Embedded Systems
Compilation & Memory Management

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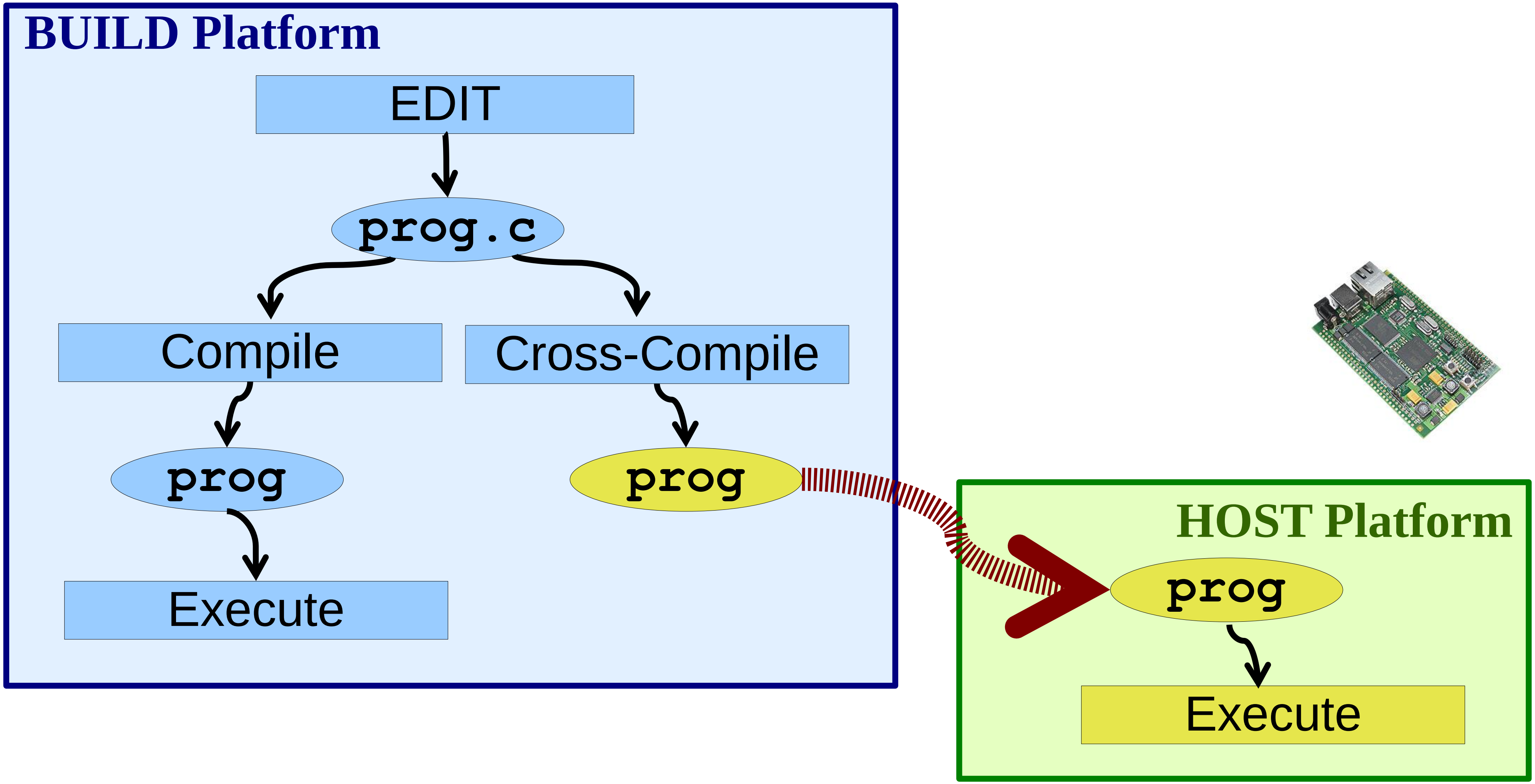
Cross-Compiling

- On embedded systems, it is not always possible to have:
  - a compiler,
  - an editor,
  - a debugger,
  - ...
- How do we develop software for embedded systems?

ans: Cross-compiling

Cross-Compiling



Compiling, Linking & Memory Management of C Programs

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- **Compilation of C Programs**
- **Shared Libraries**
- **Memory Management in C Programs**
- **Memory Management by Operating Systems**

Programming in C

- **Why C ?**
  - Most OSs in current use are written in C
  - Standard POSIX defines calls to OS in C language
    - » POSIX – Portable Operating System Interface
    - » POSIX - IEEE Std 1003.1
    - » POSIX has Real-Time extensions available
- This lecture will NOT be teaching C!
  - Focus on the **compilation** of C programs, instead

C programming language: Example

```
#include <stdio.h>

int main() {
  printf(“Hello World!”);
}
```

- C code organization is based on **functions**
- C programs start by executing the main() function
  - All C programs have **one** main() function.

How to Execute Programs: Compiler

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- CPUs do not understand high level programming languages (C, Java, Pascal, Fortran, Ada...). How to execute these programs?
  - By **compiling** them...
    - » The compiler (another program) converts original programs into **equivalent CPU-readable** programs.
    - » The program **actually executed** is the CPU-readable version.

How to Execute Programs: Interpreter

- How can we execute a program written using a high level programming language?

–By interpreting it (Python, Perl):

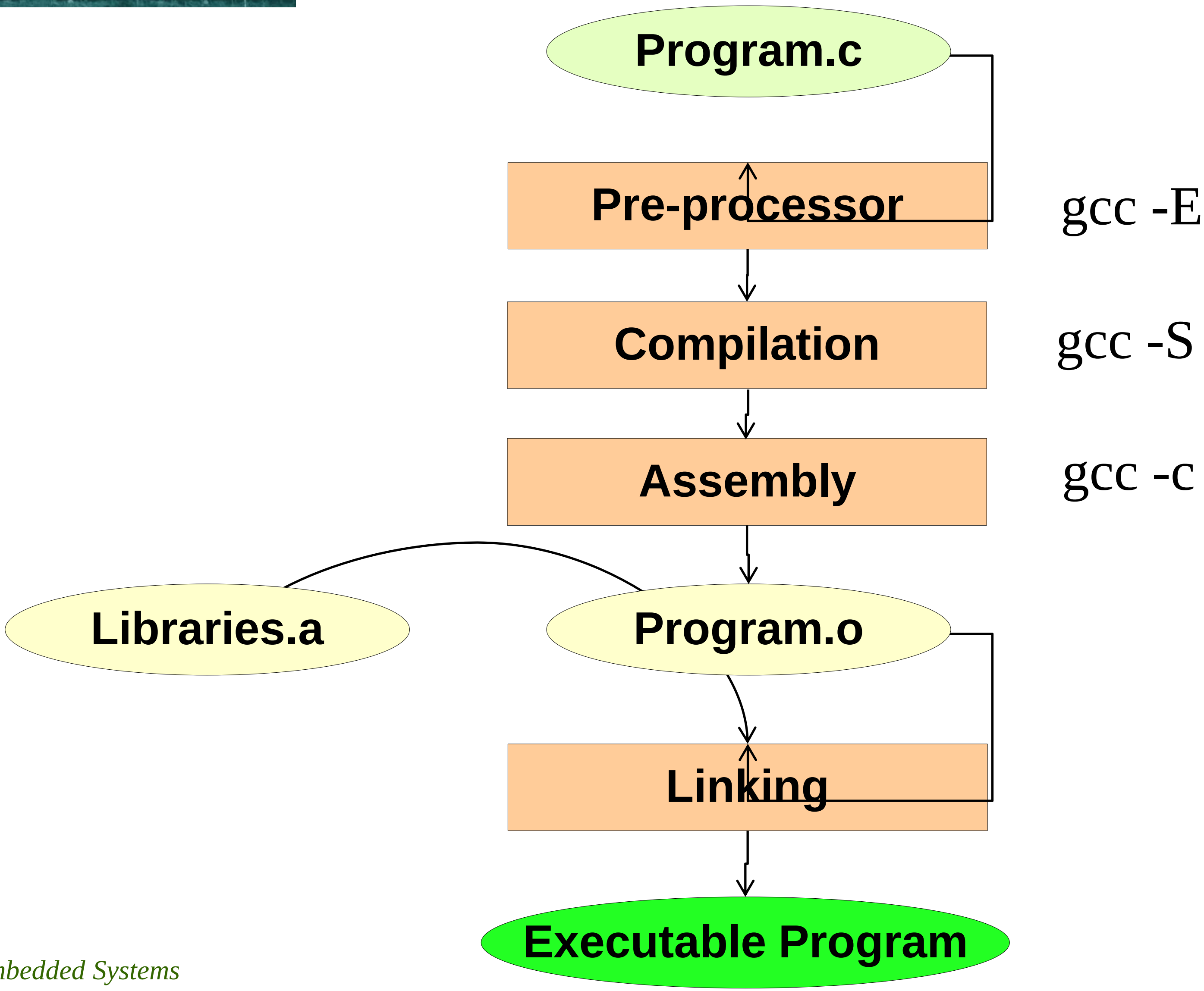
»Use another program (i.e. the interpreter) that interprets the high level instructions, and for each instruction will immediately execute the necessary CPU instructions that would produce the same effect.

»Every time you wish to execute the high level program, we execute the interpreter and ask it to interpret the high level program.

How to Execute Programs: Virtual Machine

- How can we execute a program written using a high level programming language?
  - By compiling and interpreting the result!
    - »Use a compiler that will generate an equivalent program in an intermediate level programming language (i.e. *bytecode*).
    - »Every time you wish to execute the high level program, we execute the interpreter and ask it to interpret the intermediate level program.
    - »Example: JAVA

Stages of Compiling a C Program



Stage 1: Pre-processing

- Processing done purely at the textual level:

-Remove comments

-Process pré-processing directives
(i.e. those commands preceded by '#', ex: '#include')

- Example:

```
#include <stdio.h>
#define MESSAGE "Hello World!"

int main() {
  printf(MESSAGE);
}
```

Stage 1: Pre-processing

- Pre-process...

```
gcc -E hello.c -o hello.cpp_out
```

- Result:

-The command '#include <stdio.h>' is replaced by the contents of the file '/usr/include/stdio.h'

-This file includes other '#include' commands, which menas other files will be included in the resulting output!

-All occurrences of 'MESSAGE' will be replaced by '"Hello World!"'

```
printf("Hello World!");
```

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Stage 2: Compiling

- Converts the C program into Assembly
- Compile...

```
gcc -x cpp-output -S hello.cpp_out
```

(or more simply)

```
gcc -S hello.c
```

- The resulting file (hello.s), contains:

```
LC0:
 .ascii "Hello, world!\12\0"
main:
 pushl    %ebp
 movl     %esp, %ebp
 subl     $8, %esp
 andl     $-16, %esp
movl      $0, %eax
subl      %eax, %esp
subl      $12, %esp
pushl     $.LC0
call      printf
addl      $16, %esp
leave
ret
```

Stage 3: Assembly

- Convert the Assembly code into Machine code

–The resulting machine code is relocatable:
i.e. it is independent on the memory address on which it is located. (by using, for example, relative jumps, and including unresolved symbols...).

- Assembling...

```
gcc -x assembler -c hello.s
```

(or more simply)

```
gcc -c hello.c
```

Stage 3: Assembly

- Analyses of resulting file hello.o

```
readelf -h hello.o
ELF Header:
  Magic:   7f 45 4c 46 01 01 01 00 00 00 00
  Class:         ELF32
  Data:          2's complement, little endian
  Version:       1 (current)
  OS/ABI:        UNIX - System V
  ABI Version:   0
  Type:          REL (Relocatable file)
  Machine:       Intel 80386
  Version:       0x1
  Entry point address:   0x0
(...)
```

ABI-> Application Binary Interface

Reversing Stage 3: Dis-assembly

```
Objdump -d hello.o
Disassembly of section .text:
00000000 <main>:
 0:    55                push   %ebp
 1:    89 e5             mov    %esp,%ebp
 3:    83 ec 08          sub    $0x8,%esp
 6:    83 e4 f0          and    $0xfffffff0,%esp
 9:    b8 00 00 00 00 mov    $0x0,%eax
 e:    29 c4             sub    %eax,%esp
10:    83 ec 0c          sub    $0xc,%esp
13:    68 00 00 00 00 push   $0x0
18:    e8 fc ff ff ff call   19 <main+0x19>
1d:    83 c4 10          add    $0x10,%esp
20:    c9                leave
21:    c3                ret
```

Comparing... Assembly with Disassembly

hello.s

```
main:
 pushl    %ebp
 movl     %esp,  %ebp
 subl     $8,    %esp
 andl     $-16,  %esp
 movl     $0,    %eax
 subl     %eax,  %esp
 subl     $12,   %esp
 pushl    $.LC0
 call     printf
 addl     $16,   %esp
 leave
 ret
```

hello.o (disassembled)

```
<main>:
push %ebp
mov  %esp,%ebp
sub  $0x8,%esp
and  $0xfffffff0,%esp
mov  $0x0,%eax
sub  %eax,%esp
sub  $0xc,%esp
push $0x0
call 19 <main+0x19>
add  $0x10,%esp
leave
ret
```

Comparing...
Assembly with Disassembly

hello.s → **hello.o** (disassembled)

```
main:                    <main>:
 (...)                   (...)
 pushl    $.LC0          push $0x0
 call     printf         call 19 <main+0x19>
```

- Machine code in hello.o is **NOT** executable!
  - It contains unresolved symbols
    - ex. `$.LC0` (reference to string `"Hello World!"`)
  - Contains addresses as an offset to location of `main()`, these are not the final addresses (reclocatable).

Stage 4: Linking

- Linking relocatable code of several files and libraries. May or may not result in executable code.

- linking...

```
gcc -static -o hello hello.o
```

(or more simply)

```
gcc -static -o hello hello.c
```

- Result: executable file → hello

Stage 4: Linking

- Analysing the resulting hello file...

```
readelf -h hello
ELF Header:
  Magic:   7f 45 4c 46 01 01 01 00 00 00 00
  Class:         ELF32
  Data:          2's complement, little endian
  Version:       1 (current)
  OS/ABI:        UNIX - System V
  ABI Version:   0
  Type:          EXEC (Executable file)
  Machine:       Intel 80386
  Version:       0x1
  Entry point address:    0x8048100
(...)
```

Stage 4: Linking

- Analysing the resulting hello file...

```
objdump -d hello
8048204 <main>:
8048204: 55                push %ebp
8048205: 89 e5             mov  %esp,%ebp
8048207: 83 ec 08          sub  $0x8,%esp
804820a: 83 e4 f0          and  $0xfffffff0,%esp
804820d: b8 00 00 00 00    mov  $0x0,%eax
8048212: 29 c4             sub  %eax,%esp
8048214: 83 ec 0c          sub  $0xc,%esp
8048217: 68 c8 fa 08 08    push $0x808fac8
804821c: e8 9f 05 00 00    call 80487c0 <_IO_printf>
8048221: 83 c4 10          add  $0x10,%esp
8048224: c9                leave
8048225: c3                ret
```

Comparing...

hello.s → hello.o → hello

```
main:
   (...)
   pushl $.LC0
   call  printf
```

```
<main>:
(...)
push $0x0
call 19 <main+0x19>
```

```
main:
(...)
push $0x808fac8
call 80487c0
```

- Machine code of hello file **is executable**!
  - All symbols were replaced by memory addresses
    - » ex. `$.LC0 - $0x808fac8`
  - The addresses are absolute
    - » ex. `call 19 <main+0x19> - call 80487c0`

Comparing...

hello.s → **hello.o** → **hello**

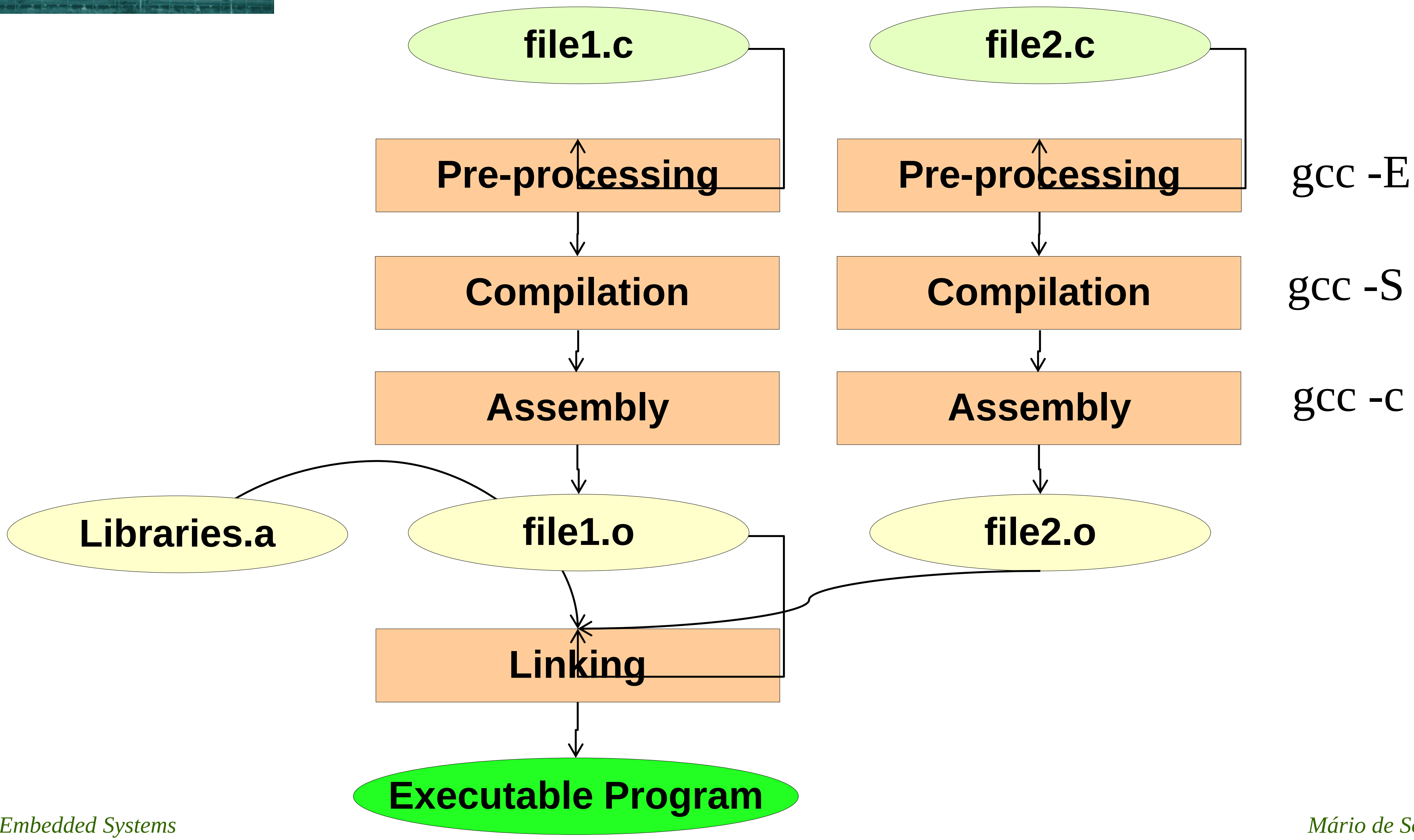
```
hello.s
main:
   (...)
   pushl $.LC0
   call  printf
```

```
hello.o
<main>:
(...)
push $0x0
call 19 <main+0x19>
```

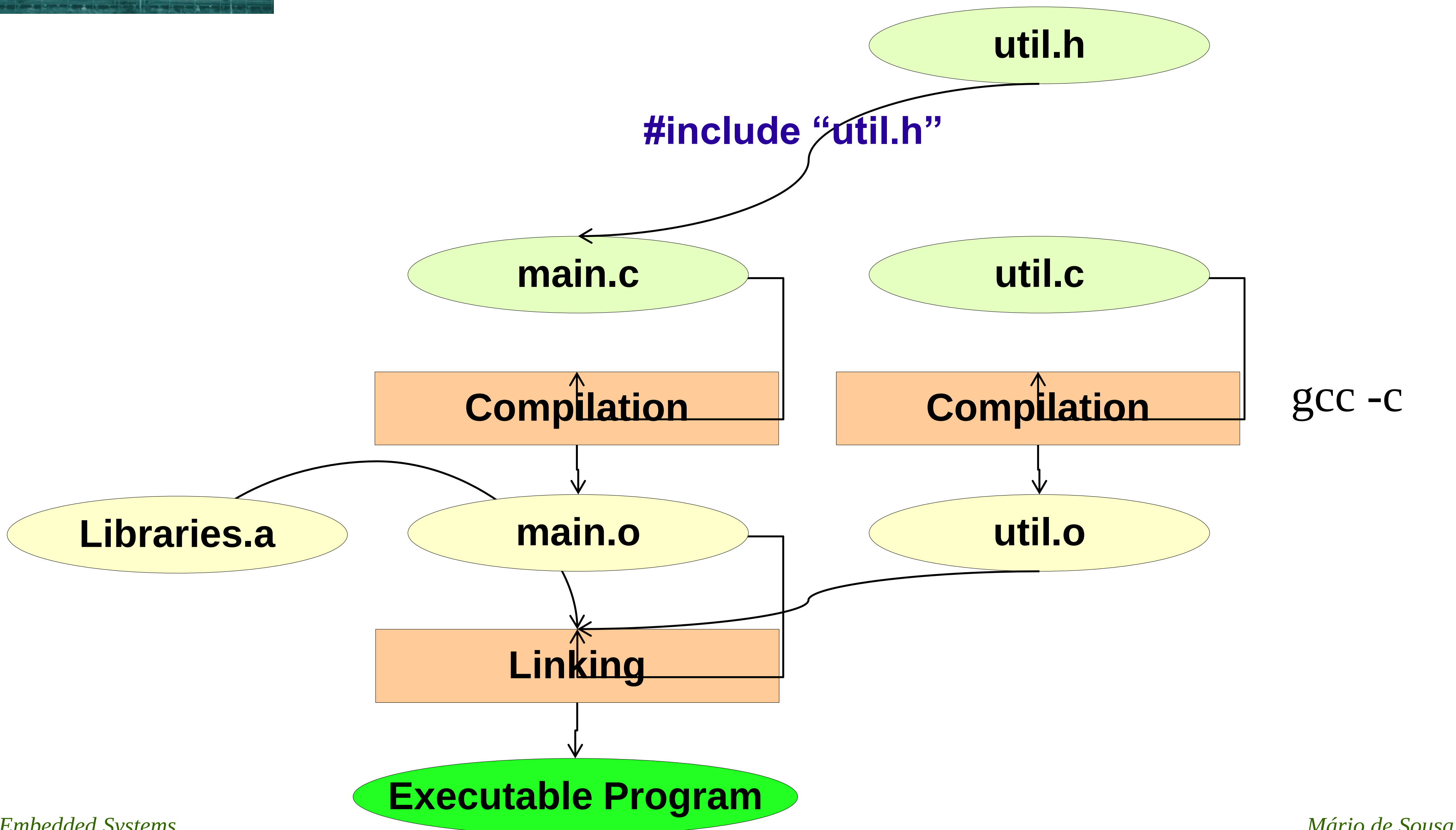
```
hello
main:
(...)
push $0x808fac8
call 80487c0
```

- The executable programme assumes it will always execute from the same memory address!!!
- What if we want to execute several instances simultaneously?

Stages of Compiling a C Program



Stages of Compiling a C Program



Compiling, Linking & Memory Management of C Programs

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- Compilation of C Programs
- Shared Libraries
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- Memory Management by Operating Systems

Using Libraries

- hello.c uses the `printf()` function from the C library

- Option 1 – **Static linkage**
  - The `printf()` function is copied into the final executable file (hello) during linking
  - **`gcc -static -o hello hello.o`**

- Option 2 – **Dynamic Linkage**
  - The executable file merely contains a reference to the library that contains the code for `printf()`
  - The code for the `printf()` function is read from the library every time the executable 'hello' program is run.
  - **`gcc -o hello hello.o`**

Linking
Static vs Dynamic

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Disk usage

- Static linking results in larger executable program files. The same code is stored multiple times, once in each program that uses that function!
- hello: dynamic → 11 kB, static → 475 kB.

Removal of bugs in the library

- Dynamic linking only requires that the libraries themselves be recompiled
- Static linking requires recompilation of all programs that depend on that library.

Dynamic Linking

Libraries for dynamic linking

- In UNIX environments, these are known as *Shared Libraries.* In Linux, the files have the '.so' extension (*Shared Object*)

- In Windows, these are known as DLL – *Dynamically Linked Library*

Dynamic Linking

- How can you know which libraries a compiled program uses?

```
$ gcc -c -o hello hello.o
$ ldd hello

libc.so.6 => /lib/i686/libc.so.6(0x40024000)
/lib/ld-linux.so.2 => /lib/ld-linux.so.2 (0x40000000)
```

- What is this library → `ld-linux.so` ?

–Contains the code responsible for loading into memory the functions in shared libraries!

–As an exception, this shared library is loaded into memory directly by `execve()`

Compiling, Linking & Memory Management of C Programs

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- **Compilation of C Programs (revisited): Portability**
- **Shared Libraries**
- **Memory Management in C Programs**
- **Memory Management by Operating Systems**

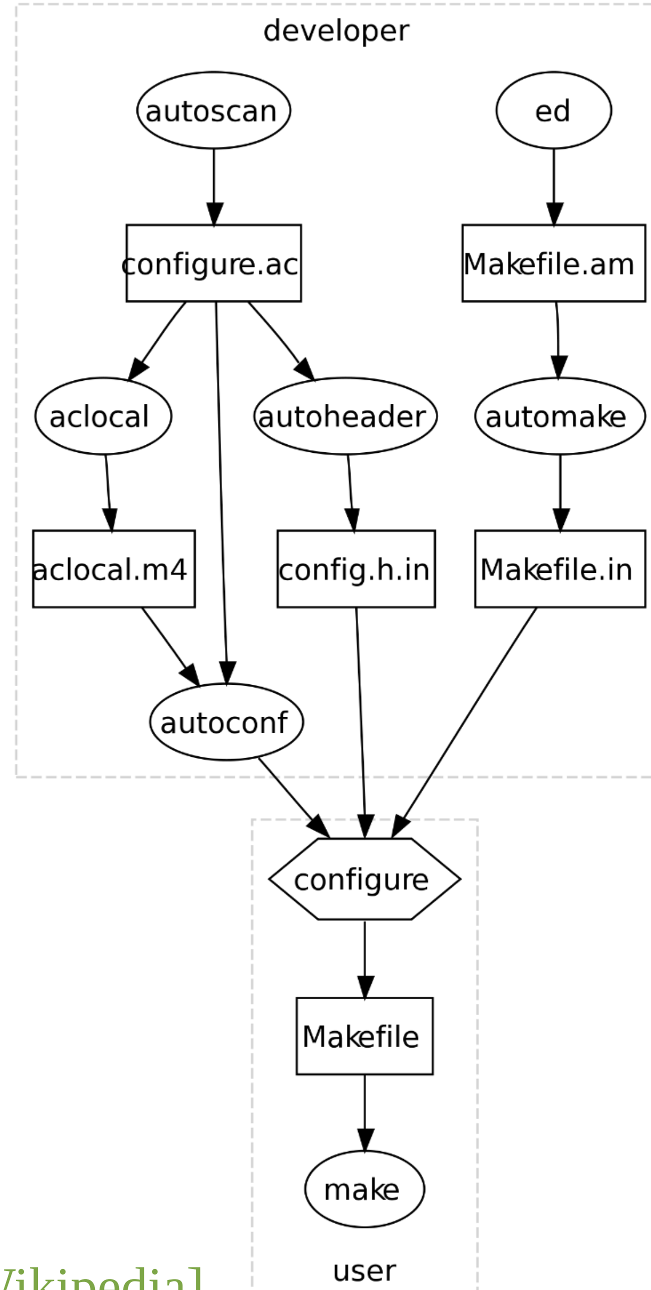
Portable Compilation

- Computers may have many different architectures...
  - -endianness
  - -word size
  - -alignment
  - -default signedness
  - -No MMU (Memory Management Unit)
  - -Library location (in the file system hierarchy)
- How to portably compile programs?

  → Use auxiliary tools!!
  - -example: GNU Build System

Portable Compilation

- GNU Build System
  - make, automake,
  - autoconf, autoscan, autoheader, aclocal,
  - libtool
- A user, who wishes to compile the project, simply executes:
  - ./configure
  - make
  - make install



[Wikipedia]

Portable Compilation

- `./configure`
  - Determines the current computer's architecture, and configures the '`Makefile`' appropriately
    - » determines whether called functions are present in the libraries
    - » Determines library location
    - » ...
- `make`
  - Compiles the program, using the configurations defined

Portable Compilation

- **./configure --host=avr32-linux**

-Determines the architecture of the computer that will **execute** the program, and configures the '**Makefile**' accordingly.

»existence of specific functions in the libraries

NOTE: which compiler to use?

(may require compilation and execution of programs... where?
In the Build Platform!)

NOTE: libraries must be in the same location in both the Build and Host Platforms!!!!

»Library location

»...

Compiling, Linking & Memory Management of C Programs

- **Compilation of C Programs**
- **Shared Libraries**
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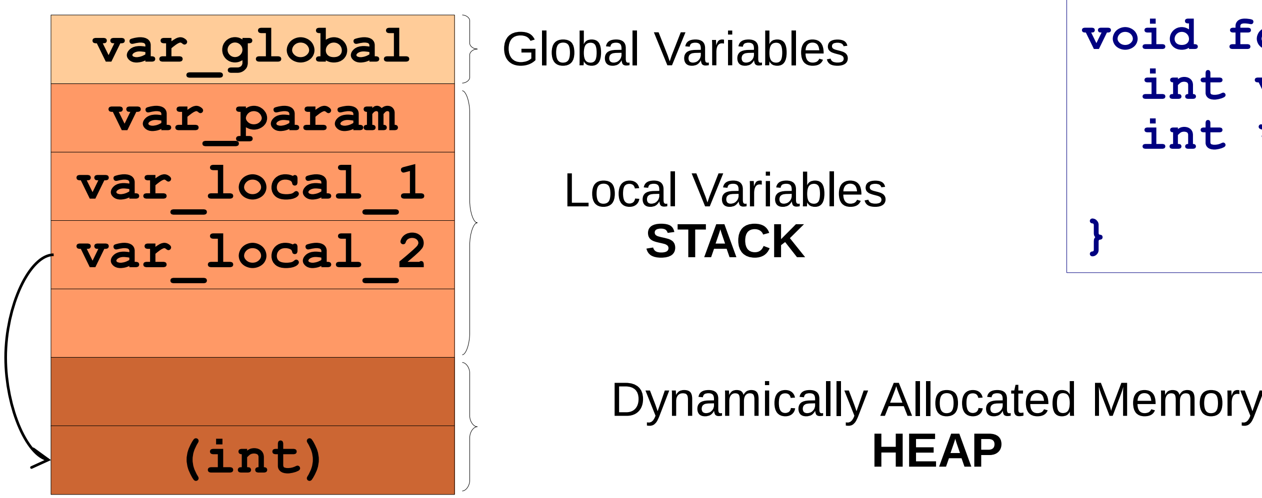
Memory Management in C Programs

- A program uses memory to store:

-Global variables

-Local Variables

-Dynamically allocated memory (**malloc()**)



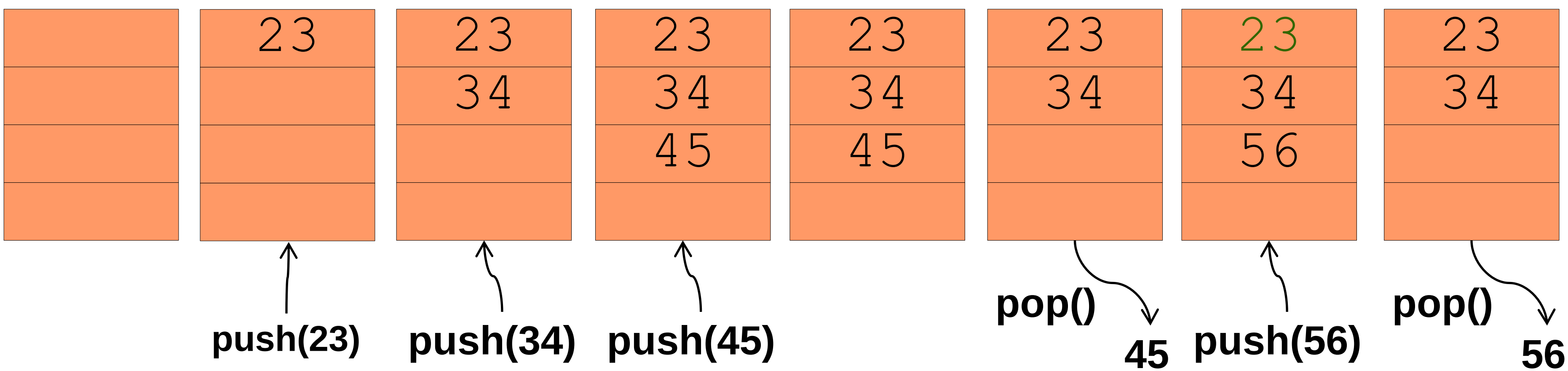

```
int var_global;

void foo(int var_param) {
  int var_local;
  int *var_local2 =
          malloc(sizeof(int));
}
```

STACK Management

- The number of local variables will change during program execution. It depends on the currently active functions!

- The memory area used for local variables is managed as a *stack*

–*Stack:* LIFO (Last In First Out) data structure



Recursive Functions & the Stack

```
int sum(int n) {
  if (n == 0) return 0;
  return n + sum(n-1);
}
int main() {return sum(2);}
```

main()	sum(2)	sum(1)	sum(0)	return 0	return 1	return 3	return 3
	n=2	n=2	n=2	n=2	n=2	3	
		n=1	n=1	n=1	1		
			n=0	0			

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C Functions & the stack

- In C, the stack is use for:
  - Passing of function arguments/parameters
  - Store the return address (a.k.a. program counter)
  - Store local variables
  - Store the return value
  - Temporarily store the CPU registers.
- Each compiler will establish a convention regarding how the above information is organized/stored in the stack when a function is called.
  - This structure is known as a *Stack Frame* or *Activation Record*
  - When calling OS functions, a specific organization must be used -> known as ABI – Application Binary Interface

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HEAP Management

- Sequence by which memory os allocated and freed is 'random' (i.e. unknown by the heap manager). Memory is allocated in blocks...
- Heap memory management will depend on the specific implementation of:

`malloc(), free(), realloc(), calloc(), memalign()`

NOTE: You can overload the default implementation of these functions with your

HEAP Management: Example

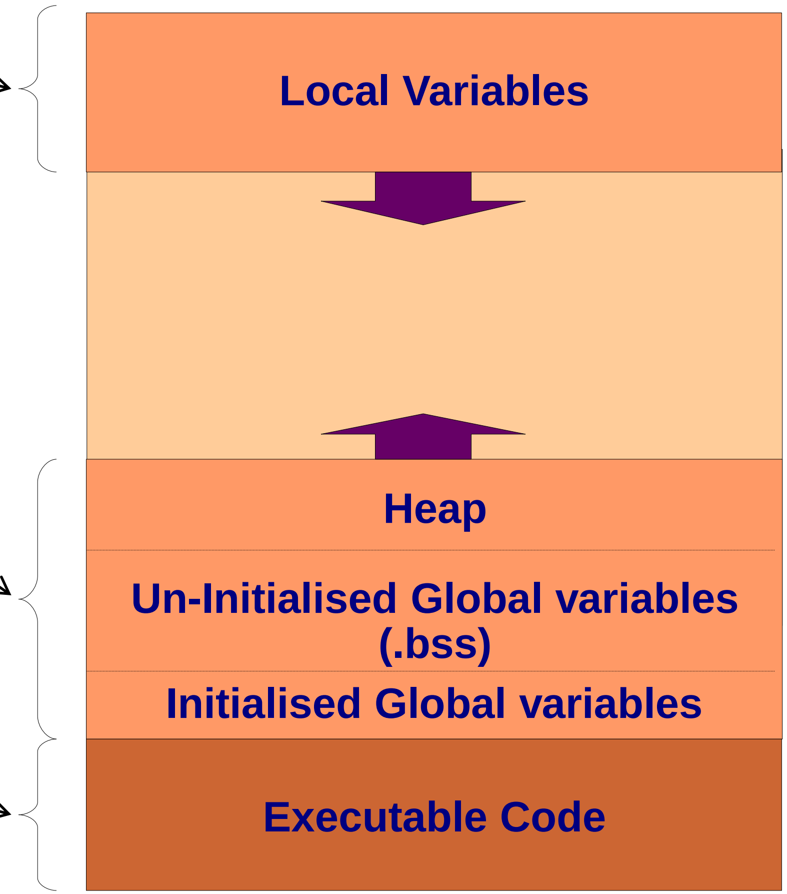
```
int main() {
 char *v1 = malloc(1);
 char *v2 = malloc(2);
 char *v3 = malloc(3);
 free(v2);
 char *v4 = malloc(1);
 char *v5 = malloc(3);
 free(v1);
 free(v3);
 free(v4);
 char *v6 = malloc(5);
}
```

1									
1	2	2							
1	2	2	3	3	3				
1			3	3	3				
1	4		3	3	3				
1	4		3	3	3	5	5	5	
	4		3	3	3	5	5	5	
	4					5	5	5	
						5	5	5	
6	6	6	6	6		5	5	5	

Assuming malloc() uses first-fit algorithm!

Unix Process: Memory Use

- Stack Segment
  - -Variable size
- Data Segment
  - -Read/Write
  - -Variable size
  - -Initialised variables are loaded from program file
- Text Segment
  - -Executable code
  - -Read-only
  - -Fixed size



Compiling, Linking & Memory Management of C Programs

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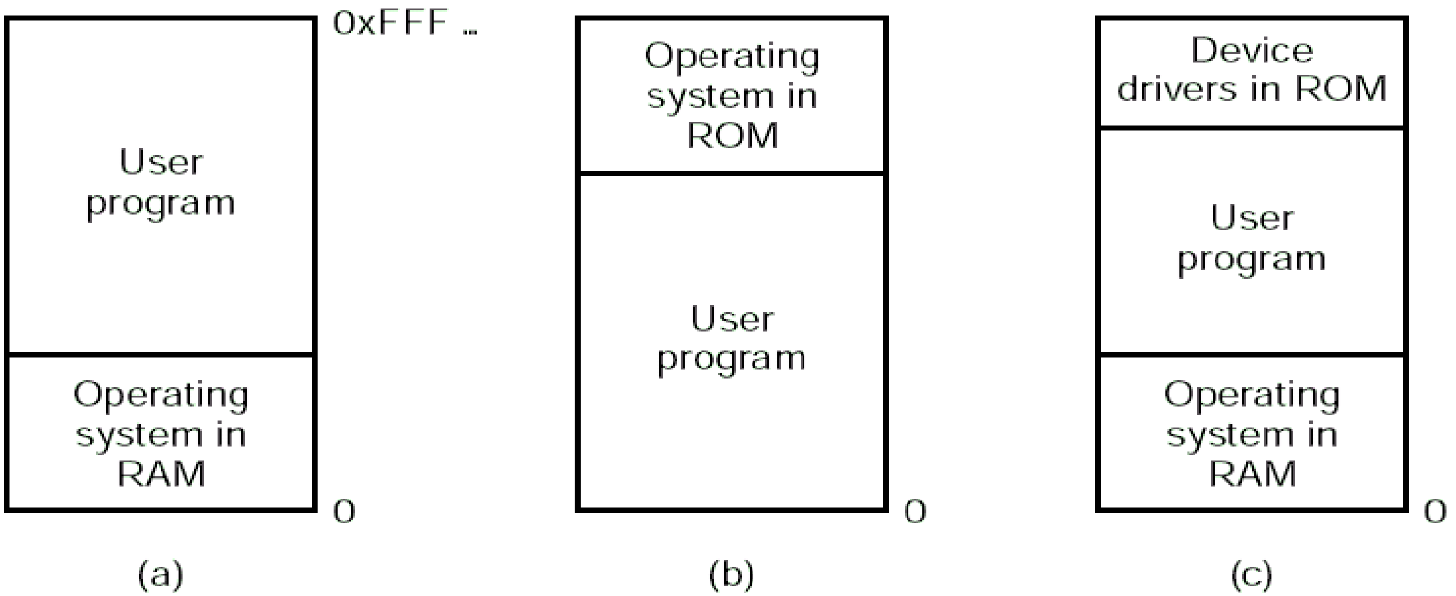
- **Memory Management by Operating Systems**

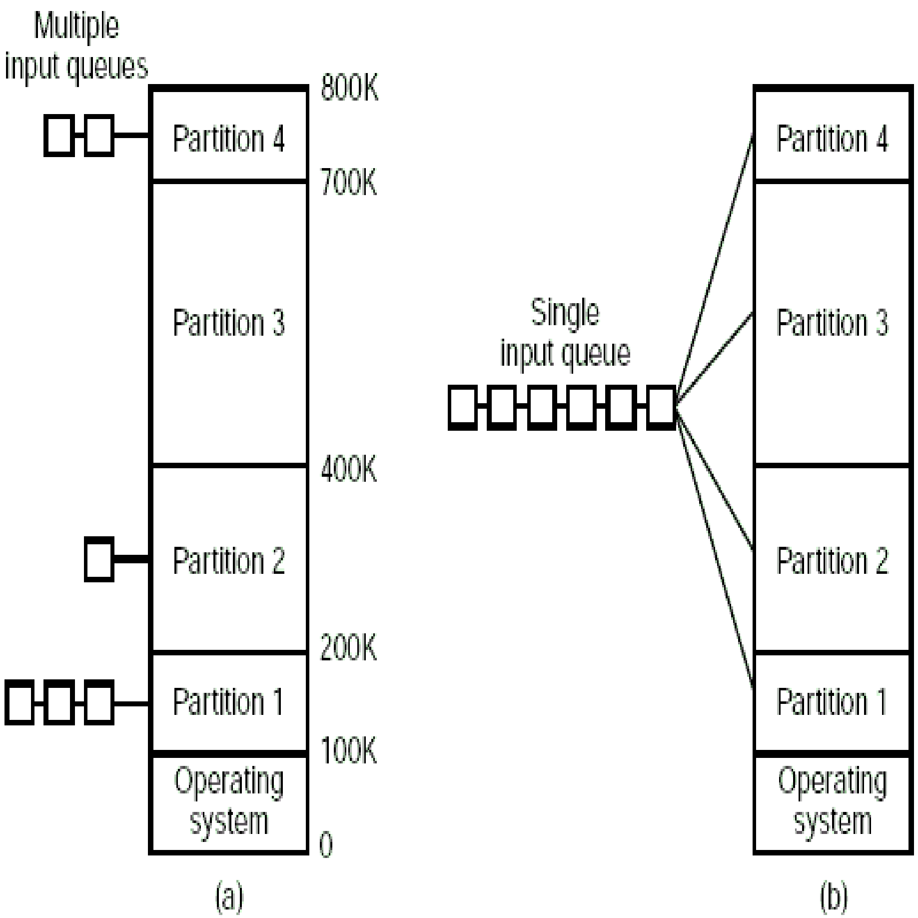
Memory Management in Single Process Operating Systems.



- Typical of micro-controllers with no OS
- Also used by MS-DOS.
- Device-Drivers in ROM -> a.k.a. BIOS.

Picture from “Modern Operating Systems”, Andrew Tanenbaum

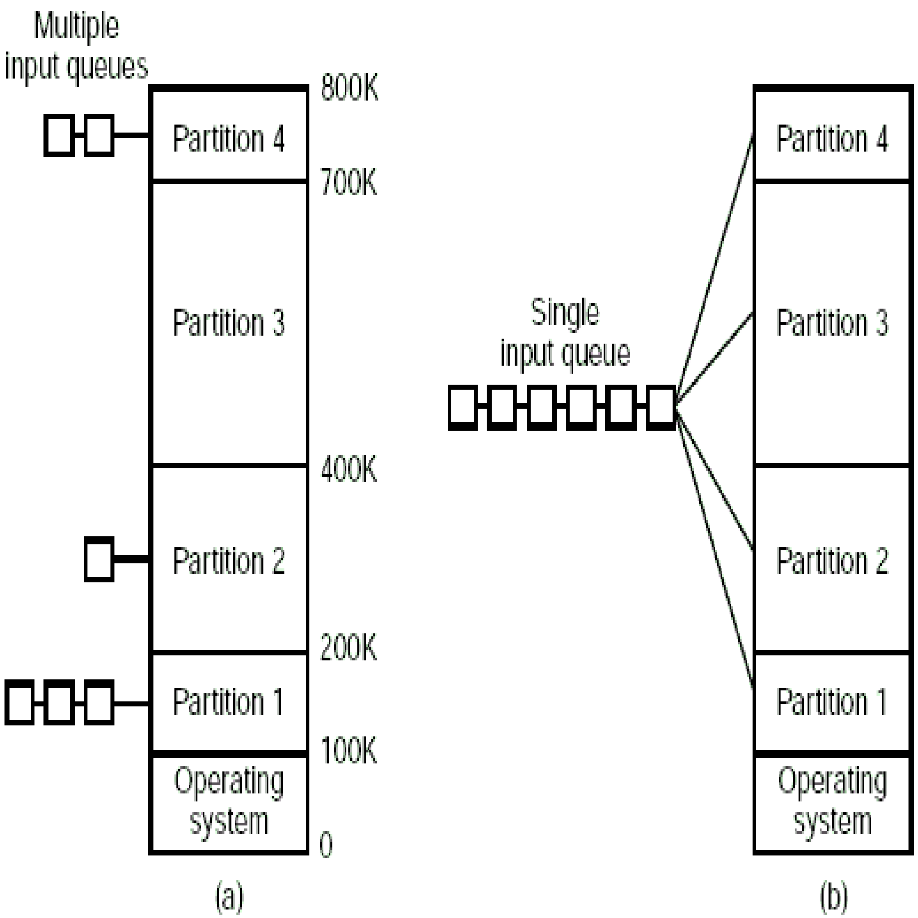
Multi Process Operating Systems: -> Partitioned de Memory



- Memory divided into partitions
  (possibly differing sizes)
- OS will attribute a partition to each process.
  (choose smallest free partition big enough for process)
- When run out of partitions -> maintain a pending process queue

Picture from “Modern Operating Systems”, Andrew Tanenbaum

Multi Process Operating Systems: -> Partitioned de Memory



Picture from "Modern Operating Systems", Andrew Tanenbaum

- Drawbacks:

-Program size limited to size of largest partition.

-Program size always smaller than computer's RAM memory.

-Ineficient use of memory (programs must completely reside in RAM memory)

Multi Process Operating Systems: -> Virtual Memory

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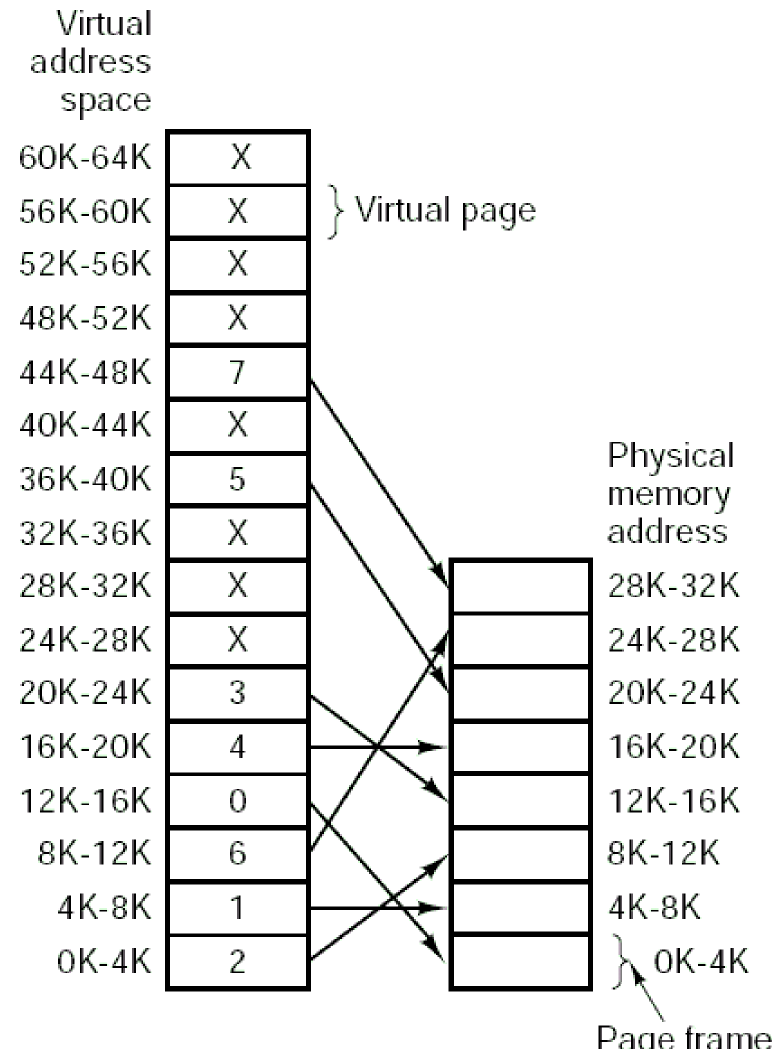
- Main idea: the same process gets several partitions...
(use smaller partitions)

- Each process gets its own virtual address space



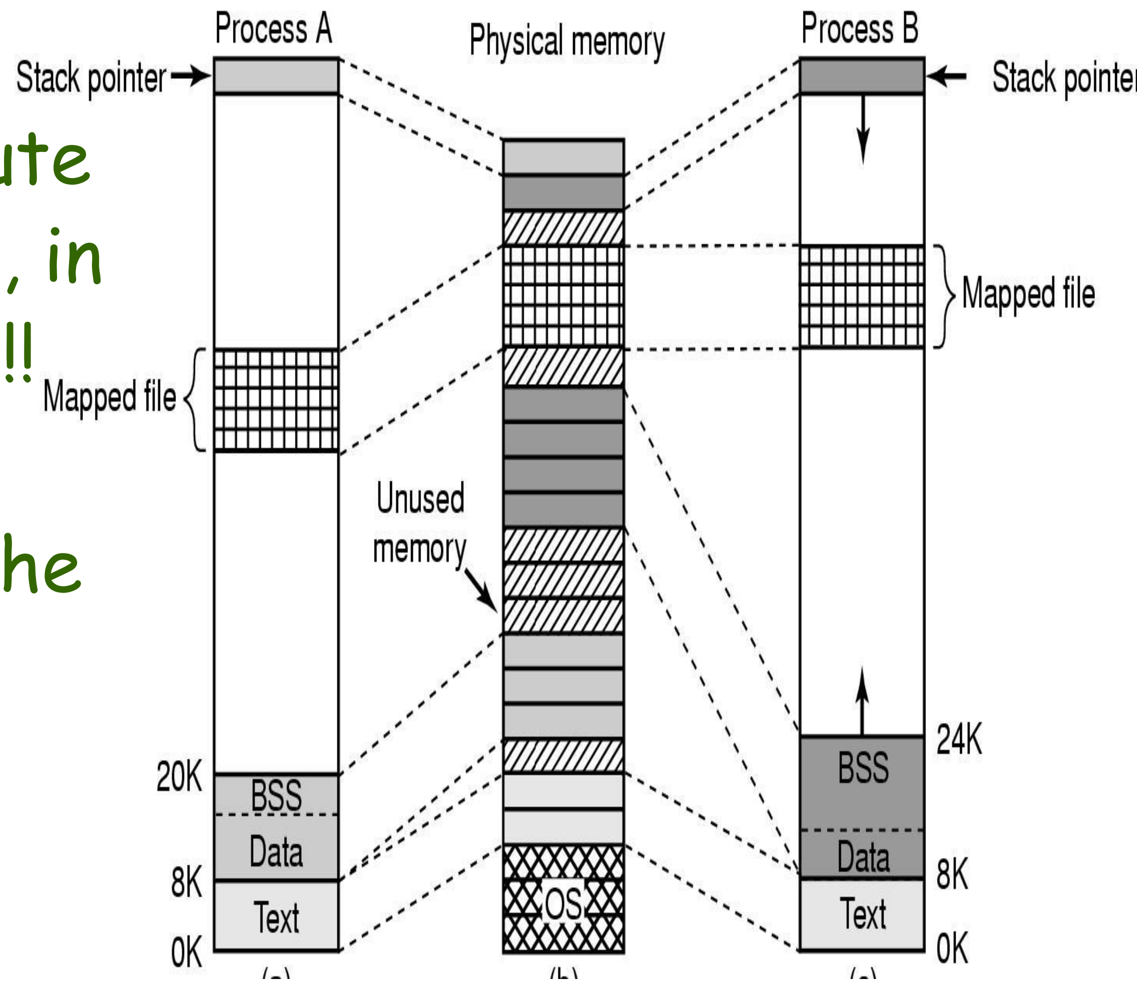
Picture from “Modern Operating Systems”, Andrew Tanenbaum

Multi Process Operating Systems: -> Virtual Memory

- It is now possible to:

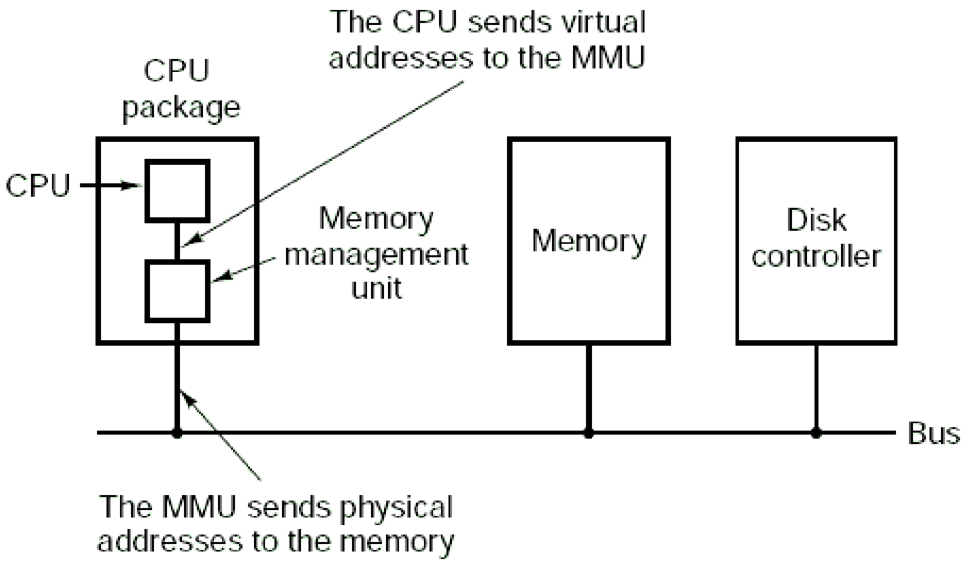
-have two program execute distinct executable code, in the same virutal address!!

-Have two instances of the same program share the same physical memory block
(read-only: memory block will contain executable code or constant global variables).



Picture from "Modern Operating Systems", Andrew Tanenbaum

Multi Process Operating Systems: -> Virtual Memory

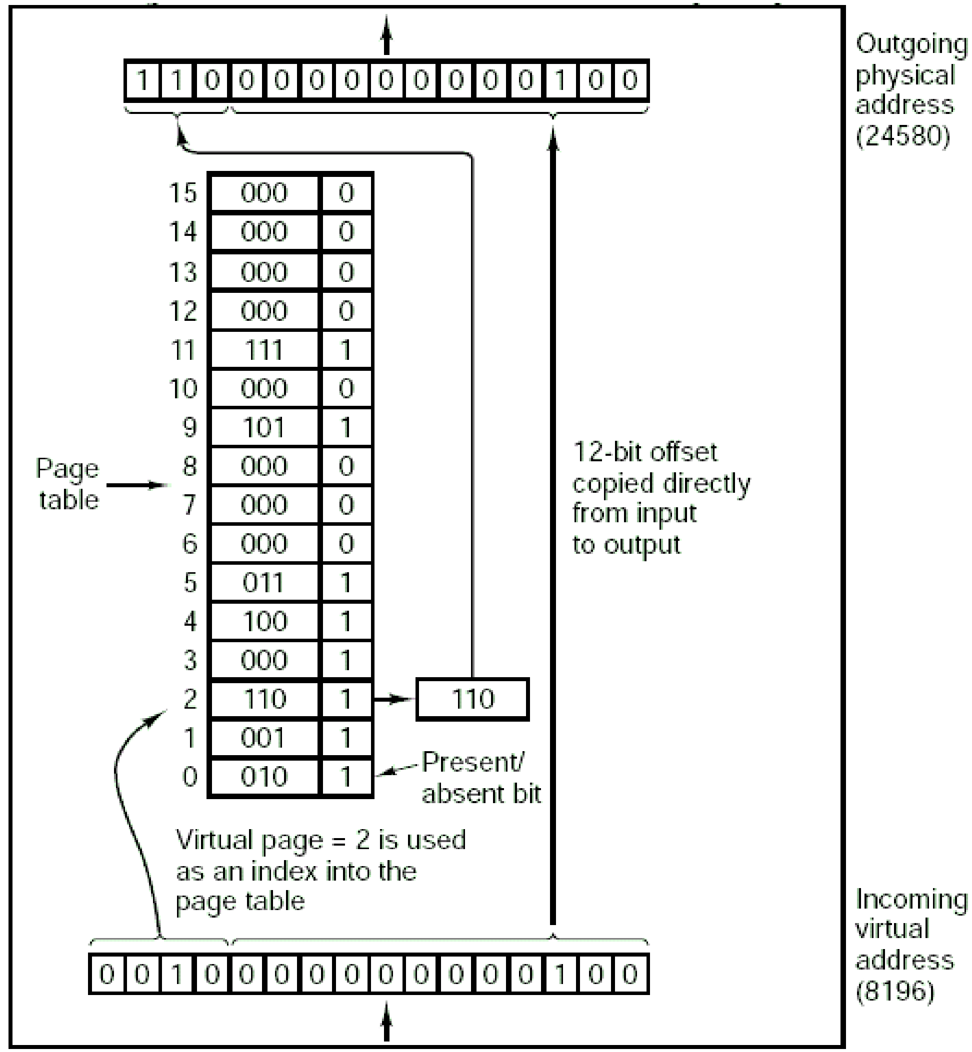


- Conversion from virtual to physical address is done in hardware
- MMU: Memory Management Unit
- (Doing it in hardware allows program to run at full speed!)

Picture from “Modern Operating Systems”, Andrew Tanenbaum

Multi Process Operating Systems: -> Virtual Memory

- Maping is done using only the most significant bits of virtual address
- Uses a 'Page Table' for conversion
- Each process has its own unique 'Page Table'!!



Picture from "Modern Operating Systems", Andrew Tanenbaum

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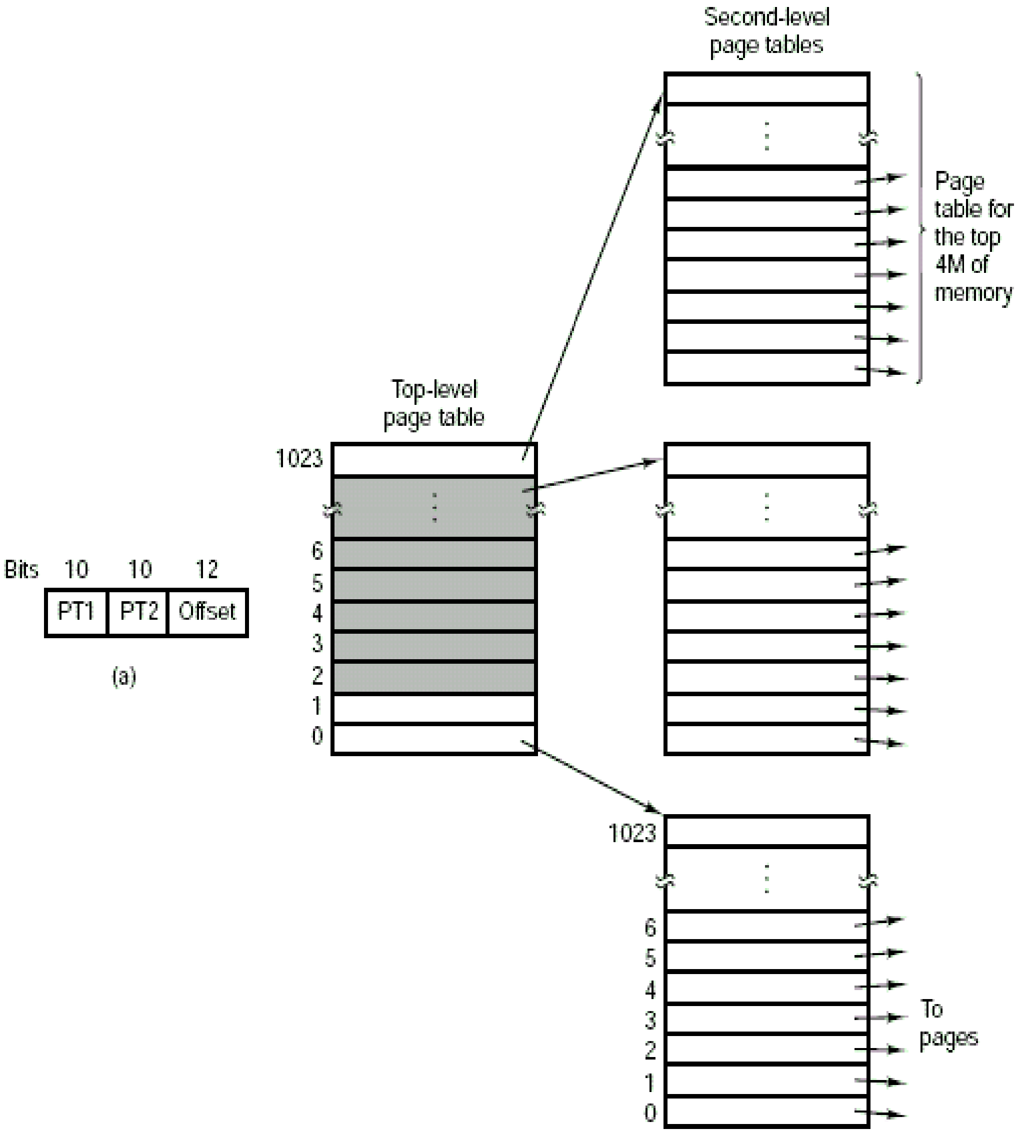
Multi Process Operating Systems: -> Virtual Memory



Example:

-CPU with 32 bits addresses,

-4 Kbyte page size (12 bits),

-=> page table will need 4 Mbyte!!!

Usually, each program will only use a small fraction of the virtual address space.

-Use a multi-level page table architecture

Picture from “Modern Operating Systems”, Andrew Tanenbaum

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Multi Process Operating Systems: -> Virtual Memory

Drawbacks:

-Each memory access requires aditional memory reads (from the page tables) to convert to the real address space => SLOW!!!.

Solution:

-Use a special cache memory for the page table. Cache will maintain copies of the most recently used page tables.

-Known as: Translation Loookaside Buffer (TLB).

-When a process switched occurs, all entries in the TLB become invalid! (remember, each process has its own unique page table)

Multi Process Operating Systems:
-> Virtual Memory

Advantage:

–Better use of available memory (smaller memory blocks)

BUT:

–The memory used together by all programs cannot exceed available RAM memory!

Solution: Paged Memory

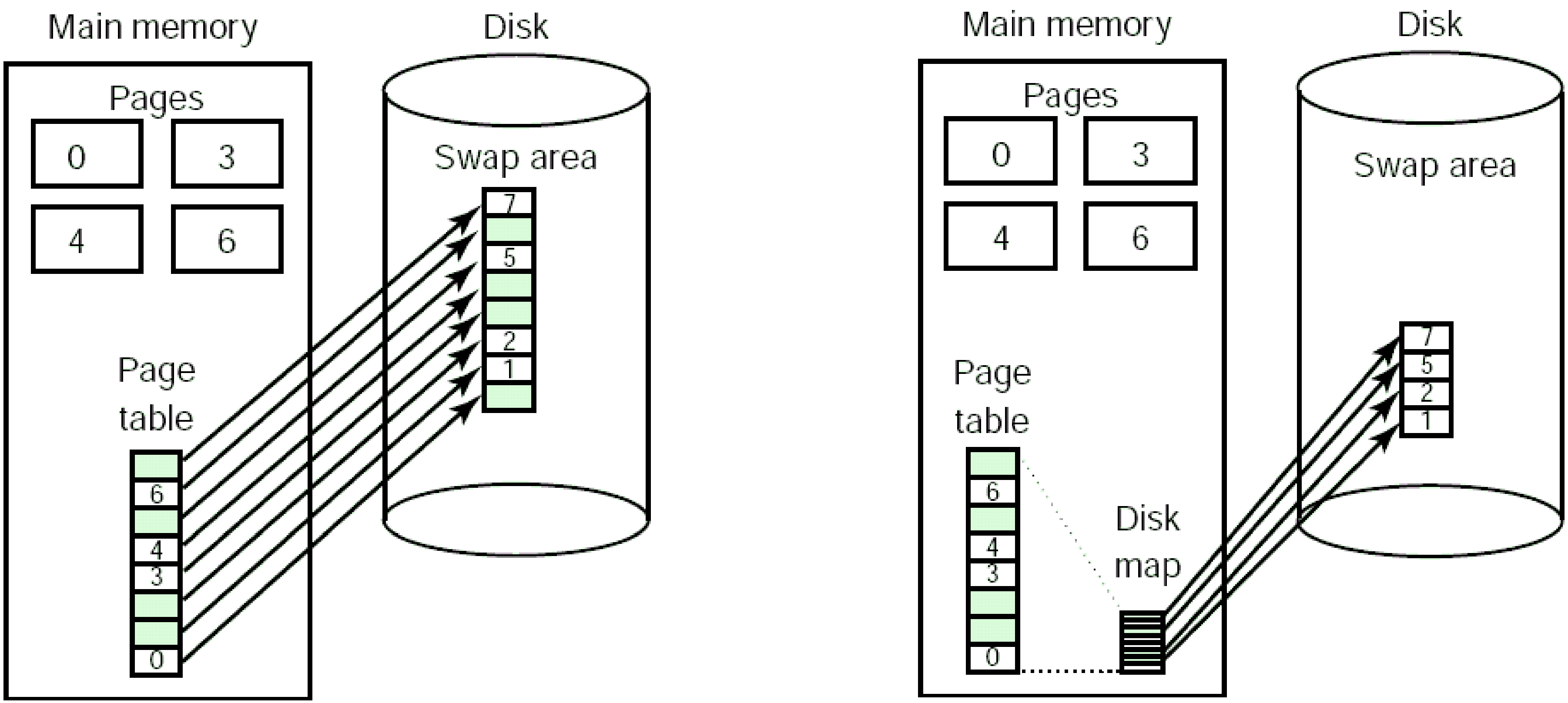
–Less often used memory blocks are stored on hard disc!

–May be stored

» in a file (less efficient, more flexible)

» in a specific hard disk partition (more efficient, less flexible)

Paged Memory



Picture from “Modern Operating Systems”, Andrew Tanenbaum

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