Information Security
CS3002

Lecture 14
12th October 2023

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Control Hijacking

Source: web.nvd.nist.gov

NIST’s Definition: Buffer overflow

“A condition at an interface under which more input can be placed into a buffer or data holding area than the capacity allocated, overwriting other information. Attackers exploit such a condition to crash a system or to insert specially crafted code that allows them to gain control of the system.”

Control Hijacking - Buffer Overflow

- **A buffer overflow**, or **buffer** overrun, is an anomaly where a program, while writing data to a **buffer**, overruns the **buffer's** boundary and overwrites adjacent memory locations.
- **Causes:**
  - Systems software is often written in C(OS, compilers, databases, network servers)
  - C is high-level assembly so..
    - Exposes raw pointers to memory
    - Does not perform bound checking on arrays.
  - Attack also leverages architectural knowledge of how x86 code works.
    - The Direction that stack grows.
    - Layout of stack variables.

- Buffer overflows are important in sense as it matters which process you are hijacking. If you are getting root process hijacked then that’s a real disaster.

Buffer Overflow Basics

- Caused by programming error
- Allows more data to be stored than capacity available in a fixed sized buffer
  - buffer can be on stack, heap, global data
- Overwriting adjacent memory locations
  - corruption of program data
  - unexpected transfer of control
  - memory access violation
  - execution of code chosen by attacker

Buffer Overflow Attacks

- To exploit a buffer overflow an attacker
  - must identify a buffer overflow vulnerability in some program
    - inspection, tracing execution, fuzzing tools

  - understand how buffer is stored in memory and determine potential for corruption

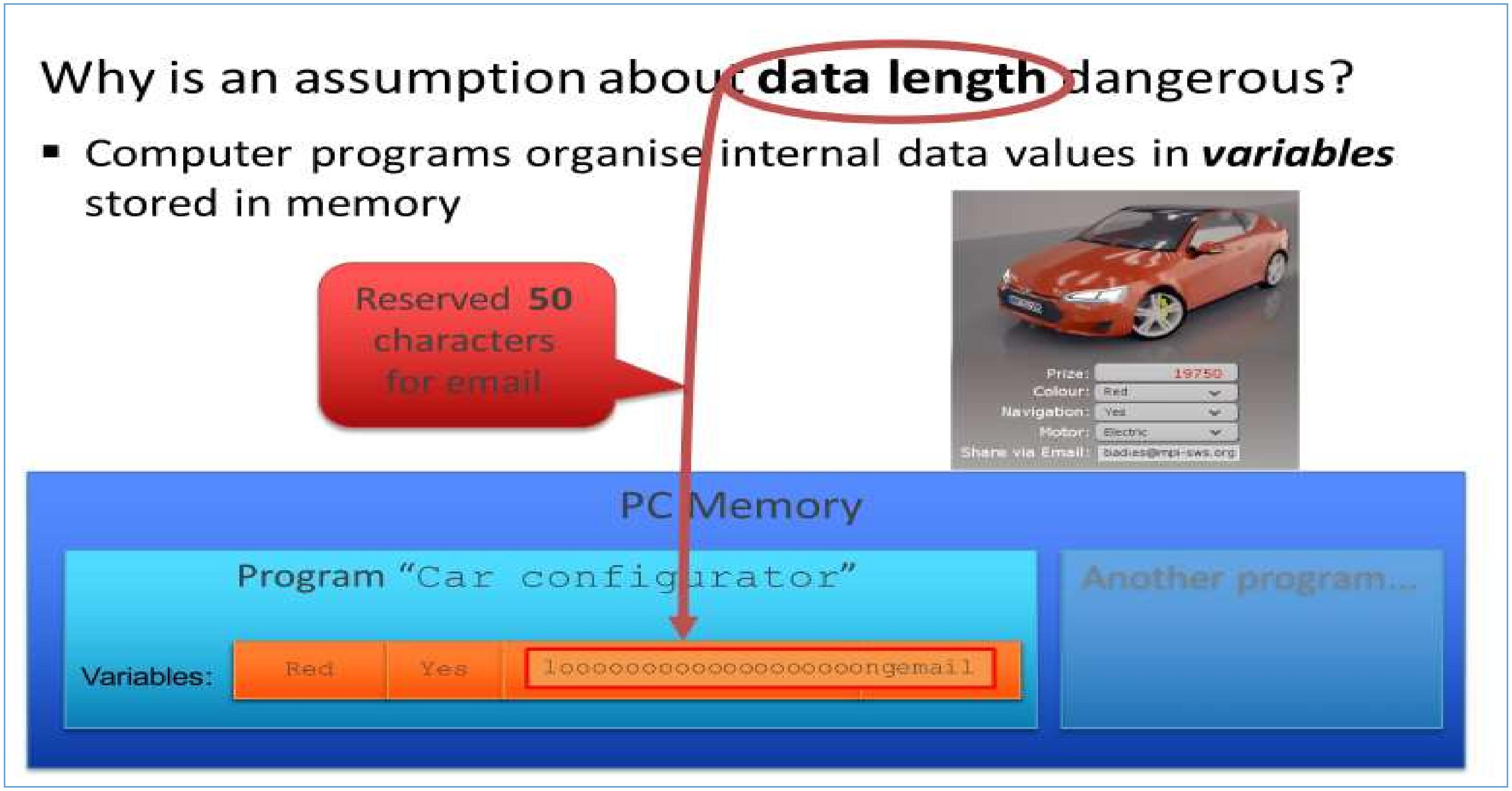
A Little Programming Language

- At machine level, all data is an array of bytes
  - interpretation depends on instructions used

- Modern high-level languages have a strong notion of type and valid operations
  - not vulnerable to buffer overflows
  - does incur overhead, some limits on use

- C and related languages have high-level control structures, but allow direct access to memory
  - hence are vulnerable to buffer overflow
  - have a large legacy of widely used, unsafe, and hence vulnerable code

Control Hijacking - Buffer Overflow (cont.)



Why is an assumption about **data length** dangerous?

- Computer programs organise internal data values in ***variables*** stored in memory

Reserved **50** characters for email

Prize: 19750

Colour: Red

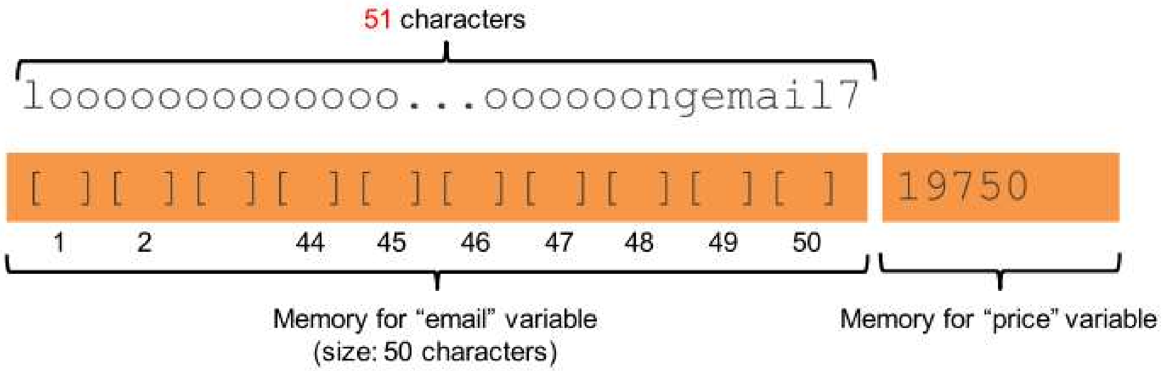
Navigation: Yes

Motor: Electric

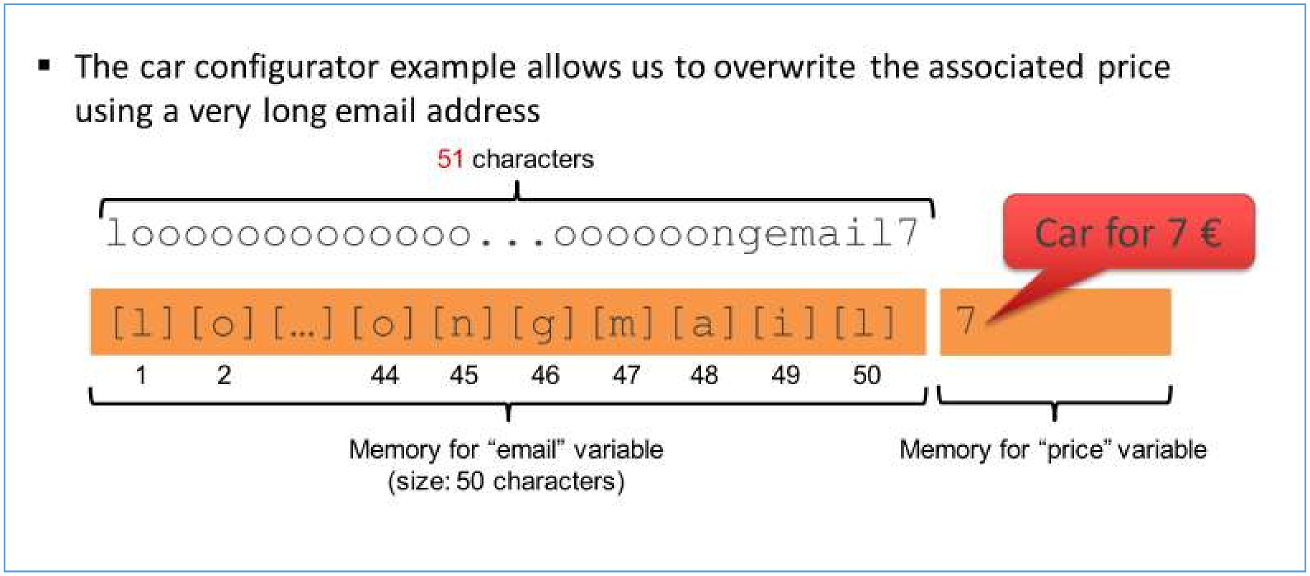
Share via Email: badies@mpi-sws.org

Control Hijacking - Buffer Overflow (cont.)

- The car configurator example allows us to overwrite the associated price using a very long email address



Control Hijacking - Buffer Overflow (cont.)

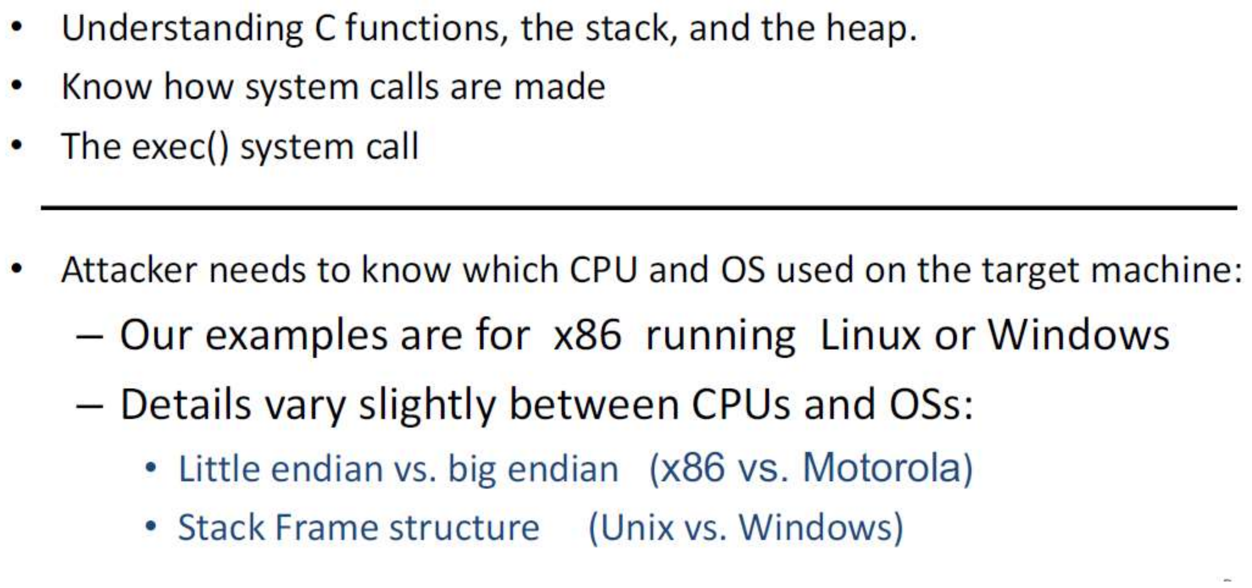


- The car configurator example allows us to overwrite the associated price using a very long email address

51 characters
looooooooooooooo...oooooongemail7
Car for 7 €
[l] [o] [...] [o] [n] [g] [m] [a] [i] [l]
7
1
2
44
45
46
47
48
49
50
Memory for “email” variable
(size: 50 characters)
Memory for “price” variable

Control Hijacking - Buffer Overflow (cont.)

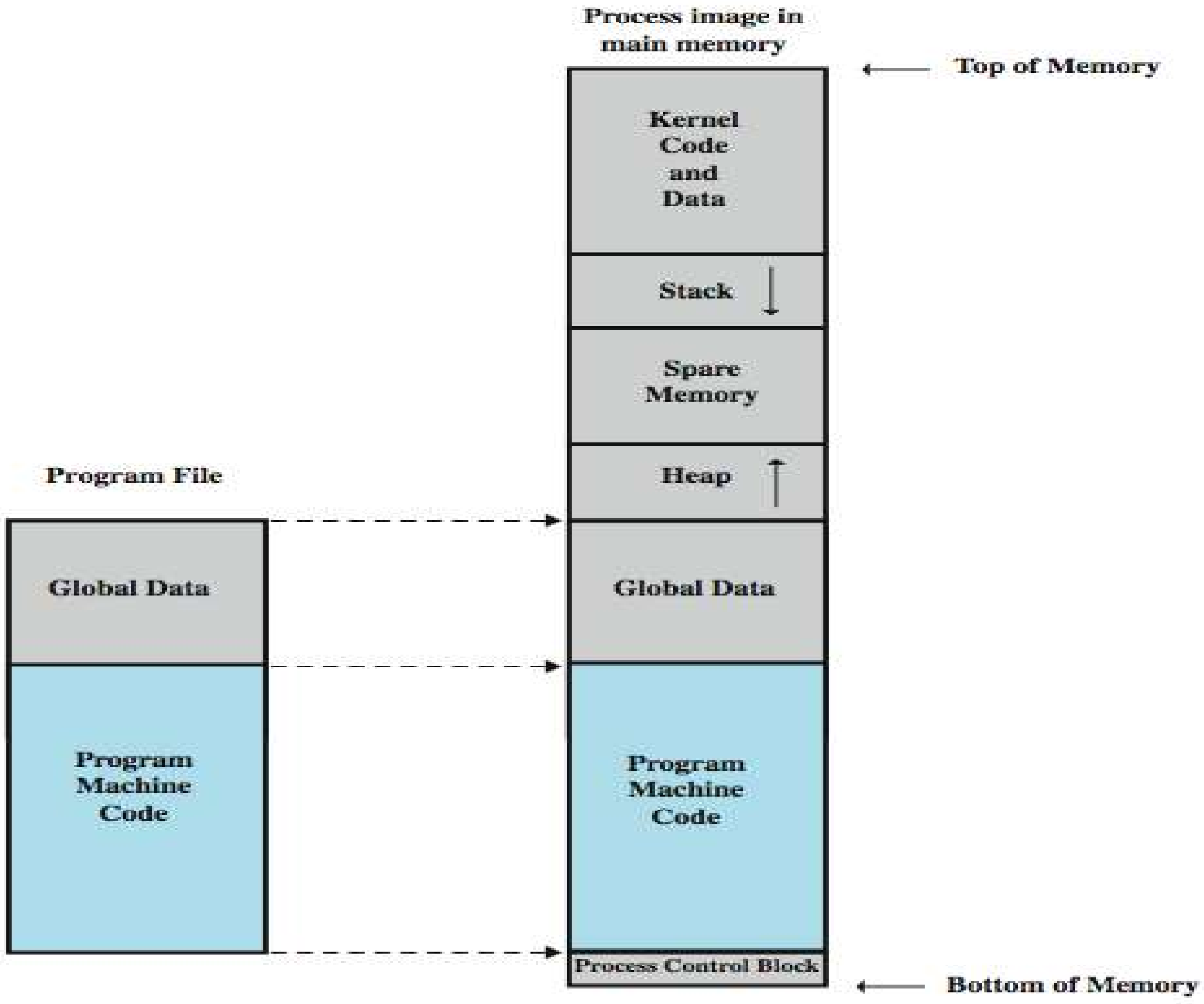
- Extremely common bug in C/C++ programs.
- What does it need?



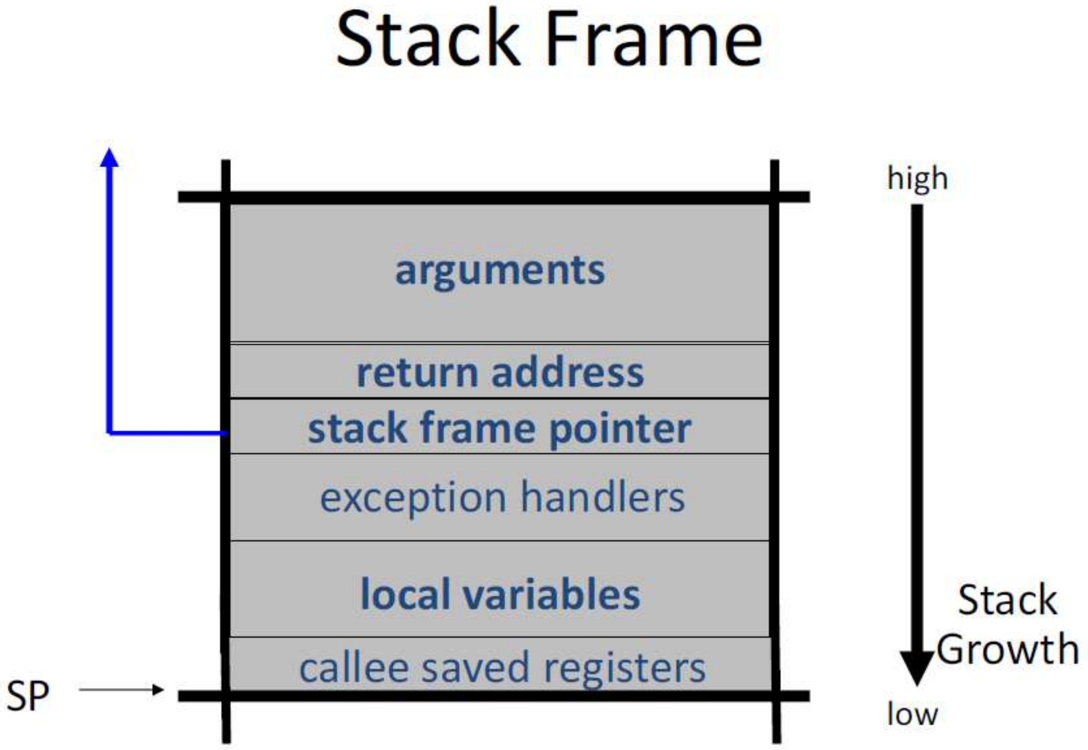
- Understanding C functions, the stack, and the heap.
- Know how system calls are made
- The exec() system call

- Attacker needs to know which CPU and OS used on the target machine:
  - Our examples are for x86 running Linux or Windows
  - Details vary slightly between CPUs and OSs:
    - Little endian vs. big endian (x86 vs. Motorola)
    - Stack Frame structure (Unix vs. Windows)

Control Hijacking - Buffer Overflow (cont.)



Control Hijacking - Buffer Overflow (cont.)



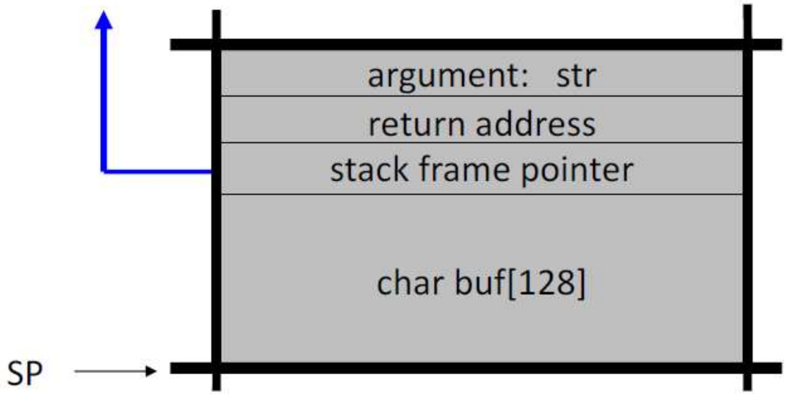
Control Hijacking - Buffer Overflow (cont.)

Suppose a web server contains a function:

```
void func(char *str) {
    char buf[128];

    strcpy(buf, str);
    do-something(buf);
}
```

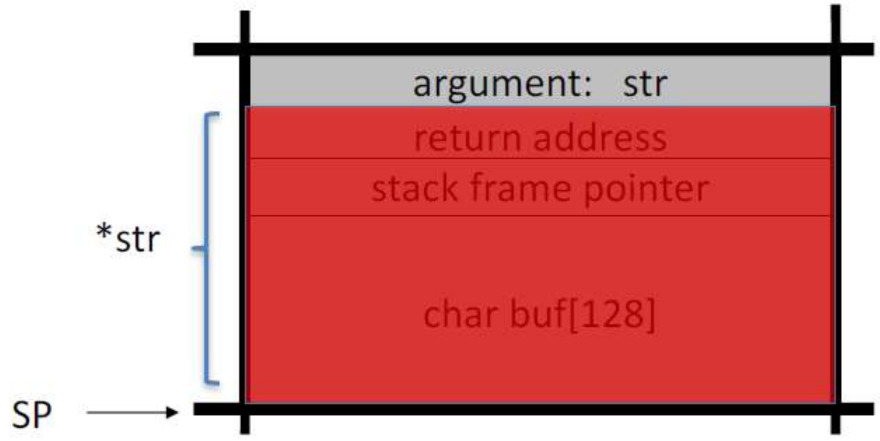
When func() is called stack looks like:



Control Hijacking - Buffer Overflow (cont.)

What if `*str` is 136 bytes long?

After `strcpy`:



```
void func(char *str) {
    char buf[128];

    strcpy(buf, str);
    do-something(buf);
}
```

Problem:

no length checking in strcpy()

Dan Boneh

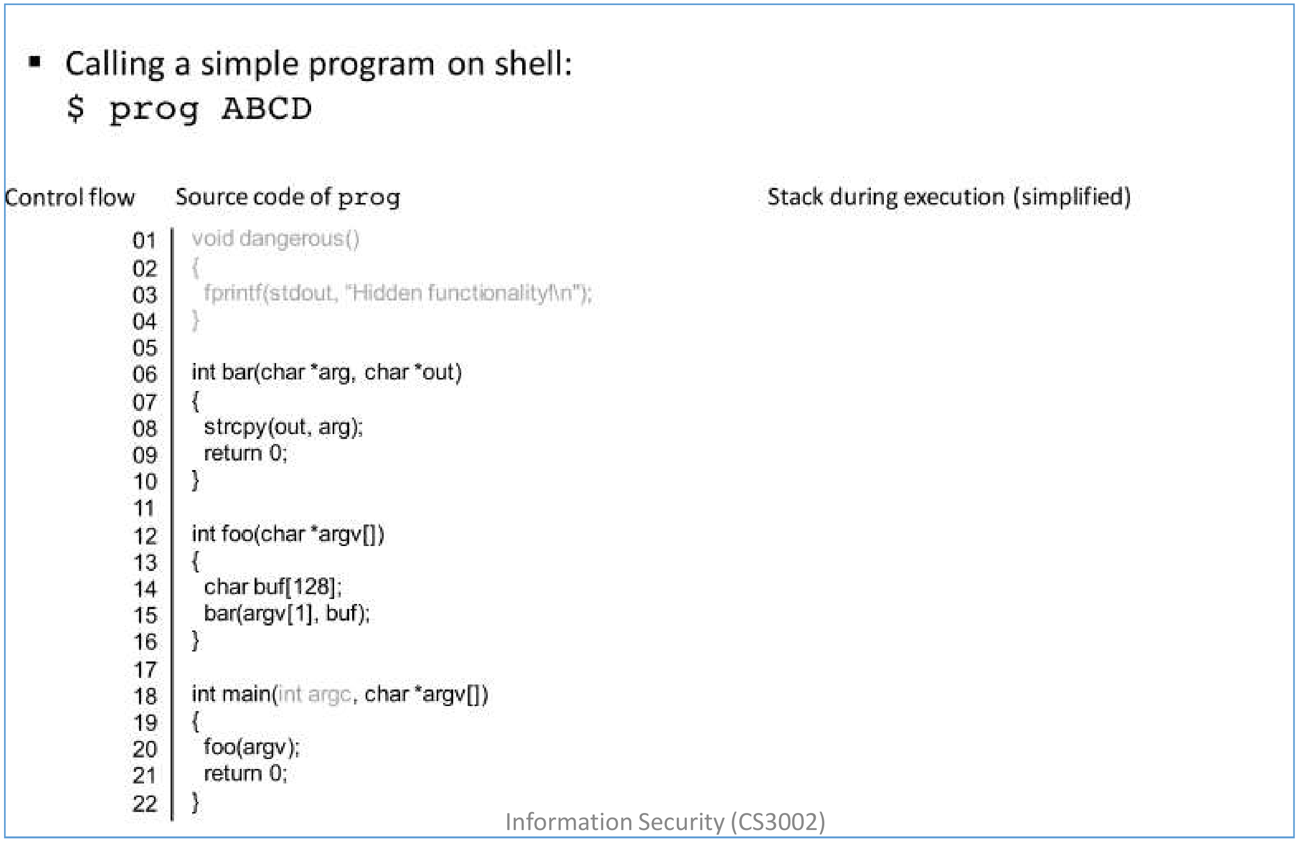
Control Hijacking - Buffer Overflow (cont.)

Many Unsafe Functions that lead to Buffer Overflows:

strcpy (char *dest, const char *src)
strcat (char *dest, const char *src)
gets (char *s)
scanf (const char *format, …) and many more.

- “Safe” libc versions strncpy(), strncat() are misleading
  – e.g. strncpy() may leave string unterminated.
- Windows C run time (CRT):
  – strcpy_s (*dest, DestSize, *src): ensures proper termination

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:
  `$ prog ABCD`

Control flow

Source code of `prog`

Stack during execution (simplified)

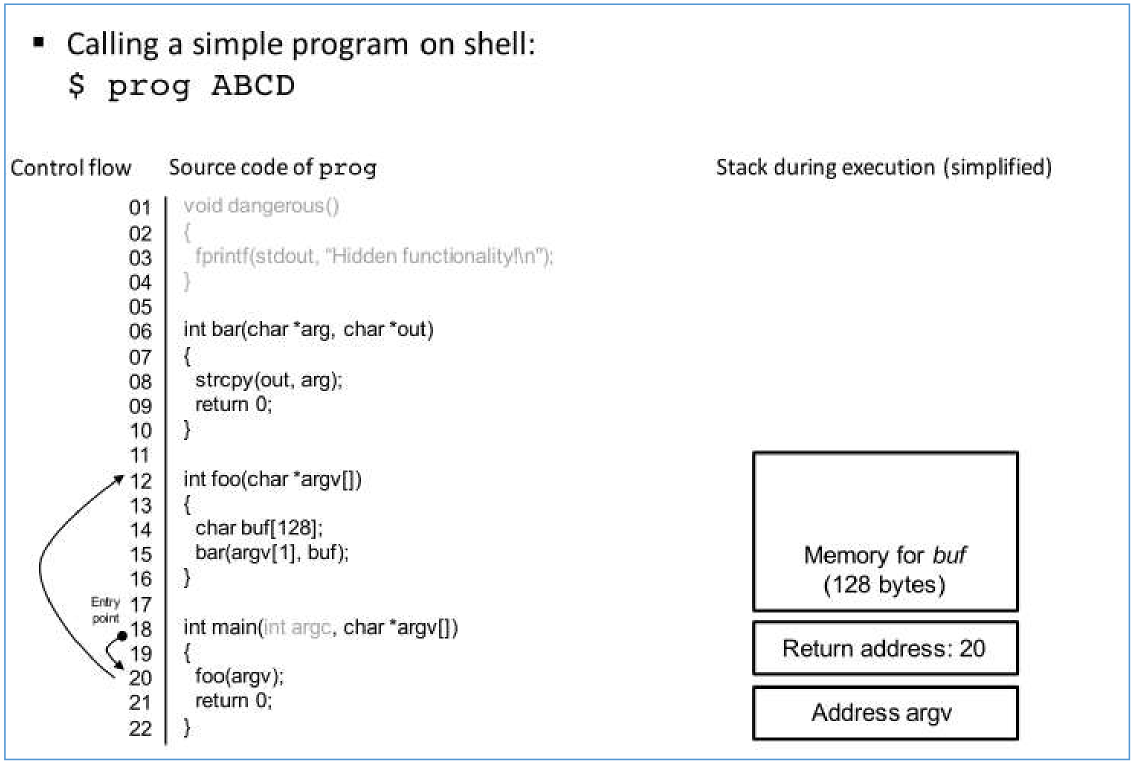
```
void dangerous()
{
  fprintf(stdout, "Hidden functionality!\n");
}

int bar(char *arg, char *out)
{
  strcpy(out, arg);
  return 0;
}

int foo(char *argv[])
{
  char buf[128];
  bar(argv[1], buf);
}

int main(int argc, char *argv[])
{
  foo(argv);
  return 0;
}
```

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



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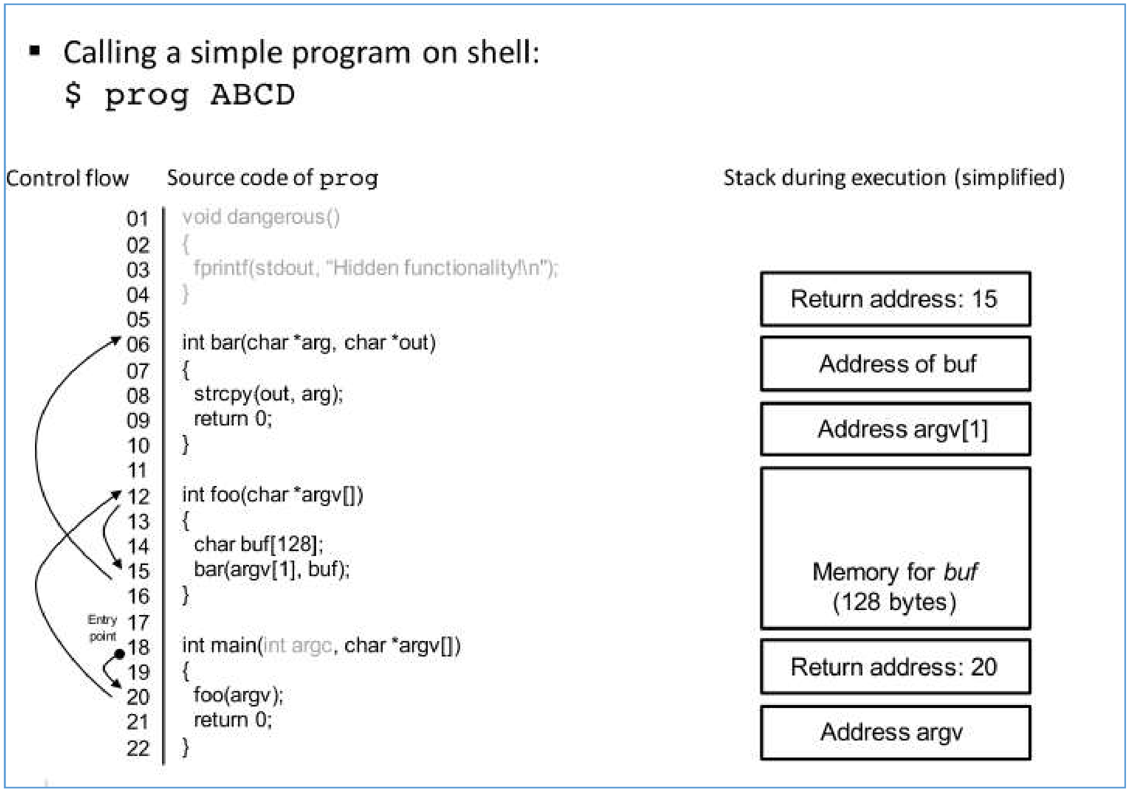
Control Hijacking - Buffer Overflow (cont.) Control Flow with Stack



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Control flow

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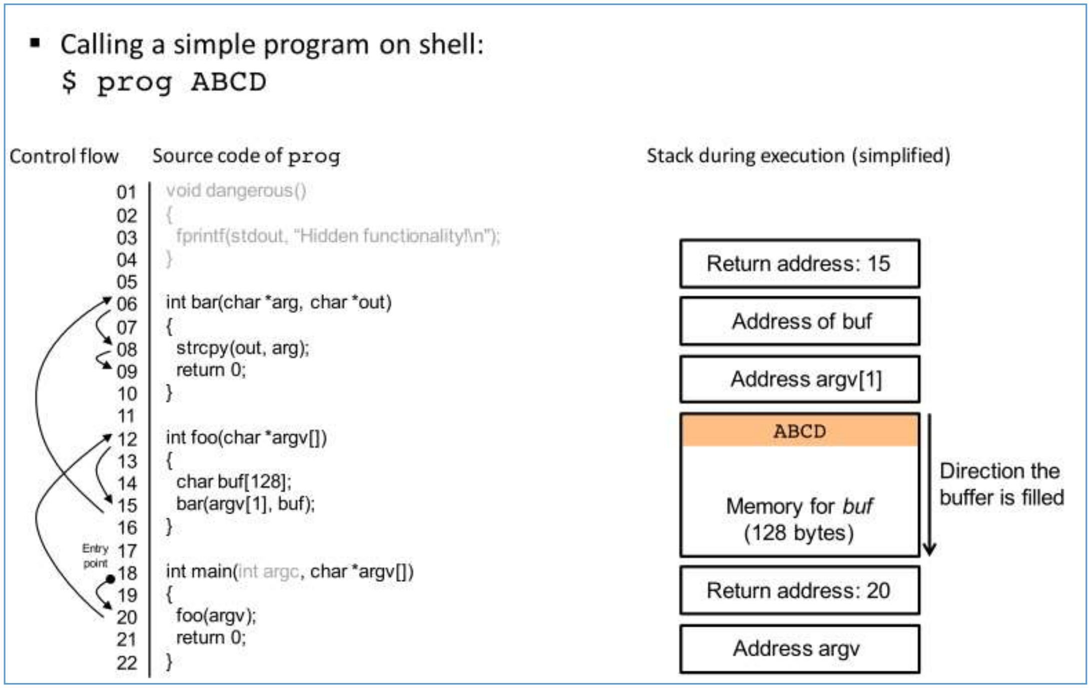
Stack during execution (simplified)

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:

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$ prog ABCD
```

Control flow

Source code of prog

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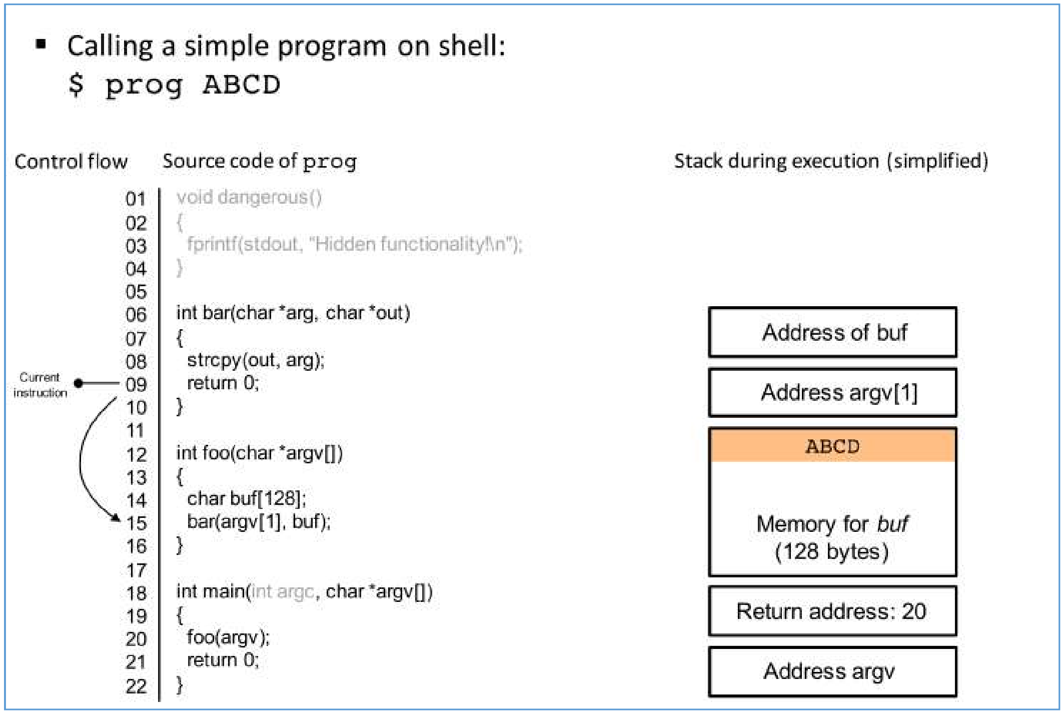
Stack during execution (simplified)

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:
  `$ prog ABCD`

Control flow | Source code of `prog` | Stack during execution (simplified)

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19  {
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21    return 0;
22  }
```

Address of buf

Address argv[1]

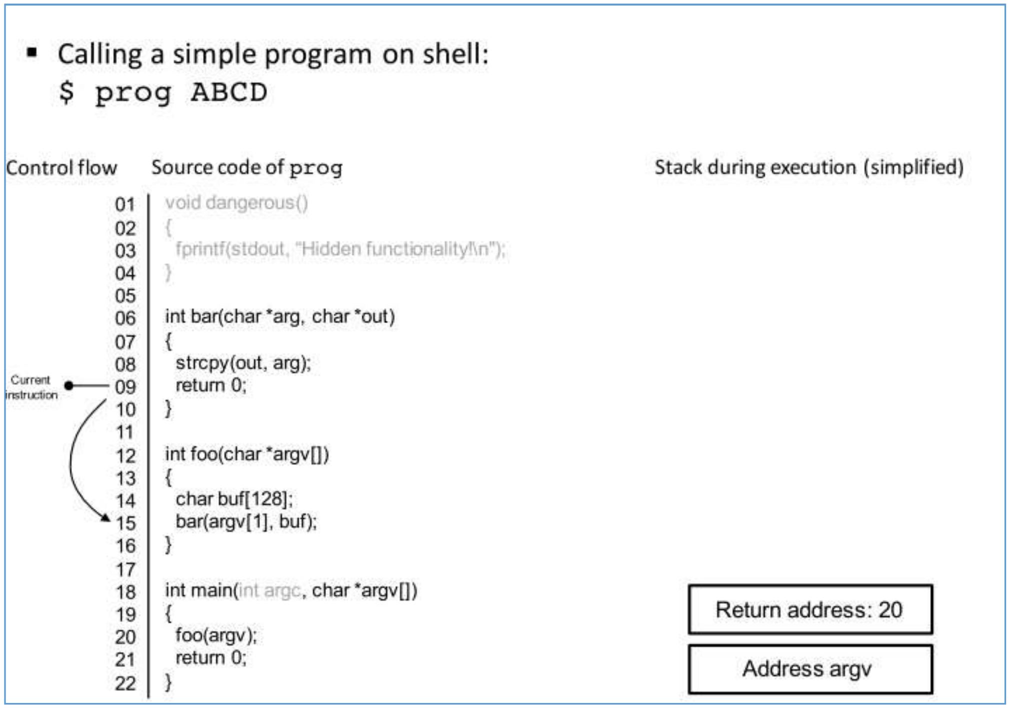
ABCD

Memory for *buf*
(128 bytes)

Return address: 20

Address argv

Control Hijacking - Buffer Overflow (cont.) Control Flow with Stack



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17
18  int main(int argc, char *argv[])
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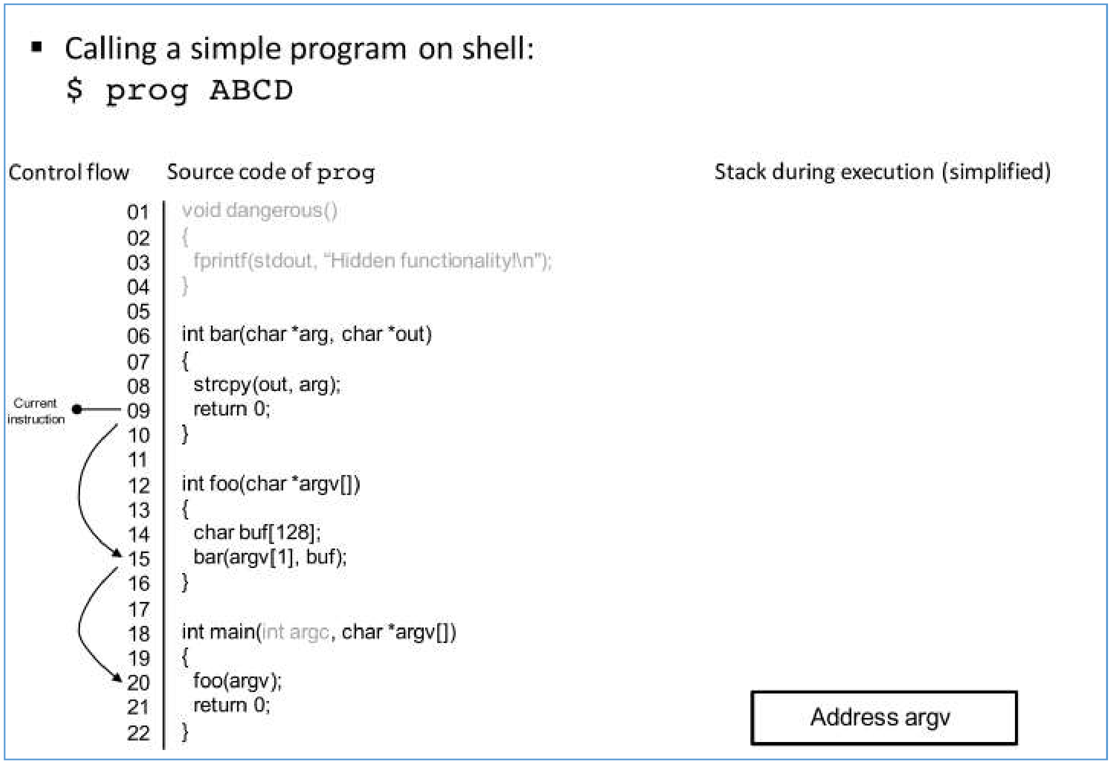
22  }
```

Stack during execution (simplified)

Return address: 20

Address argv

Control Hijacking - Buffer Overflow (cont.) Control Flow with Stack



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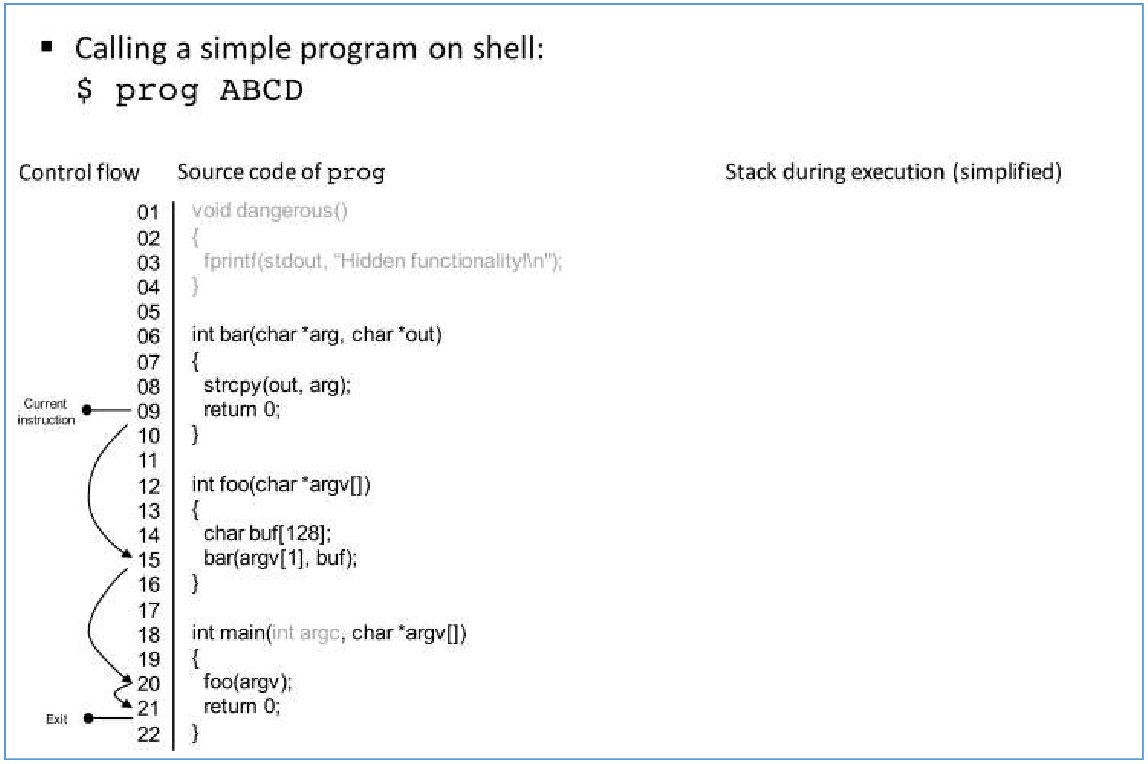
Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:

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Control flow

Source code of `prog`

Stack during execution (simplified)

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{
  fprintf(stdout, "Hidden functionality!\n");
}

int bar(char *arg, char *out)
{
  strcpy(out, arg);
  return 0;
}

int foo(char *argv[])
{
  char buf[128];
  bar(argv[1], buf);
}

int main(int argc, char *argv[])
{
  foo(argv);
  return 0;
}
```
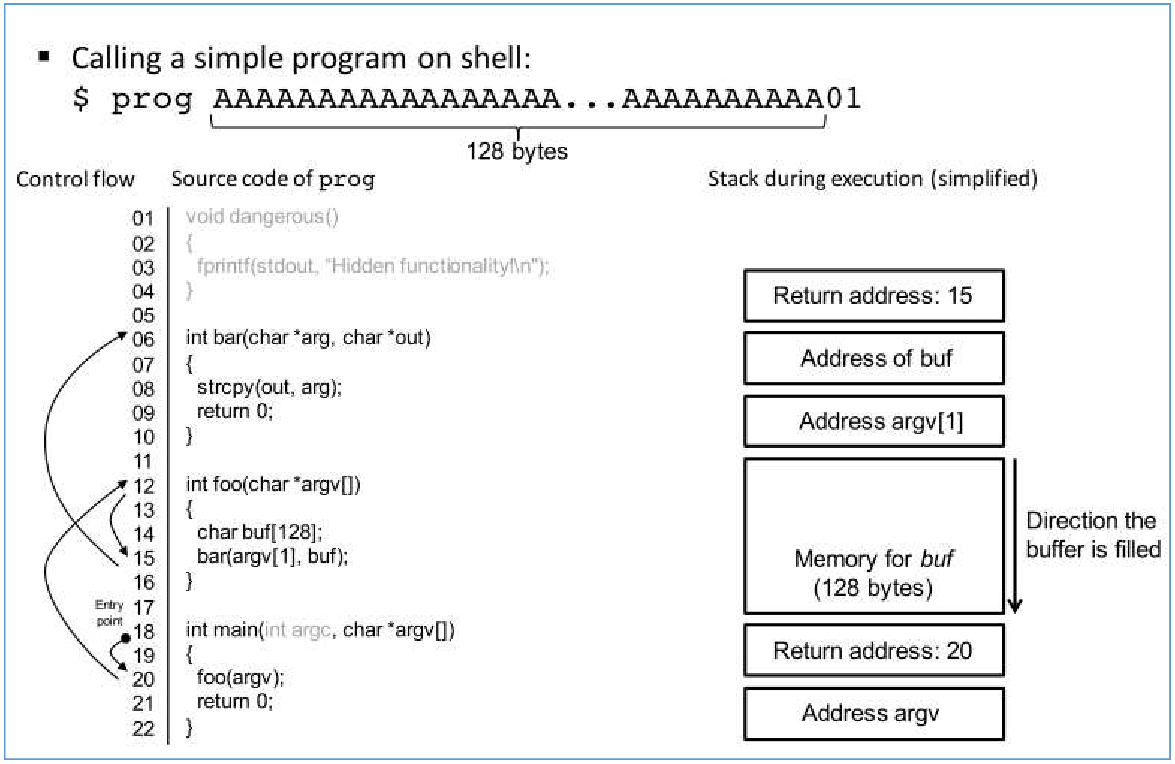

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:

```
$ prog AAAAAAAAAAAAAAAAA...AAAAAAAAAA01
```

```
01  void dangerous()
02  {
03    fprintf(stdout, "Hidden functionality!\n");
04  }
05
06  int bar(char *arg, char *out)
07  {
08    strcpy(out, arg);
09    return 0;
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12  int foo(char *argv[])
13  {
14    char buf[128];
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```
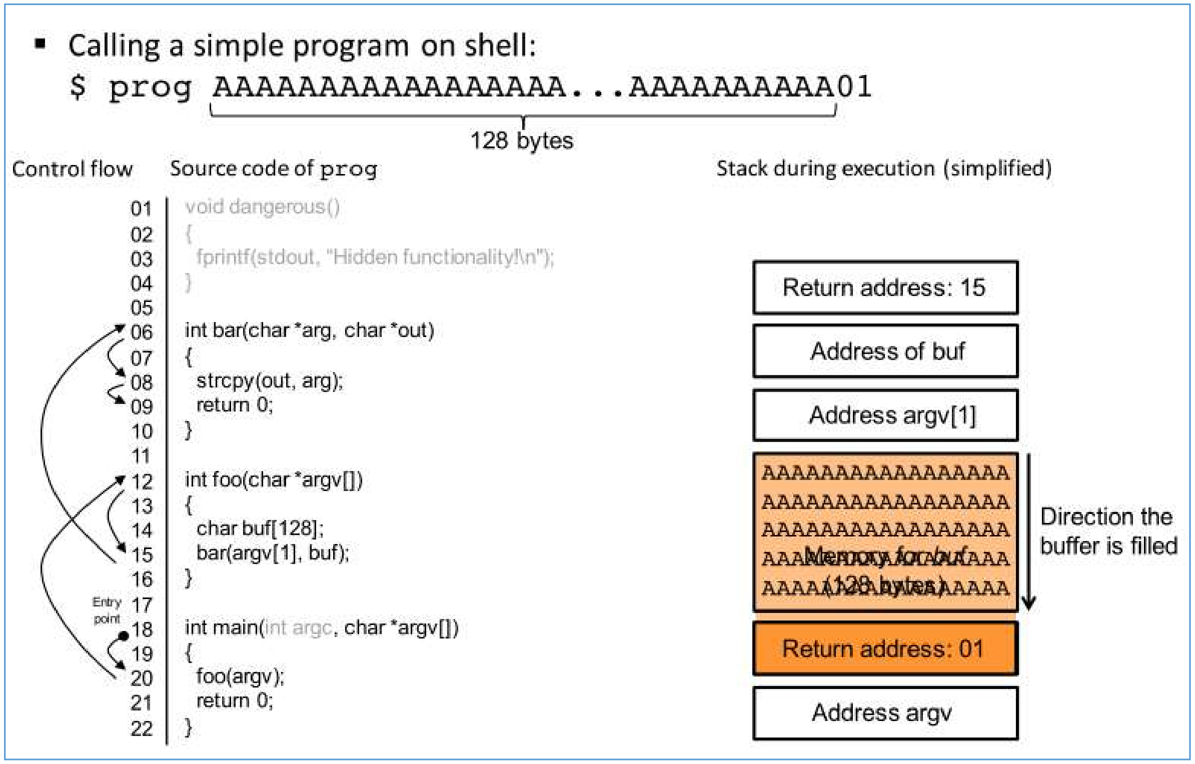

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:

```
$ prog AAAAAAAAAAAAAAAAA...AAAAAAAAAA01
```

128 bytes

Control flow | Source code of `prog` | Stack during execution (simplified)

```
01  void dangerous()
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04  }
05
06  int bar(char *arg, char *out)
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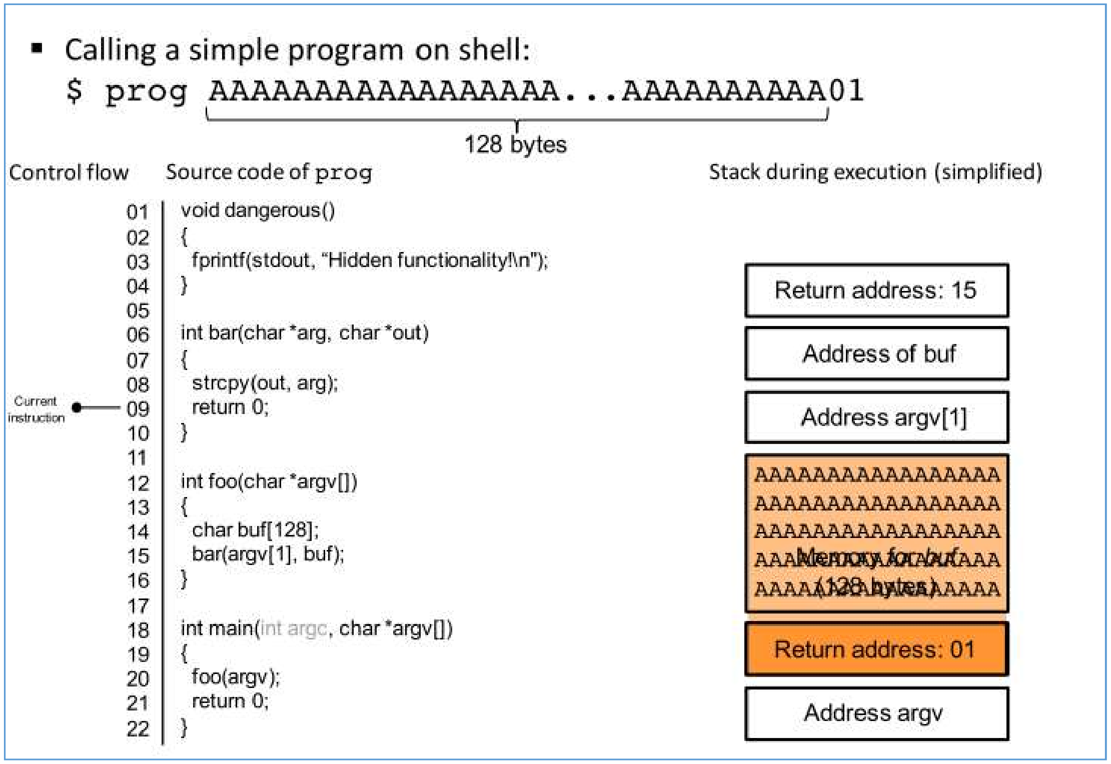
Control Hijacking - Buffer Overflow (cont.) Control Flow with Stack



- Calling a simple program on shell:

```
$ prog AAAAAAAAAAAAAAAAA...AAAAAAAAAA01
```

128 bytes

Control flow

Source code of `prog`

```
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18  int main(int argc, char *argv[])
19  {
20    foo(argv);
21    return 0;
22  }
```

Stack during execution (simplified)

Return address: 15

Address of buf

Address argv[1]

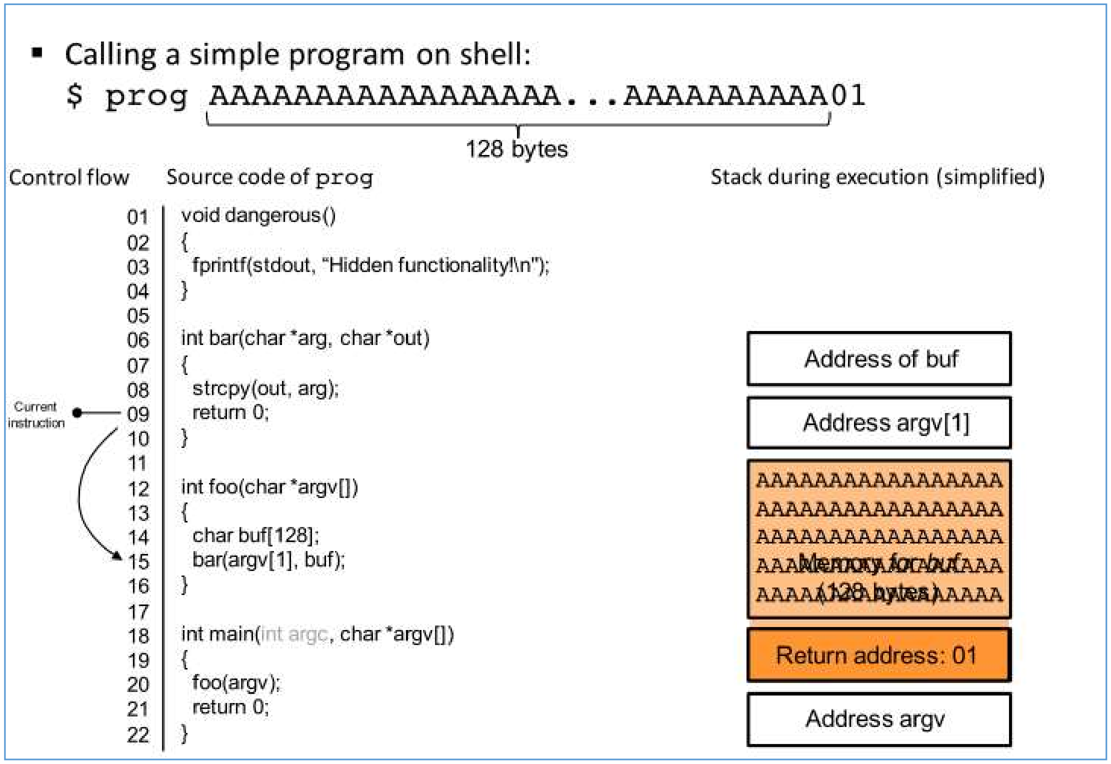
AAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAA

Memory for *buf*
(128 bytes)

Return address: 01

Address argv

Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack



- Calling a simple program on shell:

```
$ prog AAAAAAAAAAAAAAAAA...AAAAAAAAAA01
```

128 bytes

Control flow

Source code of `prog`

```
01  void dangerous()
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06  int bar(char *arg, char *out)
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```

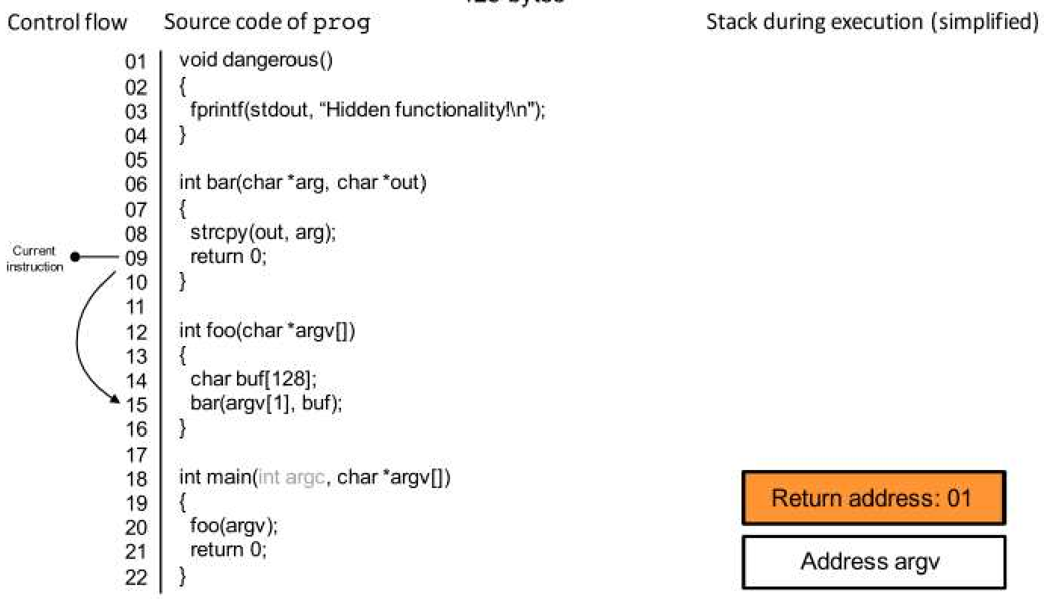
Stack during execution (simplified)

Control Hijacking - Buffer Overflow (cont.) Control Flow with Stack

- Calling a simple program on shell:

```
$ prog AAAAAAAAAAAAAAAAA...AAAAAAAAAA01
```

128 bytes



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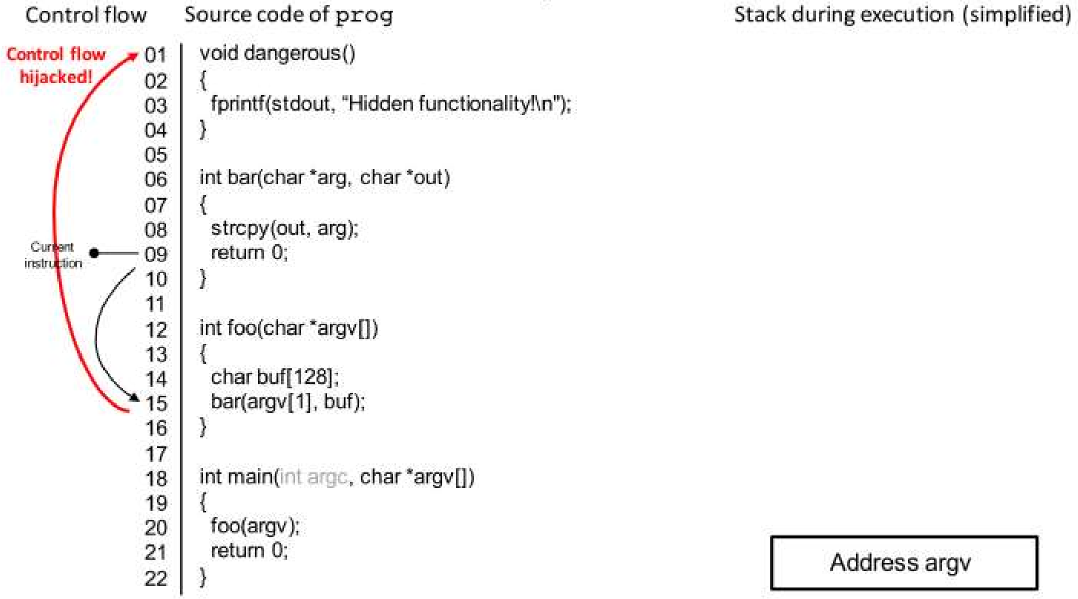
Control Hijacking - Buffer Overflow (cont.)
Control Flow with Stack

- Calling a simple program on shell:

$$\texttt{\$ prog } \underbrace{\texttt{AAAAAAAAAAAAAAAAA...AAAAAAAAAA}}_{\text{128 bytes}}\texttt{01}$$



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```

What can attacker do now?

Jumps wherever he wants

- Attacker now is running the code with the privileges of process that it’s hijacked.
  - Root_user, admin, super_user
  - Send spam mails by overtaking mail server
  - Defeat the firewall / Private Network compromised / Trust Broken

Real Life Examples

- Buffer overflow vulnerabilities were exploited by the first major attack on the Internet. Known as the Morris worm, this attack infected more than 60,000 machines (10%) and shut down much of the Internet for several days in 1988.
- Source: Carolyn Duffy Marsan, Morris Worm Turns 20: Look what it's Done, Network World, October 30, 2008 http://www.techworld.com.au/article/265692/morris_worm_turns_20_look_what_it_done/

Robert Tappan Morris
https://pdos.csail.mit.edu/~rtm/

Real Life Examples (cont.)

- A buffer overflow in a 2004 version of AOL's AIM instant-messaging software exposed users to buffer overflow vulnerabilities. If a user posted a URL in their "I'm away" message, any of his or her friends who clicked on that link might be vulnerable to attack. AOL's response was to suggest that users update to a new version that would fix the bug.
- Source: Paul Roberts "AOL IM 'Away' message flaw deemed critical", Infoworld, August 9, 2004 http://www.infoworld.com/article/04/08/09/HNaolimflaw_1.html

Adversary Motivations

- Use any privileges of the process
- Often leverage overflow to gain easier access to the system.
  - Originally on UNIX, run shell /bin/sh (shell code)
- If the process running as root or administrator , can do anything
- Even if not can send spam emails, read files.
- Can attack other machines behind a firewall.

Buffer Overflow Defenses (Self-Study)

- Buffer overflows are widely exploited
- Large amount of vulnerable code in use
  - despite cause and countermeasures known
- Two broad defense approaches
  - compile-time - harden new programs
  - run-time - handle attacks on existing programs

Compile-Time Defenses: Programming Language

- Use a modern high-level languages with strong typing
  - not vulnerable to buffer overflow
  - compiler enforces range checks and permissible operations on variables

- Do have cost in resource use

- And restrictions on access to hardware
  - so still need some code in C like languages

Compile-Time Defenses: Safe Coding Techniques

- If using potentially unsafe languages e.g. C

- Programmer must explicitly write safe code
  - by design with new code
  - ***extensive after code review*** of existing code, (e.g., OpenBSD)

- Buffer overflow safety a subset of general safe coding techniques

- Allow for graceful failure ***(know how things may go wrong)***
  - check for sufficient space in any buffer

Compile-Time Defenses: Language Extension, Safe Libraries

- Proposals for safety extensions (library replacements) to C
  - performance penalties
  - must compile programs with special compiler
- Several safer standard library variants
  - new functions, e.g. strlcpy()
  - safer re-implementation of standard functions as a dynamic library, e.g. Libsafe

Compile-Time Defenses: Stack Protection

- Stackgaurd: add function entry and exit code to check stack for signs of corruption
  - Use random canary
  - e.g. Stackguard, Win/GS, GCC
  - check for overwrite between local variables and saved frame pointer and return address
  - abort program if change found
  - issues: recompilation, debugger support
- Or save/check safe copy of return address (in a safe, non-corruptible memory area), e.g. Stackshield, RAD

Run-Time Defenses: Non Executable Address Space

- Many BO attacks copy machine code into buffer and transfer ctrl to it

- Use virtual memory support to make some regions of memory non-executable (to avoid exec of attacker's code)
  - e.g. stack, heap, global data
  - need h/w support in MMU
  - long existed on SPARC/Solaris systems
  - recent on x86 Linux/Unix/Windows systems

- Issues: support for executable stack code

Run-Time Defenses: Address Space Randomization

- Manipulate location of key data structures
  - stack, heap, global data: change address by 1 MB
  - using random shift for each process
  - have large address range on modern systems means wasting some has negligible impact

- Randomize location of heap buffers and location of standard library functions

Run-Time Defenses: Guard Pages

- Place guard pages between critical regions of memory (or between stack frames)
  - flagged in MMU (mem mgmt unit) as illegal addresses
  - any access aborts process

- Can even place between stack frames and heap buffers
  - at execution time and space cost