Security in Software Applications

Buffer Overflow

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Essence of the problem

Suppose in a C program we have an array of length 4:

```
char buffer[4]
```

What happens if we execute the statement below ?

```
buffer[4]='a'
```

Anything *can happen !*

If the data written (ie. the "a") is user input that can be controlled by an attacker, this vulnerability can be exploited: anything that the attacker wants can happen.

Solution to the problem

Check array bounds at runtime

– Algol 60 proposed this back in 1960!

Unfortunately, C and C++ have not adopted this solution, for efficiency reasons.

(Ada, Perl, Python, Java, C#, and even Visual Basic have.)

As a result, buffer overflows have been the no 1 security problem in software ever since.

Problems caused by buffer overflows

Problems caused by buffer overflows:

- The first Internet worm, and all subsequent ones (CodeRed, Blaster, ...), exploited buffer overflows

- Buffer overflows cause in the order of 50% of all security alerts

– Eg check out *CERT, cve.mitre.org, or bugtraq*

- Trends
  - Attacks are getting cleverer, defeating even more clever countermeasures
- Attacks are getting easier to do, by script kiddies

Problems caused by buffer overflows

Any C(++) code acting on untrusted input is at risk

Eg

- code taking input over untrusted network
  - eg. sendmail, web browser, wireless network driver,...

- code taking input from untrusted user on multi-user system,
  - esp. services running with high privileges (as ROOT on Unix/Linux, as SYSTEM on Windows)
- code acting on untrusted files
  - that have been downloaded or emailed
- also embedded software, eg. in devices with (wireless) network connection such as mobile phones with Bluetooth, wireless smartcards, airplane navigation

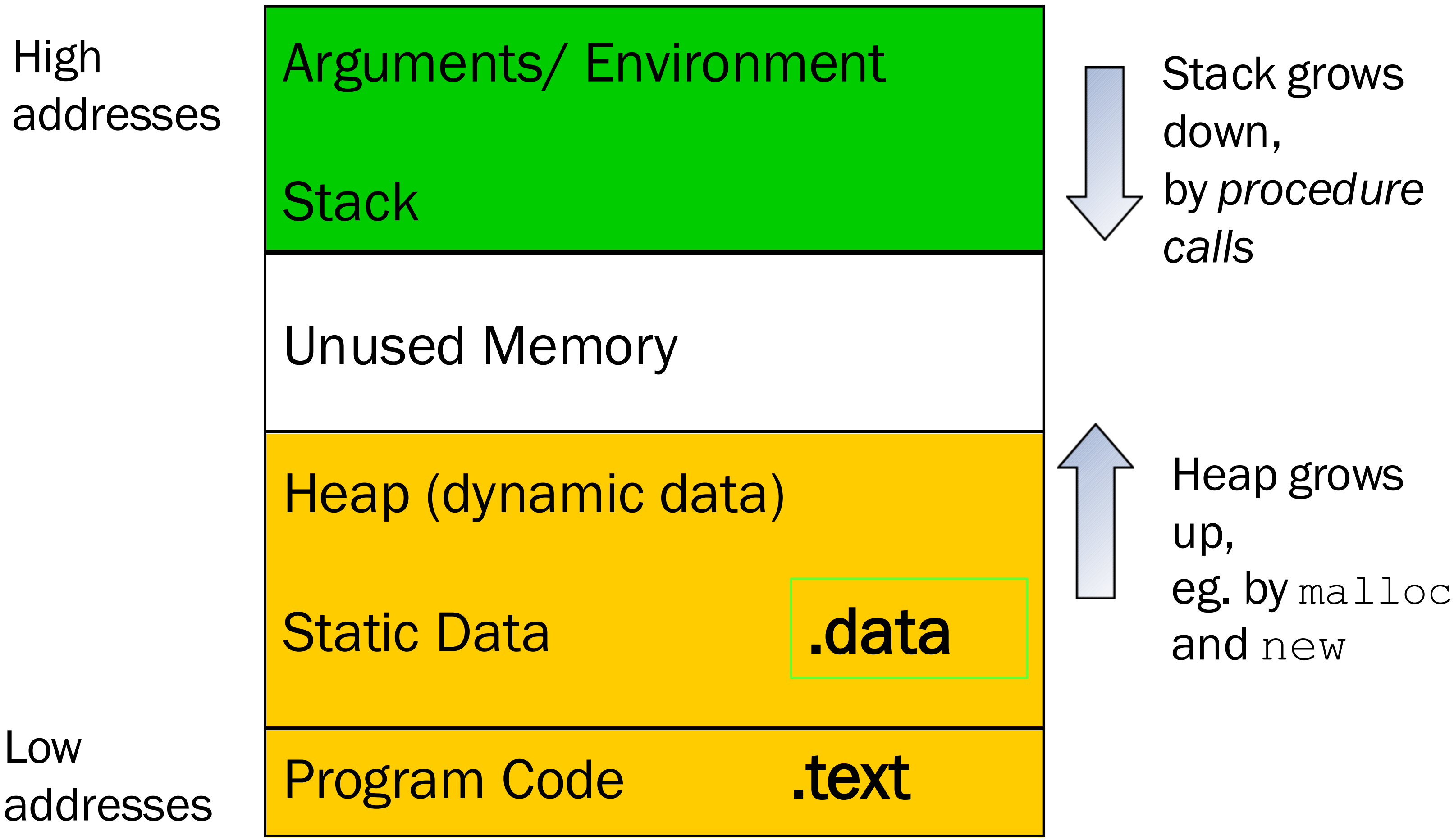
Memory Management in C/C++

- Program responsible for its memory management
- Memory management is very error-prone
  - Who here has had a C(++) program crash with a segmentation fault?

- Typical bugs:
  - Writing past the bound of an array
  - Dangling pointers
    - missing initialisation, bad pointer arithmetic, incorrect de-allocation, double de-allocation, failed allocation, …

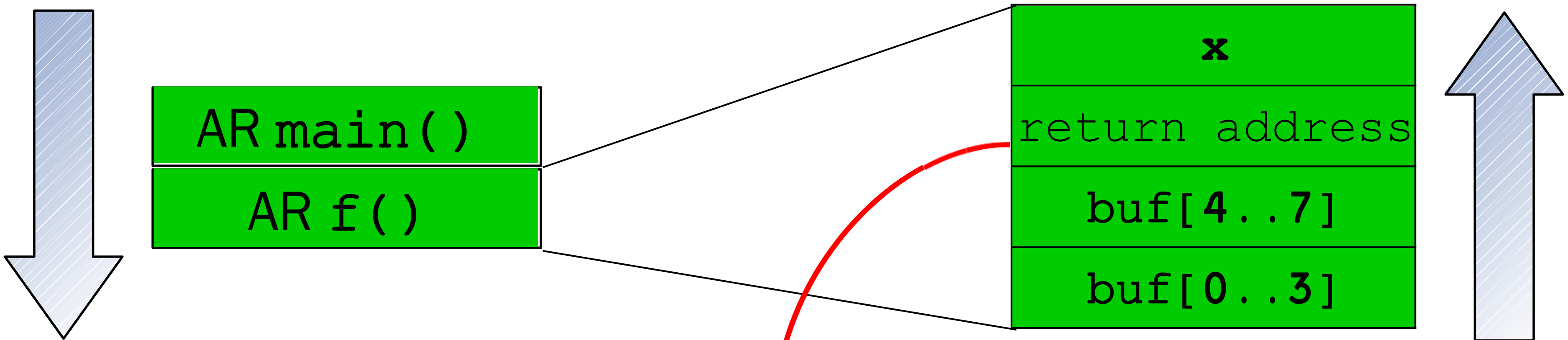
- Memory leaks
- For efficiency, these bugs are not detected at runtime, as discussed before:
  - behaviour of a buggy program is undefined

Proceess Memory Layout



Stack Overflow

The stack consists of Activation Records:



Stack grows downwards

Buffer grows upwards

```
void f(int x) {
   char[8] buf;
   gets(buf);

}
void main()     {
   f(…); …


}
void format_hard_disk(){…}
```

Stack Overflow

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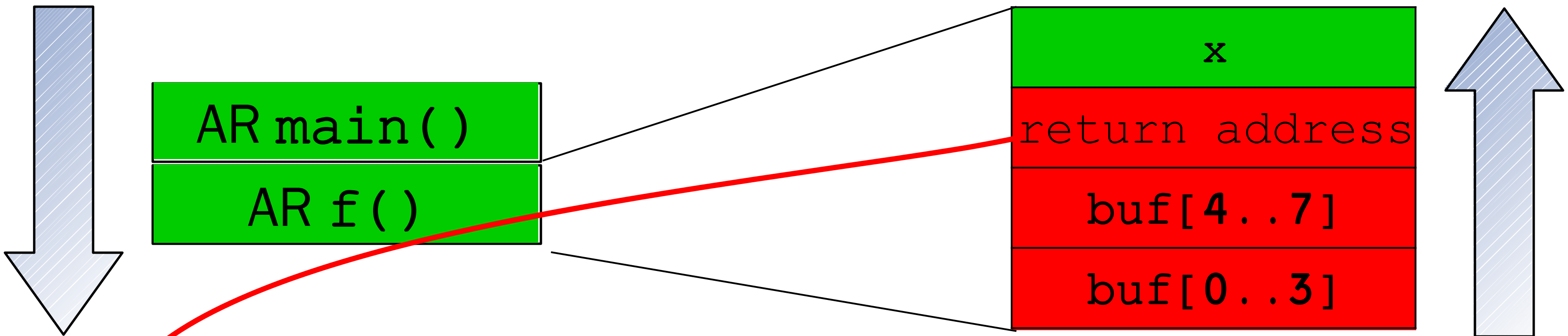

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Buffer grows upwards

```
void f(int x) {
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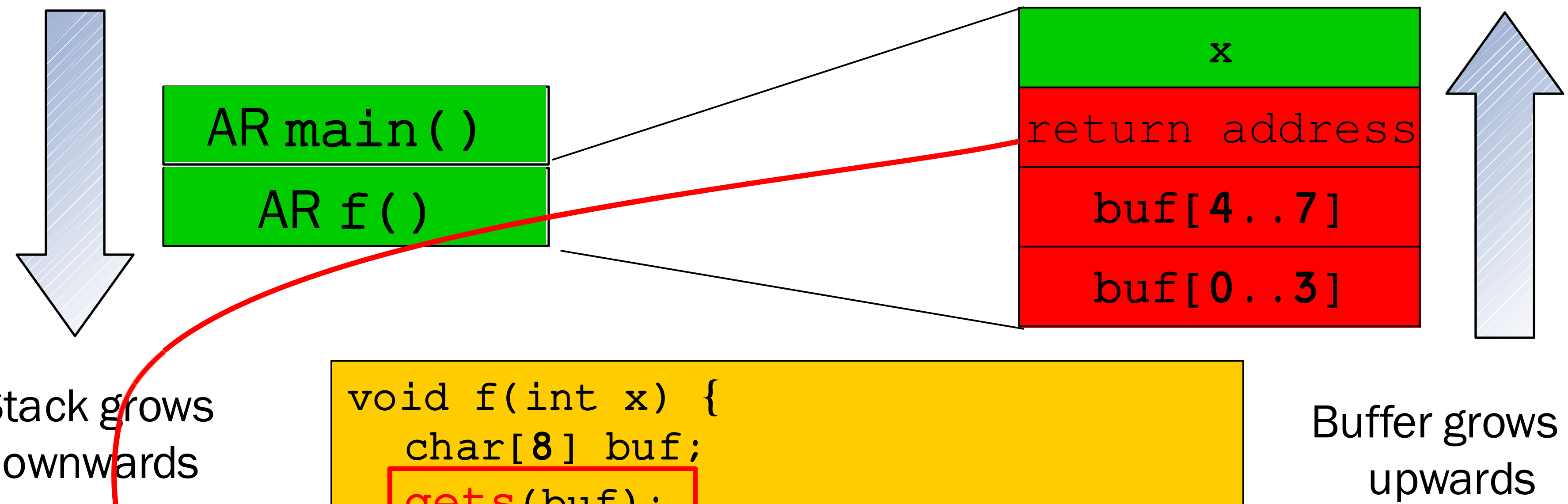


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   char[8] buf;
   gets(buf);
}
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   f(…); …

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Stack Overflow

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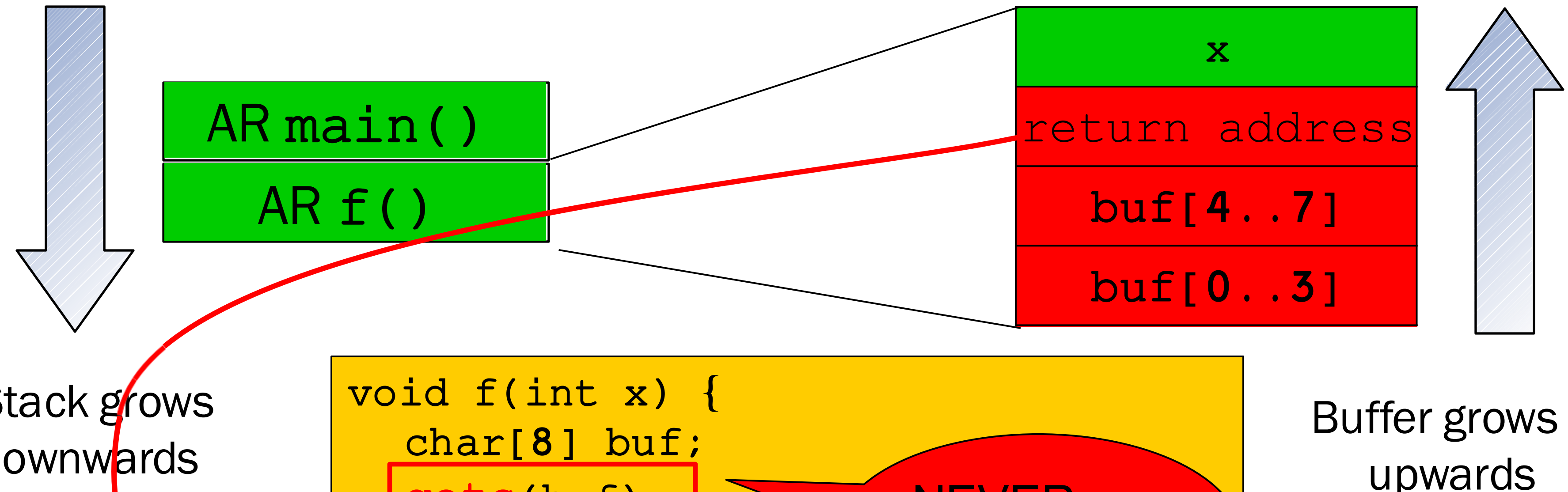



```
void f(int x) {
   char[8] buf;
   gets(buf);
}
void main()   {
   f(…); …

}
void format_hard_disk(){…}
```

NEVER
Use gets()!

Stack Overflow

- Lots of details to get right:
  - No nulls in (character-)strings
  - Filling in the correct return address:
    - Fake return address must be precisely positioned
    - Attacker might not know the address of his own string
  - Other overwritten data must not be used before return from function
- – …

Stack Overflow

- **Stack overflow** is overflow of a buffer allocated on the stack
- **Heap overflow** idem, of buffer allocated on the heap

Common causes:

- poor programming with of *arrays* and *strings*
  - esp. library functions for null-terminated strings
- problems with *format strings*

But other low-level coding defects than can result in buffer overflows, eg *integer overflows* or *data races*

Example: **gets()**

```
 char buf[20];
gets(buf); // read user input until
           // first EoL or EoF character
```

- *Never* use **gets**
- Use **fgets(buf, size, stdin)** instead

Example: **strcopy()**

```
 char dest[20];
strcpy(dest, src); // copies string src to dest
```

- **strcpy** assumes that
  - **dest** is long enough
  - **src** is null-terminated
- Use **strncpy(dest, src, size)** instead

Spot the defect

```
char buf[20];
char prefix[] = ”http://”;
...
strcpy(buf, prefix);
   // copies the string prefix to buf
strncat(buf, path, sizeof(buf));
   // concatenates path to the string buf
```

Spot the defect

```
char buf[20];
char prefix[] = ”http://”;
...
strcpy(buf, prefix);
   // copies the string prefix to buf
strncat(buf, path, sizeof(buf));
   // concatenates path to the string buf
```

strncat’s 3rd parameter is number of chars to copy, not the buffer size

Another common mistake is giving **sizeof(path)** as 3rd argument...

Spot the defect

```
char src[9]; char dest[9];

char base_url = ”www.ru.nl”;
strncpy(src, base_url, 9);
    // copies base_url to src
strcpy(dest, src);
    // copies src to dest
```

Spot the defect

base_url is 10 chars long, incl. its null terminator,
so **src** won't be null-terminated

```
char src[9]; char dest[9];

char base_url = "www.ru.nl";
strncpy(src, base_url, 9);
    // copies base_url to src
strcpy(dest, src);
    // copies src to dest
```

Spot the defect

base_url is 10 chars long, incl. its null terminator,
so **src** won't be null-terminated

```
char src[9]; char dest[9];

char base_url = "www.ru.nl";
strncpy(src, base_url, 9);
    // copies base_url to src
strcpy(dest, src);
    // copies src to dest
```

so **strcpy** will overrun the buffer **dest**

Example: `strcpy` and `strncpy`

- Don't replace

  ```
  strcpy(dest, src)
  ```

  by

  ```
  strncpy(dest, src, sizeof(dest))
  ```

  but by

  ```
  strncpy(dest, src, sizeof(dest)-1)
  dst[sizeof(dest-1)] = `\0`;
  ```

  if `dest` should be null-terminated!

- Btw: a *strongly typed programming language* could of course enforce that strings are always null-terminated...

Spot the defect

```
 char *buf;
 int i, len;

read(fd, &len, sizeof(len));
       // read sizeof(len) bytes, ie. an int
       // and store these in len
buf = malloc(len);
read(fd,buf,len);
```

Spot the defect

We forget to check for bytes representing a negative int, so **len** might be negative

```
char *buf;
int i, len;

read(fd, &len, sizeof(len));
        // read sizeof(len) bytes, ie. an int
        // and store these in len
buf = malloc(len);
read(fd,buf,len);
```

`len` cast to unsigned and negative length overflows

`read` then goes beyond the end of **buf**

Spot the defect

```
 char *buf;
 int i, len;

read(fd, &len, sizeof(len));
        // read sizeof(len) bytes, ie. an int
        // and store these in len
buf = malloc(len);
read(fd,buf,len);
```

Remaining problem may be that **buf** is not null-terminated

Spot the defect

```
 char *buf;
 int i, len;

read(fd, &len, sizeof(len));
        // read sizeof(len) bytes, ie. an int
        // and store these in len
buf = malloc(len);
read(fd,buf,len+1);
buf[len] = '\0'; // null terminate buf
```

Absence of language-level security

In programming languages *with "security" provisions*, the programmer would not have to worry about

- *writing past the bounds of the array* (`IndexOutOfBoundsException` for example)
- *implicit conversion from signed to unsigned integers* (forbidden or warned by compiler/typechecker)
- `malloc` returning null value (OutOfMemoryException for example)
- `malloc` non initializing memory (by default)
- *integer overflow* (`IntegerOverflowException` for example)

Spot the defect

```
#ifdef UNICODE
#define _sntprintf _snwprintf #define TCHAR
wchar_t
#else
#define _sntprintf _snprintf #define TCHAR
char
#endif




TCHAR buff[MAX_SIZE];
_sntprintf(buff, sizeof(buff), ”%s\n”, input);
```

Spot the defect

```
#ifdef UNICODE
#define _sntprintf _snwprintf #define TCHAR
wchar_t
#else
#define _sntprintf _snprintf #define TCHAR
char
#endif
```

_snwprintf's 2nd param is # of chars in buffer, not # of bytes

```
TCHAR buff[MAX_SIZE];
_sntprintf(buff, sizeof(buff), ”%s\n”, input);
```

The *CodeRed* worm exploited such an ANSI/Unicode mismatch

Spot the defect

```
#define MAX_BUF = 256

void BadCode (char* input)
{     short len;
      char buf[MAX_BUF];

      len = strlen(input);

      if (len < MAX_BUF) strcpy(buf,input);
}
```

Spot the defect

```
#define MAX_BUF = 256

void BadCode (char* input)
{     short len;
      char buf[MAX_BUF];

      len = strlen(input);

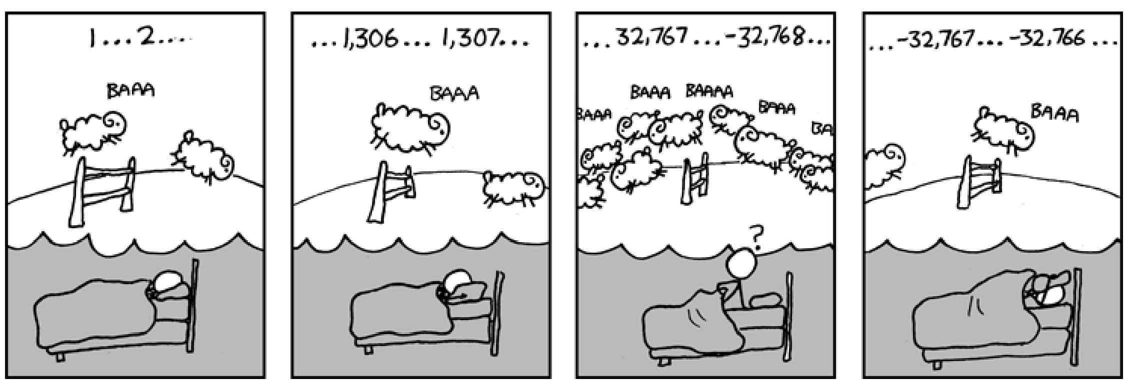
      if (len < MAX_BUF) strcpy(buf,input);
}
```

What if **input** is longer than 32K ?

`len` will be a negative number, due to integer overflow

hence: potential *buffer overflow*

The *integer overflow* is the root problem, but the *(heap) buffer overflow* that this enables make it exploitable



Spot the defect

```
bool CopyStructs(InputFile* f, long count)
{     structs = new Structs[count];
      for (long i = 0; i < count; i++)
          { if !(ReadFromFile(f,&structs[i]))
                  break;
          }
  }
```

Spot the defect

```
bool CopyStructs(InputFile* f, long count)
{     structs = new Structs[count];
      for (long i = 0; i < count; i++)
          { if !(ReadFromFile(f,&structs[i])))
                  break;
          }
  }
```

effectively does a `malloc(count*sizeof(type))` which may cause *integer overflow*

And this integer overflow can lead to a (heap) buffer overflow.
(Microsoft Visual Studio 2005(!) C++ compiler adds check to prevent this)

Spot the defect

```
char buff1[MAX_SIZE], buff2[MAX_SIZE];
// make sure url a valid URL and fits in buff1 and buff2:
if (! isValid(url)) return;
if (strlen(url) > MAX_SIZE - 1) return;
// copy url up to first separator, ie. first '/', to buff1 out = buff1;
do {
   // skip spaces
    if (*url != ' ') *out++ = *url;
} while (*url++ != '/');
strcpy(buff2, buff1);
...
```

Spot the defect

```
char buff1[MAX_SIZE], buff2[MAX_SIZE];
// make sure url a valid URL and fits in buff1 and buff2:
if (! isValid(url)) return;
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do {
   // skip spaces
    if (*url != ' ') *out++ = *url;
} while (*url++ != '/');
strcpy(buff2, buff1);
...
```

length up to the first null

what if there is no ‘/’ in the URL?

Spot the defect

```
char buff1[MAX_SIZE], buff2[MAX_SIZE];
// make sure url a valid URL and fits in buff1 and buff2:
if (! isValid(url)) return;
if (strlen(url) > MAX_SIZE - 1) return;
// copy url up to first separator, ie. first '/', to buff1 out = buff1;
do {
   // skip spaces
    if (*url != ' ') *out++ = *url;
} while (*url++ != '/')
&& (*url != 0);
  strcpy(buff2, buff1);
...
```

Spot the defect

```
char buff1[MAX_SIZE], buff2[MAX_SIZE];
// make sure url a valid URL and fits in buff1 and buff2:
if (! isValid(url)) return;
if (strlen(url) > MAX_SIZE - 1) return;
// copy url up to first separator, ie. first '/', to buff1 out = buff1;
do {
   // skip spaces
    if (*url != ' ') *out++ = *url;
} while (*url++ != '/')
&& (*url != 0);
  strcpy(buff2, buff1);
...
```

Order of tests is wrong (note the first test includes ++)

What about 0-length URLs?

Is buff1 always null-terminated?

Spot the defect

```
#include <stdio.h>

int main(int argc, char* argv[])
{    if (argc > 1)
        printf(argv[1]);
     return 0;
}
```

This program is vulnerable to *format string attacks*, where calling the program with strings containing special characters can result in a buffer overflow attack.

Format String attacks

- Complete new type of attack, invented/discovered in 2000. Like integer overflows, it can lead to buffer overflows.

- Strings can contain special characters, eg **%s** in

```
printf("Cannot find file %s", filename);
```

  Such strings are called format strings
- What happens if we execute the code below?

```
printf("Cannot find file %s");
```

- What *may* happen if we execute

```
printf(string)
```

  where **string** is user-supplied ?

  Esp. if it contains special characters, eg `%s`, `%x`, `%n`, `%hn`?

Format String attacks

- `%x` reads and prints 4 bytes from stack
  - this may leak sensitive data
- `%n` writes the number of characters printed so far onto the stack
  - this allow stack overflow attacks...

- Note that format strings break the “don’t mix data & code” principle.
- Easy to spot & fix:

  replace `printf(str)` by `printf("%s",str)`

Dynamic Countermeasures

Protection by kernel

- *Non-executable memory* (NOEXEC)
  - Prevents attacker executing her code
- Addr*ess space layout randomisation* (SLR)
  - Generally makes attacker's life harder
- *Instruction set randomisation*
  - Hardware support needed to make this efficient enough

Protection inserted by the compiler

- *Stack canaries* to prevent or detect malicious changes to the stack; examples to follow
- *Obfuscation* of memory addresses

Doesn't prevent against heap overflows

Dynamic Countermeasures: Stack Canaries

- introduced in *StackGuard* in gcc
- a dummy value - *stack canary or cookie* - is written on the stack in front of the *return address* and checked when function returns
- a careless stack overflow will overwrite the canary, which can then be detected.
- a careful attacker can overwrite the canary with the correct value.
- additional countermeasures:
  - use a random value for the canary
  - XOR this random value with the return address
  - include string termination characters in the canary value

Further Improvements

- *PointGuard*
  - also protects other data values, eg function pointers, with canaries
- *ProPolice's Stack Smashing Protection (SSP)* by IBM
  - also *re-orders stack elements* to reduce potential for trouble
- *Stackshield* has a special stack for return addresses, and can disallow function pointers to the data segment

Dynamic Countermeasures

NB none of these protections is perfect!

Eg

- even if attacks to return addresses are caught, integrity of other data other the stack can still be abused
- clever attacks may leave canaries intact
- where do you store the "master" canary value
  - a cleverer attack could change it
- none of this protects against heap overflows
  - eg buffer overflow within a struct...
- ....

Other Countermeasures

- We can take countermeasures at different points in time
  - before we even begin programming
  - during development
  - when testing
  - when executing code

  to prevent, to detect – at (pre)compile time or at runtime -, and to migitate problems with buffer overflows

Prevention

- Don’t use C or C++
- Better programmer awareness & training

Eg read – and make other people read -

- Building Secure Software, J. Viega & G. McGraw, 2002
- Writing Secure Code, M. Howard & D. LeBlanc, 2002
- 19 deadly sins of software security, M. Howard, D LeBlanc & J. Viega, 2005
- Secure programming for Linux and UNIX HOWTO, D. Wheeler,
- Secure C coding, T. Sirainen
- The Secure Coding Cookbook for C and C++ by John Viega and Matt Messier
- Secure Coding: Principles and Practices by Robert Seacord, 2013

Dangerous C system calls

Extreme risk

- gets

High risk

- strcpy
- strcat
- sprintf
- scanf
- sscanf
- fscanf
- vfscanf
- vsscanf
- streadd
- strecpy
- strtrns
- realpath
- syslog
- getenv
- getopt
- getopt_long
- getpass

Moderate risk

- getchar
- fgetc
- getc
- read
- bcopy

Low risk

- fgets
- memcpy
- snprintf
- strccpy
- strcadd
- strncpy
- strncat
- vsnprintf

Prevention – Use better libraries

- there is a choice between using statically vs dynamically allocated buffers
  - *static* approach easy to get wrong, and chopping user input may still have unwanted effects
  - *dynamic* approach susceptible to out-of-memory errors, and need for failing safely

Prevention – Use better libraries (strings)

- `libsafe.h` provides safer, modified versions of eg strcpy
  - prevents buffer overruns beyond current stack frame in the dangerous functions it redefines
- `libverify` enhancement of libsafe
  - keeps copies of the stack return address on the heap, and checks if these match

`strlcpy(dst,src,size)` and `strlcat(dst,src,size)`

with `size` the size of `dst`, not the maximum length copied.

Consistently used in OpenBSD

Prevention – Use better libraries (strings)

- `glib.h` provides Gstring type for dynamically growing null-terminated strings in C
  - but failure to allocate will result in crash that cannot be intercepted, which may not be acceptable

`Strsafe.h` by Microsoft guarantees null-termination and always takes destination size as argument

C++ `string` class
  - but `data()` and `c-str()` return low level C strings, ie `char*`, with result of `data()` is not always null-terminated on all platforms…

Detection (before shipping)

- Testing
  - Difficult! How to hit the right cases?
  - *Fuzz testing* - test for crash on long, random inputs – can be succesful in finding some weaknesses
- Code reviews
  - Expensive & labour intensive
- Code scanning tools (aka static analysis) Eg
  - *RATS* – also for PHP, Python, Perl
  - *Flawfinder* , *ITS4*, *Deputy, Splint*
  - *PREfix, PREfast* by Microsoft plus other commercial tools

More prevention & detection

The most extreme form of static analysis:

- Program verification
  - Proving by mathematical means (eg hoare logic) that memory management of a program is safe
  - Extremely labour-intensive
  - E.g. hypervisor verification project by microsoft & verisoft.

    Https://www.Microsoft.Com/en-us/research/project/vcc-a-verifier-for-concurrent-c/

Reducing attack surface

- Not running or even installing certain software, or enabling all features by default, mitigates the threat

Summary

- Buffer overflows are the top security vulnerability
- Any C(++) code acting on untrusted input is at risk
- Getting rid of buffer overflow weaknesses in C(++) code is hard (and may prove to be impossible)
  - Ongoing arms race between countermeasures and ever more clever attacks.
  - Attacks are not only getting cleverer, using them is getting easier

More general

Buffer overflow is an instance of three more general problems:

1) Lack of *input validation*
2) Mixing *data & code*
   - Data and return address on the stack
3) Believing in & relying on an *abstraction*
   - In this case, the abstraction of procedure calls offered by C

Attacks often exploit holes in abstractions that are not 100% enforced

Moral of the story

- Don't use C(++), if you can avoid it
  - But use a language that provides memory safety, such as java or C#
- If you do have to use c(++), become or hire an expert
- **Reading**
  - *A Comparison of Publicly Available Tools for Dynamic Buffer Overflow Prevention*, by John Wilander and Mariam Kakkar