Lecture #43: Topics in Static Analysis, Contd.

- We looked into using it to check correctness, but static analyses also useful in program optimization.
- **Problem:** Consider this loop in Java:

```
for (i = 1; i < A.length; i += 1)
   A[i] += A[i-1];
```

- Java guarantees that array bounds are never violated, as if we had written:

```
for (i = 1; i < A.length; i += 1)
   if (i < 0 || i >= A.length || i-1 < 0 || i-1 >= A.length)
     throw new ArrayIndexOutOfBoundsException ();
   else
     A[i] += A[i-1];
```

- But conditionals in a tight loop like this are not good on some architectures at least.

Eliminating Array-Bounds Checks

- Let's rewrite our problem a little:

```
i = 1
while (i < A.length) {
   assert i ≥ 0 ∧ i < A.length ∧ i − 1 ≥ 0 ∧ i − 1 < A.length?;
   A[i] += A[i-1];
   i = i+1
}
```

- (Where this **assert** has teeth—blows up if false).
- All we know is that at top of loop, `i < A.length`, and (from semantics of Java) that `A.length >= 0`.
- See if assertion simplifies to true:

$$0 \le A.\text{length} \wedge i < A.\text{length}$$
$$\Rightarrow i \ge 0 \wedge i < A.\text{length} \wedge i - 1 \ge 0 \wedge i - 1 < A.\text{length}$$
$$\equiv$$
$$i - 1 \ge 0$$

- So not quite. We don't need to test against A.length, but the test $i - 1 \ge 0$ remains.

So, Is It True Anyway?

- So now we have

```
i = 1
while (i < A.length) {
   assert i − 1 ≥ 0;
   A[i] += A[i-1];
   i = i+1
}
```

- Can we show the assertion to be an invariant?
- Pretty obvious, really. Must show

$$\{\text{true}\}\ \ \text{i = 1}\ \ \{i - 1 \ge 0\},\ \text{ and}$$
$$\{i - 1 \ge 0\}\ \ \text{A[i] += A[i-1]; i = i+1}\ \ \{i - 1 \ge 0\}$$

- We haven't given a postcondition for the loop, so just take it to be **true**, making the usual exit condition for the **while** rule trivial.
- The assertions above can be verified mechanically.
- So the **assert** is proved, and the check is unnecessary.

Java Byte-Code Verification

- Java `.class` files essentially contain machine code (called *bytecode*) for a standard *virtual machine,* implementable by interpreter or byte-code to machine-code compiler.
- Programs may be transmitted as byte codes; no need for source.
- Java's security features (are supposed to) allow one to run untrusted code, and be assured that it is limited in what it can do.
- But Java runtime system's integrity, including these security features, depends on the bytecode's behaving themselves, not writing to invalid locations, etc.
- How do we know a class file downloaded from the net behaves?
- Java system *verifies* byte-code files prior to loading them. How?

Things to Verify

- Class files must have right format, instructions must be properly formed. Easily checked.
- Jumps must not go beyond bounds of method; method must terminate in return. Also easy.
- Instance variable and instance method references must be selected from proper types.
- Argument types to calls and return types must be valid.
- Assignments to instance variables must have valid types.
- Access privileges observed, exceptions properly declared.
- These things can be verified if we can tell the types in local variables and on the stack.

Validating Types

- Java virtual machine is a stack machine with registers (any number) for local variables and compiler temporaries.
- Type information comes from information in the class files about types of instance variables, types of formal parameters, and return types of methods.
- First N local variables initially contain `this` and parameters; their types are known.
- But nothing explicit in the class files about types on the stack, or in other local variables.
- So we use a form of *abstract interpretation,* execute program, but keep type information instead of actual values.

Basic Blocks

- Easy enough to divide method's bytecode into basic blocks.
- Within one basic block, simulate the stack and locals.
- Suppose we know initially that stack is empty and local variables v0, v1, and v2 have types List, int, and String.
- Then after executing

```
push v0
push v1
call List.get(int)->Object

cast->String
store v3
push v3
etc.
```

```
# stack: List
# stack: List, int
# Parameters are valid
# stack: Object
# stack: String
# stack: ; v3: String
# stack: String, v3: String
```

- We know types on stack and in locals at each point. All necessary checks possible.

Joins

- This leaves the problem of what to do when a basic block has more than one predecessor. What's in its initial starting stack and variables?
- Basic idea is to join the data.
- Example:

```
BLOCK1:
  ...
  jump BLOCK3     # stack: String, int, int; v3: ArrayList
BLOCK2:
  ...
                  # stack: Object, Object, int; v3: String
BLOCK3:           # stack: ? v3: ?
```

- We require that the two stacks have the same depth.
- We can "join" types of corresponding stack elements and of v3's to get something that is valid however we get to BLOCK3:

```
BLOCK3:     # stack: Object, int, int; v3: Object
```

- It's OK to treat anything as an int, since that never breaks anything.

Analysis Challenges

- The perennial problem: are x.y and z.y the same variable?
- Impact on whether one has to re-fetch z.y, or whether one can execute pieces of a program in parallel, if one accesses x.y and the other accesses z.y
- Similar problem in arrays: can A[i] and A[j] access the same location?
- Impact on parallelization, vectorization, and many optimizations.
- In a language where pointer x might access storage on another processor, need to know if x really is just a local pointer. Impact on speed.
- Storage analysis: is this storage location now garbage? Idea is to cut down on garbage collection time by doing some of it statically.