Analyzing Software using Deep Learning

Lecture 5: Name-based Program Analysis

Prof. Dr. Michael Pradel

Software Lab, TU Darmstadt

Plan for Today

- **Name-based bug detection**

  Based on ”Deep Learning to Find Bugs” by Pradel and Sen, 2017

- **Predicting meaningful identifier names**

  Based on ”Context2Name: A Deep Learning-Based Approach to Infer Natural Variable Names from Usage Contexts” by Bavishi et al., 2018

Focus: Natural Language in Code

Source code contains natural language information

Example:

```
filteredNames = filter(userNames);
sortedNames = sort(filteredNames);
printToScreen(sortedNames);
```

Focus: Natural Language in Code

Source code contains natural language information

Example:

```
a = b(c);
d = e(a);
f(d);
```

Focus: Natural Language in Code

Source code contains natural language information

Example:

```
filteredNames = filter(userNames);
sortedNames = sort(filteredNames);
printToScreen(sortedNames);
```

Identifiers convey the intended semantics

Challenges

Identifier names are informal

- Jargon instead of universal vocabulary
- Ambiguity in meaning

Identifiers names are diverse

- Abbreviations, e.g., message versus msg
- Meaningless names, e.g., a, b, c
- Compound names, e.g., LinkedList

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Great match with deep learning: Reasoning about probabilities

Name-based Bug Detection

Goal: Learn a bug detector that reasons about identifier names

Source code

Warnings

Motivating Example

What's wrong with this code?

```
function setPoint(x, y) { ... }


var x_dim = 23;
var y_dim = 5;
setPoint(y_dim, x_dim);
```

Motivating Example

What's wrong with this code?

```
function setPoint(x, y) { ... }

var x_dim = 23;
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```
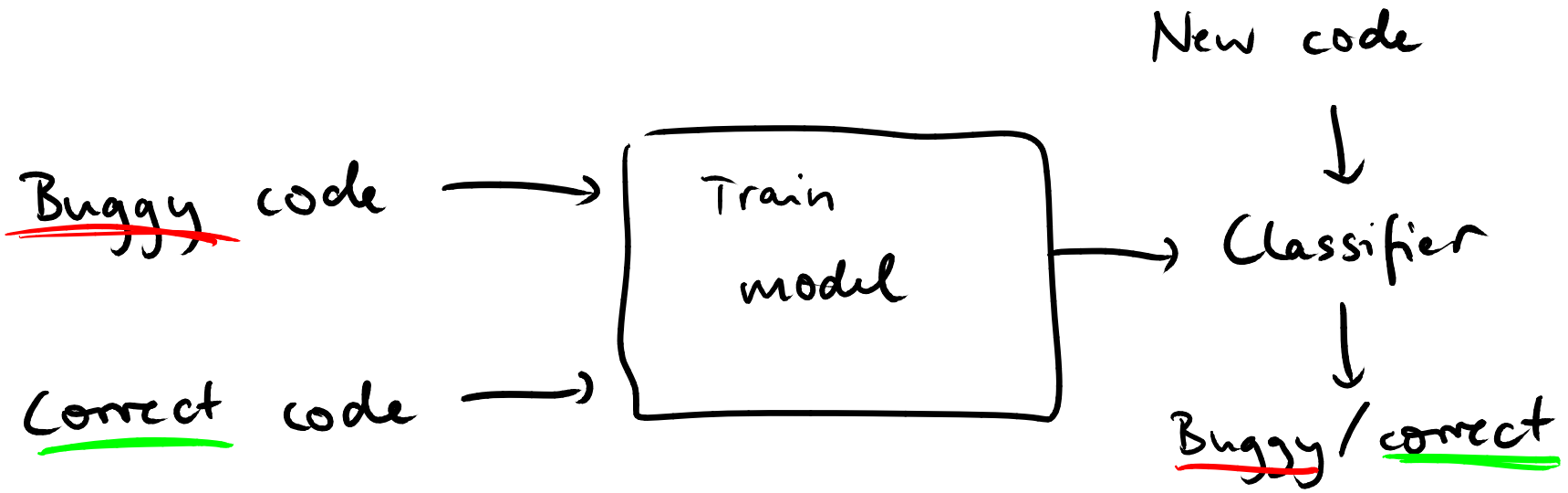

Incorrect order of arguments

Overview of DeepBugs

Idea: Train a model to distinguish correct from incorrect code



Challenge 1: Reason about Names

How to reason about identifier names?

Prior work: Lexical similarity

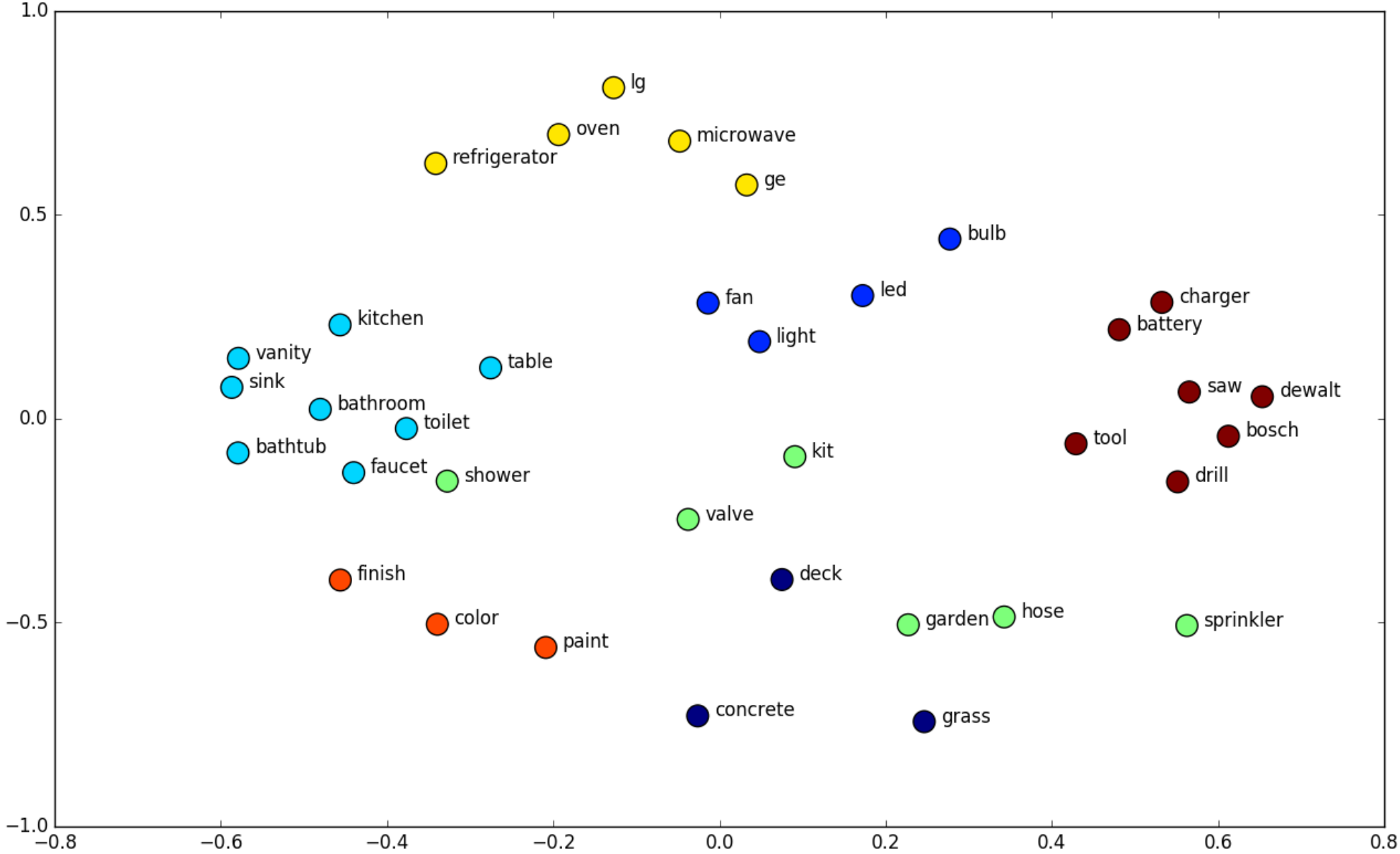
- `x` similar to `x_dim`

Want: Semantic similarity

- `x` similar to `width`
- `list` similar to `seq`

Word Embeddings

- **Known problem in natural language processing**
- **Word embeddings**
  - Continuous vector representation for each word
  - Similar words have similar vectors


lg
oven
microwave
refrigerator
ge
bulb
led
fan
charger
kitchen
battery
light
vanity
table
sink
saw
dewalt
bathroom
toilet
bosch
tool
bathtub
kit
faucet
shower
drill
valve
finish
deck
color
garden
hose
sprinkler
paint
concrete
grass
1.0
0.5
0.0
−0.5
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8

Word2Vec

- **State-of-the-art technique to learn word embeddings: Word2Vec**
- **Learn embeddings from context in which a word occurs**
  - ”You shall know a word by the company it keeps”
  - Context: Surrounding words in sentences

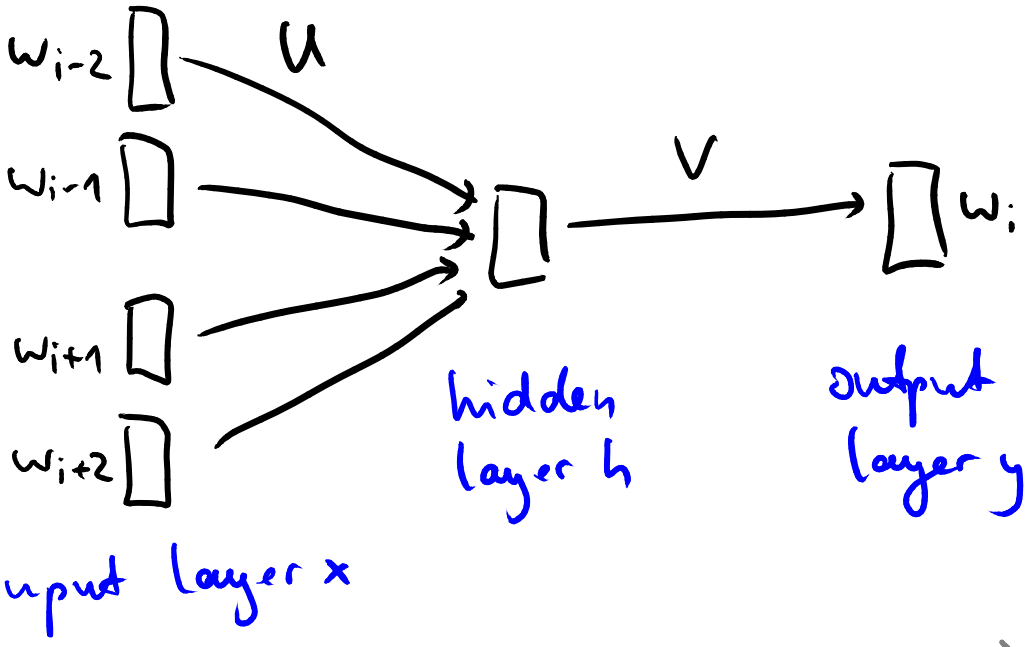
Word 2 Vec: Overview

- Given: Sequences of words
  - ↳ E.g., w_1 w_2 w_3 w_4 w_5 w_6
- Represent each word via one-hot encoding
  - ↳ $w_1 \rightarrow$ 00001000
  - $w_2 \rightarrow$ 01000000
  - length = size of vocabulary (large!)

  } Based on fixed vocabulary of frequent words
- Learn shorter, semantics-encoding representation of w_i from k surrounding words (= context)
  - ↳ E.g., k=4: w_3 has context w_1, w_2, w_4, w_5

Variant 1: Continuous Bag of Words (CBOW)

Predict word from context



(here: context of size $k = 4$)

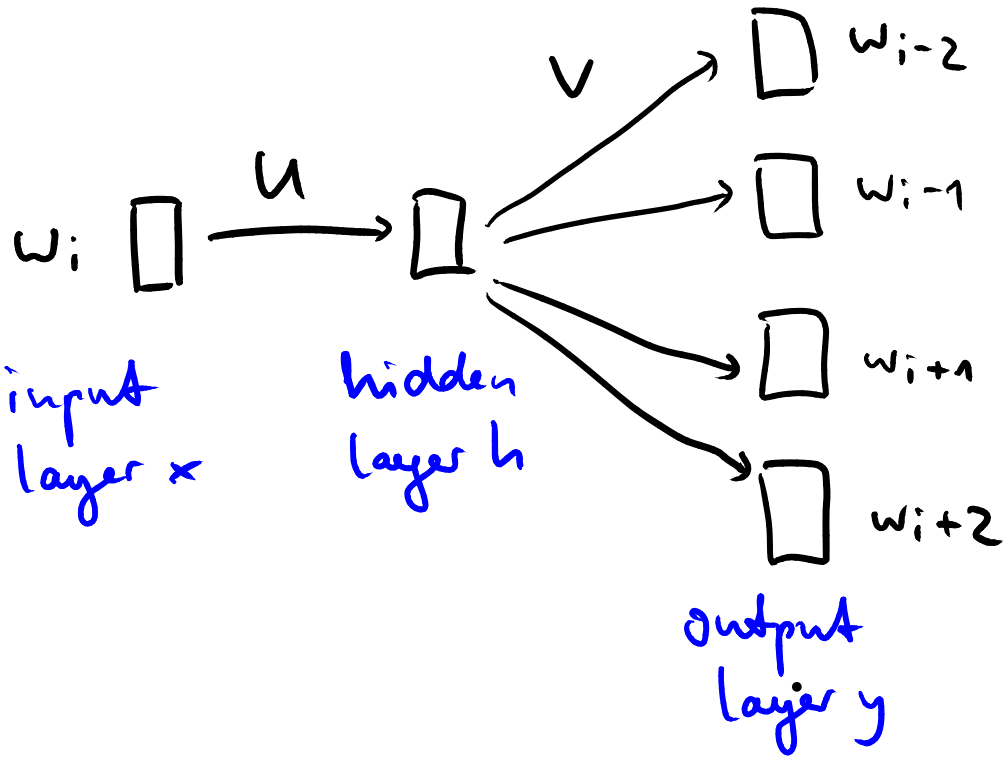
$$h = \frac{1}{k} \cdot U \cdot \left(\sum_{j} w_j \right)$$

j: $i - \frac{k}{2}, \ldots, i + \frac{k}{2}$ (without i)

$$y = \text{softmax}(V \cdot h)$$

Variant 2: Skip-gram

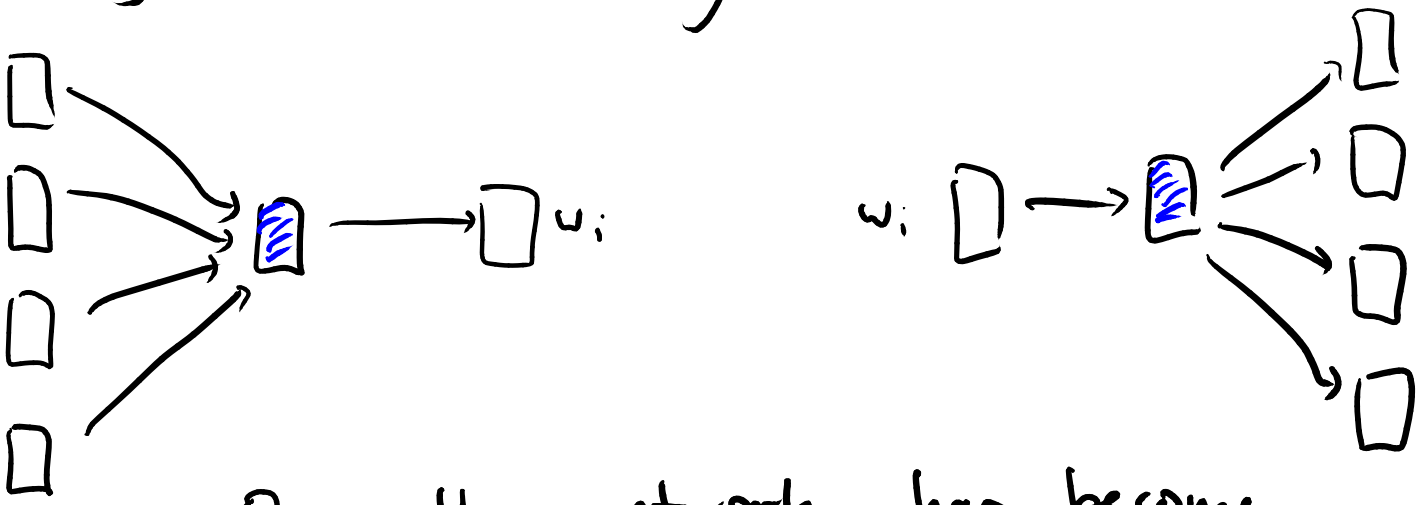
Predict context from word



$$h = U \cdot x$$

$$y = \text{softmax}(V \cdot h)$$

Getting the Embedding



Once the network has become good at its task (through training):

Use hidden layer as embedding for word w_i

Quiz: Word2Vec

Consider a sequence of words ”the quick brown fox jumps over the lazy dog”. Which of the following are correct?

- Word2Vec learns an embedding for the entire sentence.
- Word2Vec learns an embedding for each individual word.
- Skip-gram learns to predict how likely it is that ”quick” and ”brown” occur around ”fox”.
- CBOW learns to predict the probability that ”over” occurs in the context of ”jumps” and ”the”.

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Word2Vec for Source Code

Natural language		Programming language
Sentences	⇢	Program
Words	⇢	Tokens

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```
function setPoint(x, y) { ... }


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```

Word2Vec for Source Code

Natural language	Programming language
Sentences	Program
Words	Tokens

```
function setPoint(x, y) { ... }

var x_dim =
var y_dim =
setPoint(y_dim, x_dim);
```

Context of `x`:

`function - setPoint - ( - , - y - )`

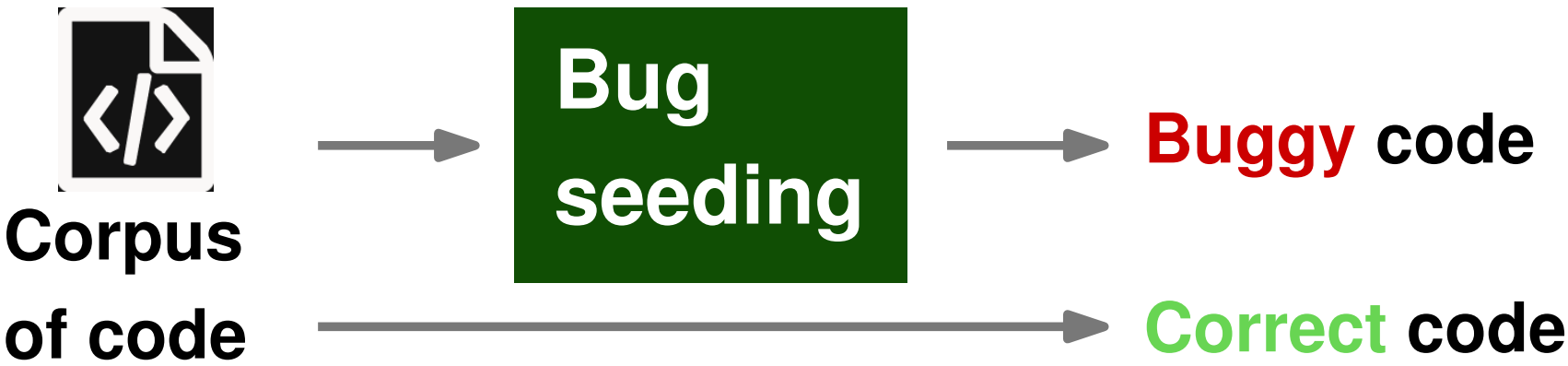
Challenge 2: Training Data

Effective learning requires millions of examples

- To learn a bug detector:
  Need both correct and buggy code examples
- Most available code is correct: Easy to get correct examples
- How to get many examples of buggy code?
  - Want: Buggy due to the same bug pattern

Generate Buggy Code

Idea: **Artificially introduce bugs**



Example

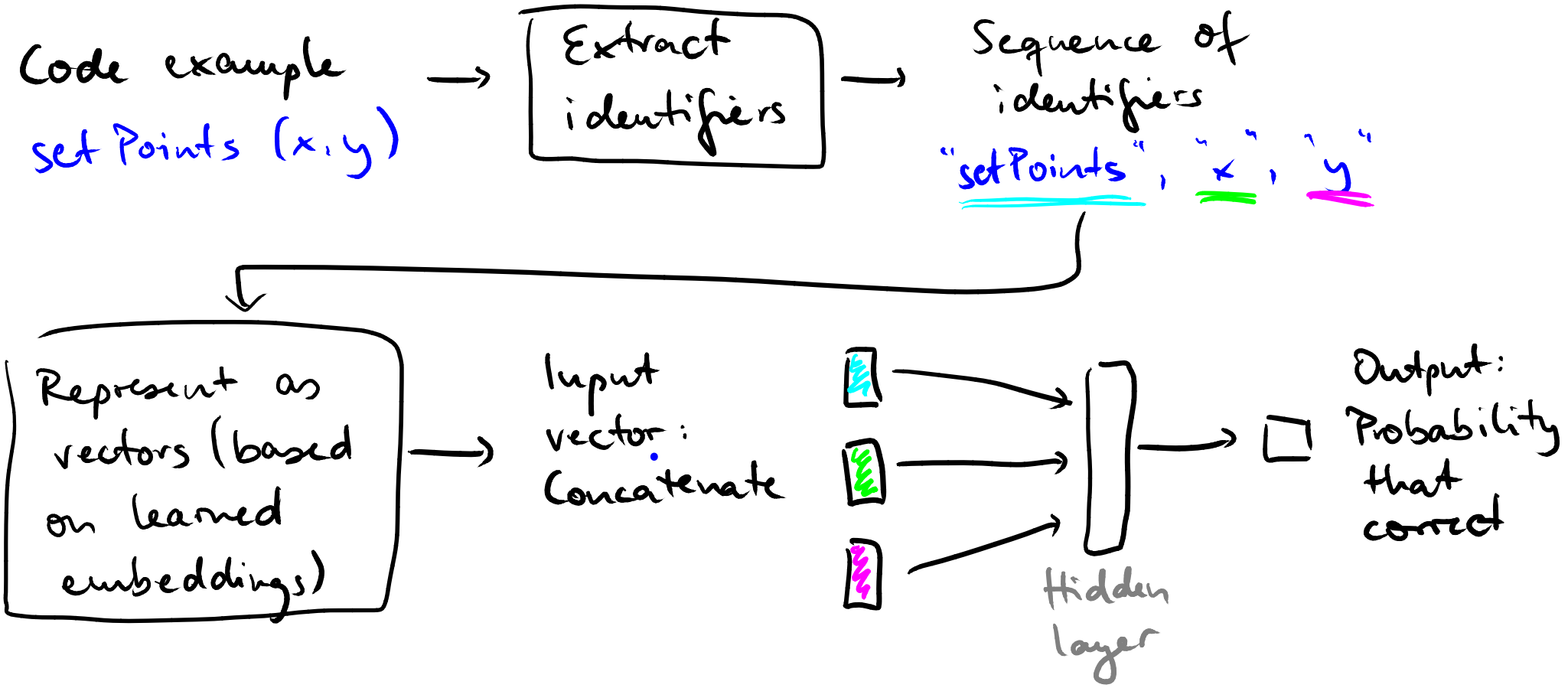
For swapped function arguments:

- Visit every function call with ≥ 2 arguments
- Positive example: Original order of arguments
- Negative example: Swap first two arguments

```
setPoint(x, y);
```

```
setPoint(y, x);
```

DeepBugs: Putting Everything Together



Beyond Swapped Arguments

Same idea works for other bug patterns

- Assignments of incorrect values
- Incorrect binary operators
- Swapped operands of binary operations

Beyond Swapped Arguments

Same idea works for other bug patterns

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```
var callback = function() { .. }
```

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Beyond Swapped Arguments

Same idea works for other bug patterns

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"abc"

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Same idea works for other bug patterns

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var callback = function() { ... }
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"abc"

- Incorrect binary operators

```
if (x == undefined) ...
```

- Swapped operands of binary operations

Beyond Swapped Arguments

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var callback = function() { ... }
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>

- Swapped operands of binary operations

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- Assignments of incorrect values

```
                                                  "abc"
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              >
if (x == undefined) ...
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- Swapped operands of binary operations

```
bytes[i + 1] >> 4
```

Beyond Swapped Arguments

Same idea works for other bug patterns

- Assignments of incorrect values

```
                                                  "abc"
var callback = function() { ... }
```

- Incorrect binary operators

```
                 >
if (x == undefined) ...
```

- Swapped operands of binary operations

```
          4 >> bytes[i + 1]
bytes[i + 1] >> 4
```

How Well Does it Work?

- **Evaluation with 69 million lines of JavaScript and three bug detectors**
- **Results**
  - 89%–95% accuracy
  - 102 real-world bugs with 68% true positive rate
  - Less than 20 milliseconds per checked file

Examples of Bugs

```
// From Angular.js
browserSingleton.startPoller(100,
    function(delay, fn) {
        setTimeout(delay, fn);
    });
```

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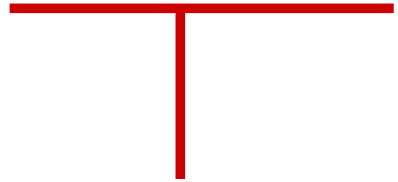

First argument must be callback function

Examples of Bugs

```
// From DSP.js
for(var i = 0; i<this.NR_OF_MULTIDELAYS; i++){
  // Invert the signal of every even multiDelay
  mixSampleBuffers(outputSamples, ...,
      2%i==0, this.NR_OF_MULTIDELAYS);
}
```

Examples of Bugs

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// From DSP.js
for(var i = 0; i<this.NR_OF_MULTIDELAYS; i++){
  // Invert the signal of every even multiDelay
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```

Should be `i%2==0`

Plan for Today

- **Name-based bug detection**

  Based on ”Convolutional Neural Networks over Tree Structures for Programming Language Processing” by Mou et al., 2016

- **Predicting meaningful identifier names** 

  Based on ”Context2Name: A Deep Learning-Based Approach to Infer Natural Variable Names from Usage Contexts” by Bavishi et al., 2018

Predicting Natural Names

- **Goal:**
  Predict natural names for variables

- **Usage scenario:**
  Understand minified code

Motivating Example

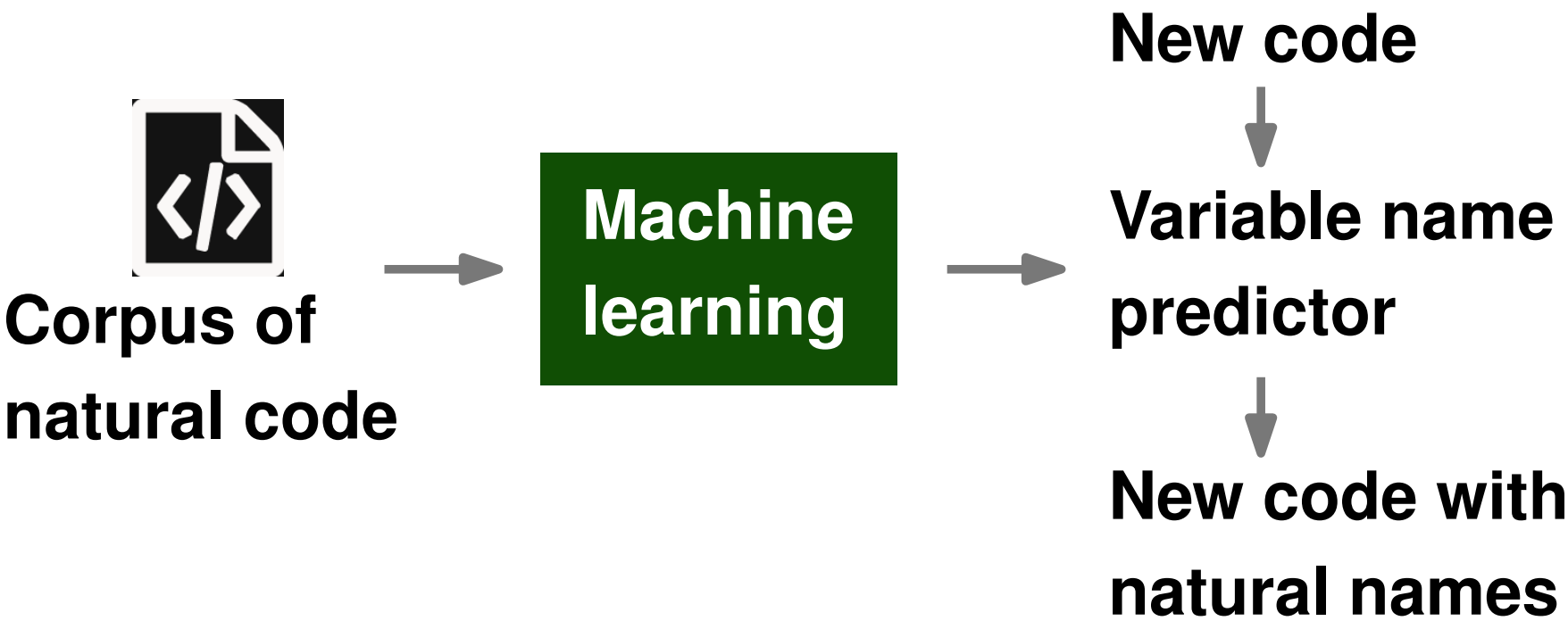
```
function http(e, n, t, s, i, f) {
  s = JSON.stringify(s);
  e.open(t, n, i);
  if (i) {
    e.onreadystatechange = function() {
      if (e.status == 200) {
        f(e.responseText);
      }
    }
  }
  ...
}
```

Motivating Example

```
function http(req, url, method, s, i, f) {
  body = JSON.stringify(body);
  req.open(method, url, async);
  if (async) {
    req.onreadystatechange = function() {
      if (req.status == 200) {
        response(req.responseText);
      }
    }
  }
  ...
}
```

Overview of Context2Name

Train a model to predict a suitable name from the way a variable is used



Challenge 1: Usage as a Vector

How to represent the usage of a variable as a compact vector?

```
function http(e, n, t, s, i, f) {
  s = JSON.stringify(s);
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    }
  }
  ...
}
```

Extracting Usage Contexts

- One usage context per occurrence of each variable
- Context = Tokens before & after occurrence

```
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  e.open(t, n, i);
  if (i) {
    e.onreadystatechange = function() {
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```
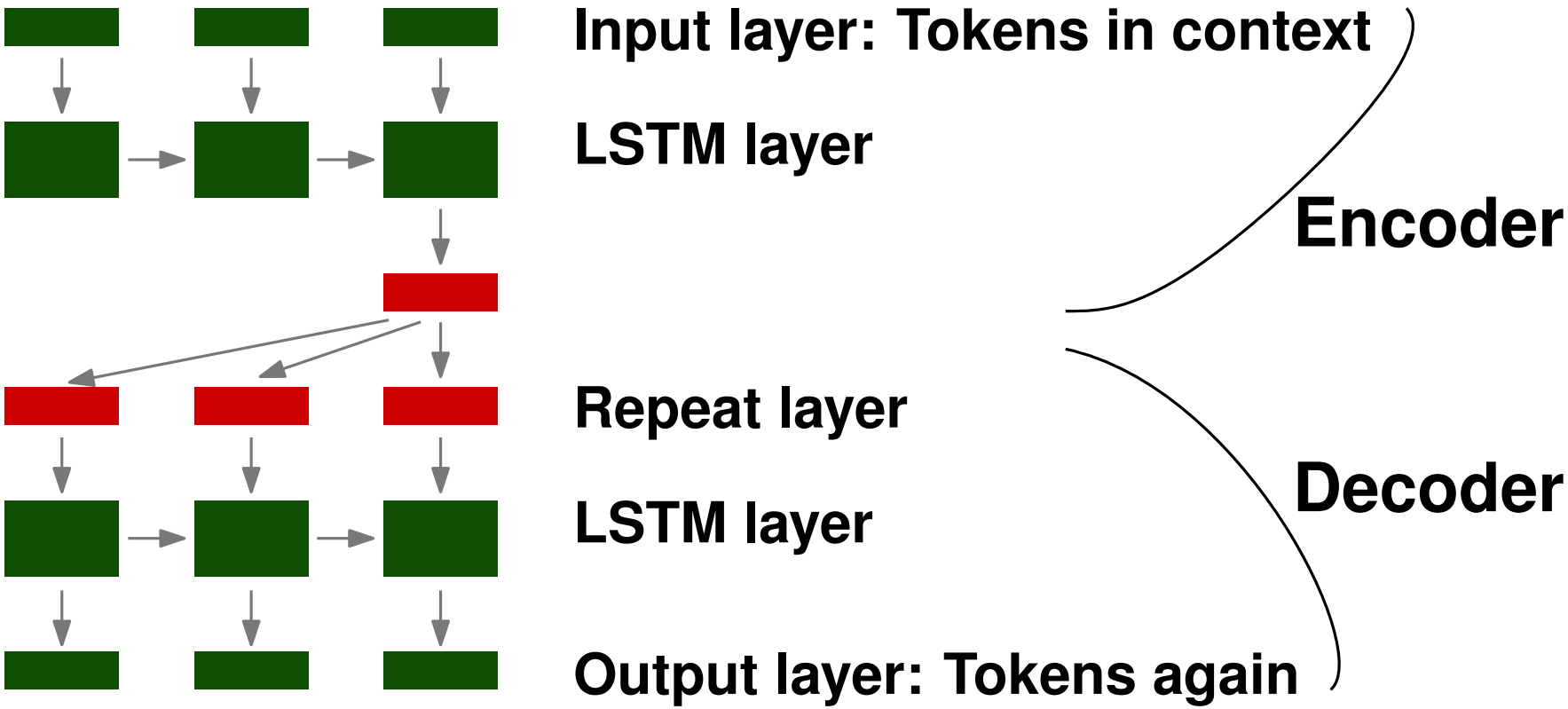

Compressing Usage Vectors

Compress usage contexts via auto-encoder



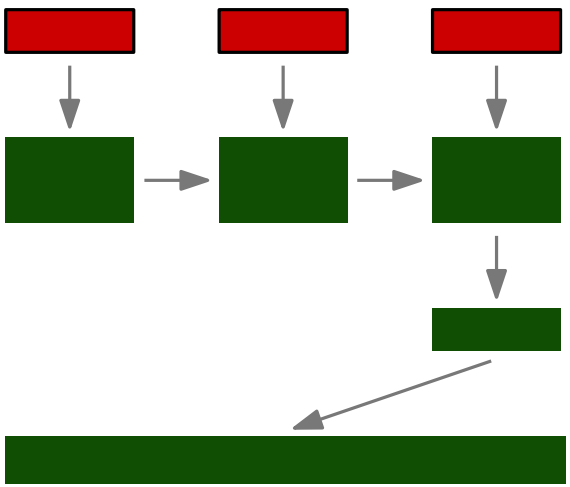
Challenge 2: Predict Name

Given: Representation of usage contexts

How to predict a suitable name?

Predicting Variable Names

- Learn from corpus of natural code
- Recurrent neural network



Input layer: Sequence of contexts

LSTM layer

Output: Names (length=60000)

Replace Names in Code

- For each minified name, **select name** predicted with **maximum probability**
- **Consistently replace** all occurrences of the variable

```
function http(e, n, t, s, i, f) {
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Replace Names in Code

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  s = JSON.stringify(s);
  req.open(t, url, i);
  if (i) {
    ...
  }
  ...
}
```

How Well Does it Work?

- **Evaluation with 69 million lines of JavaScript**
- **Results**
  - Correctly predicts 48% of all minified names
  - Complements existing non-deep learning approaches: 5.3% additional names
  - Prediction time: 2.9 milliseconds per name

Open Challenges

- **Name-based program analysis is in its infancy**
- **Many more problems to tackle**
  - Bug detection beyond the currently covered bug patterns
  - Suggest better identifier names than those chosen by developers
  - Classify code, e.g., to identify authors

Summary

Name-based program analysis

- Use natural language information in source code
- Reason about identifiers based on learned embeddings
- Useful for bug detection and to de-obfuscate source code