Threading Software Watermarks

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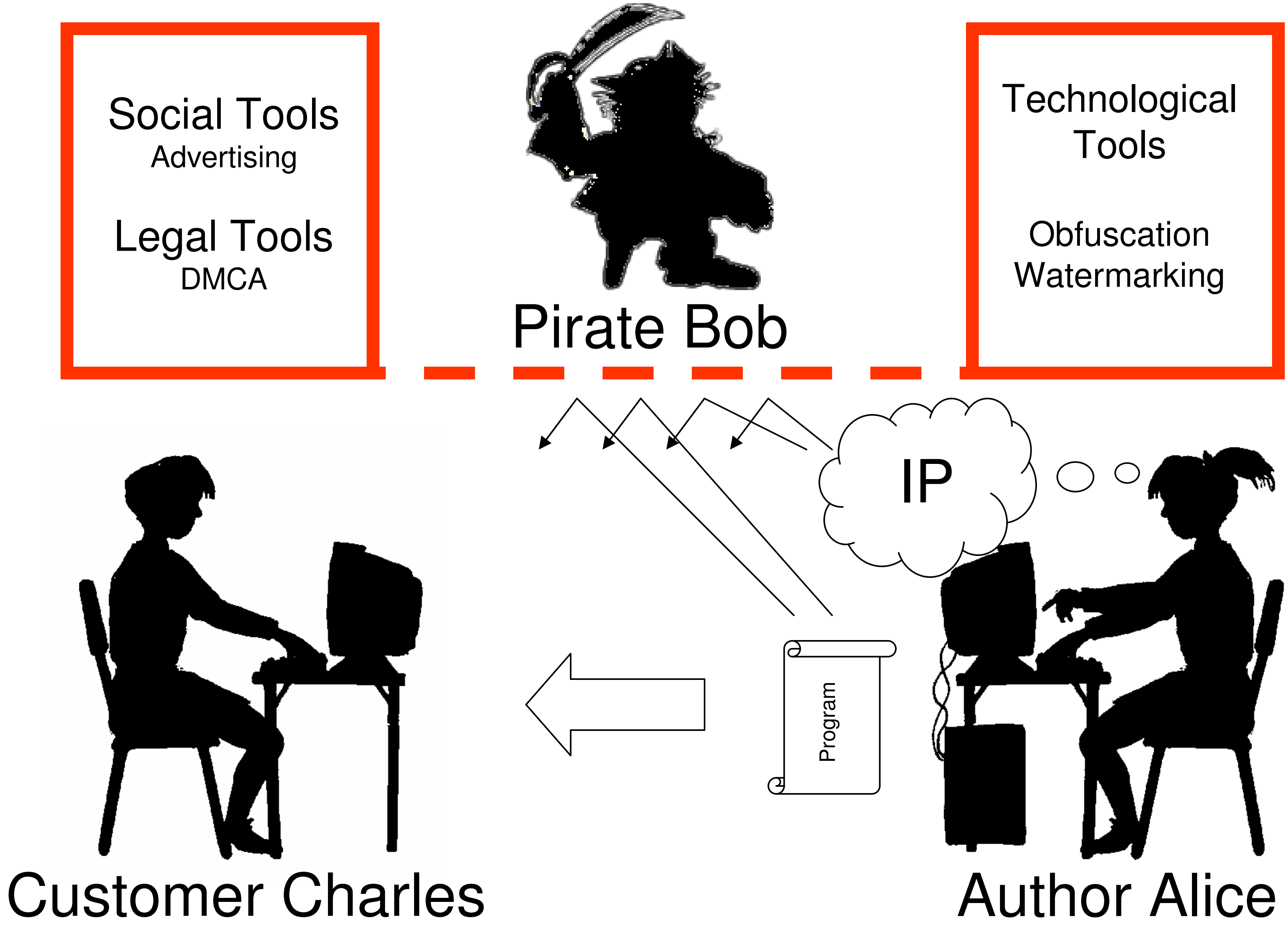
Scenario


Social Tools
Advertising
Legal Tools
DMCA
Pirate Bob
Technological Tools
Obfuscation
Watermarking
IP
Program
Customer Charles
Author Alice

What is…

- Software Watermarking

  – embedding identifying information into a program

  – Program is semantically equivalent to the original
  – Embedded information can be extracted or detected
  – Recognition is potentially keyed on a secret key

What is…

- Dynamic Watermarking

  – embed information in the runtime behavior of a program

  – watermarked program must be run before the mark can be extracted
  – static analysis to determine runtime characteristics is hard

  – Only one other dynamic watermarking scheme exists: CT algorithm

Outline

How do you robustly embed information in a software program using threads?

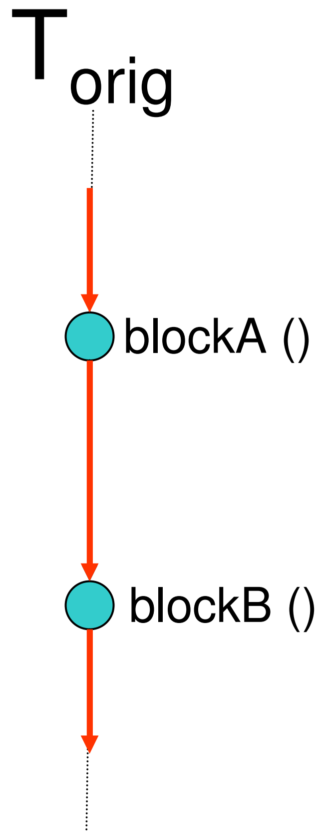
- We are interested in watermarks that are
  - robust
  - dynamic
- Outline
  - Using threads for encoding watermarks
  - Implementation in Java
  - Attacks against this scheme
  - Summary of notable features of our design

Why Threads?

- Ideally embedding a watermark should:
  - insert information
  - complicate analysis such that removing the watermark becomes difficult
- Static analysis of multithreaded programs is hard
  - Djikstra, Ousterhout, Collberg
- Collberg et al. suggest using threads for obfuscation
- We go further and show how to embed watermarks using threads

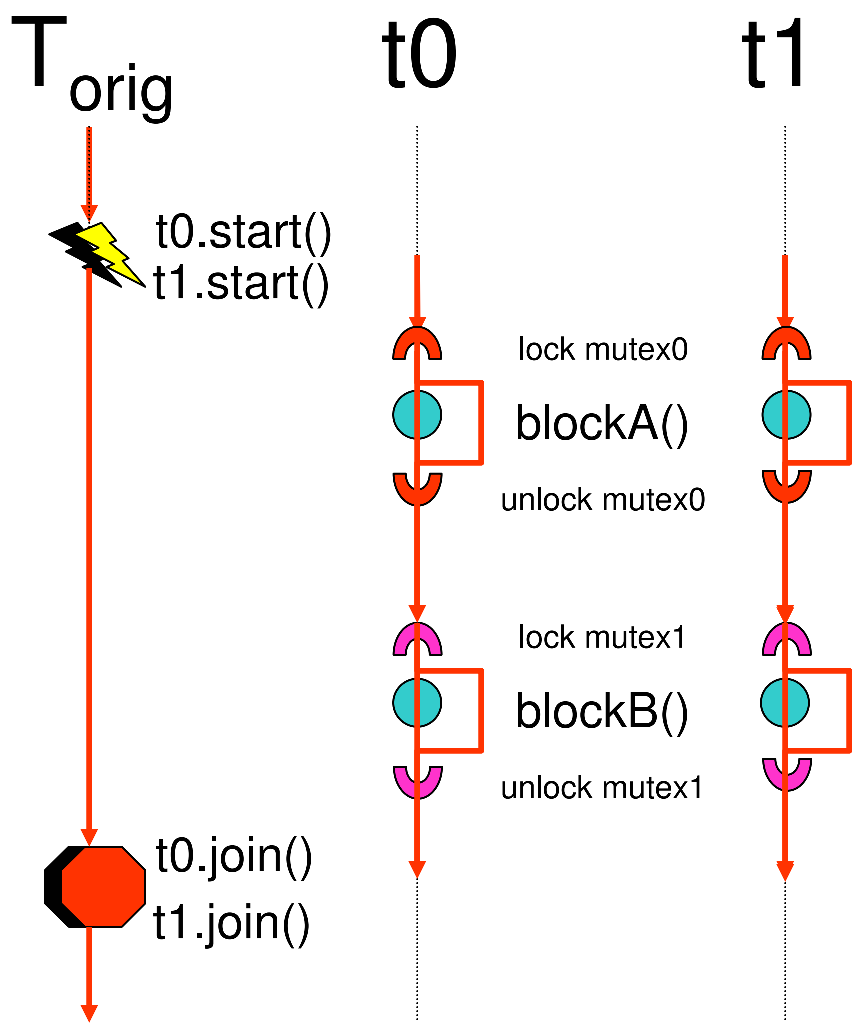
Encoding Information in Threads

```
public class Foo {

    public void run () {
        blockA();
        blockB();
    }

    :

    public static void main ( String args ) {
        Foo foo = new Foo();
        foo.run();
    }

}
```



Encoding Information in Threads

```
Thread t0 = new Thread () {
    public void run () {
            lock mutex0 ;
            if ( ! doneA ) {
                    blockA ();
                    doneA = true ;
            }
            unlock mutex0;
            lock mutex1;
            if ( ! doneB ) {
                    blockB ();
                    doneB = true ;
            }
            unlock mutex1;
    }
};
Thread t1 = new Thread ( t0 );
t1. start (); t0. start ();
t1. join (); t0. join ();
```



Four possible paths

Encoding Information in Threads

```
Thread t0 = new Thread () {
    public void run () {
        lock mutex0 ;
        if ( ! doneA ) {
            blockA ();
            doneA = true ;
        }
        lock mutex1;
        unlock mutex0;
        if ( ! doneB ) {
            blockB ();
            doneB = true ;
        }
        unlock mutex1;
    }
};
Thread t1 = new Thread ( t0 );
t1. start (); t0. start ();
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```
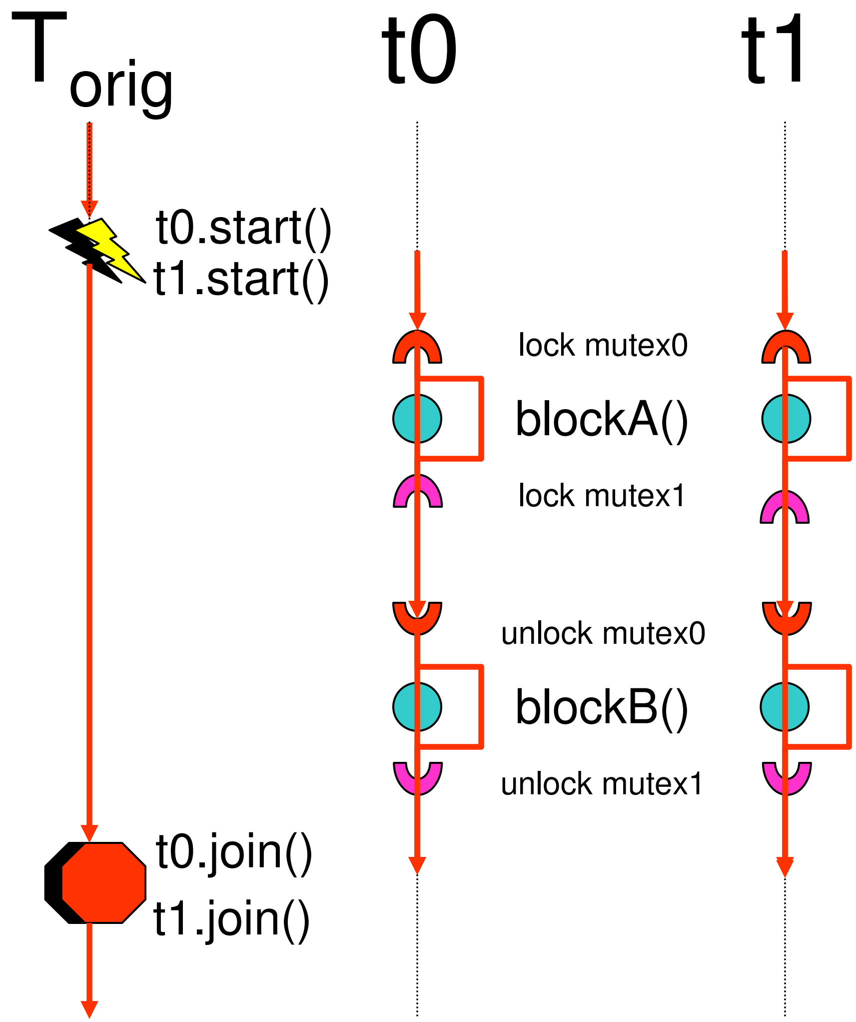



Two possible paths

Encoding Information in Threads

- Original program executes:
  - (t0, blockA), (t0, blockB)
  - (t0, blockA), (t1, blockB)
  - (t1, blockA), (t0, blockB)
  - (t1, blockA), (t1, blockB)

- Encoded program executes:
  - (t0, blockA), (t0, blockB)
  - (t1, blockA), (t1, blockB)
- Different encoded program:
  - (t0, blockA), (t1, blockB)
  - (t1, blockA), (t0, blockB)

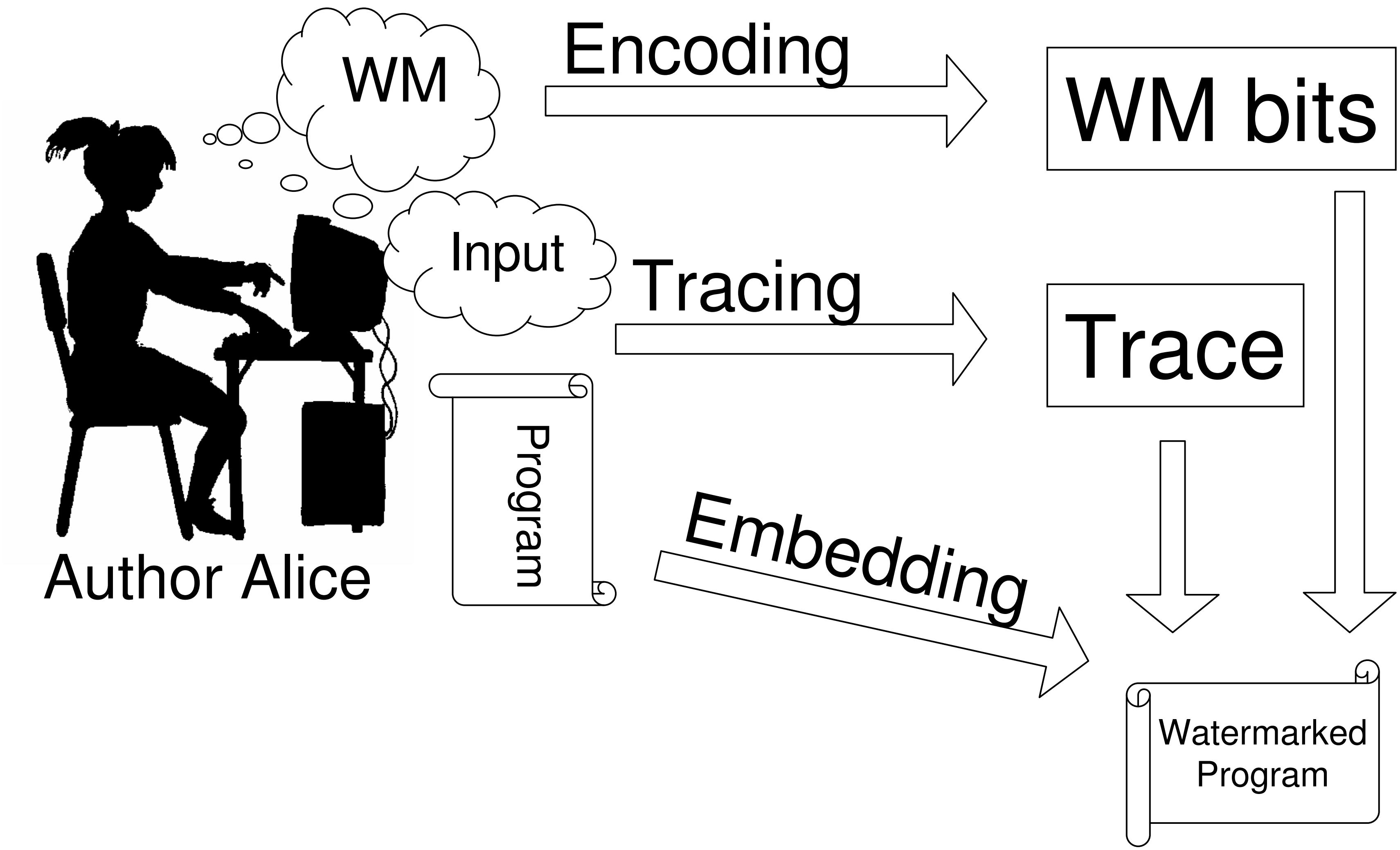
Can be used to encode a bit

Decompiling to Java

- Java requires well-nested monitors
  - at source level Java uses only a **synchronized** block
- Poorly nested monitors cannot be easily decompiled
  - **synchronized** blocks cannot capture these semantics
- No alteration of the JVM is needed
  - exploit semantic difference between Java language & JVM
  - dynamically all monitor enter and exit calls are matched
  - security guarantees made by Java are maintained
- One more impediment for the attacker

Thread-based Watermarking

- Overview



Encoding

"Copyright Alice, 2004"

Encoding function

436470797269…

Error correcting code

Bits to embed = 0100101001…

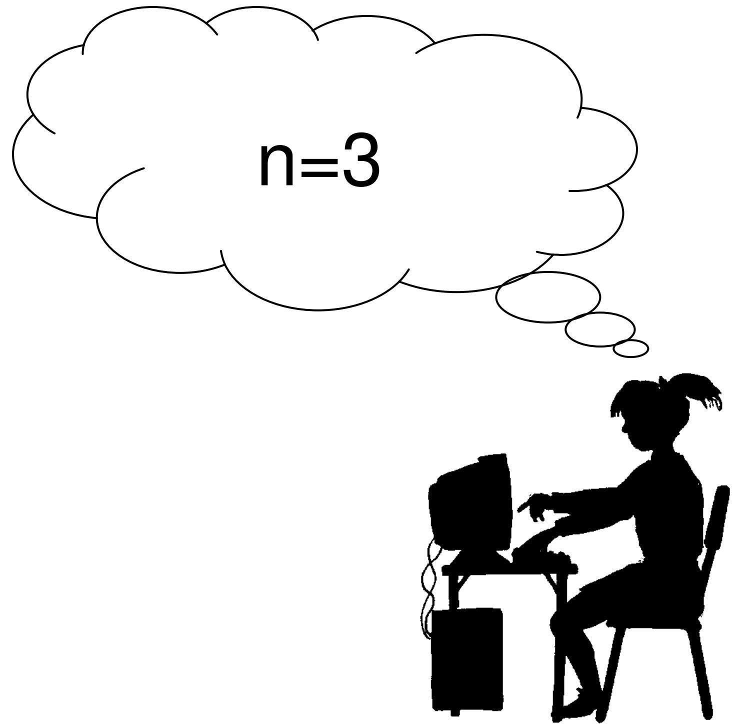
Tracing

```
public int foo ( int n ) {
    blockA;
    if ( blockB ) {
        blockC;
    } else {
        blockD;
        blockE;
    }
}
```

embed bit 0

embed bit 1

embed bit 1



- Alice selects a path through the program: A, B, D, E
- A subset of basic blocks that get executed on that path: A, D, E
- Embedding code in the basic blocks inserts the watermark
- For example Alice can embed “011” in A, D and E as shown

Embedding

- Divide each selected basic block into three pieces
- Create three new threads
- Execute the three pieces using the three threads
- Use locks to maintain semantic correctness
- Control which threads execute which piece

- Bit 0
  - (tA, piece1), (tB, piece2), (tC, piece3)

- Bit 1
  - (tA, piece1), (tB, piece2), (tA, piece3)

Detecting Thread Watermarks

(t3, mutex0)	(t1, mutex0)
(t3, mutex1)	(t3, mutexOrig)
(t2, mutex0)	(t3, mutex0)
⋮	(t2, mutex1)

- Annotate the program for tracing
- Run the program with secret input
- Decode the sequence of threads and locks found

Decoding Thread Watermarks

- Patterns of locks

  - Bit 0
    - tA, tA, tB, tC, tA, tA, tB
  - Bit 1
    - tA, tA, tB, tC, tC, tA, tB

Pattern Matching Attacks

- To keep the recognition dynamic, we have to prevent static pattern matching attacks distinguishing between bit0 and bit1

Bit 0

```
if ( doneC || doneD ) {
    ⋮
    monitorexit mutex1;
    ⋮
    monitorexit mutex0;
    ⋮
}
```

Bit 1

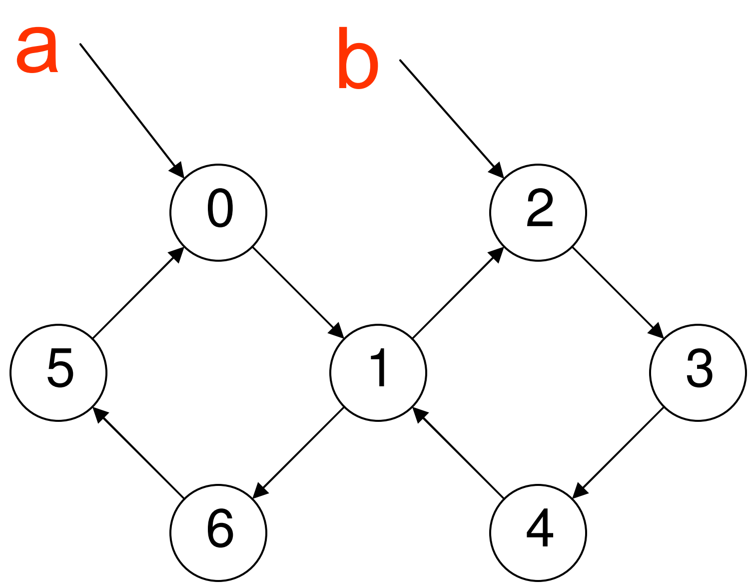
```
if ( ! doneD ) {
    ⋮
    monitorexit mutex0;
    ⋮
    monitorexit mutex1;
    ⋮
}
```

Pattern Matching Defense

- Static analysis will discover:
  - **monitorexit** takes different operands
  - predicates are different
- Merging predicates
  - use opaque predicates to collapse predicates
- Merging operands
  - operands to **monitorexit** in JVM appear on the stack
  - can obscure stack arguments
    - pointer aliasing

Opaque Predicates

- Opaque predicate is a
  - Non obvious tautology
  - Boolean expression
  - Value known to watermarker at watermarking time
  - Difficult for the attacker to deduce



Opaque Predicate Merge

- merge different predicates into a single statically indistinguishable predicate

- Bit 0
  (((doneC || doneD) && opaqueTrue) ||
  (!doneD && opaqueFalse))

- Bit 1
  (((doneC || doneD) && opaqueFalse) ||
  (!doneD && opaqueTrue))

Pattern Matching Defense

- Static analysis will discover:
  - predicates are different
  - **monitorexit** takes different operands
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- Merging operands
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Statistics

- Initial experiments using sample Java programs indicate:
  - Significant slowdown factor of ~8 on embedding a 48-bit watermark in a tightly optimized benchmark program without any I/O.
  - More modest slowdown factor <2 on GUI programs with a lot of user I/O
  - Achieved by avoiding tight loops and hotspots

  - Embedding a 48-bit watermark → 60kB increase in size
  - Size increase approx. linear with number of bits inserted

Evaluation

- Obfuscation Attacks
  - renaming attacks
  - block reordering
  - method inlining/outlining
- Decompilation/Recompilation Attacks
  - only well-nested monitors can be expressed using synchronized blocks at Java source level
  - current decompilers fail to decompile watermarked programs
  - decompilation is possible in theory
    - Dava emulates these locks using a library
- Additive Attacks
  - insert additional thread switches into the program
  - inserts additional bits into the decoded bit string

Conclusion

- Problem:

How can we use threads to embed information in a program?

- Solution
  - Encode the watermark as a bit string
  - Embed the bit string
    - locks control which threads execute selected basic blocks
  - Detect watermark
    - trace the order in which locks get acquired
- Stealth – prevent static analysis
  - Use pointer aliasing to hide which locks are used; and
  - Use opaque predicates to merge different predicates

Questions

- Questions?