THE UNIVERSITY
OF BRITISH COLUMBIA

MANDOLINE: *Dynamic Slicing of Android Applications with Trace-Based Alias Analysis*

ICST, 2021

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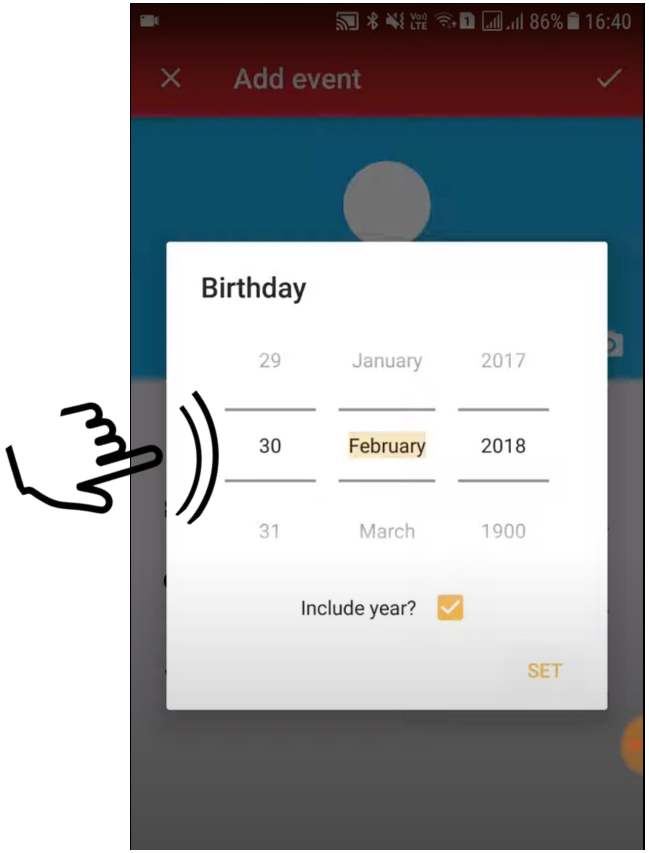
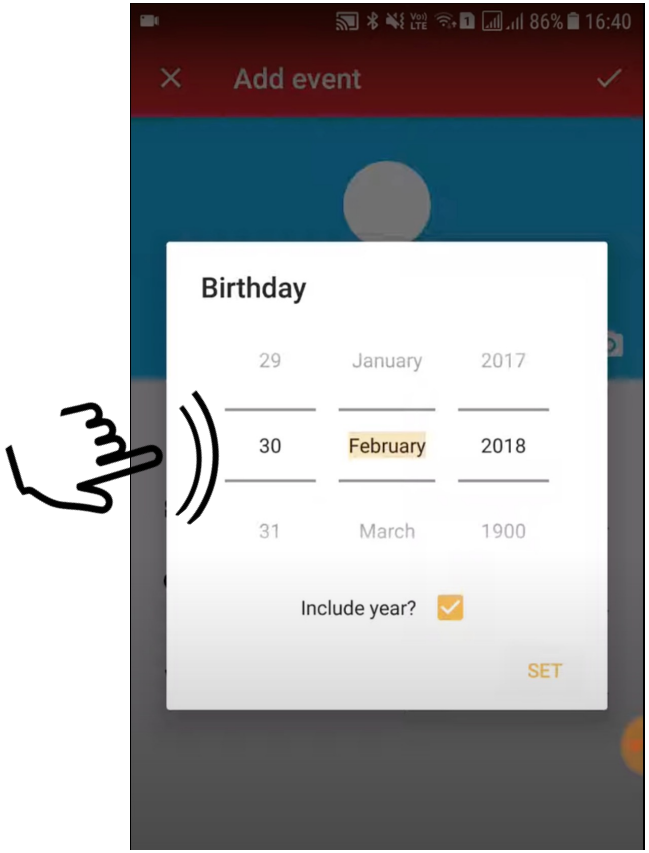
Buggy Android App

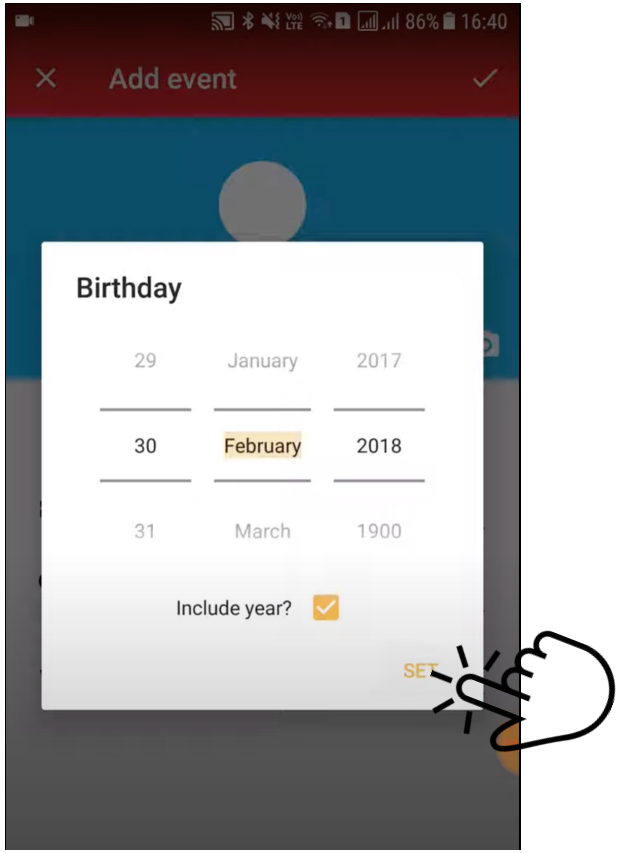


User selects monthly recurring event day

Buggy Android App



User selects monthly recurring event day



Crash! There's no February 30th!

Debugging

```
Date date = new Date(day,month,year);
```

Debugging

```
int day = userInput.d;

Date date = new Date(day,month,year);
```

Debugging

```
bar() {

    foo(selected);
}
foo(Object userInput) {
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```

Debugging

```
bar() {

    selected.d = picker.getValue();

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foo(Object userInput) {
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Debugging

```
bar() {

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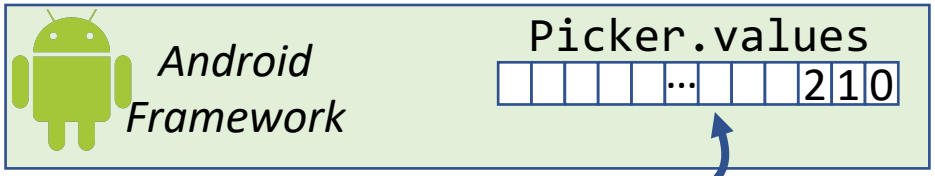


Debugging

```
bar() {

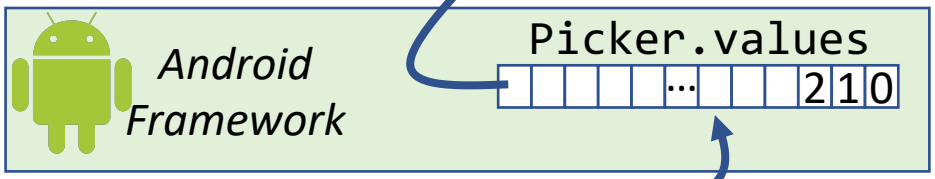
    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
foo(Object userInput) {

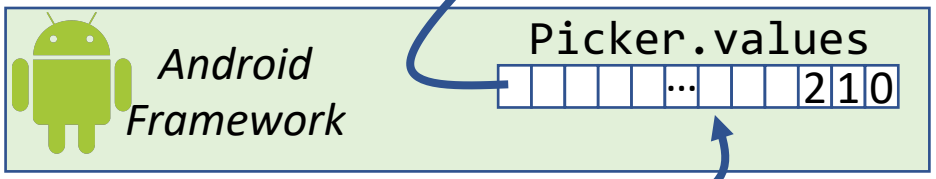
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```



Debugging

```
bar() {
    picker.setMaxValue(31);
```




```
    selected.d = picker.getValue();

    foo(selected);
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foo(Object userInput) {
    int day = userInput.d;

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```

Automated by slicing
slice << code size

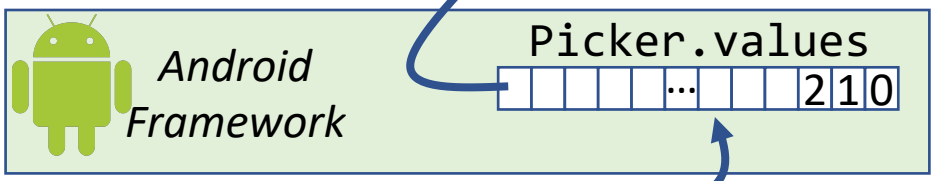
Debugging with Slicing

```
bar() {
    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
foo(Object userInput) {
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```



= Data-flow

Challenge1: Fields

```
bar() {

    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
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    int day = userInput.d;

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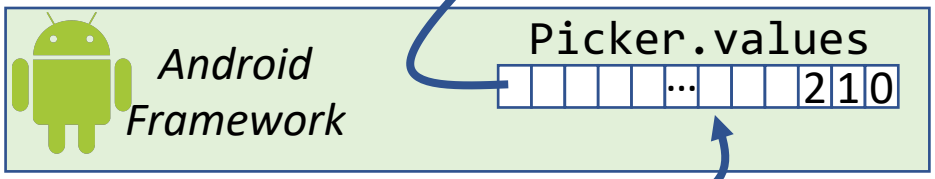

Challenge1: Fields

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    picker.setMaxValue(31);

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    Date date = new Date(day,month,year);
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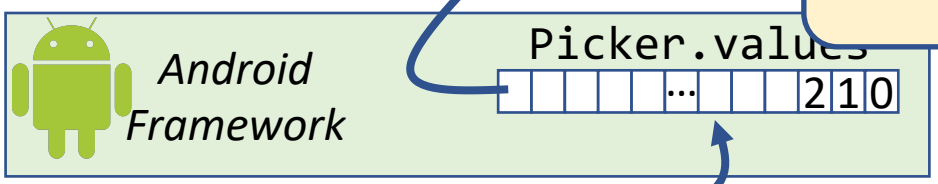

Same field, different names

Challenge1: Fields

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bar() {
    picker.setMaxValue(31);

    selected.d = picker.getValue();

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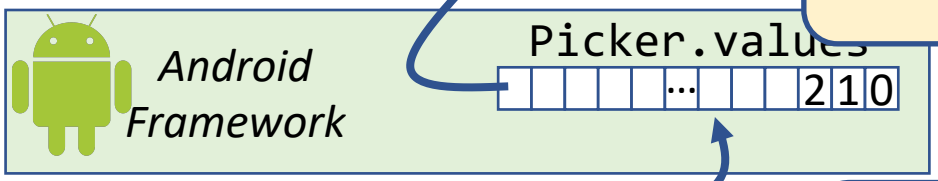
```



Same field, different names

Simple solution:
record memory address
= slow for Android

Challenge1: Fields

```
bar() {
    picker.setMaxValue(31);

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    int day = userInput.d;

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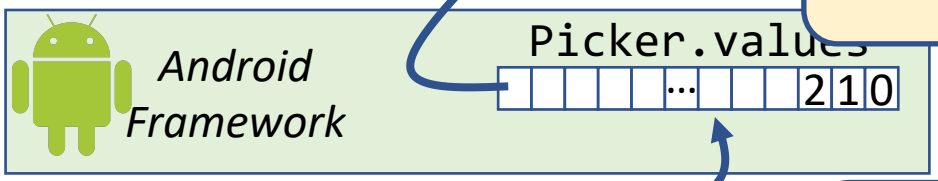


Same field, different names

Simple solution:
record memory address
= slow for Android

Android kills slow apps

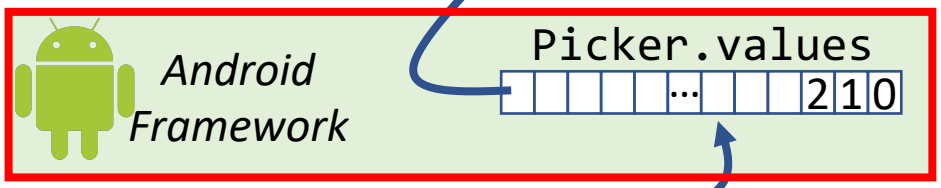
Challenge2: Framework

```
bar() {
    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
foo(Object userInput) {
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```



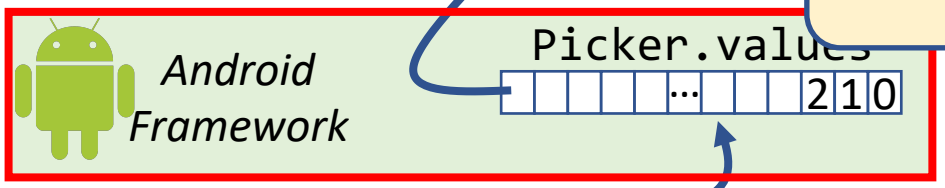
Challenge2: Framework

```
bar() {
    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
foo(Object userInput) {
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```



Rely on framework methods

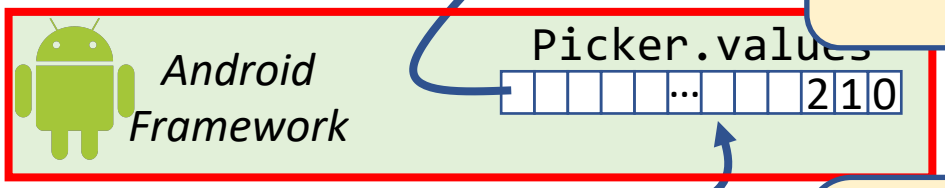
Challenge2: Framework

```
bar() {
    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
foo(Object userInput) {
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```



Rely on framework methods

Simple solution:
Instrument entire framework

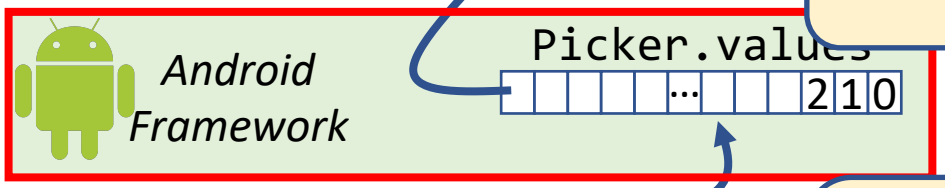
Challenge2: Framework

```
bar() {
    picker.setMaxValue(31);

    selected.d = picker.getValue();

    foo(selected);
}
foo(Object userInput) {
    int day = userInput.d;

    Date date = new Date(day,month,year);
}
```



Rely on framework methods

Simple solution:
Instrument entire framework

Not practical

Our Insight

Our Insight

`selected.d`

↑

`userInput.d`

→

Light-weight Instrumentation on-device

+

field data-flow analysis on the trace

Our Insight

`selected.d`

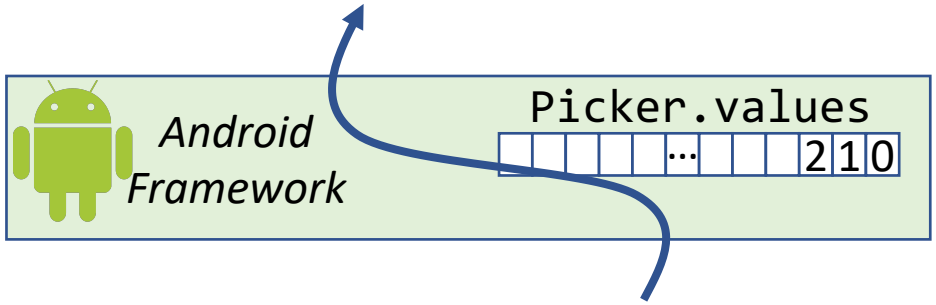
↑

`userInput.d`

→ Light-weight Instrumentation on-device

+

field data-flow analysis on the trace



→ framework modeling

Trace-Based Field Analysis

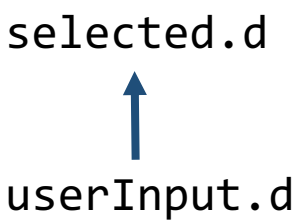
Goal: Field data-flows w/o object addresses

```
selected.d
     ↑
userInput.d
```

Trace-Based Field Analysis

Goal: Field data-flows w/o object addresses

- How to produce a trace with light-weight instrumentation?



Trace-Based Field Analysis

Goal: Field data-flows w/o object addresses

```
selected.d
    ↑
userInput.d
```

- How to produce a trace with light-weight instrumentation?
- What information to use in the trace instead of object addresses?

Light-Weight Instrumentation

```
jane.age = 15
john     = jane
john.age = 25
res = jane.age
```

Light-Weight Instrumentation

```
1  jane.age = 15
2  john     = jane
3  john.age = 25
4  res = jane.age
```

Record executed statement IDs

Field Data-Flow Analysis

```
1  jane.age = 15
2  john     = jane
3  john.age = 25
4  res = jane.age
```

Field Data-Flow Analysis

```
1   jane.age = 15
2   john     = jane
3   john.age = 25
4   res = jane.age
```

use

Field Data-Flow Analysis

```
1   jane.age = 15
2   john     = jane
3   john.age = 25
4   res = jane.age
```

use

Field Data-Flow Analysis

```
1   jane.age = 15
2   john     = jane
3   john.age = 25
4   res = jane.age
```

definition?

use

Field Data-Flow Analysis

```
1   jane.age = 15
2   john     = jane
3   john.age = 25
4   res = jane.age
```

definition?

use

Field Data-Flow Analysis

```
     john aliases jane
john.age aliases jane.age
```

```
age = 15
```

definition?

```
2  john      = jane

3  john.age = 25

4  res = jane.age
```

use

Field Data-Flow Analysis

```
     john aliases jane
john.age aliases jane.age
```

```
age = 15
```

definition?

```
2  john      = jane
```

definition

```
3  john.age = 25
```

```
4  res = jane.age
```

use

Field Alias Analysis

```
1  jane.age = 15
2  john     = jane
3  john.age = 25
4  res = jane.age
```

Field Alias Analysis

```
1   jane.age = 15
2   john     = jane
3   john.age = 25
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use

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1   jane.age = 15
2   john     = jane
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use

Field Alias Analysis

```
1   jane.age = 15
2   john     = jane
3   john.age = 25
4   res = jane.age
```

use

Field Alias Analysis

Search for `john.age` too

```
1  jane.age = 15
2  john     = jane
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4  res = jane.age
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use

Field Alias Analysis

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use

Field Alias Analysis

Search for `john.age` too

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1  jane.age = 15
2  john     = jane
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definition

use

Field Alias Analysis

Search for `john.age` too

```
1  jane.age = 15
2  john     = jane
3  john.age = 25
4  res = jane.age
```

definition

use

Backward + forward analysis on trace

Field Alias Analysis

```
Input: ICDG, t, v
Output: T'
begin
    V ← {v}                                          ▹ Aliases of the variable v
    S ← BackwardAnalysis(ICDG, V, t)                 ▹ Alias statements
    return LastDefined(S, t)                         ▹ Definitions of v and its fields

Procedure BackwardAnalysis(ICDG, V, t)
    begin
        S ← ∅
        ▹ Traverse the ICDG in inverse execution order
        foreach t' s.t. (t', t) ∈ ICDG do
            if method(t) ≠ method(t') then
                V ← ChangeScope(V, method(t), method(t'))
            if ∃v ∈ V s.t. v and LHS(t') have a common prefix then
                ▹ t' is a definition of a variable in V
                S ← S ∪ {t'}                         ▹ Add the definition statement
            <V_b,V_f> ← AliasAnalysis(↑, V, t')
            S ← S ∪ BackwardAnalysis(ICDG, V_b, t')
            S ← S ∪ ForwardAnalysis(ICDG, V_f, t')
        return S

Procedure ForwardAnalysis(ICDG, V, t)
    begin
        S ← ∅
        ▹ Traverse the ICDG in execution order
        foreach t' s.t. (t, t') ∈ ICDG do
            if method(t) ≠ method(t') then
                V ← ChangeScope(V, method(t), method(t'))
            if ∃v ∈ V s.t. v is a prefix of LHS(t') then
                ▹ t' is a definition of a field of a variable in V
                S ← S ∪ {t'}                         ▹ Add the definition statement
            <V_b,V_f> ← AliasAnalysis(↓, V, t')
            S ← S ∪ BackwardAnalysis(ICDG, V_b, t')
            S ← S ∪ ForwardAnalysis(ICDG, V_f, t')
        return S

Procedure AliasAnalysis(d, V, t')
    ▹ Initialize with the original set of variables
    if d =↑ then
        V_b ← V; V_f ← ∅
    else if d =↓ then
        V_b ← ∅; V_f ← V
    foreach v ∈ V s.t. v and RHS(t') have a common prefix do
        ▹ LHS(t') is a new alias for v
        V_f ← V_f ∪ ExtendFields(LHS(t'))            ▹ Follow it forward
    foreach v ∈ V s.t. v is a prefix of LHS(t') do
        ▹ t' is a re-definition of a field of v
        ▹ Follow the assigned variable both backward and forward
        V_b ← V_b ∪ RHS(t')
        V_f ← V_f ∪ RHS(t')
    foreach v ∈ V s.t. LHS(t') is a prefix or equal to v do
        ▹ t' is a full re-definition of v
        if d =↑ then
            V_b ← V_b \ {v}                          ▹ Do not search before the definition
            ▹ Follow the assigned variable both backward and forward
            V_b ← V_b ∪ ExtendFields(RHS(t'))
            V_f ← V_f ∪ ExtendFields(RHS(t'))
        else if d =↓ then
            V_f ← V_f \ {v}                          ▹ Do not search for new variables
    return <V_b,V_f>
```

Field Alias Analysis

```
Input: ICDG, t, v
Output: T'
begin
    V ← {v}                                          ▹ Aliases of the variable v
    S ← BackwardAnalysis(ICDG, V, t)                 ▹ Alias statements
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Procedure BackwardAnalysis(ICDG, V, t)
    begin
        S ← ∅
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        foreach t' s.t. (t', t) ∈ ICDG do
            if method(t) ≠ method(t') then
                V ← ChangeScope(V, method(t), method(t'))
            if ∃v ∈ V s.t. v and LHS(t') have a common prefix then
                ▹ t' is a definition of a variable in V
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            <V_b,V_f> ← AliasAnalysis(↑, V, t')
            S ← S ∪ BackwardAnalysis(ICDG, V_b, t')
            S ← S ∪ ForwardAnalysis(ICDG, V_f, t')
        return S
Procedure ForwardAnalysis(ICDG, V, t)
    begin
        S ← ∅
        ▹ Traverse the ICDG in execution order
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            if method(t) ≠ method(t') then
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            if ∃v ∈ V s.t. v is a prefix of LHS(t') then
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        return S
Procedure AliasAnalysis(d, V, t')
    ▹ Initialize with the original set of variables
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        ▹ Follow the assigned variable both backward and forward
        V_b ← V_b ∪ RHS(t')
        V_f ← V_f ∪ RHS(t')
    foreach v ∈ V s.t. LHS(t') is a prefix or equal to v do
        ▹ t' is a full re-definition of v
        if d =↑ then
            V_b ← V_b \ {v}                          ▹ Do not search before the definition
            ▹ Follow the assigned variable both backward and forward
            V_b ← V_b ∪ ExtendFields(RHS(t'))
            V_f ← V_f ∪ ExtendFields(RHS(t'))
        else if d =↓ then
            V_f ← V_f \ {v}                          ▹ Do not search for new variables
    return <V_b,V_f>
```

Search for field definitions <u>backward</u>

Field Alias Analysis

```
Input: ICDG, t, v
Output: T'
begin
    V ← {v}                                          ▹ Aliases of the variable v
    S ← BackwardAnalysis(ICDG, V, t)                 ▹ Alias statements
    return LastDefined(S, t)                         ▹ Definitions of v and its fields

Procedure BackwardAnalysis(ICDG, V, t)
    begin
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            if method(t) ≠ method(t') then
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            S ← S ∪ BackwardAnalysis(ICDG, V_b, t')
            S ← S ∪ ForwardAnalysis(ICDG, V_f, t')
        return S

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            if ∃v ∈ V s.t. v is a prefix of LHS(t') then
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        return S

Procedure AliasAnalysis(d, V, t')
    ▹ Initialize with the original set of variables
    if d =↑ then
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        V_b ← V_b ∪ RHS(t')
        V_f ← V_f ∪ RHS(t')
    foreach v ∈ V s.t. LHS(t') is a prefix or equal to v do
        ▹ t' is a full re-definition of v
        if d =↑ then
            V_b ← V_b \ {v}                          ▹ Do not search before the definition
            ▹ Follow the assigned variable both backward and forward
            V_b ← V_b ∪ ExtendFields(RHS(t'))
            V_f ← V_f ∪ ExtendFields(RHS(t'))
        else if d =↓ then
            V_f ← V_f \ {v}                          ▹ Do not search for new variables
    return <V_b,V_f>
```

Search for field definitions <u>forward</u>

Field Alias Analysis

```
Input: ICDG, t, v
Output: T'
begin
    V ← {v}                                          ▷ Aliases of the variable v
    S ← BackwardAnalysis(ICDG, V, t)                 ▷ Alias statements
    return LastDefined(S, t)                         ▷ Definitions of v and its fields

Procedure BackwardAnalysis(ICDG, V, t)
    begin
        S ← ∅
        ▷ Traverse the ICDG in inverse execution order
        foreach t' s.t. (t', t) ∈ ICDG do
            if method(t) ≠ method(t') then
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            if ∃v ∈ V s.t. v and LHS(t') have a common prefix then
                ▷ t' is a definition of a variable in V
                S ← S ∪ {t'}                         ▷ Add the definition statement
            <V_b,V_f> ← AliasAnalysis(↑, V, t')
            S ← S ∪ BackwardAnalysis(ICDG, V_b, t')
            S ← S ∪ ForwardAnalysis(ICDG, V_f, t')
        return S

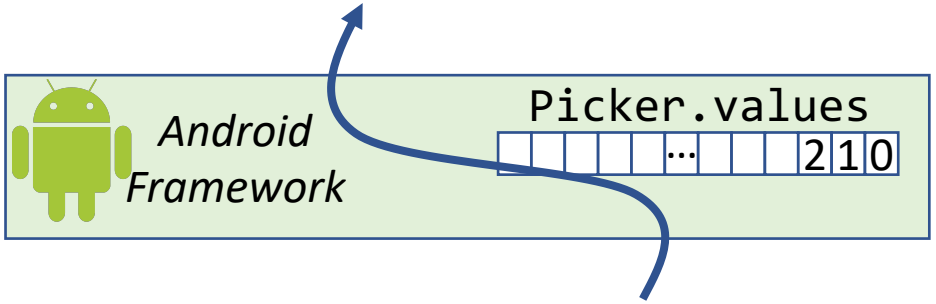
Procedure ForwardAnalysis(ICDG, V, t)
    begin
        S ← ∅
        ▷ Traverse the ICDG in execution order
        foreach t' s.t. (t, t') ∈ ICDG do
            if method(t) ≠ method(t') then
                V ← ChangeScope(V, method(t), method(t'))
            if ∃v ∈ V s.t. v is a prefix of LHS(t') then
                ▷ t' is a definition of a field of a variable in V
                S ← S ∪ {t'}                         ▷ Add the definition statement
            <V_b,V_f> ← AliasAnalysis(↓, V, t')
            S ← S ∪ BackwardAnalysis(ICDG, V_b, t')
            S ← S ∪ ForwardAnalysis(ICDG, V_f, t')
        return S
```

```
Procedure AliasAnalysis(d, V, t')
    ▷ Initialize with the original set of variables
    if d =↑ then
        V_b ← V; V_f ← ∅
    else if d =↓ then
        V_b ← ∅; V_f ← V
    foreach v ∈ V s.t. v and RHS(t') have a common prefix do
        ▷ LHS(t') is a new alias for v
        V_f ← V_f ∪ ExtendFields(LHS(t'))            ▷ Follow it forward
    foreach v ∈ V s.t. v is a prefix of LHS(t') do
        ▷ t' is a re-definition of a field of v
        ▷ Follow the assigned variable both backward and forward
        V_b ← V_b ∪ RHS(t')
        V_f ← V_f ∪ RHS(t')
    foreach v ∈ V s.t. LHS(t') is a prefix or equal to v do
        ▷ t' is a full re-definition of v
        if d =↑ then
            V_b ← V_b \ {v}                          ▷ Do not search before the definition
            ▷ Follow the assigned variable both backward and forward
            V_b ← V_b ∪ ExtendFields(RHS(t'))
            V_f ← V_f ∪ ExtendFields(RHS(t'))
        else if d =↓ then
            V_f ← V_f \ {v}                          ▷ Do not search for new variables
    return <V_b,V_f>
```

Decide on variables to search for and the direction

Framework Data-Flows

Goal: Data-flows inside the Framework



How to find data-flows inside framework w/o instrumentation?

Taint-Propagation Models

StubDroid [1] & FlowDroid [2]

[1] Arzt, Steven, and Eric Bodden. "StubDroid: automatic inference of precise data-flow summaries for the android framework." ICSE, 2016
[2] Arzt, Steven, et al. "FlowDroid: Precise context, flow, field, object-sensitive and lifecycle-aware taint analysis for android apps." PLDI, 2014

Taint-Propagation Models

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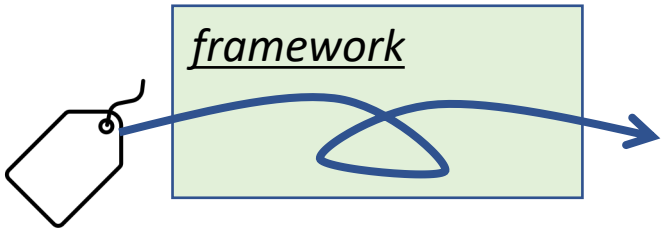

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Taint-Propagation Models

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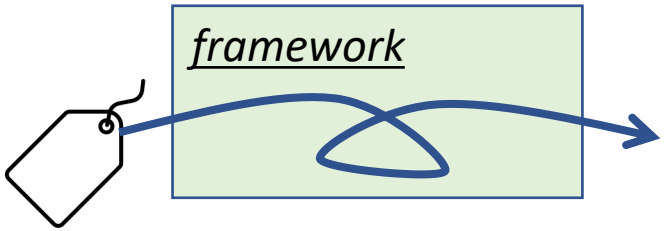

Express how taint propagates

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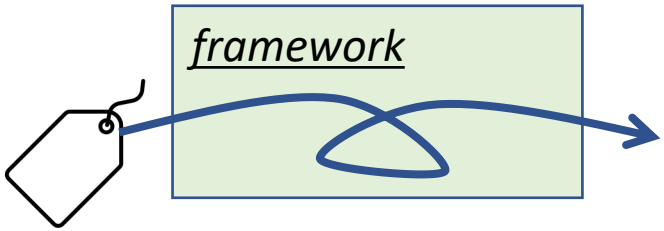
Taint-Propagation Models

StubDroid [1] & FlowDroid [2]



Express how taint propagates

From:

- Parameters
- Receiver

} + Fields

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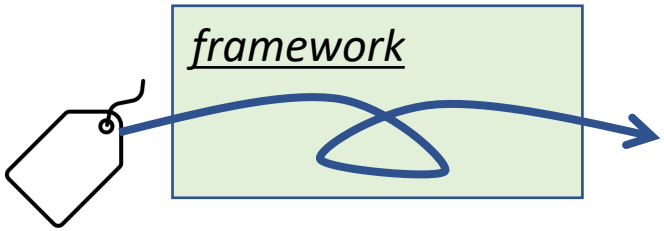
[2] Arzt, Steven, et al. "FlowDroid: Precise context, flow, field, object-sensitive and lifecycle-aware taint analysis for android apps." PLDI, 2014

Taint-Propagation Models

StubDroid [1] & FlowDroid [2]



Express how taint propagates

From:

- Parameters
- Receiver

} + Fields

To:

- Parameters
- Receiver
- Return

} + Fields

[1] Arzt, Steven, and Eric Bodden. "StubDroid: automatic inference of precise data-flow summaries for the android framework." ICSE, 2016
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Taint-Propagation Models

```
Array::set(index, value) {
    this.inA[index] = value;
}
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Taint-propagation:

`value` → `this.inA`

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Taint-propagation:

`value` → `this.inA`

`index` ✗

`this` ✗

Taint-Propagation Models

```
Array::set(index, value) {
    this.inA[index] = value;
}
```

```
Log::info(value) {
    print(value);
}
```

Taint-propagation:

value → this.inA

index ✗→

this ✗→

Taint-Propagation Models

```
Array::set(index, value) {
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Taint-propagation:

`value` → `this.inA`

`index` ✗

`this` ✗

`value` ✗

Taint-Propagation Models

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Array::set(index, value) {
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Taint-propagation:

value → this.inA

index ✗

this ✗

```
Log::info(value) {
  print(value);
}
```

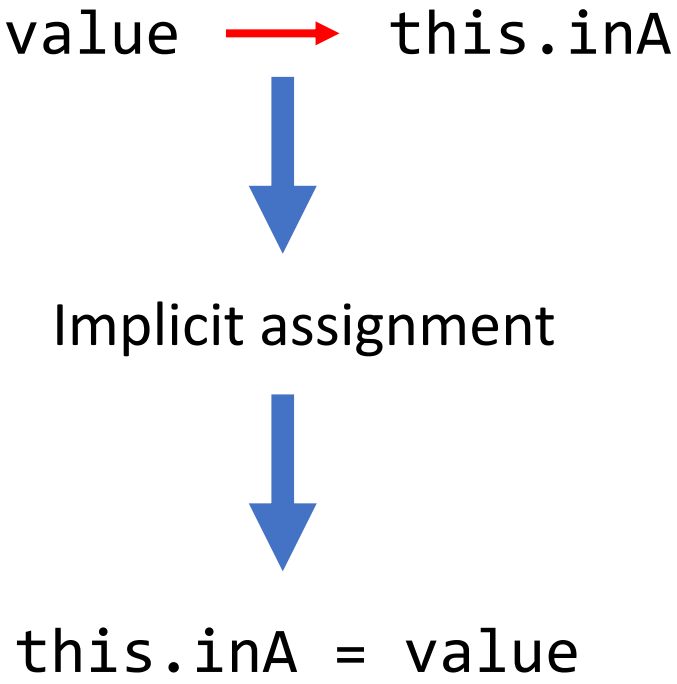
value ✗

Accurate taint propagation rules for Java and Android methods

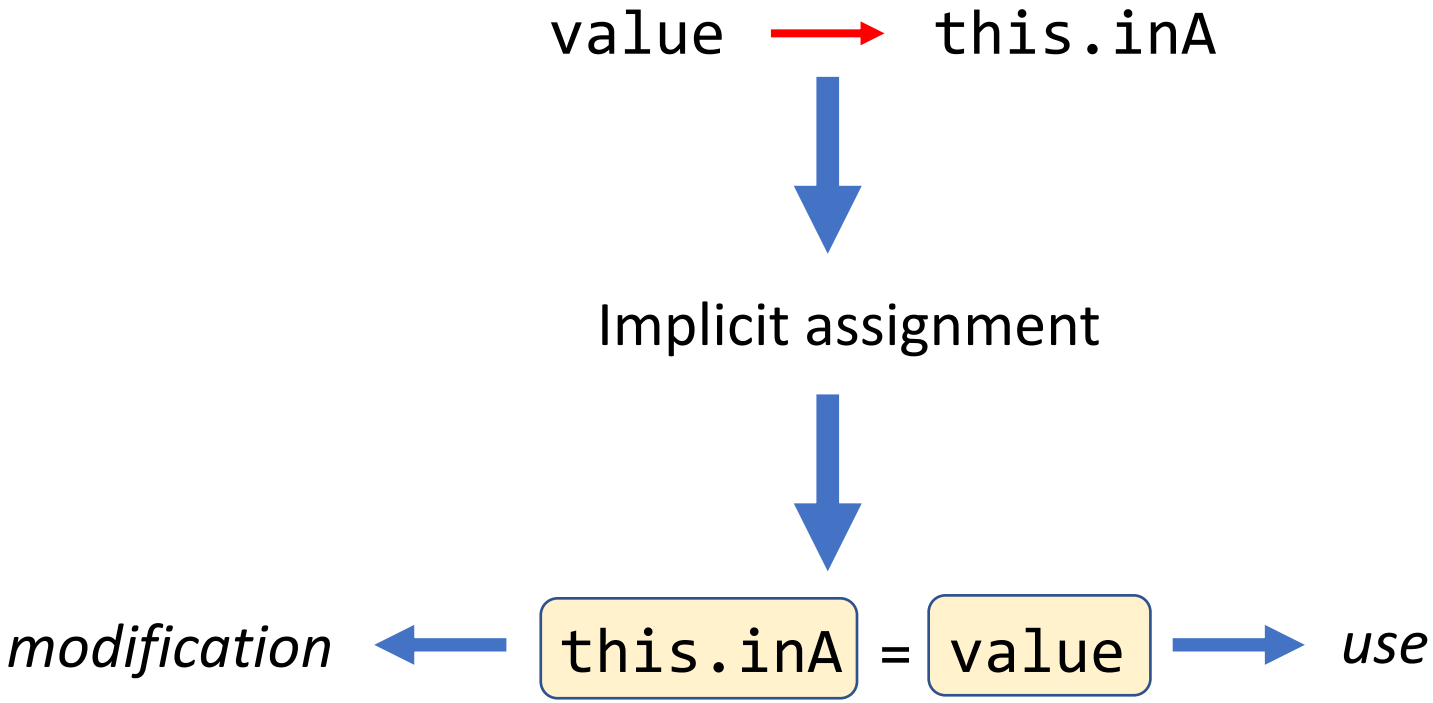
Modeling w/ Implicit Assignemnts

`value` → `this.inA`

Modeling w/ Implicit Assignemnts



Modeling w/ Implicit Assignemnts



Framework Modeling: Example

Code	Model
`x = 5`	
`array.set(1, x)`	
`y = array.get(1)`	`y = array.inA`

Framework Modeling: Example

Code

```
x = 5

array.set(1, x)

y = array.get(1)
```

Model

```
y = array.inA
```

Framework Modeling: Example

Code		Model
`x = 5`		
`array.set(1, x)`	→	`array.inA = x`
`y = array.get(1)`	→	`y = array.inA`

Framework Modeling: Example

Code		Model
`x = 5`		
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Framework Modeling: Example

Code		Model
`x = 5`		
`array.set(1, x)`	→	`array.inA = x`
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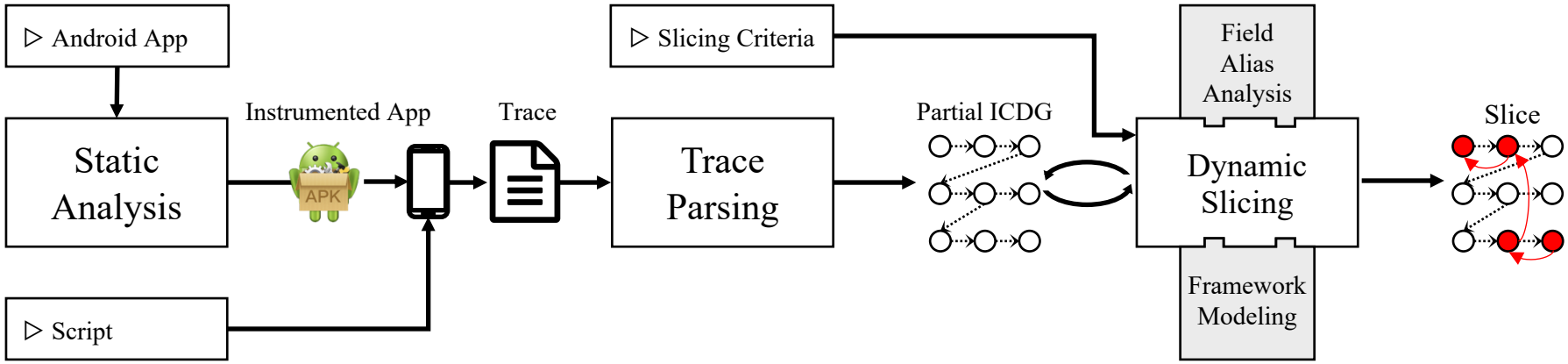
Our Solution: MANDOLINE



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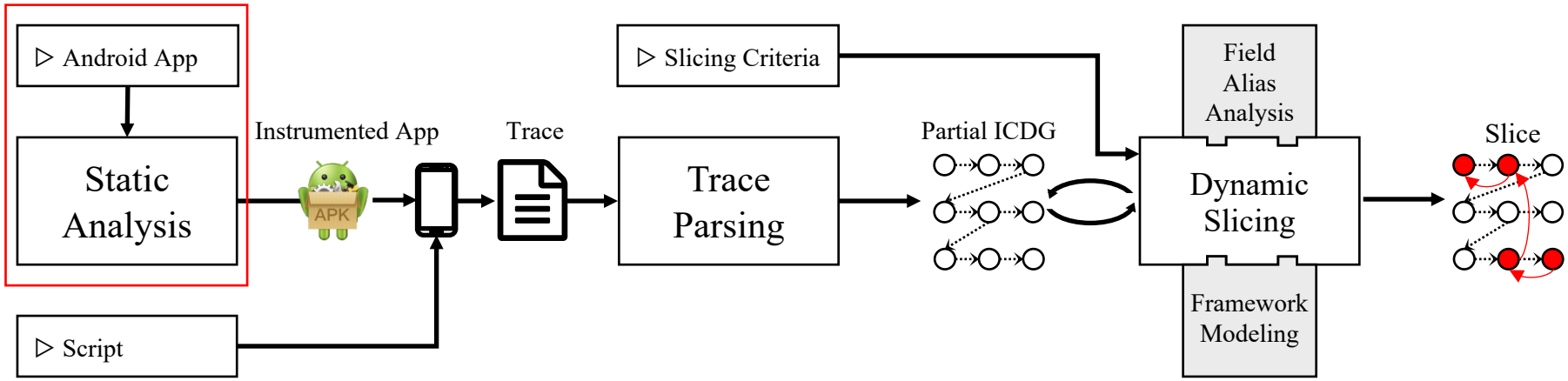

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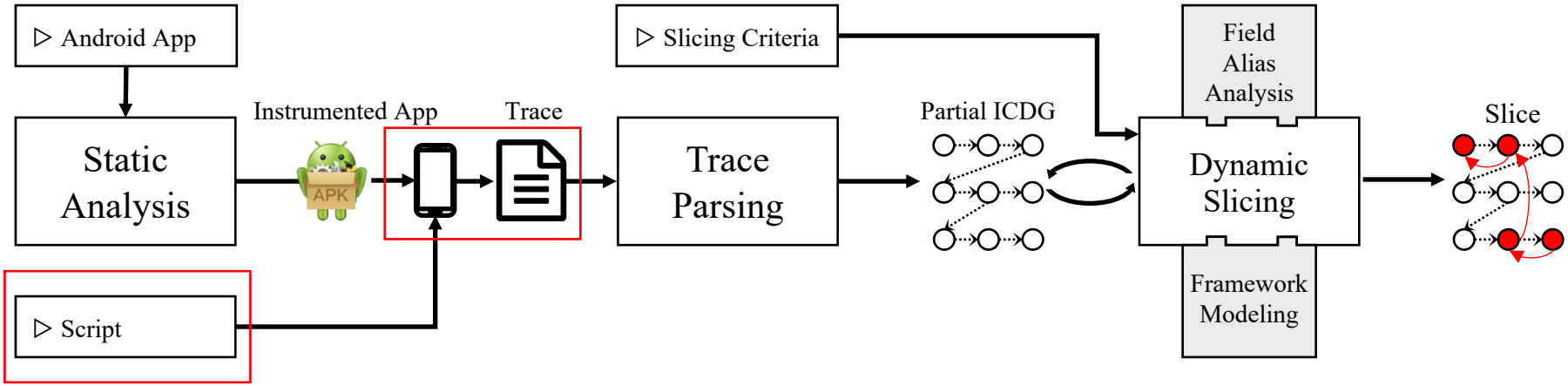

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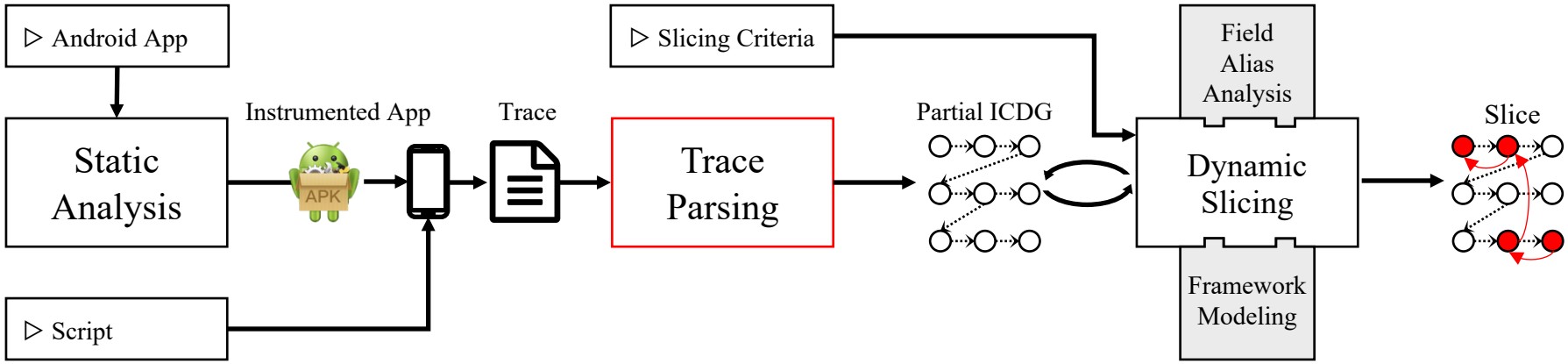

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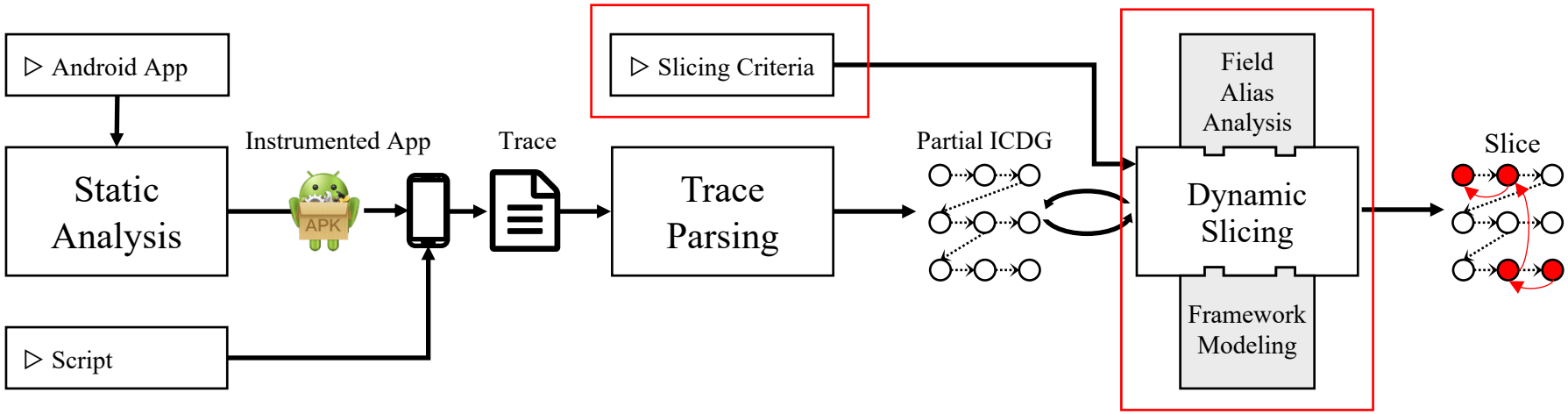


Evaluation

RQ1: Accuracy

vs. state-of-the-art

RQ2: Performance

Subjects

12 Apps from DroixBench [3] and ReCDroid [4]

- Faulty apps w/ crashes
- Reproducible crashes
- Crashes = slicing criteria

[3] Tan, Shin Hwei, et al. "Repairing crashes in android apps." ICSE, 2018.
[4] Zhao, Yu, et al. "Recdroid: automatically reproducing android application crashes from bug reports." ICSE, 2019

Baseline

AndroidSlicer [5] (state-of-the-art)

- First slicer for Android apps
- Inter-callback data-flows
- Misses data-flows in fields and framework

AndroidSlicer++:

- Fixed implementation issues
- Improved instrumentation
- Allows fair comparison

[5] Azim, Tanzirul, et al. "Dynamic slicing for android." ICSE, 2019

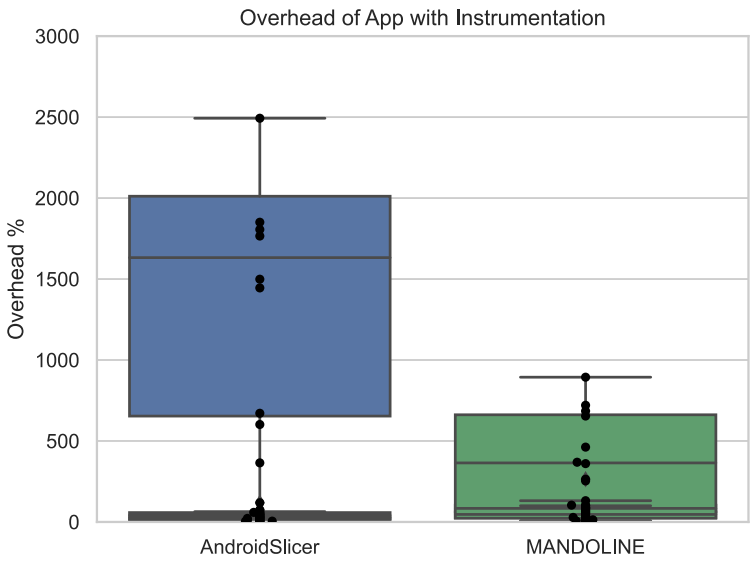
Benchmark

Manually produced slices

- Cross validated by two researchers
- First Android slices benchmark
- State-of-the-art [5] only compared slice to trace sizes

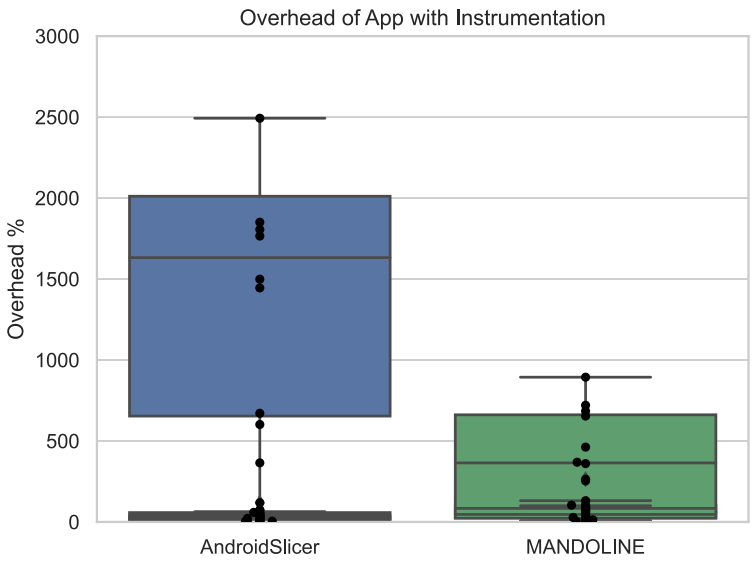
[5] Azim, Tanzirul, et al. "Dynamic slicing for android." ICSE, 2019

Accuracy and Peformance



Accuracy and Peformance

RQ1



Accuracy and Peformance

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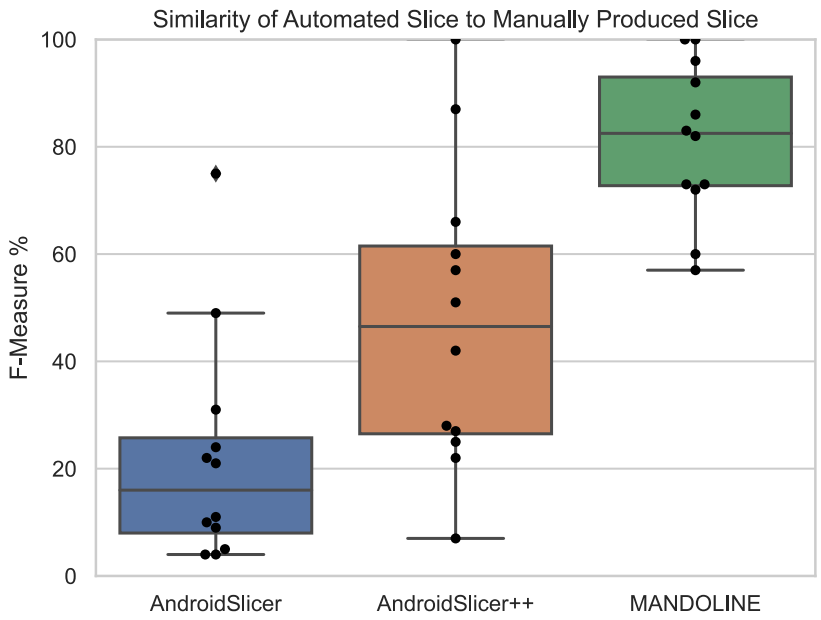
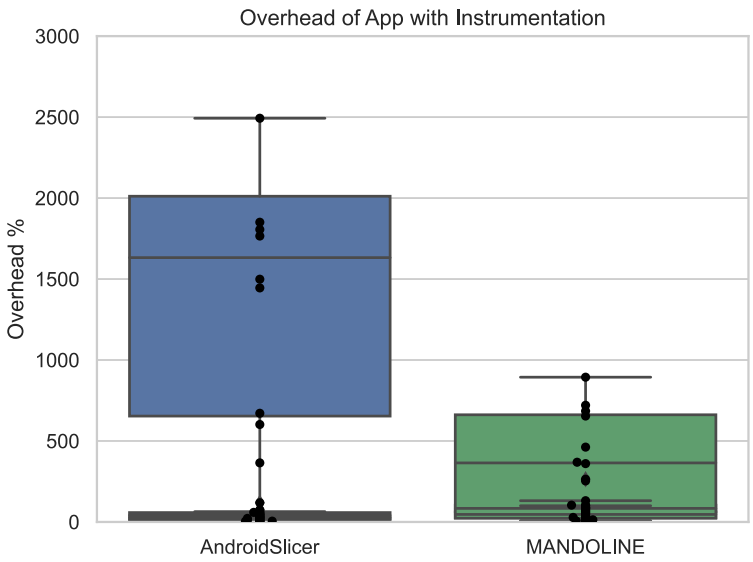
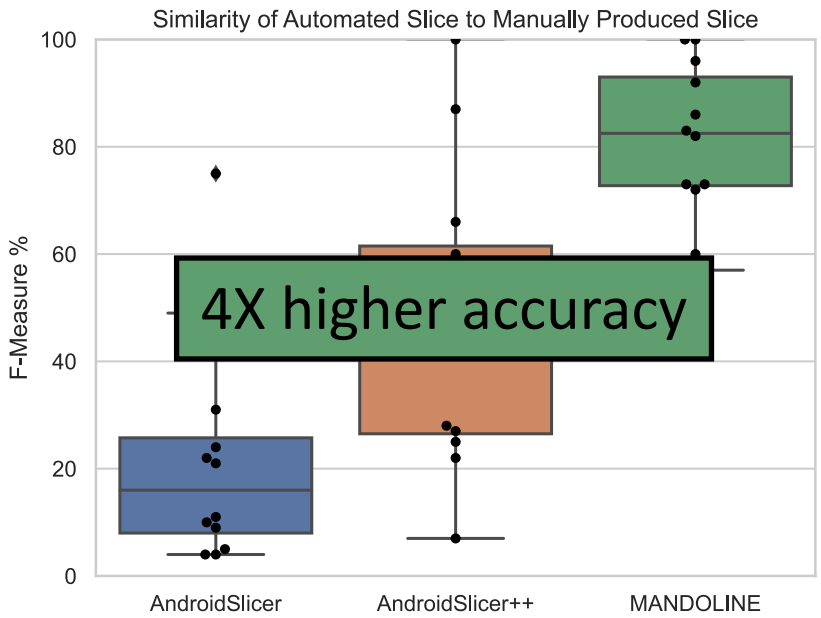
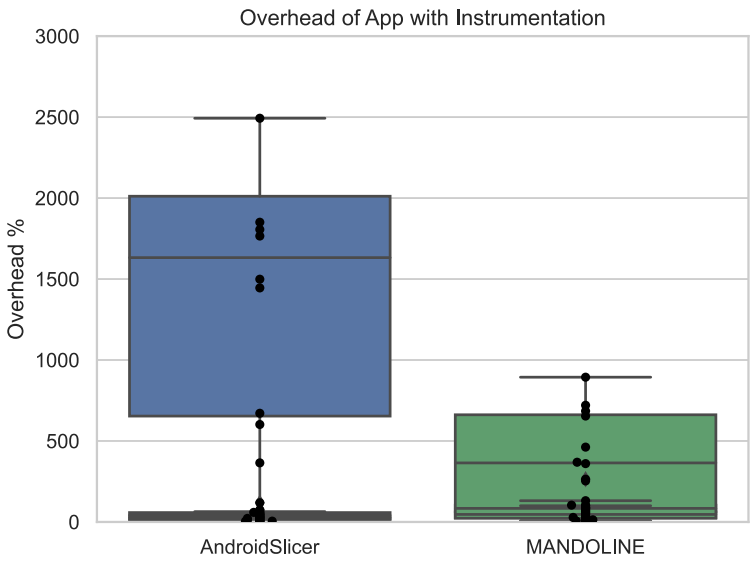




Accuracy and Peformance

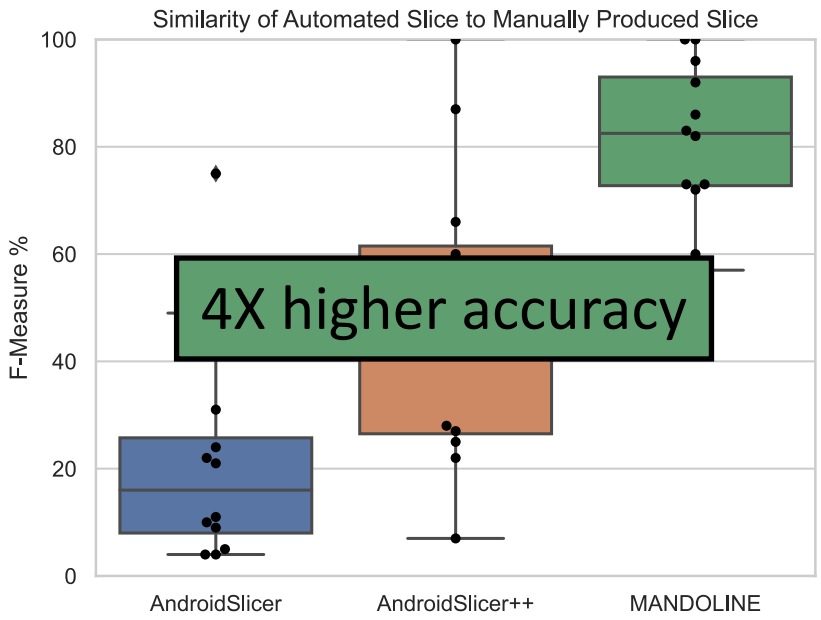
RQ1



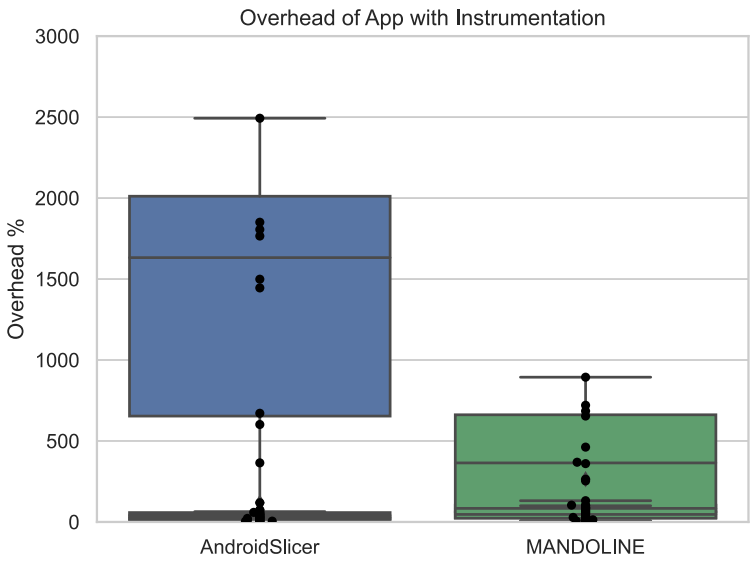


Accuracy and Peformance

RQ1



RQ2



Accuracy and Peformance

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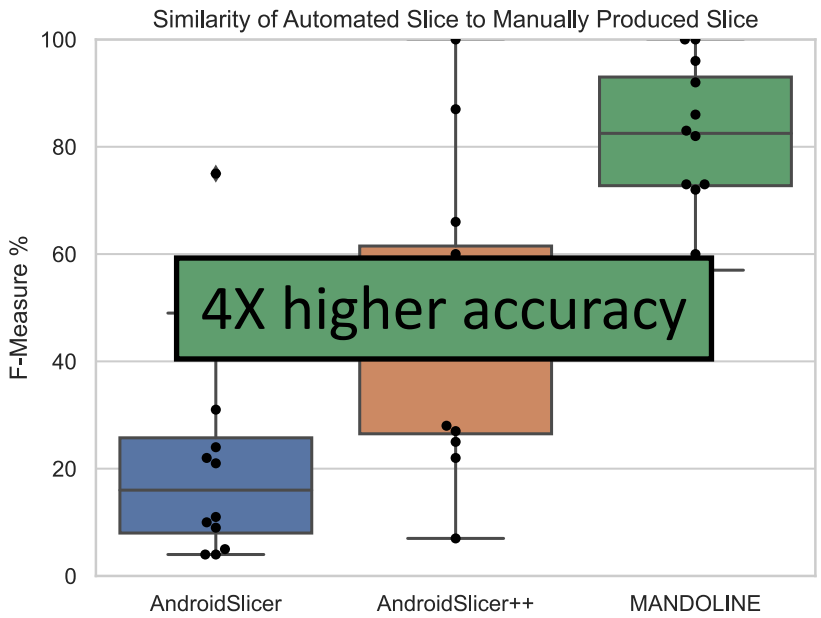

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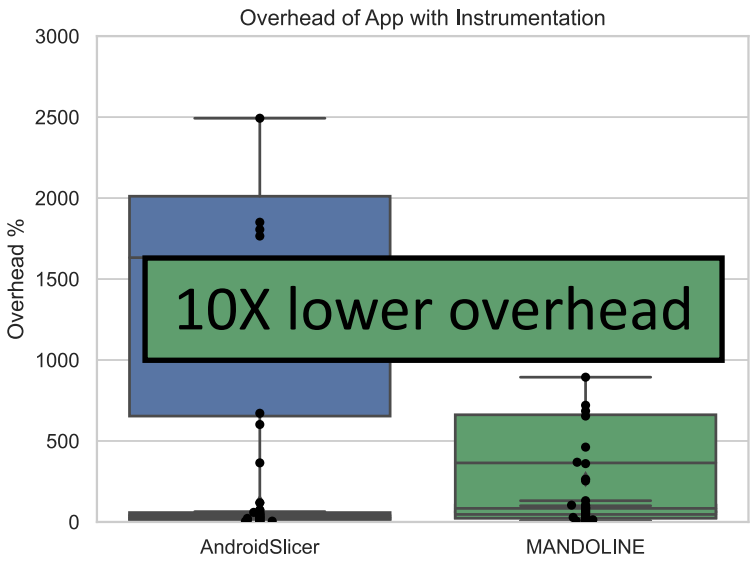

Accuracy and Peformance

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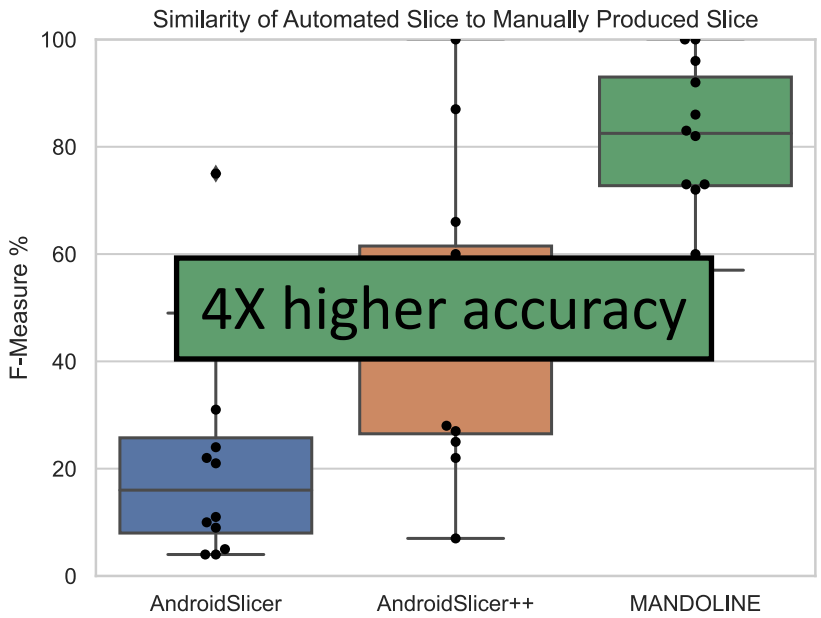

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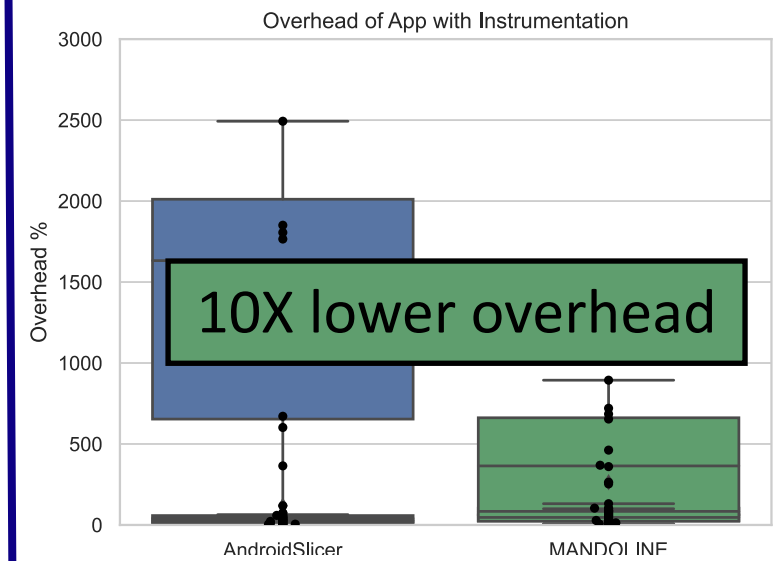

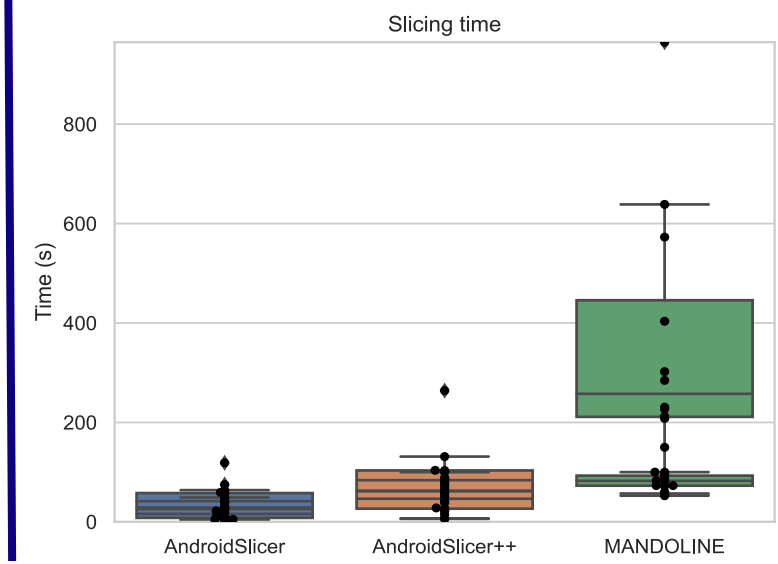

Accuracy and Peformance

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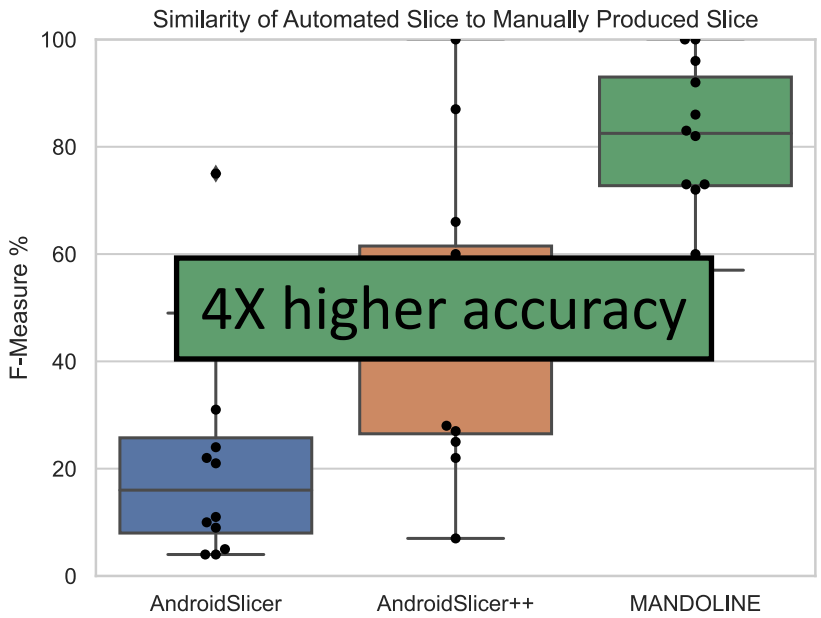
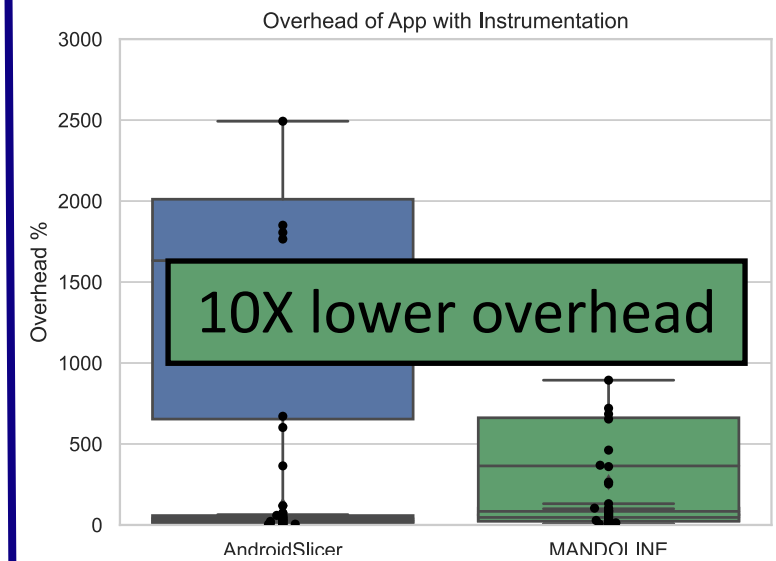
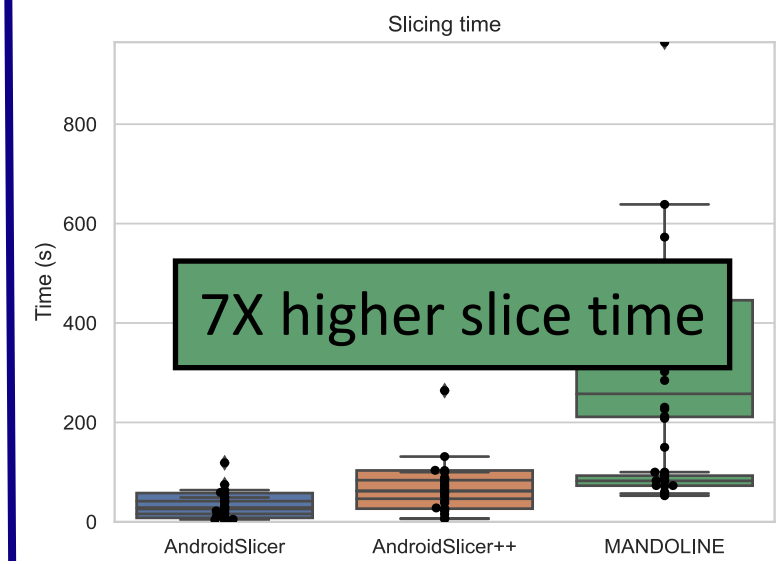


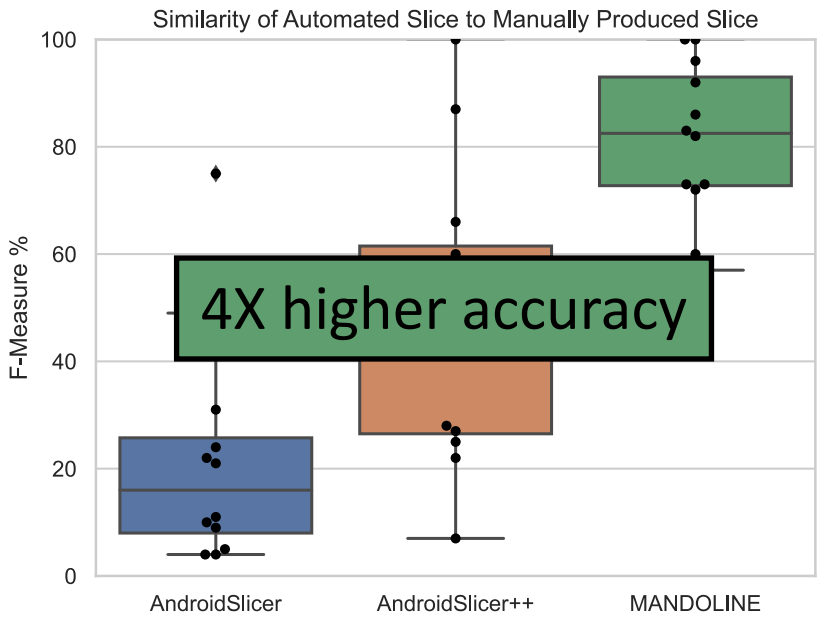
RQ2





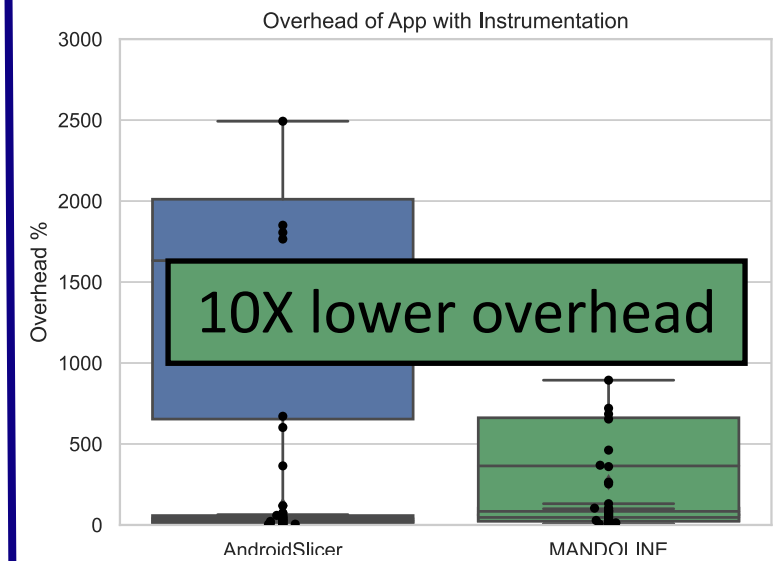
Accuracy and Peformance

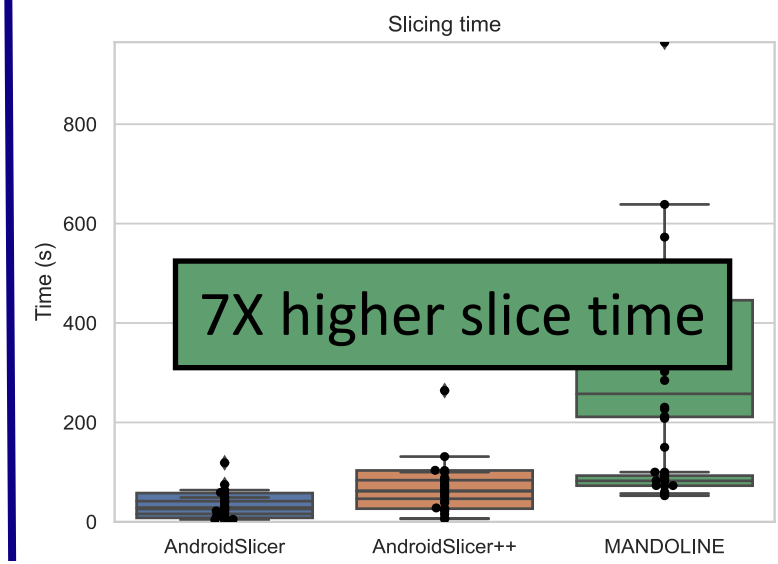
RQ1



Acceptable slice time given huge accuracy improvement

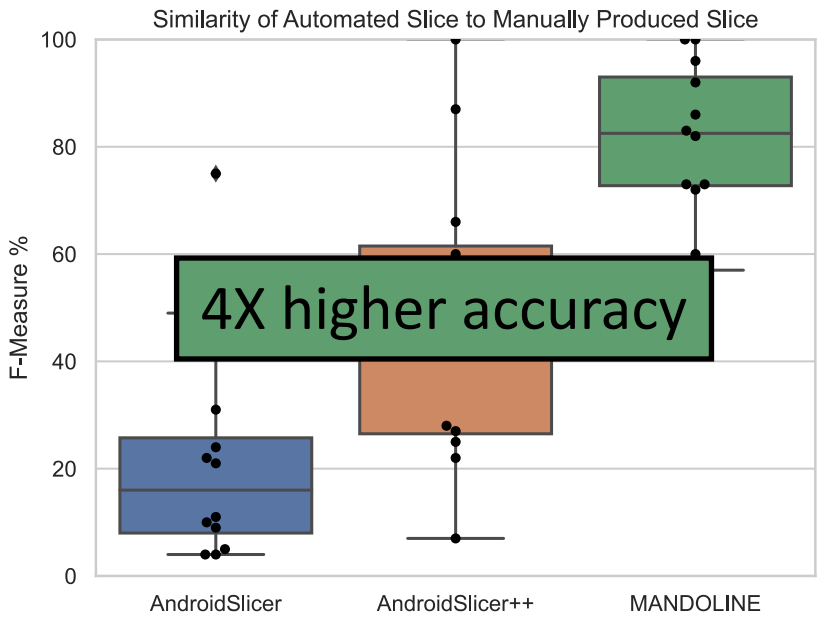
RQ2





Accuracy and Peformance

RQ1



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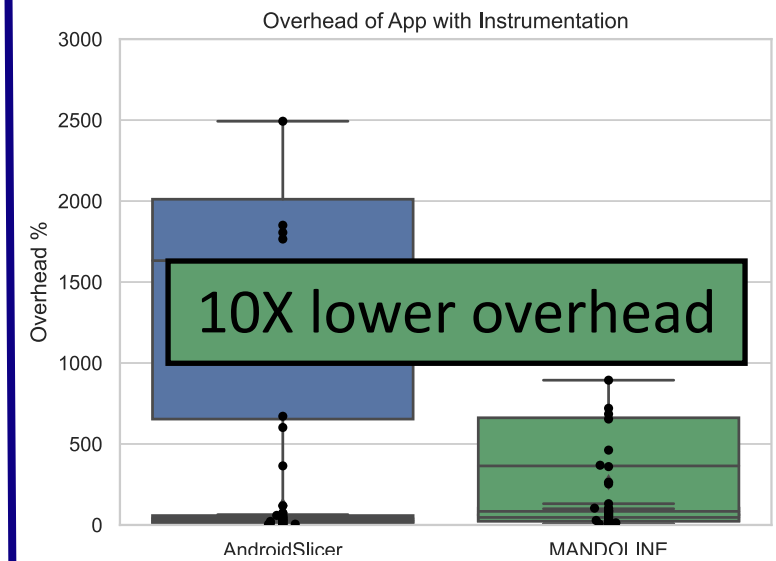
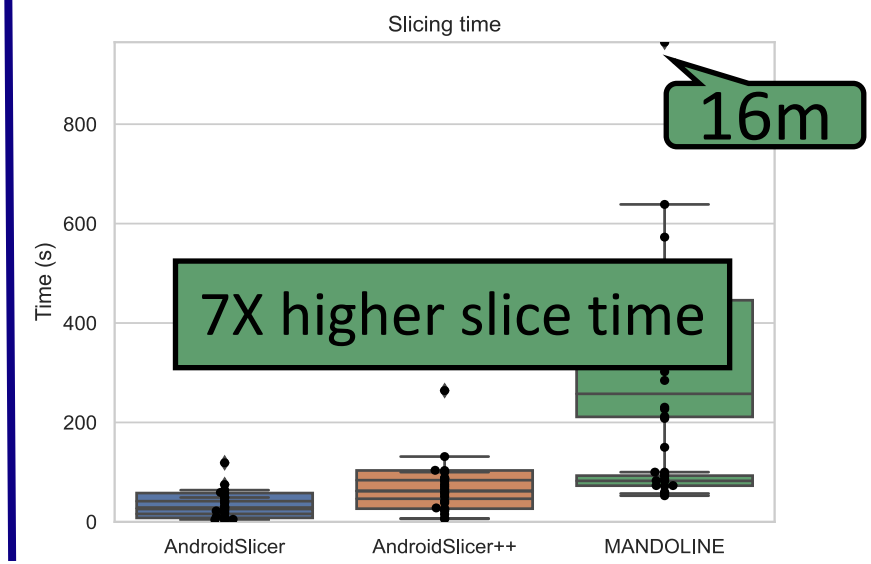


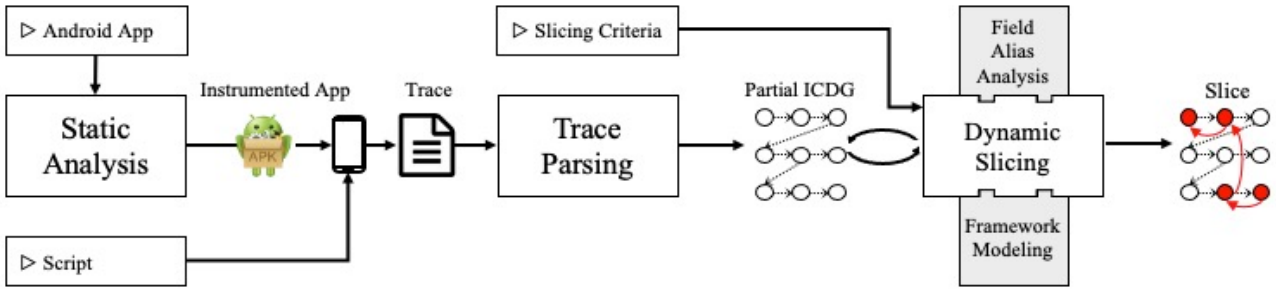


Summary

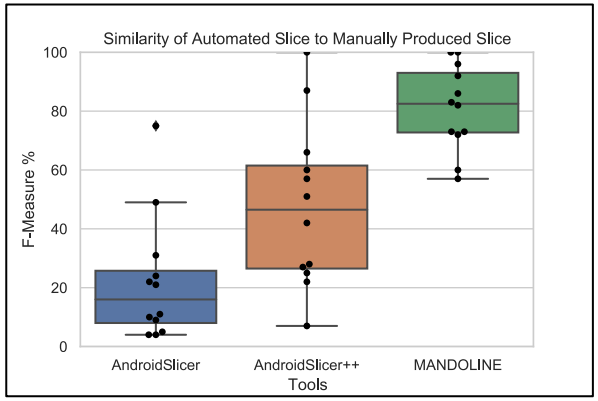
Insights

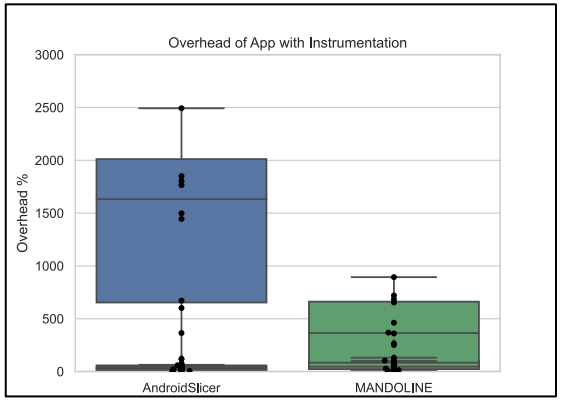
- Extract field data flows from the trace using alias analysis
- Use framework models from static analysis

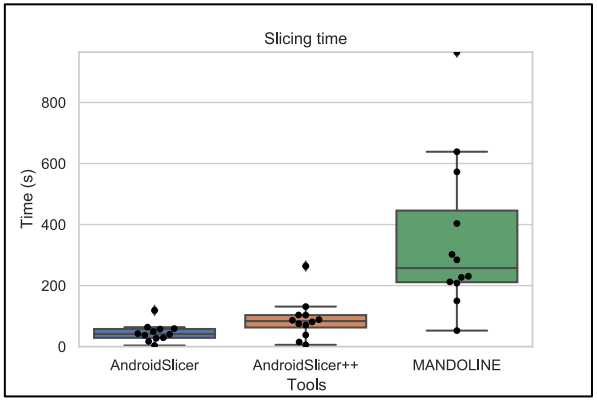
Approach



Results







Code + Benchmark suite: https://resess.github.io/PaperAppendices/Mandoline/

Contact: Khaled Ahmed, UBC, khaledea@ece.ubc.ca