A Cross-Architecture Instruction Embedding Model for Natural Language Processing-Inspired Binary Code Analysis

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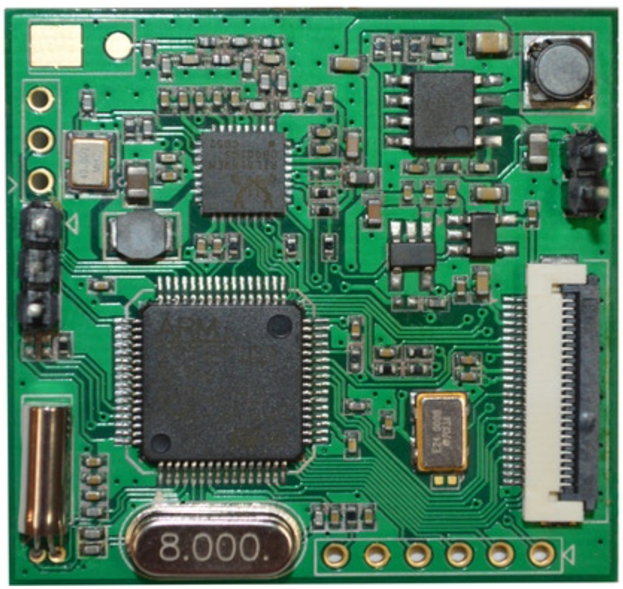
Closed-Source Software

- When using proprietary software, often we are only left with binaries
- Software on embedded devices (*firmware*) is usually closed-source
- *Binary code analysis* is an important method for analyzing programs through their binaries. It can be applied to tasks, such as code plagiarism detection, vulnerability discovery, and malware detection

Software is increasingly cross-compiled for various architectures



x86 ARM MIPS

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Our Insight

x86 assembly language

Binary code analysis can be approached by borrowing ideas and techniques of *Natural Language Processing*.

NLP:

- words → word embeddings (i.e., high-dimensional vectors)

NLP-inspired binary code analysis:

- instructions are regarded as words
- instruction → instruction embeddings

Background: Word Embeddings

- Word embeddings are **high-dimensional vectors** that *encode word meanings*

- One-hot encoding: Given a dictionary of 100 words, each word occupies one dimension out of 100 in an all-0 vector

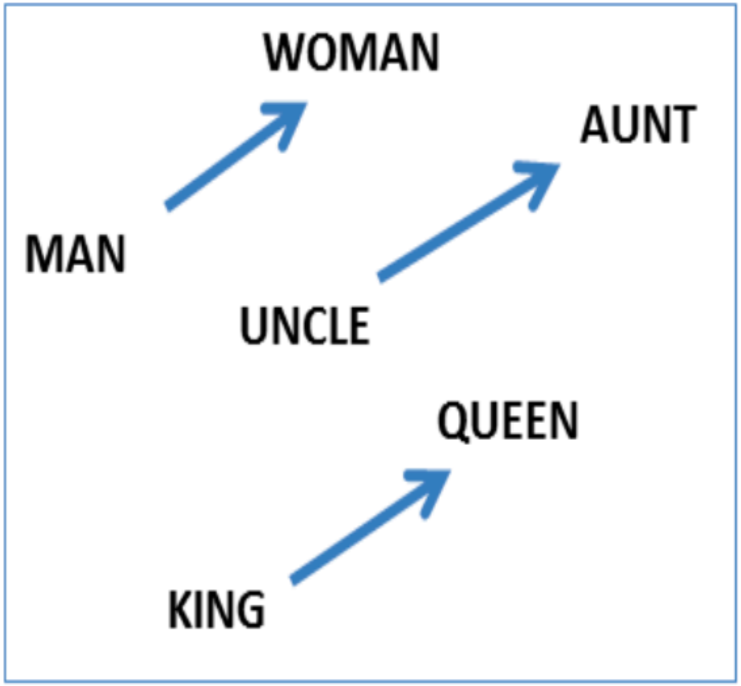
Cat = [1 0 0 0 0 …] Bird = [0 0 1 0 0 …]

Dog = [0 1 0 0 0 …] Pig = [0 0 0 1 0 …]

But this does not tell us how words are similar or different

Background: Word Embeddings

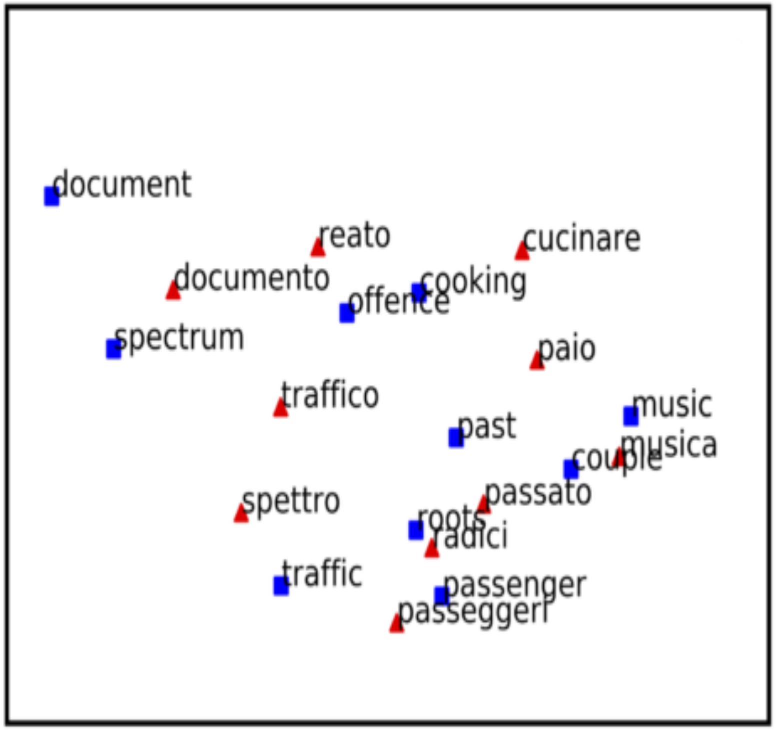
- To reflect what words *mean*, dimensions will instead encode patterns of how words are distributed across texts
- ***Insight:*** if two words tend to appear in the *same* contexts, then the two words probably share the same meaning



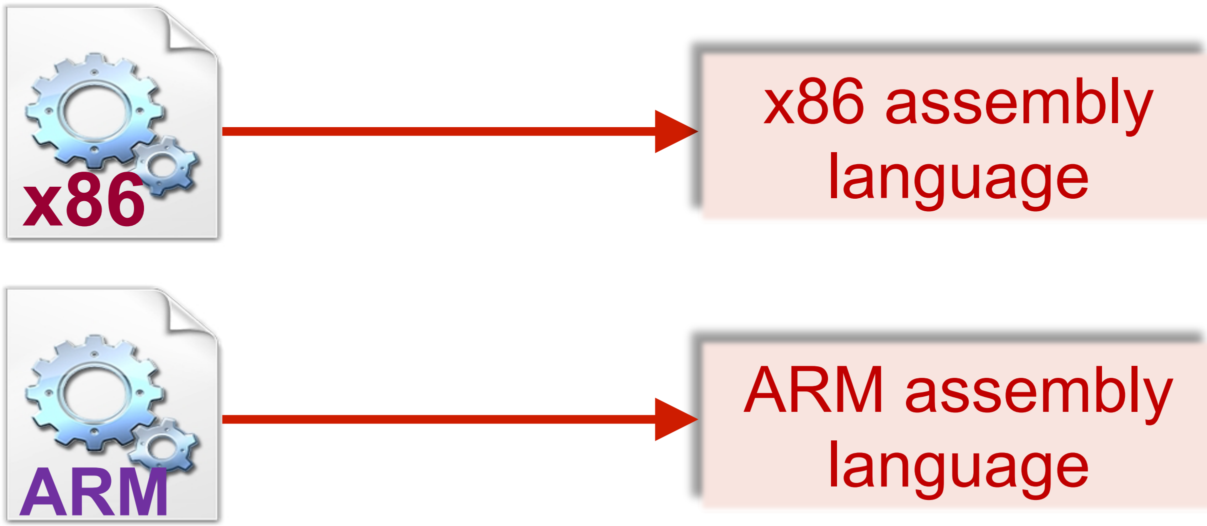
Background: ***Multilingual*** Word Embeddings

- Multiple human languages
- Various multilingual NLP tasks

- *Multilingual* word embedding models learns word embeddings such that: *similar words in different human languages have similar embeddings*



Cross-Architecture Binary Code Analysis



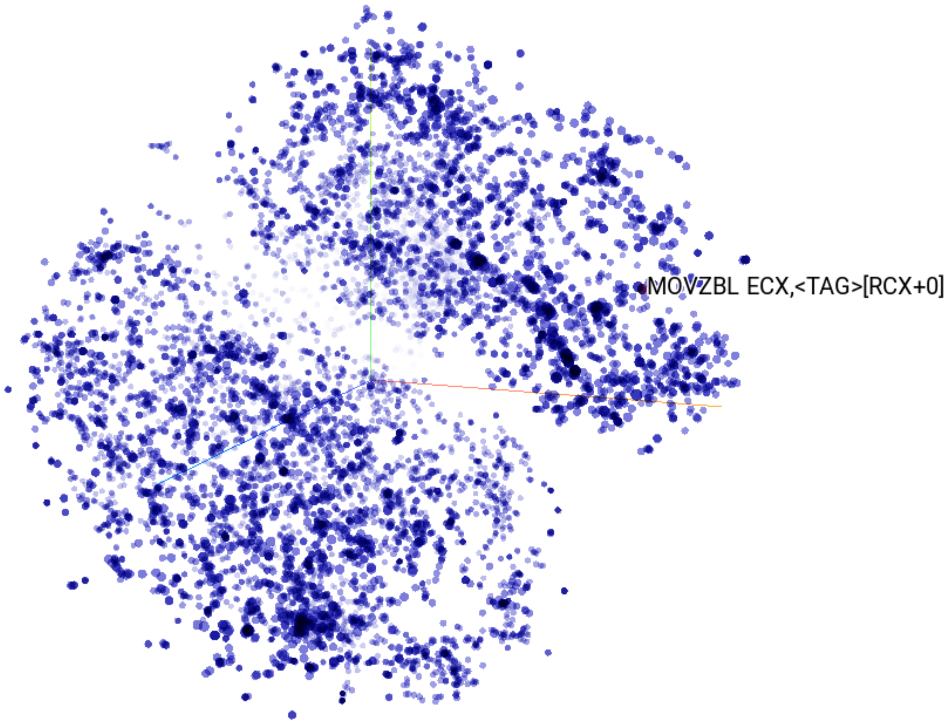
NLP-inspired binary code analysis:

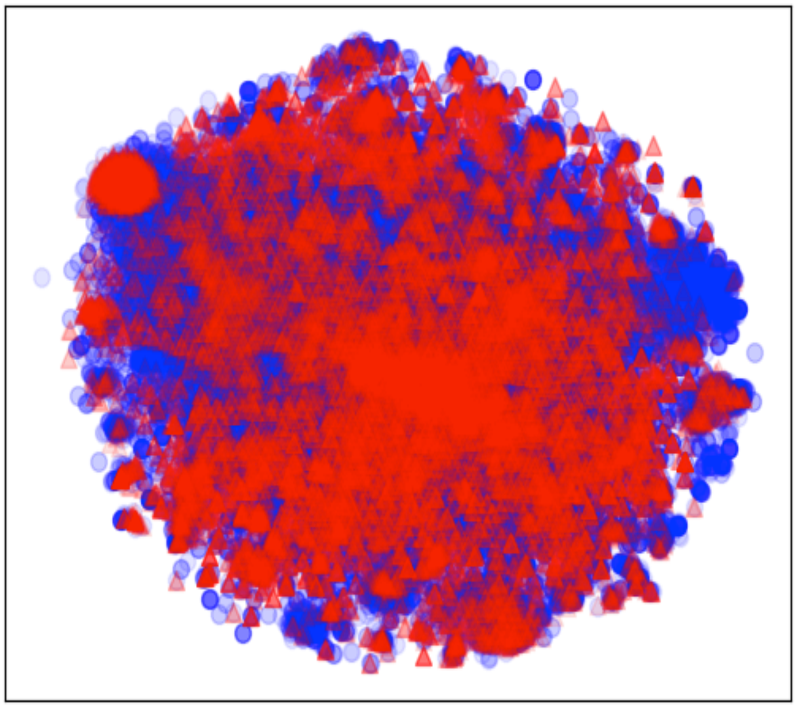
- instructions are regarded as words
- instruction → instruction embeddings

Cross-architecture binary code analysis:

- instruction → cross-architecture instruction embeddings
- similar instructions from different arch. have similar embeddings

Motivation





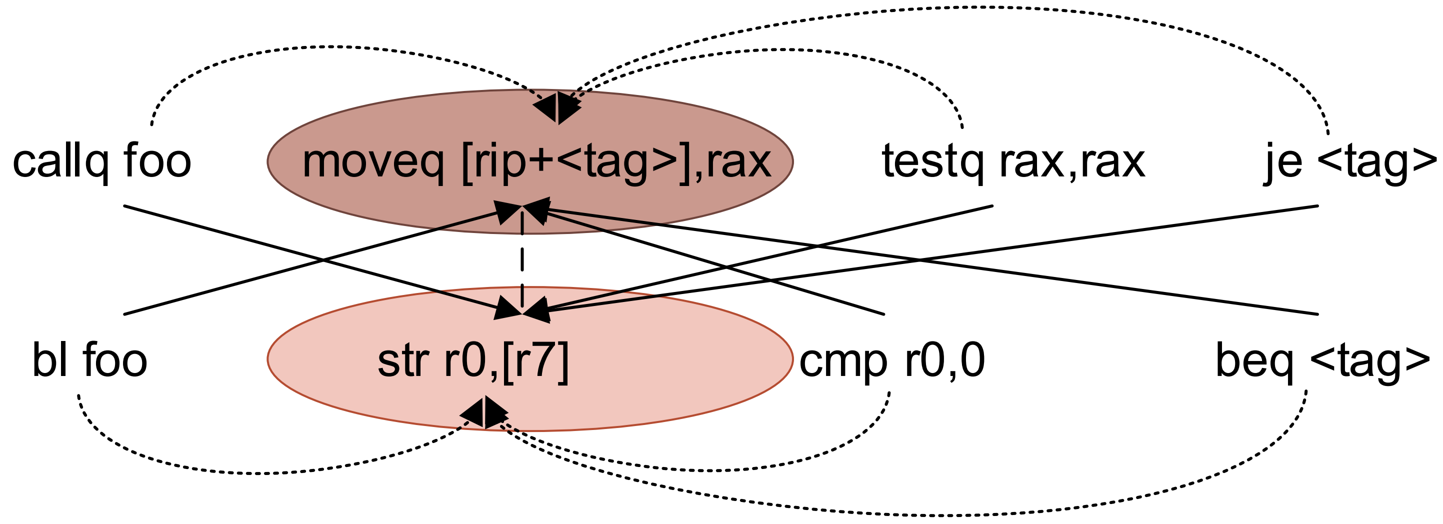
All ARM and x86 instructions; if the embeddings are trained separately

All ARM and x86 instructions; if the embeddings are trained jointly

Potential Applications

- Code similarity comparison:
  - Summing up all the embeddings of instructions in a function/basic block, and using the sum to represent the function/basic block for similarity comparison
  - Some previous work based on deep learning (e.g., **InnerEye[NDSS'19], Arm2Vec[S&P'19], i2V-RNN[BAR'19]**) use complex neural network models, such as LSTM, structure2vec
- Transferability:
  - Training a classifier using the code of x86, and directly applying the classifier to the code of ARM
- ……

Our Training Approach



- We adopt the BiVec model, a multilingual word embedding model.
- Finding the alignment links: simply assume ***linear alignments***
  - Each instruction in one sequence *M* at position *i* is aligned to the instruction in another sequence *N* at position $\lceil i \times |N| / |M| \rceil$
  - E.g., M = {u1, u2, u3, u4}, N = {v1, v2, v3}, the alignment links: u1<->v1; u2<->v2; u3<->v3; u4<->v3;

Evaluation

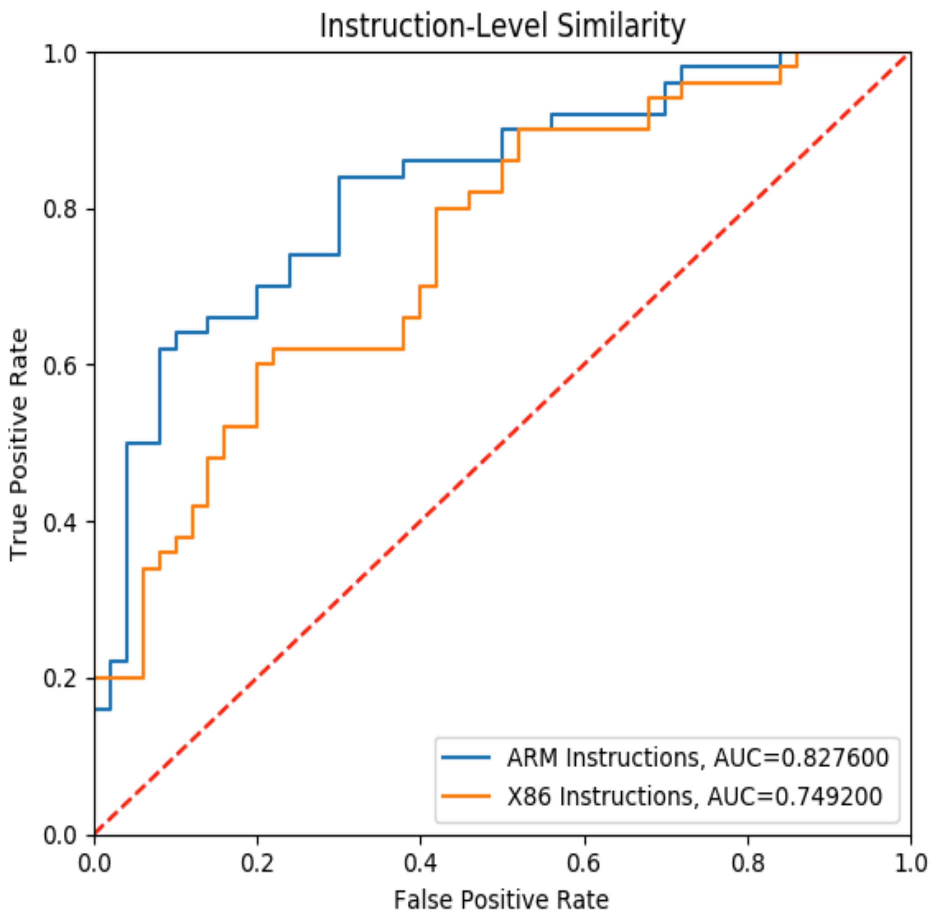
- **Dataset:** 202,252 semantically similar basic blocks generated by our another work [1]

- Two types of experiments:
  - Instruction similarity tasks:
    - Mono-architecture instruction similarity task
    - Cross-architecture instruction similarity task
  - Cross-architecture basic-block similarity comparison task

[1] "*Neural Machine Translation Inspired Binary Code Similarity Comparison beyond Function Pairs*," NDSS'19

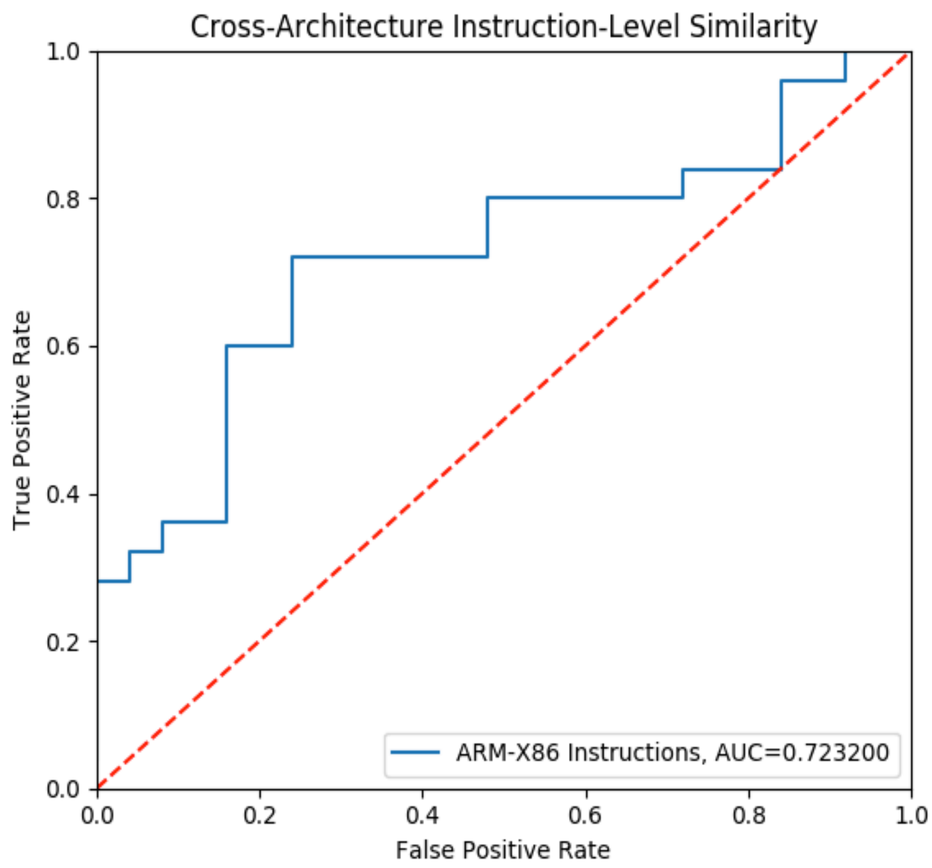
Mono-Architecture Instruction Similarity Task

- 100 instruction pairs were randomly chosen and labeled (50 similar, 50 dissimilar). This was determined by *opcodes*.
- Cosine similarity
  - **ARM AUC = 0.82**
    X86 AUC = 0.74



Cross-Architecture Instruction Similarity Task

- 50 pairs of instructions across architectures were randomly chosen and labeled (25 similar, 25 dissimilar). Again, *opcodes* were used to decide this.
  - **AUC = 0.72**
- The results are good, but an advanced way of finding alignment links between instrcutions would improve the results.

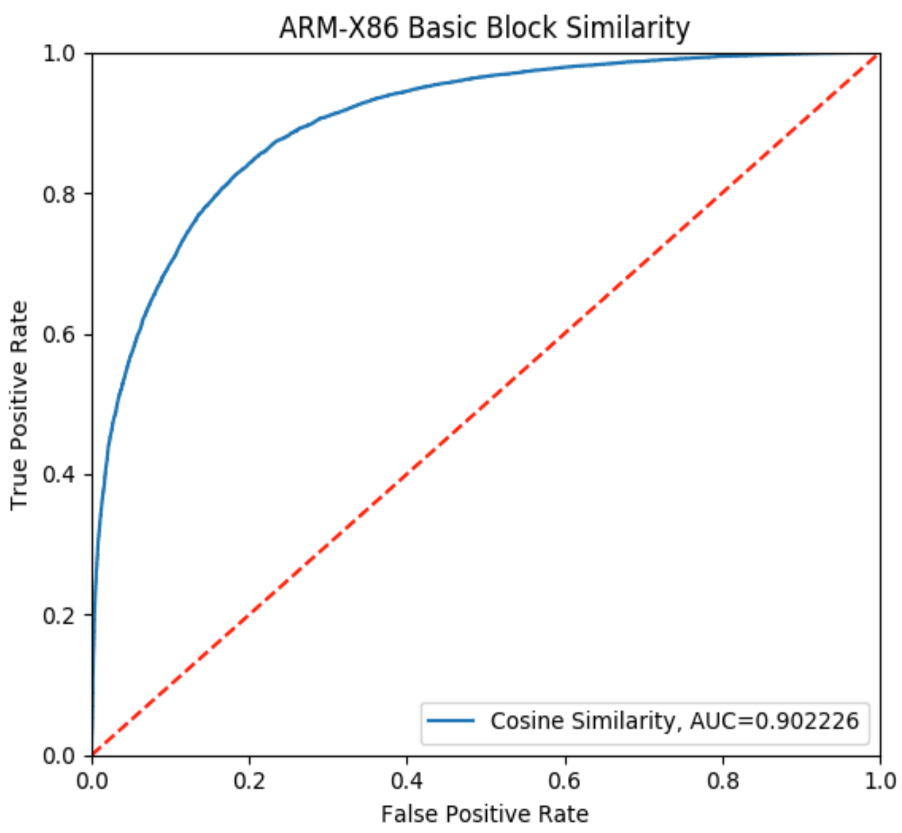


Cross-Architecture Basic-Block Similarity Test

- 90% of similar basic block pairs for training
- 10% of similar block pairs and another 20,633 dissimilar pairs (selected from [1]) for testing

- Summation of all instruction embeddings to represent a block
  - **AUC = 0.90**

- Recent work (such as Gemini in CCS'17) uses manually selected features to represent a basic block; a SVM classifier based on such features can only achieve **AUC = 0.85**



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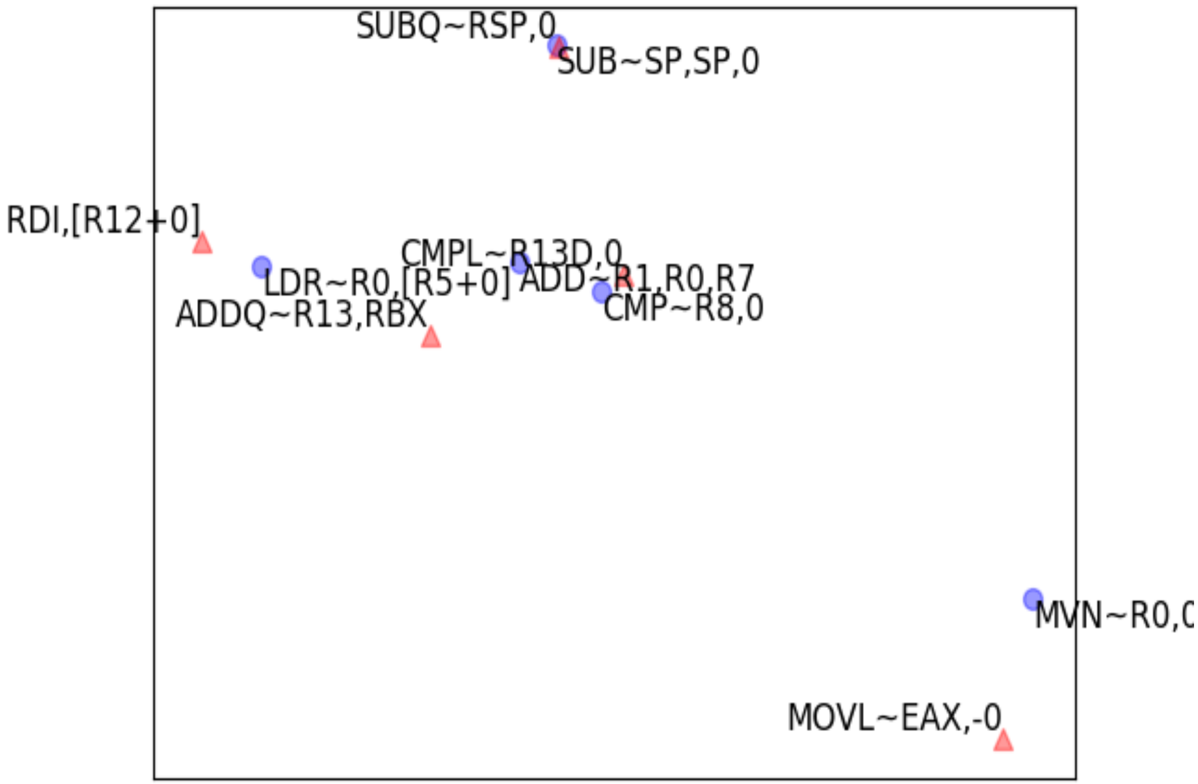
T-SNE Visualizations



Visualization of five ARM and x86 instruction pairs. A blue circle and red triangle represent an ARM and x86 instruction, respectively

Summary

- The first work discusses cross-architecture instruction embeddings
- We build the cross-architecture instruction embedding model, such that similar instruction, regardless of their architectures, have embeddings close together in the vector space
- We conduct various experiments to evaluate the quality of the learned instruction embeddings
- The proposed model may be applied to many cross-architecture binary code analysis tasks, such as vulnerability finding, malware detection, and plagiarism detection

https://github.com/nlp-code-analysis/cross-arch-instr-model