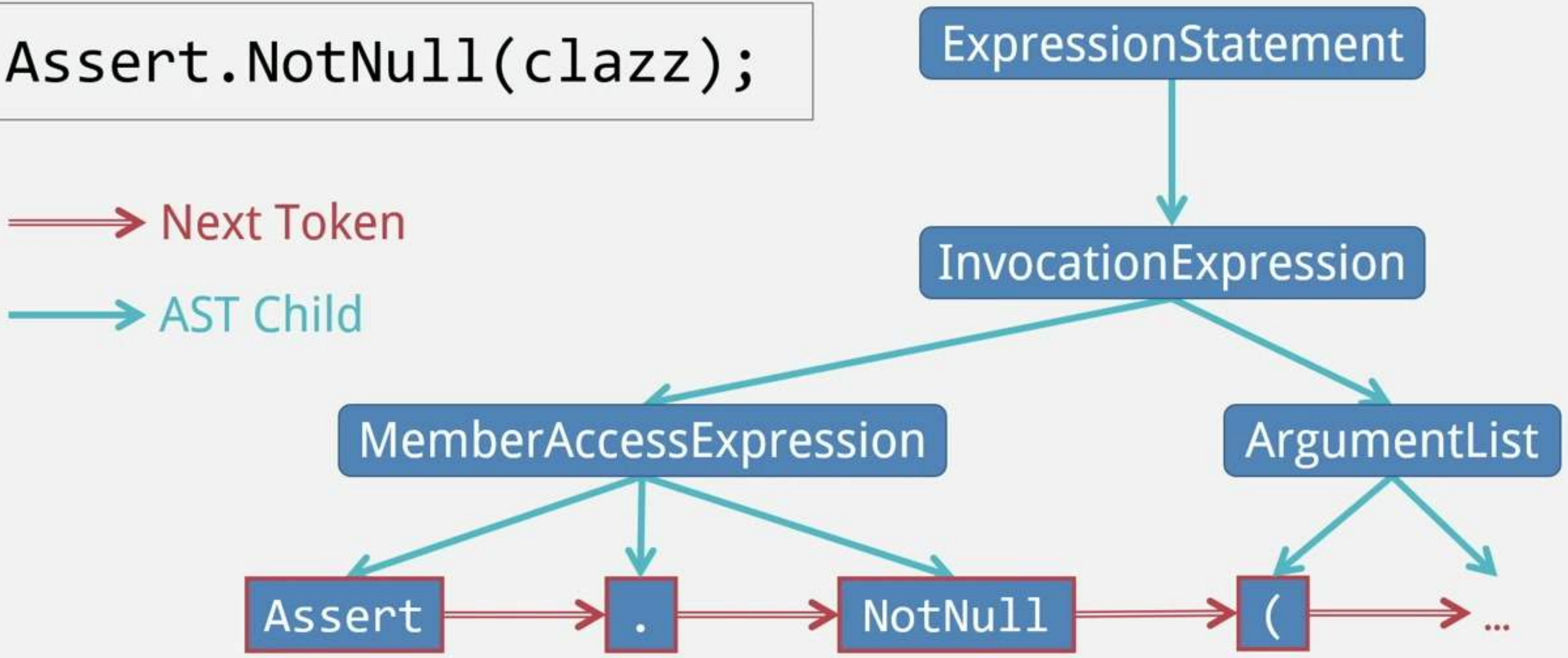
  return sum;
}
```

Programs as Graphs: Key Idea

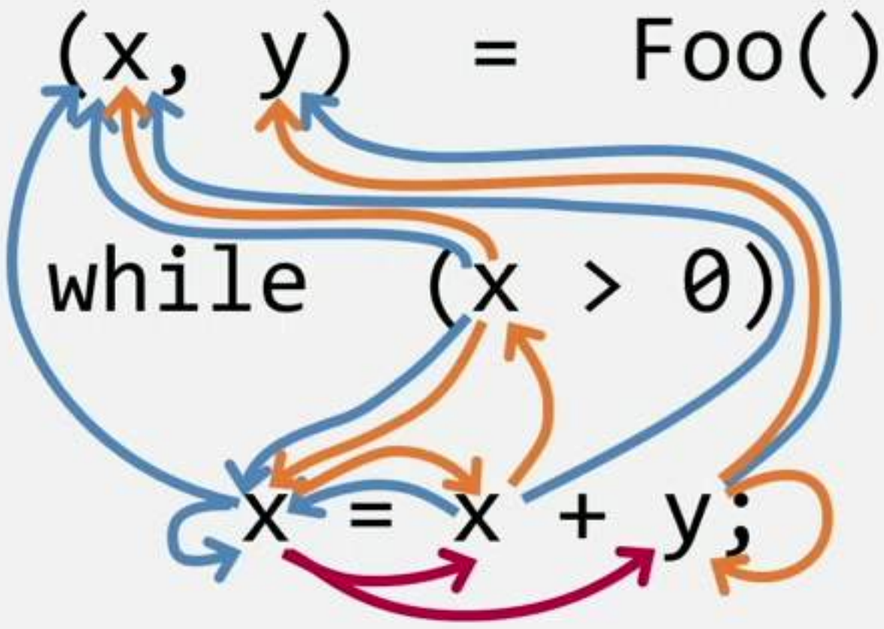


Programs as Graphs: Syntax

```
Assert.NotNull(clazz);
```



Programs as Graphs: Data Flow



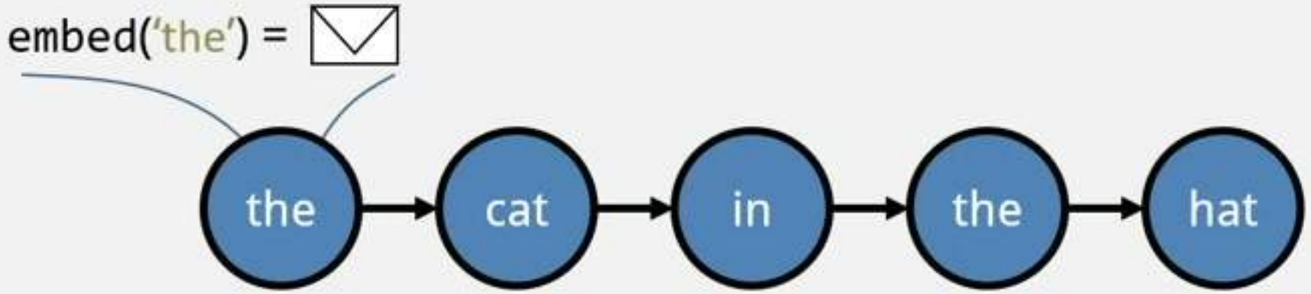
Last Write

Last Use

Computed From

Graph Neural Networks: Extending RNNs

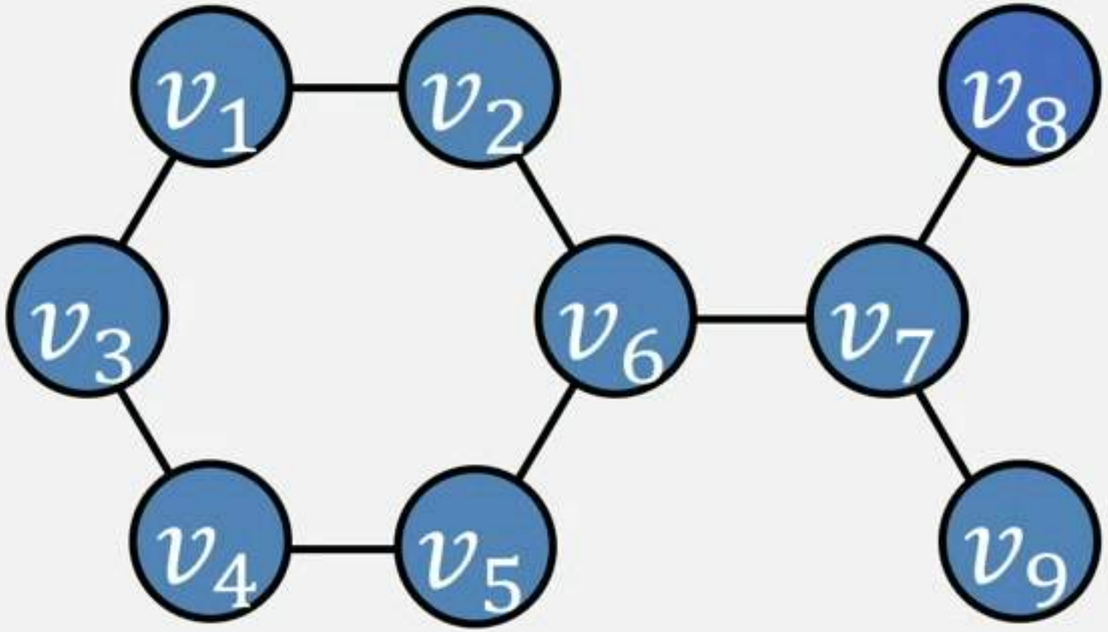
[Li et al., 2016] [Allamanis et al., 2018]



Chain structured data
(e.g. text)

▲ Recurrent unit

Graph Neural Networks: States



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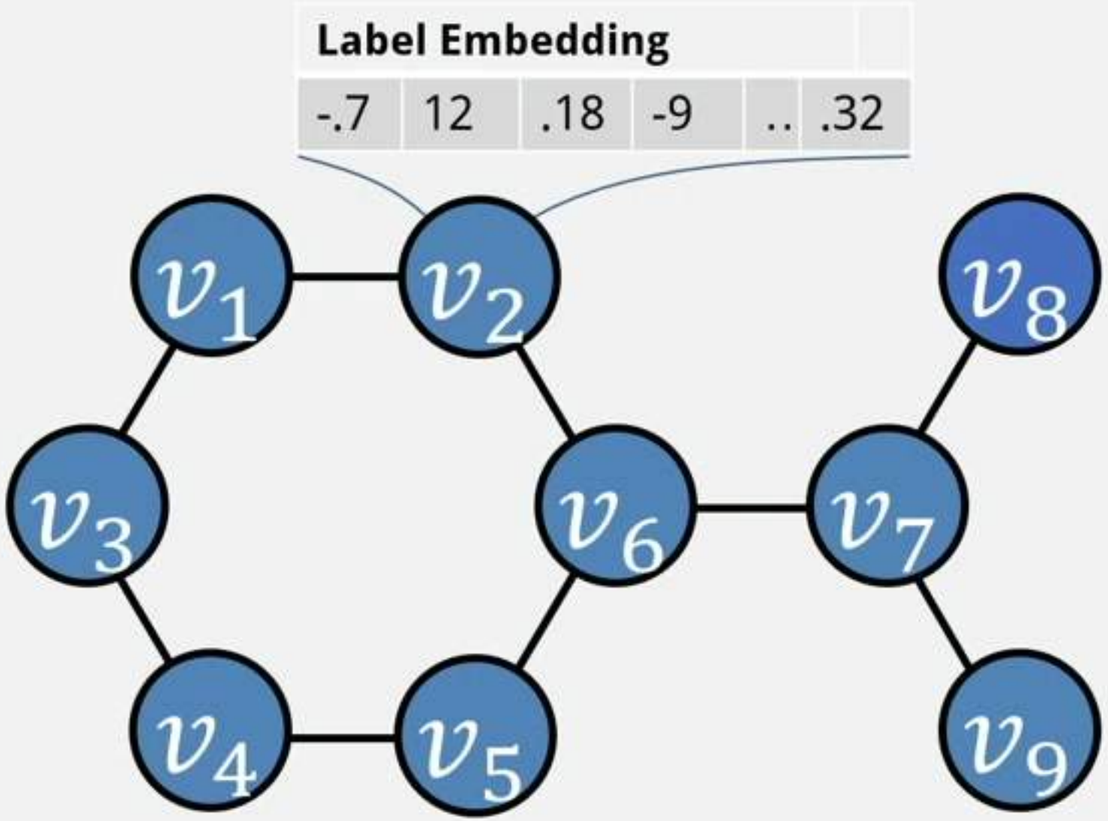

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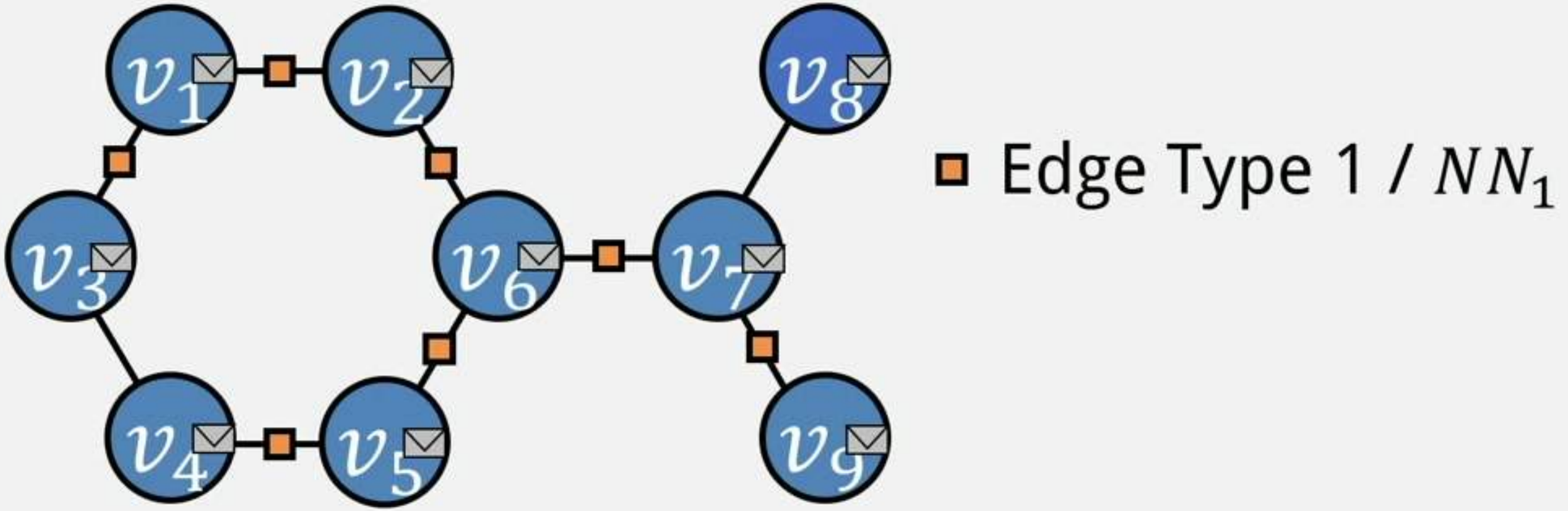

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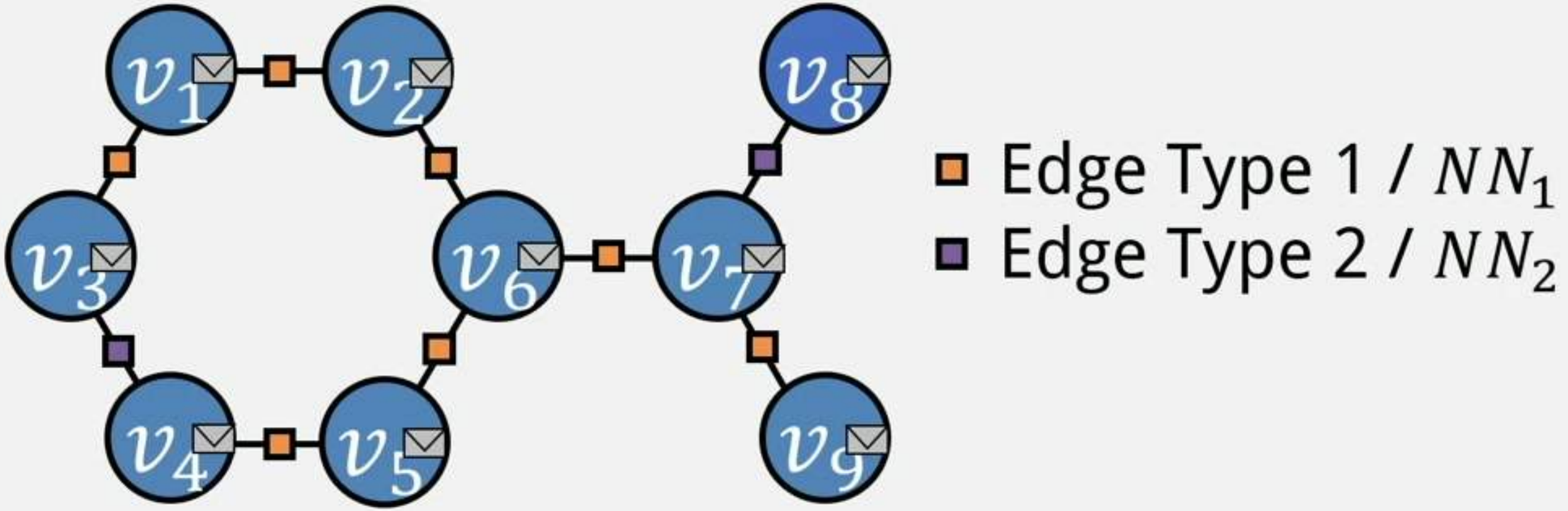
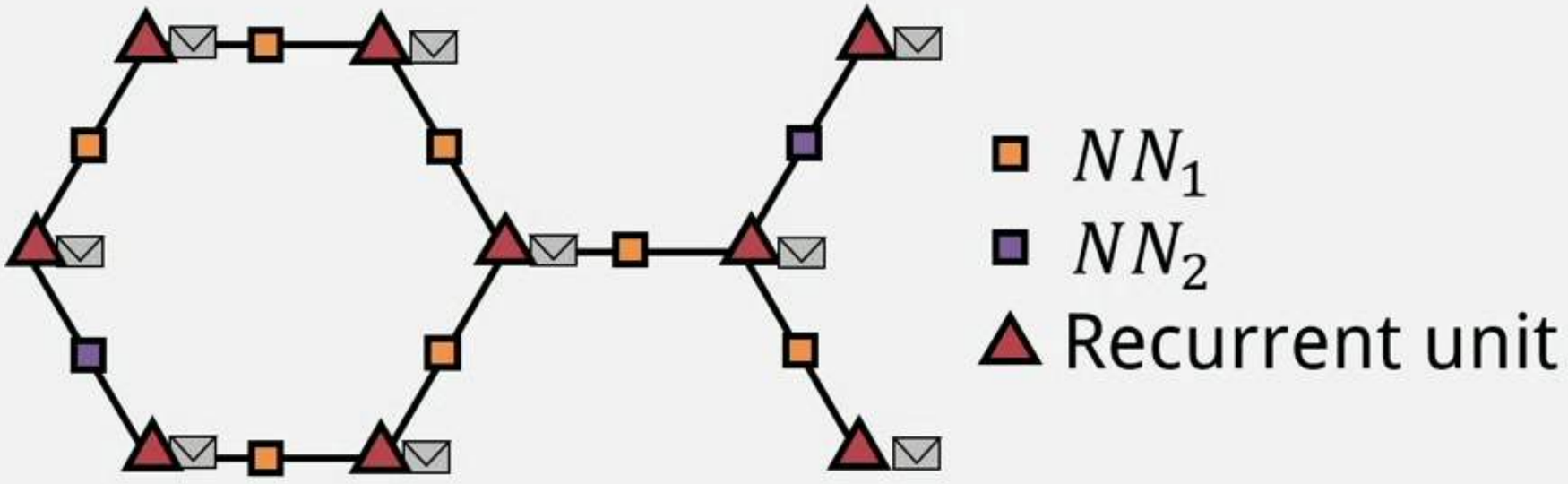


Graph Neural Networks: Propagation



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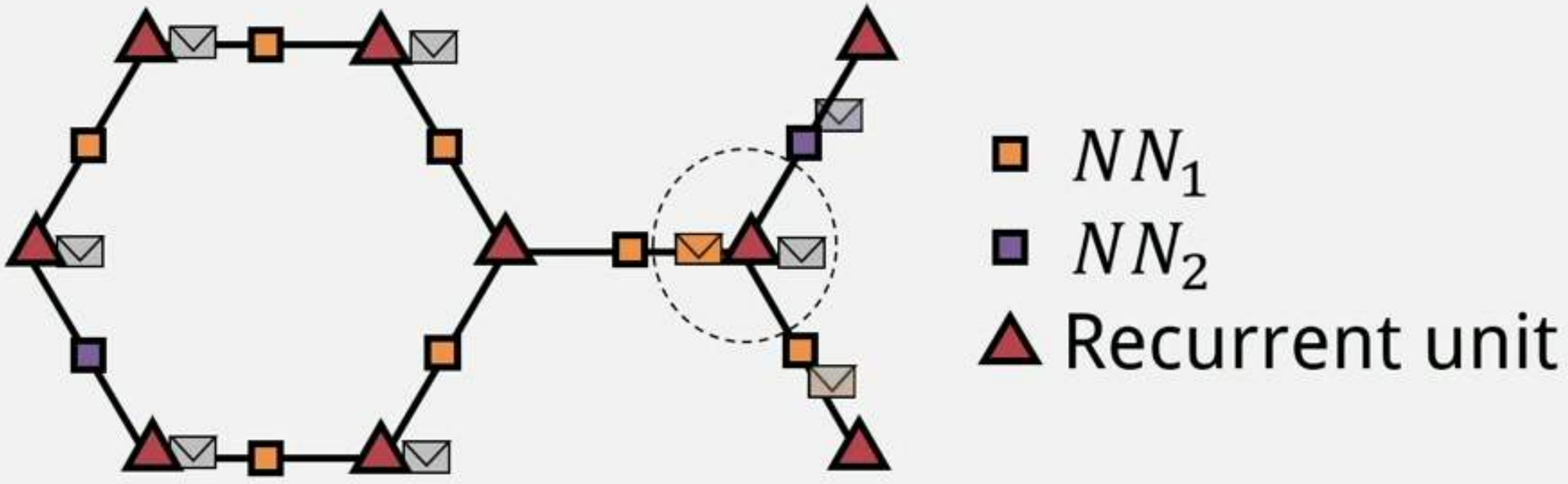

Expression Completion Task

```
int methParamCount = 0;
if (paramCount > 0) {
  IParameterTypeInformation[] moduleParamArr =
    GetParamTypeInformations(Dummy.Signature, paramCount);
  methParamCount = moduleParamArr.Length;
}
if (                                          ) {
  IParameterTypeInformation[] moduleParamArr =
    GetParamTypeInformations(Dummy.Signature,
                             paramCount - methParamCount);
}
```

Expression Completion Task

Code Context

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"Classic" Graph Neural Network

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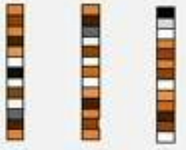
"Classic" Graph Neural Network

Hole Representation

In-Context Variable Representations



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if (                                    ) {
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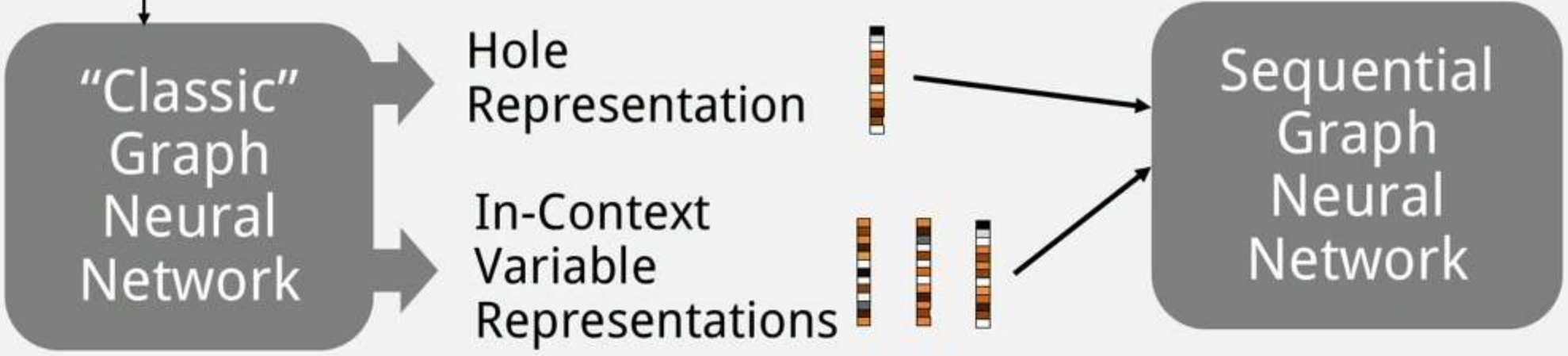
    GetParamTypeInformations(Dummy.Signature,
                             paramCount - methParamCount);
}
```

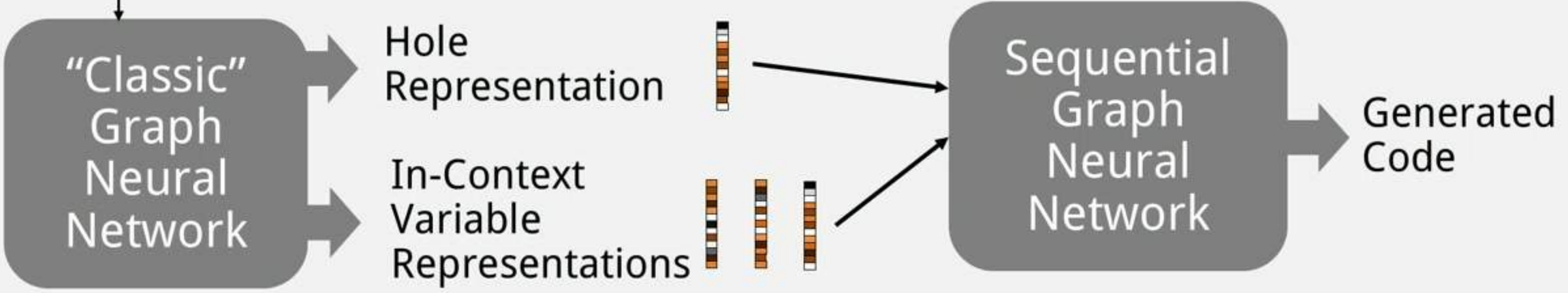
Code Context



Expression Completion Task

```
int methParamCount = 0;
if (paramCount > 0) {
  IParameterTypeInformation[] moduleParamArr =
    GetParamTypeInformations(Dummy.Signature, paramCount);
  methParamCount = moduleParamArr.Length;
}
if ( paramCount > methParamCount ) {
  IParameterTypeInformation[] moduleParamArr =
    GetParamTypeInformations(Dummy.Signature,
                             paramCount - methParamCount);
}
```

Code Context



Sequential Graph Neural Network

[Brockschmidt et al., 2018]

Expression

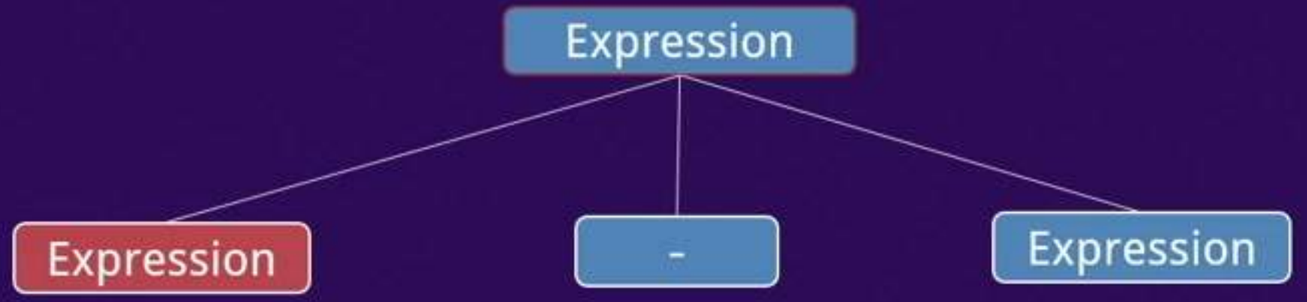
Variables in Scope

`i`

`j`

Sequential Graph Neural Network

[Brockschmidt et al., 2018]



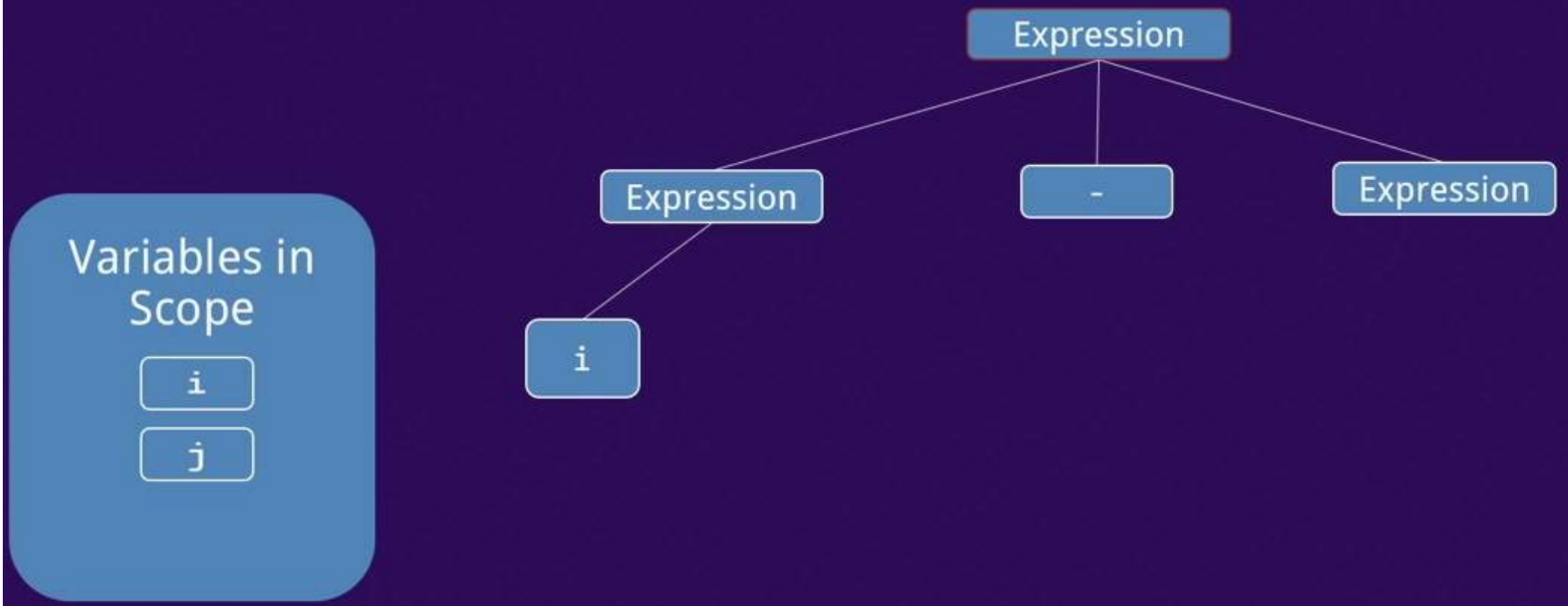
Variables in Scope

`i`

`j`

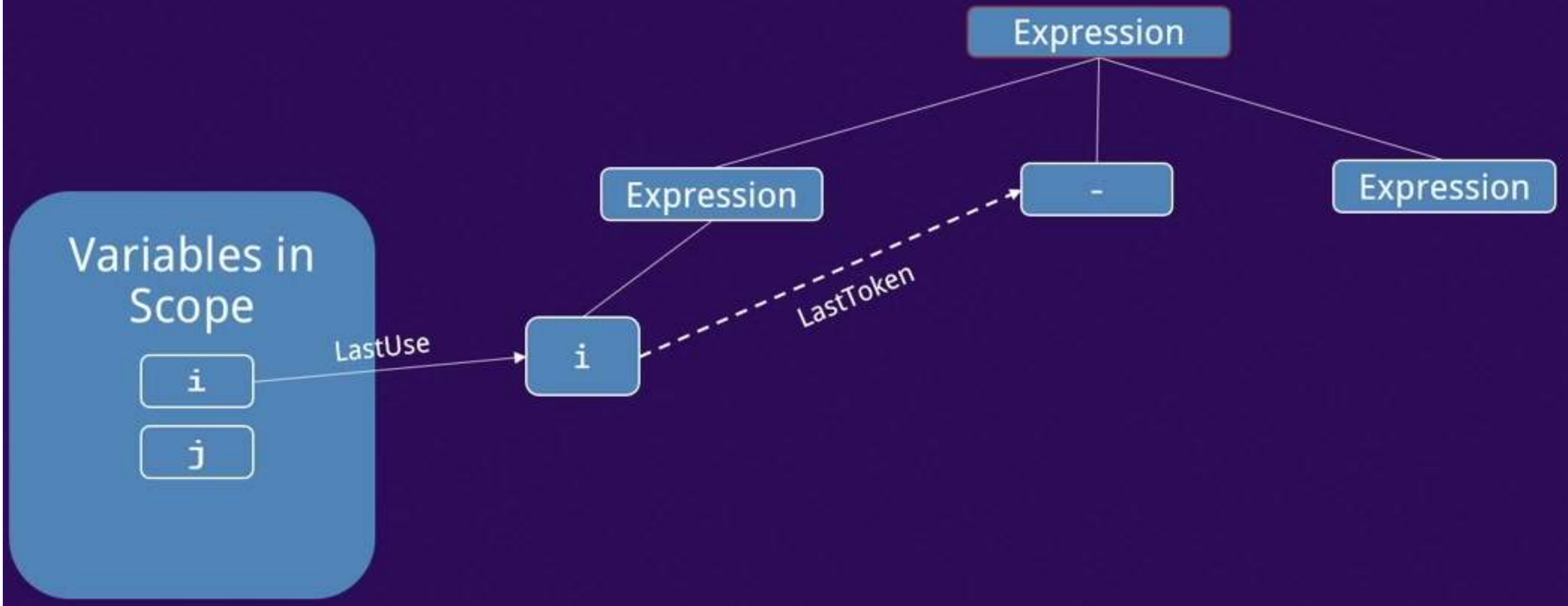
Sequential Graph Neural Network

[Brockschmidt et al., 2018]



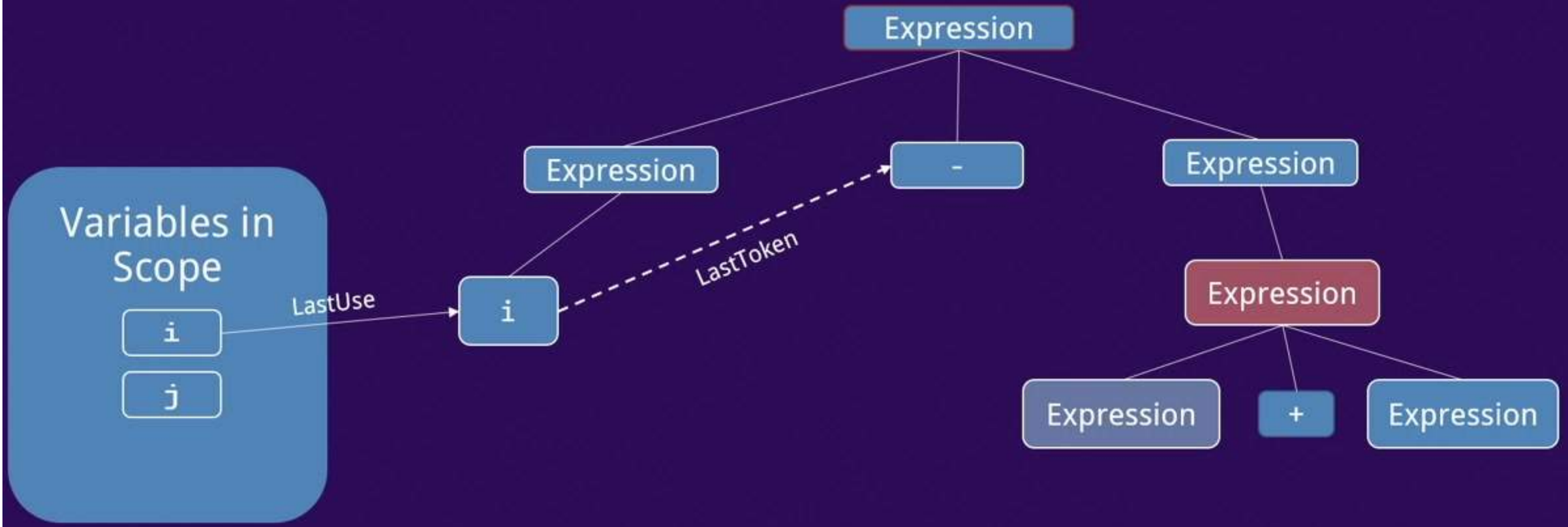
Sequential Graph Neural Network

[Brockschmidt et al., 2018]



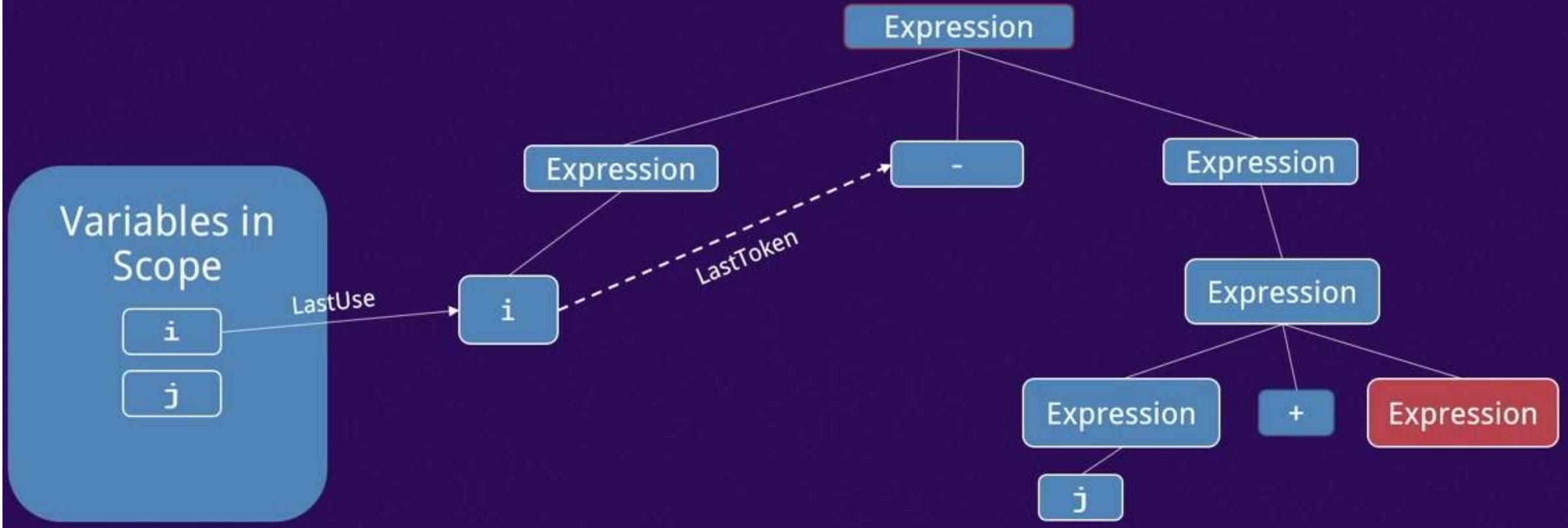
Sequential Graph Neural Network

[Brockschmidt et al., 2018]



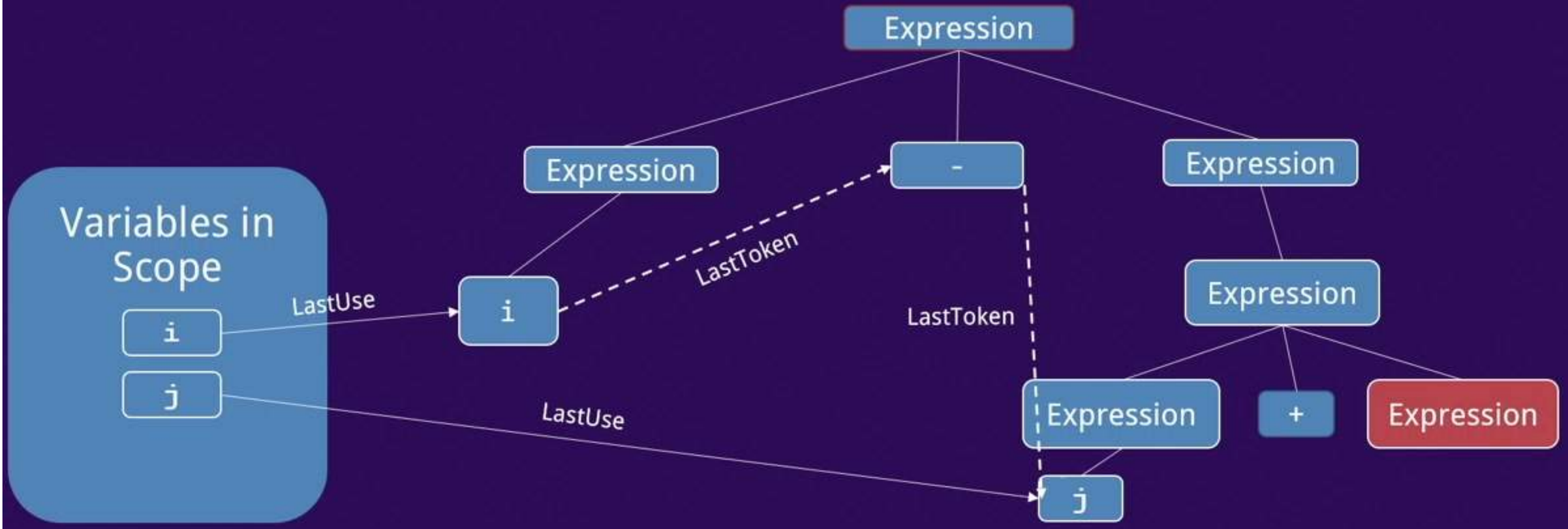
Sequential Graph Neural Network

[Brockschmidt et al., 2018]



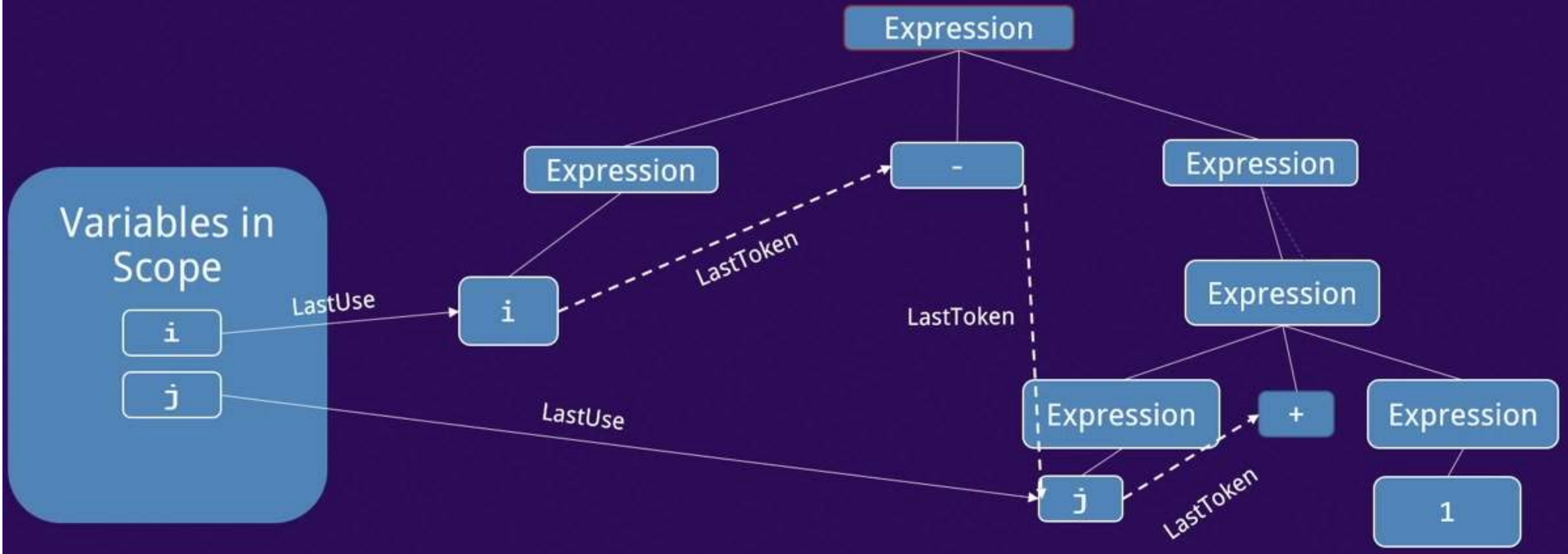
Sequential Graph Neural Network

[Brockschmidt et al., 2018]



Sequential Graph Neural Network

[Brockschmidt et al., 2018]



Examples

```
int methParamCount = 0;
if (paramCount > 0) {
  IParameterTypeInformation[] moduleParamArr =
    GetParamTypeInformations(Dummy.Signature, paramCount);
  methParamCount = moduleParamArr.Length;
}
if ( paramCount > methParamCount ) {
  IParameterTypeInformation[] moduleParamArr =
    GetParamTypeInformations(Dummy.Signature,
                             paramCount - methParamCount);
}
```

$\mathcal{G} \rightarrow \mathcal{NAG}$:

`paramCount > methParamCount` (34.4%)

`paramCount == methParamCount` (11.4%)

`paramCount < methParamCount` (10.0%)

```
caretPos--;
if (caretPos < 0) {
   caretPos = 0;
}

int len = inputString.Length;
if (caretPos >= len) {
   caretPos = len - 1;
}
```

$\mathcal{G} \rightarrow \mathcal{NAG}$:

`len++` (33.6%)

`len-1` (21.9%)

`len+1` (14.6%)

```
char character = originalName[i];
if ( character == '<' ) {
   ++startTagCount;
   builder.Append('`');
} else if (startTagCount > 0) {
   if (character == '>') {
      --startTagCount;
   }
```

$\mathcal{G} \rightarrow \mathcal{NAG}$:

`character == UNK_CHAR_LITERAL` (75.5%)

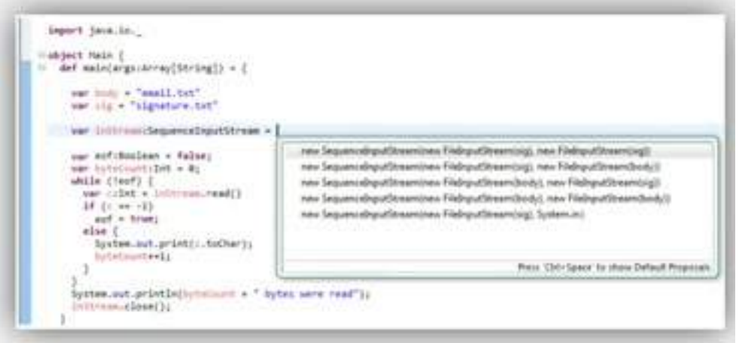
`character == '` (2.6%)

`character != 'UNK_CHAR` (2.5%)

Application: Code generation

Program context/template

Programming language



Further reading

Gulwani, S., Polozov, O., and Singh, R. (2017). Program synthesis. *Foundations and Trends in Programming Languages*, 4(1-2), 1-119.

Microsoft PROSE SDK. https://microsoft.github.io/prose/

Bornholt, J. Program synthesis explained. https://homes.cs.washington.edu/~bornholt/post/synthesis-explained.html

Polozov, O. Program Synthesis in 2017-18. https://alexpolozov.com/blog/program-synthesis-2018/

Solar-Lezama, A. The Sketch Programmers Manual.

Takeaways

- Program synthesis = Language + Spec + Search algorithm
- For PBE, enumerative/deductive search ensures correctness
  - Performance improved using neural-guided search
- For other specs (language, context), use graph-based or recurrent neural networks
  - Ensure correctness using execution guidance & program structure
- Solicit or learn hints: sketches, grammars, ranking functions
- Make use of existing frameworks: PROSE, Sketch, Rosette