Data flow analysis for Uranus applications

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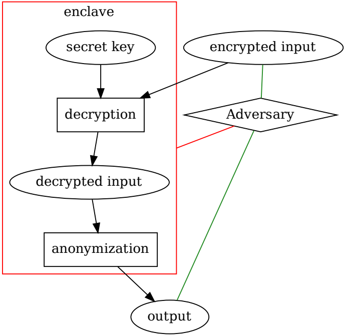
Outline

Background

SGX Enclaves

- Servers outsourced to third-party cloud providers
- Threat model: Adversaries with privileged access to OS, BIOS or hardware
- Enclave protects both code and memory from these adversaries



Uranus [2]

- OpenJDK fork that supports Intel SGX
- Methods marked as `@JECall` enters enclaves until return
- Methods marked as `@JOCall` exits enclaves until return
- Useful for integration with libraries like Hadoop and Spark
- Question: Where should `@JECall` and `@JOCall` be placed?
- Question: Is code in these libraries safe as enclave code?

The problem: Performance/Security Tradeoff

- More code outside enclave:
  - Increased risk of leaking protected data
  - Some leaks may come from unexpected side channels
- More code into enclave:
  - Limited EPC (Enclave Page Cache)
    - Up to 100 MB of EPC
    - Out of memory $\implies$ extremely slow swap
    - JVM applications especially memory-greedy
  - Principle of Least Privilege
    - Vulnerabilities in enclave code bypass enclave protection
    - Vulnerabilities in code outside must only use specific entry points
    - Reduce attack surface

The solution

- Select the minimum cover of sensitive data
- *enclavlow* [1]: an information flow analysis tool
- Sources of sensitive data marked with `sourceMarker`
- Anonymization marked with `sinkMarker`
- Identity functions; expected to be optimized them away by JIT

```
@JECall
static int process(byte[] encrypted) {
  byte sum = 0;
  byte[] password = sourceMarker(new byte[]{1, 2, 3, 4, 5, 6});
  byte[] decrypted = decrypt(password, encrypted);
  for(byte b : decrypted) sum ^= b;
  return sinkMarker(sum);
}
```

[1] coined from the words "enclave" and "flow"

Threat model

- Adversary has no read/write access to enclave code and memory
- Adversary has arbitrary access to any system resource, *including* non-enclave Java and JVM memory
- The actual adversary also has access to hardware resources, including sensor modules, system clock, etc.
- These resources can be used to implement side channel attacks, which are system-dependent, environment-dependent and architecture-dependent
- Example: Timing attack based on CPU branch prediction optimization
- Our adversary model excludes these side channel attacks

Changes on Uranus model

- Applications are expected to run on a Uranus-based JVM.
- Some behaviour disallowed by Uranus assumed permissible under explicit indication
- Assignment to objects outside enclaves
  - Reads are assumed copied into enclave
  - Writes are assumed always leaking
- Assignment to static fields
  - Reads are cloned into enclave
  - Writing enclave-local data may not be expected behaviour
  - Assumed immediate leak
- Expected to integrate into Uranus for compile-time checking/optimization

Approach

Intuition: Trivial ways of leaking data

```
static int outside; // static variables stored outside enclave
@JOCall void println(int x);

int secret() {
  return sourceMarker(123456);
}

@JECall int foo() {
  store = secret(); // assigning to static field
  println(secret()); // passing secret to a JOCall
  return secret(); // returning secret out of a JECall
}
```

Intuition: Non-trivial ways of leaking data

- Assigning to an outside-enclave object:

```
@JECall void x(Box box) {
  box.value = secret();
}
```

- Leaking control flow into variables:

```
if(secret() >= 3) outside++;
for(int i=0; i < secret(); i++) outside++;
```

- Implicit exceptions:

```
int[] array = new int[3];
array[secret()] = 1;
```

- Transitive application of above

Flow graph

- Analysis framework: Soot [1]
- Each readable/writable data entry as a node
- $(x, y) \in E \implies$ placement of y outside enclave reduces indistinguishability of x
- $(x, y), (y, z) \in E$: transitive
- $(x, y), (x, z) \in E$: Leaking *either* y *or* z distinguishes x
- No way to represent requirement of *both* y *and* z

Procedure

1. Each method is analyzed independently as a Local Flow Graph (LFG)
2. LFG contracted into subgraph of only "public" nodes called Contract Flow Graph (CFG)
3. CFGs merged together into Aggregate Flow Graph (AFG),

Local flow graph

- Analyze each method independently using Soot's `ForwardBranchedFlowAnalysis`
- Soot calls the `flowThrough` method for each 3AC (jimple) statement
- Each `flowThrough` maps the state in the previous step to a new state
- For branching statements, each branch has a its own state
- When flows converge, soot calls the `merge` method to map two states into a new one

Implementing `flowThrough` for assignment operations

- For each type of value, define
  - rvalue nodes
  - lvalue nodes for assignment
  - and lvalue nodes for deletion
- Pseudocode:

```
Algorithm assign($left = $right):
  for each lvalues($left, FLAG_DELETION) as $node:
    delete (*, $node) from flow graph
  for each lvalues($left) as $leftNode:
    add (CTRL, $leftNode) to flow graph
    for each rvalues($right) as $rightNode:
      add ($rightNode, $leftNode) to flow graph // intuitive
  for each lvalues($right) as $leftNode:
    for each rvalues($left) as $rightNode:
      add ($rightNode.*, $leftNode.*) to flow graph // field projection
```

Global nodes

- Static node
  - All reads use Uranus cache
  - Writes are assumed immediate leak
- Explicit source/sink
  - Explicit sink is cosmetic

Method signature nodes

- Parameter nodes
  - Supports both read and write
- This node
  - just an alternative parameter
- Return node
- Throw node
  - just an alternative return path

The CTRL node

- Tracks what data affect the current flow
- Each branched block has its CTRL node
- $(x, \mathrm{CTRL}) \in E \implies \exists$ predicate p such that the branch represented by CTRL executes if and only if $p(x)$
- $(\mathrm{CTRL}_1, \mathrm{CTRL}_2) \in E$ when CTRL_2 is a subbranch of CTRL_1
- $(\mathrm{CTRL}, y) \in E \implies$ leaking y may distinguish whether CTRL was run
- Merging states: select Lowest Common Ancestor

Other nodes

- Local variables
  - Including temp values created by Jimple
- Method calls
  - Blackbox proxies to signature nodes

Contraction and aggregation

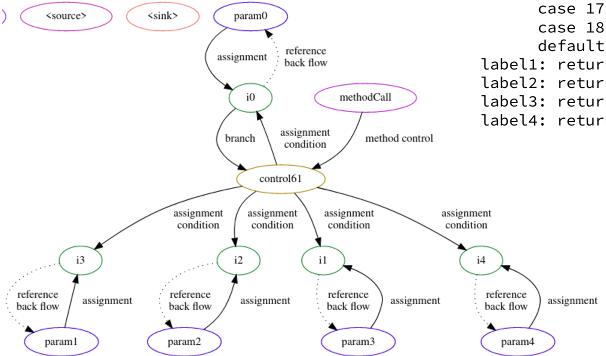
- At each return point, track flow from "public" nodes into the following nodes:
  - `this`
  - `static`
  - explicit sink
  - parameters
  - method calls (proxy nodes)
- At aggregation, connect each proxy node to the actual implementation
  - Polymorphism?

Case study

Case study: Branching (tableswitch)

```
public static int switchMux(int x,
    int a, int b, int c, int d) {
  switch (x) {
    case 16: return a;
    case 17: return b;
    case 18: return c;
    default: return d;
  }
}
```

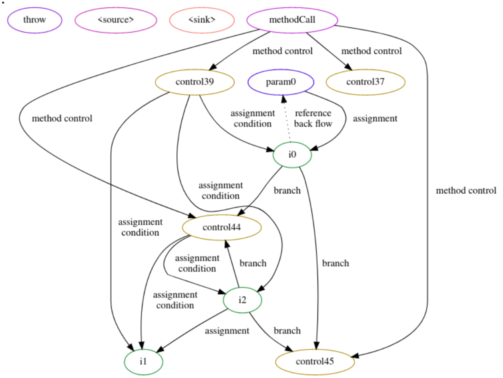
```
public static int switchMux
    (int, int, int, int, int) {
  int i0, i1, i2, i3, i4;
  i0 := @parameter0: int;
  i3 := @parameter1: int;
  i2 := @parameter2: int;
  i1 := @parameter3: int;
  i4 := @parameter4: int;
  tableswitch(i0) {
      case 16: goto label1;
      case 17: goto label2;
      case 18: goto label3;
      default: goto label4; };
label1: return i3;
label2: return i2;
label3: return i1;
label4: return i4; }
```



Case study: Loops

```java
public static int loopInc(int i) {
  int a = 0;
  for (int j = 0; j < i; j++) {
     a += j;
  }
  return a;
}
```

```
public static int loopInc(int) {
  int i0, i1, i2;
  i0 := @parameter0: int;
  i1 = 0;
  i2 = 0;
label1:
  if i2 >= i0 goto label2;
  i1 = i1 + i2;
  i2 = i2 + 1;
  goto label1;
label2: return i1; }
```

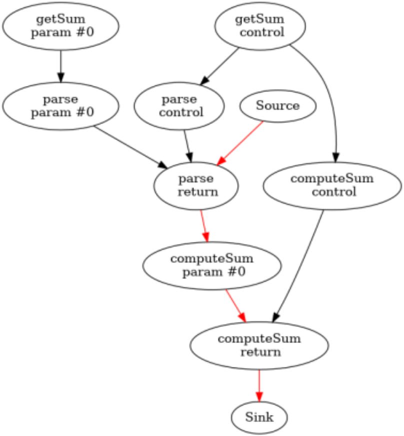


AFG: Full Example

```
@JECall
int getSum(byte[] enc) {
  byte[] dec = parse(enc);
  return sinkMarker(computeSum(dec)); }

byte[] parse(byte[] enc) {
  byte[] otp = sourceMarker(PRIVATE_KEY);
  byte[] result = new byte[enc.length];
  for(int i = 0; i < buf.length; i++)
    result[i] = enc[i] ^ otp[i];
  return result; }

int computeSum(byte[] bytes) {
  int result = 0;
  for(byte b : bytes) result += (int) result;
  return result; }
```



Limitations

False negatives: implicit exceptions

- Conditional runtime errors leaks data
  - `NullPointerException`
  - `IndexOutOfBoundsException`
- Too sensitive to raise an exception path for every array access and object access
- Good practice: exceptions should be caught at enclave boundary anyway!
- Solutions usually achieved at the language level, e.g. `@NonNull`, `@Size`
- Do not reinvent the wheel

False positives: identical branches

- This does not leak `secret` (assuming `doSomething*()` do not leak control flow)

```java
boolean foo() {
  int secret = getSecret();
  if(secret > 1) {
    doSomething();
    return false;
  } else {
    doSomethingElse();
    return false;
  }
}
```

- Suggested fix: factorize common code out of branches (good code style)

False positives: self-anonymization

- This does not leak `secret` (assuming `doSomethingWith(int)` does not leak)

```
int foo(int a) {
  int secret = getSecret();
  a += secret;
  doSomethingWith(a);
  a -= secret;
  return a;
}
```

- Suggested fix: create a clone of `a`
- Immutability paradigms?
  - We are considering the *compiled binary* layer, so functional programming languages do not help

Tackling polymorphism

- Computing all combinations of instance classes requires exponential time.
- Solution: union of CFGs of all possible subclasses
    - Iago attacks is still possible if code is used elsewhere in enclave
    - Therefore all subclasses, not only those through call analysis, are considered

Tackling JNI calls

- Assumptions:
  - parameters are independent
  - return value is the output
  - control flow is not leaked
- False negative example: `System.arraycopy`
- Uranus turns system calls into `OCall`s, which leak control flow.

Conclusion

- Assist with decisions on performance/security tradeoff
- Incorporated into Uranus
- Room for improvement on false negative cases
- Integration with source level analysis

References

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