Code: analysis, bugs, and security

supported by Bitdefender

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Course goals

improve skills: write robust, *secure code*

understand program *internals*

learn about security *vulnerabilities*, detection, prevention

use tools to *reverse engineer and analyze* code

perhaps in the future: analyze and counter malware

Code, data, stack, ...

Reviewing the basics:
logically, the program has different memory areas:
- code
- (global) data
- stack (for function calls)
- heap (for dynamic allocation)

What can we find out about them by running a program ?
(print various addresses and extract info)

Program addresses, at first sight

Addresses are in different numeric ranges

Recursive call: new copies for each instance
  can determine size of *stack frame*

Total address range (from code to stack) is HUGE
  orders of magnitude more than computer memory
    ⇒ these are *logical* (virtual), not physical addresses

Running the program repeatedly, addresses differ
  Address Space Layout Randomization
    estimate: how many bits vary ?
  protects against attacks that need to know address values

Typical memory layout of C programs

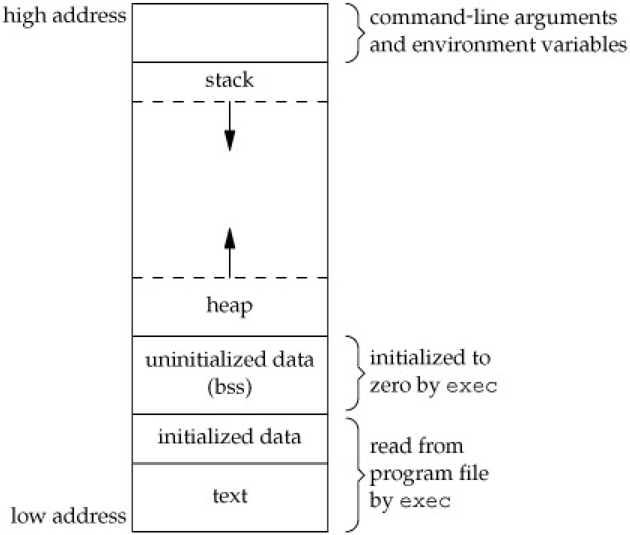
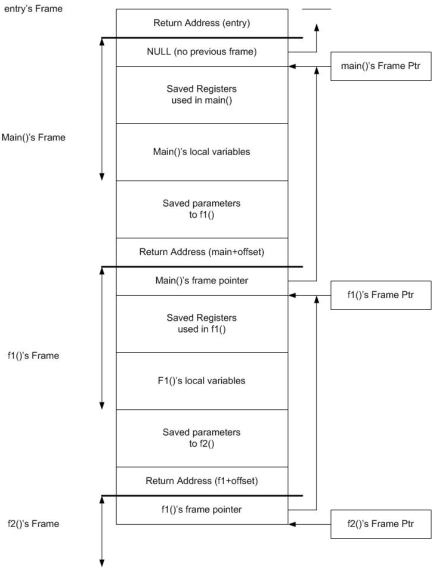


Figure: `http://www.geeksforgeeks.org/memory-layout-of-c-program/`

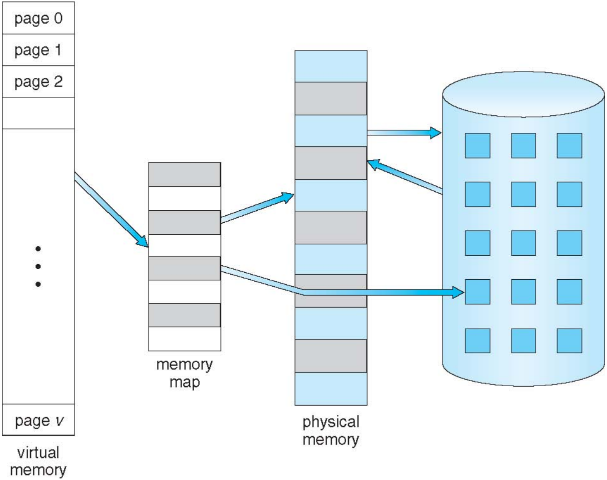
Typical stack frame layout

```
void f2(...) { }

int f1(...) {
  f2(...);
}

int main() {
 ... = f1(...);
}
```



http://www.backerstreet.com/red/stack_frames.htm

Virtual Memory That is Larger Than Physical Memory



Virtual memory in a nutshell

A mapping from logical to physical addresses
supported by processor hardware (memory management unit) and operating system

– provides *abstraction*
(program not concerned with size and usage of physical memory)
virtual address space can be larger than physical memory
memory *pages* transferred to/from secondary memory (disk) as needed

– provides *protection*
can set up *permissions* for memory segments
memory space of one process protected from another
but: can also set up *sharing*

Address Translation

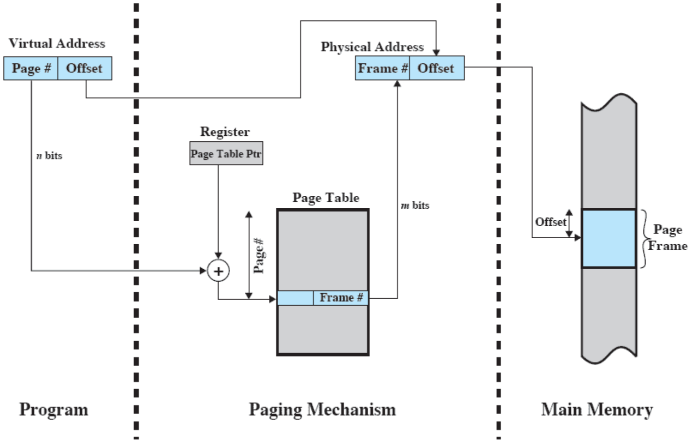


Figure 8.3 Address Translation in a Paging System

Figure: W. Stallings, Operating Systems, 6th ed.

Arrays and pointers

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CANNOT assign ~~`p[0] = 'f'`~~ (`"test"` is a string *constant*)

can do `p = s;` then `p[0] = 'f';` can assign `p = "ana";`

`sizeof(p)` is `sizeof(char *)` `&p` is NOT `p`

⇒ WRONG: ~~`scanf("%4s", &p);`~~ RIGHT: `scanf("%4s", p);`

(if `p` is valid address and has room)

Arrays and pointers

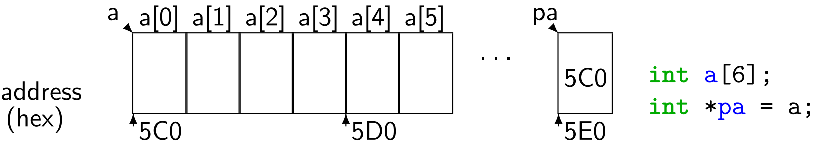
The *name of an array* is a *constant address*

Can declare `int a[LEN], *pa;` and assign `pa = a;`

Similar: `a` and `pa` have same type: `int *`

But: `pa` is a *variable* ⇒ uses memory; *can assign* `pa = addr`

`a` is a *constant* (array has fixed address) *can't assign* ~~`a = addr`~~



`*a` and `*pa`: indirections with different operations in machine code:

`*a` references object from *constant* address (*direct* addressing)

`*pa` must first get *value* of variable `pa` (an address), loading it from the *constant* address `&pa`) *then* dereference it (*indirect* addressing)

Binary data representation

Suppose we want to process a bitmap file

Bitmap file header

This block of bytes is at the start of the file and is used to identify the file. A typical application reads this block first to ensure that the file is actually a BMP file and that it is not damaged. The first 2 bytes of the BMP file format are the character "B" then the character "M" in ASCII encoding. All of the integer values are stored in little-endian format (i.e. least-significant byte first).

Offset hex	Offset dec	Size	Purpose
00	0	2 bytes	The header field used to identify the BMP and DIB file is `0x42 0x4D` in hexadecimal, same as `BM` in ASCII. The following entries are possible: ▪ **BM** – Windows 3.1x, 95, NT, ... etc. ▪ **BA** – OS/2 struct bitmap array ▪ **CI** – OS/2 struct color icon ▪ **CP** – OS/2 const color pointer ▪ **IC** – OS/2 struct icon ▪ **PT** – OS/2 pointer
02	2	4 bytes	The size of the BMP file in bytes
06	6	2 bytes	Reserved; actual value depends on the application that creates the image
08	8	2 bytes	Reserved; actual value depends on the application that creates the image
0A	10	4 bytes	The offset, i.e. starting address, of the byte where the bitmap image data (pixel array) can be found.

https://en.wikipedia.org/wiki/BMP_file_format

Bitmap file format (cont'd)

Offset (hex)	Offset (dec)	Size (bytes)	Windows BITMAPINFOHEADER[1]
0E	14	4	the size of this header (40 bytes)
12	18	4	the bitmap width in pixels (signed integer)
16	22	4	the bitmap height in pixels (signed integer)
1A	26	2	the number of color planes (must be 1)
1C	28	2	the number of bits per pixel, which is the color depth of the image. Typical values are 1, 4, 8, 16, 24 and 32.
1E	30	4	the compression method being used. See the next table for a list of possible values
22	34	4	the image size. This is the size of the raw bitmap data; a dummy 0 can be given for BI_RGB bitmaps.
26	38	4	the horizontal resolution of the image. (pixel per meter, signed integer)
2A	42	4	the vertical resolution of the image. (pixel per meter, signed integer)
2E	46	4	the number of colors in the color palette, or 0 to default to 2^n
32	50	4	the number of important colors used, or 0 when every color is important; generally ignored

To work with ints that are *exactly* 2 bytes, 4 bytes, etc., need *fixed-width integers*: `stdint.h` (since C99)

`int8_t`, `int16_t`, `int32_t`, `int64_t`,
`uint8_t`, `uint16_t`, `uint32_t`, `uint64_t`

Big-endian and little-endian

BMP specification: “all integers are stored in little-endian format”

little-endian: least-significant byte first

`0x12345678` is stored as `0x78 0x56 0x34 0x12`

Intel x86

big-endian: most-significant byte first

`0x12345678` is stored as `0x12 0x34 0x56 0x78`

Mac, PPC, Sun, Internet (also called ’network byte order’)

Make sure values are read/written from/to file in correct byte order

We'll use: Program analysis infrastructures

Allow program representation and manipulation
at source or binary level

Built-in analyses + API to write your own

LLVM: one of the most widely used, complete compiler toolchain

PIN (Intel): run-time instrumentation of *binary* code
BAP (D. Brumley, CMU): OCaml + Python bindings
team won DARPA Cyber Grand Challenge 2016

angr (UC Santa Barbara): Python framework
also used in Cyber Grand Challenge

CIL (G. Necula, Berkeley): OCaml + Perl
outputs instrumented C code

Source code representation

Example: statement representation in CIL analysis infrastructure

```
type stmtkind =
  | Instr of instr list    (* straight-line instructions *)
  | Return of exp option * location (* The return statement. *)
  | Goto of stmt ref * location     (* A goto statement. *)
  | Break of location  (* break to end of nearest loop/switch *)
  | Continue of location (* continue to start of nearest loop *)
  | If of exp * block * block * location (* A conditional. *)
  | Switch of exp * block * (stmt list) * location
  | Loop of block * location * (stmt option) * (stmt option)
  (* a while(1) loop with continue and break *)
  | Block of block         (* block of statements. *)
```

Low-level code instrumentation

Example: LLVM analysis infrastructure

```
int delta(int a, int b, int c) {
  return b * b - 4 * a * c;
}
```

LLVM internal representation:

```
define i32 @delta(i32 %a, i32 %b, i32 %c) #0 {
  %1 = mul nsw i32 %b, %b
  %2 = shl i32 %a, 2
  %3 = mul nsw i32 %2, %c
  %4 = sub nsw i32 %1, %3
  ret i32 %4
}
```

To instrument code, traverse statements (control flow graph), identify interesting statements, insert new ones.

e.g. can log all/some memory writes

Compiler instrumentation against vulnerabilities

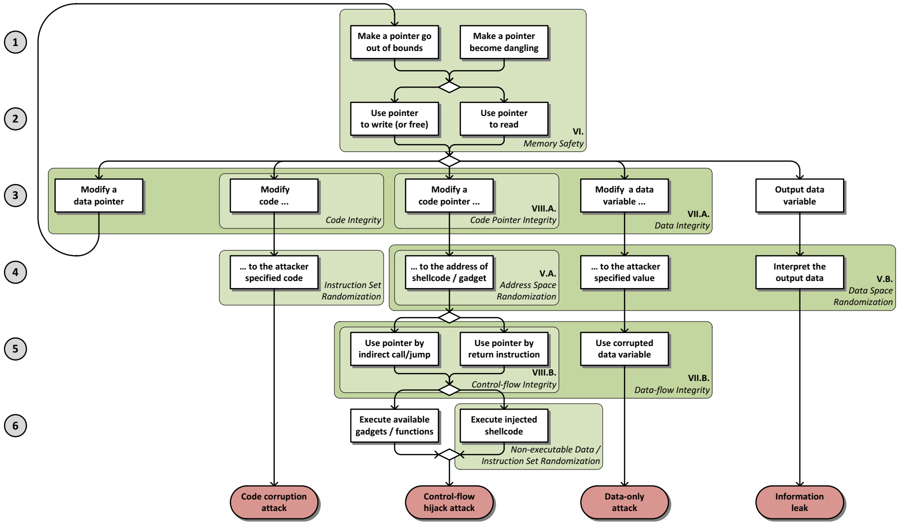
Address sanitizer (with recent clang / gcc versions)

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int main(void) {
  char *p = malloc(20);
  strcpy(p, "test");
  puts(p);
  free(p);
  p[1] = 'a';  // wrong
}
```

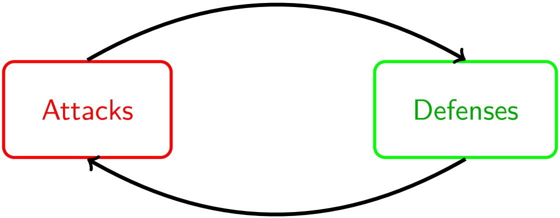
```
% gcc -fsanitize=address usefree.c
% ./a.out
==31741==ERROR: AddressSanitizer:  heap-use-after-free on
address 0x60300000efe1 at pc 0x0000004008c6 bp
0x7ffeef2227b0 sp 0x7ffeef2227a8
WRITE of size 1 at 0x60300000efe1 thread T0
#0 0x4008c5 in main /home/marius/curs/bitdef/usefree.c:11
```

Software security: memory vulnerabilities



Szekeres, Payer, Wei, Song. SoK: Eternal War in Memory, IEEE S&P 2013

Software security: increasingly automated



automated vulnerability detection + exploit generation

comparison of old (buggy) + patched program versions
$\Rightarrow$ exploit generation

'compilers' for return-oriented programming exploits, etc.

A good read (insights into research advances):

G. Vigna et al., (State of) The Art of War: Offensive Techniques in Binary Analysis, IEEE Security & Privacy, 2016