CONFUSE

LLVM-based Code Obfuscator

PLT Course Project Demo
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Outline

1. Introduction To Code Obfuscation
2. LLVM
3. Obfuscation Techniques
    1. String Transformation
    2. Junk Code
    3. Opaque Predicates
4. Testing
5. Conclusion

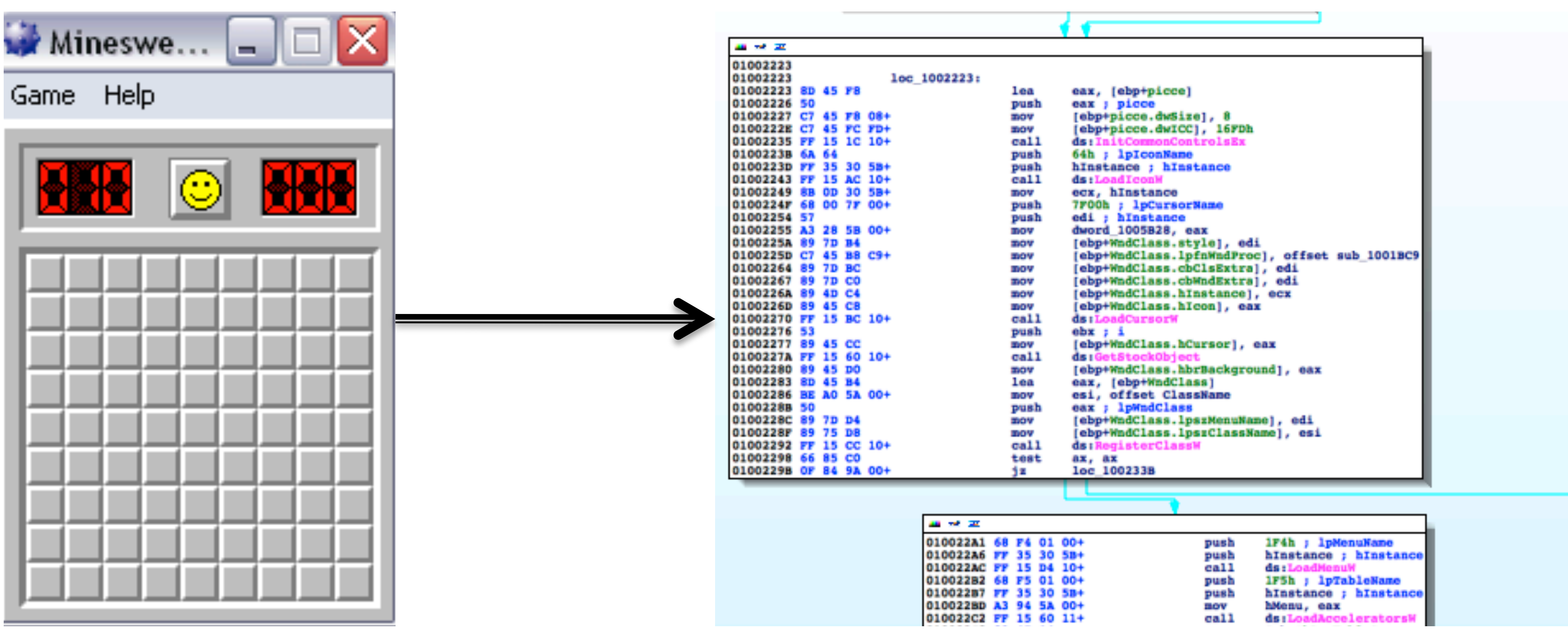
Code Obfuscation

- Problem
  - Compiled binaries can be easily disassembled and “reversed”
  - Readily available tools
    - Disassemblers (e.g. IDA-Pro)
    - Decompilers (e.g. Hex-Rays)

    } Reverse Engineering
- A need to “complicate” software
  - While retaining semantics

Code Obfuscation

- Sample disassembly (IDA Pro Disassembler)



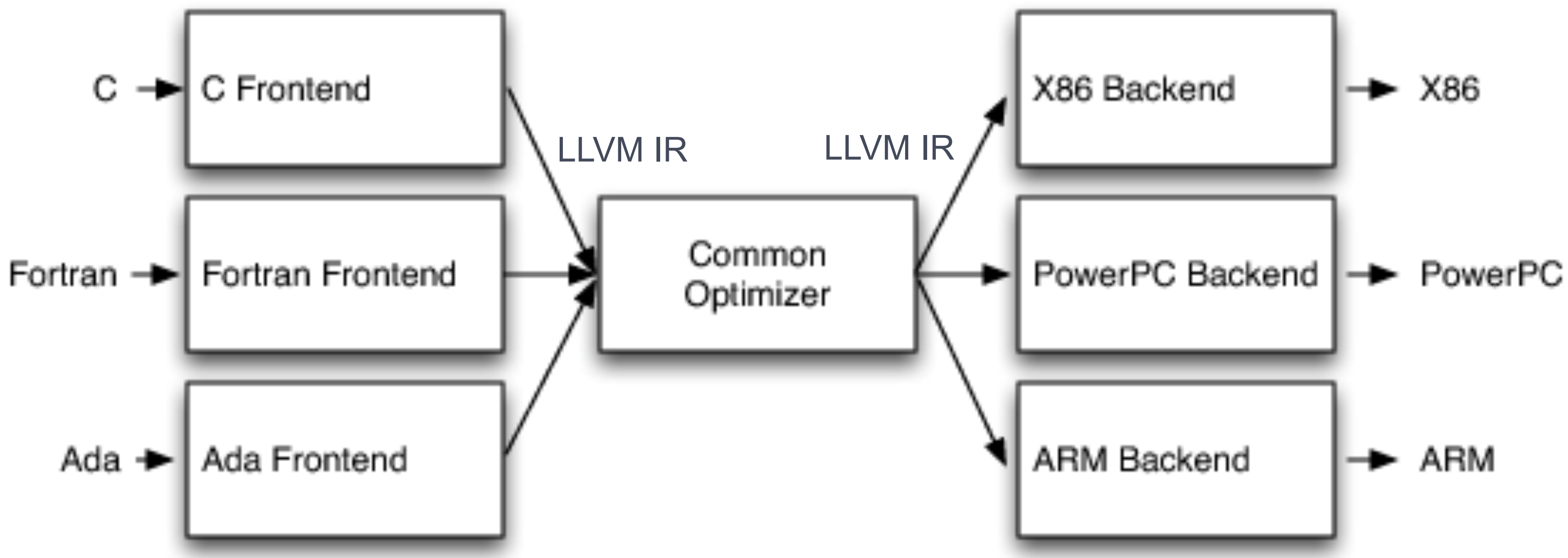
Code Obfuscation

- Motivation
  - To make binary programs more resistant to reverse-engineering efforts
  - Protection of intellectual property
  - Malware

Code Obfuscation

- Obfuscation can occur at virtually any point:
  - Front-end (source code)
  - Optimizer (intermediate representation)
  - Back-end (assembly)
  - After compilation (machine code)
- Our approach
  - Obfuscate C source files
  - Add optimization (obfuscation) passes for the LLVM optimizer

LLVM Design


C
C Frontend
Fortran
Fortran Frontend
Ada
Ada Frontend
LLVM IR
Common Optimizer
LLVM IR
X86 Backend
PowerPC Backend
ARM Backend
X86
PowerPC
ARM

LLVM

- Optimizer Design
  - Multiple passes executed sequentially
  - Passes written in C++
  - 2 Types of passes
    - Analysis
    - Transform
  - Transform passes are not using each other
  - They might use analysis passes though

LLVM IR

- Low level, RISC-like
- 3-Address Code (Static Single Assignment)
- Infinite number of registers
- 3 Flavors of representation
  - In memory data structure
  - Bit-code
  - Textual

HelloWorld.ll

```
declare i32 @puts (i8*)
@global_str = constant [13 x i8] c"Hello World!\00"
define i32 @main() {
	%temp = getelementptr [13 x i8]* @global_str, i64 0, i64 0
	call i32 @puts(i8* %temp)
	ret i32 0
}
```

Obfuscation Techniques

- 3 different techniques
  - String Transformation
  - Junk Code
  - Opaque Predicates
- Implemented as different (independent) passes
- Can be used separately or in conjunction

String Transformation

```
h = hash(x);
if (h == H1) {
/* code for H1 */
}
else if (h == H2) {
/* code for H2 */
}
else if (h == H3) {
/* code for H3 */
}
```

- What does x represent?

String Transformation

```
if (strcmp(x, "open") == 0) {
/* code for open */
}
else if (strcmp(x, "delete") == 0) {
/* code for delete
}
else if (strcmp(x, "edit") == 0) {
/* code for edit
}
```

Cryptographic Hash Functions

- Small changes in input
  - Totally different digest
- Uniform distribution
- Heavily used for authentication
  - Digital signatures
  - MAC

String Transformation

- Used SHA-1 cryptographic function
  - Has 2^{-52} chance of collision (latest attack)
- Remove string literals from file if their sole use is in comparisons
- Supports:
  - strcmp
  - strncmp

Junk Code Insertion

- Approach:
  - Transform variable assignment operations to semantically equivalent instructions
- Challenge:
  - Need to ensure transformations do not get “optimized” away
- Key idea:
  - Transform using arithmetic operations

Junk Code Insertion

- Sample transformation
  - Add additional instructions
  - Insert before store instructions

```
int func1(int x)
{
    x++;
    return x;
}
```

```
[======before insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   store i32 0, i32* %x, align 4
[instruction  4]:   %0 = load i32* %x, align 4
[instruction  5]:   %inc = add nsw i32 %0, 1
[instruction  6]:   store i32 %inc, i32* %x, align 4
[instruction  7]:   ret i32 0
```

```
[======after insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   store i32 0, i32* %x, align 4
[instruction  4]:   %0 = load i32* %x, align 4
[instruction  5]:   %inc = add nsw i32 %0, 1
[instruction  6]:   %temp = add i32 %inc, 5
[instruction  7]:   %temp1 = mul i32 %temp, 4
[instruction  8]:   %temp2 = sub i32 %temp1, 20
[instruction  9]:   %temp3 = sdiv i32 %temp2, 4
[instruction  10]:   store i32 %temp3, i32* %x, align 4
[instruction  11]:   ret i32 0
```

Junk Code Insertion

- Different methods of transformation – <u>Method 1</u>
  - Preserve value of *x* after insertion.

$$
\begin{aligned}
&1.\ (b(x+a)-ab)/b \\
&= (bx+ba-ab)/b \\
&= bx/b \\
&= x
\end{aligned}
$$

3-address code

```
t1 = x + a;
t2 = b * t1;
t3 = t2 - c;
x = t3 / b;
```

Instruction

```
%temp = add i32 %inc, 5
%temp1 = mul i32 %temp, 4
%temp2 = sub i32 %temp1, 20
%temp3 = sdiv i32 %temp2, 4
```

Junk Code Insertion

- Different methods of transformation – Method 2
  - Preserve value of *x* after insertion.

$$
\begin{aligned}
2.\ & ((ax+b)-(cx+b))/(a-c) \\
&= (a-c)*x/(a-c) \\
&= x
\end{aligned}
$$

3-address code

```
t1 = a * x;
t2 = t1 + b;
t3 = c * x;
t4 = t3 + b;
t5 = t2 - t4;
x = t5 / d;
```

Instruction

```
%temp = mul i32 %inc, 2
%temp1 = add i32 %temp, 3
%temp2 = mul i32 %inc, 1
%temp3 = add i32 %temp2, 3
 %temp4 = sub i32 %temp1, %temp3
 %temp5 = sdiv i32 %temp4, 1
```

Junk Code Insertion

- Randomly apply transformation methods
  - Method 1 : +4 instructions
  - Method 2: +6 instructions

```c
int main()
{
    int x = 5;
    x = func1(x);
    x = func2(x);
    return x;
}
```

```
main
[======after insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   store i32 5, i32* %x, align 4
[instruction  4]:   %0 = load i32* %x, align 4
[instruction  5]:   %call = call i32 @func1(i32 %0)
```

2

```
[instruction  6]:   %temp = mul i32 %call, 8
[instruction  7]:   %temp1 = add i32 %temp, 8
[instruction  8]:   %temp2 = mul i32 %call, 1
[instruction  9]:   %temp3 = add i32 %temp2, 8
[instruction 10]:   %temp4 = sub i32 %temp1, %temp3
[instruction 11]:   %temp5 = sdiv i32 %temp4, 7
[instruction 12]:   store i32 %temp5, i32* %x, align 4
[instruction 13]:   %1 = load i32* %x, align 4
[instruction 14]:   %call1 = call i32 @func2(i32 %1)
```

1

```
[instruction 15]:   %temp6 = add i32 %call1, 9
[instruction 16]:   %temp7 = mul i32 %temp6, 2
[instruction 17]:   %temp8 = sub i32 %temp7, 18
[instruction 18]:   %temp9 = sdiv i32 %temp8, 2
[instruction 19]:   store i32 %temp9, i32* %x, align 4
[instruction 20]:   %2 = load i32* %x, align 4
[instruction 21]:   ret i32 %2
```

Junk Code Insertion

- Values inserted are random
  - a = 9, b = 8
  - a= 5, b = 7

```
main
[======after insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   store i32 5, i32* %x, align 4
[instruction  4]:   %0 = load i32* %x, align 4
[instruction  5]:   %call = call i32 @func1(i32 %0)
[instruction  6]:   %temp = add i32 %call, 9
[instruction  7]:   %temp1 = mul i32 %temp, 8
[instruction  8]:   %temp2 = sub i32 %temp1, 72
[instruction  9]:   %temp3 = sdiv i32 %temp2, 8
[instruction  10]:   store i32 %temp3, i32* %x, align 4
[instruction  11]:   %1 = load i32* %x, align 4
[instruction  12]:   %call1 = call i32 @func2(i32 %1)
[instruction  13]:   %temp4 = add i32 %call1, 5
[instruction  14]:   %temp5 = mul i32 %temp4, 7
[instruction  15]:   %temp6 = sub i32 %temp5, 35
[instruction  16]:   %temp7 = sdiv i32 %temp6, 7
[instruction  17]:   store i32 %temp7, i32* %x, align 4
[instruction  18]:   %2 = load i32* %x, align 4
[instruction  19]:   ret i32 %2
```

```
main
[======before insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   store i32 5, i32* %x, align 4
[instruction  4]:   %0 = load i32* %x, align 4
[instruction  5]:   %call = call i32 @func1(i32 %0)
[instruction  6]:   store i32 %call, i32* %x, align 4
[instruction  7]:   %1 = load i32* %x, align 4
[instruction  8]:   %call1 = call i32 @func2(i32 %1)
[instruction  9]:   store i32 %call1, i32* %x, align 4
[instruction  10]:   %2 = load i32* %x, align 4
[instruction  11]:   ret i32 %2
[Instruction]  store i32 %call, i32* %x, align 4
```

Junk Code Insertion

- Chain transformation together multiple times

```c
int func2(int x)
{
    x--;
    return x;
}
```

```
[======after insertion======]
[instruction  0]:   %x.addr = alloca i32, align 4
[instruction  1]:   store i32 %x, i32* %x.addr, align 4
[instruction  2]:   %0 = load i32* %x.addr, align 4
[instruction  3]:   %dec = add nsw i32 %0, -1
[instruction  4]:   %temp = add i32 %dec, 5
[instruction  5]:   %temp1 = mul i32 %temp, 8
[instruction  6]:   %temp2 = sub i32 %temp1, 40
[instruction  7]:   %temp3 = sdiv i32 %temp2, 8
[instruction  8]:   %temp4 = add i32 %temp3, 5
[instruction  9]:   %temp5 = mul i32 %temp4, 5
[instruction  10]:   %temp6 = sub i32 %temp5, 25
[instruction  11]:   %temp7 = sdiv i32 %temp6, 5
[instruction  12]:   store i32 %temp7, i32* %x.addr, align 4
[instruction  13]:   %1 = load i32* %x.addr, align 4
[instruction  14]:   ret i32 %1
```

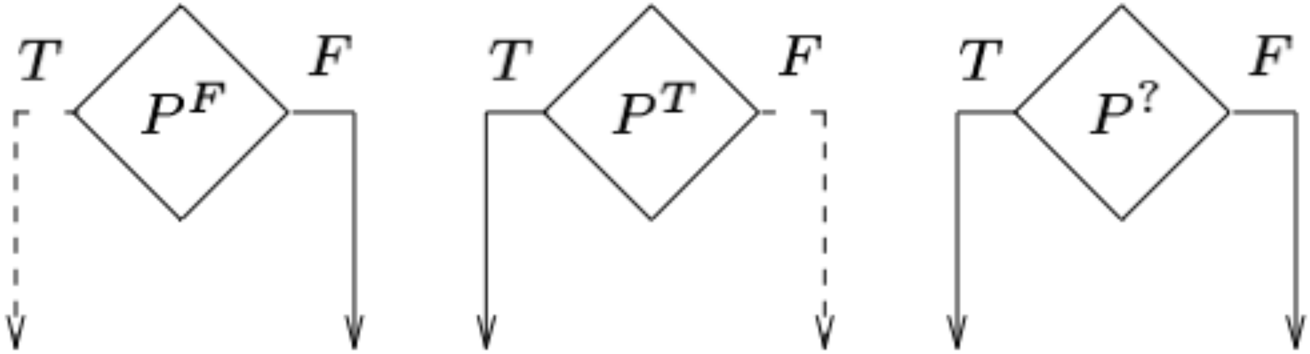
```
func2
[======before insertion======]
[instruction  0]:   %x.addr = alloca i32, align 4
[instruction  1]:   store i32 %x, i32* %x.addr, align 4
[instruction  2]:   %0 = load i32* %x.addr, align 4
[instruction  3]:   %dec = add nsw i32 %0, -1
[instruction  4]:   store i32 %dec, i32* %x.addr, align 4
[instruction  5]:   %1 = load i32* %x.addr, align 4
[instruction  6]:   ret i32 %1
[Instruction]  store i32 %dec, i32* %x.addr, align 4
```

Opaque Predicates

- Control Flow Obfuscation Method
- Adds new branch to the CFG
- Predicate is the condition of the new branch
- “Opaque“ since it is known at compilation time but not easy to infer at runtime

Opaque Predicates

- How to ensure preservation of semantics?
- Put valid instructions in the taken branch, junk code or nothing in the not-taken.

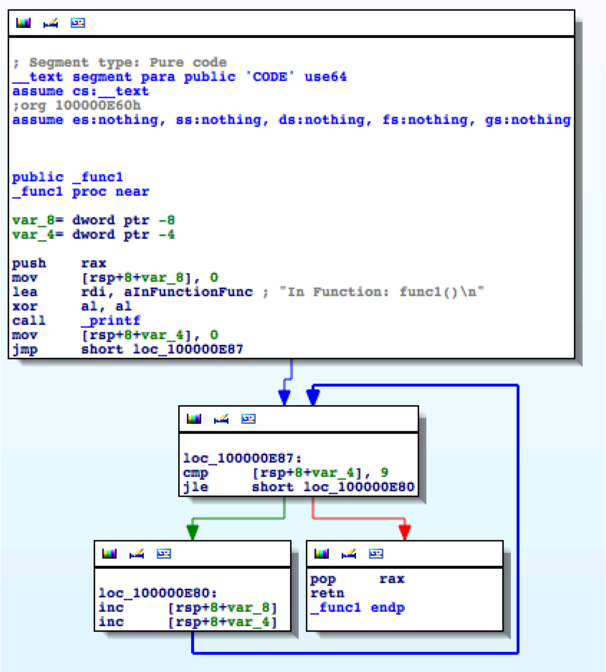


Opaque Predicates

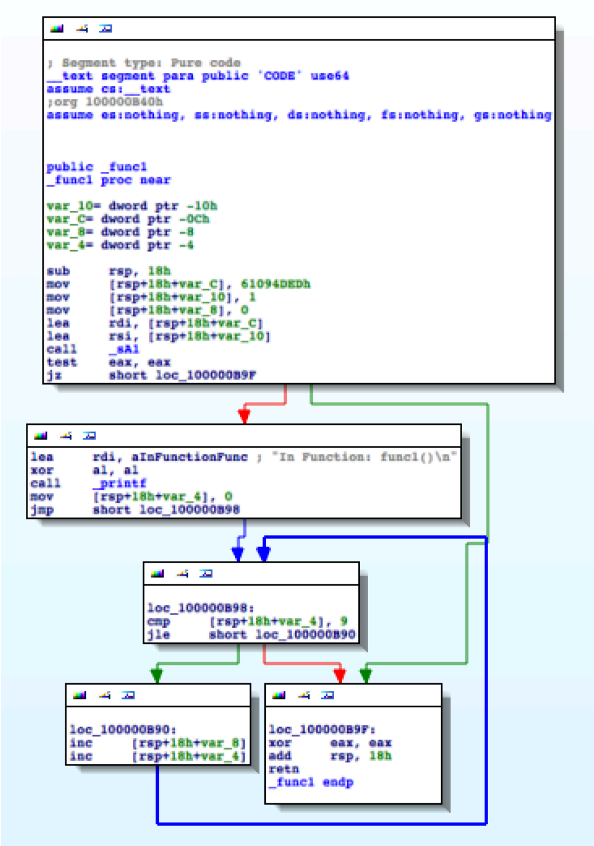
- How to ensure hardness against automatic solvers?
- Relies on mathematical identities
  - e.g. $(x^3-x) \bmod 3 = 0$
- Cyclomatic Complexity increases, causing growth in truth conditions of solvers.

Opaque Predicates

Original



Obfuscated



Testing

- Testing Architecture
  - Regression test suite
    - Individual obfuscation
    - Combined passes
  - Integrated Makefile to automate obfuscation
    - Outputs both LLVM IR files and binaries for diff-ing
  - IDAPython Script
    - Disassembles a program and evaluates cyclomatic complexity of programs

Testing

- Regression Testing
  - lit – LLVM Integrated Tester
    - Tool included in LLVM framework for executing LLVM and Clang test suites
  - Test files are *.c* source files instrumented with testing scripts

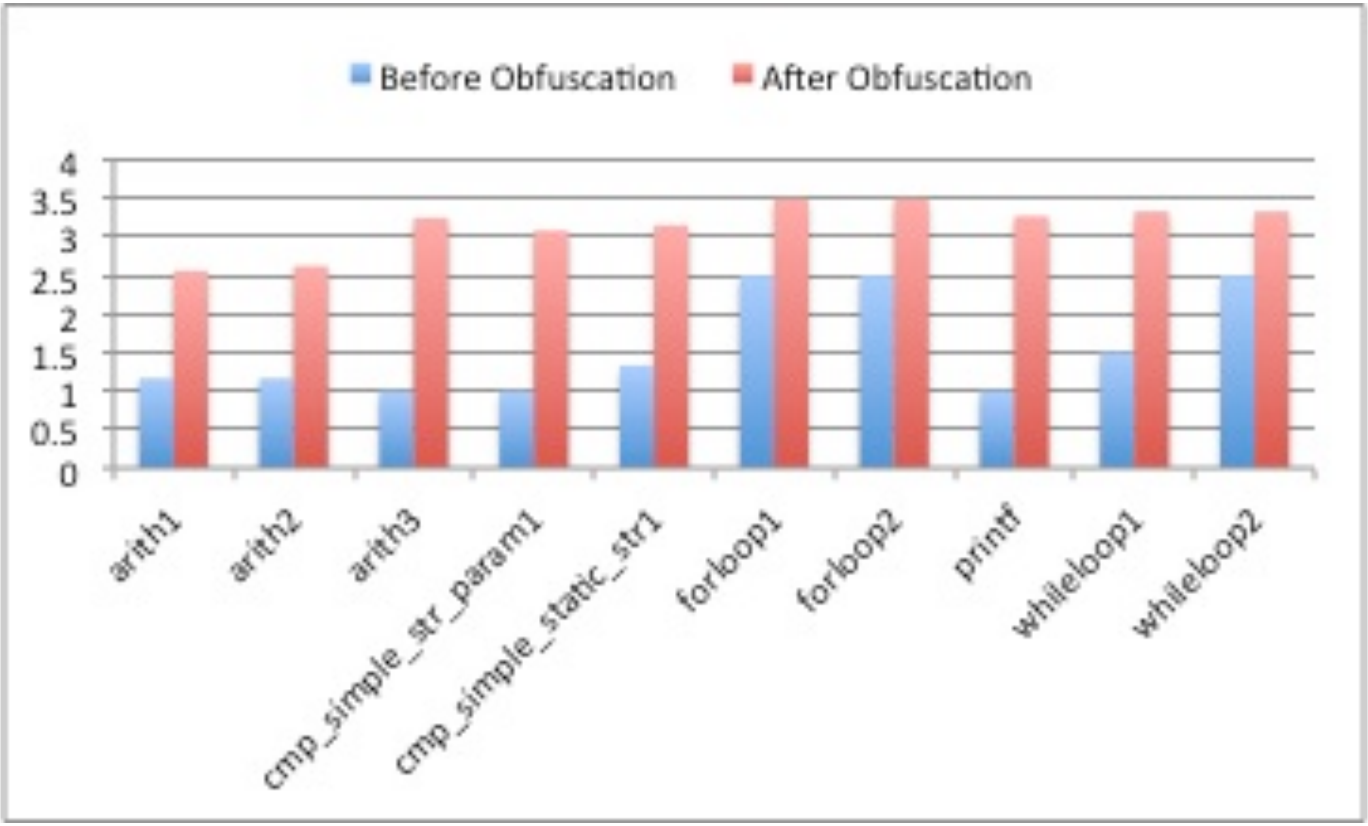
```
// RUN: clang -emit-llvm %s -c -o -| opt -load lib.dylib -objunk > %t1
// RUN: lli %t1 > %t2
// RUN: diff %t2 %s.out
#include <stdio.h>
void main () { … }
```

Testing

- Test Design
  - String obfuscation
    - Variants of string comparison functions
    - Using strings as actual parameters or as string buffers
  - Junk code obfuscation
    - for / while loops with iterations
    - Arithmetic operations
  - Opaque predicate obfuscation
    - Reuse the tests above

Testing

- Evaluation of Cyclomatic Complexity



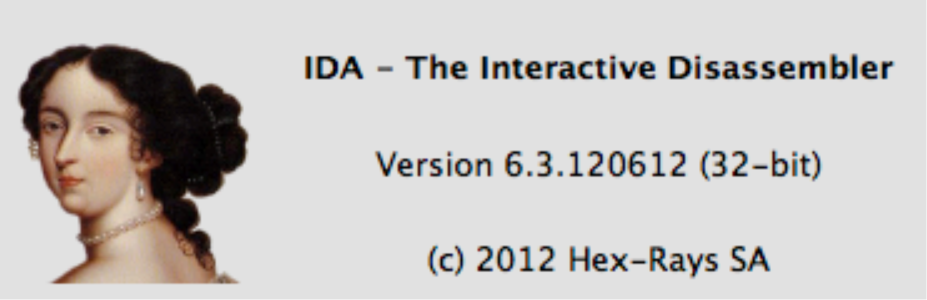
DEMO

Environment

Bitbucket

LLVM
COMPILER INFRASTRUCTURE

Vim



Conclusions

- (we passed the comp :P)
- Very interesting project
  - Going against what this course is teaching!
- An optimization problem
  - How to “de-optimize” without being optimized
  - Deg of obfuscation vs Overhead

Questions?

Backup slides

Junk Code Insertion

- Need to ensure transformations do not get "optimized" away

```
define i32 @main() #0 {
entry:
  %call = tail call i32 @rand() #2
  %rem = srem i32 %call, 3
  %temp = shl i32 %rem, 3
  %temp3 = sdiv i32 %temp, 8
  %call1 = tail call i32 (i8*, ...)* @printf(i8* getelementptr inbounds ([8 x i8
]* @.str, i64 0, i64 0), i32 %temp3) #2
  ret i32 %temp3
}
```

```
define i32 @main() #0 {
entry:
  %call = tail call i32 @rand() #2
  %rem = srem i32 %call, 3
  %temp4 = mul i32 %rem, 7
  %temp5 = sdiv i32 %temp4, 7
  %call1 = tail call i32 (i8*, ...)* @printf(i8* getelementptr inbounds ([8 x i8
]* @.str, i64 0, i64 0), i32 %temp5) #2
  ret i32 %temp5
}
```

Junk Code Insertion

- Challenge faced -- eliminated by LLVM optimizer
  - irrelevant code

```c
int main()
{
    int x = rand() % 3;
    printf("x = %d\n" , x);
    return x;
}
```

```
main
[======after insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   %call = call i32 @rand() #3
[instruction  4]:   %rem = srem i32 %call, 3
[instruction  5]:   %temp = mul i32 %rem, 6
[instruction  6]:   %temp1 = add i32 %temp, 8
[instruction  7]:   %temp2 = mul i32 %rem, 5
[instruction  8]:   %temp3 = add i32 %temp2, 8
[instruction  9]:   %temp4 = sub i32 %temp1, %temp3
[instruction  10]:   %temp5 = sub
[instruction  11]:   store i32 %r
[instruction  12]:   %0 = load i
[instruction  13]:   %call1 = cal
ounds ([8 x i8]* @.str, i32 0, i3
[instruction  14]:   %1 = load i3
[instruction  15]:   ret i32 %1
```

```
define i32 @main() #0 {
entry:
  %call = tail call i32 @rand() #2
  %rem = srem i32 %call, 3
  %call1 = tail call i32 (i8*, ...)* @printf(i8* getelementptr inbounds ([8 x i8
]* @.str, i64 0, i64 0), i32 %rem) #2
  ret i32 %rem
}
```

Junk Code Insertion

- Challenge faced -- eliminated by LLVM optimizer
  - Only mul and div
  - Only add and sub

```c
int main()
{
    int x = rand() % 3;
    printf("x = %d\n" , x);
    return x;
}
```

```
main
[======after insertion======]
[instruction  0]:   %retval = alloca i32, align 4
[instruction  1]:   %x = alloca i32, align 4
[instruction  2]:   store i32 0, i32* %retval
[instruction  3]:   %call = call i32 @rand() #3
[instruction  4]:   %rem = srem i32 %call, 3
[instruction  5]:   %temp = mul i32 %rem, 5
[instruction  6]:   %temp1 = sdiv i32 %temp, 5
[instruction  7]:   %temp2 = ad
[instruction  8]:   %temp3 = su
[instruction  9]:   store i32 %
[instruction  10]:   %0 = load
[instruction  11]:   %call1 = ca
ounds ([8 x i8]* @.str, i32 0,
[instruction  12]:   %1 = load
[instruction  13]:   ret i32 %1
```

```
define i32 @main() #0 {
entry:
  %call = tail call i32 @rand() #2
  %rem = srem i32 %call, 3
  %call1 = tail call i32 (i8*, ...)* @printf(i8* getelementptr inbounds ([8 x i8
]* @.str, i64 0, i64 0), i32 %rem) #2
  ret i32 %rem
}
```