DexLego: Reassembleable Bytecode Extraction for Aiding Static Analysis

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Outline

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- Introduction
- System Overview
- Implementation
- Evaluation
- Conclusions

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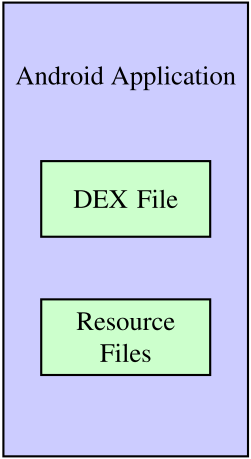
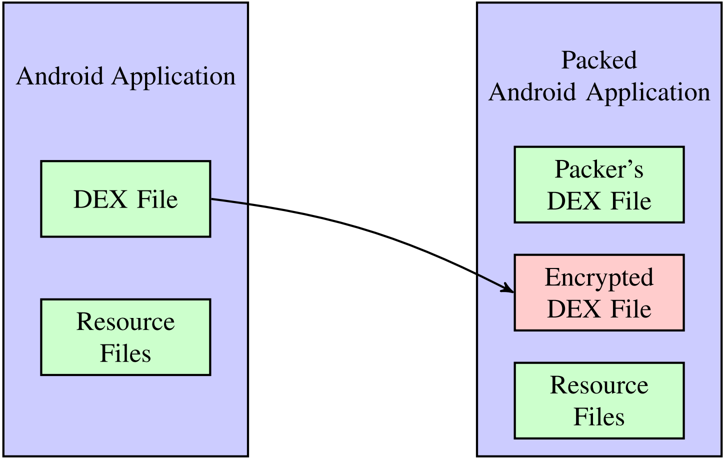
Why still doing static analysis?

Packing Technique



Packing Technique



Packing Technique

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- Previous Android Unpacking Systems: DexHunter [1], AppSpear [2]
  - Assuming a clear transition between the packer's code and the original code.
  - Using method-level collection to collect code.

Self-modifying Code

```java
public void example() {
    helper();
    Log.d("Hello World!");
}
```

Self-modifying Code

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```java
public void example() {
    helper();
    Log.d("Hello World!");
}
```

```java
public void example() {
    helper();
    Log.d("Password is 1234!")
}
```

- Android allows the applications modify its bytecode at runtime.
- These changes cannot be detected by current static analysis tools.

Reflection

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```java
public class Main extends Activity {
   protected void onCreate(Bundle savedInstanceState) {
     //...
     // 55 is the index of method "reflectiveLeak" in the method array of class "Main"
     Method reflectiveLeakMethod = getClass().getMethods()[55];
     reflectiveLeakMethod.invoke(this, "sensitive data");
   }

   public void reflectiveLeak(String data) {
     // leak data
     SmsManager.getDefault().sendTextMessage("800-123-456", null, data, null, null);
   }
}
```

Dynamic Code Loading

- Additional DEX files can be downloaded from cloud at runtime.
- Malicious activities in these DEX files are ignored by current static analysis tools.

Why not using dynamic analysis?

Challenges of Dynamic Analysis

- Implicit Flows
- Performance Overhead vs Accuracy

Our Goal

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DexLego: Instruction-level collecting and offline reassembling

- Use dynamic approach to collect executed instruction.
- Improve the current static analysis via offline reassembling.

Outline

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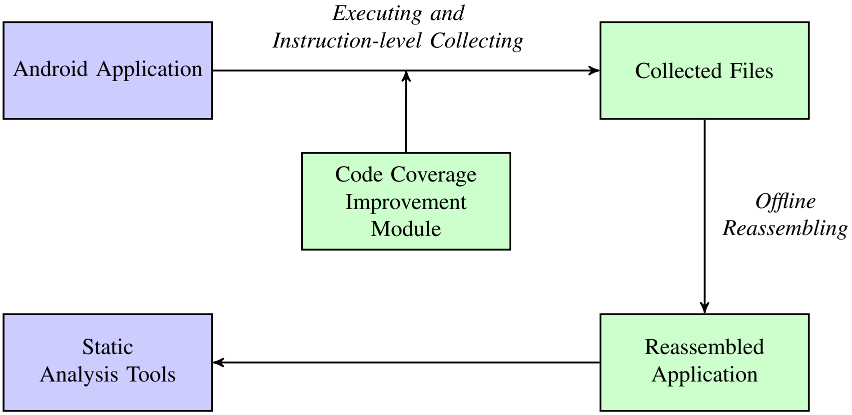
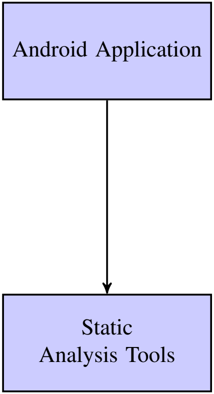
System Overview



System Overview



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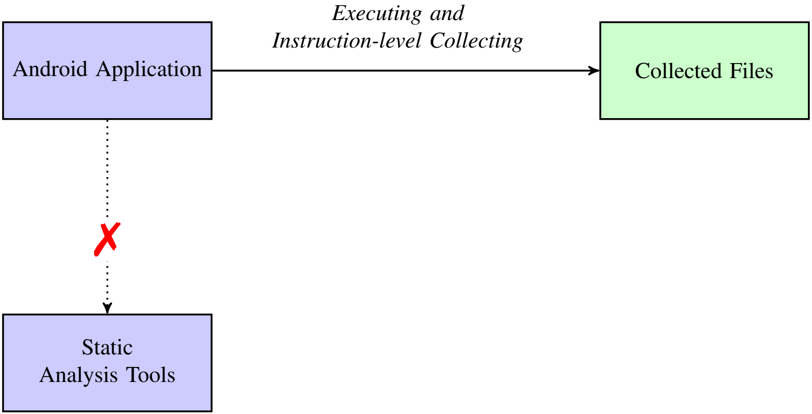

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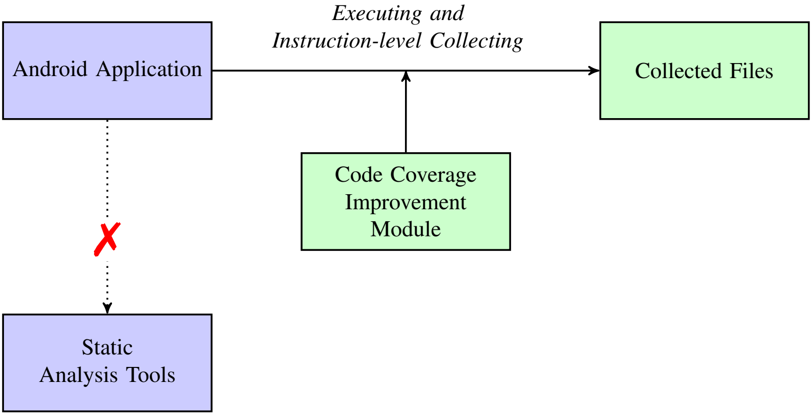

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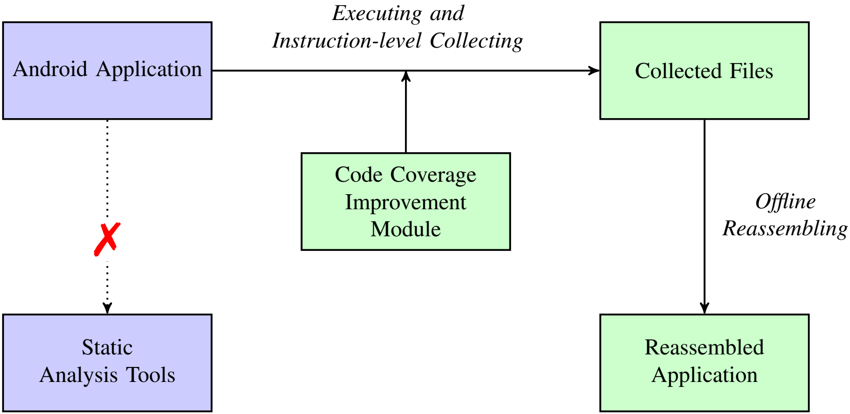

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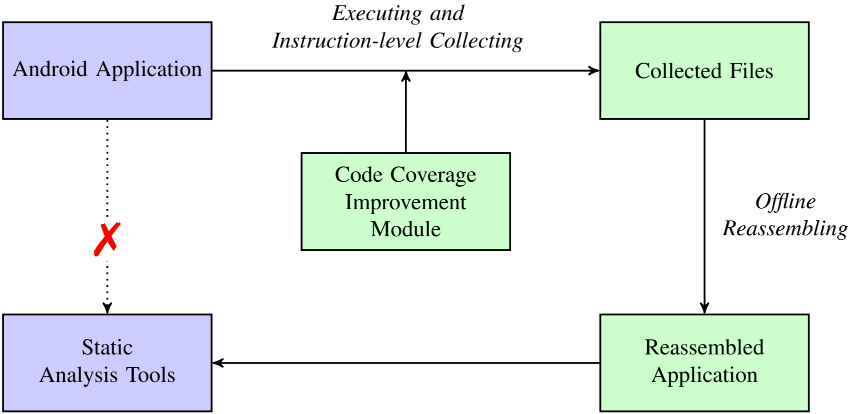

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Simply list the executing instructions one-by-one?

Instruction-level Collection

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```java
public void example() {
    int i;
    for (i = 0; i < 10000; ++i) {
        Log.d("Hello World!");
    }
}
```

Instruction-level Collection

```
public void example() {
    int i;
    for (i = 0; i < 10000; ++i) {
        Log.d("Hello World!");
    }
}
```

```
public void example() {
    Log.d("Hello World!");
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    ...
}
```

Instruction-level Collection

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- Record both the index and the content of each instruction.
- Instruction with same index and content will not be repeatedly collected.

How about self-modifying code?

Instruction-level Collection

- **Collection Tree**
  - A independent tree for each execution of each method.
  - Each node indicates a piece of changed code.

Instruction-level Collection

```
1  // No malicious activities
2  public void benign() {}
3
4  // Leak data
5  public void malicious() {}
6
7  // Modify line 12 to
       "malicious()" at runtime
8  public void helper() {}
9
10 public void execute() {
11     for (int i = 0; i < 2; ++i) {
12         benign();
13         helper();
14     }
15 }
```

Instruction-level Collection

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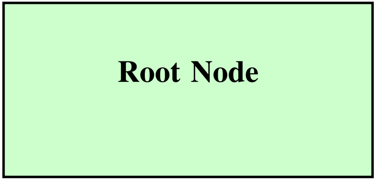

Instruction-level Collection

i = 0

```
1  // No malicious activities
2  public void benign() {}
3
4  // Leak data
5  public void malicious() {}
6
7  // Modify line 12 to
       "malicious()" at runtime
8  public void helper() {}
9
10 public void execute() {
11     for (int i = 0; i < 2; ++i) {
12         benign();
13         helper();
14     }
15 }
```

Root Node

for (int i = 0; i < 2; ++i) {

}

Instruction-level Collection

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i = 0

```
1   // No malicious activities
2   public void benign() {}
3
4   // Leak data
5   public void malicious() {}
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        "malicious()" at runtime
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10  public void execute() {
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12          benign();
13          helper();
14      }
15  }
```

Root Node

```
for (int i = 0; i < 2; ++i) {
        benign();

}
```

Instruction-level Collection

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i = 0

```
1  // No malicious activities
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9
10 public void execute() {
11     for (int i = 0; i < 2; ++i) {
12         benign();
13         helper();
14     }
15 }
```

Root Node

```
for (int i = 0; i < 2; ++i) {
    benign();
    helper();
}
```

Instruction-level Collection

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i = 1

```
1  // No malicious activities
2  public void benign() {}
3
4  // Leak data
5  public void malicious() {}
6
7  // Modify line 12 to
       "malicious()" at runtime
8  public void helper() {}
9
10 public void execute() {
11     for (int i = 0; i < 2; ++i) {
12         malicious();
13         helper();
14     }
15 }
```

Root Node

```
for (int i = 0; i < 2; ++i) {
        benign();
        helper();
}
```

Instruction-level Collection

i = 1

```
1  // No malicious activities
2  public void benign() {}
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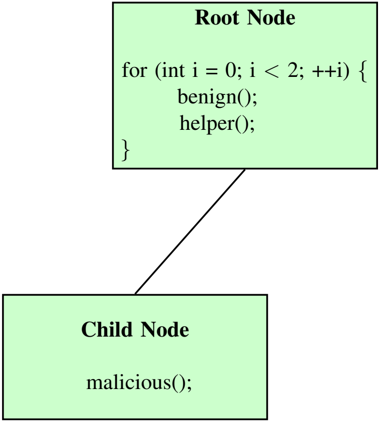

Instruction-level Collection

i = 1

```
1  // No malicious activities
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3
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6
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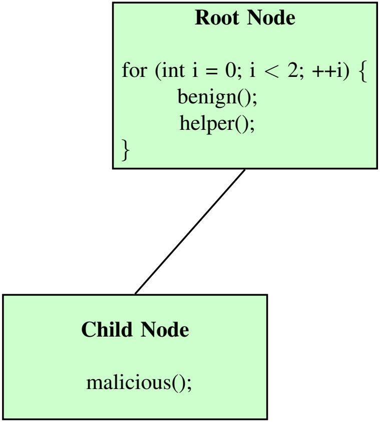
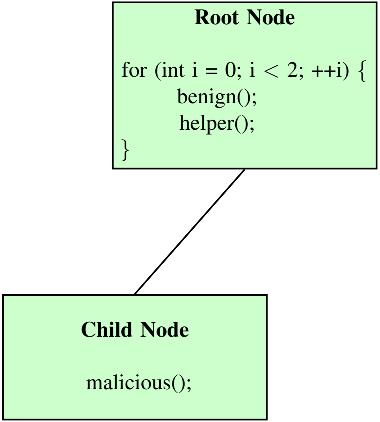


Bytecode Reassembling



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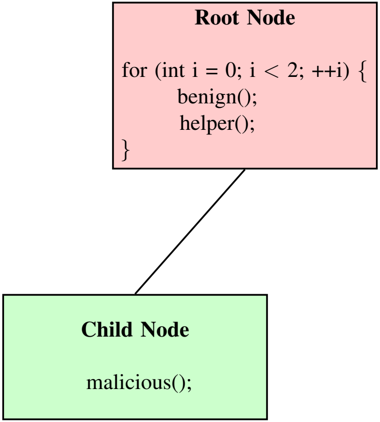
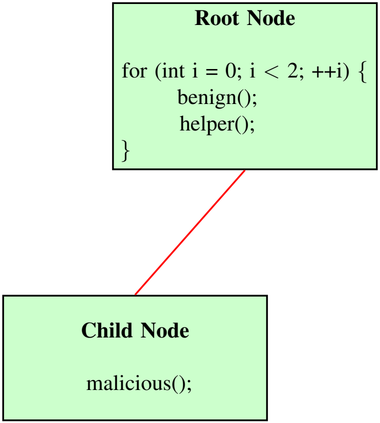



```java
public void execute() {
    for (int i = 0; i < 2; ++i) {
        benign();
        helper();
    }
}
```

Bytecode Reassembling




```
public void execute() {
    for (int i = 0; i < 2; ++i) {
        if (RANDOM_VALUE) {
            benign();
        } else {

        }
        helper();
    }
}
```

Bytecode Reassembling

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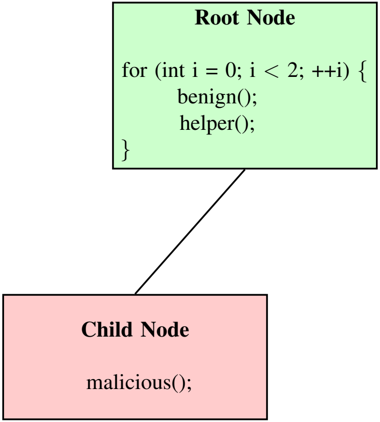


```
public void execute() {
    for (int i = 0; i < 2; ++i) {
        if (RANDOM_VALUE) {
            benign();
        } else {
            malicious();
        }
        helper();
    }
}
```

Implementation

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- Replace the reflective calls with the direct calls during bytecode collection.
- Use force execution to improve the code coverage.

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Evaluation

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- Testbed Specification
  - LG Nexus 5X
  - A dual-core 1.8 GHZ Cortex-A57 cluster and a quad-core 1.4 GHZ Cortex-A53 cluster
  - Android 6.0 and TWRP Recovery

Can we correctly reconstruct the behavior of apps?

Evaluation

Table: Test Result of Different Packers.

Applications	HTMLViewer	Calculator	Calendar	Contacts
# of Instructions	217	2,507	78,598	103,602
360 [3]	✓	✓	✓	✓
Alibaba [4]	✓	✓	✓	✓
Tencent [5]	✓	✓	✓	✓
Baidu [6]	✓	✓	✓	✓
Bangcle [7]	✓	✓	✓	✓

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How is DexLego comparing with other tools?

Evaluation

- 134 samples from DroidBench [8].
- 3 static analysis tools: FlowDroid [9], DroidSafe [10], HornDroid [11].
- 2 unpacking tools: DexHunter [1], AppSpear [2].

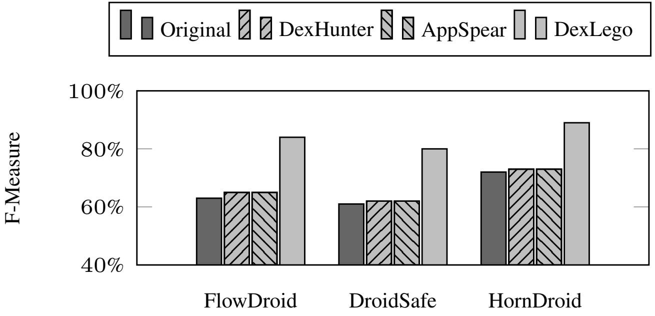

Figure: F-Measure of DroidBench samples.

Can DexLego work with real-world packed apps?

Evaluation

Table: Analysis Result of Packed Real-world Applications.

Package Name	Version	# of Installs	Original	Reassembled
com.lenovo.anyshare	3.6.68	100 million	0	4
com.moji.mjweather	6.0102.02	1 million	0	5
com.rongcai.show	3.4.9	100 thousand	0	3
com.wawoo.snipershootwar	2.6	10 million	0	4
com.wawoo.gunshootwar	2.6	10 million	0	5
com.alex.lookwifipassword	2.9.6	100 thousand	0	2
com.gome.eshopnew	4.3.5	15.63 million	0	3
com.szzc.ucar.pilot	3.4.0	3.59 million	0	5
com.pingan.pabank.activity	2.6.9	7.9 million	0	14

How about code coverage?

Evaluation

Table: Samples from F-Droid [12].

Package Name	Version	# of Instructions
be.ppareit.swiftp	2.14.2	8,812
fr.gaulupeau.apps.InThePoche	2.0.0b1	29,231
org.gnucash.android	2.1.7	56,565
org.liberty.android.fantastischmemopro	10.9.993	57,575
com.fastaccess.github	2.1.0	93,913

Table: Code Coverage with F-Droid Applications.

	Class	Method	Line	Branch	Instruction
Sapienz [13]	44%	37%	32%	20%	32%
Sapienz + DexLego	87%	88%	82%	78%	82%

Performance overhead?

Evaluation

- 7.5x, 1.4x, and 2.3x overhead on Java score, native score, and overall score, respectively.

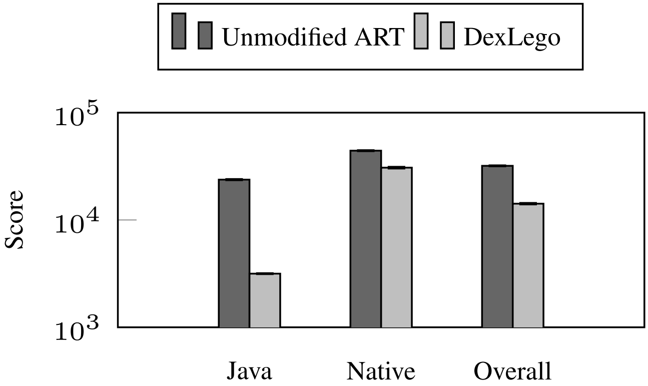

Figure: Performance Measured by CF-Bench [14].

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Conclusions

- DexLego leverages instruction-level bytecode collecting and offline reassembling to aid existing static analysis tools.

- It helps to overcome the weakness of static analysis and increases the analysis accuracy with reasonable performance overhead.

References I

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[1] Y. Zhang, X. Luo, and H. Yin, "DexHunter: Toward extracting hidden code from packed Android applications," in *Proceedings of the 20th European Symposium on Research in Computer Security (ESORICS'15)*., 2015.

[2] W. Yang, Y. Zhang, J. Li, J. Shu, B. Li, W. Hu, and D. Gu, "AppSpear: Bytecode decrypting and DEX reassembling for packed Android malware," in *Proceedings of the 18th International Symposium on Research in Attacks, Intrusions and Defenses (RAID'15)*, 2015.

[3] Qihoo 360 Inc., "360Protector," http://jiagu.360.cn/protection, 2014.

[4] Alibaba Inc., "AliProtector," http://jaq.alibaba.com/, 2014.

[5] Tencent Inc., "TencentProtector," http://legu.qcloud.com/, 2014.

[6] Baidu Inc., "BaiduProtector," http://app.baidu.com/jiagu/, 2014.

[7] Bangcle Ltd., "BangcleProtector," https://www.bangcle.com/, 2013.

[8] EC SPRIDE Secure Software Engineering Group, "DroidBench," https://github.com/secure-software-engineering/DroidBench, 2013.

[9] S. Arzt, S. Rasthofer, C. Fritz, E. Bodden, A. Bartel, J. Klein, Y. Le Traon, D. Octeau, and P. McDaniel, "FlowDroid: Precise context, flow, field, object-sensitive and lifecycle-aware taint analysis for Android apps," in *Proceedings of the 35th ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI'14)*, 2014.

[10] M. I. Gordon, D. Kim, J. H. Perkins, L. Gilham, N. Nguyen, and M. C. Rinard, "Information flow analysis of Android applications in DroidSafe," in *Proceedings of the 22nd Network and Distributed System Security Symposium (NDSS'15)*, 2015.

[11] S. Calzavara, I. Grishchenko, and M. Maffei, "HornDroid: Practical and sound static analysis of Android applications by SMT solving," in *Proceedings of the 1st IEEE European Symposium on Security and Privacy (EuroS&P'16)*, 2016.

References II

[12] F-Droid, "F-Droid," https://f-droid.org/, 2011.

[13] K. Mao, M. Harman, and Y. Jia, "Sapienz: Multi-objective automated testing for Android applications," in *Proceedings of the 25th ACM SIGSOFT International Symposium on Software Testing and Analysis (ISSTA'16)*, 2016.

[14] Chainfire, "CF-Bench," https://play.google.com/store/apps/details?id=eu.chainfire.cfbench, 2013.

Thank you!

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Questions?

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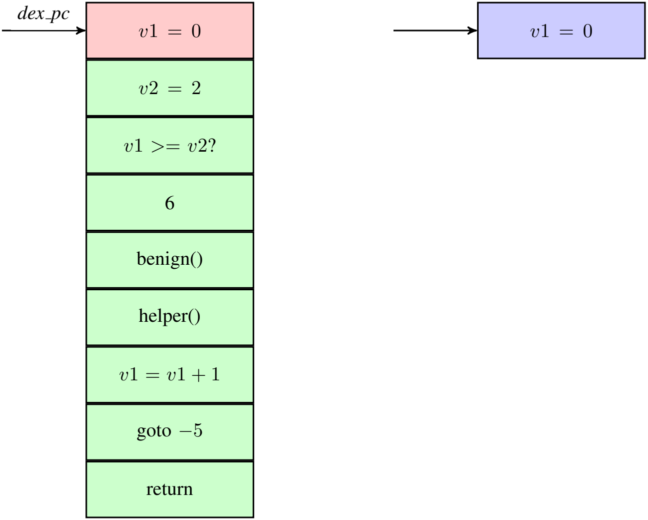
`http://compass.cs.wayne.edu`

Branch Instruction



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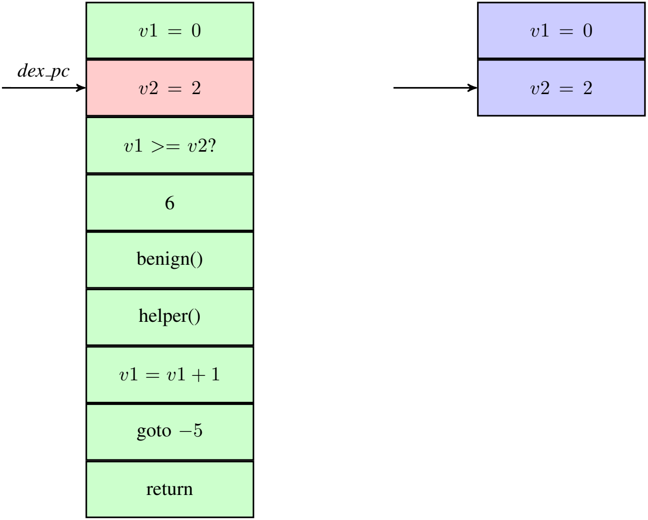

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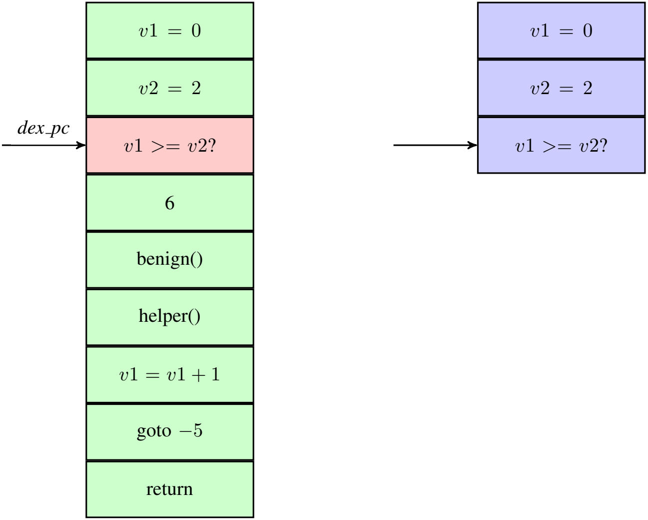

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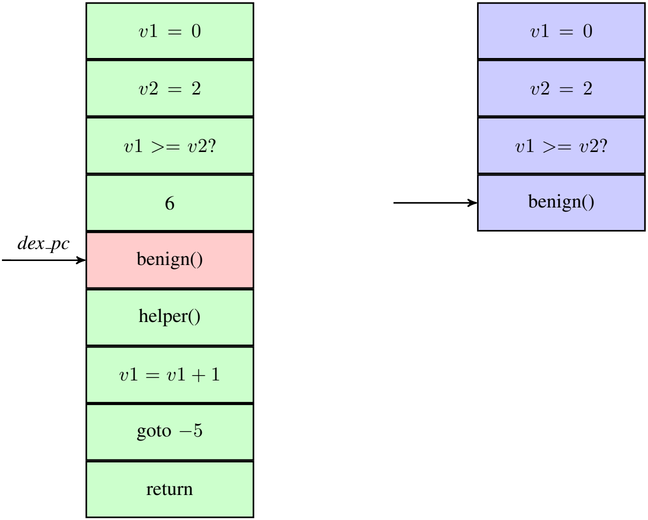

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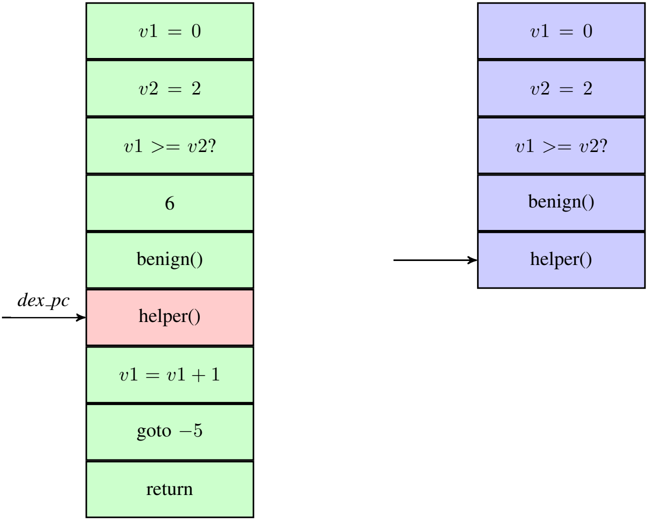

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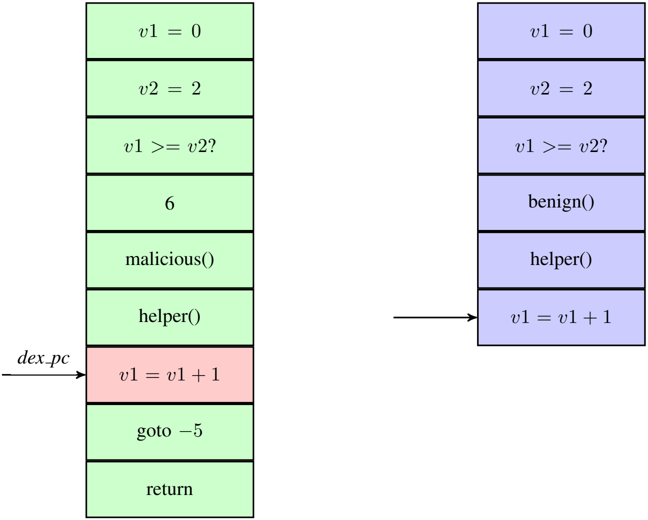

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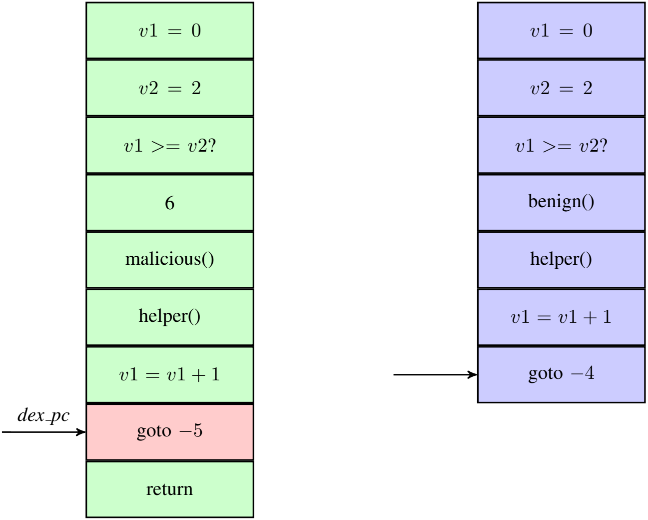

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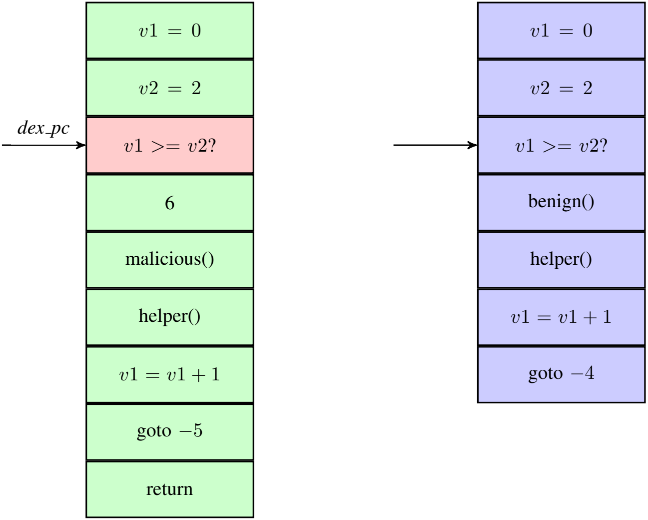

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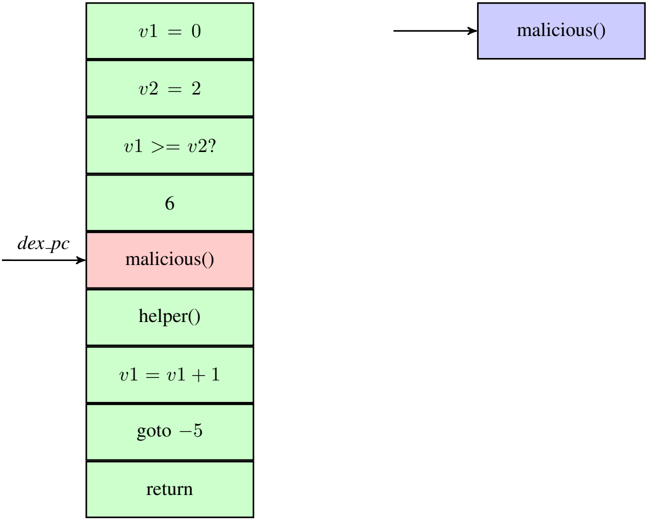

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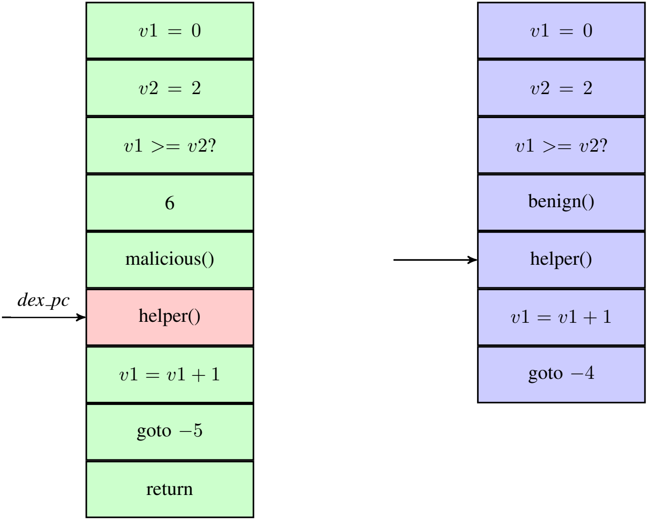

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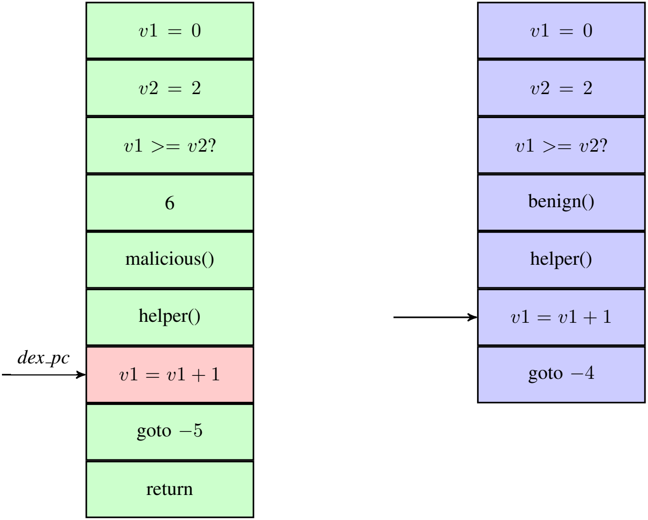

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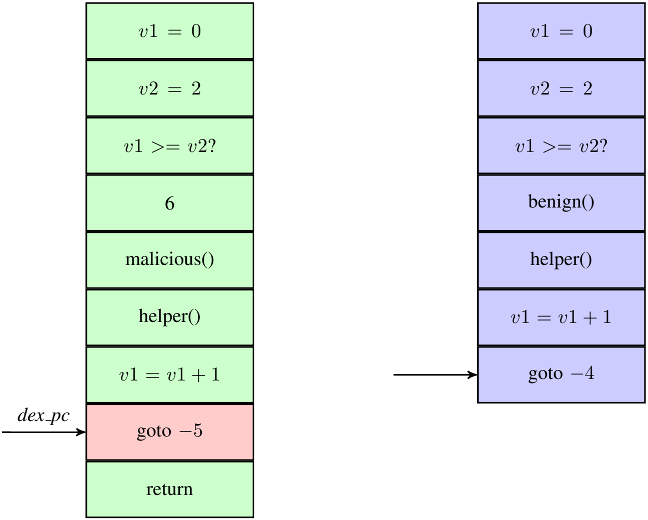

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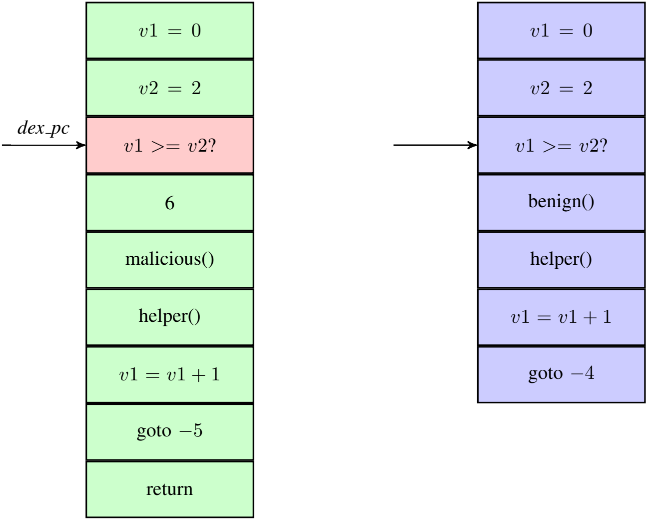

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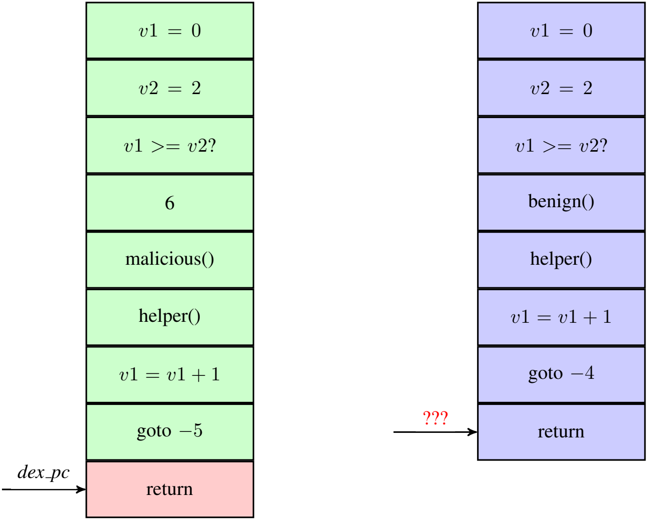

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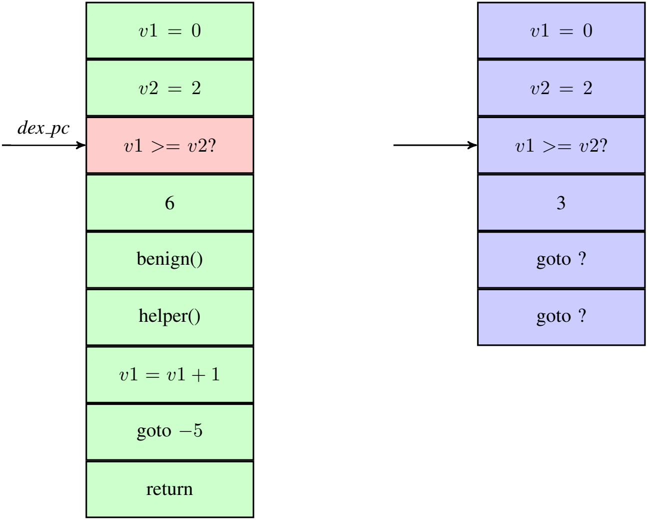

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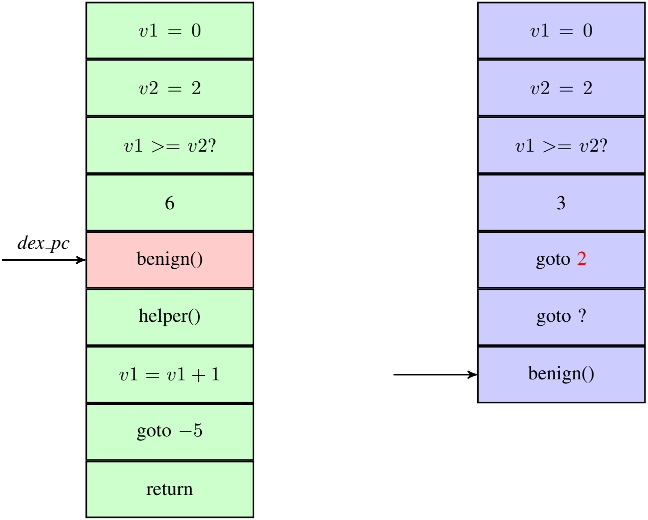

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