University of Glasgow | School of Computing Science

Evolution of Systems Programming

Advanced Operating Systems (M)
Lecture 11

Real-time and Embedded Programming

- Real time and embedded systems differ from conventional desktop applications
  - Must respect timing constraints – scheduling theory in prior lectures
  - Must interact with hardware and the environment
  - Often very sensitive to correctness and robust operation
  - Often very sensitive to cost, weight, or power consumption
- Implications to consider:
  - Proofs of correctness, scheduling tests, etc.
  - Limited resources: low level programming environments; high awareness of systems issues; interaction with hardware
  - Challenges imposed on operating system and programming environment by resource constraints and programming model

Yes, but...

- Continued advances in hardware, supporting both traditional embedded systems and new ubiquitous computing platforms
  - Moore's "law" shows no sign of abating
- Where are corresponding advances in software?
  - Desirable to raise abstraction level: ease program development and increase productivity, employ modern software engineering techniques and high(er) level languages
  - Simplify proofs of correctness

Evolution of Systems Programming

- Use increased system performance to provide:
  - Language and runtime support for low-level programming: interrupt handling; device access; etc.
  - Language and runtime support for automatic memory management, including real-time garbage collection
  - Language and runtime support for real-time systems: periodic threads; timed statements/timing annotations
  - Language and runtime support for concurrency: type systems to ensure correctness; message passing; transactional memory
- Emphasis on real-time, embedded, and ubiquitous systems
  - iOS and Android begin to show the possibilities – but, what next?

Low-level Programming: Device Access

- Various approaches to low-level hardware access
  - C-style: simple and expressive, non-portable
  - Ada: verbose, precise specification, portable
- Can language and runtime support help?
  - Well-defined integral types and easy support for bit manipulation desirable
  - Clear that object-oriented ideas useful for device driver families:
    - MacOS X I/O Kit – object oriented device drivers using a subset of C++ (without exceptions, multiple inheritance, templates, RTTI) (http://developer.apple.com/library/mac/documentation/DeviceDrivers/Conceptual/IOKitFundamentals/IOKitFundamentals.pdf)
    - Linux uses object-based approach for many drivers, implemented in C: higher performance, but MacOS X drivers easier to write
    - Simple object-oriented extensions to C to define sub-class relationships that can abstract out common behaviour would provide great benefit
  - Better ways to represent state machines, timeouts, and interrupt handlers at language level likely beneficial → concurrency and real-time support

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Low-level Programming: Interrupt Handling

- Interrupt handling system dependent
  - Few systems support linking user code into interrupt handlers
  - Ada real-time systems annex a notable exception:

```
package Ada.Interrupts is
  type Interrupt_Id is ...;
  type Parameterless_Handler is access protected procedure;

  function  Is_Reserved(Interrupt:Interrupt_Id) return Boolean;
  function  Is_Attached(Interrupt:Interrupt_Id) return Boolean;
  function  Current_Handler(Interrupt:Interrupt_Id) return Parameterless_Handler;
  procedure Attach_Handler(Handler:Parameterless_Handler, Interrupt:Interrupt_Id);
  procedure Detach_Handler(Interrupt:Interrupt_Id);
  ...
end Ada.Interrupts;
```

  - Could provide similar standard facilities in other languages
    - Must vector through hardware abstraction layer and kernel, but relatively straightforward to implement as a standard library for adding interrupt handlers to a microkernel OS
    - Could eliminate platform-specific hooks, allow portable code
    - More interesting: interaction with message-passing concurrency mechanisms

Automatic Memory Management

- Real-time systems community has a strong distrust of automatic memory management
  - E.g., the real-time extensions to Java augmented the memory model with non-garbage collected regions and manual memory management
  - But, memory management problems abound
    - Memory leaks and unpredictable memory allocation performance (calls to `malloc()` can vary in execution time by several orders of magnitude)
    - Memory corruption and buffer overflows
- Can automatic memory management be provided that satisfies the real-time systems community?
  - Predictable, low-overhead, real-time garbage collection
  - Languages with type systems that can control resource management or enforce access controls without hardware memory protection
    - The RAII idiom in C++ or `using` in C# give hints in this direction

Garbage Collection

- Traditional algorithms not suitable
  - Triggered at unpredictable times; unpredictable collection delays as data is moved to avoid heap fragmentation
- Active research into real-time garbage collection
  - Two basic approaches:
    - Work based: every request to allocate an object or assign an object reference does some garbage collection; amortise collection cost with allocation cost
    - Time based: schedule an incremental collector as a periodic task
  - Obtain timing guarantees only by limiting amount of garbage that can be collected in a given interval
    - Implication: user must indicate maximum memory consumption and allocation rate, to determine cost of the garbage collector
    - Workable solutions exist for many periodic real-time applications; same issue as certain scheduling algorithms placing constraints on application design

D. Frampton, *et al.*, "Generational Real-Time Garbage Collection: A Three-Part Invention for Young Objects", Proc. ECOOP 2007. DOI 10.1007/978-3-540-73589-2_6

→ Lectures 14 and 15

Memory Protection

- Traditional memory protection is unpredictable
  - Slows context switch and system call times due to managing page tables
  - Requires illegal access traps and error handlers: difficult to implement

- Can guarantee safety without hardware protection
  - Strongly typed language, checked array bounds, no pointer arithmetic: looks more like Java than C
    - Difficulty is in efficient representation of data, and handling aliasing of memory regions
    - Examples: BitC, Cyclone
  - Much verification done at compile time; reduces run-time unpredictability
  - Example: Singularity operating system from Microsoft Research
    - Mostly written in extended C#, small microkernel in C++; language ensures that inter-process communication is done via strongly-typed message passing; no hardware memory protection
    - http://research.microsoft.com/os/singularity/

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Timing and Real-time Systems

- How to ensure predictable timing?
  - Theory of real-time scheduling well-developed, provided requirements are clearly specified
  - Introduce abstractions for periodic threads into the language and runtime support system
    - E.g., the real-time extensions to Java add RealtimeThread

```
class RealtimeThread extends java.lang.Thread
{
    // ...additional constructors to specify
    // SchedulingParameters
    ...

    // ...adds additional methods:
    public void    setScheduler(Scheduler s);
    public void    schedulePeriodic();
    public boolean waitForNextPeriod();
    ...
}
```

  - Add timing annotations, let compiler/runtime validate scheduling proof?
    - Compiler much better at counting cycles than a human on modern processor architectures
    - Likely feasible to estimate worst-case execution time for many embedded codes, which can be compared with task timing annotations
    - Computationally infeasible in the general case (due to loops, etc.) but most real time systems are more constrained: otherwise how can they be manually proved to meet timing bounds?
    - Helps debugging if not proving correctness

B. Cook, A. Podelski, and A. Rybalchenko, "Proving Program Termination", CACM, May 2011. DOI: 10.1145/1941487.1941509

Timing Annotations

- Is adding such timing annotations feasible?
    - Properties of periodic tasks straight forward, if expressed in language
    - Aperiodic/sporadic tasks harder, but often meaningful statistics
    - But what about low-level behaviour?
        - Annotate that an expression should take no more than x milliseconds; check generated code
        - Operating system calls and library functions will need to be annotated
    - What are hidden timing behaviours of system?
        - Scheduler and system call overhead
        - `malloc()`/`free()`, garbage collection
        - Cache, memory hierarchy, memory protection
        - Speculative execution, pipelining, super-scalar and out-of-order execution
- Programmers cannot count cycles; yet many still program as if it were possible – need compiler help

Support for Concurrency

- Concurrency increasingly important
  - Multicore systems now ubiquitous
  - Asynchronous interactions between software and hardware devices
- Threads and synchronisation primitives problematic
  - Low level; easy to make mistakes; hard to reason about correctness
- Are there alternatives that avoid these issues?
  - Implicit concurrency; execution models which hide complexity
  - Functional and/or message passing algorithms
    - Example: Ericsson AXD301 160 Gbps ATM switch had 99.9999999% uptime and was (mostly) written in the Erlang functional programming language

J. Armstrong, "Making reliable distributed systems in the presence of software errors", PhD thesis, KTH, Stockholm, December 2003, http://www.sics.se/~joe/thesis/armstrong_thesis_2003.pdf

  - Transactional memory coupled with functional languages (e.g., Haskell) for automatic rollback and retry of transactions

→ Lectures 16-19

Reliability Through Clarity

- State and requirements hidden in existing code
  - Need to infer high-level goals from low-level implementation
  - Yet Moore's law continues: performance increasing for fixed price point, power consumption
- Better languages and runtime support will allow programmers to express high-level goals, system to check implementation meets them
  - Requires paradigm shift away from current implementation strategies

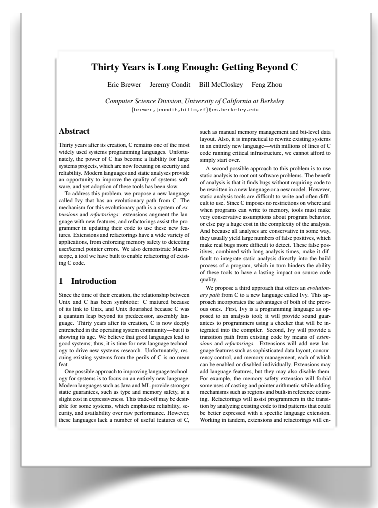
Further Reading

- J. Shapiro, “Programming language challenges in systems codes: why systems programmers still use C, and what to do about it”, Proceedings of the 3rd workshop on Programming Languages and Operating Systems, San Jose, CA, October 2006, DOI 10.1145/1215995.1216004


Programming Language Challenges in Systems Codes
Why Systems Programmers Still Use C, and What to Do About It
Jonathan Shapiro, Ph.D.

Read this – will discuss in tutorial 4 tomorrow

- E. Brewer, J. Condit, B. McCloskey, and F. Zhou, “Thirty Years is Long Enough: Getting Beyond C”, Proceedings of the 10th workshop on Hot Topics in Operating Systems, Santa Fe, NM, June 2005. http://www.usenix.org/event/hotos05/final_papers/brewer.html


Thirty Years is Long Enough: Getting Beyond C
Eric Brewer Jeremy Condit Bill McCloskey Feng Zhou
Computer Science Division, University of California at Berkeley

- T. Sweeney, “The Next Mainstream Programming Language”, Keynote at the 33rd Symposium on Principles of Programming Languages, Charleston, January 2006. http://www.cs.princeton.edu/~dpw/popl/06/Tim-POPL.ppt