NL2Type: Inferring Types from Natural Language Information

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Why Infer Types?

- **Dynamically typed languages:**
  Extremely popular
- **Lack of type annotations:**
  - Type errors
  - Hard-to-understand APIs
  - Poor IDE support
- **Gradual types to the rescue**

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- **Gradual types to the rescue**

But: Annotating types is painful

Running Example

Type signature of this function?

```
/** Calculates the area of a rectangle.
  * @param length The length of the rectangle.
  * @param breadth The breadth of the rectangle.
  * @returns The area of the rectangle in meters.
*/
getArea: function(length, breadth) {
  ...
}
```

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Identifiers and comments:
Implicit type hints

NL2Type

Idea: **Predict types from natural language information**

Identifiers & comments → **NL2Type** → **Type annotations**

Natural language in code

- Usually ignored by program analyses
- But: Extremely valuable

Usage Scenario 1

Predict missing type annotations

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Usage Scenario 2

Find inconsistent annotations

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Usage Scenario 3

Improve auto-completion and code navigation

```
area = getArea(23, 42);
name = firstName();
...
writer.appendNumber( ??? )
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Rank suggestions based on inferred types

Overview of NL2Type

Corpus of annotated functions →

- Data extraction
- ↓
- NL preprocessing
- ↓
- Data representation
- ↓
- Neural network training
- ↓

New function → **NL2Type model** → Likely type signature

Data Extraction

- **Lightweight AST-based static analysis**
- **From each function, extract:**
  - Names of function and parameters
  - Comments associated with function, parameters, and return type
  - Types of parameters and return type

Data Extraction: Example

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NL Preprocessing

Challenges

- Huge vocabulary
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- Uninformative words

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Addressed by

- Tokenizing identifiers: getArea $\rightarrow$ get, area
- Lemmatizing words: Calculates $\rightarrow$ calculate
- Removing stop words: the, of, etc.

Data Representation: NL Words

How to feed the NL data into a neural network?

”area” → Learned embedding → [0.32, 2.17, ..., 1.89]

- Map each word into a compact vector (length=100)
- Embeddings encode semantic similarity
- Different embeddings for identifiers and comments

Data Representation: Types

How to represent types as vectors?

number → **One-hot encoding** → **[0, 0, ..., 1, 0]**

- Encode most frequent types as one-hot vectors (default: 1000 types)
- Infrequent types encoded as ”other”
  → Think: ”don’t know”

Training the Neural Network

Type as one-hot vector

↑

Recurrent neural network

↑

Sequence of embeddings of NL info

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Sequence of embeddings of NL info

Flag: Return type + Words in fct. comment + Words in param. names + Words in fct. name + Words in return comment

Shape: 43x100

Training the Neural Network

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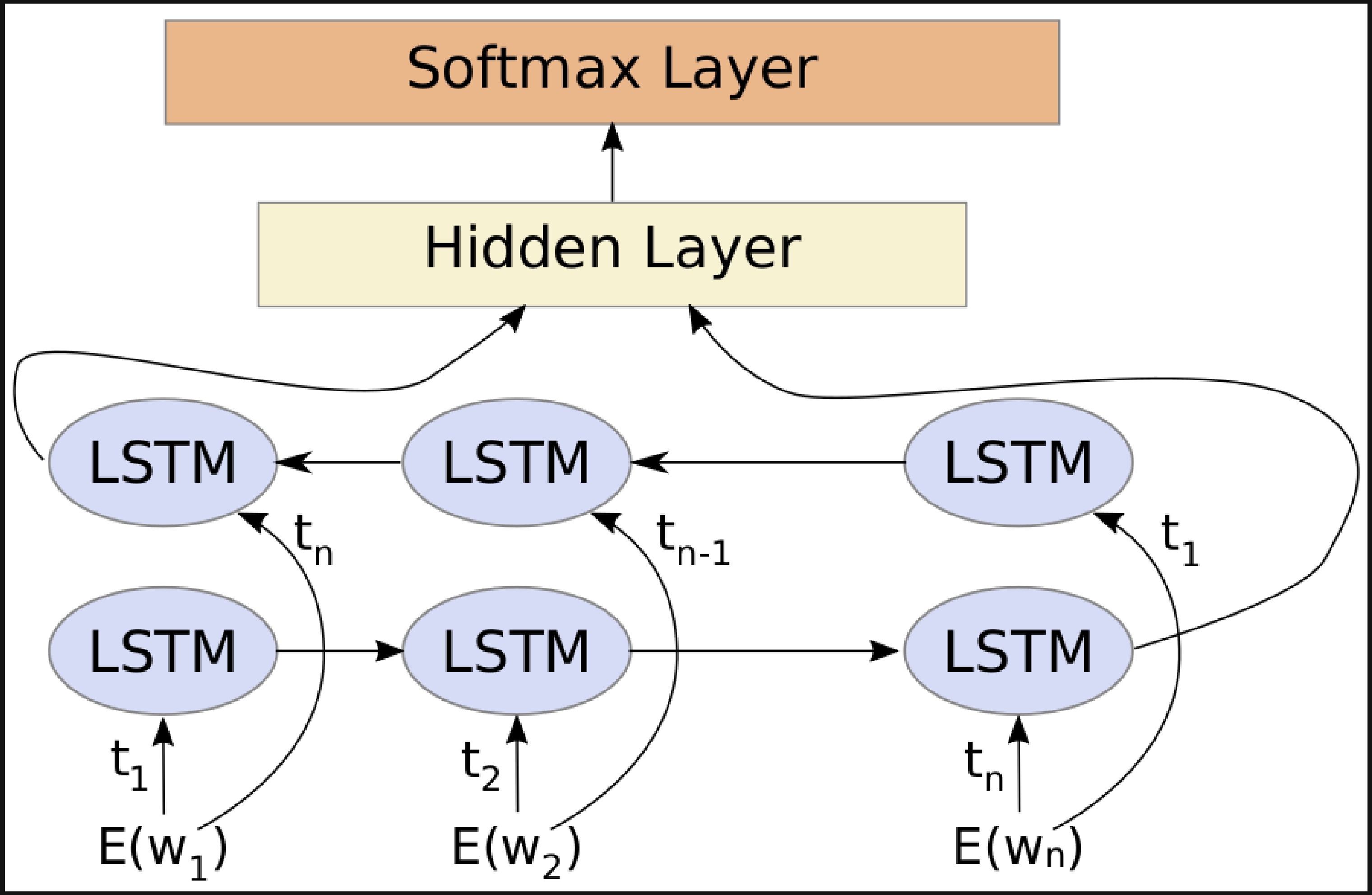
Sequence of embeddings of NL info

Flag: Param. type + Words in param. comment + Padding + Words in param. name + Padding

Shape: 43x100

Bi-directional RNN



hidden layer size: 256, batch size: 256, epochs: 12,
dropout: 20%, loss: categorical cross entropy, optimizer: Adam

Prediction

Softmax: Probabilities of different types

↑

Recurrent neural network

↑

Sequence of embeddings of NL info

Prediction

Softmax: Probabilities of different types

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Recurrent neural network

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Sequence of embeddings of NL info

How confident is the model in a prediction?

- Naive approach: Rank by probability
- Problem: Model is overconfident

Prediction

Softmax: Probabilities of different types

↑

Recurrent neural network

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Sequence of embeddings of NL info

How confident is the model in a prediction?

- Better approach:
  Dropout during prediction [Gal, ICML'16]

Implementation

- Data extraction: Parser of JSDoc tool
- Preprocessing: NLTK library
- Embedding learning:
  Word2Vec by gensim
- Neural network:
  Keras and TensorFlow

Evaluation: Data

- **162k JavaScript files**
  - JS150 corpus [Raychev, POPL'16]
  - Popular libraries from cdnjs.com
- **618k data points**
  - 31% return types, 69% parameter types
  - 80% have a comment

Evaluation: Metrics

- **Precision and recall in top-k predictions**

$$precision = \frac{pred_{corr}}{pred_{all}} \qquad recall = \frac{pred_{corr}}{data\ points}$$

- **Usefulness of inconsistencies**
  - Manually inspect predictions that differ from actual annotation

Effectiveness of Prediction

Approach	Top-1		
	Prec	Rec	F1
NL2Type	84.1	78.9	81.4

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Approach	Top-1			Top-3			Top-5		
	Prec	Rec	F1	Prec	Rec	F1	Prec	Rec	F1
NL2Type	84.1	78.9	81.4	93.0	87.3	90.1	95.5	89.6	92.5

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Scenario:
Fully automated annotation

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Scenario:
Semi-automated annotation
or improved IDE support

Effectiveness of Prediction

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No comm.	72.3	68.3	70.3	86.6	81.8	84.1	91.4	86.3	88.8
Baseline	18.5	17.3	17.9	49.0	46.0	47.4	66.3	62.3	64.2

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Use function names and parameter names only

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Predict k most frequent types

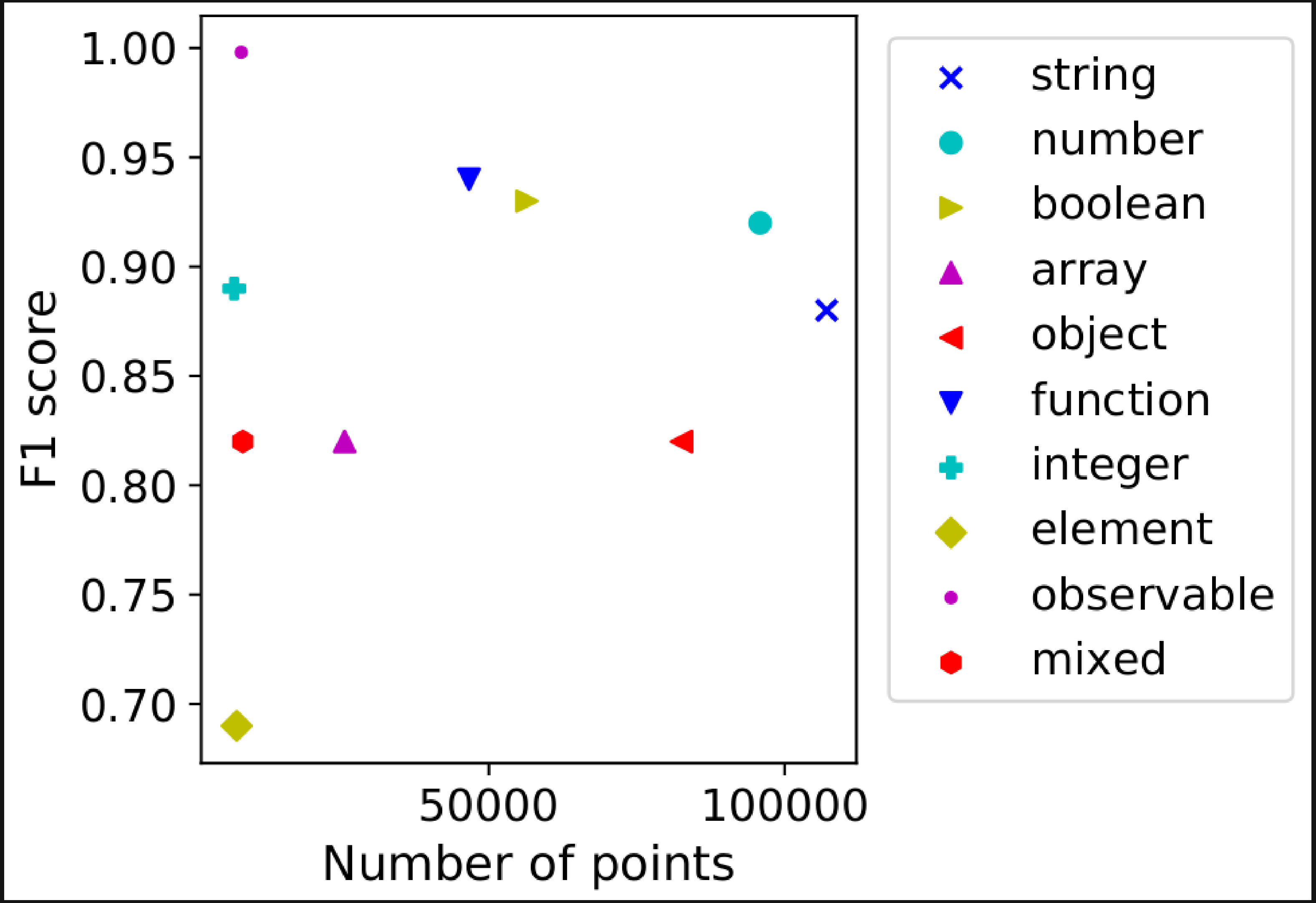
Example: Correct Prediction

```
/** Get the appropriate anchor and focus node/offset
 * pairs for IE.
 * @param {???} node
 * @return {???}
 */
function getIEOffsets(node) {
...
}
```

Example: Correct Prediction

```
/** Get the appropriate anchor and focus node/offset
 * pairs for IE.
 * @param {DOMElement} node
 * @return {object}
 */
function getIEOffsets(node) {
...
}
```

Effectiveness by Type



Comparison with Prior Work

- **JSNice: Structural relations between program elements** [Raychev, POPL'15]
  - Precision: 62.5% $\rightarrow$ 84.1%
  - Recall: 45% $\rightarrow$ 78.9%
- **DeepTyper: Seq-to-seq based on parallel corpus** [Hellendoorn, FSE'18]
  - Precision: 68.6% $\rightarrow$ 77.5% *
  - Recall: 44.0% $\rightarrow$ 44.6% *

* on a TypeScript-based corpus

Usefulness of Inconsistencies

Manual classification of top-50 warnings:

Category	Total	Percentage
Inconsistencies	25	50%
Non-standard type annotations	14	28%
Misclassifications	11	22%

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78% true positives

Examples

Inconsistency: Incorrect annotation

```
/** Utility function to ensure that object properties
  * are copied by value, and not by reference
  * @param {Object} target Target object to copy
  * properties into
  * @param {Object} source Source object for the
  * proporties to copy
  * @param {string} propertyObj Object containing
  * properties names we want to loop over
*/
function deepCopyProperties(target, source, propertyObj
...
}
```

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Examples

Non-standard type annotation

```
/** Tests to see if a point (x, y) is within a range
  * of current Point
  * @param {Numeric} x - the x coordinate of tested poi
  * @param {Numeric} y - the x coordinate of tested poi
  * @param {Numeric} radius - the radius of the vicinit
**/
near: function(x, y, radius) {
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Examples

Incorrect prediction

```
/** Calculate the average of two 3d points
  * @param {Point3d} a
  * @param {Point3d} b
  * @return {Point3d} The average, (a+b)/2
  */
Point3d.avg = function(a, b) {
  ...
}
```

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Incorrect prediction

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Efficiency

- **Data extraction**: 44ms per function
- **Preprocessing**: 23ms per function
- **Training**: 93 minutes (one-time effort)
- **Prediction**: 5ms per function

Intel Xeon E5-2650 processor with 48 cores, 64GB of memory, NVIDIA Tesla P100 GPU with 16GB of memory

Why Does It Work?

Developers use **meaningful names**

Source code is **repetitive**

Annotated code available as **training data**

Probabilistic models + NL = ♡

Conclusions

- **NL2Type: Predict types from NL info**
  - F1-score of 81.4% (top-1) to 92.5% (top-5)
  - 39/50 detected inconsistencies motivate a code improvement
- **Open challenges**
  - Integrate into development workflow
  - Long tail of types