Analyzing Software using Deep Learning

Lecture 2:
RNN-based Code Completion and Repair

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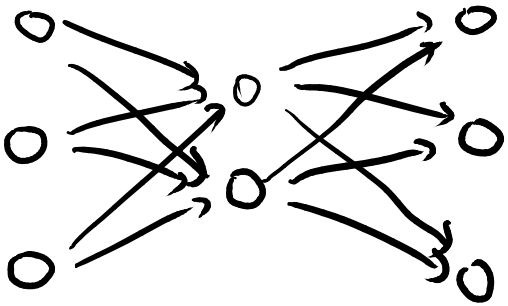
Plan for Today

- **Deep learning basics**
  - Finish up last lecture
- **Recurrent neural networks (RNNs)** ←
- **Code completion with statistical language models**

  Based on PLDI 2014 paper by Raychev et al.
- **Repair of syntax errors**

  Based on ”Automated correction for syntax errors in programming assignments using recurrent neural networks” by Bhatia & Singh, 2016

From Neurons to Layers

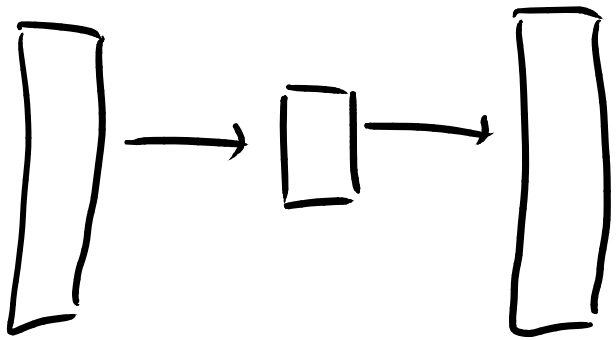


For every neuron:

$$\text{output} = f(w \cdot x + b)$$

x, f, b ... scalars, e.g. in $\mathbb{R}$

w .. vector, e.g., in $\mathbb{R}^n$



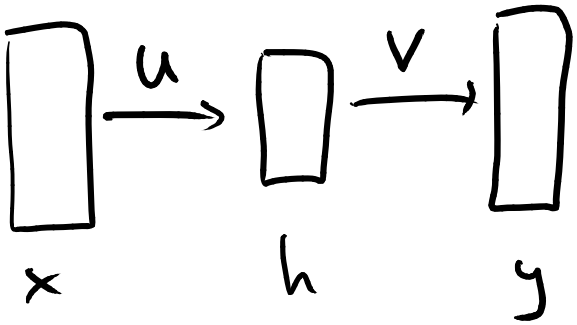
For each layer:

$$\text{output} = f(W \cdot x + b)$$

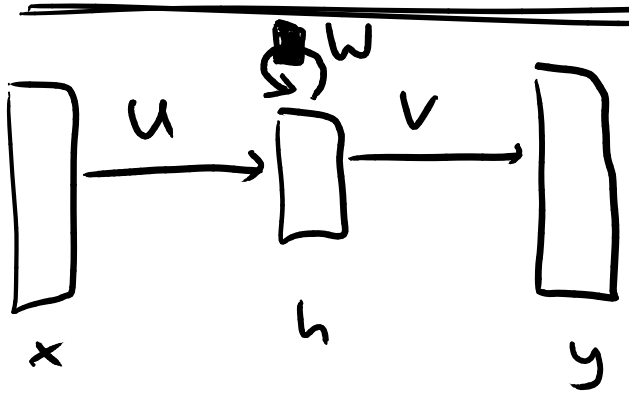
x, f, b.. vector, e.g., in $\mathbb{R}^n$

W.. matrix, e.g., in $\mathbb{R}^{m \times n}$

Feedforward networks



Recurrent networks



x, h, y .. input layer, hidden layer, output layer

U, V, W .. weight matrices

$\longrightarrow$ ... function

$\xrightarrow{\square}$ .. function with delay of single time step

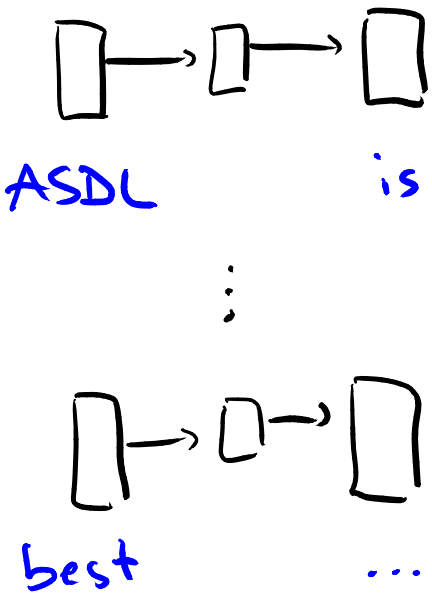
→ useful for representing <u>sequences</u> of inputs & outputs

→ store information about previous inputs

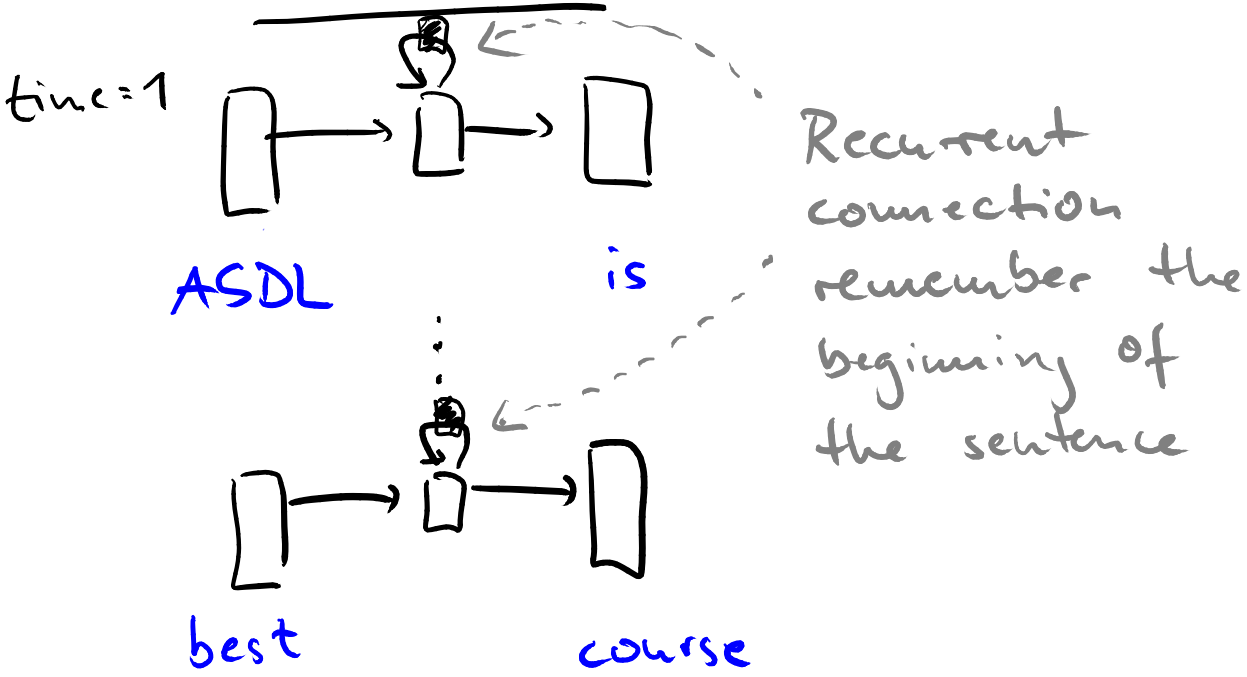
Example: Predict next word in sentence

ASDL is the best .... (course)

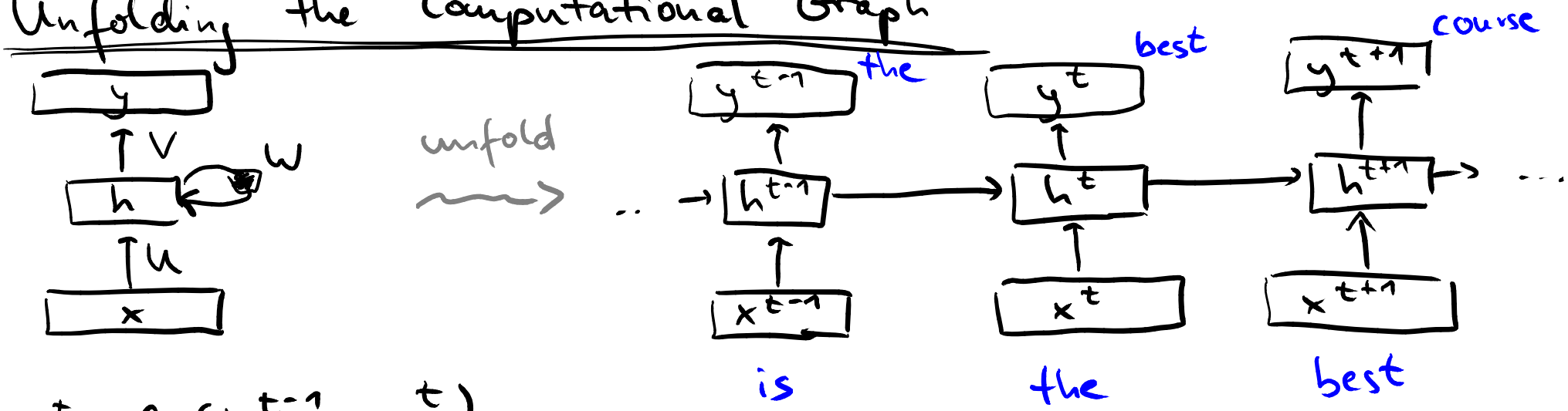
Feedforward



Recurrent



Unfolding the Computational Graph

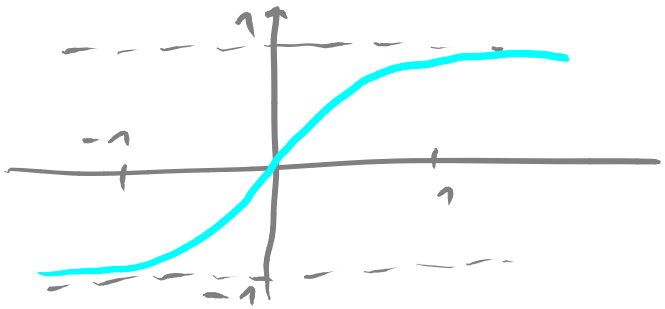


$$h^t = f(h^{t-1}, x^t)$$

$$y^t = f(h^t)$$

e.g. $h^t = \tanh(W \cdot h^{t-1} + U \cdot x^t + b)$

e.g. $y^t = \text{softmax}(V \cdot h^t + c)$



Softmax Function

- Goal: Interpret output vector as a probability distribution
- "Squashes" vector of k values $\in \mathbb{R}$ into vector of k values $\in [0, 1]$ that sum up to 1
- Definition:

  $\sigma(y)_j = \dfrac{e^{y_j}}{\sum_i^k e^{y_i}}$ for $j = 1, .., k$
- Example:

  $\sigma([1, 2, 3, 4, 1, 2, 3]) =$

  $[0.024, 0.064, 0.175, 0.475, 0.024, 0.064, 0.175]$

Quiz

Which of the following vectors may be the output of the softmax function?

1.) $y = [0.0, 0.0, 0.0, 0.0]$

2.) $y = [0.0, 0.25, 0.25, 0.5]$

3.) $y = [0.0, 1.0, 0.0, 0.0]$

4.) $y = [0.1, 0.1, 0.2, 0.3]$

Quiz

Which of the following vectors may be the output of the softmax function?

1.) $\cancel{y = [0.0, 0.0, 0.0, 0.0]}$ **sum is not 1**

2.) $y = [0.0, 0.25, 0.25, 0.5]$

3.) $y = [0.0, 1.0, 0.0, 0.0]$

4.) $\cancel{y = [0.1, 0.1, 0.2, 0.3]}$ **sum is not 1**

Applications of RNNs

Useful for tasks where the input (and maybe also the output) is a sequence

Examples:

- Unsegmented connected handwriting recognition
- Machine translation of natural languages
- Video classification by frames
- Speech recognition
- Sentiment analysis of twitter messages

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Code Completion

- Given: Partial program with one or more holes
- Goal: Find suitable code to fill into the holes
- Basic variants in most IDEs
- Here: Fill holes with sequences of method calls
  - Which methods to call
  - Which arguments to pass

Example

```
SmsManager smsMgr = SmsManager.getDefault();
int length = message.length();
if (length > MAX_SMS_MESSAGE_LENGTH) {
  ArrayList<String> msgList =
      smsMgr.divideMsg(message);
  // hole H1
} else {
  // hole H2
}
```

Statistical Language Models

- Dictionary of words
- Sentences: sequences of words
- Model: Probability distribution over all possible sentences

Example: English

$Pr(\text{"hello world"}) > Pr.(\text{"world hello"})$

- Most basic model: Predict next word based on all previous words

$$Pr(s) = \prod_{i=1}^{m} Pr(w_i \mid h_{i-1}) \quad \text{where} \quad s = w_1 \cdot \ldots \cdot w_m$$

$$h_i = w_1 \cdot \ldots \cdot w_i .$$

Model-based Code Completion

- **Program code $\approx$ sentences in a language**
- **Code completion $\approx$ Finding the most likely completion of the current sentence**

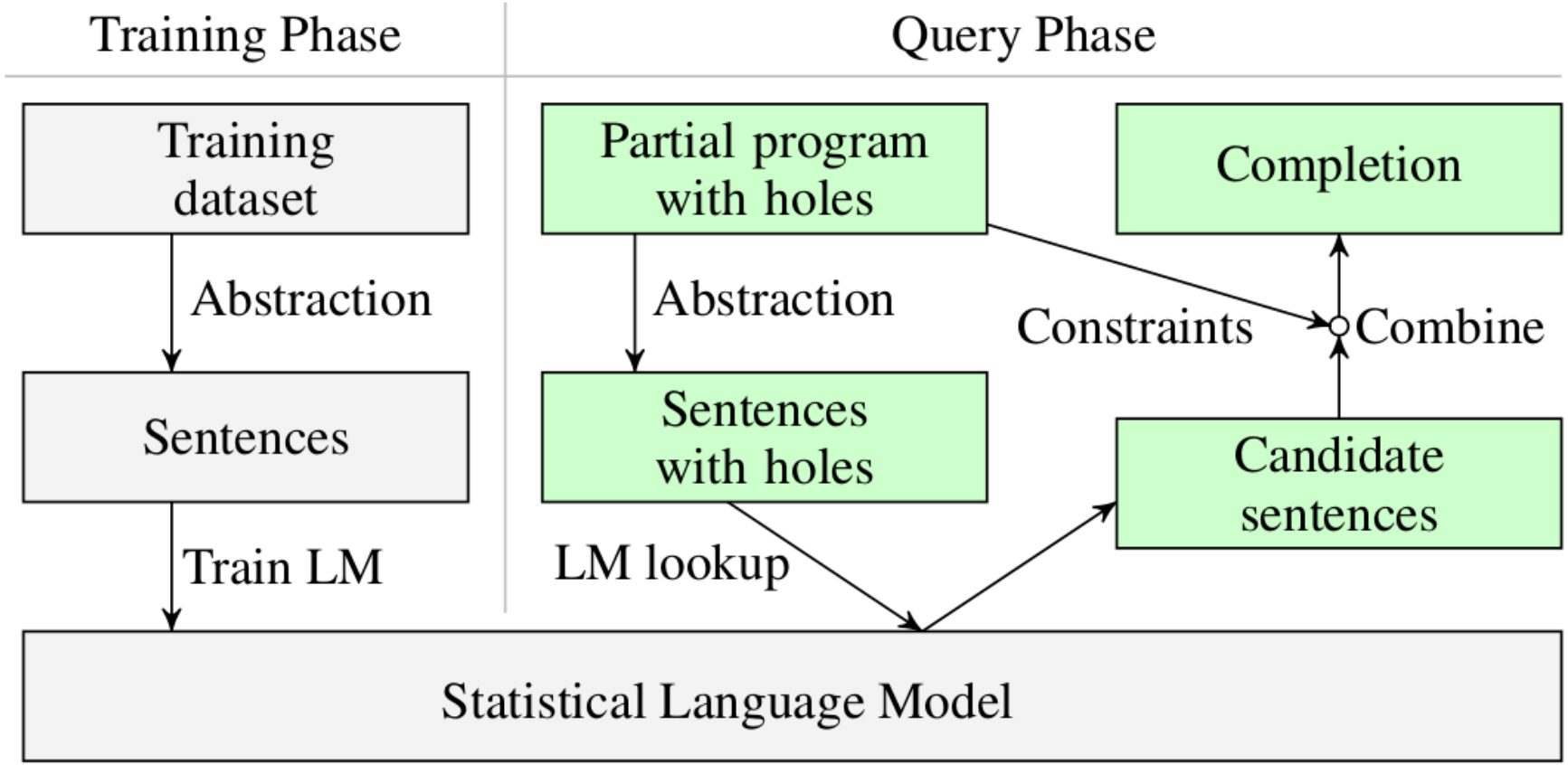
Model-based Code Completion

- **Program code $\approx$ sentences in a language**
- **Code completion $\approx$ Finding the most likely completion of the current sentence**

Challenges

- How to abstract code into sentences?
- What kind of language model to use?
- How to efficiently predict a completion

Overview of SLANG Approach



From ”Code Completion with Statistical Language Models”
by Raychev et al., 2014

n-gram Language Model

Problem of "all history" model: Training data may not contain anything about h_i

Idea: Next word depends on $n-1$ previous words

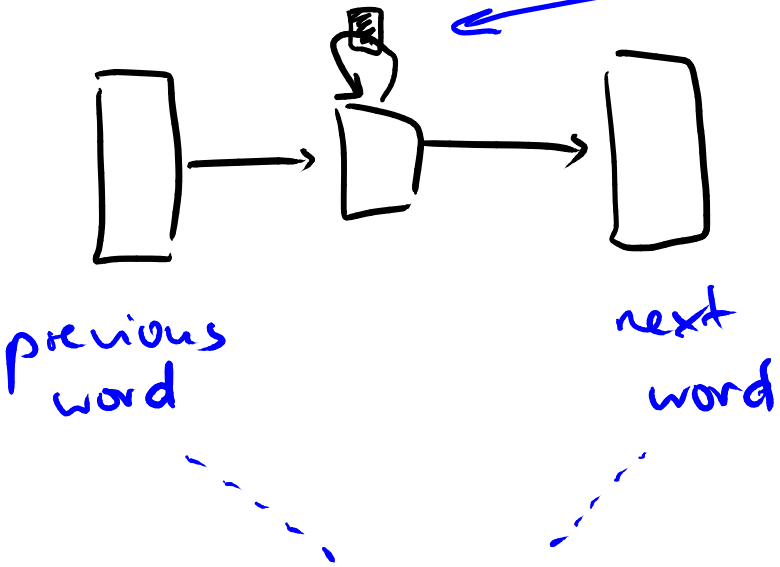
$$Pr(s) = \prod_{i=1}^{m} Pr(w_i \mid w_{i-(n-1)} \cdot \ldots \cdot w_{i-1})$$

Example: $Pr(\text{to} \cdot \text{be} \cdot \text{or} \cdot \text{not} \cdot \text{to} \cdot \text{be})$ $\quad n=3$

$$= Pr(\text{to} \mid \varepsilon) \cdot Pr(\text{be} \mid \text{to}) \cdot Pr(\text{or} \mid \text{to} \cdot \text{be}) \cdot \ldots \cdot Pr(\text{be} \mid \text{not} \cdot \text{to})$$

Probability of n-grams: Estimated from corpus of training examples

RNN-based Model



store information about (all) previous words

Encoded as vector: One-hot encoding

- Length = size of dictionary
- All values are zero except position of word set to one

Sequences of Method Calls

Abstracting code into sentences

- Method call $\approx$ word
- Sequence of method calls $\approx$ sentence
- Separate sequences for each object
- Objects can occur in call as base object, argument, or return value

Option 1: Dynamic Analysis

Execute program and observe each method call

Advantage:

- Precise results

Disadvantage:

- Only analyzes executed code

```
if (getInput() > 5) {  // Suppose always taken
  obj.foo();           // in analyzed execution
} else {
  obj.bar();  // Never gets analyzed
}
```

Option 2: Static Analysis

Reason about execution without executing the code

Advantage:

- Can consider all execution paths

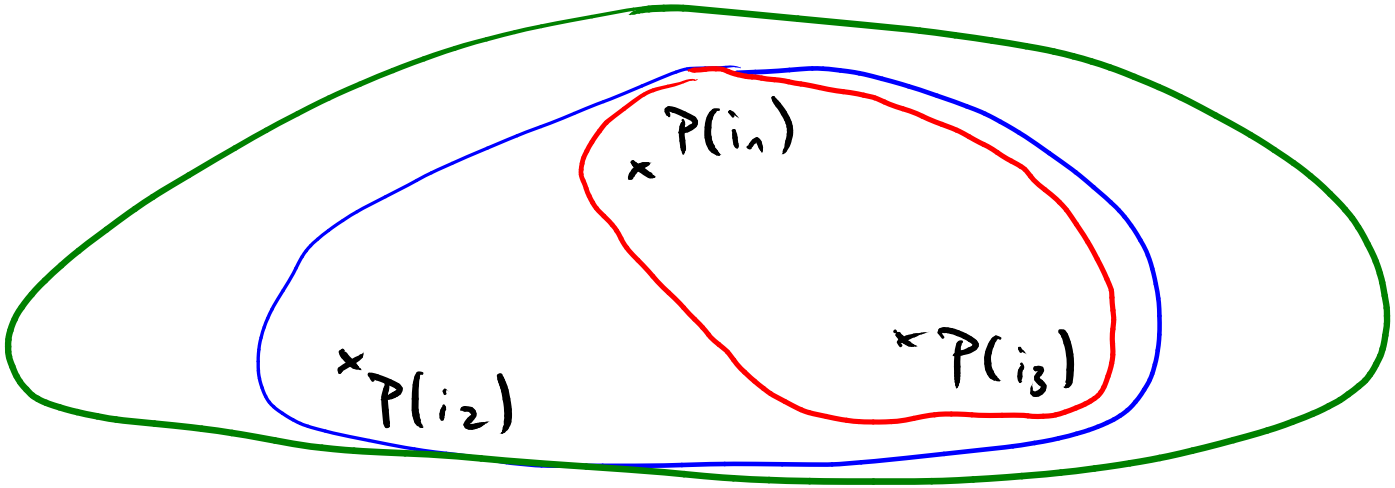
Disadvantage:

- Need to abstract and approximate actual execution

```
if (getInput() > 5) {
  a.foo();  // Does this call ever get executed?
}
b.bar();    // May a and b point to the same object?
```

Over- & Underapproximation

Program P, Input i, Behavior $P(i)$



All possible behaviors (what we want to analyze, ideally)

Underapproximation (most dynamic analyses)

Overapproximation (most static analyses)

Static Analysis of Call Sequences

SLANG approach: Static analysis

- Bound the number of analyzed loop iterations
- On control flow joins, take union of possible execution sequences
- Points-to analysis to reason about references to objects

Example

```
SmsManager smsMgr = SmsManager.getDefault();
int length = message.length();
if (length > MAX_SMS_MESSAGE_LENGTH) {
  ArrayList<String> msgList =
      smsMgr.divideMsg(message);
} else {}
```

Example

```
SmsManager smsMgr = SmsManager.getDefault();
int length = message.length();
if (length > MAX_SMS_MESSAGE_LENGTH) {
  ArrayList<String> msgList =
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} else {}
```

5 sequences:

Object	Calls
smsMgr	(getDefault, ret)
smsMgr	(getDefault, ret) · (divideMsg, 0)
message	(length, 0)
message	(length, 0) · (divideMsg, 1)
msgList	(divideMsg, ret)

Training Phase

- Training data used for paper:
  3 million methods from various Android projects
- Extract sentences via static analysis
- Train statistical language model
  - Both n-gram and RNN model

Query Phase

- Given: Method with holes
- For each hole:
  - Consider all possible completions of the partial call sequence
  - Query language model to obtain probability
    - Average of n-gram and RNN models
- Return completed code that maximizes overall probability

Example

```
SmsManager smsMgr = SmsManager.getDefault();
int length = message.length();
if (length > MAX_SMS_MESSAGE_LENGTH) {
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  // hole H1
} else {
  // hole H2
}
```

Example

```
SmsManager smsMgr = SmsManager.getDefault();
int length = message.length();
if (length > MAX_SMS_MESSAGE_LENGTH) {
  ArrayList<String> msgList =
      smsMgr.divideMsg(message);
  smsMgr.sendMultipartTextMessage(..., msgList, ...);
} else {
  smsMgr.sendTextMessage(..., message, ...);
}
```

Scalability Tricks

Search space of possible completions:
Too large to explore in reasonable time

Refinements to reduce space

- Users may provide hints
  - How many calls to insert
  - Which objects to use
- Replace infrequent words with ”unknown”
- Obtain candidate calls using bi-gram model
- Query language model only for candidates

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