Using Model Checking to Generate Test Cases for Android Applications

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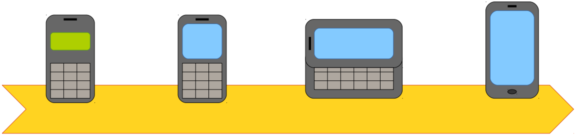
Introduction

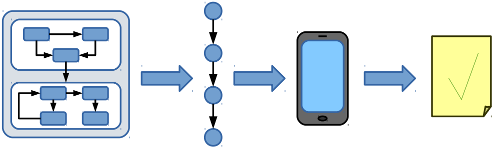


- Smartphones have become ubiquitous computing devices
- Continuously and rapidly evolving technology
- Event-driven user interface, focusing on one task at a time
- With a traditional multi-tasking operating system underneath

Introduction

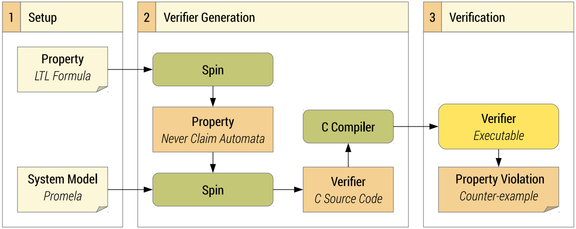
- Typical errors of concurrent software may happen
- Other bugs are inherent to mobile platforms, such as
  - Incorrect implementation of lifecycle in apps or services
  - Handling of unexpected events
  - API or device compatibility problems
- Different analysis techniques have been proposed
  - Model checking ANDROID applications with JPF
  - Testing, monitoring and runtime verification
  - Automatic generation of random input events

Our proposal



- Model the possible user behaviors using state machines
  - Nested state machines representing apps, screens, etc.
  - Nondeterministic behavior within each state machine
  - Composition of state machines
- Generate test cases by exploring this model
- Monitor and analyze the execution of the test cases
- Implemented for ANDROID

Test case generation with model checking

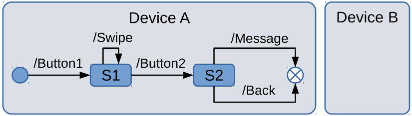


- We use the SPIN model checker to generate test cases
- SPIN is focused on the design and validation of computer protocols, although it has been applied to many other areas
- Given a system specification written in PROMELA, SPIN can check the occurrence of a property over all possible executions and provide counterexamples

Test case generation with model checking

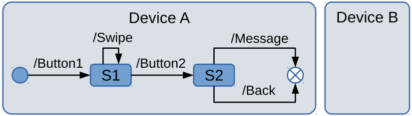
- Model → PROMELA specification
- Device → PROMELA process
  - Multiple devices run concurrently
  - Device state machine implemented as a loop
- Each loop branch corresponds to a transition
  - Guard declares transition trigger (e.g. button press, swipe)
  - Right hand side records transition and updates current state
- SPIN will explore exhaustively all possibilities (e.g. when several guards are true at the same time) to generate all possible test cases

Test case generation with model checking



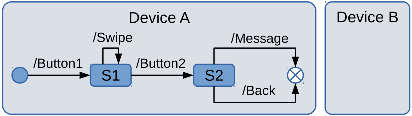

```
active proctype device_A() {

}
active proctype device_B() {

}
```

Test case generation with model checking



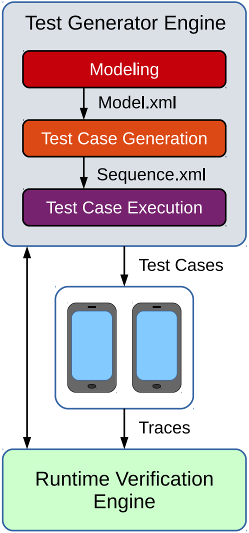

```
mtype = { state_init, state_1, state_2, ... };
typedef Device { byte transitions[MAX_TR]; short index; bool finish; }
Device devices[DEVICES];
mtype state[DEVICES];

active proctype device_A() {
    state[DEVA] = state_init;







    devices[DEVA].finish = true;
}

active proctype device_B() {
    state[DEVB] = state_init;
    ...
    devices[DEVB].finish = true;
}
```

Test case generation with model checking



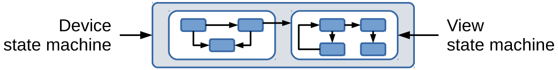

```
mtype = { state_init, state_1, state_2, ... };
typedef Device { byte transitions[MAX_TR]; short index; bool finish; }
Device devices[DEVICES];
mtype state[DEVICES];

active proctype device_A() {
    state[DEVA] = state_init;
    do
    :: state[DEVA] == state_init -> transition(DEVA, BUTTON_1); state[DEVA] = state_1
    :: state[DEVA] == state_1    -> transition(DEVA, SWIPE);    state[DEVA] = state_1
    :: state[DEVA] == state_1    -> transition(DEVA, BUTTON_2); state[DEVA] = state_2
    :: state[DEVA] == state_2    -> transition(DEVA, MESSAGE);  break
    :: state[DEVA] == state_2    -> transition(DEVA, BACK);     break
    od;
    devices[DEVA].finish = true;
}

active proctype device_B() {
    state[DEVB] = state_init;
    ...
    devices[DEVB].finish = true;
}
```

Architecture



- Test Generator Engine
  - User models app user flows, associates events with UI controls (extracted with UIAUTOMATORVIEWER)
  - SPIN explores the model, generates an XML test case for each possible flow
  - Test cases are translated into JAVA classes which use the UIAUTOMATOR tool and run in the devices
- Runtime Verification Engine
  - Monitors the execution of the test cases
  - Implemented by the DRAGONFLY tool

Formal description of models



- Mobile applications are modeled through the composition of state machines, at different levels: view and device
- View state machines
  - A view represents a screen in an application
  - Only one view active in a device at the same time
  - User interacts with the currently active view
  - A transition may trigger another view to become active
- Device state machines
  - Composed of one or more view state machines
  - Handle transitions between view through connection states

Formal description of models

- $\stackrel{-}{\to}$ / $\stackrel{-}{\to}_i$: transition relation of the view state machines M/M_i
- $\stackrel{-}{\to}_c$ transition relation that connects view state machines
- $\stackrel{-}{\to}_d$ transition relation that connects device state machines
  - Constructed from relations $\stackrel{-}{\to}$ / $\stackrel{-}{\to}_i$ and $\stackrel{-}{\to}_c$
- Transitions are labeled with the event required to fire them
  - E.g. $s \stackrel{e}{\to} s'$: event e must be fired to transit from s to s'
- Test case: sequence of events

View state machines

View state machine

$M = \langle \Sigma, I, \xrightarrow{-}, E, C, F \rangle$

- Σ: finite set of states
- $I \subseteq \Sigma$: set of initial states
- $C \subseteq \Sigma$: *connection states* (to a different state machine)
- $F \subseteq \Sigma$: set of final states
- E: set of user events
- $\xrightarrow{-} \subseteq \Sigma \times E \times \Sigma$: labeled transition relation
- I, C and F are mutually disjoint

- E can be divided into two disjointed sets:
  - E^+: user events (e.g. button press, swipe)
  - E^-: system events (e.g. message reception)

View state machines

Flow

Given a view state machine $M = \langle \Sigma, I, \bar{\rightarrow}, E, C, F \rangle$, we define the set $Flow(M) = \{s_0 \xrightarrow{e_1} s_1 \xrightarrow{e_2} \cdots \xrightarrow{e_n} s_n | s_0 \in I, s_n \in F \cup C\}$ of all sequences of transitions, allowed by M, starting at an initial state of M, and ending at a final or connection state of M

- Given a flow $\phi = s_0 \xrightarrow{e_1} \cdots \xrightarrow{e_n} s_n \in Flow(M)$, the sequence of events (i.e. the test case) determined by ϕ is $test(\phi) = e_1 \cdot \cdots \cdot e_n$
- Given a state machine M, the set of test cases allowed by M is $TC(M) = \{test(\phi) | \phi \in Flow(M)\}$

Composition of view state machines

- Given a set of state machines $M_i = \langle \Sigma_i, I_i, \rightarrow_i, E_i, C_i, F_i \rangle$
  - $\Sigma = \cup_{i=1}^{n} \Sigma_i$
  - $I = \cup_{i=1}^{n} I_i$
  - $E = \cup_{i=1}^{n} E_i$
  - $C = \cup_{i=1}^{n} C_i$
  - $F = \cup_{i=1}^{n} F_i$
- $\mathscr{E} \subseteq E$ the set of *call events* that provoke the switch between active view state machines

Connection relation

The connection of view state machines $M_1, \ldots, M_n$ is given by a binary relation $\mathscr{R}(M_1, \cdots, M_n) \subseteq C \times \mathscr{E} \times I$, that connects connection states with initial states

- We denote 3-tuples (s_i, e, s_j) of $\mathscr{R}(M_1, \cdots, M_n)$ as $s_i \xrightarrow{e}_c s_j$

Composition of view state machines

Device state machine

Given a finite set of view state machines, $M_i = \langle \Sigma_i, I_i, \stackrel{-}{\rightarrow}_i, E_i, C_i, F_i \rangle$, and a connection relation of $M_1, \ldots, M_n$, the device state machine

$$\mathscr{D} = M_1 ||| \cdots ||| M_n ||| \mathscr{R}(M_1, \cdots, M_n)$$

is defined as the state machine $\langle \Sigma \times \Sigma^* \times \mathscr{E}^*, I, \stackrel{-}{\rightarrow}_d, E, F \rangle$ where

- Σ^* is the set of finite sequences of states of Σ, and $\mathscr{E}^*$ is the set of finite sequences of call events
- transition relation $\stackrel{-}{\rightarrow}_d$ is defined by the following rules

Composition of view state machines

- The states of a device state machine are called *configurations*
- A configuration is a 3-tuple $\langle s, h, eh \rangle$
  - s: the current state of the active view state machine
  - $h = s_1 \cdot s_2 \cdots s_n$: the stack of states that constitutes the history of created view state machines, where $s_i \in C$
  - $eh = e_1 \cdot e_2 \cdots e_n$: the history of events that provoked the creation of new view state machines, where $e_i \in \mathscr{E}$

Composition of view state machines

- Transition within a view state machine:

$$\textbf{R1.} \quad \frac{s \xrightarrow{e}_i s'}{\langle s, h, eh \rangle \xrightarrow{e}_d \langle s', h, eh \rangle}$$

Composition of view state machines

- Transition to a new state machine, without reusing:

$$\textbf{R2.}\ \frac{s \in C_i, s \xrightarrow{e}_c s', \neg reuse(e)}{\langle s, h, eh\rangle \xrightarrow{e}_d \langle s', h \cdot return(s), eh \cdot e\rangle}$$

- Reusing, but no previous view state machine to reuse:

$$\textbf{R3.}\ \frac{s \in C_i, s' \in I_j, s \xrightarrow{e}_c s', reuse(e), top(s_1 \cdots s_n, j) = \bot}{\langle s, h, eh\rangle \xrightarrow{e}_d \langle s', h \cdot return(s), eh \cdot e\rangle}$$

- Reusing:

$$\textbf{R4.}\ \frac{s \in C_i, s' \in I_j, s \xrightarrow{e}_c s', reuse(e), top(s_1 \cdots s_n, j) = s_k}{\langle s, s_1 \cdots s_n, e_1 \cdots e_n\rangle \xrightarrow{e}_d \langle s_k, s_1 \cdots s_{k-1}, e_1 \cdots e_{k-1}\rangle}$$

Composition of view state machines

- Flow continues with the previous view state machines, after the current one finishes:

$$\textbf{R5.}\ \frac{s \in F_i, auto\_return(e)}{\langle s, h \cdot s', eh \cdot e\rangle \xrightarrow{-}_d \langle s', h, eh\rangle}$$

- If *auto_return*(e) is false, the current configuration cannot evolve

Composition of view state machines

- Given a device state machine $\mathscr{D}$:
  1. The *trace-based semantics* determined by $\mathscr{D}$ ($\mathscr{O}(\mathscr{D})$) is given by the set of finite/infinite sequences of configurations (flows) produced by the transition relation $\xrightarrow{-}_d$ from an initial state, that is, $\mathscr{O}(\mathscr{D}) = \{\langle s_0, \varepsilon, \varepsilon\rangle \xrightarrow{e_0}_d \langle s_1, h_1, eh_1\rangle \cdots | s_0 \in I\}$.
  2. Given a flow $\phi = c_0 \xrightarrow{e_1}_d c_1 \xrightarrow{e_2}_d c_2 \cdots \in \mathscr{O}(\mathscr{D})$, the test case determined by ϕ is the sequence of events $test(\phi) = e_1 \cdot e_2 \cdots$
  3. The set of *test cases* determined by a set of flows $\mathscr{T}$ is $TC(\mathscr{T}) = \{test(t) | t \in \mathscr{T}\}$.
- Thus, a flow $\phi \in \mathscr{O}(\mathscr{D})$ consists of a (finite or infinite) sequence of view state machine flows connected through connection states

Composition of device state machines

- Composition of several devices is carried out by interleaving
- Communication between devices is modeled with user events in the sender (e.g. e^+) and system events in the receiver (e.g. e^-)
- *dh*: set of system events produced but not yet consumed
- Sender transition:

$$\textbf{R6.}\ \frac{c_0 \xrightarrow{e^+}_d c_1}{\langle c_0, c'_0, dh\rangle \xrightarrow{e^+}_{d||d'} \langle c_1, c'_0, dh + \{e^+\}\rangle}$$

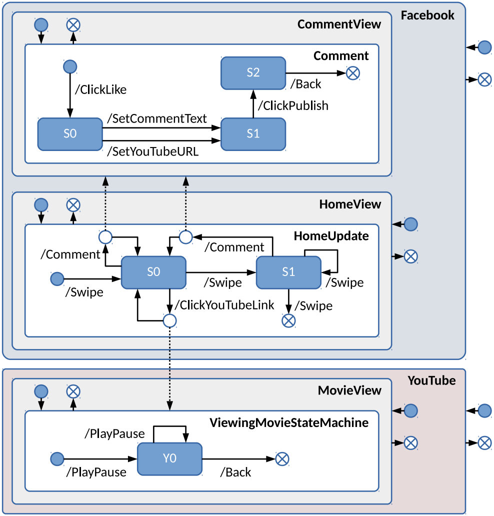
- Receiver transition (cannot proceed until $e^+ \in dh$)

$$\textbf{R7.}\ \frac{c'_0 \xrightarrow{e^-}_{d'} c'_1,\ e^+ \in dh}{\langle c_0, c'_0, dh\rangle \xrightarrow{e^-}_{d||d'} \langle c_0, c'_1, dh - \{e^+\}\rangle}$$

Case study

- A single ANDROID device with two applications: Facebook and YouTube
  - A user comments on Facebook posts, and visits links that play on the YouTube application
- Modeling
  - Can be done during application development of afterwards
  - State machines could be modeled with UML, then translated into final the XML model
  - We allow several levels of nesting: device $\rightarrow$ application $\rightarrow$ view $\rightarrow$ state machine

Case study


Facebook
CommentView
Comment
S2
/Back
/ClickPublish
/ClickLike
/SetCommentText
S0
S1
/SetYouTubeURL
HomeView
HomeUpdate
/Comment
/Comment
S0
S1
/Swipe
/Swipe
/Swipe
/ClickYouTubeLink
/Swipe
YouTube
MovieView
ViewingMovieStateMachine
/PlayPause
Y0
/PlayPause
/Back

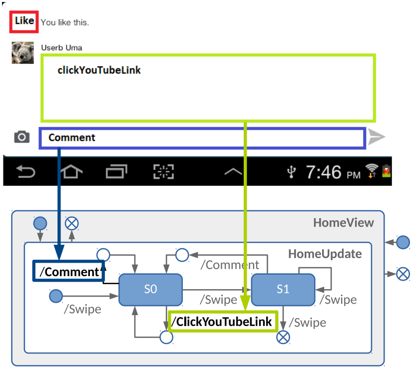
Case study

```xml
<Application name="Facebook" package="com.facebook.android">
  <Views>
    <View name="HomeView" controlsFile="Home.xml" >
      <StateMachines>
        <StateMachine name="HomeUpdate">
          <States><State name="S0"/><State name="S1"/></States>
          <Transitions>
            <Transition ID="1" event="Swipe" prev="" next="S0" type="Simple"/>
              <Transition ID="2" event="Comment" prev="S0" next="S0"
                  through="CommentView" type="View"/>
              <Transition ID="3" event="Swipe" prev="S0" next="S1" type="Simple"/>
              <Transition ID="4" event="ClickYouTubeLink" prev="S0" next="S0"
                  through="ViewingMovieStateMachine" type="StateMachine"/>
            <Transition ID="5" event="Swipe" prev="S1" next="S1" type="Simple"/>
            <Transition ID="6" event="Comment" prev="S1" next="S0"
                  through="CommentView" type="View"/>
            <Transition ID="7" event="Swipe" prev="S1" next="" type="Simple"/>
            ...
```

Case study

- State machine transition events must be associated with UI controls
- UIAUTOMATORVIEWER can extract control information from live ANDROID applications
- Controls include which action they support, e.g. click, long click or scroll
- Some controls can be enriched with parameters, e.g. for test input generation

Case study




```
<node index="0" text="" testGroup="" ....
  <node index="0" ....
    <node testGroup="clicLike" IsFixedValue="" PatternOrValue="" index="0"
         text="Like" resource-id="id/feed_feedback_like_container" clickable="true"
         long-clickable="false" password="false" ... />
```

Case study

- Test case generation with model checking: same principle as before, with more layers
- XML model translated into PROMELA specification
  - Device $\rightarrow$ process
  - Application/view/inner state machines $\rightarrow$ inlines (“functions”)
- Nested state machines $\rightarrow$ nested inline calls
  - Device processes contain the topmost state machines
  - A state machine may call another one by calling their inline
- Limited exploration depth
  - State must be stored in a stack (“backstack”) when transitioning to a new state machine
  - Backstack/transition history limit number of state machine transitions/transitions in a single test case
  - History part of global SPIN state: more test cases
- Test cases generated as XML

Case study

```
typedef Backstack { mtype states[MAX_BK]; short index; }
Backstack backstacks[DEVICES];
#define currentBackstack    devices[device].backstack
#define currentState        currentBackstack.states[currentBackstack.index]

active proctype device_219dcac41() {
    if
    true -> app_219dcac41_Facebook(D_219dcac41);
    true -> app_219dcac41_YouTube(D_219dcac41);
    fi;
    devices[D_219dcac41].finished = true
}

inline statemachine_Facebook_HomeView_HomeUpdate(device) {
    currentState = State_Facebook_HomeView_HomeUpdate_init;
    pushToBackstack(device, State_Facebook_HomeView_HomeUpdate_init);
    do
    :: currentState == State_Facebook_HomeView_HomeUpdate_S0 ->
        transition(device, VIEW_HomeView, 2);
        view_Facebook_CommentView(device);
        currentState = State_Facebook_HomeView_HomeUpdate_S0
    :: currentState == State_Facebook_HomeView_HomeUpdate_S0 ->
        transition(device, VIEW_HomeView, 4);
        statemachine_YouTube_MovieView_ViewingMovieStateMachine(device);
        currentState = State_Facebook_HomeView_HomeUpdate_S0
    ...
    od;
    popFromBackstack(device)
}
```

Case study

- Each XML test case is transformed into a JAVA class
  - Subclass of `UiAutomatorTestCase`
  - Compiled, installed and executed on the device

```
public class TestDevice1 extends UiAutomatorTestCase {
    // Transition  2  previous S0 next S0 on view HomeView
    public void TestFacebookComment2() throws UiObjectNotFoundException {
        UiObject control = new UiObject(new UiSelector().
            className("android.widget.TextView").index(1).textContains("Comment"));
        control.click();
    }
    // Transition  4:  previous S0 next S0 on view HomeView
    public void TestFacebookclicYouTubeLink27() throws UiObjectNotFoundException {
        UiObject control = new UiObject(new
            UiSelector().className("android.view.View").index(3));
        control.click();
    }
    // Transition  1:  previous  next Y0 on view MovieView
    public void TestYouTubeplaypause28() throws UiObjectNotFoundException {
        UiObject control = new UiObject(new
            UiSelector().className("android.view.View").index(4));
        control.click();
    }
}
```

Case study

- Test generation results
  - Backstack fixed to 4; change devices and max. transitions
  - Device A has been assigned only the Facebook application (although YouTube is reachable)
  - Both devices are independent

Devices		Config.	Results				
A	B	Transitions	# Test Cases	Time	# States	State Size	Memory
✓		20	5641	1.0 s	307234	84 B	156.8 MB
✓		26	111317	9.0 s	6063398	92 B	728.6 MB
	✓	20	5660	1.0 s	307493	84 B	156.8 MB
	✓	26	111342	9.0 s	6063735	92 B	728.6 MB
✓	✓	10	1872	7.0 s	4039337	100 B	560.3 MB
✓	✓	12	12180	52.3 s	28972472	108 B	3445.2 MB

Conclusions

- Model-based testing approach for generating test caess for ANDROID applications
- Models capture user behavior and interaction between applications; realistic behaviors vs. random input events
- Flexible models built by composing state machines
- SPIN generates are possible test cases
- Adaptable to other mobile platforms

Future work

- Connect with our runtime verification monitor DRAGONFLY
- Include additional runtime information in the traces
- Analyze other properties, e.g. energy consumption

Thanks for your attention

Questions?