Static Analysis for Android: GUIs, Callbacks, and Beyond

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Take-Home Messages

**Weak foundations** for static control-flow and data-flow analysis for Android GUIs

– Progress in the last few years [CGO14][ICSE15][AST15][PhD14][PhD15]
– Many open problems [SOAP16]

**Useful GUI models** built via static analysis

– Static analysis of resource leaks [CC16]
– Automated test generation [AST16][AST18]
– Responsiveness profiling [MobileSoft17]

**Interesting problems** beyond plain Android

– GUI analysis and testing for Android Wear [ICSE17]
Importance of Android

Large number of devices and apps
- 2.4 billion devices
- 3.7 million apps in Google Play; many other app stores

Widespread use in daily life
- Phones, tablets, electronics, wearables, appliances, auto

For SE and PL researchers: improved software quality and developer productivity through better program understanding, checking, transformation, optimization, testing, debugging, security analysis
- Need static analysis machinery as a critical building block
Foundations for Static Analysis

Control-flow analysis
- Traditional: control-flow graphs
- Android: event-driven framework-managed control flow

Data-flow analysis
- Traditional: associate a solution with each graph node; propagate along graph edges and paths
- Android: silently propagates data through the framework code; special values (e.g., integers used as ids); complex Android-specific semantics for some graph nodes
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We still don’t know how to perform general control-flow and data-flow analysis for Android
Two Building Blocks of Control-Flow Analysis

GUI widgets, events, and handlers [CGO14][PhD14]
– What is the structure of the GUI?
– Challenge: modeling of Android API semantics

GUI changes due to event handlers [ICSE15][ASE15][PhD15]
– What is the behavior of the GUI?
– Challenge: complex sequences of callbacks
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Windows, Widgets, and Handlers

GUI elements
- **Activity**: on-screen window with GUI widgets *(views)*
- **Event handlers**: defined in listener objects

Need to model statically:
- Views and their hierarchical structure
- Association of views with activities
- Association of views with listeners

Underneath, this is a form of **points-to analysis**
MyActivity.java:
    class MyActivity extends Activity {
        void onCreate() {
            this.setContentView(R.layout.main);  // Inflate
            View a = this.findViewById(R.id.my_btn);  // FindView
            Button b = (Button) a;
            ButtonListener c = new ButtonListener();
            b.setOnClickListener(c);  // SetListener
        }  
    }

ButtonListener.java:
    class ButtonListener implements OnClickListener {
        void onClick(View d) { ... }  
    }

main.xml:
    <RelativeLayout ...
        <Button android:id="@+id/my_btn" ... />
    </RelativeLayout>
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main.xml:

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Android-Specific Semantics

**Inflate**: create a hierarchy of views from XML specs and attach to an activity or to a view

**CreateView**: programmatically create with `new V`

**FindView**: look up a view in hierarchy

**SetListener**: associate view and listener

**AddView**: parent-child relationship for two views

**SetId**: programmatically set the id of a view
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    View a = this.findViewById(R.id.my_btn);  // FindView
    Button b = (Button) a;
    ButtonListener c = new ButtonListener();
    b.setOnClickListener(c);  // SetListener }
  }

  void onClick(View d) {
    ... }
}
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        View a = this.findViewById(R.id.my_btn); // FindView
        Button b = (Button) a;
        ButtonListener c = new ButtonListener();
        b.setOnClickListener(c); // SetListener
    }
}
Implementation and Evaluation

**GATOR**: Program analysis toolkit for Android
- [http://web.cse.ohio-state.edu/presto](http://web.cse.ohio-state.edu/presto)

**Analysis implementation**
- Input: Dalvik bytecode and relevant XML files
- Bytecode $\rightarrow$ Soot’s intermediate representation
- Propagation for ids, windows, listeners, views
- Output: static abstractions of activities, dialogs, menus, view hierarchies, listeners

**Good precision and running time; room for improvement (precision, cost, Android features)**
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Control-Flow Analysis of Android GUIs

Event-driven control flow
– **Event handler callback** responds to a GUI event
– The callback can trigger a **window transition**
– Additional **lifecycle callbacks** during transition

Key observation: the effects of a GUI event depend on the **history** of prior events

What are all possible sequences of GUI events, windows transitions, and related callbacks?
Our Solution

Window transition graph (WTG)
- Static model to represent possible sequences of GUI events, windows, and callbacks

Static analysis to build the WTG
- Key new abstraction: window stack, which represents the stack of currently-alive windows
class ChooseFileActivity extends Activity {
    void onItemClick(ListView l, View item) {
        if (...) return;
        Intent i = new Intent(OpenFileActivity.class);
        startActivity(i);  }
}

class OpenFileActivity extends Activity {
    void onOptionsItemSelected(MenuItem item) {
        if (item == aboutItem) {
            startActivity(new Intent(About.class));
        }
        if (item == optionsItem) {
            startActivity(new Intent(Options.class));
            this.finish();  }
    }
}

class Options extends Activity {
    void onClick(View v) {
        startActivity(new Intent(About.class));
        this.finish();  }
}

class About extends Activity { ... }
class ChooseFileActivity extends Activity {
  void onItemClick(ListView l, View item) {
    if (...) return;
    Intent i = new Intent(OpenFileActivity.class);
    startActivity(i); } }

class OpenFileActivity extends Activity {
  void onOptionsItemSelected(MenuItem item) {
    if (item == aboutItem) {
      startActivity(new Intent(About.class));
    } if (item == optionsItem) {
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class Options extends Activity {
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class About extends Activity { ... }
class **ChooseFileActivity** extends Activity {
void **onItemClick**(ListView l, View item) {
    if (…) return;
    Intent i = new Intent(OpenFileActivity.class);
    startActivity(i); }
}

class **OpenFileActivity** extends Activity {
void **onOptionsItemSelected**(MenuItem item) {
    if (item == aboutItem) {
        startActivity(new Intent(About.class)); }
    if (item == optionsItem) {
        startActivity(new Intent(Options.class));
        this.finish(); }
}

class **Options** extends Activity {
void **onClick**(View v) {
    startActivity(new Intent(About.class));
    this.finish(); }
}

class **About** extends Activity { ... }

Example: information for edge e2
widget: item
event type: click
window stack: push(a2)
callbacks: onItemClick(item), onPause(a1), onCreate(a2), onStart(a2), onResume(a2), onStop(a1)
class ChooseFileActivity extends Activity {
    void onItemClick(ListView l, View item) {
        if (...) return;
        Intent i = new Intent(OpenFileActivity.class);
        startActivity(i); } }

class OpenFileActivity extends Activity {
    void onOptionsItemSelected(MenuItem item) {
        if (item == aboutItem) {
            startActivity(new Intent(About.class)); }
        if (item == optionsItem) {
            startActivity(new Intent(Options.class));
            this.finish(); } }

class Options extends Activity {
    void onClick(View v) {
        startActivity(new Intent(About.class));
        this.finish(); } }

class About extends Activity { ... }
class ChooseFileActivity extends Activity {
    void onItemClick(ListView l, View item) {
        if (...) return;
        Intent i = new Intent(OpenFileActivity.class);
        startActivity(i); }
    }

class OpenFileActivity extends Activity {
    void onOptionsItemSelected(MenuItem item) {
        if (item == aboutItem) {
            startActivity(new Intent(About.class));
        }
        if (item == optionsItem) {
            startActivity(new Intent(Options.class));
            this.finish(); }
    }
}

class Options extends Activity {
    void onClick(View v) {
        startActivity(new Intent(About.class));
        this.finish(); }
}

class About extends Activity { ... }

Example: information for edge e6
widget: aboutItem
event type: click
window stack: pop(m) push(a3)
callbacks: ...
class ChooseFileActivity extends Activity {
    void onItemClick(ListView l, View item) {
        if (...) return;
        Intent i = new Intent(OpenFileActivity.class);
        startActivity(i); } }

class OpenFileActivity extends Activity {
    void onOptionsItemSelected(MenuItem item) {
        if (item == aboutItem) {
            startActivity(new Intent(About.class)); }
        if (item == optionsItem) {
            startActivity(new Intent(Options.class));
            this.finish(); } }

class Options extends Activity {
    void onClick(View v) {
        startActivity(new Intent(About.class));
        this.finish(); } }

class About extends Activity { ... }

Example: information for edge e8
widget: optionsItem
event type: click
window stack: pop(m) pop(a2) push(a4)
callbacks: ...
Final Graph

e0: launch, push(a1)
e1: item, click, —
e2: item, click, push(a2)
e3: back, pop(a2)
e4: menu, push(m)
e5: back, pop(m)
e6: aboutItem, click, pop(m) push(a3)
e8: optionsItem, click, pop(m) pop(a2) push(a4)
e7: back, pop(a3)
e9: back, pop(a4)
e10: btn, click, pop(a4) push(a3)
e11: back, pop(a3)
Path Validity

Invalid path: push(a2) push(m) pop(m) push(a3) pop(a3)
The top of the stack should be a2, but the last node on the path is a1
Valid path: push(a2) push(m) pop(m) push(a3) pop(a3) 
The top of the stack should be **a2**, and indeed the last node on the path is **a2**
Importance of Path Validity Check

Reduction in number of WTG paths of length $m$

Percent reduction

$\Delta% (m=2)$  $\Delta% (m=3)$
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Resource Leak Detection

Resource leaks can drain the battery
– Mismanagement of energy-intensive resources such as the GPS and hardware sensors

Leak patterns
– Defined two patterns of run-time behavior in Android GUIs that can cause energy leaks

Algorithms for static detection
– Designed a static control-flow and data-flow analysis to detect potential leaks
class Demo extends Activity {
    void onCreate() { ... }
    void onResume() {
        Button b = ...;
        OnClickListener l = new OnClickListener() {
            void onClick(View v) {
                Manager.instance.registerListeners(); } 
        };
        b.setOnClickListener(l); }
    void onDestroy() { ... }
}

class Manager implements LocationListener {
    static Manager instance = new Manager();
    void registerListeners() {
        LocationManager lm = ...;
        lm.requestLocationUpdates(this); } 
    }

Defect sequence: 
t1, t3, t2
onCreate(a), onResume(a), onClick(b), onDestroy(a)
Leak Patterns

Pattern 1: Lifetime containment

– An activity $w$ acquires an energy-intensive resource but does not release it by the time $w$ is destroyed

$$T = \langle t_1, t_2 \ldots t_n \rangle$$

– $t_1$ triggers $push(w)$ and $t_n$ triggers $pop(w)$

– push/pop sequence between the two is balanced

– callbacks along $T$ acquire an energy-intensive resource but do not release it

Pattern 2: Long-wait state

– An activity $w$ acquires an energy-intensive resource and enters a long-wait state without releasing the resource
Static Detection

**Callbacks** \([c_1, o_1], [c_2, o_2] \ldots [c_m, o_m]\) along a path
- For \(c_i\) invoked with context \(o_i\): compute set \(A_i\) of acquired resources and set \(R_i\) of released resources
- Need constant propagation and several traversals of \(c_i\)’s control-flow graph

**Leak:** if a resource is in \(A_i\) but not in \(R_{i+1}, \ldots, R_m\)
Evaluation and Conclusions

Compared with prior work on dynamic leak detection [Liu et al. TSE 2014]
− All GUI-based defects discovered by that prior work were also discovered by our static analysis
− 3 new defects found

Precision
− 17 defects reported; 16 validated on a physical device
− Only 1 false positive, but arguably still a problem

Static resource leak detection in Android GUIs is feasible and precise
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Background

**Android Wear (AW)**

– Google’s platform for wearable devices (e.g., smartwatches)
– AW apps can run independently, or in conjunction with companion app in the handheld device

**Open problem:** notifications that are issued on the handheld but displayed on the wearable GUI
GUI Example
Abstractions for Static Analysis

\[ x = \text{addaction}(y,z) \quad \text{Add actions to wearable extender} \]

\[ x = \text{setaction}(y,z) \quad \text{Set intent (for “Open on phone” action)} \]

\[ x = \text{extend}(y,z) \quad \text{Attach wearable extender to notification builder} \]

\[ x = \text{build}(y) \quad \text{Build notification from a notification builder} \]

\[ \text{notify}(x) \quad \text{Issue notification} \]

\[ x = \text{buildpending}(y) \quad \text{Wrap intent into pending intent} \]

\[ x = \text{buildaction}(y) \quad \text{Building action from pending intent} \]

\[ x = \text{addpage}(y,z) \quad \text{Add notification as page to another notification} \]
Testing framework
- **AW UIAutomator**: communicate with handheld and wearable
- **GUI crawler**: record GUI elements on the wearable, to check coverage

Instrumentation
- Insert & record IDs for GUI elements
What Next?

**Stronger static analysis foundations**
- Semantics: inference, validation, evolution

**More uses of static GUI analysis**
- Automated code rewriting for better performance
- ...

**Beyond Android phones and tablets**
- Android Wear, Android Things, Android Auto
- Short-term: standalone Android Wear apps