CSE 410/565 Computer Security
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Lecture 14: Software Security

Department of Computer Science and Engineering
University at Buffalo

Software Security

- Exploiting software vulnerabilities is paramount to computer break-ins
- Common software vulnerabilities
  - input validation
  - buffer overflow
  - integer overflow
  - format string problems
  - interaction with environment variables
  - failure to handle errors

Buffer Overflow

- Buffer overflow is a very common software vulnerability
  - the first major exploit was Morris Internet Worm in 1988 that exploited buffer overflow in fingerd
  - many others followed, such as Code Red worm in 2001
  - large percentage of all exploits in CERT vulnerability advisories describe buffer overflow or heap overflow problems
    - check US-CERT (United States Computer Emergency Readiness Team) alerts and ICS-CERT (Industrial Control Systems Cyber Emergency Response Team) advisories
- Buffer overflows often lead to total compromise of the host

Buffer Overflow

- A buffer overflow or buffer overrun is a condition under which more input can be placed in a buffer than the allocated capacity
  - the extra input for which there is no allocated memory overwrites other information
  - the locations being overwritten could hold other variables, parameters, and control flow data such as return addresses
- Developing buffer overflow attacks includes
  - locating buffer overflow within an application
  - designing an exploit
- Attacker needs to know which CPU and OS are running on the target machine

Buffer Overflow

- Simple example of buffer overflow in C

```
void func(char *str1) {
    char str2[8];

    strcpy(str2, str1);
    printf("%s, %s\n", str1, str2);
}
```

  - what happens if we call `func("abc")`?
  - how about `func("reallylongstring")`?

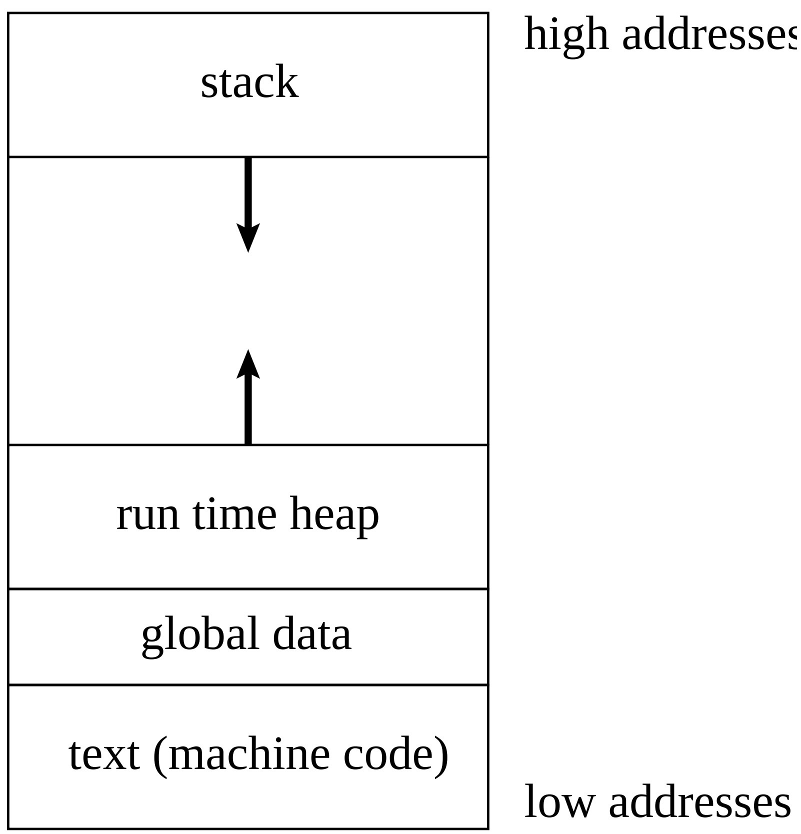
- The problem occurs because `strcpy` doesn't check the amount of data being copied

Buffer Overflow

- Not all languages are vulnerable
  - some languages (Java, Python) provide strong type checking and have predefined operations on types
  - they don't permit storing more data than allocated space
  - but safety comes at resource usage cost
- Writing an exploit involves understanding process memory and stack layout
  - in what direction the stack grows
  - what data and in what order are placed on the stack
  - how information is represented

Process Memory Layout

- Generic process memory layout



Stack Buffer Overflow

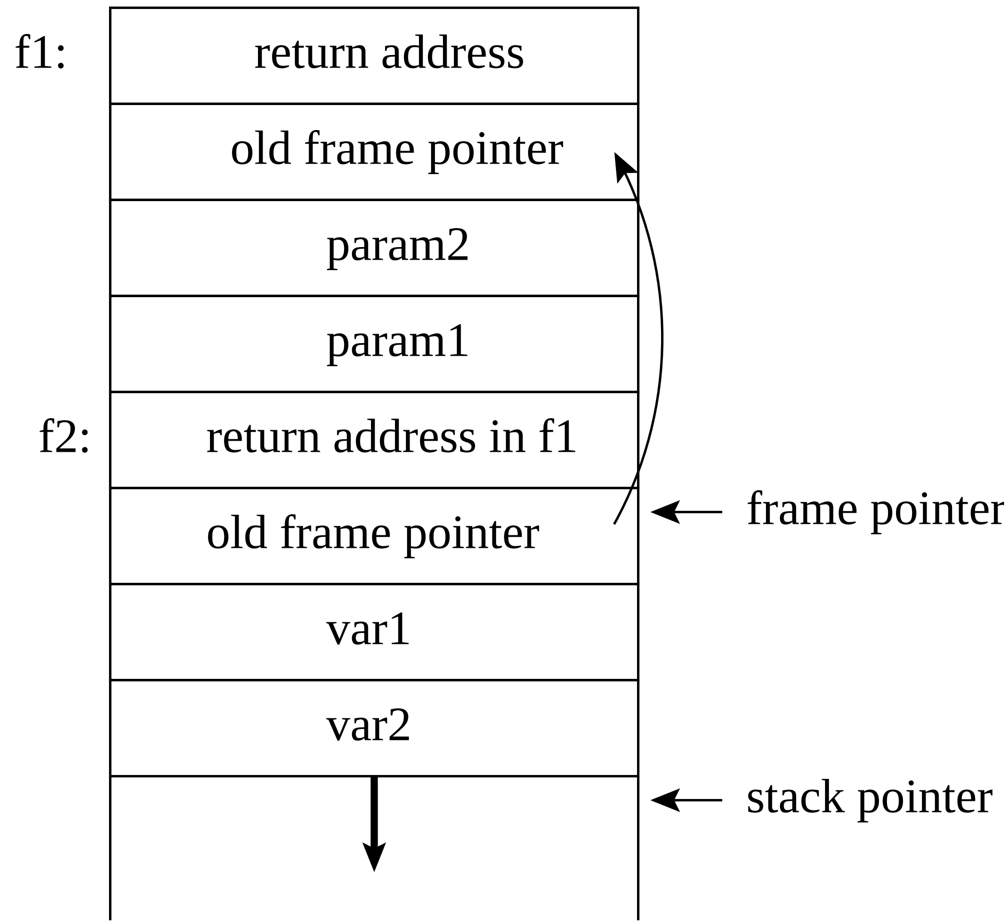
- Stack buffer overflow or stack smashing occurs when the buffer is located on the stack
- When a function is called, its data are placed on the stack
  - this includes arguments, local variables, and return address
- The calling function first
  - pushes the parameters for the called function onto the stack
    - normally in the reverse order
  - executes the call instruction which pushes the return address onto the stack

Stack Buffer Overflow

- The called function
  - pushes the current frame pointer onto the stack
    - the frame pointer points to the calling routine's stack
  - sets the frame pointer to be the current stack pointer value
  - allocates space for local variables
  - runs the called function
  - sets the stack pointer back to the value of the frame pointer
  - pops the old frame pointer
  - executes the return instruction which pops the return address off the stack giving control to the calling function
- The calling function pops parameters off the stack and continues

Stack Buffer Overflow

- Suppose function `f1` calls `f2(param1, param2)`



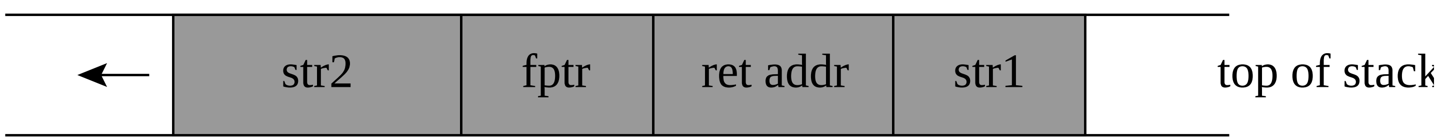
Stack Buffer Overflow

- Let's go back to our code example

```
void func(char *str1) {
    char str2[8];

    strcpy(str2, str1);
    printf("%s, %s\n", str1, str2);
}
```

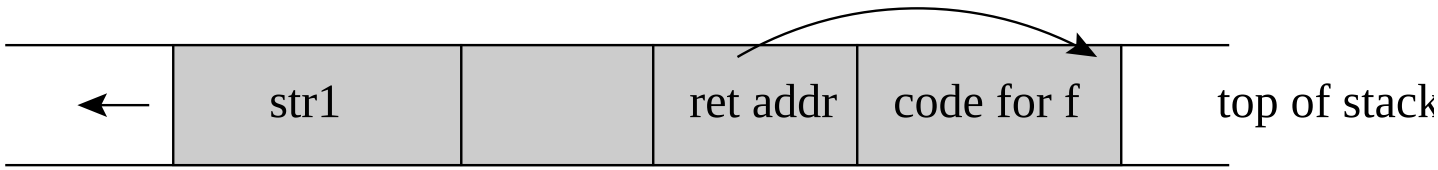
- The stack will look like



- What if `str1` is 16 bytes long? After copying we get

Stack Buffer Overflow

- Now suppose that `str1` looks like this



  - where program `f`: `exec("/bin/sh")`

- Now when function `func` exits, the user will be given a shell

- What happens
  - attack code runs on the stack
  - to determine the return address, attacker needs to guess position of the stack when `func` is called

Stack Buffer Overflow

- The main problem with the above program was that there is no range checking in `strcpy()`
- Some unsafe C library functions
  - `strcpy(char *dest, char *src)`
  - `strcat(char *dest, char *src)`
  - `gets(char *str)`
  - `scanf(const char *format, ...)`
  - `printf(const char *format, ...)`

Buffer Overflow Execution

- As an example, consider attacking a web server
  - web server has a function with buffer overflow vulnerability which takes a URL
  - attacker can craft a long URL to obtain shell on web server
- Difficulties in constructing buffer overflow exploit
  - exploit code cannot contain the '`\0`' character
  - overflow should not crash the program before the vulnerable function exits

Buffer Overflow

- How does one find buffer overflow vulnerabilities?
  - do it yourself
    - run the program (such as a web server) on your local machine
    - use long inputs with a specific pattern
    - if the program crashes, search core dump for the pattern to determine overflow location
  - use an existing automated tool
    - e.g., eEye Retina scanner, ISIC (IP Stack Integrity & Stability Checker)
- Once a vulnerability is found, use disassemblers and debuggers to construct an exploit

Buffer Overflow

- What can be done to defend against buffer overflow attacks?
- Various mechanisms exist
  - compile-time defenses
    - type safe language choice
    - static code analysis
    - safe libraries
    - stack protection
  - run-time defenses
    - stack protection
    - address space randomization

Buffer Overflow Defenses

- Choice of programming language
  - some languages (Java, ML) have a strong notion of variable type and define a set of permitted operations on them
  - they are not vulnerable to buffer overflow attacks
    - if they use external libraries written in an unsafe language, they can still be vulnerable
  - such languages are becoming increasingly popular
  - disadvantages
    - there is resource consumption cost at both compile time and run time
    - some functionality might be lost due to the distance from the architecture and machine language

Buffer Overflow Defenses

- Static source code analysis
  - statically check source code to detect buffer overflows
  - this allows to automate code review process
  - there are several consulting companies and several existing tools
    - Coverity, Microsoft PREfix and PREfast, etc.
  - find many bugs, but not all
- Safe coding practices
  - buffer overflows can be prevented by handling errors gracefully
  - first check buffer size to ensure that sufficient space has been allocated
  - more complex data structure require additional care

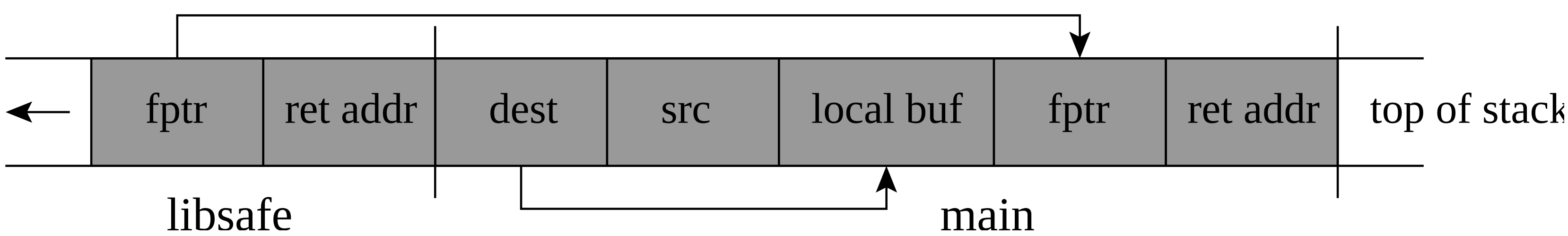
Buffer Overflow Defenses

- Example problems that can be detected through static source code analysis

null pointer dereference	uninitialized variables
use after freeing	invalid use of negative values
double freeing	underallocations of dynamic data
array indexing errors	memory leaks
mismatched array on create/delete	file handle leaks
potential stack overrun	network resource leaks
potential heap overrun	unused values
returning pointer to local variables	unhandled return values
logically inconsistent code	use of invalid iterators

Buffer Overflow Defenses

- Use of safe libraries
  - replace standard unsafe library routines with a safer version
  - libsafe is a well-known example
    - dynamically loaded library
    - ensures that copy operations don't extend beyond the current stack frame
    - e.g., in `strcpy(dest,src)`, if `loc(fp) − loc(dest) > strlen(src)`, permit copy; otherwise, terminate the application



- Language extensions for adding range checking also exist

Buffer Overflow Defenses

- Stack protection mechanisms
  - mark stack segment as non-executable
    - this will prevent several types of buffer overflow attacks
    - this is now supported in many operating systems
    - there are disadvantages
      - it does not prevent all types of overflow exploits
      - some applications need executable stack (e.g., LISP interpreters)
  - disallow changes to the stack frame during function execution
    - instruct the function entry and exist code to check the stack for corruption
    - if any modification is found, abort the program

Buffer Overflow Defenses

- StackGuard is one of the best known stack protection mechanisms
  - insert a canary value between the old frame pointer address and local variables
  - the entry code places a canary, and the exit code checks it for corruption

←	local vars	canary	fptr	ret addr	params	top of stack

  - random canary
    - the canary value is chosen at random during program startup
    - it is known to all functions, but unpredictable to attacker

Buffer Overflow Defenses

- StackGuard (cont.)
  - terminator canary
    - set canary value to '`\0`' (or an equivalent terminator value)
    - string functions will not copy beyond the terminator
    - attacker cannot use string functions to corrupt stack
  - StackGuard is available as a gcc extension
    - performance overhead is minimal: 8% for Apache web server
    - similar functionality exists for Windows
    - other versions such as PointGuard might provide protection against more types of overflow exploits

Buffer Overflow Defenses

- StackGuard (cont.)
  - disadvantages
    - all programs that require protection need to be recompiled
    - can cause problems with other programs such as debuggers
    - some stack smashing attacks can leave canaries untouched
- StackShield
  - stack frame is protected without altering the stack with canaries
  - on function entry, added code writes a copy of the return address to a safe memory region
  - the exit code compares the return address with the stored value and aborts the program in case of corruption
  - StackShield is also available as a gcc extension

Buffer Overflow Defenses

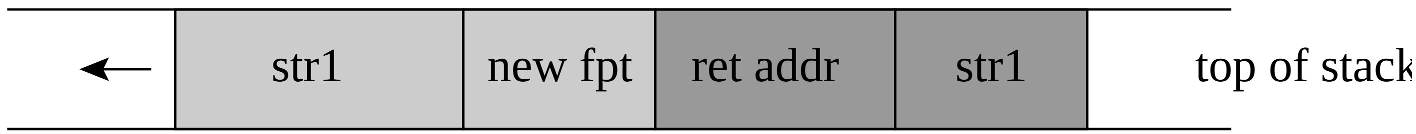
- Randomization
  - buffer overflow exploits need to know (virtual) address to which to pass control
    - address of attack code in the buffer
    - address of library routines for return-to-libc attack
  - the same address is used on many machines
    - Slammer worm infected 75,000 MS SQL servers using the same code on every machine
  - the idea is to introduce artificial diversity
    - make stack and other addresses unpredictable and different from one execution to another

Buffer Overflow Defenses

- Address space randomization
  - arrange key data areas randomly in address space of a process
    - e.g., positions of heap, stack, libraries
  - correct address guessing is significantly more difficult
  - support for this defense exists in many operating systems
- Instruction set randomization
  - each program has a different and secret instruction set
  - uses translator to randomize instructions at load time
  - attacker no longer can execute her own code
  - what constitutes the instruction set depends on the environment

Other Types of Overflow Attacks

- Frame pointer replacement
  - the attack overwrites the buffer and stored frame pointer



  - the buffer contains a dummy stack frame with a return address pointing to the shellcode in the same buffer
  - this can be used when only a limited buffer overflow is possible

- Off-by-one attack
  - as a variant of the above attack, a programming error might permit copying just one byte more than the available space
  - this happens when the size of the buffer is checked incorrectly

Other Types of Overflow Attacks

- Off-by-one attack (cont.)
  - example code:

```
void f(char *str) {
    char buf[16];
    if (strlen(str) <= sizeof(buf)) {
        strcpy(buf, str);
    }
}
```

  - only one byte of the frame pointer can be overwritten

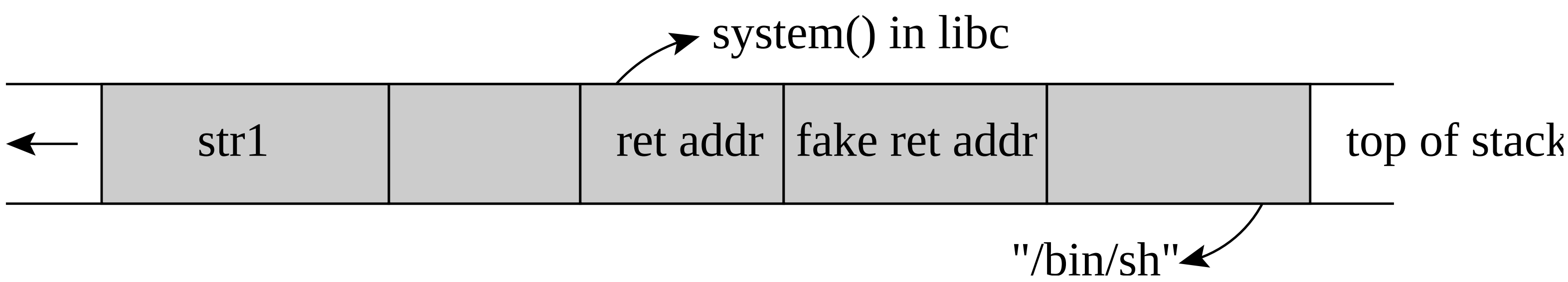
    - it corresponds to the least significant byte on x86 architectures
    - a one byte change might be enough!

Other Types of Overflow Attacks

- Return to system call attack
  - also known as return-to-libc attack
  - assume that the stack is made non-executable as a protection mechanism
  - a new type of attack overwrites the return address to jump to existing code
    - `system()` call in `libc` is most commonly used
  - what needs to be done
    - overwrite frame pointer with a suitable value
    - replace return address with address of the library function
    - write a value that the library function will believe is return address

Other Types of Overflow Attacks

- Return to system call attack (cont.)
  - finally, specify parameters to the library function
    - i.e., call the shell



  - what happens?
    - when the attacked function returns, it transfers control to the return address, which calls the library function
    - the library function treats the value on top of the stack as a return address and the values before as its parameters

Other Types of Overflow Attacks

- Heap overflow
  - with stack protection techniques, attackers started exploiting overflows in non-stack buffers
  - the heap that stores dynamically allocated data structures is such a target
  - if heap contains a buffer vulnerable to overflow, other data on the heap may be overwritten
  - heap doesn't contain return addresses to transfer controls, but can contain pointers to functions
    - attacker can overwrite the pointer to reference code in the same buffer that calls shellcode
    - if the function is called, the attack can succeed

Other Types of Overflow Attacks

- Heap overflow (cont.)
  - defenses include making heap non-executable and heap address randomization
- Other types of overflow
  - similar vulnerabilities exist for static (global) data
  - such data is allocated in different space, but the threats remain similar to heap overflow
  - finally, there are also integer overflow and format string overflow attacks

Buffer Overflow Resources

- Additional articles
  - "Smashing the stack for fun and profit" by Aleph One, 1996
  - "Buffer overflows: attacks and defenses for the vulnerability of the decade" by Cowan at el., 2000
  - "Bypassing non-executable-stack during exploitation using return-to-libc" by c0ntex, 2005
- What is next
  - other types of software vulnerabilities
  - input validation, environment variables, race conditions, etc.