

ECE445M/ECE380L.12 Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 7: Memory Management, Heap, Processes, Process Management

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Operating System

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

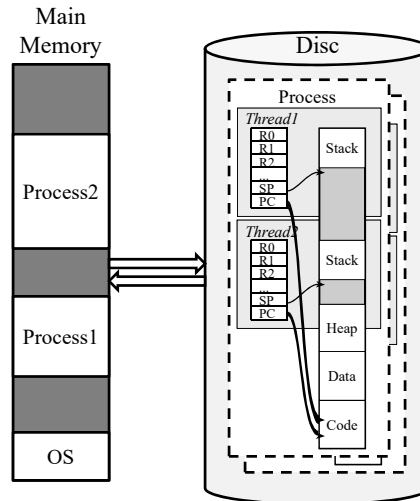
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Memory Management

- 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



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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

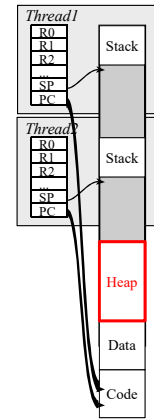
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Heap

- Separate piece of main memory
 - “Memory region” in μ COS-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

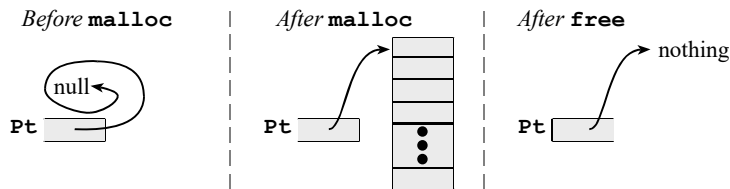


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Dynamic Memory Allocation



```
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);
}
```

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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

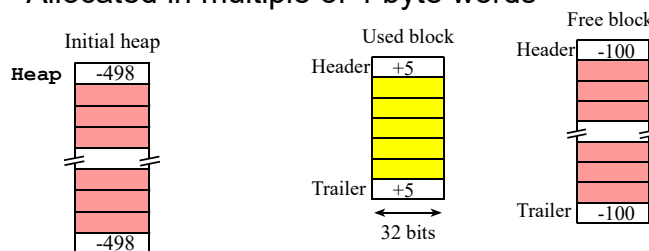
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Heap Manager Example

- 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



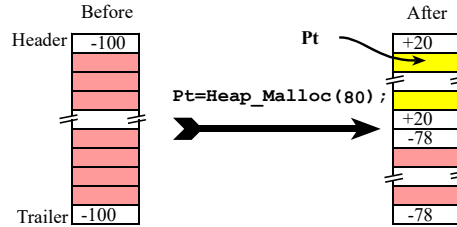
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Heap_Malloc

- 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



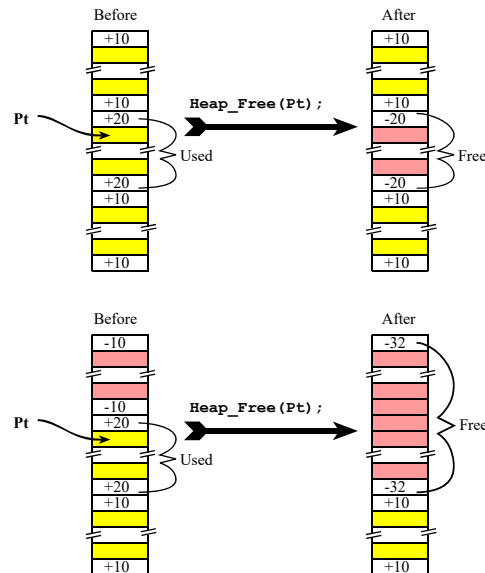
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Heap_Free

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



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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

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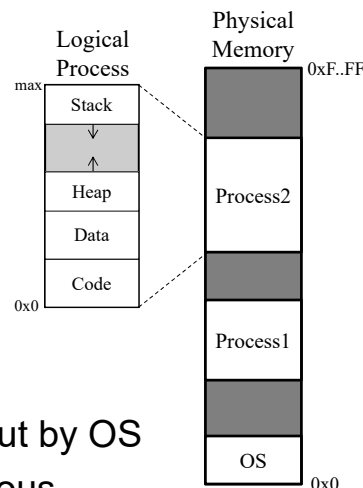
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Processes

- 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



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ELF Files

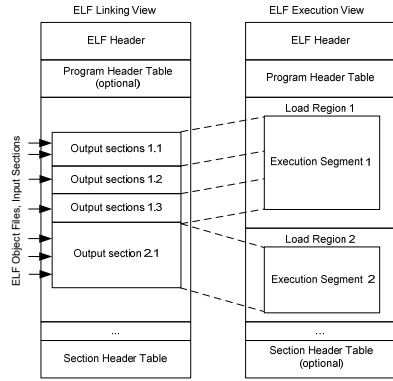
- Executable and Linkable Format (ELF)

- 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
```

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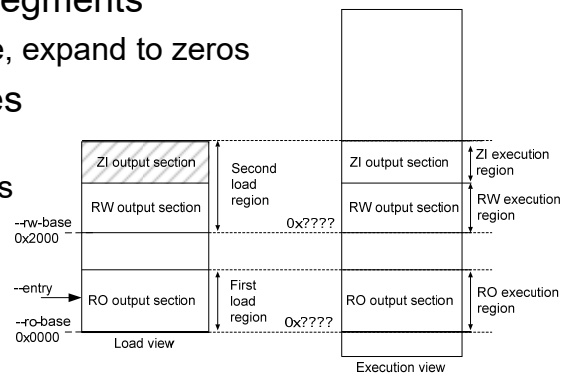
ELF Executable

- 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

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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

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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**, **Bnn** (not: **BX**)
 - Data within segment: **LDR Rx,=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]
...

```

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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?

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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                               R_ARM_THM_CALL  dummy
EBFFFFFFE BL dummy ; #ofs = -4 (f) → EB000000 BL f ; #ofs = 0
E59F00nn LDR r0, [pc, #n] ; [addr_d] E59F00nn LDR r0, [pc, #n] ; LDR r0, =d
E5900000 LDR r0, [r0] E5900000 LDR r0, [r0]
...
addr_d                               R_ARM_THM_ABS32  addr_d
00000000 DCD 0x00000000 (d) → dddddddd DCD 0xdddddddd
    
```

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

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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

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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
```

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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
    
```

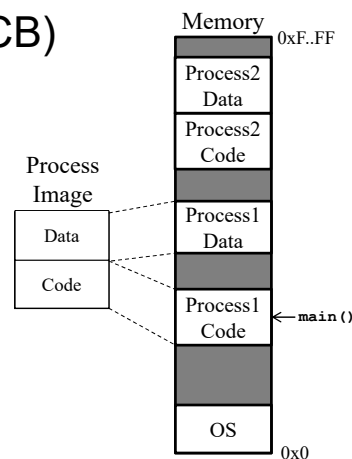
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Process Management

- 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

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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

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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)

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* Email Prof or TAs

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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)) { ... }
    ...
}
```

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