Non-termination of Dalvik bytecode via compilation to CLP

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Abstract
We present a set of rules for compiling a Dalvik bytecode program into a logic program with array constraints. Non-termination of the resulting program entails that of the original one, hence the techniques we have presented before for proving non-termination of constraint logic programs can be used for proving non-termination of Dalvik programs.

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1 Introduction

Android is currently the most widespread operating system for mobile devices. Applications running on this system can be downloaded from anywhere, hence reliability is a major concern for its users. In this paper, we consider applications that may run into an infinite loop, which may cause a resource exhaustion, for instance the battery if the loop continuously uses a sensor as the GPS. Android programs are written in Java and compiled to the Google’s Dalvik Virtual Machine (DVM) bytecode format [3] before installation on a device. We provide a set of rules for compiling a Dalvik bytecode program into a constraint logic program [5]. Non-termination of the resulting program entails that of the original one, hence the technique we have presented before [6] for proving non-termination of constraint logic programs can be used for proving non-termination of Dalvik programs. We model the memory and the objects it contains with arrays, so we compile Dalvik programs to logic programs with array constraints and we consider the theory of arrays presented in [1].

2 The Dalvik Virtual Machine

We briefly describe the operational semantics of the DVM (see [3] for a complete description). Unlike the JVM which is stack-based, the DVM is register-based. Each method uses its own array of registers and invoked methods do not affect the registers of invoking methods. The number of registers used by a method is statically known. At the beginning of an execution, the \( N \) arguments to a method land in its last \( N \) registers and the other registers are initialized to 0. Many Dalvik bytecode instructions are similar, so we concentrate on a restricted set which exemplifies the operations that the DVM performs.

\( \text{const } d, c \) Move constant \( c \) into register \( d \) (i.e., the register at index \( d \) in the array of registers of the method where this instruction occurs).

\( \text{move } d, s \) Move the content of register \( s \) into register \( d \).

\( \text{add } d, s, c \) Store the sum of the content of register \( s \) and constant \( c \) into register \( d \).
if-lt $i,j,q$ If the content of register $i$ is less than the content of register $j$ then jump to program point $q$, otherwise execute the immediately following instruction.

goto $q$ Jump to program point $q$.

invoke $S,m$ where $S = s_0,s_1,...,s_p$ is a sequence of register indexes and $m$ is a method. The content $r^{s_0}$ of register $s_0$, ..., $r^{s_p}$ of register $s_p$ are the actual parameters of the call. Value $r^{s_0}$ is called receiver of the call and must be 0 (the equivalent of null in Java) or a reference to an object $o$. In the former case, the computation stops with an exception. Otherwise, a lookup procedure is started from the class of $o$ upwards along the superclass chain, looking for a method with the same signature as $m$. That method is run from a state where its last registers are bound to $r^{s_0},r^{s_1},...,r^{s_p}$.

return Return from a void method.

new-instance $d,\kappa$ Move a reference to a new object of class $\kappa$ into register $d$.

iget $d,i,f$ (resp. iput $s,i,f$) The content $r^{i}$ of register $i$ must be 0 or a reference to an object $o$. If $r^{i}$ is 0, the computation stops with an exception. Otherwise, $o(f)$ (the value of field $f$ of $o$) is stored into register $d$ (resp. the content of register $s$ is stored into $o(f)$).

3 Compilation to CLP clauses

We model a memory as a pair $(a,i)$ where $a$ is an array of objects and $i$ is the index into this array where the next insertion will take place. An object $o$ is an array of terms of the form $[w,f_1(v_1),...,f_n(v_n)]$ where $w$ is the name of the class of $o$, $f_1,...,f_n$ are the names of the fields defined in this class and $v_1,...,v_n$ are the current values of these fields in $o$. So, the first component of a memory is an array of arrays of terms and a memory location is an index into this array. Memory locations start at 1 and 0 corresponds to the null value.

Our compilation rules are given in Fig. 1–3. We associate a predicate symbol $p_d$ to each program point $q$ of the Dalvik program $P$ under consideration. We generate clauses with constraints on integer and array terms. Our constraint theory combines the theory of integers with that of arrays defined in [1]. Our CLP domain of computation $D$ (values interpreting constraints) is the union of $\mathbb{Z}$ with the set $\text{Obj}$ of arrays of terms of the form $f(i)$ where $i$ is an integer and with the set of arrays of elements of $\text{Obj}$. The read $a[i]$ returns the value stored at position $i$ of the array $a$ and the write $a[i \leftarrow e]$ is a modified so that position $i$ has value $e$. For multidimensional arrays, we abbreviate $a[i][j]$ with $a[i,...,j]$.

Each rule considers an instruction $ins$ occurring at a program point $q$. We let $\hat{V} = V_0,...,V_{r-1}$ and $\hat{V}' = V'_0,...,V'_{r-1}$ be sequences of distinct variables where $r$ is the number of registers used by the method where $ins$ occurs. For each $i \in [0,r-1]$, variable $V_i$ (resp. $V'_i$) models the content of register $i$ before (resp. after) executing $ins$. We let $M$ denote the input memory and $M'$ the output memory. So, $\hat{V}$ and $M$ (or $A[I]$) in the head of the clauses are input parameters while $M'$ is an output parameter. We let $id$ denote the sequence $(V'_0 = V_0,...,V'_{i-1} = V_{r-1})$ and $id_{-i}$ (where $i \in [0,r-1]$) the sequence $(V'_0 = V_0,...,V'_{i-1} = V_{i-1},V'_{i+1} = V_{i+1},...,V'_{r-1} = V_{r-1})$. By $|X|$ we mean the length of sequence $X$. For any method $m$, $q_m$ is the program point where $m$ starts, $reg(m)$ is the set of all the methods with the same signature as $m$.

Some compilation rules are rather straightforward. For instance, const $d,c$ moves constant $c$ into register $d$, so in Fig. 1 the output register variable $V'_d$ is set to $c$ while the other register variables remain unchanged (modelled with $id_{-d}$). Rules for move, add and goto are similar. In Fig. 2, we consider method calls. The instruction invoke $s_0,...,s_p,m$ is compiled into a set of clauses (one for each method with the same signature as $m$) which
impose that $V_{s_0}$ (the receiver of the call) is a non-null location (i.e., $V_{s_0} > 0$). Therefore, if $V_{s_0} \leq 0$, the execution of the generated CLP program fails, as the original Dalvik program.

If $V_{s_0} > 0$, the lookup procedure begins. For each $m' \in \text{sign}(m)$, this is modelled with the call \text{lookup}_{p}(M, V_{s_0}, m, q_{m'}) which starts from the class of the object at location $V_{s_0}$ in memory $M$ and searches for the closest method $m''$ with the same signature as $m$ upwards along the superclass chain. If $m'' = m'$, this call succeeds, otherwise it fails. Then, $m'$ is executed, modelled with $p_{q_{m'}}(X_{m'}, M, M_1)$, with some registers $X_{m'}$ initialized as expected. When the execution of $m'$ has finished, control jumps to the following instruction (i.e., $p_{q+1}(V', M_1, M')$). In Fig. 3, we consider some memory-related instructions that we compile to clauses with array constraints.

**Theorem 1.** Let $P$ be a Dalvik bytecode program and $P_{CLP}$ its CLP compilation. If there is a computation $p_{q_0} p_{q_1} ...$ in $P_{CLP}$ then there is an execution $q_0 q_1 ...$ of $P$.

More precisely, if there is a finite (resp. infinite) computation in $P_{CLP}$ starting from a query $p_{q_0}(v, [a, i], M')$ (where $v$, $a$ and $i$ are values in $\mathcal{D}$ and $M'$ is an output variable), then there is a finite (resp. infinite) execution of $P$, using the same program points, starting from values corresponding to $v$ and $a$ in the DVM registers and memory.

### 4 Non-termination inference

The following proposition is a CLP reformulation of a result presented in [4].

**Proposition 2.** Let $r = p(\tilde{x}) \leftarrow c, p(\tilde{y})$ and $r' = p'(\tilde{x}') \leftarrow c', p(\tilde{y}')$ be some clauses. Suppose there exists a set $\mathcal{G}$ such that formulæ $[\forall \tilde{x} \exists \tilde{y} \exists \tilde{x} \in \mathcal{G} \Rightarrow (c \land \tilde{y} \in \mathcal{G})]$ and $[\exists \tilde{x}' \exists \tilde{y}' \exists \tilde{x}' \land \tilde{y}' \in \mathcal{G}]$ are true. Then, $p'$ has an infinite computation in $\{r, r'\}$. 
non-termination of Dalvik bytecode

\[ p_q(\tilde{V}, [\tilde{I}], M') \leftarrow \{ O[0] = w, \quad O[1] = f_1(0), \ldots, \quad O[n] = f_n(0), \quad A_1 = A(I \leftarrow O), \quad V_d = I, \quad I_1 = I + 1 \} \cup id_{-d}, \quad p_{q+1}(V', [A_1, I_1], M') \]  

\[ p_q(\tilde{V}, [\tilde{I}], M') \leftarrow \{ V_i > 0, \quad A[V_i, F] = f(V_d) \} \cup id_{-d}, \quad p_{q+1}(V', [A, I], M') \]  

\[ p_q(\tilde{V}, [\tilde{I}], M') \leftarrow \{ V_i > 0, \quad O = A[V_i], \quad O[F] = f(X), \quad O_1 = O(F \leftarrow f(V_o)), \quad A_1 = A(V_i \leftarrow O_1) \} \cup id, \quad p_{q+1}(V', [A_1, I], M') \]  

Consider the Android program in Fig. 4, with the Java syntax on the left and the corresponding Dalvik bytecode \( P \) on the right, where \( v_0, v_1, \ldots \) denote registers 0, 1, \ldots. Method \( \text{loop} \) in class \( \text{MyActivity} \) is called when the user taps a button displayed by the application. Execution of this method does not terminate because in the call to \( m \), the objects \( o_1 \) and \( o_2 \) are aliased and therefore by decrementing \( x.i \) we are also decrementing \( \text{this}.i \) in the loop of method \( m \). We get the following clauses for program points 0 and 14:

\[ p_0(\tilde{V}, [\tilde{I}], M') \leftarrow \{ \tilde{A}[V_1, F] = i(\tilde{V}_0) \} \cup id_{-0}, \quad p_1(\tilde{V}', [\tilde{A}, I], M') \]  

\[ p_{14}(\tilde{V}, M, M') \leftarrow \{ V_0 > 0 \} \cup id, \quad \text{lookup}_P(M, V_0, \text{Loops->m(ILoops)}V, 0), \quad p_0(0, V_0, V_2, V_1, M, M_1), \quad p_{15}(\tilde{V}', M_1, M') \]  

Let \( P_{CLP} \) denote the CLP program resulting from the compilation of \( P \). The set of binary unfoldings [2] of \( P_{CLP} \) contains the following clauses:

\[ r : \quad p_0(\tilde{V}, [\tilde{I}], M') \leftarrow \{ V_1 > 0, \quad O = A[V_1], \quad O[F] = i(X), \quad X < V_2, \quad O_1 = O(F \leftarrow i(X + 1)), \quad A_1 = A(V_1 \leftarrow O_1), \quad V_3 > 0, \quad O' = A_1[V_3], \quad O'[F'] = i(X'), \quad V_0' = X' - 1, \quad O_1' = O'(F' \leftarrow i(V_0')), \quad A_2 = A_1(V_3 \leftarrow O_1') \cup id_{-0}, \quad p_0(\tilde{V}', [A_2, I], M') \]  

\[ r' : \quad p_{10}(\tilde{V}, [\tilde{I}], M') \leftarrow \{ O[0] = \text{loops}, \quad O[1] = i(0), \quad A_1 = A(I \leftarrow O), \quad I_1 = I + 1, \quad I > 0 \}, \quad p_{10}(0, I, 2, I, [A_1, I_1], M_1) \]  

where \( r \) corresponds to the path 0 \( \rightarrow 1 \rightarrow 3 \rightarrow 4 \rightarrow \cdots \rightarrow 9 \rightarrow 0 \) and \( r' \) to the path 10 \( \rightarrow 11 \rightarrow 12 \rightarrow 13 \rightarrow 14 \rightarrow 0 \) in \( P \). In \( r' \), \( O \) corresponds to both \( o_1 \) and \( o_2 \), which expresses that \( o_1 \) and \( o_2 \) are aliased. Note that \( I \), the address of \( O \), is passed to \( p_0 \) both as second and fourth parameter, which corresponds in \( r \) to \( V_1 \) (this in method \( m \)) and \( V_3 \) (\( x \) in \( m \)). Moreover, when \( V_1 = V_3 \) in \( r \), we have \( O' = O_1, \quad F' = F \) and \( X' = X + 1 \), hence \( V_0' = X' - 1 = X \). Therefore, we have \( O_1' = O \), so \( A_2 = A \). The logical formulas of Proposition 2 are true for the set \( \mathcal{G} = \{(\tilde{v}, \text{mem}, \text{mem}') \in D^3|v_1 = v_3\} \). Hence, \( p_{10} \) has an infinite computation in \( \{r, r'\} \), which implies [2] that \( p_{10} \) has an infinite computation in \( P_{CLP} \). So by Theorem 1, \( P \) has an infinite execution from program point 10.
public class Loops {
    int i;
    public void m(int n, Loops x) {
        while (this.i < n) {
            this.i++;
            x.i--;
        }
    }
}

public class MyActivity extends Activity {
    public void loop(View v) {
        Loops o1 = new Loops();
        Loops o2 = o1;
        o1.m(2, o2);
    }
}

Figure 4 The non-terminating method loop is called when the user taps a button.

5 Future Work

We plan to implement the technique described above and to write a solver for array constraints. Currently, our compilation rules only consider the operational semantics of Dalvik, a part of the Android platform. We also plan to extend them by considering the operational semantics of other components of Android, for instance activities that we have studied in [7].

References