Programming Embedded Systems

Lecture 13
Overview of memory management

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Lecture outline

- Memory architecture of micro-controllers, in particular ARM CORTEX M3
- Memory management in embedded software
- Scoped memory in Real-time Java

Memory architecture of micro-controllers

(in particular considering ARM CORTEX M3)

Architecture

- MCUs often use a Harvard approach
  - Separate memory + buses for code (ROM) and data (RAM)
  - Code is executed “in place” (not copied to RAM before execution)
- Some amount of RAM/ROM is integrated in MCU
  - Typically: much ROM, little RAM
- Can be extended using external memory if needed

Read-only memory (ROM)

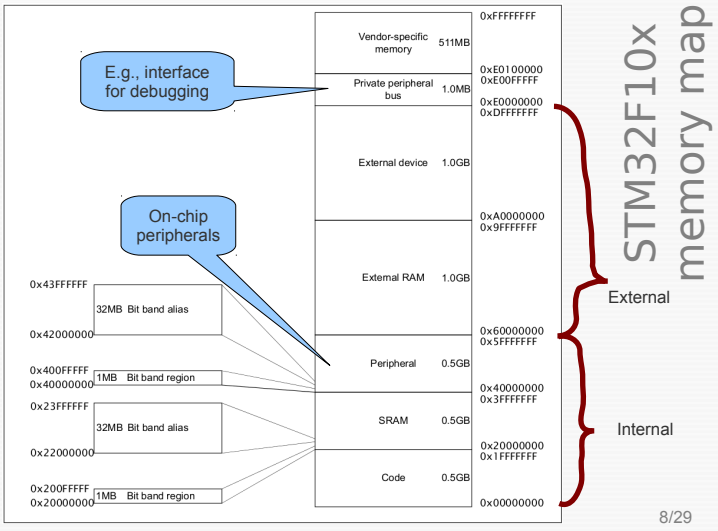
- Used to store code + static data (e.g., lookup tables)
- Unrestricted reading, separate procedure for writing
- Most common (today): flash memory
- Other kinds: PROM, UV-EPROM, EEPROM
- STM32F10x has 16KiB – 1MiB of ROM

Random-access memory (RAM)

- Used for data (stack, heap)
  - In principle also for code, but uncommon
- Two main kinds: SRAM, DRAM → Both very common
- Often accessed through a hierarchy of caches
  - Not so common for internal RAM in MCUs; difficult WCET analysis
- STM32F10x has 4KiB – 96KiB of internal SRAM, no cache (but low latency)

CORTEX M3 memory map

- RAM + ROM + special-purpose regions are uniformly mapped into a 32bit address space
- Details depend of CORTEX M3 version



Bit band interface

- Motivation: accessing individual bits in memory is cumbersome
  - Multiple instructions to set/reset bit, not atomic
  - But very often necessary: access control bits, locks, etc.

Bit band interface (2)

- **Bit band alias:** 32MiB region B that allows to access individual bits of a 1MiB region A
  - Every bit in A corresponds to a word (4 byte) in B
  - 0 ↔ `0x00000000`
  - 1 ↔ `0xFFFFFFFF`

Managing memory

Ways to manage memory

- At compile-time
- At startup-time
- Dynamically during runtime

Management at compile time

- Compiler/linker creates segments for different kinds of code/data
  - code (read-only, .text)
  - read-only data

  } put into ROM
  - read-write data
  - zero-initialised read-write data
- Further segments possible, as needed
- Code/data is directly flashed to MCU; RAM is initialised during start-up

Management at compile time

- Mapping of data to segments can be automatic or explicit (compiler-specific)
  - `#pragma` to specify segment
- Layout of segments in memory can be chosen

In MDK-ARM

- Zero-initialised read-write data (→ .bss, RAM):

```
char rwData[1024];
```

Default segment used

- Read-write data (→ .data, RAM):

```
char rwData[3] = {1, 2, 3};
```

- Read-only data (→ .constdata, ROM):

```
const char roData[3] = {1, 2, 3};
```


In embedded systems

- *Most common way of memory management:* Allocate all required memory at compile-time (in read-write or read-only segments, as needed)
- Little risk of runtime errors due to memory management (e.g., it is checked at compile-time whether enough memory is present)

Dynamic memory management

- Manual management: `malloc`, `free`
- More flexible, might be necessary in some cases
  - E.g., to implement OS functions: allocate stack for tasks, task control blocks, queues, semaphores, etc.

Dynamic memory management (2)

- Can cause various problems in embedded systems
  - Possibly insufficient memory at runtime
  - Fragmentation
  - Implementation of `malloc`, `free` can be of substantial size
  - `malloc`, `free` thread-safe?
- Compromise: no `free`, `malloc` is only used during startup

Dynamic memory management (3)

- FreeRTOS comes with 3 allocators (programmer can choose)
  - Heap_1: only `malloc` is implemented, memory is never freed
  - Heap_2: also provides `free`
  - Heap_3: in addition, thread-safe implementation
- Size of managed heap is specified in FreeRTOSConfig.h:

```
#define configTOTAL_HEAP_SIZE        ( ( size_t ) ( 17 * 1024 ) )
```


More high-level memory management?

Memory in Real-time Java

Real-time Java (RTSJ)

- Specification extending Java with features for real-time/embedded syst.
  - Implemented in some JVMs, JDKs: e.g., Oracle, IBM, jRate (based on GCJ)
  - Available for some micro-controllers: e.g., AVR ATmega8
- Version 1: JSR 1; version 1.1: JSR 282
- Different kinds of threads + memory
- Additional APIs

Real-time garbage collectors

- GCs for real-time systems are hard to get right
  - Interruptions by GC have to be scheduled correctly
  - GC must keep up with application
  - Overhead in memory consumption due to delayed deallocation
- Too large, complicated, not trustworthy
  → Only useful for soft real-time systems

Kinds of memory in RTSJ

- Heap memory
  - “Real-time” garbage-collected, otherwise same as in normal Java
- Immortal memory
  - Memory that is never reclaimed
- Scoped memory
  - Region-based memory management
  - Allocation using `new`, deallocation by deleting whole regions

Basic idea of scoped memory

- Organise memory in different **regions**
  e.g.,
  one region for long-living objects of a thread,
  one region for temporary objects of a method, ...
- Allocate memory as usual, but within regions (using `malloc`, `new`, etc.)
- Free memory by explicitly deleting whole regions

Scoped memory

- Every thread runs in a **memory allocation context**
  - Some amount of reserved memory
  - Chosen explicitly by programmer
  - Contexts can be entered and left
  - Nested contexts possible → stack
- While in allocation context A, objects created with `new` are stored in A

Scoped memory (2)

- Contents of an allocation context are cleared when the last thread exits the context

Example

```
LTMemory mem = new LTMemory(8*1024, 8*1024);
Action action = new Action();

for(int i=0; i<...; ++i)
  mem.enter(action);

class Action implements Runnable {
  public void run() {
    StringBuffer b = new StringBuffer ();
    b.append("xyz");
    // ...
  }
}
```

Allocates region of 8KiB memory

Execute some code with allocation context "mem". Region is cleared after each iteration

Allocation as normal; objects are stored in "mem"

Example of nested scopes

```
LTMemory longLiving = new LTMemory (...);

longLiving.enter(new Runnable() {
  public void run() {
    LTMemory temporary = new LTMemory (...);

    Object x = new ...;

    Runnable computation = new Runnable() {
      public void run() {
        Object y = new ...;
        // create loads of temporary objects
      }
    }

    temporary.enter(computation);

    Object z = new ...;
  }
});
```

Allocated in "longLiving"

Allocated in "temporary"

Further reading

- Peter C. Dibble, "Real-Time Java Platform Programming"