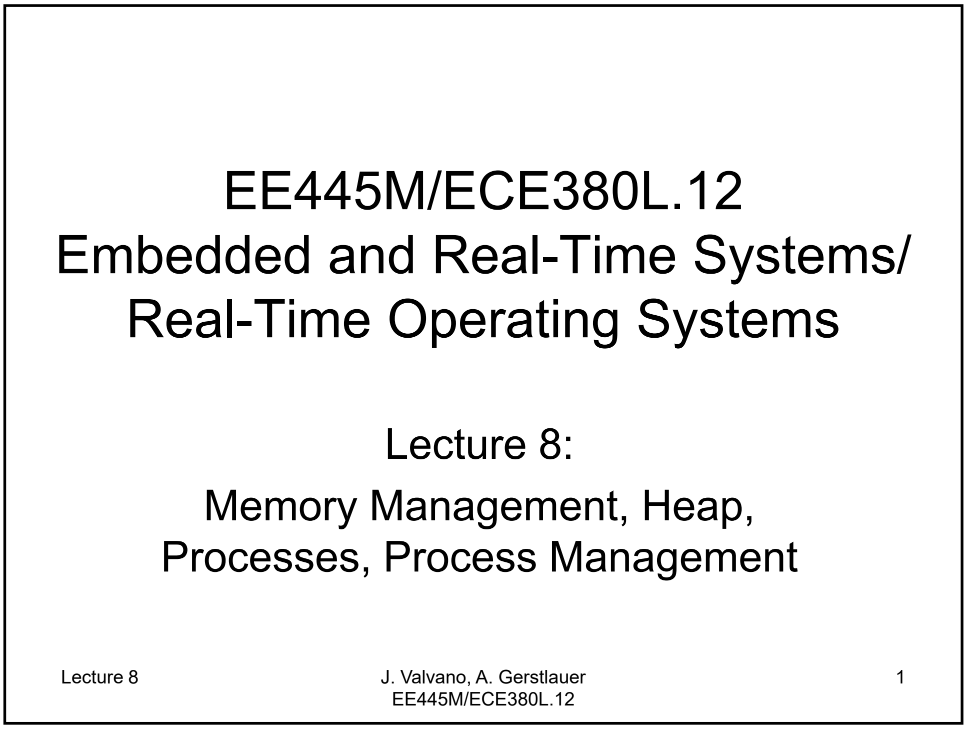
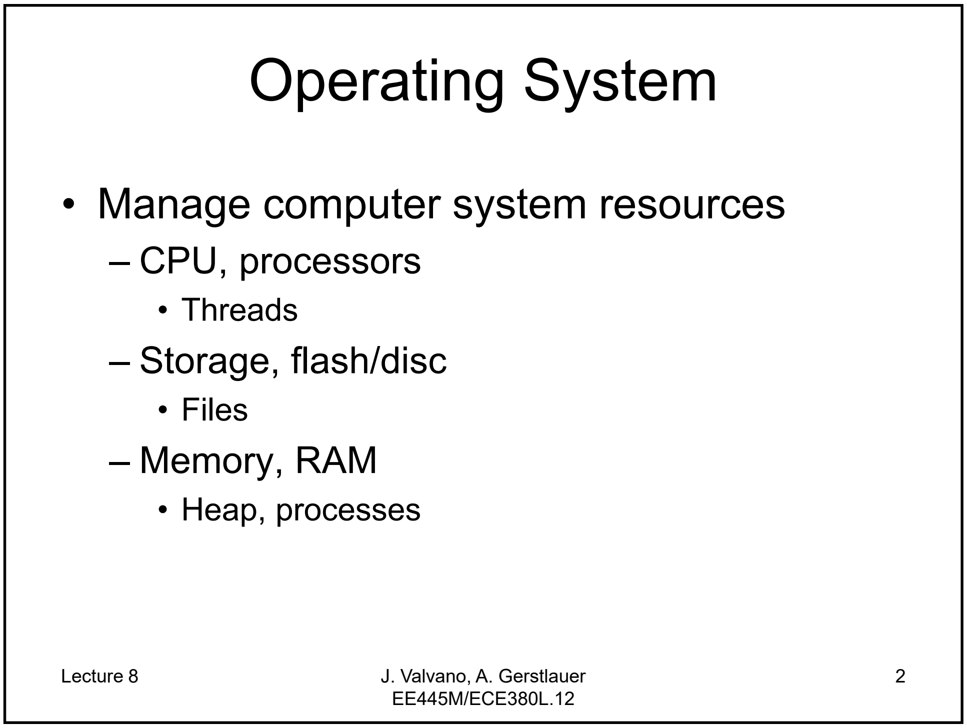


EE445M/ECE380L.12 Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 8:

Memory Management, Heap, Processes, Process Management

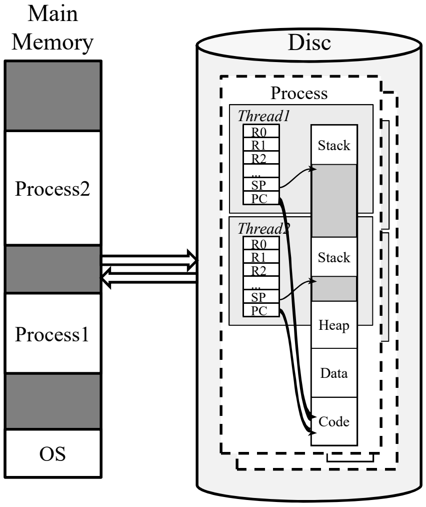


Operating System

- Manage computer system resources
  - CPU, processors
    - Threads
  - Storage, flash/disc
    - Files
  - Memory, RAM
    - Heap, processes

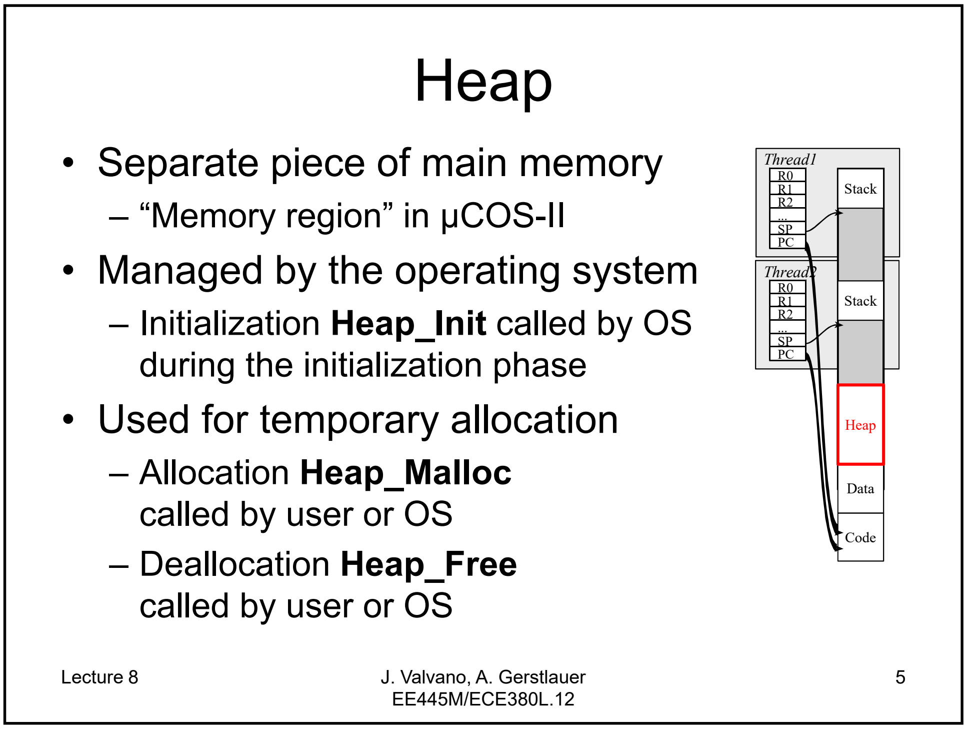
Memory Management

- Allocation
  - Static, permanent
    - Globals, OS code
  - Dynamic, temporary
    - Stack, heap, process code & data
- Sharing
  - Per-thread: stack
  - Per-program/-process: heap, code, data
- Protection
  - Access control



Fragmentation

- Internal
  - Wasted space inside allocated region
  - Convenience of the operating system
  - Contains no information
  - Wasted in order to improve speed or provide for a simpler implementation
- External
  - Unusable storage is outside the allocated regions
  - Largest block that can be allocated is less than the total amount of free space
  - Occurs because memory is allocated in contiguous blocks
  - Occurs over time as free storage becomes divided into many small pieces
  - Worse when application/OS allocates/deallocates blocks of storage of varying sizes



Heap

- Separate piece of main memory
  - “Memory region” in µCOS-II
- Managed by the operating system
  - Initialization **Heap_Init** called by OS during the initialization phase
- Used for temporary allocation
  - Allocation **Heap_Malloc** called by user or OS
  - Deallocation **Heap_Free** called by user or OS

Thread1
R0
R1
R2
...
SP
PC
Stack
Thread2
R0
R1
R2
...
SP
PC
Stack
Heap
Data
Code

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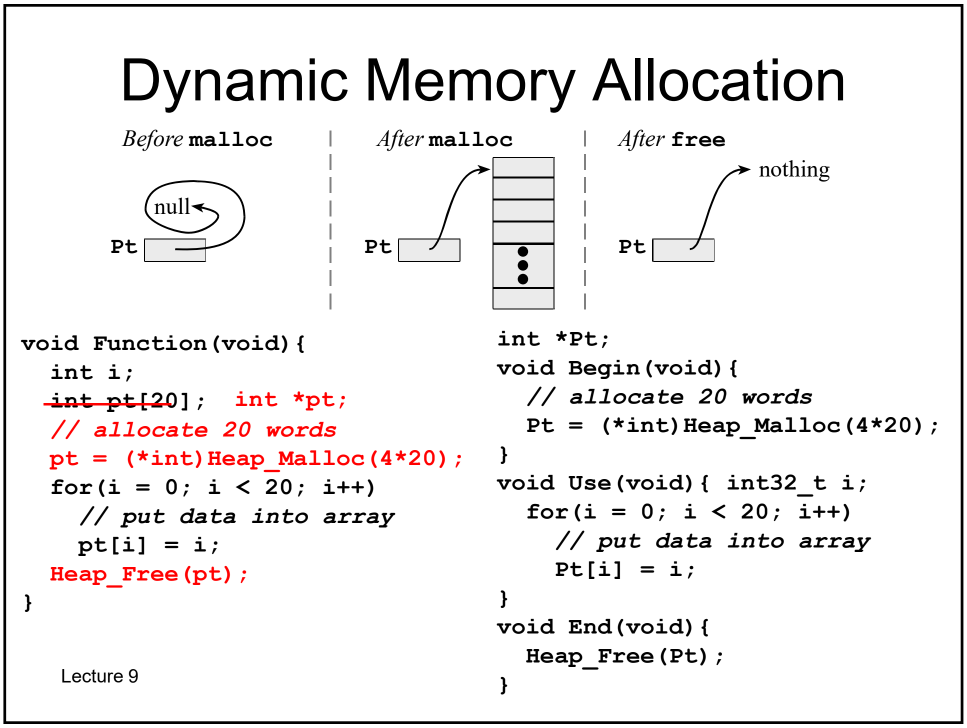


Dynamic Memory Allocation

Before malloc
null
Pt
After malloc
Pt
After free
nothing
Pt

```
void Function(void){
  int i;
  ~~int pt[20~~];  int *pt;
  // allocate 20 words
  pt = (*int)Heap_Malloc(4*20);
  for(i = 0; i < 20; i++)
    // put data into array
    pt[i] = i;
  Heap_Free(pt);
}
```

```
int *Pt;
void Begin(void){
  // allocate 20 words
  Pt = (*int)Heap_Malloc(4*20);
}
void Use(void){ int32_t i;
  for(i = 0; i < 20; i++)
    // put data into array
    Pt[i] = i;
}
void End(void){
  Heap_Free(Pt);
}
```

Lecture 9

Heap Manager

- Heap_Init
  - Allocate & initialize heap memory
    - Statically allocated storage assigned by compiler

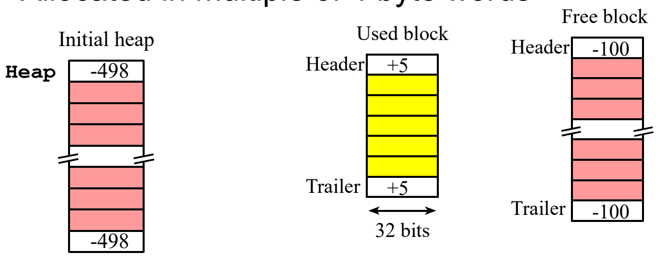
```
static long Heap[500]; // 2000 byte heap
```

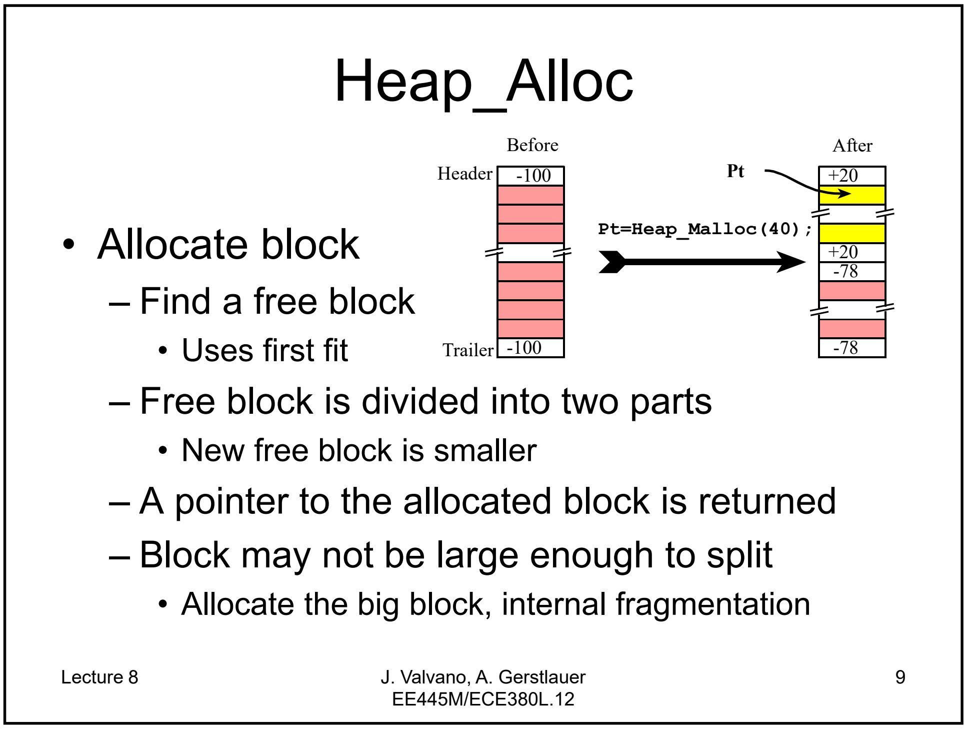
- Heap_Malloc
  - Allocate block in heap free space
    - Must use contiguous allocation
    - First fit, best fit, worst fit
- Heap_Free
  - Reclaim block into heap free space

Heap_4C123.zip

Heap Manager Example

- Blocks of variable size
  - Size counter at beginning/end of each block
    - Positive if used (allocated), negative if free
  - Internal fragmentation
    - Overhead for size header/trailer
    - Allocated in multiple of 4 byte words





Heap_Alloc

- Allocate block
  - Find a free block
    - Uses first fit
  - Free block is divided into two parts
    - New free block is smaller
  - A pointer to the allocated block is returned
  - Block may not be large enough to split
    - Allocate the big block, internal fragmentation

```
Pt=Heap_Malloc(40);
```

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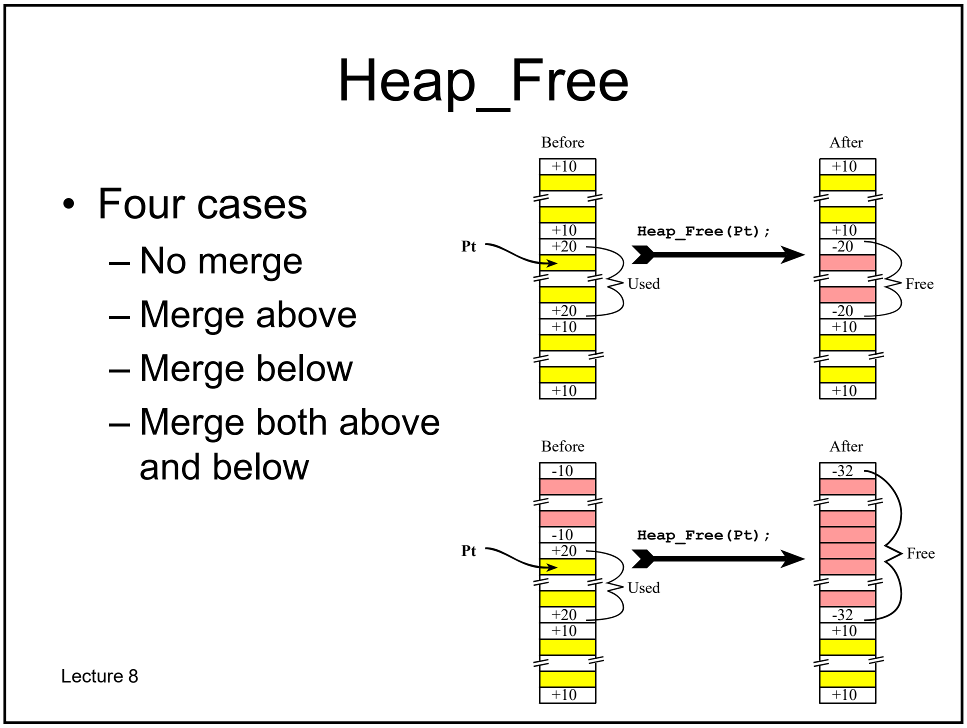


Heap_Free

- Four cases
  - No merge
  - Merge above
  - Merge below
  - Merge both above and below

```
Heap_Free(Pt);
```

```
Heap_Free(Pt);
```

Lecture 8

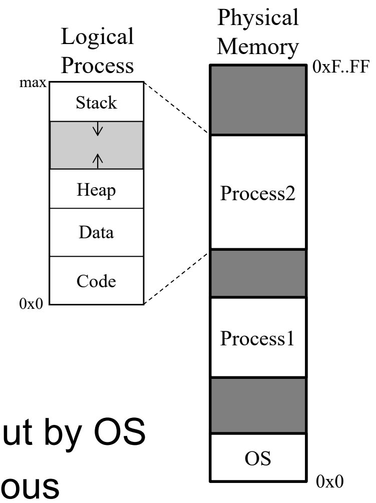
Knuth’s Buddy Allocation

- Maintain heap as collection of blocks each with a size of 2^m
- When user requests a block of size **n**
  - Find smallest block with $2^m \geq$ **n**
  - Split block into half until best fit
- When user releases a block
  - Merge with other half (buddy block of same order), if possible

Final Exam 2010

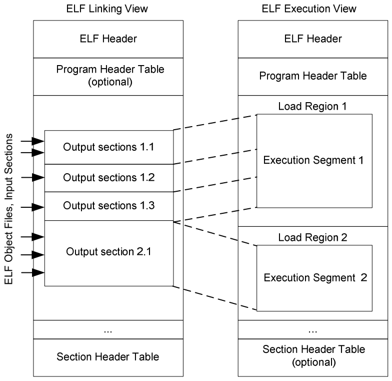
Processes

- OS manages processes
  - CPU scheduling
  - Code/data memory
- Independent programs
  - Separately compiled
  - Logical address space
- Brought in/out of memory
  - On load/exit, swapped in/out by OS
  - Contiguous or non-contiguous



ELF Files

- Executable and Linkable Format (ELF)
  - Linking: sections
    - Object files -> executables
    - Code (RO / .text)
    - Data (RW / .data)
    - Zero data (ZI / .bss)
    - String/symbol table
    - … (debug info) …
  - Execution: segments
    - Executable process image
    - Contiguous load regions
    - One or more sections per segment

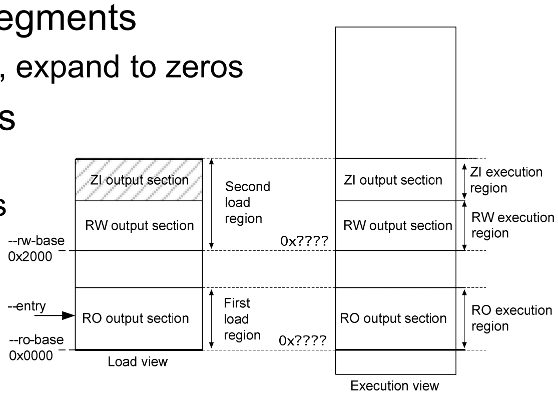


Source: infocenter.arm.com

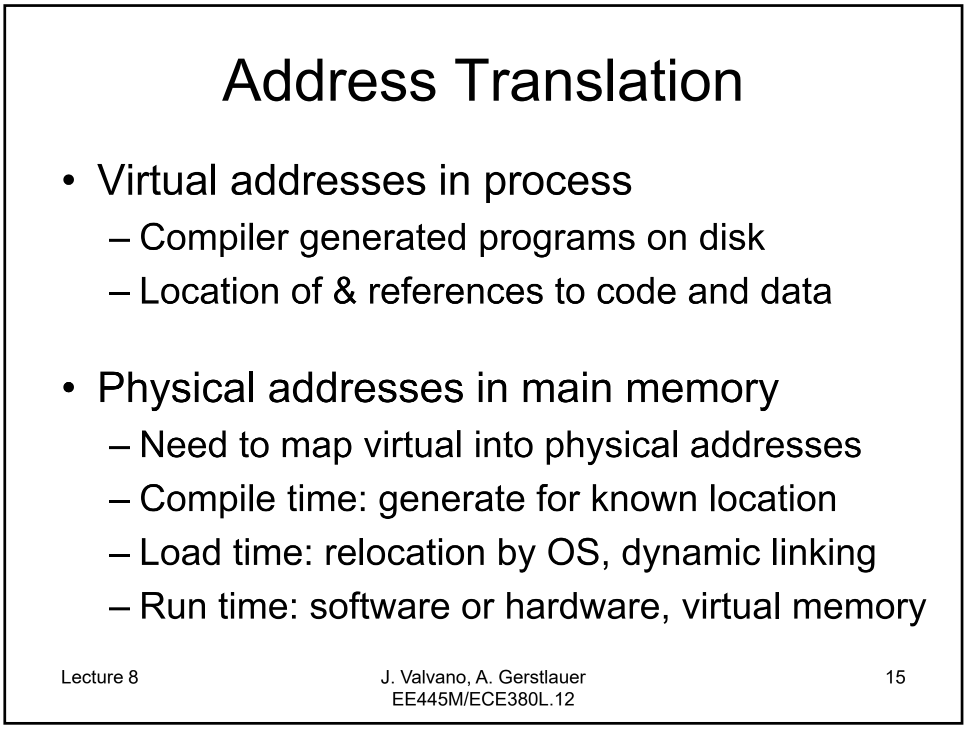
C:\Keil_v5\ARM\ARMCC\BIN\fromelf.exe --text User.axf

ELF Executable

- Process memory image
  - Load regions/segments
    - ZI empty in file, expand to zeros
  - Base addresses
    - Execution vs. load addresses
- Entry point
  - Starting address of execution

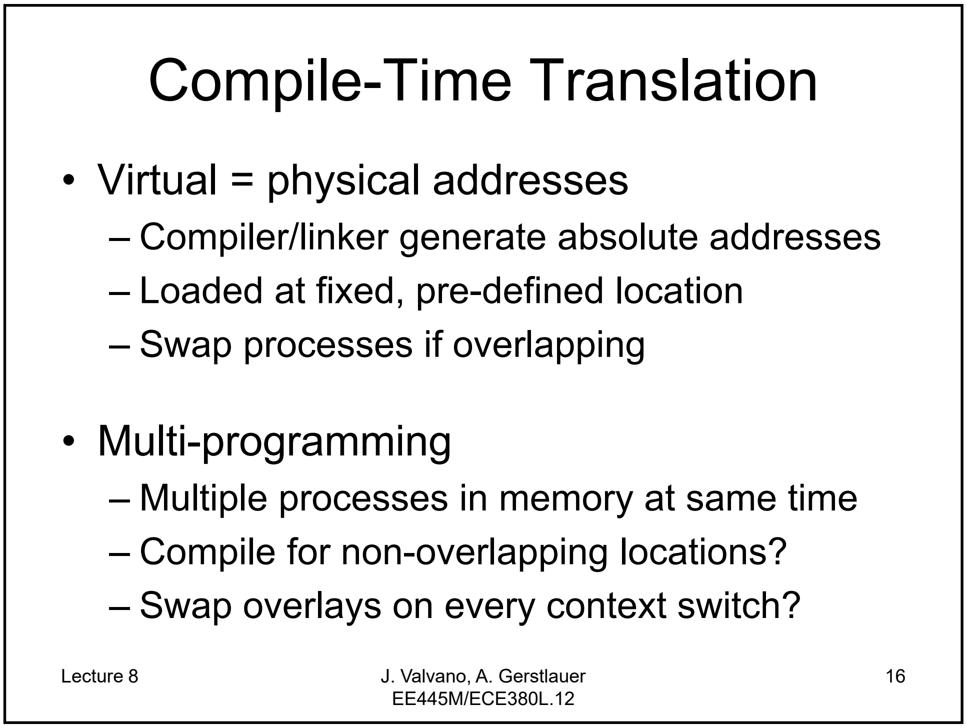


Source: infocenter.arm.com



Address Translation

- Virtual addresses in process
  - Compiler generated programs on disk
  - Location of & references to code and data
- Physical addresses in main memory
  - Need to map virtual into physical addresses
  - Compile time: generate for known location
  - Load time: relocation by OS, dynamic linking
  - Run time: software or hardware, virtual memory



Compile-Time Translation

- Virtual = physical addresses
  - Compiler/linker generate absolute addresses
  - Loaded at fixed, pre-defined location
  - Swap processes if overlapping
- Multi-programming
  - Multiple processes in memory at same time
  - Compile for non-overlapping locations?
  - Swap overlays on every context switch?

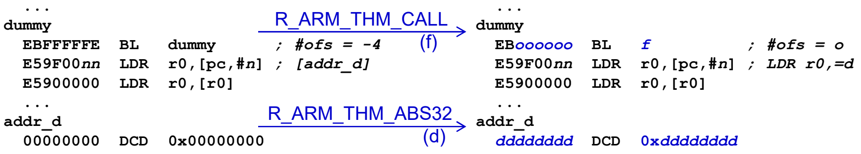
Run-Time Position Independence

- Position-independent code (PIC)
  - Code/RO segment compiled to run anywhere
  - All references within segment are PC-relative
    - Default for ARM short jumps: **B**, **BL**, **B*nn*** (not: **BX**)
    - Data within segment: **LDR R*x*,=*v*** / **[PC,#*n*]**
- Position-independent data
  - References from code to data/RW segment
  - R9 as static base (SB) register
    - Must point to base address of data/RW segment
    - All references as offsets added to R9/SB

```
 ...
LDR  r1,[r9,#ofs]
 ...
LDR  r0,=ofs
ADD  r0,r9,r0
LDR  r0,[r0]
 ...
```

Load-Time Relocation

- Relocatable process image
  - Compiler/linker place code/data in segments
    - ELF symbol table
  - Generate dummy addresses for references
    - ELF relocation table entries
  - Patch addresses with real location on load



```
  ...
dummy
  EBFFFFFE  BL   dummy          ; #ofs = -4
  E59F00nn  LDR  r0,[pc,#n]    ; [addr_d]
  E5900000  LDR  r0,[r0]
  ...
addr_d
  00000000  DCD  0x00000000
```

```
  ...
dummy
  EBoooooo  BL   f              ; #ofs = o
  E59F00nn  LDR  r0,[pc,#n]    ; LDR r0,=d
  E5900000  LDR  r0,[r0]
  ...
addr_d
  dddddddd  DCD  0xdddddddd
```

C:\Keil_v5\ARM\ARMCC\BIN\fromelf.exe -y -r User.axf

Dynamic Linking

- Resolve references to external symbols
  - Code / data shared between processes
  - OS kernel and shared libraries
- ELF dynamic linking segment (.dynamic)
  - Dynamically linked external symbol table
    - Addresses must be provided by loader
  - Standard relocation entries

```
C:\Keil_v5\ARM\ARMCC\BIN\fromelf.exe -y -r User.axf
```

OS Kernel Calls

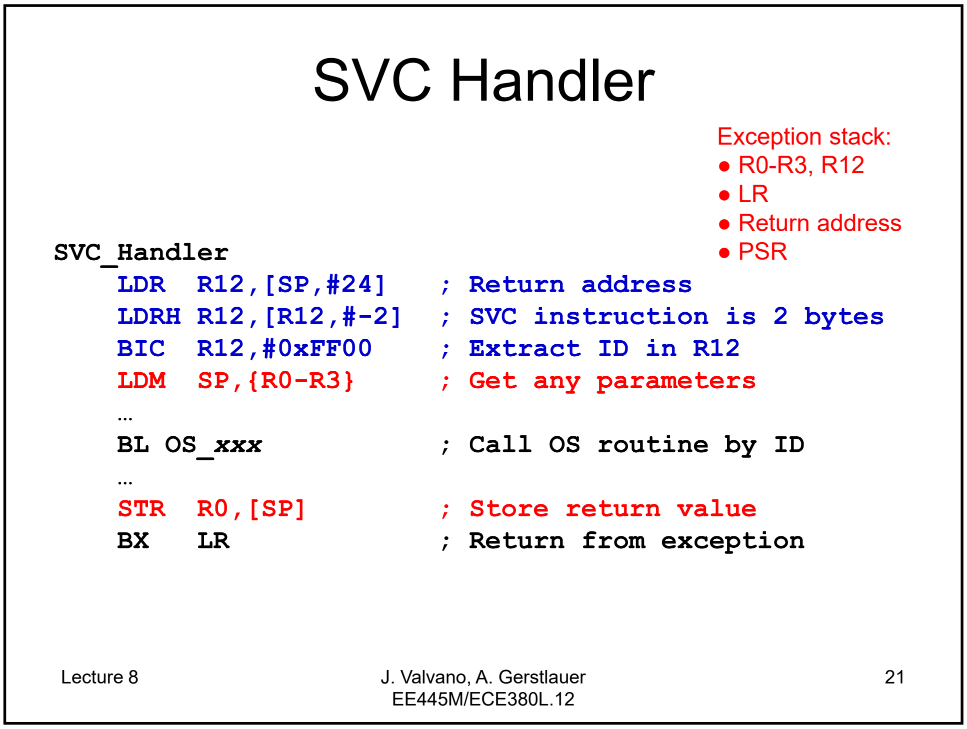
- Static or dynamic linking
  - Static linking to fixed location at compile time
  - Dynamic linking using relocation at load time
- Supervisor Calls
  - Trigger SVC exception from user code
  - SVC handler in kernel

```
EXTERN  ST7735_Msg [DYNAMIC]

; Long call RAM->ROM
Display_Msg
  LDR  R12,=ST7735_Msg
  BX   R12


OS_Sleep
  SVC  #2
  BX   LR

OS_Time
  SVC   #3
  BX    LR
```



SVC Handler

Exception stack:
- R0-R3, R12
- LR
- Return address
- PSR

```
SVC_Handler
    LDR  R12,[SP,#24]    ; Return address
    LDRH R12,[R12,#-2]   ; SVC instruction is 2 bytes
    BIC  R12,#0xFF00     ; Extract ID in R12
    LDM  SP,{R0-R3}      ; Get any parameters
    …
    BL OS_xxx            ; Call OS routine by ID
    …
    STR  R0,[SP]         ; Store return value
    BX   LR              ; Return from exception
```

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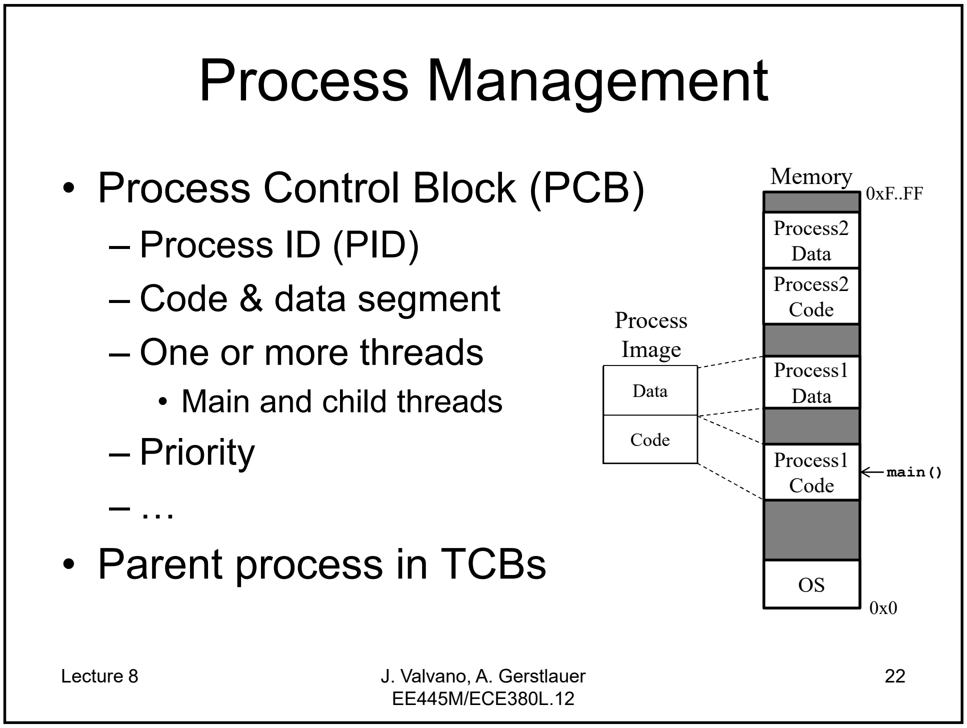

Process Management

- Process Control Block (PCB)
  - Process ID (PID)
  - Code & data segment
  - One or more threads
    - Main and child threads
  - Priority
  - …
- Parent process in TCBs

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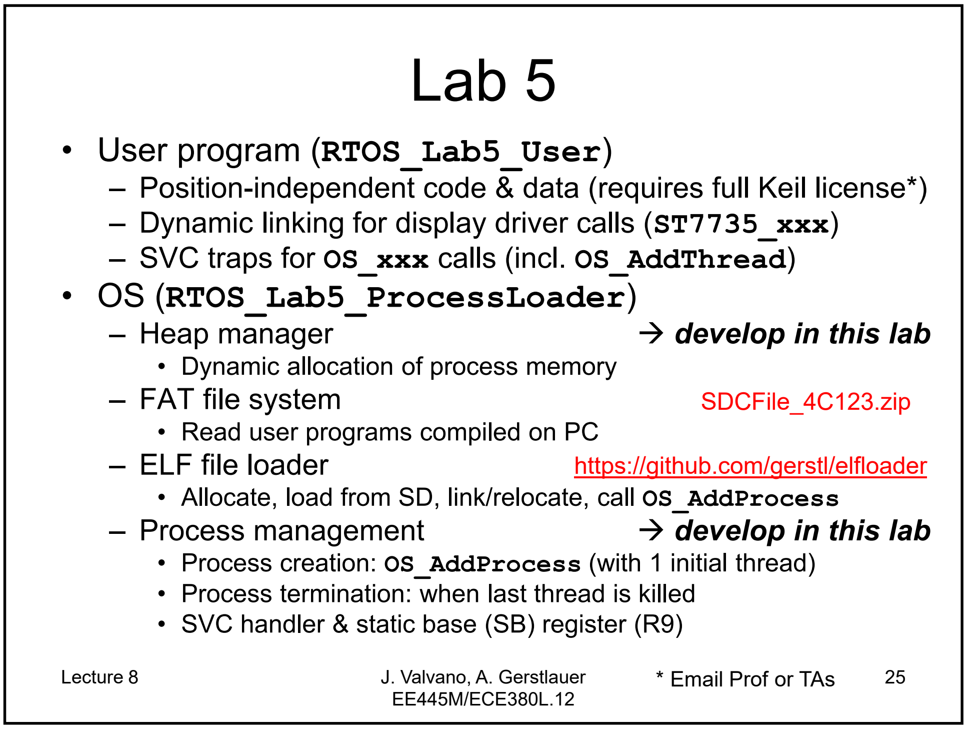
Process Creation

- Unix
  - **`fork()`**
    - Create copy of current process
  - **`exec()`**
    - Replace current process with image on disk
  - **init** process (process ID, PID = 0/1)
    - Mother of all processes created by OS
- Windows
  - **`CreateProcess()`**
    - Create new process and load program image

Process Termination

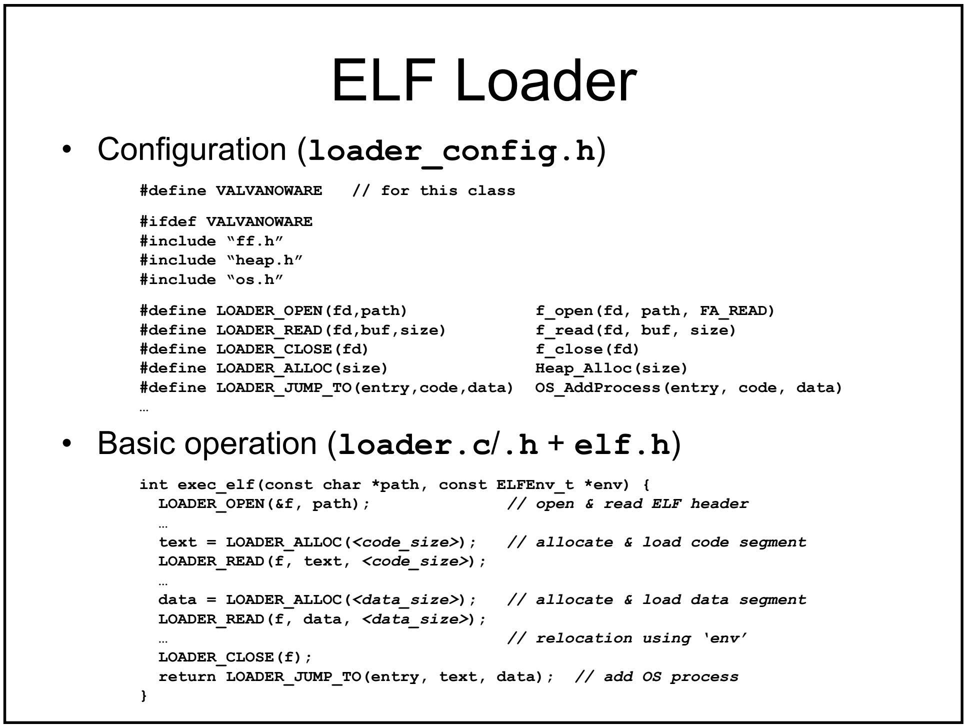
- Unix
  - **`exit()`**
    - Terminate current process
    - OS frees all resources (memory, thread, …)
    - Returns exit status
    - Automatically invoked on return from **`main()`**
- Windows
  - **`ExitProcess()`**
    - Likewise



Lab 5

- User program (**`RTOS_Lab5_User`**)
  - Position-independent code & data (requires full Keil license*)
  - Dynamic linking for display driver calls (**`ST7735_xxx`**)
  - SVC traps for **`OS_xxx`** calls (incl. **`OS_AddThread`**)
- OS (**`RTOS_Lab5_ProcessLoader`**)
  - Heap manager → ***develop in this lab***
    - Dynamic allocation of process memory
  - FAT file system SDCFile_4C123.zip
    - Read user programs compiled on PC
  - ELF file loader https://github.com/gerstl/elfloader
    - Allocate, load from SD, link/relocate, call **`OS_AddProcess`**
  - Process management → ***develop in this lab***
    - Process creation: **`OS_AddProcess`** (with 1 initial thread)
    - Process termination: when last thread is killed
    - SVC handler & static base (SB) register (R9)

* Email Prof or TAs



ELF Loader

- Configuration (**`loader_config.h`**)

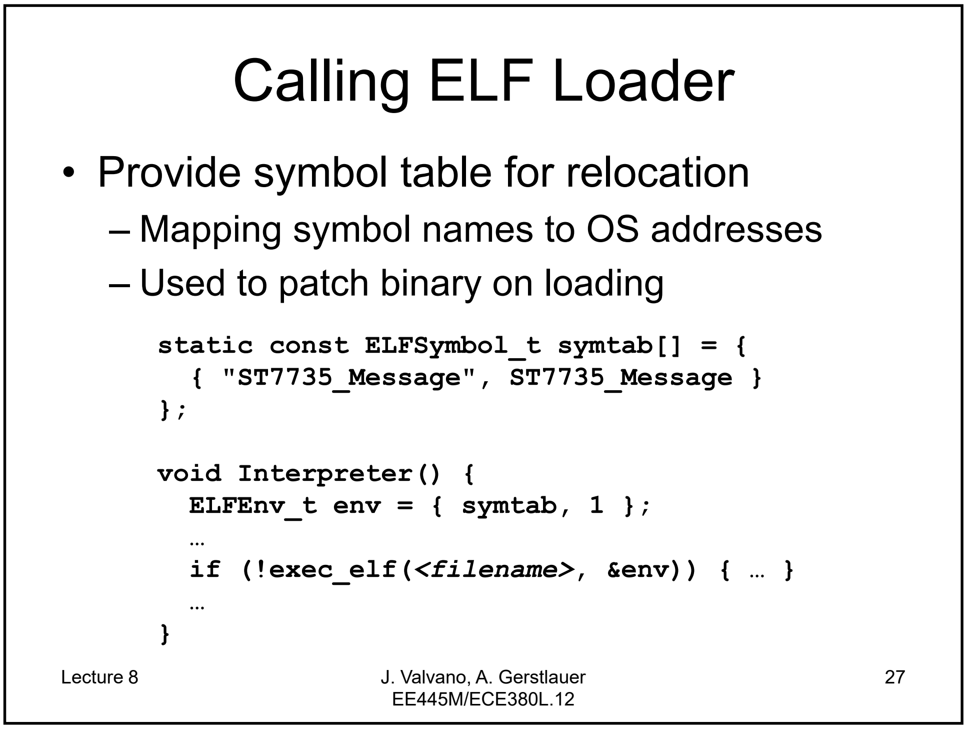
```
#define VALVANOWARE   // for this class

#ifdef VALVANOWARE
#include "ff.h"
#include "heap.h"
#include "os.h"

#define LOADER_OPEN(fd,path)              f_open(fd, path, FA_READ)
#define LOADER_READ(fd,buf,size)          f_read(fd, buf, size)
#define LOADER_CLOSE(fd)                  f_close(fd)
#define LOADER_ALLOC(size)                Heap_Alloc(size)
#define LOADER_JUMP_TO(entry,code,data)  OS_AddProcess(entry, code, data)
…
```

- Basic operation (**`loader.c`**/**`.h`** + **`elf.h`**)

```
int exec_elf(const char *path, const ELFEnv_t *env) {
  LOADER_OPEN(&f, path);               // open & read ELF header
  …
  text = LOADER_ALLOC(<code_size>);    // allocate & load code segment
  LOADER_READ(f, text, <code_size>);
  …
  data = LOADER_ALLOC(<data_size>);    // allocate & load data segment
  LOADER_READ(f, data, <data_size>);
  …                                    // relocation using 'env'
  LOADER_CLOSE(f);
  return LOADER_JUMP_TO(entry, text, data);  // add OS process
}
```



Calling ELF Loader

- Provide symbol table for relocation
  - Mapping symbol names to OS addresses
  - Used to patch binary on loading

```
static const ELFSymbol_t symtab[] = {
  { "ST7735_Message", ST7735_Message }
};

void Interpreter() {
  ELFEnv_t env = { symtab, 1 };
  …
  if (!exec_elf(<filename>, &env)) { … }
  …
}
```