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Software Security 2
Memory Management and Allocation

Michele LORETI
Univ. di Camerino
michele.loreti@unicam.it

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https://cybersecnatlab.it

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Outline

- Memory Management
- Memory Layout
- Stack
- Heap
- Bad stories

Memory management

- Many of the modern programming languages allow programmers to use data types without having to know how they are represented.
- Similarly, programmers often ignore where data is stored (allocated)…
  - compiler makes decisions, however at runtime allocation is under the control of Operating System and CPU.

Memory management

- In some programming languages, like C, memory management can be controlled by programmers:
  - memory can be dynamically allocated and deallocated;
  - memory address of variables can be obtained (pointers).
- If *x* is a variable, *&x* denotes the pointer to x, i.e., the memory address where x is stored.

Memory allocation…

Let us consider the following simple C program:

```c
#include <stdio.h>

int main() {
    int i;
    char c;
    short s;
    long l;

    printf("i is allocated at %p\n", &i);
    printf("c is allocated at %p\n", &c);
    printf("s is allocated at %p\n", &s);
    printf("l is allocated at %p\n", &l);
}
```

We can assume that:

- *int* needs 4 bytes
- *char* needs 1 byte
- *short* needs 2 bytes
- *long* needs 8 bytes.

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```

Variable declatations

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}
```

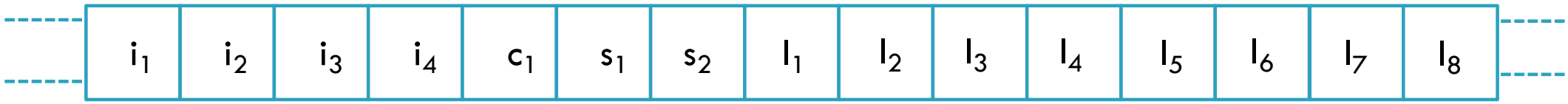
Variable addresses

We can assume that:

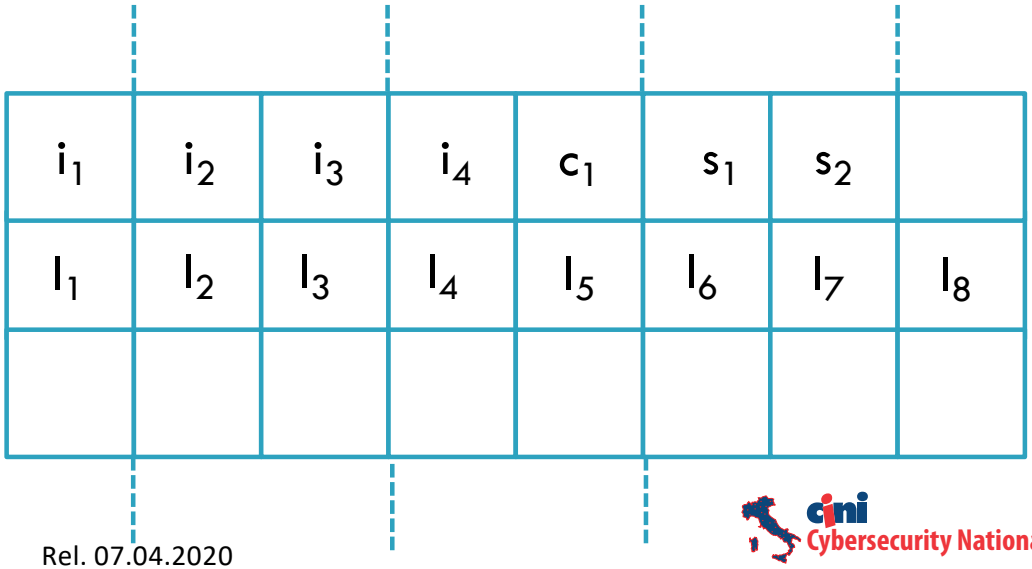
- *int* needs 4 bytes
- *char* needs 1 byte
- *short* needs 2 bytes
- *long* needs 8 bytes.

Memory allocation…

Memory is usually represented as a sequence of bytes:



In a n·8 architecture, bytes are arranged in groups of n:



Memory allocation…


```c
#include <stdio.h>

int main() {
    int i;
    char c;
    short s;
    long l;

    printf("i is allocated at %p\n", &i);
    printf("c is allocated at %p\n", &c);
    printf("s is allocated at %p\n", &s);
    printf("l is allocated at %p\n", &l);
}
```

We can run this simple program to observe how data are allocated in memory.

Memory allocation…

Different allocation policies can be used by *gcc*:

```
[CC> gcc -o alignment alignment.c
[CC> ./alignment
i is allocated at 0x7ffee117e7cc
c is allocated at 0x7ffee117e7cb
s is allocated at 0x7ffee117e7c8
l is allocated at 0x7ffee117e7c0
[CC>
```

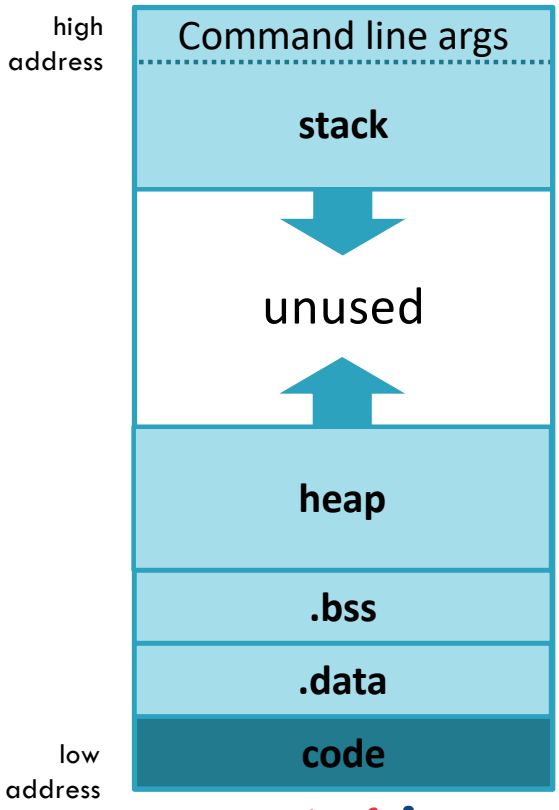
```
[CC> gcc -o alignment alignment.c -O2
[CC> ./alignment
i is allocated at 0x7ffee4dbb7c8
c is allocated at 0x7ffee4dbb7cf
s is allocated at 0x7ffee4dbb7cc
l is allocated at 0x7ffee4dbb7c0
[CC>
```


Data alignment

- Compilers may introduce padding or change the order of data in memory
- There are trade-offs between speed and memory usage.
- *C* compilers provide many optional optimization.

Memory segments

- Memory is allocated for each process (a running program) to store data and code.
- This allocated memory consists of different segments:
  - *stack:* for local variables
  - *heap:* for dynamic memory
  - *data segment:*
    - *global uninitialized variables (.bss)*
    - *global initialized variables (.data)*
  - *code segment*

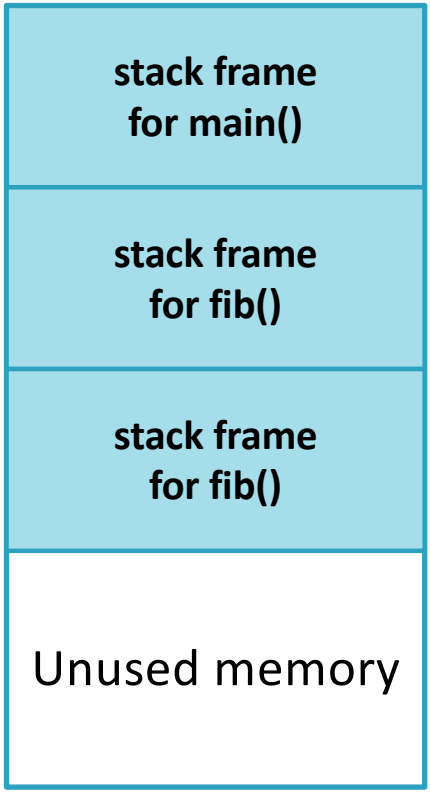


The stack

- The stack consists of a sequence of stack frames (or activation records), each for each function call:
  - allocated on *call*;
  - de-allocated on *return*.

```
int main(int argc, char **argv) {
  int f = fib( n: 10);
  printf("FIB(10)=%d\n",f);
}

int fib(int n) {
  int f1;
  int f2;
  if (n<=2) {
      return 1;
  } else {
      f1 = fib( n: n-1);
      f2 = fib( n: n-2);
      return f1+f2;
  }
}
```

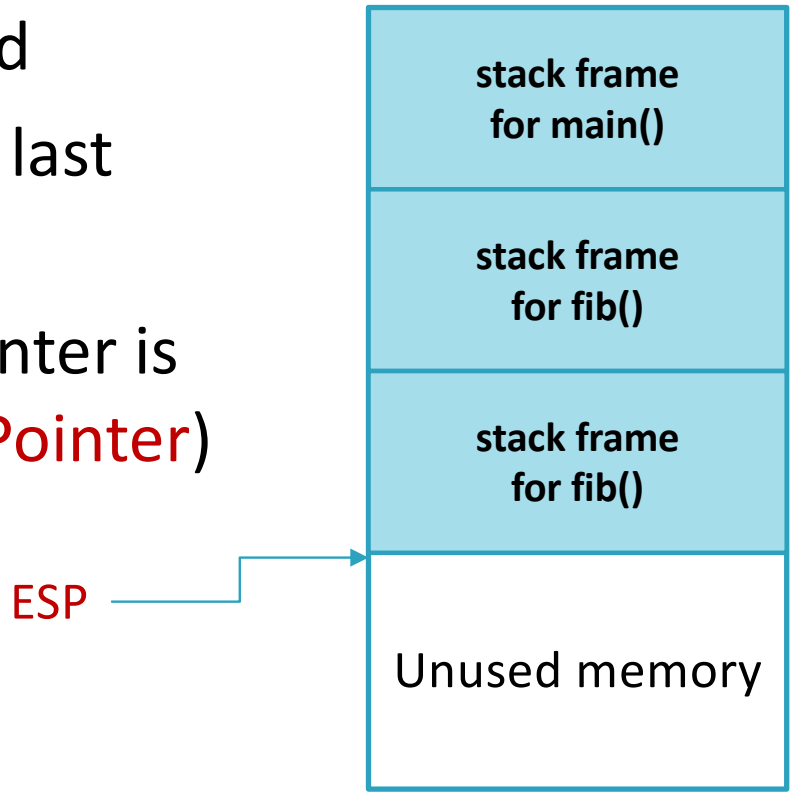


The stack

- The precise structure and organization of the stack depends on system architecture, operating system, and compilers we are using.
- For the sake of simplicity, in this lecture we will focus on *x86* architectures (32 and 64 bits) and on *gcc* compiler on *Linux*.
- More detailed information are available at the following links:
  - https://docs.microsoft.com/en-us/cpp/cpp/argument-passing-and-naming-conventions
  - http://refspecs.linuxbase.org/

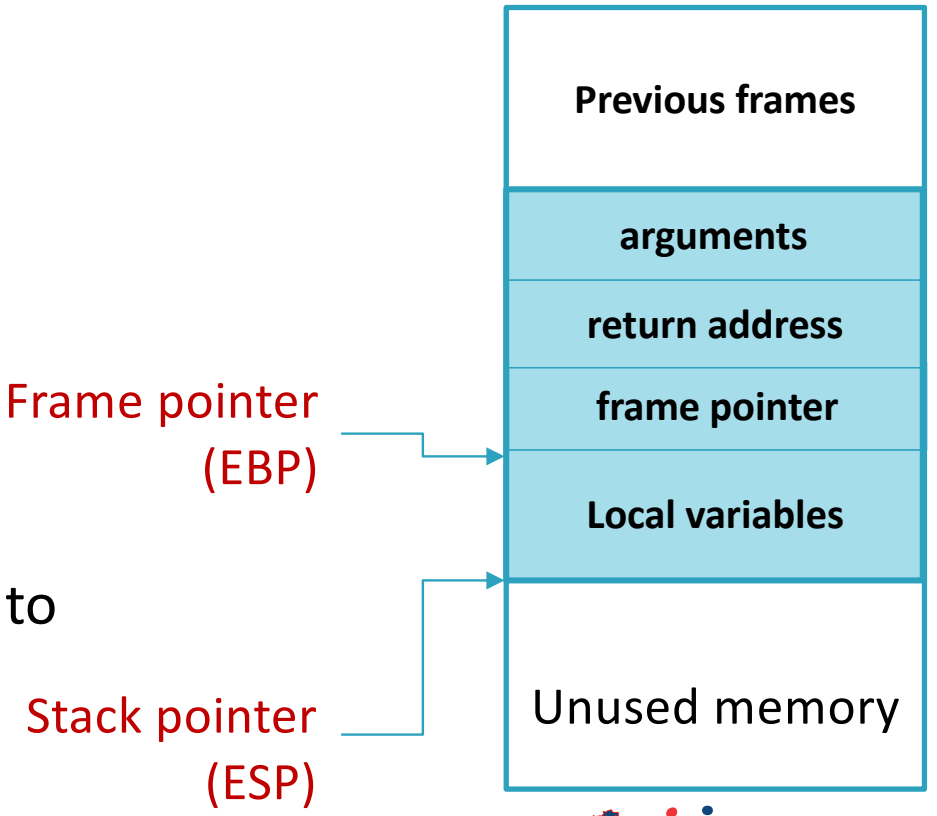
The stack

- Typically the stack grows downward
- The stack pointer (SP) refers to the last element on the stack
- On *x86* architectures, the stack pointer is stored in the ESP (Extended Stack Pointer) register.



Stack frame (for x86)

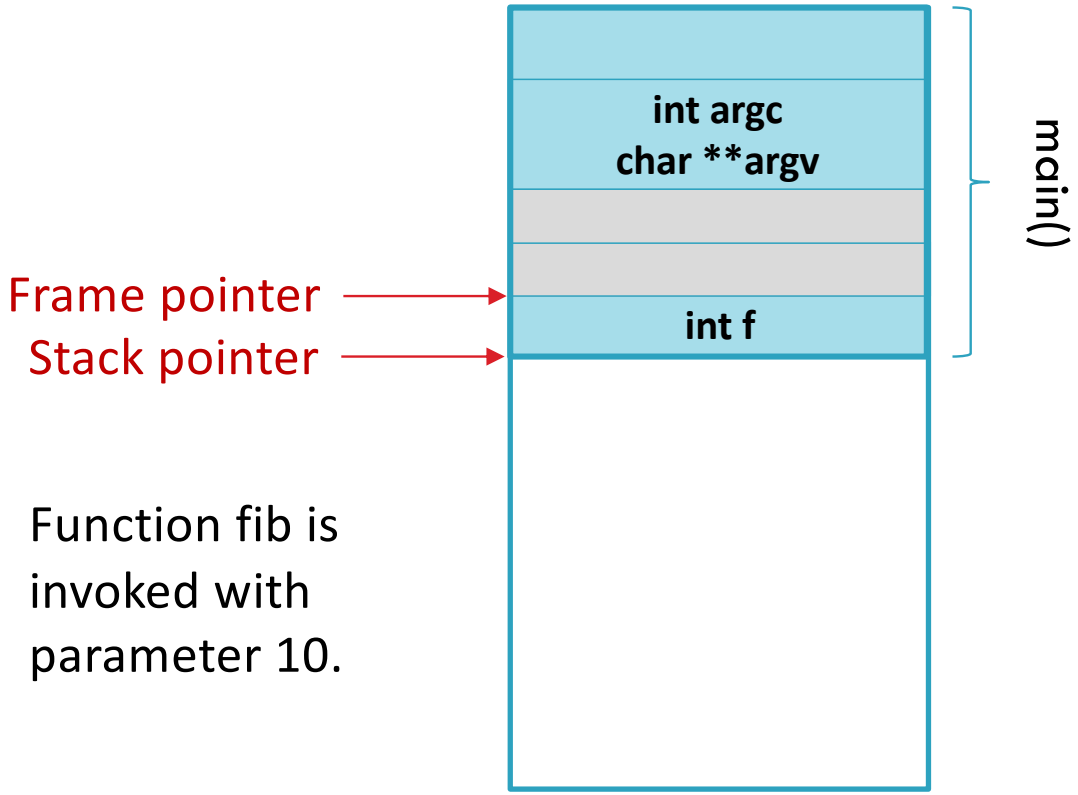
- In *x86* architecture, each stack frame contains:
  - Function arguments;
  - Local variables;
  - Copies of registries that must be restored:
    - return address
    - previous frame pointer
- Frame pointer, named Extended Base Pointer (EBP), provides a starting point to local variables.



Stack frame: example


```
int main(int argc, char **argv) {
  int f = fib( n: 10);
  printf("FIB(10)=%d\n",f);
}

int fib(int n) {
  int f1;
  int f2;
  if (n<=2) {
      return 1;
  } else {
      f1 = fib( n: n-1);
      f2 = fib( n: n-2);
      return f1+f2;
  }
}
```



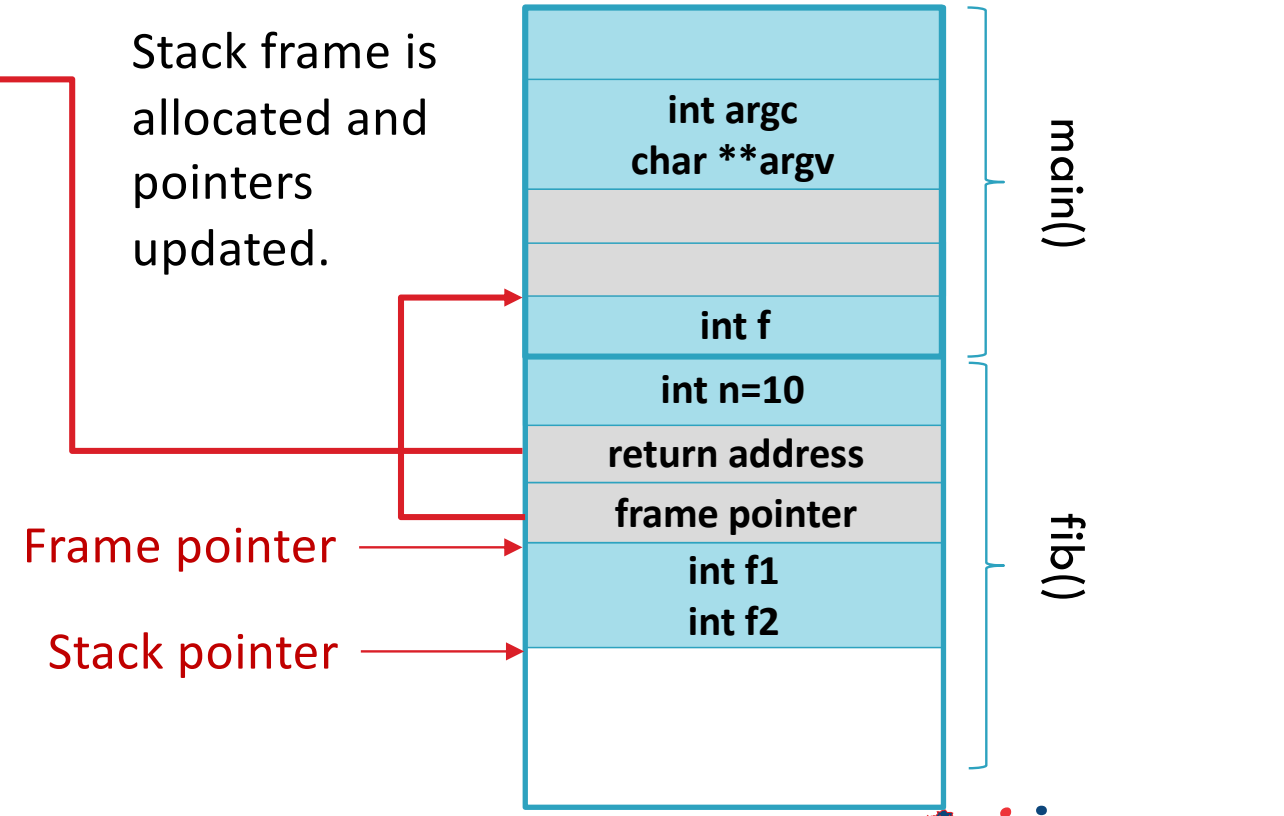
Function fib is invoked with parameter 10.

Stack frame: example


```
int main(int argc, char **argv) {
  int f = fib( n: 10);
  printf("FIB(10)=%d\n",f);
}

int fib(int n) {
  int f1;
  int f2;
  if (n<=2) {
      return 1;
  } else {
      f1 = fib( n: n-1);
      f2 = fib( n: n-2);
      return f1+f2;
  }
}
```

Stack frame is allocated and pointers updated.



Stack frame: example


```
int main(int argc, char **argv) {
  int f = fib( n: 10);
  printf("FIB(10)=%d\n",f);
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int fib(int n) {
  int f1;
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  if (n<=2) {
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      return f1+f2;
  }
}
```
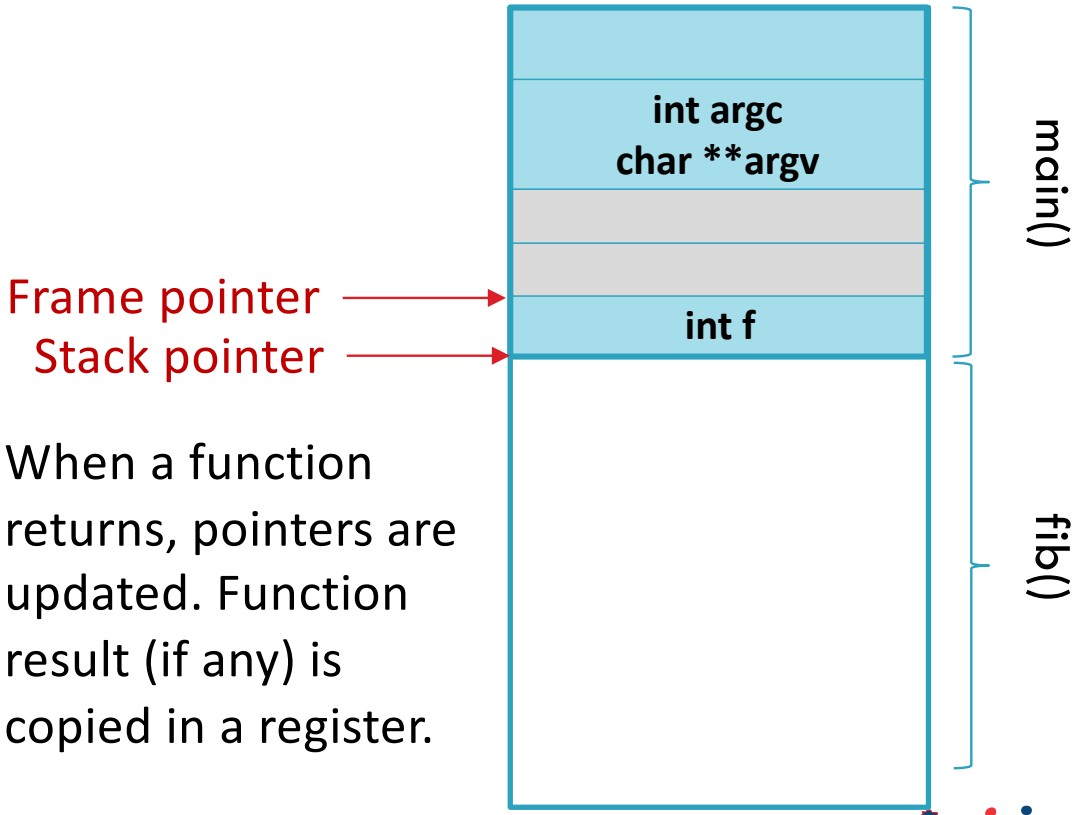



When a function returns, pointers are updated. Function result (if any) is copied in a register.

Stack frame (for x86-64)

- In the *64-bit* version of *x86:*
  - Registers are extended to 64 bits;
  - A new set of 8 registers are added.
- The arguments are not all in the stack:
  - The first 6 are passed via registers;
  - The remaining are placed in the stack (like for *x86*).
- Pointers *EBP* and *ESP* are named *RBP* and *RSP.*
- A *red zone* of 128 bytes is placed in the stack just under RSP
  - This can be used to store extra local variables and is not modified by interrupt/exception/signal handlers.

C declaration: cdecl

- The cdecl (C declaration) is a calling convention used in many compilers for *x86*
  - A calling convention describes how functions receive their parameters from caller and how they return they results.
- In cdecl arguments are passed on the stack, while values are returned via registers.
- Function arguments are pushed on the stack in the *right-to-left order.*
- The caller *cleans* the stack after the function call returns.

Security issues

- In the stack, variables do not have any default initialization:
  - uninitialized local variables can be used to read values from previous function calls;
- The space assigned to the stack is finite and a function call may fail because there is no more memory:
  - We must guarantee that this does not happen or handle it in a safe way.
- Program and control data are mixed in the stack:
  - By accessing over buffers limit may corrupt the return address!

The heap

- Memory allocation and de-allocation in the stack is very fast
  - However, this memory cannot be used after a function returns
- The heap is used to store dynamically allocated data that outlive function calls:
  - This area is under programmer's responsibility.

Memory management functions

- Basic *C* functions for memory management are:
  - *malloc(int),* given an integer *n* allocates an area of *n* (continuous) byes and returns a pointer to that area;
  - *free(void*)*, deallocates the memory associated with a pointer.

Stack and Heap pointers

- We have always to preserve reference to allocated areas in the heap
  - Otherwise we cannot use them!
- These references (pointers) can be stored in the stack or in the heap.
- We could store pointers to the stack in the heap
  - This can be dangerous! Referenced memory could be released!

Memory security problems

- In *C* memory safety is not guaranteed and malicious or insecure code can access data anywhere on stack and heap:
  - via pointer arithmetic;
  - by overrunning array bounds.
- Security problems with memory are due to:
  - Running out of memory;
  - Lack of initialization of memory;
  - Bugs in program code.

List of common errors (1/3)

- Dereferencing an uninitialized or freed address:

```
int *p;
int z = *p;
```

```
int *p = malloc(sizeof(int));
...
free(p)
...
int z = *p;
```

In both the cases we are going to use an invalid memory location. The result is unpredictable.

List of common errors (2/3)

- Freeing an already freed pointer or a pointer that was not dynamically allocated :

```
int *p = malloc(sizeof(int));
...
free(p)
...
free(p)
```

```
int z = 10;
int *p = &z;
...
free(p)
```

In both the cases the result is unpredictable. It may cause abnormal termination, or memory corruption.

List of common errors (3/3)

- Attempt to access to memory beyond the allocated buffer:

```
int *p1 = malloc(100*sizeof(int));
int *p2 = malloc(200*sizeof(int));

p2=p1;

p2[150]=10;
```

We have an overflow: a memory area outside the buffer is changed!

Good practices

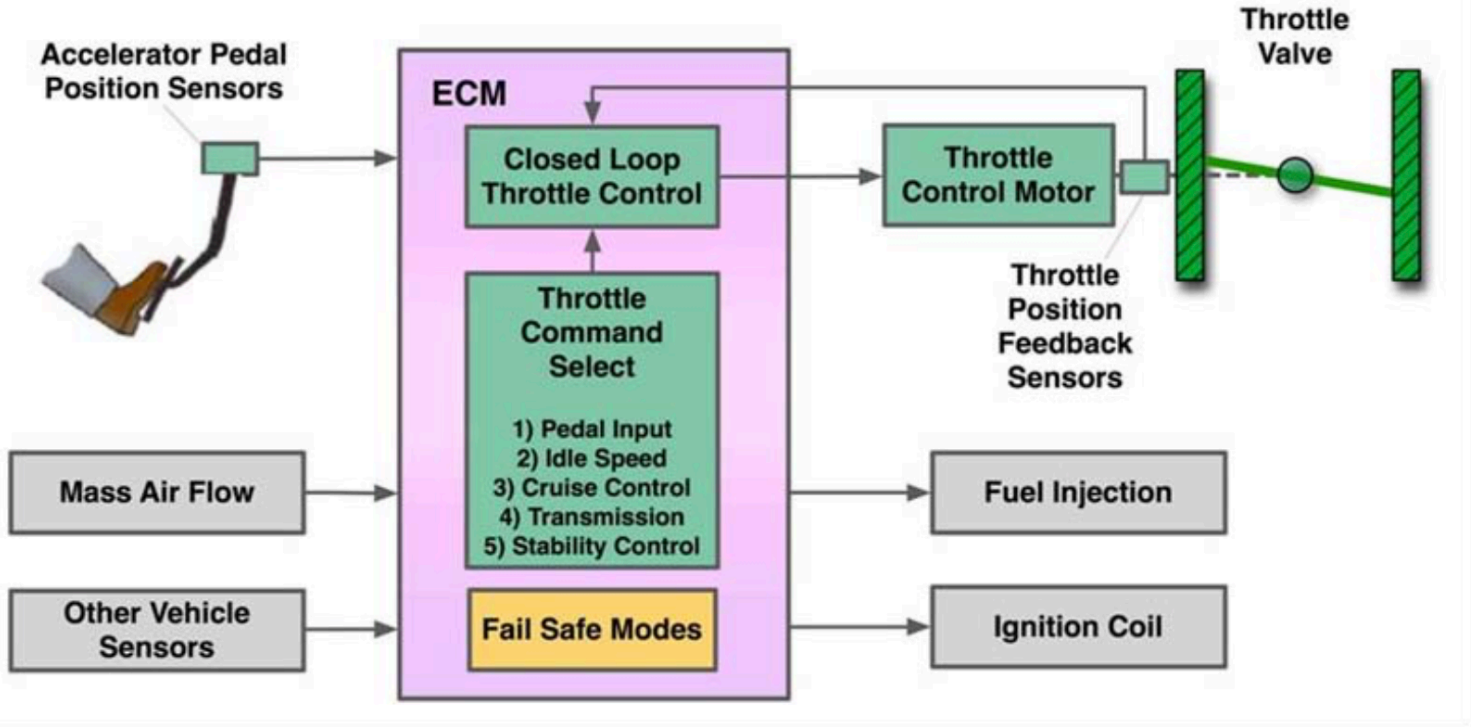
- Every *malloc* should have an associated *free*.
- Pointers should be initialized when defined (either to a valid address or to *NULL)*.
- Pointers should be assigned to *NULL* after being freed.
- Test if a pointer is *NULL* before using it (defensive programming).

Bad stories…

- Bugs in memory allocation can be the source of serious software vulnerabilities.
- Two well known examples are:
  - Toyota unintended acceleration (UA) cases;
  - Heartbleed bug in OpenSSL.

Unintentionally Acceleration

- NASA team investigates UA (2010-2011)



Unintentionally Acceleration

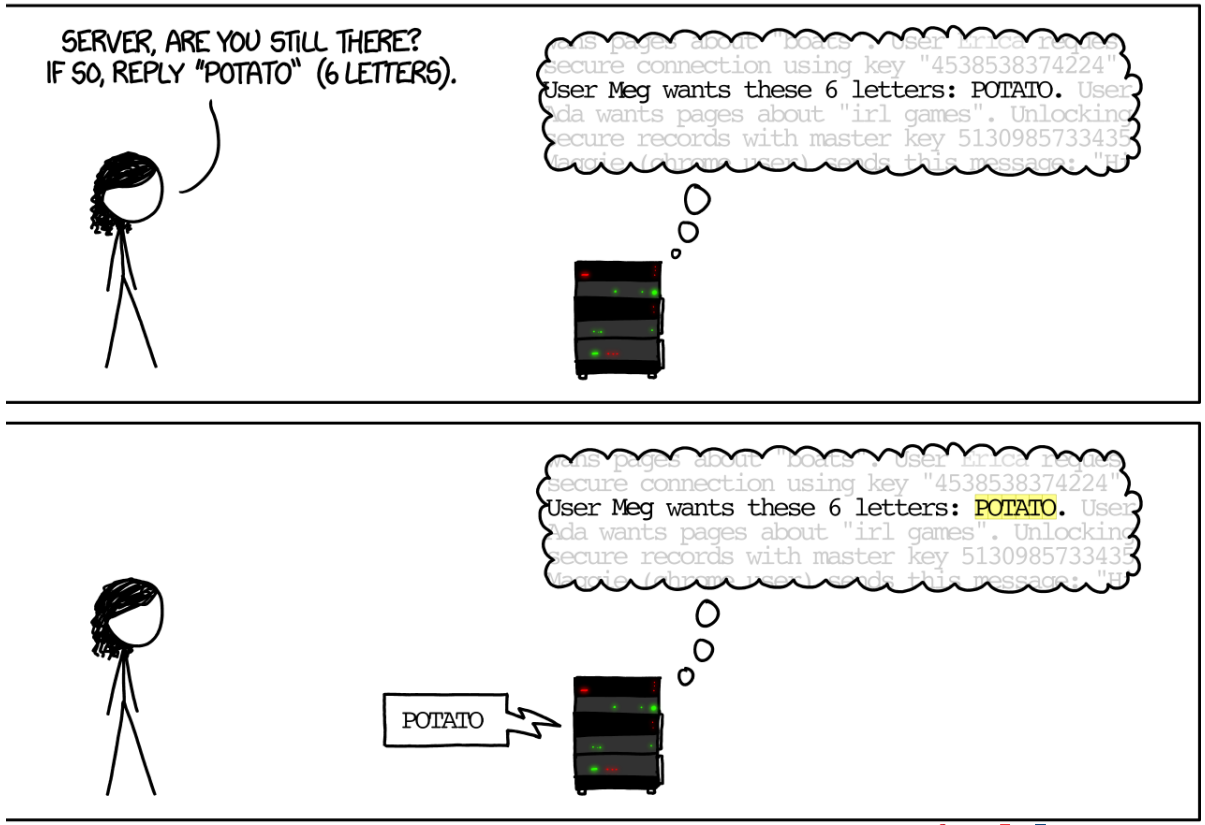
- The bug originated from a stack overflow that may corrupt critical variables of the Operating System.

Heartbleed bug

- The heartbeat functionality in SSL can be used to check if a connection is still alive.
- Malformed input can be provided to OpenSSL to let it print a large part of the stack (possibly containing private keys).
- The same problem effects some TLS implementations (see CVE-2016-9244).

Heartbleed bug

Xkcd provides a nice explanation how the bug works:



https://xkcd.com/1354/

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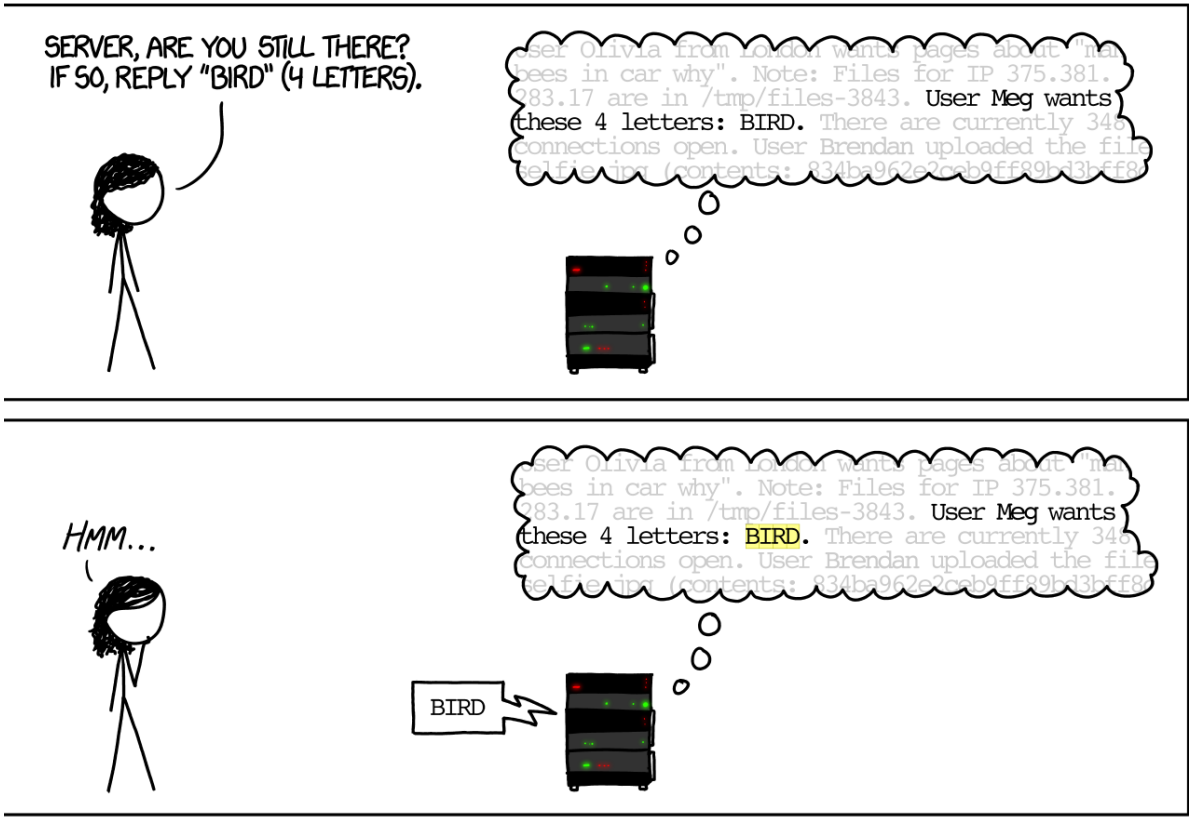

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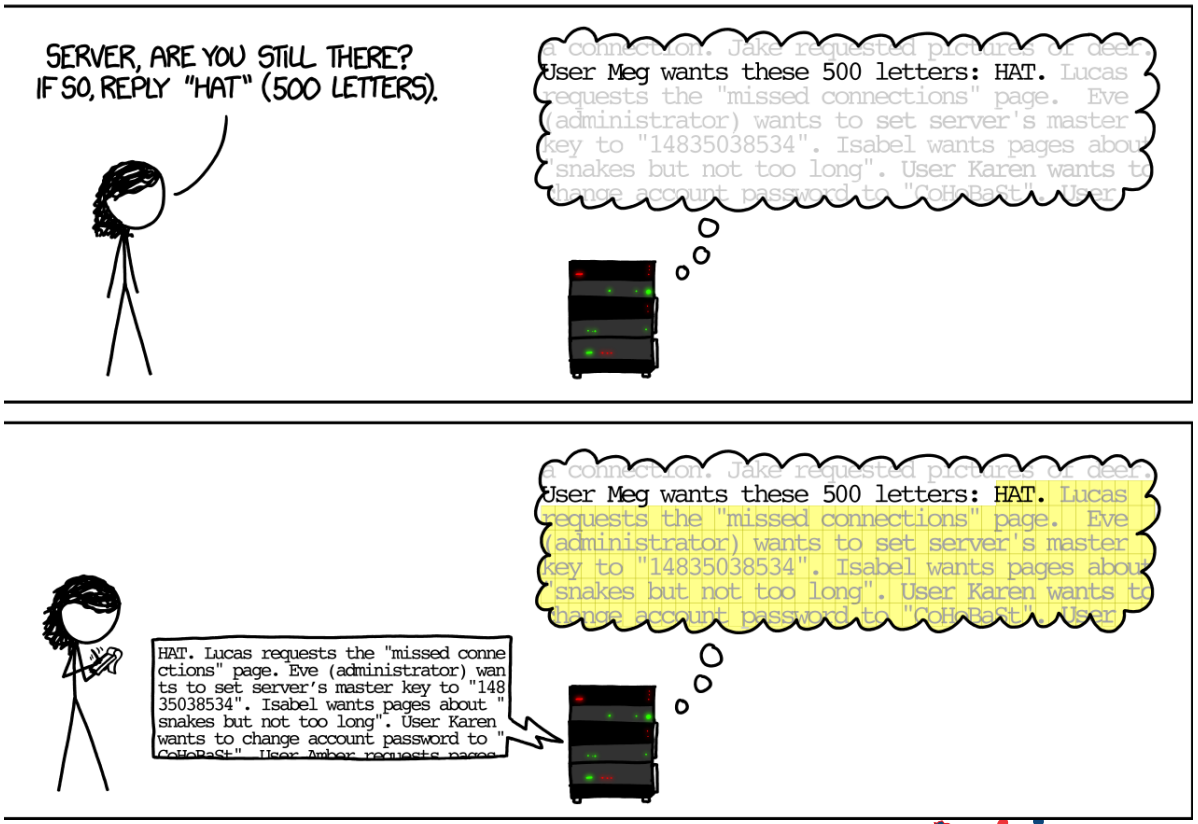

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