# Low-Level and Embedded Programming (1)

Real-Time and Embedded Systems (M)

Lecture 18

UNIVERSITY
*of*
GLASGOW



# 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

Copyright © 2006 University of Glasgow
All rights reserved

# Low Level and Embedded Programming

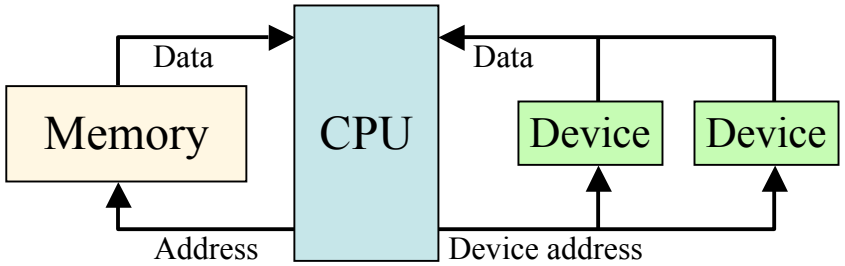
- Real time and embedded systems programming differs from conventional desktop applications programming
  - Must respect timing constraints
  - Must interact with environment
  - Often very sensitive to correctness and robust operation
  - Often very sensitive cost, weight, or power consumption

- 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

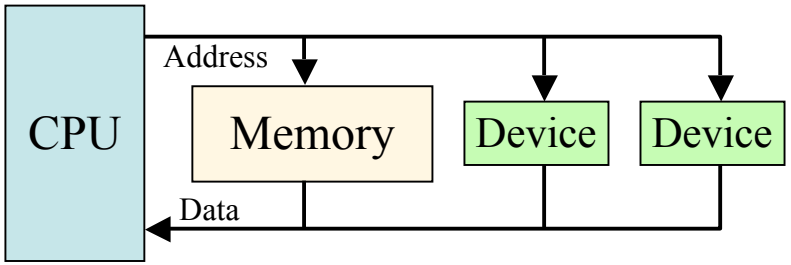
Copyright © 2006 University of Glasgow
All rights reserved.

# 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



Separate device bus

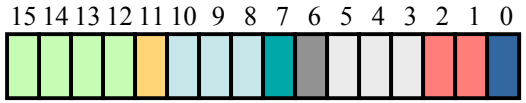


Memory mapped architecture

Copyright © 2006 University of Glasgow
All rights reserved

# 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

Copyright © 2006 University of Glasgow
All rights reserved.

# 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 bites in a byte
  - Bit and byte ordering
  - Alignment or atomicity of memory access
  - (defined by compiler/OS for each platform)

Copyright © 2006 University of Glasgow
All rights reserved

# 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

Copyright © 2006 University of Glasgow
All rights reserved

# 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

Copyright © 2006 University of Glasgow
All rights reserved.

# 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 ~600μs typical interrupt handler latency, often runs with 100Hz clock for task scheduling (i.e. 10000μs 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 15μs interrupt handler latency, all scheduled tasks execute within at most 35μs of their scheduled time
    - Other hard real-time operating systems offer similar guarantees

Copyright © 2006 University of Glasgow
All rights reserved

# 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…

Copyright © 2006 University of Glasgow
All rights reserved.

# 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

Copyright © 2006 University of Glasgow
All rights reserved

# 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?

Copyright © 2006 University of Glasgow
All rights reserved.

# 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

Copyright © 2006 University of Glasgow
All rights reserved

# 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

Copyright © 2006 University of Glasgow
All rights reserved.

# 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

Copyright © 2006 University of Glasgow
All rights reserved

# 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
```

Copyright © 2006 University of Glasgow
All rights reserved

# 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

[Adapted from Renesas website]

Copyright © 2006 University of Glasgow
All rights reserved

# 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

Copyright © 2006 University of Glasgow
All rights reserved

# 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…

Copyright © 2006 University of Glasgow
All rights reserved

# System Longevity

- Embedded systems often safety critical or difficult to upgrade

| | |
|---|---|
| Medical devices | CD or DVD player |
| Automotive or flight control | Washing machine |
| Railway signalling | Microwave oven |
| Industrial machinery | 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?

Copyright © 2006 University of Glasgow
All rights reserved.

# 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

Copyright © 2006 University of Glasgow
All rights reserved

# 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

Copyright © 2006 University of Glasgow
All rights reserved