Dynamic protection

Software Security

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Book: Chapter 12 (v1) / 15 (v2)

Dynamic protection

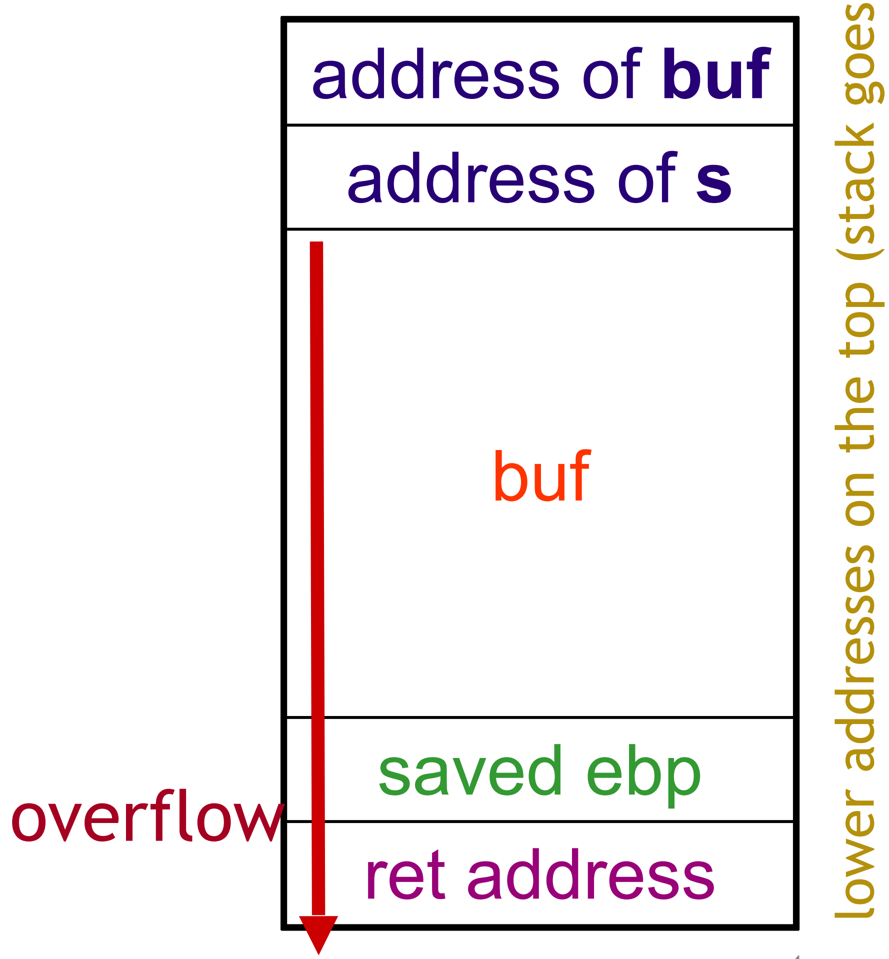
- The idea is to block attacks that may exploit existing vulnerabilities
- We consider mostly the case of memory corruption attacks
  - They are one of the most pervasive classes of attacks: buffer overflows, format strings
  - Good idea to assume that they will not completely disappear…
  - so mechanisms to minimize their effects when they do happen are important
  - The topic is vast, there are many others

Detection with canaries

Canaries / Stack cookies

```
void test(char *s) {
  char buf[10];
  strcpy(buf, s);
  …
}
```

- **Stack smashing:**

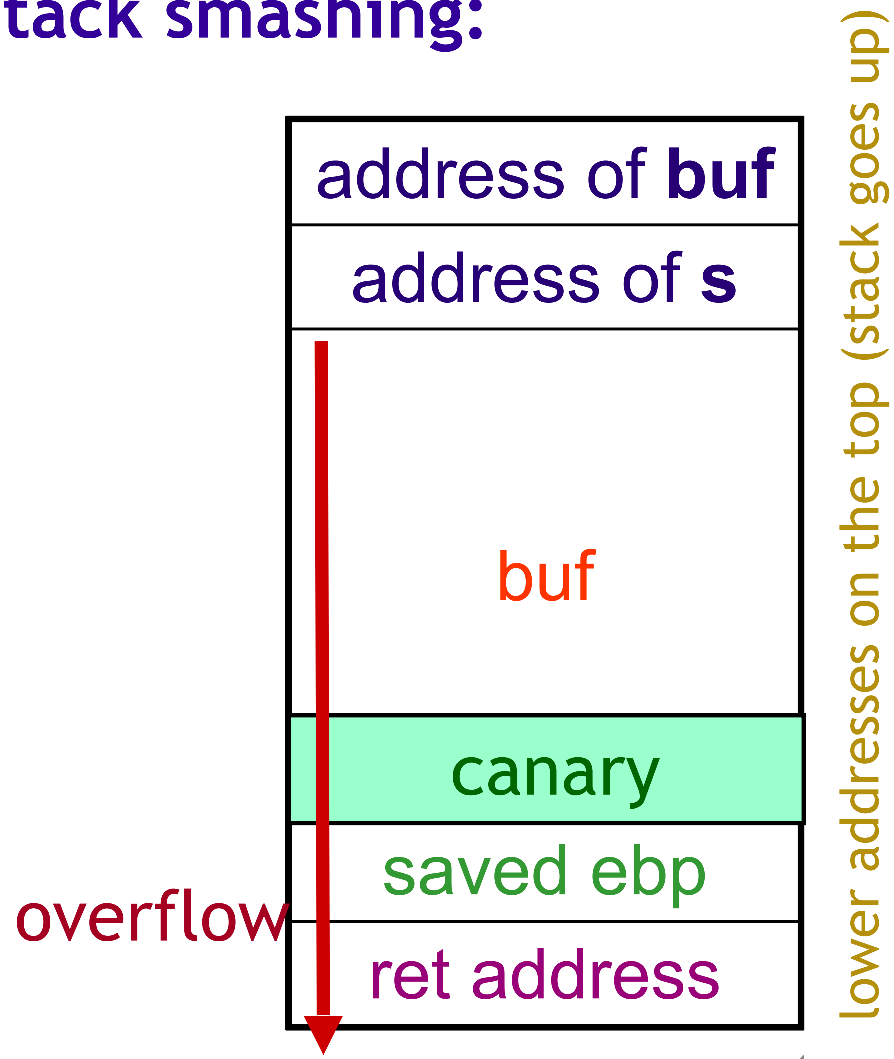


Canaries / Stack cookies

```
void test(char *s) {
  push canary;
  char buf[10];
  strcpy(buf, s);
  …
  if (canary is changed)
   {log; exit;};
}
```

- Idea: canaries in the mines
- Compile time technique
- Canary = 32bit random value
- Appeared in StackGuard; /GS flag in Visual Studio 7.0 and above
- Implemented by the compiler
  - e.g., `-fstack-protector`/ `-fno-stack-protector` in gcc

- **Stack smashing:**



Canaries / Stack cookies (cont)

- Detects some *stack smashing* attacks
  - Stack smashing attacks that overwrite the return address (saved EIP) – to jump to injected code or ret-to-libc
  - Off-by-one errors that overwrite the saved EBP
- Do not detect BO attacks that modify local variables (they are *above* the canary)
  - Function-pointer clobbering, Data-pointer modification, Exception-handler hijacking (Windows Structured Exception Handler – SEH)
- Detects, but possibly too late, BO attacks against the function arguments (are *below* the ret address)

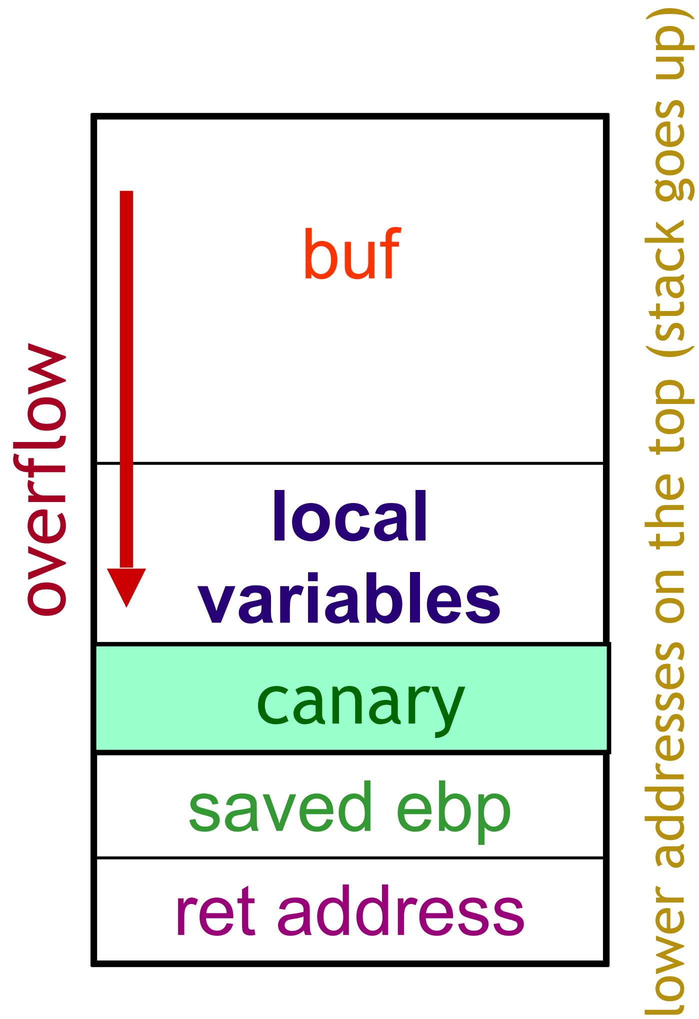
above = smaller address (in the stack); below = higher address (in the stack)

Canaries / Stack cookies (cont)

- Vulnerable to denial-of-service attacks that crash the app on purpose
- Compile time and some code (e.g. libraries, 3rd party code) cannot be recompiled; but most code surely can

Local variables protection

- Canaries do not protect local vars from overflows
- Solution: reorder the stack layout
  - All char buffers are put below all other local variables
  - Ex: ProPolice



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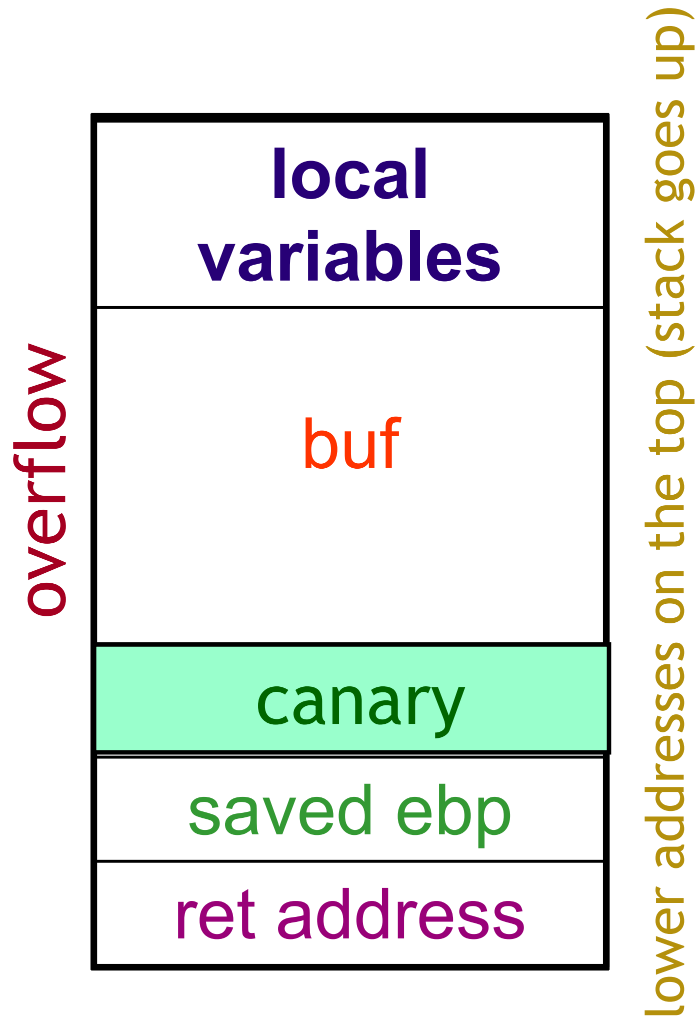
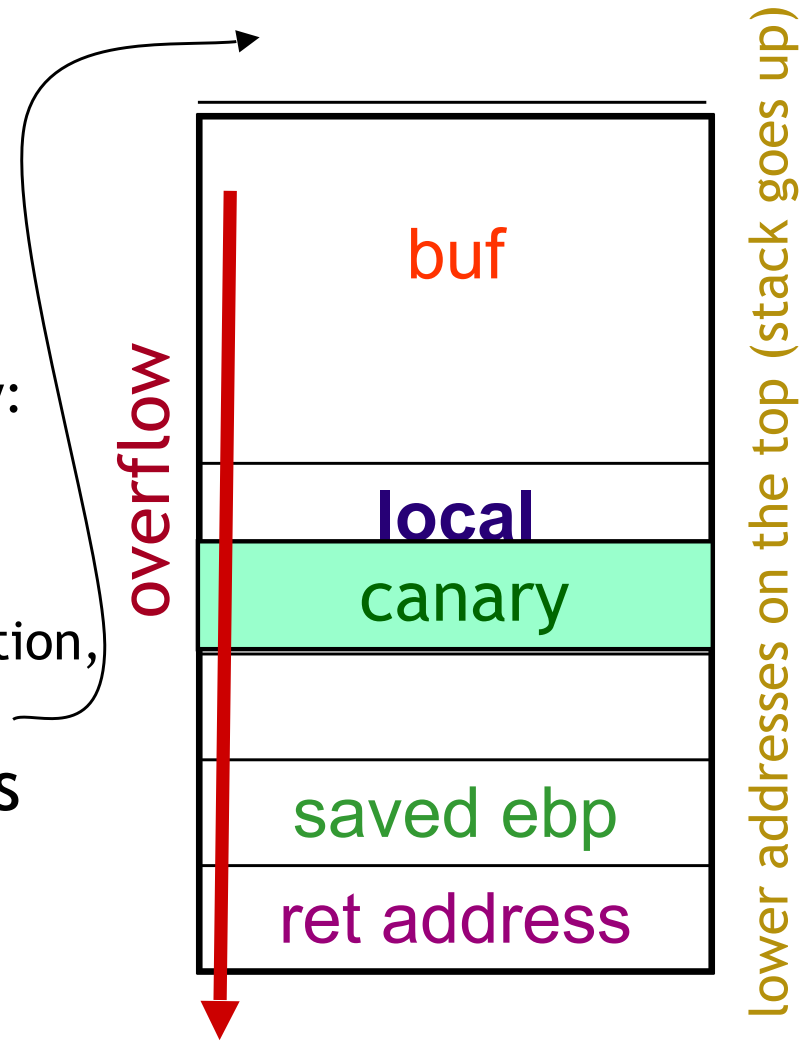


Function arguments protection

- BO may overwrite function's arguments in the stack
  - Canary detects the attack *after* these arguments were used in the function
- 2 solutions
  - Some compilers solve this automatically: they put the args in CPU registers, preventing this attack (but there aren't many registers)
  - Otherwise: in the beginning of the function, copy the args to the top of the stack
- Currently Window's /GS flag does that (either regs or top os stack)



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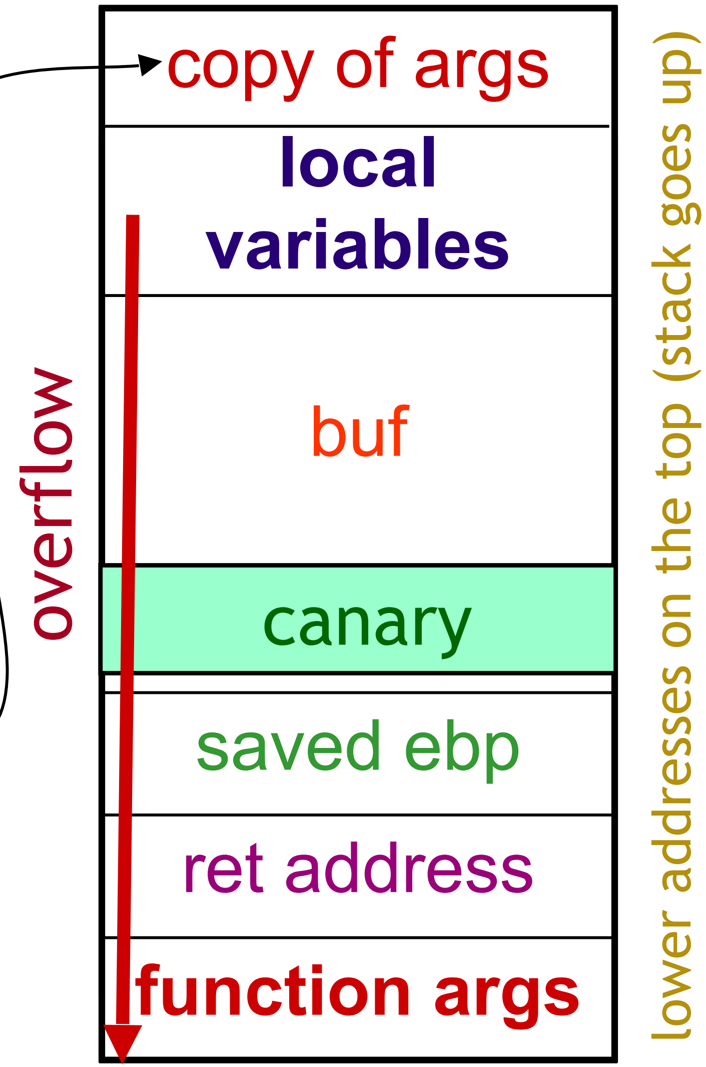


Non-executable stack and heap

Non-executable stack and heap

- Many buffer overflow attacks involve injecting shell code in the stack/heap
  - Simple protection: mark these memory pages as non-executable (NX)
  - Old idea but x86 CPUs did not support it until ~2004
  - Several names:
    - Intel – Execute Disable (XD-bit)
    - AMD – Enhanced Virus Protection
    - Microsoft – Data Execution Prevention (DEP)
    - others call it W^X (write or execute, but not both)
  - Activated by the compiler (e.g., `-z noexecstack` in gcc); usually on by default

Non-executable stack and heap (cont)

- Limitations of NX
  - Doesn't protect from ret-to-libc/return-oriented programming (ROP) attacks
  - There may be lib functions that can be called to turn-off NX
    - ex: in a Windows program a call to NtSetInformationProcess disables NX (to allow apps to load DLLs incompatible with NX)
    - not too critical as attacker would have to first exploit a vulnerability do call that function
  - Some apps can be incompatible with it
    - Apps that perform high-performance image manipulation/rendering sometimes create binary code in runtime
    - Some interpreted languages compile scripts into binary code

Randomization and obfuscation

Address space layout randomization

- Idea is to randomize the addresses where code and data are placed in runtime
  - This is not what normally happens: the memory layout tends to be the same for every execution
  - What is randomized are *not* the *physical addresses* by shuffling pages around the RAM (which always happens anyway), but the logic/linear addresses, i.e., the organization of the virtual memory of a process
  - Doesn't prevent exploitation, makes it unreliable/harder
  - Started with PAX and Exec Shield projects for Linux and in OpenBSD, now in many others including MS Windows

ASLR (cont)

- Elements that can be randomized
  - Code – addresses where apps and dynamic libraries are loaded
  - Stack – starting address of the stack of each thread
  - Heap – base address of the heap
- Not all bits are randomized to reduce fragmentation
  - Example after two reboots of Windows:

```
Kernel32 loaded at 77AC0000     LoadLibrary at 77B01E7D
Kernel32 loaded at 77160000     LoadLibrary at 771A1E7D
```

  - Program that prints var address re-executed 4 times:

Mac OS X (32 bits)	Linux Ubuntu (32 bits)

`end: 0xbffc8b7e`
`end: 0xbffc5b7e`
`end: 0xbff10b7e`
`end: 0xbfffbb7e`
	`end: 0xbfde1c7f`
	`end: 0xbfcbae1f`
	`end: 0xbfefe0df`
	`end: 0xbfda18cf`

ASLR (cont)

- What/when is randomized? (Windows)
  - User apps and some DLLs randomized whenever loaded
  - Shared DLLs (e.g., kernel32.dll) randomized only once per reboot
  - Old apps and DLLs not randomized
    - Because randomization requires that the executables include relocation information, which was not generated by old linkers
- ASLR is effective against most BO attacks
  - Stack smashing (*w/shellcode injection*), ret-to-libc
  - **Not for those against local variables**

ASLR (cont)

- Limitations
  - Anything with a static location is candidate to counter ASLR (e.g., apps or DLLs without relocation information)
  - Works only at reboot for many DLLs, therefore a local attack can first discover the memory layout, then do the main attack
  - Brute force attacks possible if target code restarts on failure
    - especially if the random space is small (e.g., 256 options in Windows)
    - => number of restarts should be limited

Instruction set randomization

- Code injection would be almost impossible if each computer had its own random instruction set (!)
- Randomized instruction set
  - Legitimate code is scrambled (e.g., XORed with a random value), then unscrambled for execution
  - Malicious code is not scrambled, but it is unscrambled, becoming (hopefully) impossible to execute
  - Scramble best at load time; at compile time, key would be fixed
  - Unscramble has to be done by a virtual machine or debugger (high overhead, not practical) or by the CPU (not available yet)

Instruction set randomization (cont)

- More practical case: SQL instruction randomization to avoid SQL injection
  - Application adds a key to each SQL command and operator
  - e.g. if key is 333 then:
  - $query = "SELECT * FROM orders WHERE id=" . $code; becomes:
  - $query = "SELECT333 * FROM333 orders WHERE333 id=333" . $code;
  - Between the web server and the DBMS there is a proxy that checks if all instructions follow the format (i.e., if they include 333). If not an error is generated
  - Example of query modified by attack:
  - SELECT333 * FROM333 orders WHERE333 id=3331 **OR 1=1**
- Same idea might be applied with other languages to avoid code injection

OR does not follow format OR333

Function pointer obfuscation

- Long-lived function pointers (typ. global vars) are often the target of memory corruption exploits
  - Provide a direct method for seizing control of program execution
  - E.g., heap overflow /format string attack that can only write a 32-bit value
- Pointer obfuscation mitigates this problem
  - The idea is to XOR the pointer with a random secret cookie
  - Keep it protected while not needed, unprotect when needed
  - Windows: EncodePointer(), DecodePointer(), EncodeSystemPointer(), DecodeSystemPointer()
- Not a complete solution, but useful with ASLR and NX
- Others have proposed checking if a function pointer points to the code segment

Integrity verification

SEH protection

- Windows Structured Exception Handling (SEH)
  - When an exception is generated, Windows examines a linked list of EXCEPTION_REGISTRATION structures in the stack
  - These structures include pointers to the handlers → can be overrun and an exception raised to force a jump to that address

SEH protection (cont)

- /SafeSEH compilation flag mitigates the problem
  - A *module* (DLL, .exe) can have an *exception table* that lists the valid EXCEPTION_REGISTRATION structures for the module
  - The validity of exception handler is checked before it's called
    - If the *module* has an *exception table* and the EXCEPTION_REGISTRATION structure is not registered there, the check fails;
    - otherwise the check is successful (if it matches or no table)
- Limitations:
  - if the *module* has no *exception table*…

Array bound checking

- BOs caused by lack of array bound checking, so doing the check solves the problem
  - Already done in languages like Java
  - Currently supported in C compilers like *gcc* (flag *Warray-bounds*)
  - However, it's easy to check `a[3]`, but not `*(a+3)` or `a[i]`

gcc gives warning	gcc doesn't give warning

`char str[10];`
`int i;`
`for (i=0; i<10; i++) {`
`        str[i] = 'a';`
`    }`
`    str[10]='\0';`
	`char str[10];`
	`int i;`
	`for (i=0; i<10; i++) {`
	`        str[i] = 'a';`
	`    }`
	`    str[i]='\0';`

Detection through interception

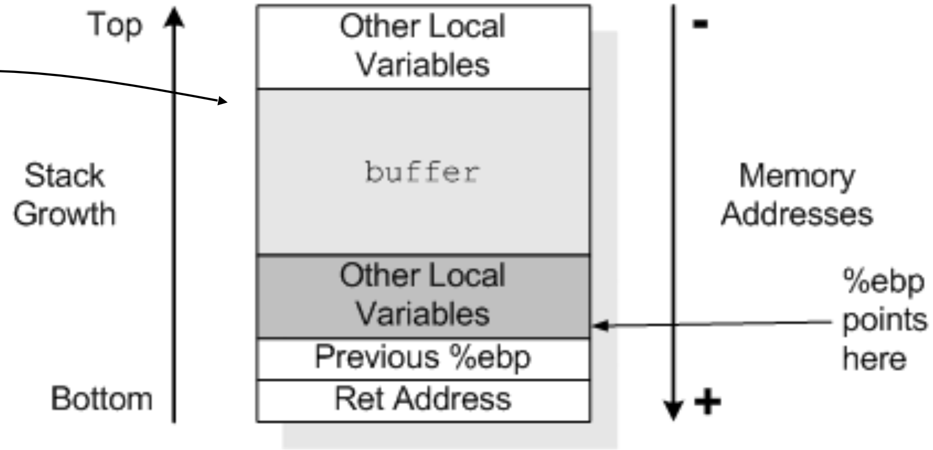
- *libsafe* - library with <u>wrappers</u> for problematic libc functions
- When a function is called, the wrapper first checks if the buffer is not being overrun
- How? Use *frame pointer* (EBP) as an upper-bound

program that does dangerous call

```
void f()
        char buffer[100];      ...
        strcpy(buffer, large_string);
        return;
}
```

<u>libsafe wrapper</u>

```
char *strcpy(char *dest, char *src) {
        calculate upper bound of dest buffer size
        check if dest has enough space for src
        call libc memcpy
        return;
}
```



buffersize upper bound = %ebp - dst

Control-flow integrity

- Stack Shield has a <u>global ret stack</u>:
  - Whenever a function is called, the return address is stored in a Global Ret Stack (besides the normal stack)
  - Before the function returns, check if the return address in the normal stack and the Global Ret Stack match
  - Global Ret Stack has by default only 256 entries, so allows a maximum depth of 256 function calls
  - Code has to be added at compile time

Control-flow integrity (cont)

- Control flow: ifs, whiles, jumps, calls,…
  – Return from functions is just one case and global ret stack a partial solution
- Generic control-flow integrity checking
  – A static analysis tool annotates the program with data about valid destinations of jumps. Ex:

```
void (*f)() = …;      /* function pointer */
…
f();  //annotated with valid destinations
```

  – Before jumping, check if the destination is valid

Filtering

Web application firewalls

- WAFs are application-level firewalls for webapps

Web application firewalls

- Interposition can be obtained in 4 ways

Sw or Hw box

  - Bridge: WAF installed as a transparent bridge (switch)
  - Router: network reconfigured to direct traffic through the WAF
  - Reverse Proxy: represents the web server for the clients.
  - Embedded: WAF is installed as a web server plug-in
  - Ex: the most popular open source WAF, ModSecurity, works in modes 3 or 4 (with the Apache web server)

WAFs (cont)

- HTTPS / encrypted traffic; 3 solutions:
  - HTTPS channel ends at the WAF (instead of the server)
  - Server provides decryption key to the WAF
  - Not an issue if the WAF is embedded
- Filtering criteria
  - Negative model: WAF has description of bad input
  - Positive model: WAF has description of good input
  - 2^{nd} is best in theory (fail-safe defaults); 1^{st} may be easier in practice in many cases (less false positives)

WAFs (cont)

- Models are sets of signatures/rules; can be:
  - Generic for certain attacks
    - Ex. authentication brute forcing, XSS, SQLI,…
  - Specific for a webapp
    - Ex. specific: block access to Perl CGIs present but not used by the app, block access to admin pages
- Origin of the signatures/rules:
  - Come with the WAF (not specific for the web app)
    - best WAFs are those with best models (ModSecurity)
  - Created manually (using the WAF language)
  - Machine learning

WAFs (cont)

- Reaction to the detection of an attack
  - Block HTTP request
  - Break TCP connection
  - Block the source IP address and break all its TCP connections
  - Block the webapp session
  - Block the webapp user

Summary

- BO detection with canaries
- Non-executable stack and heap
- Randomization and obfuscation
- Integrity verification
- Filtering