

Low-Level and Embedded Programming (1)

Real-Time and Embedded Systems (M)

Lecture 18

Lecture Outline

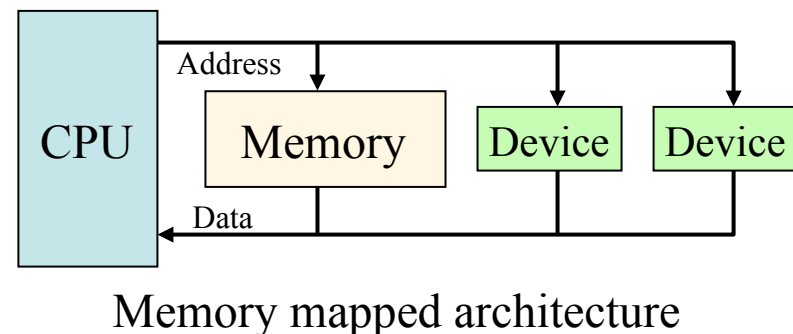
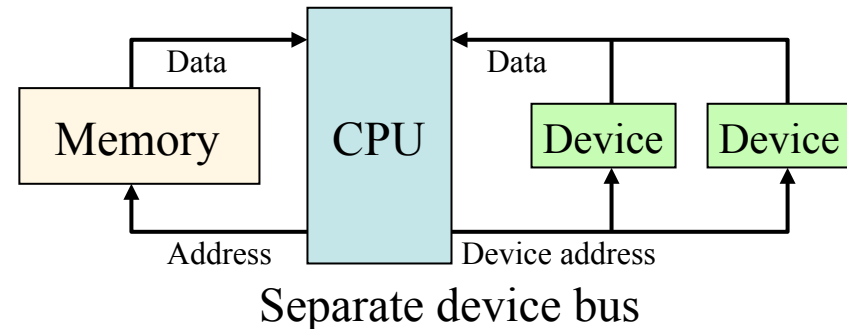
- Introduction to low level and embedded programming
- Interacting with hardware
- Interrupt and timer latency
- Memory issues
 - Protection
 - Virtual memory
 - Allocation, locking, leaks and garbage collection
 - Caches
- Power, size and performance constraints
- System longevity
- Development and debugging

Low Level and Embedded Programming

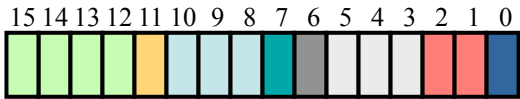
- Real time and embedded systems programming differs from conventional desktop applications programming
 - Must respect timing constraints
 - Must interact with environment
 - Often very sensitive to correctness and robust operation
 - Often very sensitive cost, weight, or power consumption
- Implications to consider:
 - Proofs of correctness, schedulability tests, etc.
 - Must consider system implementation issues, not just theory
 - Limited resources available
 - Low level programming environments typical
 - Require high awareness of system issues; interaction with hardware
 - Cannot necessarily depend on “common” language, operating system, or hardware features being present

Interacting with Hardware: Concepts

- Two architectures for device access
 - Separate device bus
 - Different assembler instructions to access devices than to access main memory
 - Separate physical connection to the device address/data bus
 - Example: Early Intel PC hardware; kept for backwards compatibility on modern systems, but rarely used
 - Program using inline assembler
 - Memory mapped I/O
 - Devices appear at some address in memory; access as-if any other part of system memory
 - Single set of assembler instructions for memory access; single address and data bus on processor
 - Example: most modern systems
 - Program using high level language



Interacting with Hardware: Concepts

- Two architectures for device control
 - Polling
 - Device sets bit in control register to indicate some action occurred
 - Software periodically inspects that register, decides whether to take some action
 - Interrupt driven
 - Device sets bit in control register to indicate some action occurred, then asserts a processor interrupt to notify software
 - Software responds to interrupt and takes appropriate action
 - Most current hardware is interrupt driven, but can usually be switched to polled mode (useful for high rate sources to avoid interrupt load, or if running a cyclic executive)
- Devices present control registers as bit fields
 - E.g. 

Bits	
15 - 12	: Errors
11	: Busy
10 - 8	: Unit select
7	: Done/ready
6	: Interrupt enable
5 - 3	: Reserved
2 - 1	: Device function
0	: Device enable
 - Requires bit-level manipulation to access fields in control word
 - Address of control word
 - Number of control words
 - Width of control words in bits
 - Bit ordering within control word
 - Some bits may be read- or write-only; some may change when read

Interacting with Hardware: C

```
struct {
    short errors      : 4;
    short busy        : 1;
    short unit_sel    : 3;
    short done        : 1;
    short irq_enable  : 1;
    short reserved    : 3;
    short dev_func    : 2;
    short dev_enable  : 1;
} ctrl_reg;

int enable_irq(void)
{
    ctrl_reg *r = 0x80000024;
    ctrl_reg tmp;

    tmp = *r;
    if (tmp.busy == 0) {
        tmp.irq_enable = 1;
        *r = tmp;
        return 1;
    }
    return 0;
}
```

- C allows definition of bit fields and explicit access to a particular memory address using pointers
 - Example on left shows simple manipulation of a control word at address 0x80000024
- Allows implementation of device drivers and interrupt handlers
- Illusion of portable code: standard C does not specify:
 - Size of basic types
 - Including number of bits in a byte
 - Bit and byte ordering
 - Alignment or atomicity of memory access
 - (defined by compiler/OS for each platform)

Interacting with Hardware: Ada

```
type ErrorType    is range 0..15;
type UnitSelType  is range 0..7;
type ResType      is range 0..7;
type DevFunc      is range 0..3;
type Flag         is (Set, NotSet);
type ControlRegister is
record
  errors      : ErrorType;
  busy        : Flag;
  unitSel     : UnitSelType;
  done        : Flag;
  irqEnable   : Flag;
  reserved    : ResType;
  devFunc     : DevFunc;
  devEnable   : Flag;
end record;

for ControlRegister use
record
  errors      at 0*Word range 12..15;
  busy        at 0*Word range 11..11;
  unitSel     at 0*Word range  8..10;
  done        at 0*Word range  7.. 7;
  irqEnable   at 0*Word range  6.. 6;
  reserved    at 0*Word range  3.. 5;
  devFunc     at 0*word range  1.. 2;
  devEnable   at 0*Word range  0.. 0;
end record;

for ControlRegister'Size use 16;
for ControlRegister'Alignment use Word;
for ControlRegister'Bit_order use Low_Order_First;
...
```

- Ada has extensive support for low-level hardware access and interrupt handlers
 - Precise control over record layout in memory, byte ordering, bit size of types, etc.
 - Perhaps overly verbose...?
 - Facilities for interrupt handlers in the language
- Allows portable code to be written that manipulates hardware devices

Interacting with Hardware

- Language support for portable hardware access conceptually nice, but less useful than might be expected
 - Real time embedded systems typically tied to platform due to specialist hardware
 - Little need for portability at the language level, since underlying system unique
- Main advantage of Ada: strong type checking for hardware access

Interrupt and Timed Task Latency

- Devices typically request service using interrupts
 - Need predictable worst-case bounds on service time, otherwise cannot reason about the system
 - Both interrupt latency and task scheduling latency
- Examples:
 - Linux has $\sim 600\mu\text{s}$ typical interrupt handler latency, often runs with 100Hz clock for task scheduling (i.e. $10000\mu\text{s}$ latency)
 - Long history of problems with system call latency, causing tasks to block for hundreds of milliseconds on certain device accesses
 - Resolved for most common devices, but still unpredictable (and long) latency with uncommon hardware
 - RTLinux claims a maximum $15\mu\text{s}$ interrupt handler latency, all scheduled tasks execute within at most $35\mu\text{s}$ of their scheduled time
 - Other hard real-time operating systems offer similar guarantees

Interrupt and Timed Task Latency

- Why such a difference?
 - Preemptable microkernel, with single address space
 - No context switch, user-to-kernel mode, overhead
 - No virtual memory or memory protection
 - No paging delays
 - No delays while page tables adjusted
 - Device drivers designed with minimal non-preemptable sections
 - Light-weight, prioritised, threads fire in response to interrupts
- Does it matter? It depends on the application...

Memory Protection

- Many embedded systems use a single flat address space
 - Applications, shared libraries, kernel, devices all visible
 - A system or library call is equivalent to a function call



- Makes system calls, interrupts, very fast and predictable
 - No context switch to kernel mode
 - No adjustment of MMU page tables
- Consequences
 - No isolation between applications, or between applications and the kernel
 - A change to one part implies that the entire system has to be revalidated; difficult as systems become larger
- Some systems offer limited protection
 - Read only mapping of program/system text; IRQ vectors
 - Optional full memory protection

Memory Protection

- Consequences of offering memory protection:
 - Unpredictable latency
 - May take longer to task switch to/from a protected task
 - Memory overhead
 - Protection provided on a per-page basis, leads to wastage
 - Overhead of maintaining the page tables and protection maps
 - Code overhead
 - Operating system is required to trap illegal access and recover system to a safe state
- Which is easiest: proving the system correct, or writing handlers to safely recover from all possible failures, delays?

Virtual Memory: Address Translation

- Two aspects to virtual memory:
 - Address translation
 - Paging to disk
- Address translation is the act of making a fragmented block of physical memory appear to be a single contiguous block
 - Useful in dynamic systems: enables requests for large blocks of memory to be allocated when there is no physically contiguous block available
 - Adds overhead, since system must manage address translation tables
 - Uses memory, increases context switch time
 - Complicates DMA device access
- Better to pre-allocate static memory pools for real-time tasks
 - Manage the sub-division of address space within the application

Virtual Memory: Paging to Disk

- Disk based virtual memory is supported by many systems that run both real time and non-real time tasks
 - Paging to disk clearly impact real-time performance
 - Unpredictable delays, depending whether page is in memory or on disk
- Systems usually provide ability to (selectively) prevent paging
 - Examples:
 - POSIX allows regions of memory to be locked into RAM and preventing from paging using `mlock(addr, len)` and `mlockall()`
 - Windows allows all memory owned by a particular thread to be locked

Memory Leaks and Garbage Collection

- An embedded system has to run for a long period of time, without user intervention
- Resource leaks can be problematic:
 - C programs typically have memory leaks due to programmer error
 - Significant problem in long-lived or resource constrained systems
 - Better to pre-allocate static buffers, avoid the chance of a memory leak
 - Be *very* careful to free memory and other resources after use
 - Do you *always* check for out of memory errors? And recover gracefully?
 - Remember the recovery code cannot allocate memory
 - This may include the stack frame needed to make a function call!
 - Modern languages use garbage collection to avoid resource leaks
 - Has a poor reputation due to unpredictable delays when collection occurs
 - E.g. Real Time Java provides ability to allocate objects from a non-garbage collected memory pool, with manual free function, to ensure predictability
 - However, real-time garbage collection algorithms – with predictable latency, at controlled times – *do* exist

Memory: What is a Small System?

- Embedded systems often very constrained compared to typical desktop computers
 - You may be running on an 8 bit processor, with kilobytes of RAM
 - Operating system typically optimised for the environment, provides only minimal required functions
 - The QNX 4.x microkernel is approximately 12kbytes in size
 - The VRTX microkernel is typically 4-8kbytes in size

– For comparison:

```
# uname -srm
Linux 2.4.25 i686
# cat tst.c
int main()
{
    return 0;
}
# gcc tst.c -o tst
# ls -l tst
-rwxrwx--- 1 csp  csp  4507 Mar 16 00:51 tst
```

Memory: What is a Small System?

- Example: Renesas H8/3217
 - 16 - 60kBytes ROM
 - 512Bytes - 2kBytes SRAM
 - 10-16MHz clock
 - 1 x 16-bit timer; 3 x 8-bit timer
 - 1 x Watchdog timer
 - 2 x UARTS; 2 x I²C interfaces
- The H8/3217 provides a solution to applications where a cost effective solution with up to 4 channels of serial communications is required
 - Monitors, Televisions
 - Radios, Stereo systems
 - Set Top Box system controllers
- The H8/3217 is a member of the H8/300 series of **high performance** 8/16-bit CPU's. This device is used in applications where a high level of communications capability is required
- The combination of 2 high speed UARTS capable of transmitting data asynchronously at 500k baud and two channels of I²C capable of transmitting at over 400k bits per second make this device **a powerful communications processor**

Effects of Cache

- You may be running on a more modern processor
 - PowerPC 405CR embedded processor
 - 32 bit RISC processor, compatible with desktop PowerPC
 - 133MHz or 266MHz clock speed
 - 500mW power consumption
 - Compare: Pentium M (“Centrino”) processor consumes up to 24.5W
 - CodePack™ compression of executables
 - Likely has several megabytes of memory
 - [Various types of PowerPC and ARM processors commonly used]
 - Relatively cheap, comparatively high performance, low power
- Has a small cache, which you may want to disable:
 - Processor and memory speeds are closely matched
 - Compare to desktop processor, with order magnitude difference
 - Simpler to predict memory access times without the cache
 - Cache improves average response times, but introduces unpredictability

Power, Size and Performance Constraints

- Embedded systems often battery powered or power sensitive
 - What influences power consumption?
 - Power consumption \propto (clock speed)²
 - Memory size and processor utilization
- May have to be physically small and/or robust
- May have strict heat production limits
- May have strict cost constraints
 - That processor is slower, but 10¢ cheaper, the production run is 1 million, you paid your salary for the next couple of years...
- Used to throwing hardware at a problem, and writing inefficient – but easy to implement – software
 - Software engineering based around programmer productivity
 - The constraints may be different in the embedded world...

System Longevity

- Embedded systems often safety critical or difficult to upgrade
 - Medical devices
 - Automotive or flight control
 - Railway signalling
 - Industrial machinery
 - CD or DVD player
 - Washing machine
 - Microwave oven
 - Pacemaker
- May need to run for several years, in environment where failures either cause injury or are expensive to fix
 - Can you guarantee your system will run for 10 years without crashing?
 - Do you check all the return codes and handle all errors?
 - Fail gracefully?

Development and Debugging

- Embedded systems typically too limited to run a compiler
- Develop using a cross compiler running on a PC, download code using a serial line, or by burning a flash ROM and installing
- Often limited debugging facilities:
 - Serial line connection to host PC
 - LEDs on the development board
 - Logic analyser or other hardware test equipment
- Formal methods, proofs or correctness, simulations become more important when real system so difficult to analyse

Summary

- Low level and embedded programming
 - Control register access, bit packing, alignment, etc.
 - Interrupts
 - Memory
 - Address translation
 - Paging and virtual memory
 - Allocation and garbage collection
 - Caching
- Consider:
 - Systems issues, how features that improve general purpose performance hinder real time systems
 - Constraints on embedded systems, differences in engineering compared with general purpose systems