Coding: Buffer Overflows

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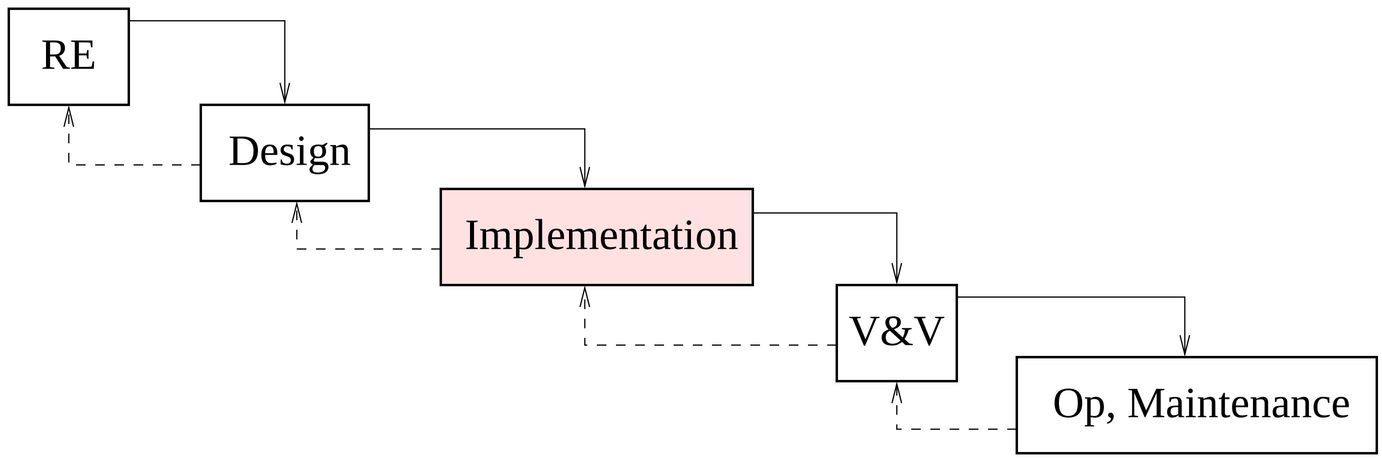
Road map[1]

☞ **Motivation**

- Pointers in C
- Compilation and memory layout
- Buffer overflows
- Defense
- Summary

[1] Some of the material from this talk was developed by Heiko Mantel, for Security Engineering 2004/05

Context: implementation



It's possible to have a great design but an insecure implementation

1. Implementation deviates from design
2. Design leaves many options open (including unsafe ones)

   E.g., design doesn't specify password lengths, their storage, ...
3. Concretization may introduce new vulnerabilities

   E.g., buffer overflows and other attacks on data and control

Motivation — buffer overflows

- Public enemy #1

  See e.g., CERT advisories or SANS top 20 vulnerabilities ranking

- Example: Morris Internet Worm (November 1988)
  - Attacked Sun3 and VAX systems running BSD
  - Fairly clever, e.g., named itself “sh” (hard to detect) and set maximum core-dump size to 0 bytes (hard to catch)
  - Propagated itself using various exploits, including a buffer overflow attack against the finger daemon *fingerd*.
  - Did not delete files, but resulting financial loss between \$100,000 and \$1,000,000 (US General Accounting Office)

Role of studying vulnerabilities (and a warning)

- Understanding vulnerabilities is vital to developing and evaluating countermeasures. Failure to consider them leads to insecure code or overconfidence in partial solutions

- Exploiting vulnerabilities (= hacking) is a criminal offense

- We expect you to use this knowledge in a responsible and ethical way

- Any experimentation must be done in a controlled environment

Buffer overflows

- A buffer is a contiguous region of memory storing data of the same type, e.g., characters
- A buffer overflow occurs when data is written past a buffer's end
- The resulting damage depends on
  - Where the data spills over to
  - How this memory region is used (e.g., flags for access control)
  - What modifications are made
- Example: Morris attack on finger
  - Intended use: finger basin@inf.ethz.ch
  - Abuse: finger ⟨exploit-code⟩ . . . ⟨return-address⟩
  - Overwrites the return address and provides exploit code

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C primer

- C (and C++) is powerful, widespread, and undisciplined!
- Basic data types

  Char (1 byte), int ($\geq$ 2 bytes), long ($\geq$ 4 bytes) ...
- Pointers: expressions like int *ptr
  - ptr is the address of a memory cell
  - *ptr is the contents of the memory cell
- Address taken using &. For i and integer and f a function,
  - &i is the address of the cell storing i
  - &f is the address of a function f

Pointers — examples

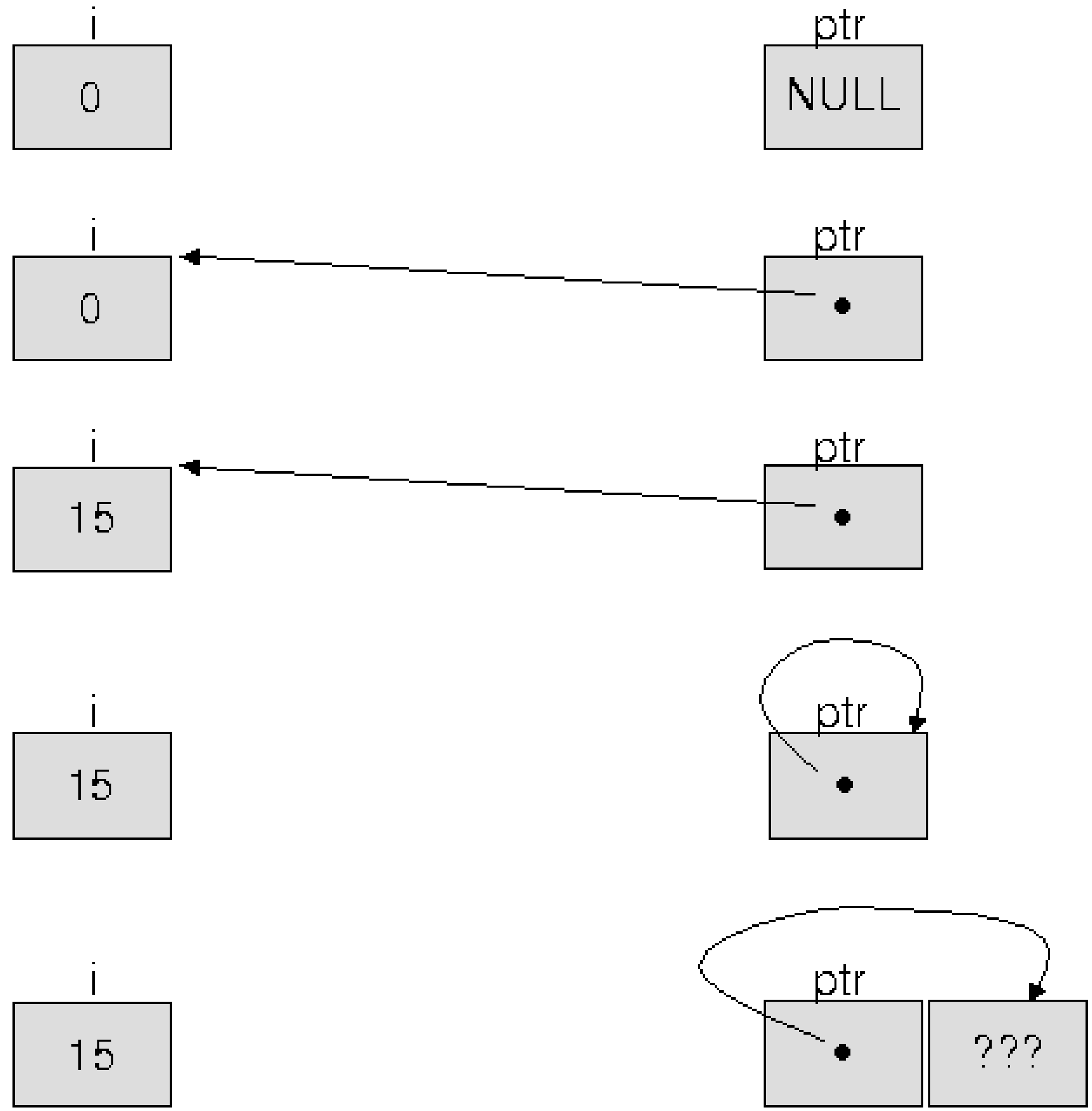
```
int i = 0;
int *ptr = NULL;

ptr = &i;

*ptr = 15;

ptr = &ptr;

ptr++;
```



Arrays

- Declaring and accessing an array
  - `char buf[8];` declares a buffer for up to 8 characters
  - Elements are `buf[0]`, `buf[1]`, .., `buf[7]`
  - No bounds checking, so `buf[13]` is also possible
- Arrays are similar to pointers: store address where buffer begins
- Some equalities

```
&(buf[0]) = buf        buf[0] = *(buf+0)
&(buf[1]) = buf + 1    buf[1] = *(buf+1)
```

- Strings are arrays of characters, with `'\0'` at end
  - E.g., string `"hi"` represented by `'h' 'i' '\0'`
  - No explicit information about length of strings
  - This savings is part of the problem!

Input, output and string handling functions

- `getchar()` reads a character from standard input
- `putchar(c)` writes a character to standard output
- `printf("Page %i has title %s\n", pageno, title)`
  - String printed to standard output may contain place holders replaced by arguments
  - Place holders provide formatting instructions.
    E.g., `%i` stands for an integer in decimal and `%s` for a string
- Various other functions store strings in buffers. E.g.
  - `gets(dst)` read string from `stdin` into `dst`
  - `strcpy(dst,src)` copy string `src` into buffer `dst`
  - `sprintf(dst, <FmtStr>,<Exp>)` print string into buffer
  - `scanf`, `fscanf`, ...

A vulnerable program

buffer of limited size

is written without limits

```
#include <stdio.h>
int main()
  { char buf[8]                      // buffer for storing the input string
    char ch;                         // auxiliary variable
    char *ptr = buf;                 // auxiliary pointer
    while ((ch=getchar()) != '\n'    // terminate on EOL
           && ch != -1)              // terminate on error
      { *ptr = ch;                   // store character
        ptr++;                       // increment pointer
      }
    *ptr = '\0';                     // terminate the string
    printf("%s\n",buf);
    return 0;
  }
```

Some example runs

$ ./my-getstring
example
example

$ ./my-getstring
long example
long example
Illegal instruction

per esempio >7 chars
ptr va a puntare (forse)
char ch, sovrascrivendolo

$ ./my-getstring
very long example
very long example
Segmentation fault

program tried to access outside the memory image of its own process

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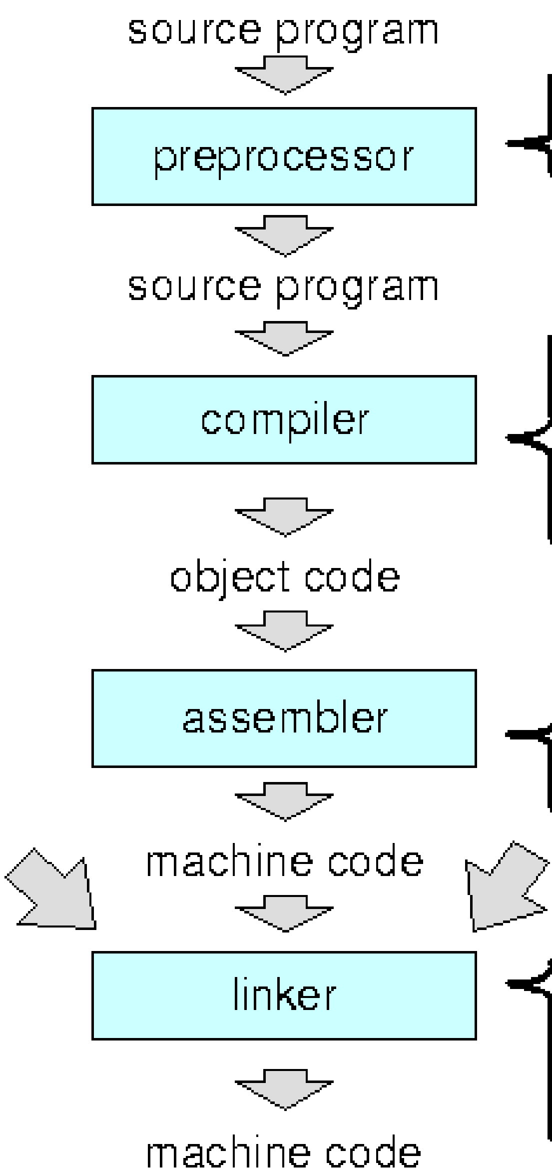
Compilation



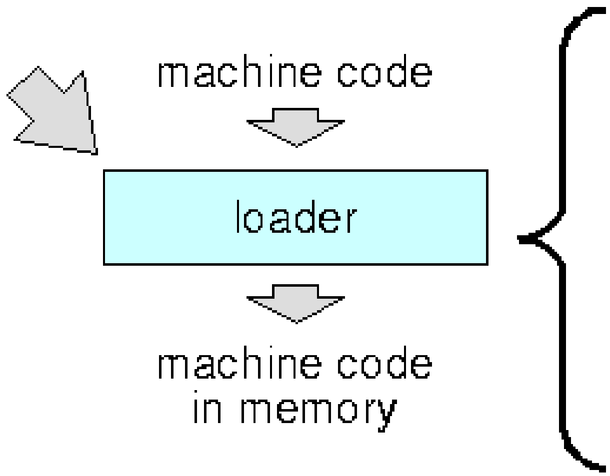
- expand macros
- include header files

- lexical analysis
- syntactic analysis
- semantic analysis
- optimization
- code generation

- translate object code into machine code

- combine multiple modules to one program
  - arrange modules in memory
- resolve external references
  - each module says what it needs and what it provides

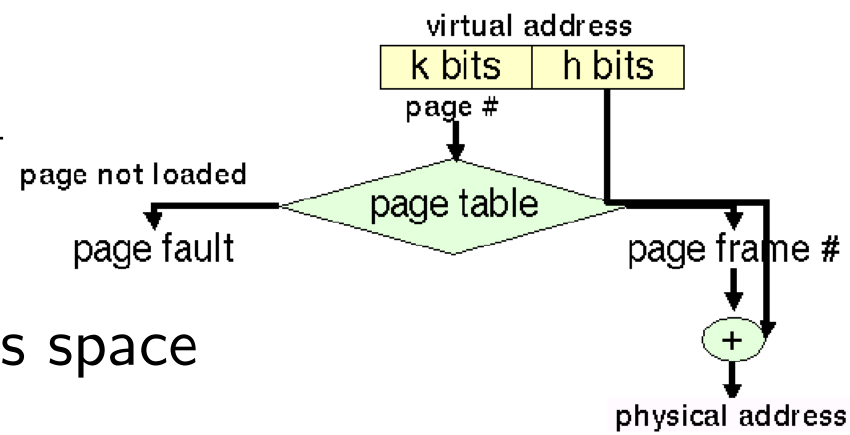
Loading



- loading of program into the address space of the process
- Adapting addresses or initializing a relocation register (hardware supported relocation)
- dynamic loading and linking of libraries for unresolved references

Recall how (virtual) memory is organized

- Memory named by virtual addresses
- Each process has its own virtual address space
- Protection: process can only access memory in its own space



A program in memory

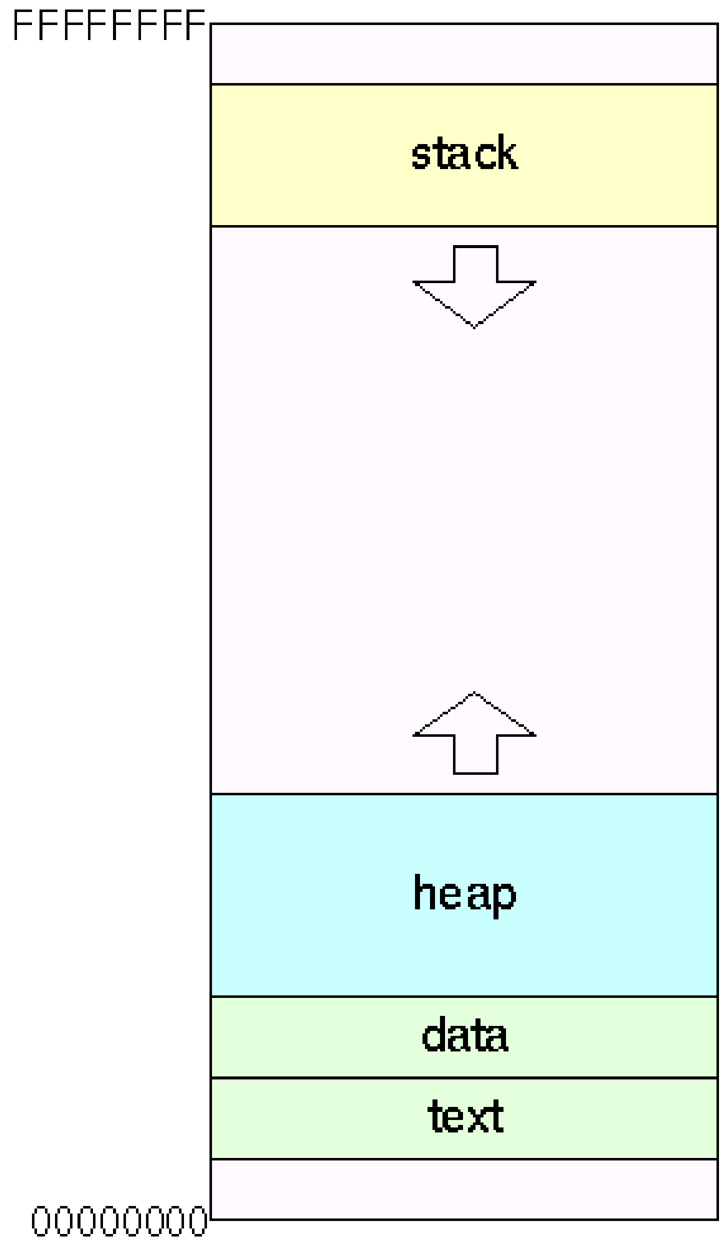
```
$ gdb my-getstring
(gdb) disas main
Dump of assembler code for function main:

0x8048440  push  %ebp
0x8048441  mov   %esp,%ebp
0x8048443  sub   $0x18,%esp
0x8048446  lea   0xfffffff8(%ebp),%eax
0x8048449  mov   %eax,0xfffffff0(%ebp)
0x804844c  call  0x80482e8 <getchar>
0x8048451  mov   %eax,%eax
0x8048453  mov   %al,0xfffffff7(%ebp)
0x8048456  mov   0xfffffff7(%ebp),%al
0x8048459  cmp   $0xa,%al
0x804845b  je    0x8048478 <main+56>
0x804845d  cmpb  $0xff,0xfffffff7(%ebp)
0x8048461  jne   0x8048468 <main+40>
0x8048463  jmp   0x8048478 <main+56>
0x8048465  lea   0x0(%esi),%esi
0x8048468  mov   0xfffffff0(%ebp),%edx
0x804846b  mov   0xfffffff7(%ebp),%al
0x804846e  mov   %al,(%edx)
0x8048470  lea   0xfffffff0(%ebp),%eax
0x8048473  incl  (%eax)
0x8048475  jmp   0x804844c <main+12>
0x8048477  nop
0x8048478  mov   0xfffffff0(%ebp),%eax
0x804847b  movb  $0x0,(%eax)
0x804847e  sub   $0x8,%esp
0x8048481  lea   0xfffffff8(%ebp),%eax
0x8048484  push  %eax
0x8048485  push  $0x8048508
0x804848a  call  0x8048328 <printf>
0x804848f  add   $0x10,%esp
0x8048492  mov   $0x0,%eax
0x8048497  leave
0x8048498  ret
0x8048499  lea   0x0(%esi),%esi
0x804849c  nop
0x804849d  nop
0x804849e  nop
0x804849f  nop
```

Layout of virtual memory

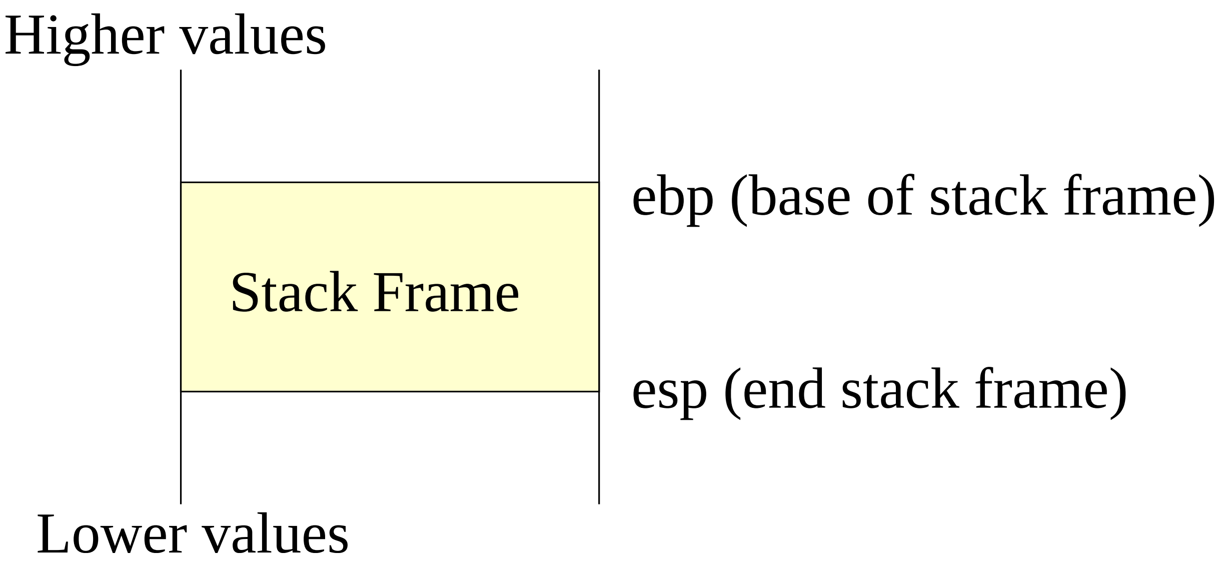
Linux on Intel x86 family

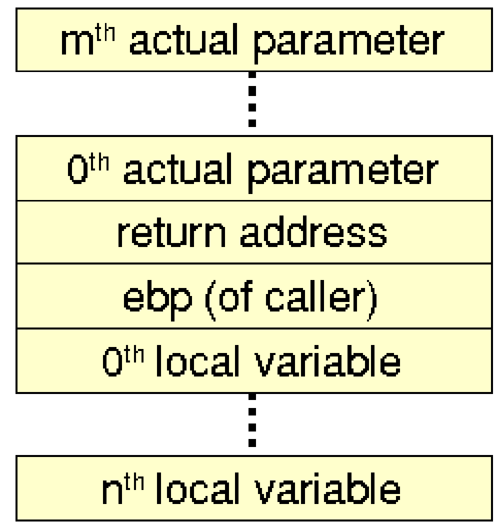
- Stack grows downward
- Stack frame holds
  - Calling parameters
  - Local variables for functions
  - Various addresses
- Heap grows upwards
  - Dynamically allocated storage generated using alloc, malloc, ...
- Data: statically allocated storage
- Text: Executable code, read only



Structure of the stack

- Stack grows downwards: one stack frame per subroutine called





- Hardware registers contain:

  ebp (extended) base pointer register: start current frame
  esp (extended) stack pointer register: top (end) of stack

Another vulnerable program

```
int main (void) {
  char pw[8];
  sprintf (pw, "root-pw");
  if (authenticate(pw) > 0) {
    printf ("[root]$ ...\n");
  } else {
    printf ("Root: incorrect password\n");
  }
  return 0;
}
```

```
#include <stdio.h>
int authenticate (char* pw) {
  int result = 0;
  char buf[8];
  printf ("Root Password: ");

  if (gets(buf) !=0 ){
    if (strcmp (buf, pw) == 0) {
      result = 1;
    }
  }
  return result;
}
```

gets() non tiene conto della misura di buf
-> fa read da stdin byte by byte

- $ ./my-authenticate

  `Root Password: guess`

  `Root: incorrect password`

- $ ./my-authenticate

  `Root Password: root-pw`

  `[root]$ ...`

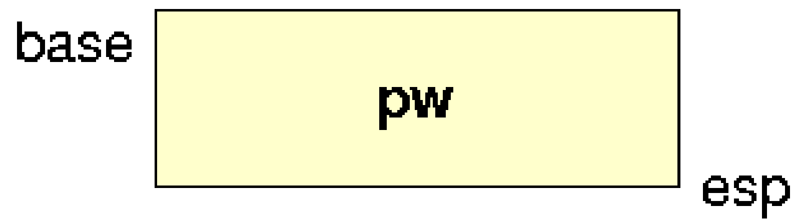
Stack dynamics in example

1. start (of main)

base esp

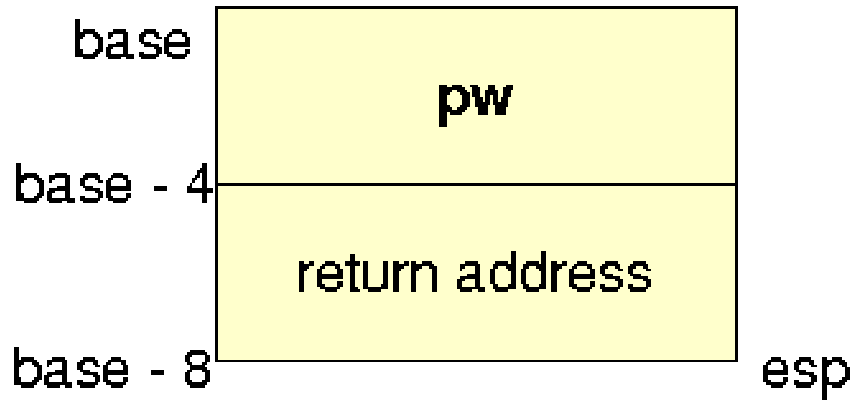
Stack dynamics in example

1. start (of main)
2. push argument pw onto stack



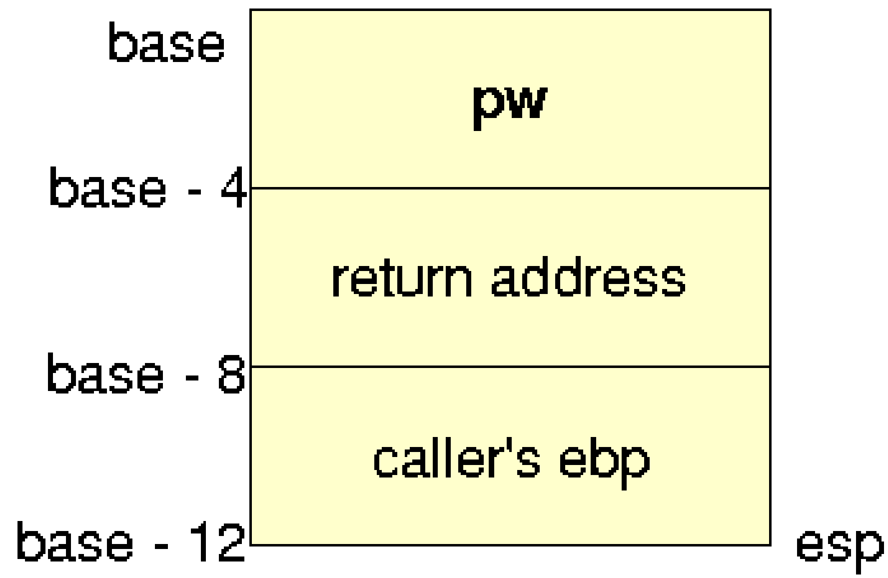
Stack dynamics in example

1. start (of main)
2. push argument pw onto stack
3. call authenticate (pushes return address onto stack)



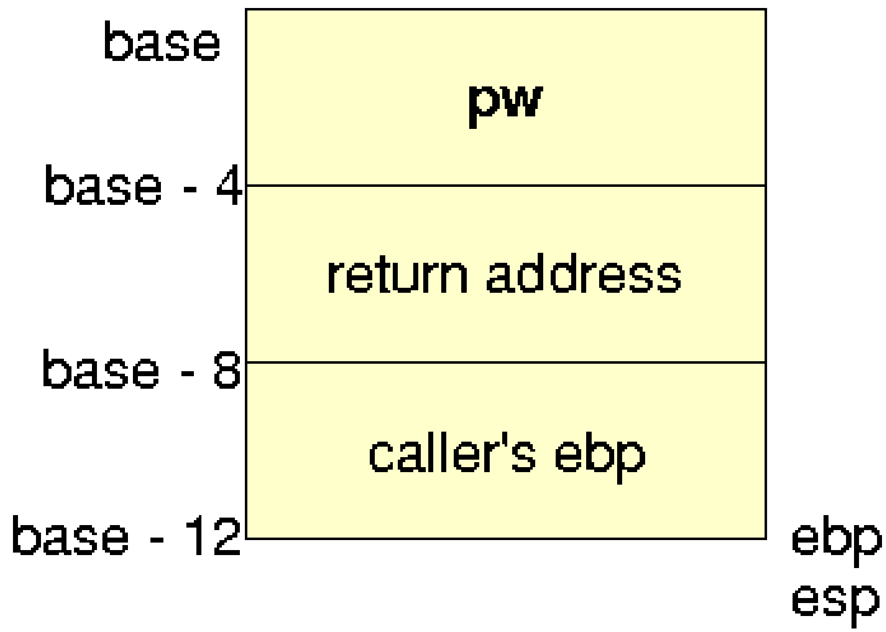
Stack dynamics in example

1. start (of main)
2. push argument pw onto stack
3. call authenticate (pushes return address onto stack)
4. push caller’s ebp onto stack



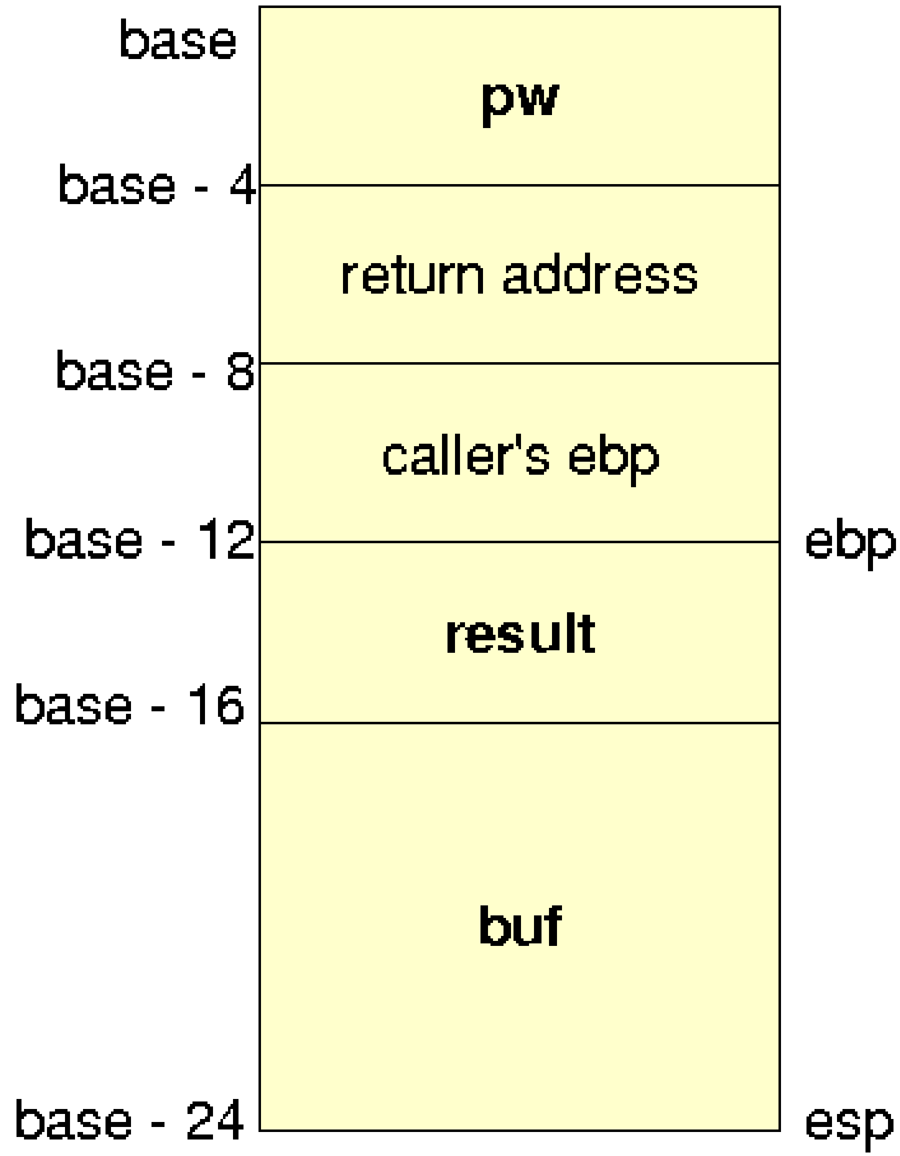
Stack dynamics in example

1. start (of main)
2. push argument pw onto stack
3. call authenticate (pushes return address onto stack)
4. push caller's ebp onto stack
5. copy esp into ebp



Stack dynamics in example

1. start (of main)
2. push argument pw onto stack
3. call authenticate (pushes return address onto stack)
4. push caller's ebp onto stack
5. copy esp into ebp
6. decrement esp, creating space for local vars



Stack dynamics in example

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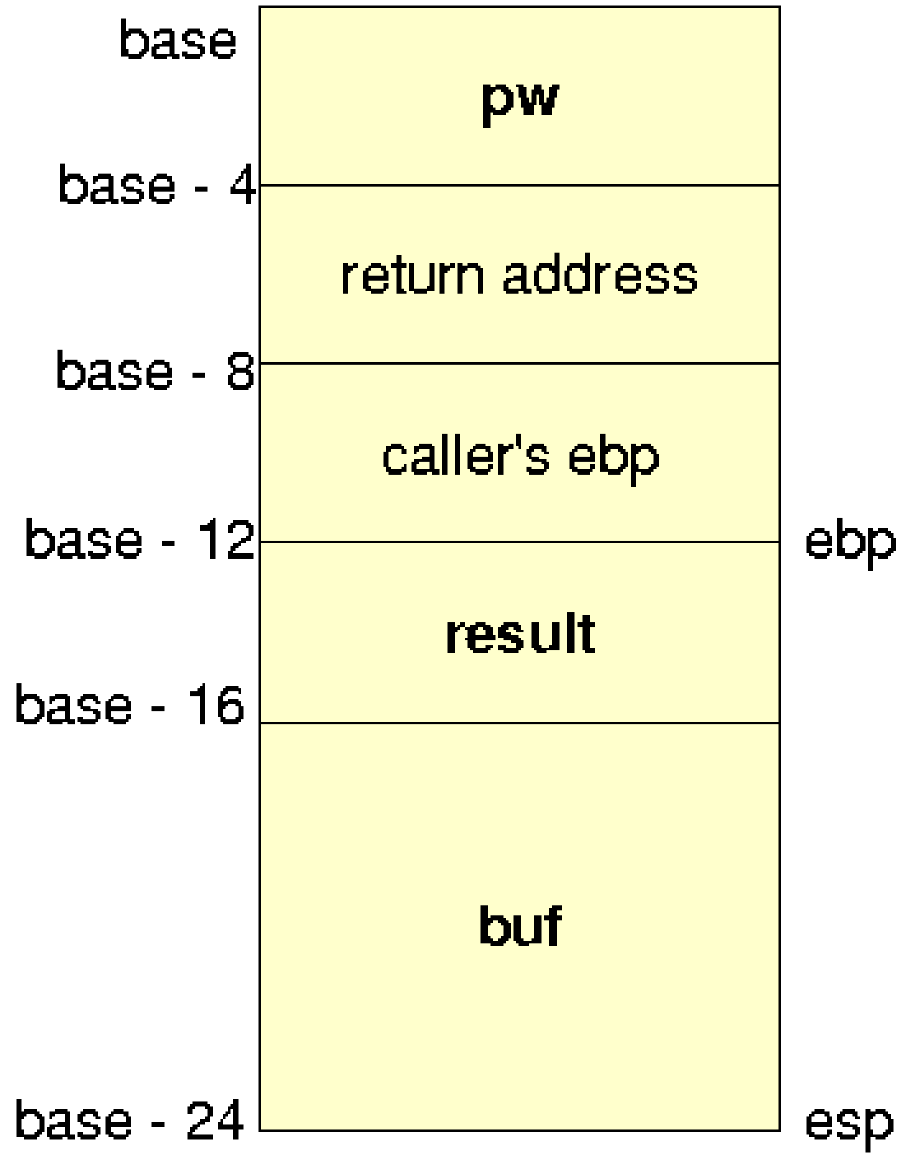
7. Compute authenticate function (stack idle)



Stack dynamics in example

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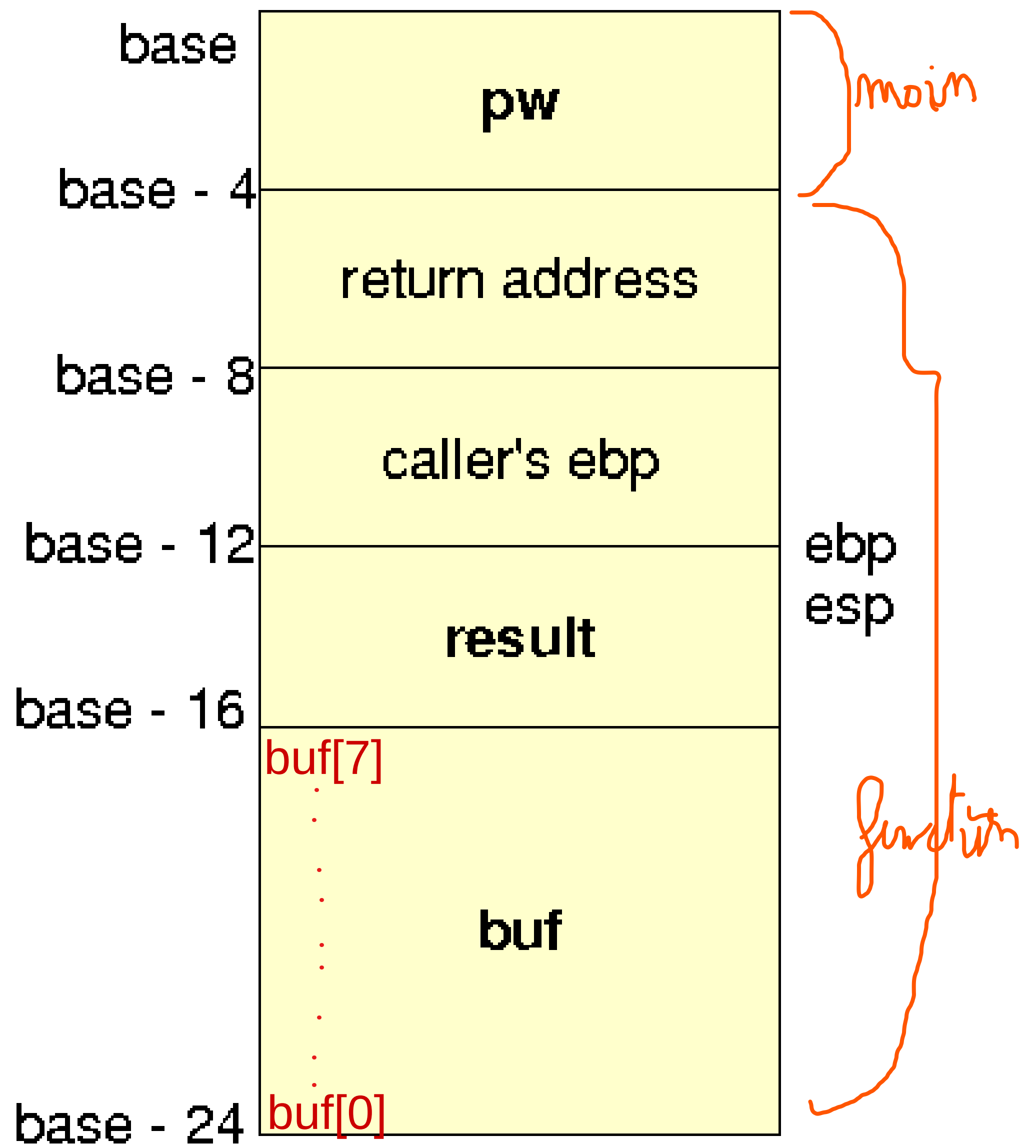
8. copy caller's ebp into esp



Stack dynamics in example

1. start (of main)
2. push argument pw onto stack
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4. push caller's ebp onto stack
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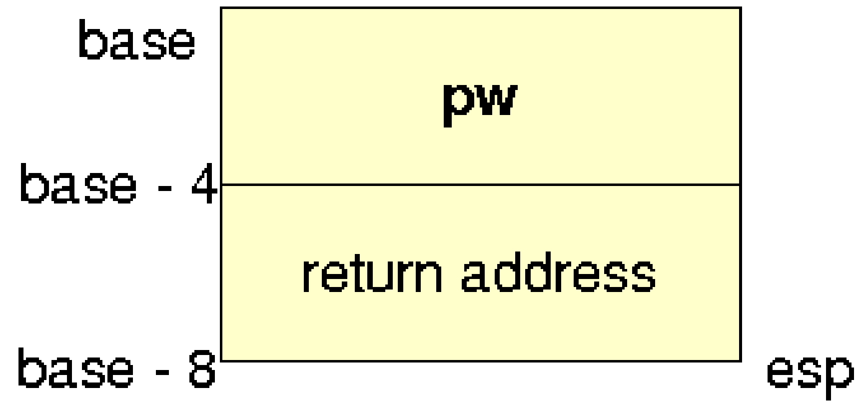
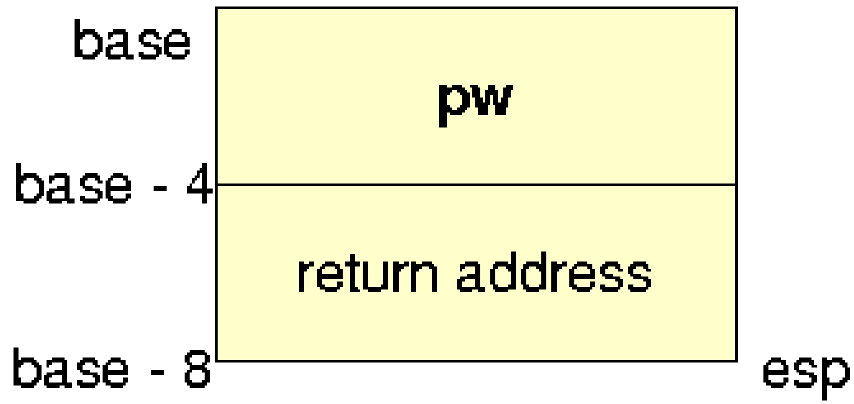
7. Compute authenticate function (stack idle)
8. copy caller's ebp into esp
9. pop vars and caller's ebp from stack



Stack dynamics in example

1. start (of main)
2. push argument pw onto stack
3. call authenticate (pushes return address onto stack)
4. push caller's ebp onto stack
5. copy esp into ebp
6. decrement esp, creating space for local vars
7. Compute authenticate function (stack idle)
8. copy caller's ebp into esp
9. pop vars and caller's ebp from stack
10. return



Road map

- Motivation
- Pointers in C
- Compilation and memory layout
- ☞ **Buffer overflows**
- Defense
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Where is vulnerability in authenticate?

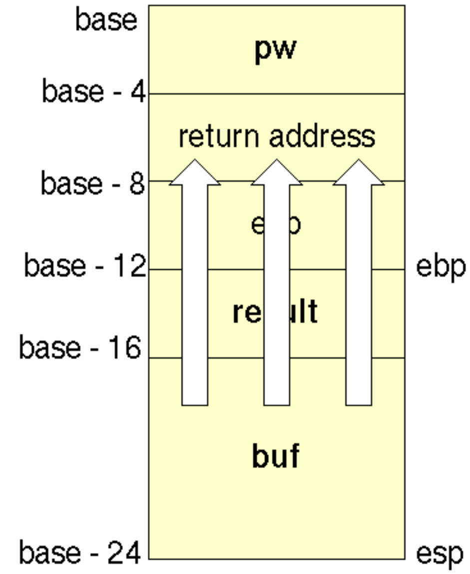
- Some non-problems
  - Variables result and buf are initialized prior to use
  - Programming logic ok. result is 1 iff input equals password supplied by pw
- The problem
  - Implementation of gets does not prevent overflow of buf
  - Stack layout

```
#include <stdio.h>
int authenticate (char* pw) {
  int result = 0;
  char buf[8];
  printf ("Root Password: ");

  if (gets(buf) !=0 ){
    if (strcmp (buf, pw) == 0) {
      result = 1;
    }
  }
  return result;
}
```

il problema è che gets() legge n bytes finchè non trova un carattere di fine (quindi anche più di 8 chars)

Example: a long password



- Given a buffer overflow, data from buf spills over into result
- Can change value of result

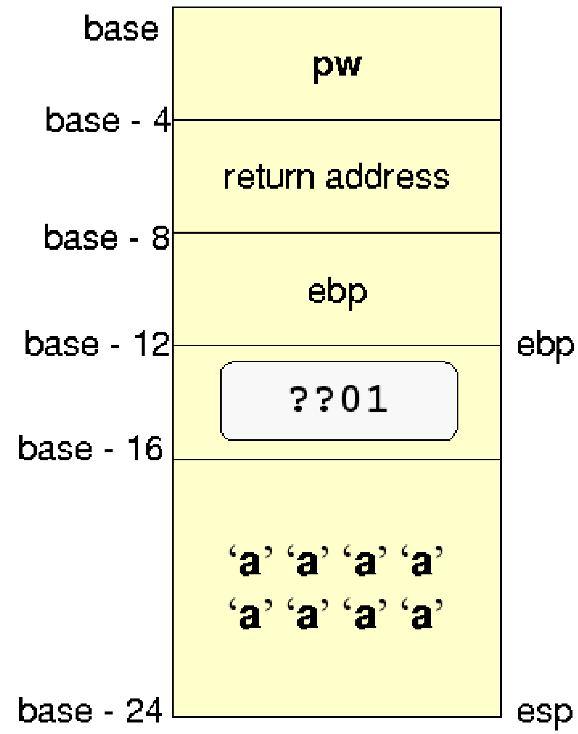
  result initialized to 0 and updated only if authentication succeeds
- Works (conceptually) as follows

```
$ ./my-authenticate
Root Password: aaaaaaaa\x01\x00
[root]$ ...
```

  buf filled with `aaaaaaaa` and hence `x01` overwrites result.
- Violation of data integrity!
  - Variables modified without explicit assignment
  - Thinking purely on the level of C misses this possibility!

David Basin

Long password (cont.)



- In reality, buffer overflows are a bit trickier
- There could be a gap between buf and result.
- If input is too long then ebp or return may be effected
- Entering hexadecimal values `\x01` and `\x00`

  Here one can enter input strings using a program via a pipe

Can we program defensively against such errors?

A defense: restoring variables

```
#include <stdio.h>
int authenticate (char* pw) {
  int result = 0;
  char buf[8];
  printf ("Root Password: ");

  if (gets(buf) !=0 ){
    if (strcmp (buf, pw) == 0) {
      result = 1;
    }
  }
  return result;
}
```

```
#include <stdio.h>
int authenticate (char* pw) {
  int result = 0;
  char buf[8];
  printf ("Root Password: ");

  if (gets(buf) !=0 ){
    if (strcmp (buf, pw) == 0) {
      result = 1;
    } else { result = 0; }
  }
  return result;
}
```

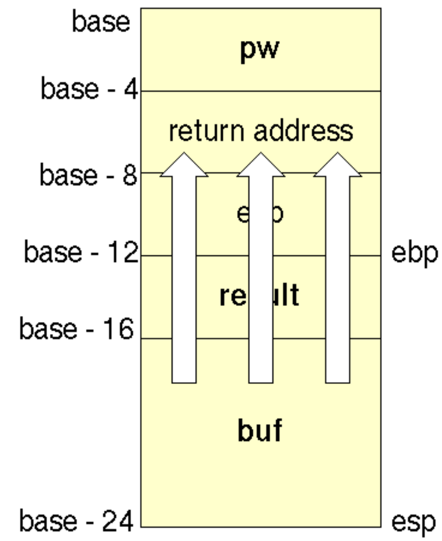
- Result is updated after gets

  Now result is correct even if buf overflows into result.

- But other dangers still remain!

  Would you recommend this defense?

Example: a very long password



- What happens on:

```
$ ./my-authenticate
Root Password:
aaaaaaaaaaaa\xbb\xbb\xbb\xbb\x11\x47\x11\x47\00+
```

- Overwrites result, ebp, and return

  buf: "aaaaaaaa"

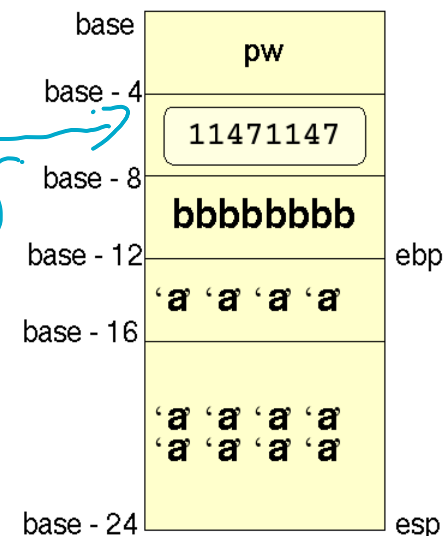
  result: "aaaa"

  stored ebp: bb bb bb bb

  return address: 47 11 47 11

la ragione qui

bisogna override tutto il resto



- Call of ret (when leaving subroutine) pops 47 11 47 11 off stack, starting execution at this memory location

Overflow has destroyed integrity of code-flow!

Exploit code (or where evil doers jump)

- Where would a malicious attacker jump to?

  One common target is to code that creates a (root-)shell

- Where in memory does this code go?

- Common approach: place exploit code on the stack

  Usually, place within the very buffer that is overflowed

- Return address must then point exactly to the exploit's entry point
  - Non-trivial in practice.
  - Trick used of starting exploit code with a "landing zone" of values representing No-op instructions

Exploit code (cont.)

- In above approach, exploit code and landing zone fit into buffer
- Alternatively, attacker places exploit code:
  - On the stack: into parameters or other local variables
  - On the heap: into some dynamically allocated memory region
  - Into environment variables (on stack)
- Another alternative is to abuse existing code

  E.g., jump to fragments of the program code or library functions
- Clever abuses have become a kind of hacker sport!

  For more on this, see Pincus/Baker article from 2004.

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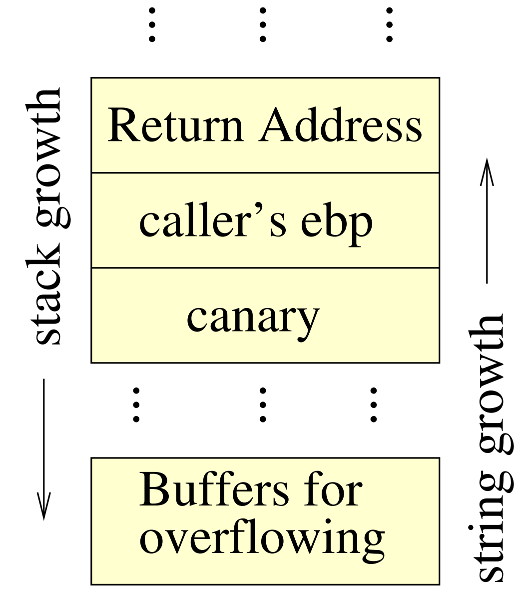
Insert a canary



- A canary is a value on the stack whose value is tested before returning.

```
void function (...) {
   int canary;
   char buf[MAX_SIZE]; // other declarations follow

   canary = CANARY_VALUE;
   gets(buf);     // or some other dangerous operation
   ...
   if(canary != CANARY VALUE)
      exit
   return; }
```

- A canary is a random value (hard for attacker to guess) or a value composed of different string terminators (CR, LF, Null, -1).
- Implementations for GCC and Microsoft Visual C++ compilers

  Known attacks exist (see Pincus/Baker)

Defensive programming

- Avoid unsafe library functions, e.g.,strcpy, gets, ...
  - Replace with safe variants, e.g., strncpy, fgets, ...
  - E.g., replace `strcpy(dst,src)` with `strncpy(dst,src,dst_size-1)`.
- Always check bound of arrays when iterating over them
- Mechanisms for doing this
  - Careful programming
  - Audit teams
  - Use grep or more sophisticated tools
- Limitations: error prone and audits are time consuming

Defensive programming (cont.)

BUGS

Never use gets(). Because it is impossible to tell without knowing the data in advance how many characters gets() will read, and because gets() will continue to store characters past the end of the buffer, it is extremely dangerous to use. It has been used to break computer security. Use fgets() instead.

— From gets(3) manual page

Automatic array bounds checking

- Approach: compiler automatically adds an explicit check to each access to an array
- Checks inserted during code generation

  Example: GCC enhancements of Jones&Kelly.
- Drawbacks
  - It can be difficult to determine the bounds of an array
  - Loss of performance can be substantial, e.g., factor 10-30!
  - Some compilers only check explicit array references, like `buf[n]`, but not pointer references, like `*(buf+n)`

Avoid C (++)

- Use a language that is type safe
  - Length of an array is part of its type
  - Assigning contents of a buffer to a smaller buffer is a type error
  - **Examples:** Pascal, Java, or ML
- Problems and limitations
  - Often the choice of programming language is not yours
  - Bugs still possible if run-time environment is programmed in an unsafe language
    Example: several buffer overflows vulnerabilities in implementations of the JAVA virtual machine
  - C(++) has its advantages, in particular for writing efficient programs "close to the machine".

Avoid buffers on stack

- Avoid declaration of local array variables in functions.
- Instead, use heap storage, e.g., allocate space with `malloc()`.
- As return address is on the stack, it can not be overwritten by a buffer-overflow on the heap.
- Does this solve all our worries?

Avoid buffers on stack

- Avoid declaration of local array variables in functions.
- Instead, use heap storage, e.g., allocate space with `malloc()`.
- As return address is on the stack, it can not be overwritten by a buffer-overflow on the heap.
- Does this solve all our worries? No!
  - Heap overflows are also a real problem (not covered here)
  - While they have no effect on control-flow integrity, they can violate data integrity.

Non-Executable Buffers

- Mark stack [or heap] as being non-executable.

  $\Rightarrow$ attacker cannot run exploit stored in buffers on stack [heap].

- Mechanisms
  - Extend OS with a register storing maximal executable address
  - Alternatively, tag pages as (non)executable in the page table

- Problems and limitations
  - Attacker can still execute code in the text segment
  - Attacker can still violate data integrity
  - Sometimes too restrictive

    Unix signal handlers usually execute on the current process stack. This lets the signal handler return to the point that execution was interrupted in the process.

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Conclusions and lessons learned

- Arrays in C can be over-written.
- The result is that data and control flow can be altered in ways not described by program itself.
- This is a massive problem and has been so for many years!
- Defense is paramount!
  - Program defensively: only use or write functions that do bounds checking.
  - Carefully weigh pros and cons of programming language used. Do advantages of C outweigh its disadvantages?
  - Compiler/hardware support for preventing overflows is available. It helps, but be aware of the limitations and overhead.

Literature

- John Viega, Gary McGraw. Building Secure Software. Addison-Wesley, 2002.
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- AlephOne. Smashing the Stack for Fun and Profit. 1996