ECE382M.20: System-on-Chip (SoC) Design

Lecture 15 – System Software Integration

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Lecture 15: Outline

- **Introduction**
  - Some definitions
  - The Expanding Challenge
- **Phases of System Software Integration**
  - From Requirements to Software Components Identification
  - Software Selection Issues during Architectural Design
  - Unit-Level Integration and Software Performance Assessment
  - Subsystem and Functional-Level Software Integration
  - System-Level Software Integration and Testing

Definitions

- **System Integration: The task of creating a properly functioning system from its constituent components**
  - Hardware
  - Firmware
  - Software
- **System Hardware Integration**
  - Are the components wired together correctly?
- **System Software Integration**
  - Typically assumes hardware integration is largely complete
  - The final step before acceptance testing and deployment

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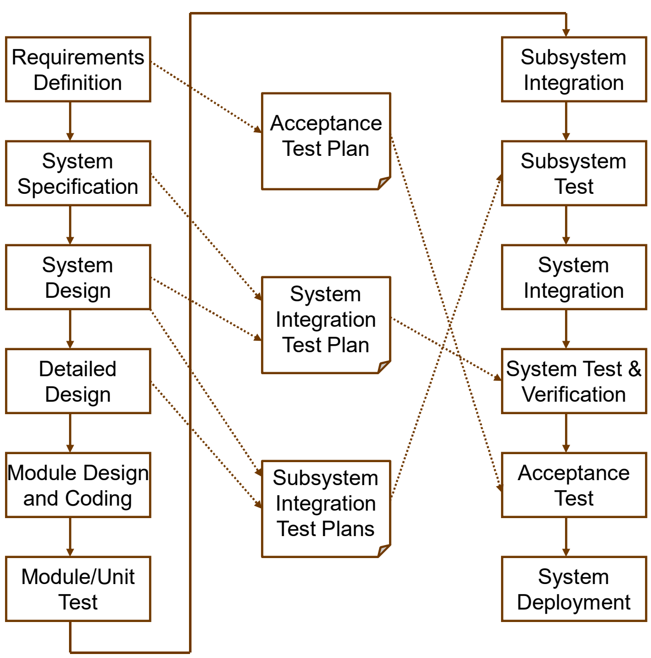
System Engineering Process



Of course, iteration occurs at all levels and among most levels…

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The Good Old Days

- **Software developed internally**
  - Design-specific software
  - No consideration given to software reuse
  - Direct access to software design, source code and developer
- **Uni-processors predominate**
  - No inter-processor and limited inter-process communications
- **Small, simple real-time operating systems (RTOS)**
  - Easy porting and configuration
- **Comparatively simple debugging and testing**
  - Single-function systems

Today: Life Gets Complicated

- **Software components gathered from many sources**
- **Heterogeneous multi-processors**
- **Customized, configurable processors**
  - Memory management units (MMUs)
- **Mix of operating systems: RTOS and Linux**
- **Mix of functions and operating modes**
  - Browser-based configuration
- **Multiple debuggers, no interoperability among tools**
- **Enormously challenging testing implications**

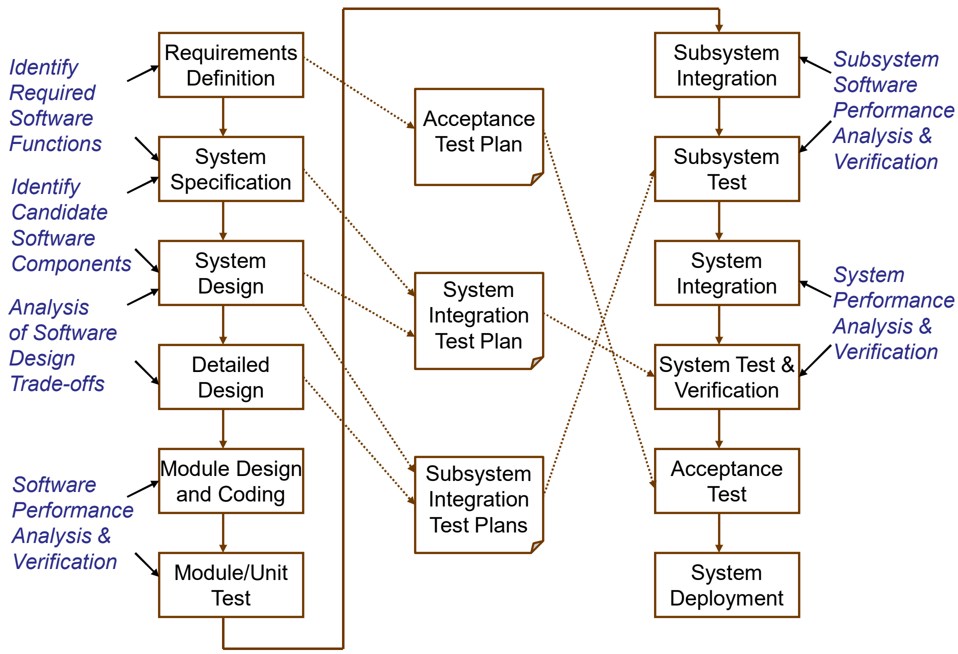
Implications for Software Integration

- ***System software integration issues must be addressed early and continually throughout the design!***
- **Tool and software component selection must be made in the context of system-level design and development considerations.**
  - Debugger interoperability increasingly critical
  - Integrated Development Environments (IDE) may have long learning curves
  - Compilers each have their own idiosyncrasies
  - Disparate operating systems don't often play well together
- **No longer just a "back-end" task**

System Software Design & Integration Phases

- **Identification of required software functions**
  - Begins during requirements specification
  - Architecture decisions may add or remove requirements
- **Mapping of required functions to candidate components**
- **Analysis of trade-offs in software component selection**
- **Initial software component selection or specification**
- **Performance analysis, verification**
- **Subsystem integration, performance analysis, verification**
- **System integration, performance analysis, verification**

System Engineering Process



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Identifying Required Software Functions

- **Embedded system design often begins with an executable specification, or a high-level language (HLL) application**
  - Or, increasingly, two, or three…
  - Natural starting place for software function identification
- **Initial hardware/software partitioning during architectural design defines required software functions**
  - This is a highly iterative process as performance bottlenecks and other design criteria come into focus
- **Some software functions are not performance critical, but may demand significant flexibility**
  - E.g., the Internet refrigerator and its embedded http server
- **End-user or OEM/VAR customization requirements also dictate required software functionality. Java, anyone?**

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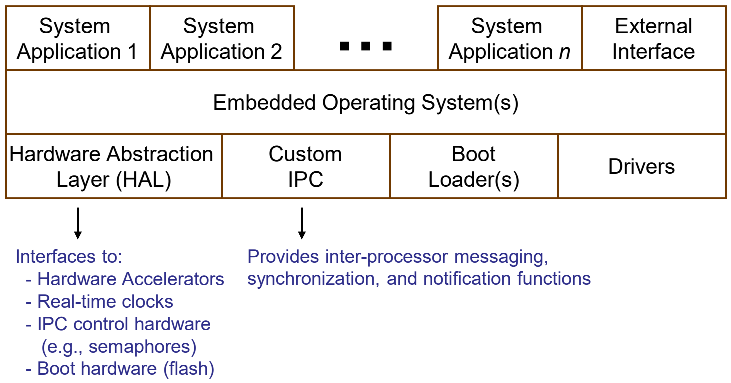
System Software Elements



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Identifying Candidate Software Elements

- **Map required software functions into specific candidate components**
- **Buy, adapt or develop?**
  - Requires consideration of all design criteria, not to mention business issues
  - ➢ Difficult to evaluate early in the project
    - ➢ But also difficult to revisit later in the effort
- **Operating system or executive selections are a key step**
  - A uniform operating system in a multi-processor SoC is extremely desirable, but not always feasible

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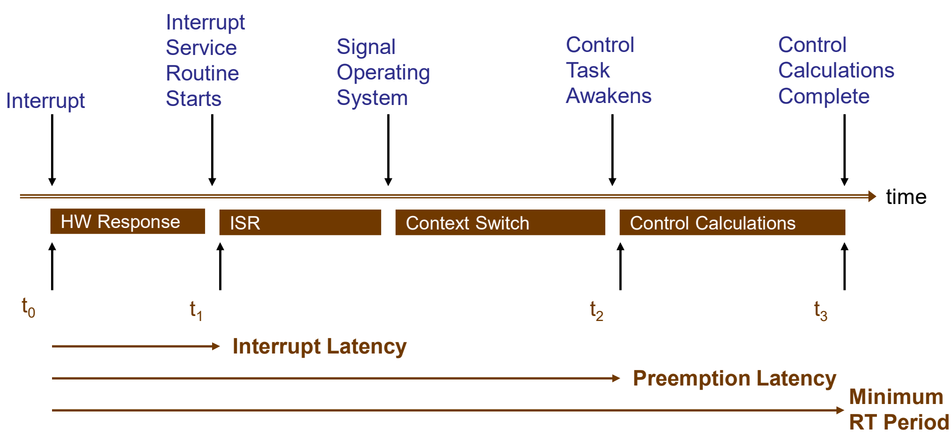
Operating System Selection Criteria

- **Real-time capabilities**
  - "Hard" real-time: guaranteed maximum latency for entering interrupt service routines (ISRs)
  - "Soft" real-time: no guarantees, but fairly quick response to real-time events (not for pacemakers, flight control, etc.)
- **General-purpose features (e.g., file system, web server)**
- **Operating system acquisition and unit costs**
- **Inter-process and -processor communication support**
- **Reliability, Quality**
- **Resource requirements**
  - Memory footprint of program and data
  - Boot, power-on-self-test (P.O.S.T.) mechanisms

Latency in Real-Time Applications



Embedded Operating System Trends

- **Linux - "Hard" real-time embedded Linux versions exist, but worst-case response times may still be too long**
  - Real-Time Application Interface (RTAI.org)
  - Linux Extensions for Real Time (LXRT) – built on RTAI
  - Mainline Linux kernel real-time patches (RT-Preempt)
- **Linux "on top" of a hard RTOS or kernel (RTLinux)**
  - Linux executes only when the RTOS is otherwise idle
  - Fine for configuration and other non-critical functions
  - Highly variable performance during normal system operation; Linux may be starved indefinitely by the RTOS
- **Growing support ecosystem for embedded Linux**
  - Porting, configuring still a non-trivial effort

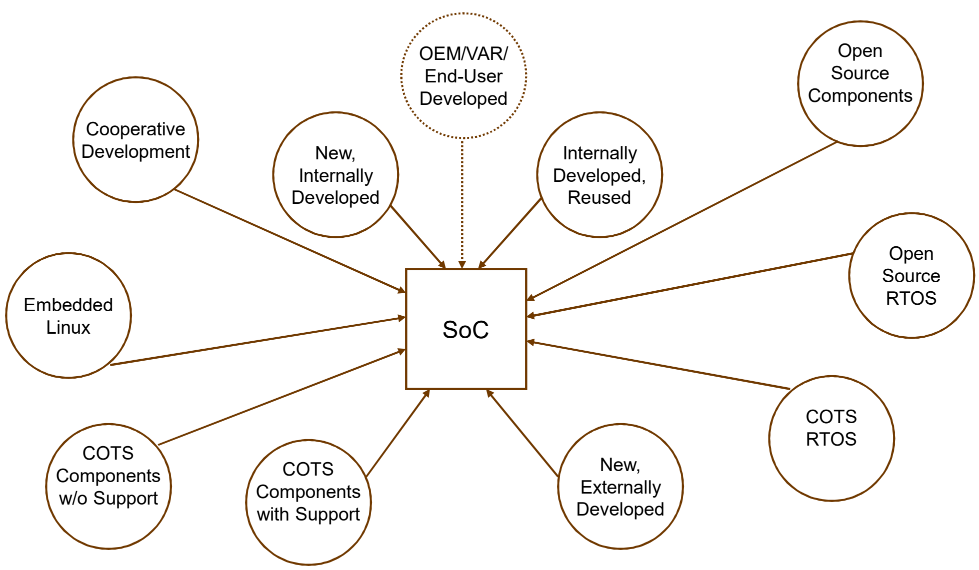
Real-Time Linux

- **Linux with Real-Time Application Interface**
  - RTAI is hard real-time kernel that runs Linux in its idle loop
  - Real-time applications run in kernel mode
- **Linux with RTAI and Linux Extensions for Real-Time**
  - LXRT Extends RTAI to support Linux real-time user mode applications
    - Enables use of Linux memory management
    - Pairs a kernel mode RT task with the user mode task
- **Long paths in Linux kernel getting shorter and shorter**
- **Real-time extensions have now merged with core kernel**
  - Tuning the kernel using scheduling policy selection

Real-Time Middleware

- **CORBA - Common Object Request Broker Architecture**
  - Standard mechanism for medium to coarse grain parallelism based on objects
    - Separation of object interface from implementation
    - Services available on a computing resource can be queried
    - Standardized argument marshalling, function calls, etc.
  - Platform and language independent
  - Object Management Group (omg.org)
    - Version 3.0 released in 2003
- **CORBA Real-Time**
  - Adds RT scheduling services to CORBA
  - Enables (but does not explicitly provide) load balancing

Embedded Software Component Sources



Software Component Selection Details (1)

- Develop internally or externally?
- Acceptable cost to develop or acquire?
- Source code or black-box, object-only module?
- Well-documented?
- Standard call specifications?
- Specific to a particular operating system or linker?
- Specific to a particular hardware component?
- E.g., device drivers
- Sufficiently small code and data footprint?

Software Component Selection Details (2)

- Performance critical? Reliable?
- Optimized for this system?
- Configurable?
- Debugging information and tool support?
- Module-level tests available?
- Run-time dependence upon other modules?
- Predictable workload characteristics?
- Inter-process/inter-processor communications?
- Short learning curve?

Component Development & Acquisition

- **Hardware abstraction layer (HAL) designed and developed early in process**
  - Supports unit-level hardware debug
  - Defines virtual machine for application software
  - Enables bit-accurate C models to support performance modeling and software development
- **Application-level software components often developed and partially debugged on general-purpose hardware before moving to target architecture**
  - Using bit-accurate C HW models underneath HAL
- **IP acquisition may be slow due to business issues**

Regression Testing

- **Regression testing is crucial at each level of software development and integration**
  - Unit, subsystem, and system level
  - Detect new design errors, deviations quickly
    - Don't go backwards
  - Must be run frequently (i.e., daily)
- **Goal is to maintain conformance with the gold model throughout the design**
- **Comparing results at each level of design not easy**
  - Behavioral don't-cares vs. explicit values at lower levels
  - Increasing time accuracy at lower levels also troublesome

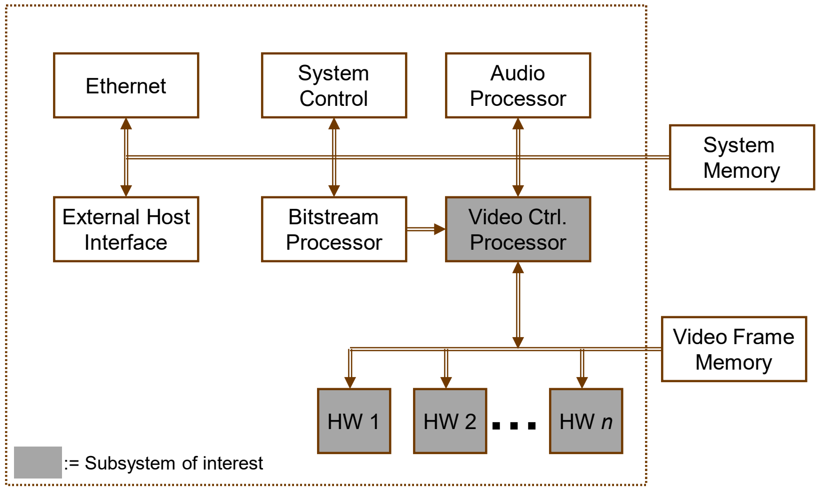
Unit-Level Hardware/Software Integration

- **Unit-level power-on initialization software**
- **Execute and profile individual software component on its target hardware or a model of same**
  - Debugging hardware, HAL, and software simultaneously
  - First meaningful opportunity to assess performance
  - Iterate until software component is "completely" debugged
- **Execute and profile all software components residing on a single target processor**
  - Assess multi-tasking overhead
  - Local busy-waiting on resources or hardware interrupts
  - Reassess resource requirements

Subsystem Software Integration

- **Typically addresses specific functionality in comparative isolation**
- **May cover a single processor and the hardware resources it manages directly**
- **First opportunity to test and debug HAL with application software**
- **Provides basis for evaluating performance estimates at the subsystem level**
  - Reflects overhead (e.g. busy-waiting, interrupt servicing) not reflected in application-only or unit-level testing
  - Enables initial programming and code-tuning for real-time execution

Subsystem Decomposition Example



- **Enables specific function-level debug and testing**
- **Requires cleanly separable hardware components and interfaces**

System Software Integration

- **Full system and application-level integration and test**
- **Mixture of canned tests and real-world workloads**
  - Extensive regression tests absolutely necessary
- **Initially based on simulation or emulation platforms**
  - Provides opportunity for early integration, detection of design defects
  - Too slow for long runs, operating system execution, etc.
- **Culminates with execution on real silicon**
- **Transition to acceptance testing**
  - All regression tests pass
  - Random, real workloads behave as expected

System-Level Debug

- **Performance measurement and tuning**
- **Deadlock avoidance verification**
  - Still not a proof
- **Real-time schedule tuning**
  - Refine interrupt versus polling tradeoffs and decisions
- **Error detection and recovery**
- **Transition to acceptance testing**
  - All regression tests pass
  - Random, real workloads behave as expected

Multi-Processor/Multi-Core Debug

- **Requires cooperating debug tool instances**
  - No common API means a sole-source debugger (for now)
- **Single processor breakpoints**
  - Other processors may halt or continue execution on breakpoints, based on user preferences
  - Precise timing usually impossible, especially with multiple clock speeds/domains
- **Synchronized single-stepping for repeatable results**
- **Multiple processor breakpoints**
  - AND, OR, XOR, IF-THEN-ELSE conditionals combine single breakpoint triggers
  - Repeatability difficult without synchronized single-stepping

Advanced Multi-Processor Debug

- **Watchpoints for data-triggered execution breaks**
  - May require hardware assist
  - Multiple watchpoints
- **Consistent user-interface**
  - Falls out of sole-source multiprocessor debugger
  - Industry needs standardized debugger API, function set
  - Vendors currently prefer closed environments, which may be fine until a processor is selected that is not supported by the debugger vendor
- **Adapting debugger to configurable or novel processor architectures not easy**

Lecture 15: Conclusions

- **Software integration must be addressed at every phase of the design process**
  - Definitely NOT merely a back-end task
  - May be key driver of system architectural design, processor selection, etc.
- **Already often the single most costly aspect of system design, current trends will continue to amplify the importance of system integration issues, particularly for software.**
  - Software components from a growing array of sources
  - Rapidly expanding number of components
  - Multiple operation modes exacerbate the testing task

