Program Analysis

Learning objectives

- Understand how automated program analysis complements testing and manual inspection
  - Most useful for properties that are difficult to test
- Understand fundamental approaches of a few representative techniques
  - Lockset analysis, pointer analysis, symbolic testing, dynamic model extraction: A sample of contemporary techniques across a broad spectrum
  - Recognize the same basic approaches and design trade-offs in other program analysis techniques

Why Analysis

- Exhaustively check properties that are difficult to test
  - Faults that cause failures
    - rarely
    - under conditions difficult to control
  - Examples
    - race conditions
    - faulty memory accesses
- Extract and summarize information for inspection and test design

Why automated analysis

- Manual program inspection
  - effective in finding faults difficult to detect with testing
  - But humans are not good at
    - repetitive and tedious tasks
    - maintaining large amounts of detail
- Automated analysis
  - replace human inspection for some class of faults
  - support inspection by
    - automating extracting and summarizing information
    - navigating through relevant information

Static vs dynamic analysis

- Static analysis
  - examine program source code
    - examine the complete execution space
    - but may lead to false alarms
- Dynamic analysis
  - examine program execution traces
    - no infeasible path problem
    - but cannot examine the execution space exhaustively

Concurrency faults

- Concurrency faults
  - deadlocks: threads blocked waiting each other on a lock
  - data races: concurrent access to modify shared resources
- Difficult to reveal and reproduce
  - nondeterministic nature does not guarantee repeatibility
- Prevention
  - Programming styles
    - eliminate concurrency faults by restricting program constructs
    - examples
      - do not allow more than one thread to write to a shared item
      - provide programming constructs that enable simple static checks (e.g., Java synchronized)
- Some constructs are difficult to check statically
    - example
      - C and C++ libraries that implement locks

Memory faults

- Dynamic memory access and allocation faults
  - null pointer dereference
  - illegal access
  - memory leaks
- Common faults
  - buffer overflow in C programs
  - access through *dangling* pointers
  - slow leakage of memory
- Faults difficult to reveal through testing
  - no immediate or certain failure

Example

```
} else if (c == '%') {
  int  digit_high = Hex_Values[*(++eptr)];
  int  digit_low  = Hex_Values[*(++eptr)];
```

- fault
  - input string terminated by an hexadecimal digit
  - scan beyond the end of the input string and corrupt memory
  - failure may occur much after the execution of the faulty statement
- hard to detect
  - memory corruption may occur rarely
  - lead to failure more rarely

Memory Access Failures

(explicit deallocation of memory - C,C++)

- Dangling pointers: deallocating memory accessible through pointers
- Memory leak: failing to deallocate memory not accessible any more
  - no immediate failure
  - may lead to memory exhaustion after long periods of execution
    - escape unit testing
    - show up only in integration, system test, actual use
- can be prevented by using
  - program constructs
    - saferC (dialect of C used in avionics applications) limited use of dynamic memory allocation -> eliminates dangling pointers and memory leaks (restriction principle)
  - analysis tools
    - Java dynamic checks for out-of-bounds indexing and null pointer dereferences (sensitivity principle)
  - Automatic storage deallocation (garbage collection)

Symbolic Testing

- Summarize values of variables with few symbolic values
  - example: analysis of pointers misuse
    - Values of pointer variables: null, notnull, invalid, unknown
    - other variables represented by constraints
- Use symbolic execution to evaluate conditional statements
- Do not follow all paths, but
  - explore paths to a limited depth
  - prune exploration by some criterion

Path Sensitive Analysis

- Different symbolic states from paths to the same location
- Partly context sensitive
  (depends on procedure call and return sequences)
- Strength of symbolic testing
  combine path and context sensitivity
  - detailed description of how a particular execution sequence leads to a potential failure
  - very costly
  - reduce costs by memoizing entry and exit conditions
    - limited effect of passed values on execution
    - explore a new path only when the entry condition differs from previous ones

Summarizing Execution Paths

- Find all program faults of a certain kind
  - no prune exploration of certain program paths (symbolic testing)
  - abstract enough to fold the state space down to a size that can be exhaustively explored
- Example:
  analyses based on finite state machines (FSM)
  - data values by states
  - operations by state transitions

Pointer Analysis

- Pointer variable represented by a machine with three states:
  - invalid value
  - possibly null value
  - definitely not null value
- Deallocation triggers transition from non-null to invalid
- Conditional branches may trigger transitions
  - E.g., testing a pointer for non-null triggers a transition from possibly null to definitely non-null
- Potential misuse
  - Deallocation in possibly null state
  - Dereference in possibly null
  - Dereference in invalid states

Merging States

- Flow analysis
  merge states obtained along different execution paths
  - conventional data flow analysis: merge all states encountered at a particular program location
  - FSM: summarize states reachable along all paths with a set of states
- Finite state verification techniques
  never merge states (path sensitive)
  - procedure call and return:
    - complete path- and context-sensitive analysis → too expensive
    - throwing away all context information → too many false alarms
    - symbolic testing: cache and reuse (entry, exit) state pairs

Buffer Overflow

```
…
int main (int argc, char *argv[]) {
        char sentinel_pre[] = "2B2B2B2B2B";
        char subject[]  = "AndPlus+%26%2B+%0D%";
   char sentinel_post[] = "26262626";
   char *outbuf = (char *) malloc(10);
   int return_code;

        printf("First test, subject into outbuf\n");
   return_code = cgi_decode(subject, outbuf);
   printf("Original: %s\n", subject);
   printf("Decoded:  %s\n", outbuf);
   printf("Return code: %d\n", return_code);

        printf("Second test, argv[1] into outbuf\n");
        printf("Argc is %d\n", argc);
   assert(argc == 2);
   return_code = cgi_decode(argv[1], outbuf);
   printf("Original: %s\n", argv[1]);
   printf("Decoded:  %s\n", outbuf);
   printf("Return code: %d\n", return_code);
…
```

Output parameter of fixed length
Can overrun the output buffer

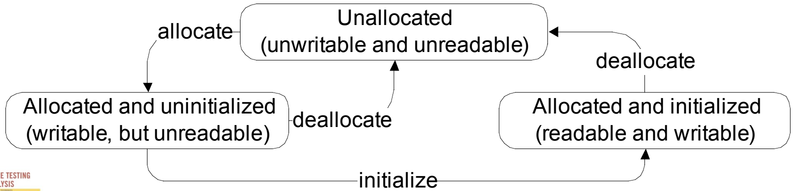
Dynamic Memory Analysis (with Purify)

```
[I] Starting main
[E] ABR: Array bounds read in printf {1 occurrence}
    Reading 11 bytes from 0x00e74af8 (1 byte at 0x00e74b02 illegal)
    Address 0x00e74af8 is at the beginning of a 10 byte block
    Address 0x00e74af8 points to a malloc'd block in heap 0x00e70000
    Thread ID: 0xd64
...
[E] ABR: Array bounds read in printf {1 occurrence}
    Reading 11 bytes from 0x00e74af8 (1 byte at 0x00e74b02 illegal)
    Address 0x00e74af8 is at the beginning of a 10 byte block
    Address 0x00e74af8 points to a malloc'd block in heap 0x00e70000
    Thread ID: 0xd64
...
[E] ABWL: Late detect array bounds write {1 occurrence}
    Memory corruption detected, 14 bytes at 0x00e74b02
    Address 0x00e74b02 is 1 byte past the end of a 10 byte block at 0x00e74af8
    Address 0x00e74b02 points to a malloc'd block in heap 0x00e70000
    63 memory operations and 3 seconds since last-known good heap state
    Detection location - error occurred before the following function call
        printf          [MSVCRT.dll]
...
       Allocation location
        malloc          [MSVCRT.dll]
...
[I] Summary of all memory leaks... {482 bytes, 5 blocks}
...
[I] Exiting with code 0 (0x00000000)
    Process time: 50 milliseconds
[I] Program terminated ...
```

Identifies the problem

Memory Analysis

- Instrument program to trace memory access
  - record the state of each memory location
  - detect accesses incompatible with the current state
    - attempts to access unallocated memory
    - read from uninitialized memory locations
  - array bounds violations:
    - add memory locations with state *unallocated* before and after each array
    - attempts to access these locations are detected immediately



Data Races

- Testing: not effective
  (nondeterministic interleaving of threads)
- Static analysis:
  computationally expensive, and approximated
- Dynamic analysis:
  can amplify sensitivity of testing to detect potential data races
  - avoid pessimistic inaccuracy of finite state verification
  - Reduce optimistic inaccuracy of testing

Dynamic Lockset Analysis

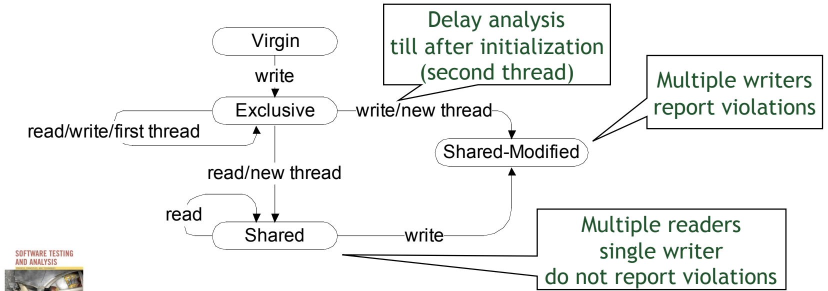
- Lockset discipline: set of rules to prevent data races
  - Every variable shared between threads must be protected by a mutual exclusion lock
  - ....
- Dynamic lockset analysis detects violation of the locking discipline
  - Identify set of mutual exclusion locks held by threads when accessing each shared variable
  - INIT: each shared variable is associated with all available locks
  - RUN: thread accesses a shared variable
    - intersect current set of candidate locks with locks held by the thread
  - END: set of locks after executing a test = set of locks always held by threads accessing that variable
    - empty set for v = no lock consistently protects v

Simple lockset analysis: example

Thread	Program trace	Locks held	Lockset(x)	
		{}	{lck1, lck2}	INIT:all locks for x
thread A	lock(lck1)			
		{lck1}		lck1 held
	x=x+1			
			{lck1}	Intersect with locks held
	unlock(lck1}			
		{}		
tread B	lock{lck2}			
		{lck2}		
	x=x+1			lck2 held
			{}	
	unlock(lck2}			Empty intersection potential race
		{}		

Handling Realistic Cases

- simple locking discipline violated by
  - initialization of shared variables without holding a lock
  - writing shared variables during initialization without locks
  - allowing multiple readers in mutual exclusion with single writers



Extracting Models from Execution

- Executions reveals information about a program
- Analysis
  - gather information from execution
  - synthesize models that characterize those executions

Example: AVL tree

```
private AvlNode insert( Comparable x, AvlNode t ){
    if( t == null )
        t = new AvlNode( x, null, null );
    else if( x.compareTo( t.element ) < 0 ){
        t.left = insert( x, t.left );
        if( height( t.left ) - height( t.right ) == 2 )
            if( x.compareTo( t.left.element ) < 0 )
                t = rotateWithLeftChild( t );
            else
                t = doubleWithLeftChild( t );
    }else if( x.compareTo( t.element ) > 0 ){
        t.right = insert( x, t.right );
        if( height( t.right ) - height( t.left ) == 2 )
            if( x.compareTo( t.right.element ) > 0 )
                t = rotateWithRightChild( t );
            else
                t = doubleWithRightChild( t );
    } else
        ;  // Duplicate; do nothing
    t.height = max( height( t.left ), height( t.right ) ) + 1;
    return t;
}
```

Behavior model at the end of `insert`:

father > left
father < right
diffHeight one of {-1,0,1}

Automatically Extracting Models

- Start with a set of predicates
  - generated from templates
  - instantiated on program variables
  - at given execution points
- Refine the set by eliminating predicates violated during execution

Predicate templates

over one variable	
constant	x=a
uninitialized	x=uninit
small value set	x={a,b,c}
over a single	*numeric variable*
in a range	x≥a,x≤b,a≤x≤b
nonzero	x≠0
modulus	x=a(mod b)
nonmodulus	x≠a(mod b)
over the sum of	*two numeric variables*
linear relationship	y=ax+b
ordering relationship	x≤y,x<y,x=y,x≠y
…	

Executing AVL tree

```
private static void testCaseSingleValues() {
  AvlTree t = new AvlTree();
  t.insert(new Integer(5));
  t.insert(new Integer(2));
  t.insert(new Integer(7));
}

private static void testCaseRandom(int nTestCase) {
  AvlTree t = new AvlTree();

  for (int i = 1; i < nTestCase; i++) {
      int value=(int)Math.round(Math.random()*100);
      t.insert(new Integer(value));
  }
}
```

The model depends on the test cases

Derived Models

useless (redundant) information

model for *testCaseSingleValues*	**model for *testCaseRandom***
father one of {2, 5, 7}	father >= 0
left == 2	left >= 0
right == 7	father > left
leftHeight == rightHeight	father < right
rightHeight == diffHeight	left < right
leftHeight == 0	fatherHeight >= 0
rightHeight == 0	leftHeight >= 0
fatherHeight one of {0, 1}	rightHeight >= 0
	fatherHeight > leftHeight
	fatherHeight > rightHeight
	fatherHeight > diffHeight
	rightHeight >= diffHeight
	diffHeight one of {-1,0,1}
	leftHeight - rightHeight + diffHeight == 0

additional information: all elements are non-negative

elements are inserted correctly

limited validity of the test case: the tree is perfectly balanced

the tree is balanced

Model and Coincidental Conditions

- Model:
  - not a specification of the program
  - not a complete description of the program behavior
  - a representation of the behavior experienced so far
- conditions may be coincidental
  - true only for the portion of state space explored so far
  - estimate probability of coincidence as the number of times the predicate is tested

Example of Coincidental Probability

`father >= 0` probability of coincidence:

- 0.5 if verified by a single execution
- 0.5^n if verified by n executions.

threshold of 0.05

- two executions with `father` =7
  - `father = 7` valid
  - `father >= 0` not valid (high coincidental probability)
- two additional execution with `father` positive
  - `father = 7` invalid
  - `father >= 0` valid

`father >= 0` valid for `testCaseRandom` (300 occurences)
not for `testCaseSingleValues` (3 occurences)

Using Behavioral Models

- Testing
  - validate tests thoroughness
- Program analysis
  - understand program behavior
- Regression testing
  - compare versions or configurations
- Testing of component-based software
  - compare components in different contexts
- Debugging
  - Identify anomalous behaviors and understand causes

Summary

- Program analysis complements testing and inspection
  - Addresses problems (e.g., race conditions, memory leaks) for which conventional testing is ineffective
  - Can be tuned to balance exhaustiveness, precision, and cost (e.g., path-sensitive or insensitive)
  - Can check for faults or produce information for other uses (debugging, documentation, testing)
- A few basic strategies
  - Build an abstract representation of program states by monitoring real or simulated (abstract) execution