System Software Integration: An Expansive View

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System-on-Chip Design

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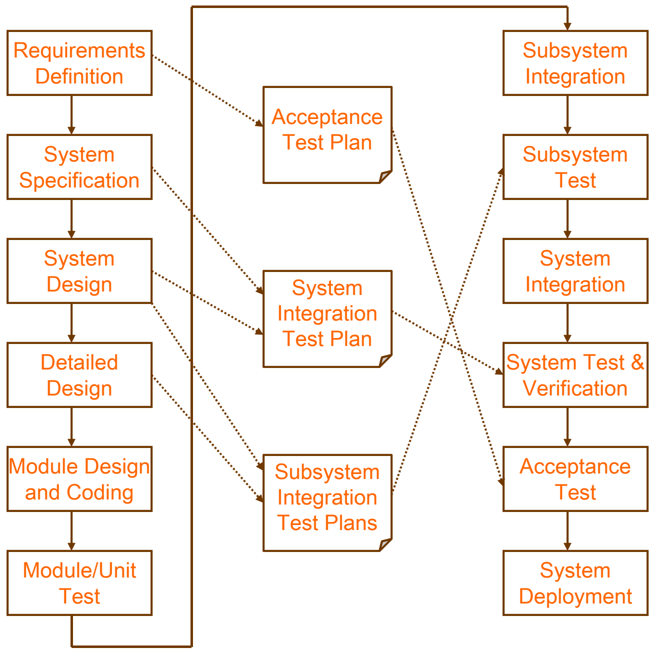
Overview

- Some Definitions
- Introduction: 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
- Conclusions

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

The System Engineering Process



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

Software Integration in Embedded Systems: "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

Software Integration in Embedded 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

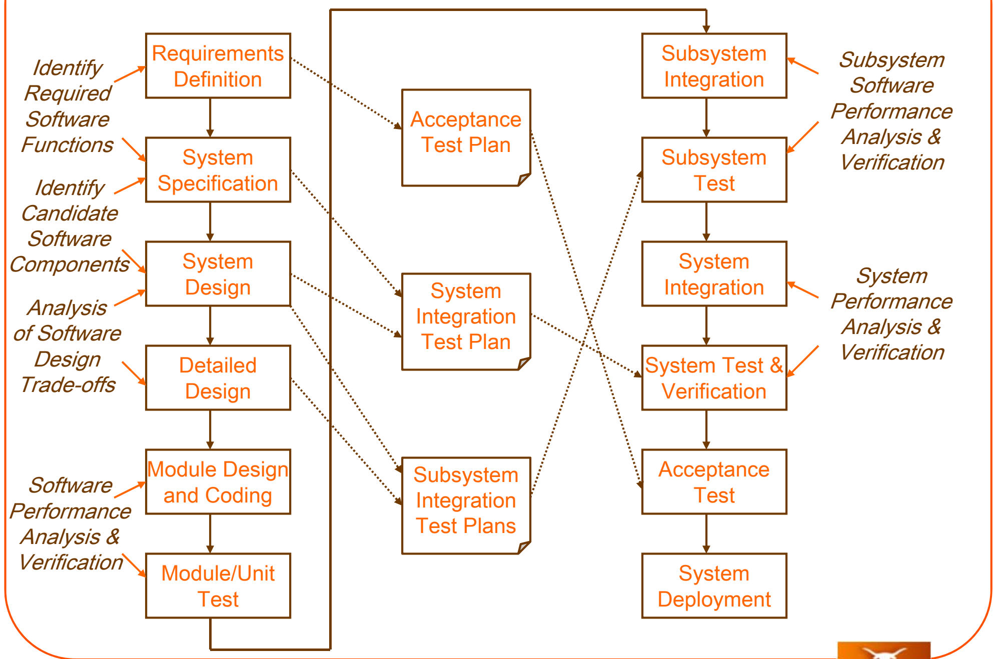
Implications for Software Integration of Embedded System Trends

- **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

Phases of the System Software Design and Integration Effort

- 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

The System Engineering Process

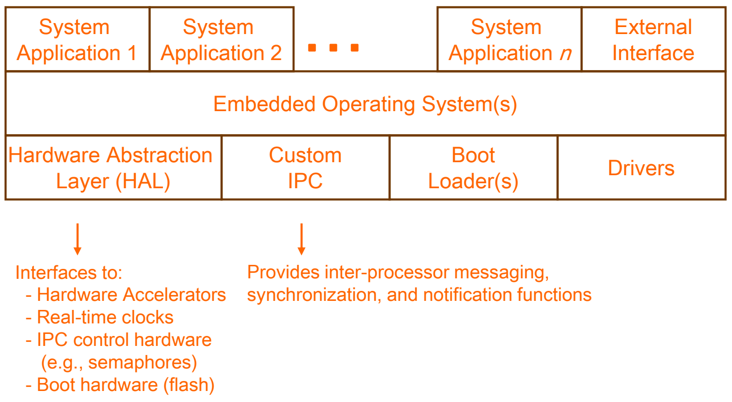


Identify Required Software Functions
Identify Candidate Software Components
Analysis of Software Design Trade-offs
Software Performance Analysis & Verification
Requirements Definition
System Specification
System Design
Detailed Design
Module Design and Coding
Module/Unit Test
Acceptance Test Plan
System Integration Test Plan
Subsystem Integration Test Plans
Subsystem Integration
Subsystem Test
System Integration
System Test & Verification
Acceptance Test
System Deployment
Subsystem Software Performance Analysis & Verification
System Performance Analysis & Verification

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 sharper 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?

System Software Elements



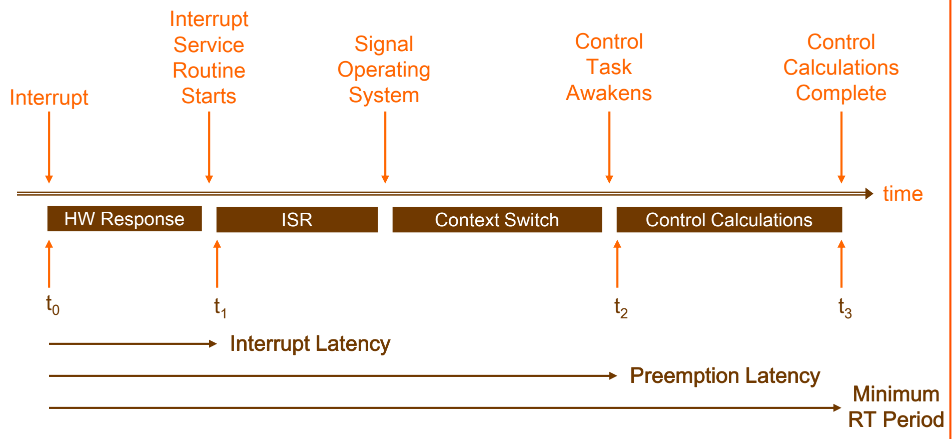
Identifying Candidate Software Components

- 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.

Operating Systems 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 inter-processor communications 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

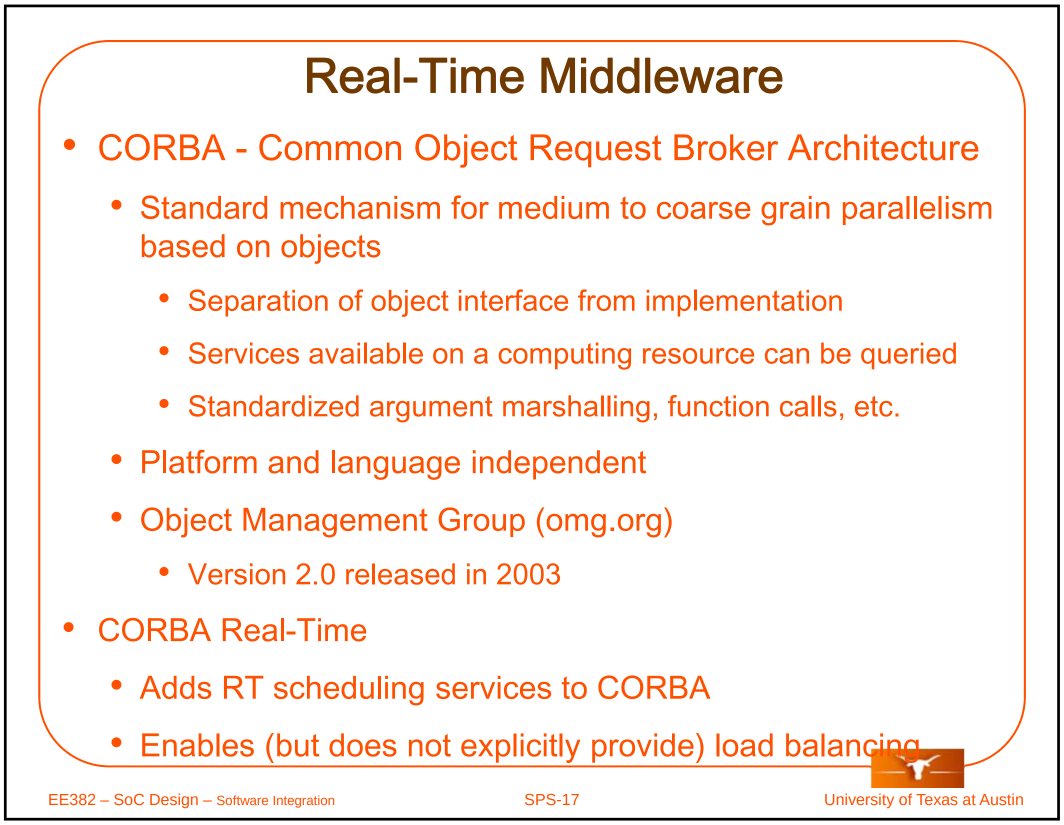


Embedded Operating System Trends

- 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
- Linux “on top” of a hard RTOS or kernel
    - 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 a 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 the 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 2.0 released in 2003
- CORBA Real-Time
  - Adds RT scheduling services to CORBA
  - Enables (but does not explicitly provide) load balancing

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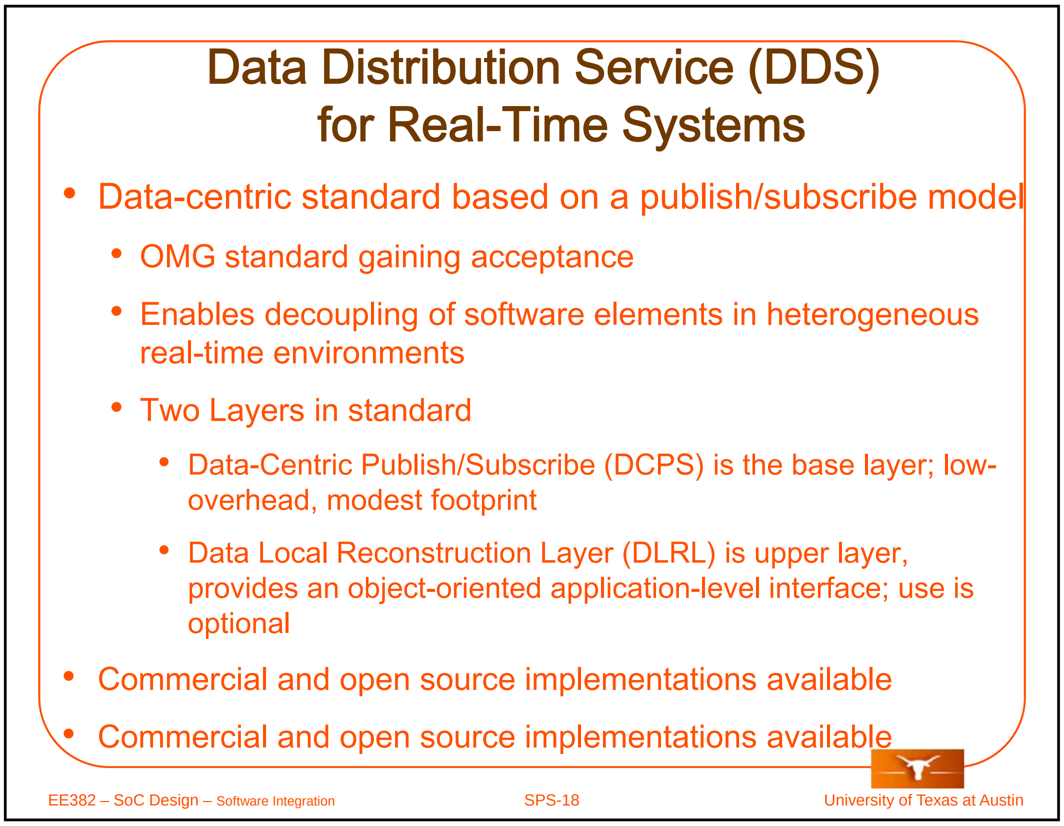

Data Distribution Service (DDS) for Real-Time Systems

- Data-centric standard based on a publish/subscribe model
  - OMG standard gaining acceptance
  - Enables decoupling of software elements in heterogeneous real-time environments
  - Two Layers in standard
    - Data-Centric Publish/Subscribe (DCPS) is the base layer; low-overhead, modest footprint
    - Data Local Reconstruction Layer (DLRL) is upper layer, provides an object-oriented application-level interface; use is optional
- Commercial and open source implementations available

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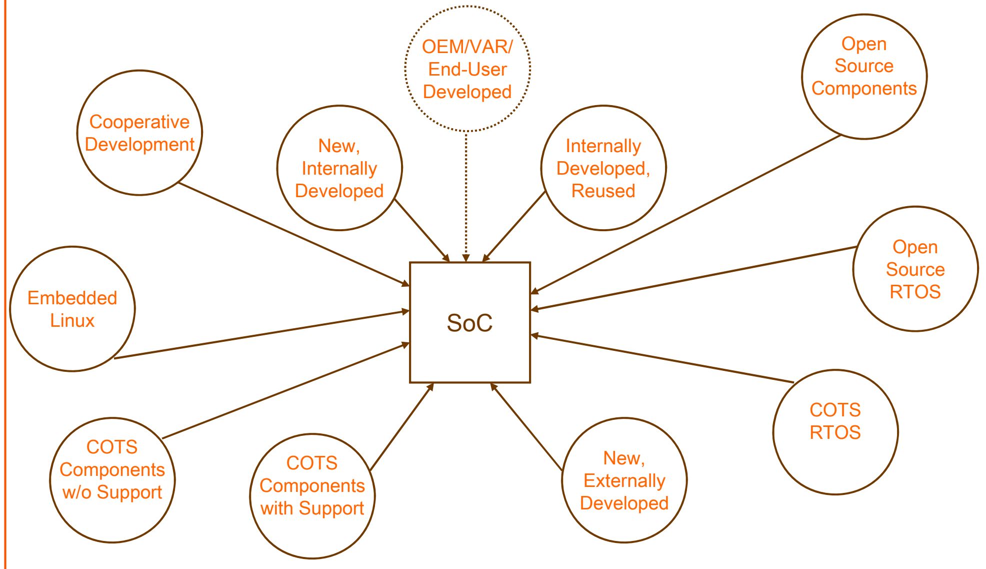
Embedded Software Component Sources


OEM/VAR/ End-User Developed
Open Source Components
Cooperative Development
New, Internally Developed
Internally Developed, Reused
Open Source RTOS
Embedded Linux
SoC
COTS RTOS
COTS Components w/o Support
COTS Components with Support
New, Externally Developed

Detailed Embedded Software Component Selection Issues

- 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?

Detailed Embedded Software Component Selection Issues (continued)

- 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?

Software Component Development and 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

The Role of 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 versus explicit values at lower levels
  - Increasing time accuracy at lower levels also troublesome

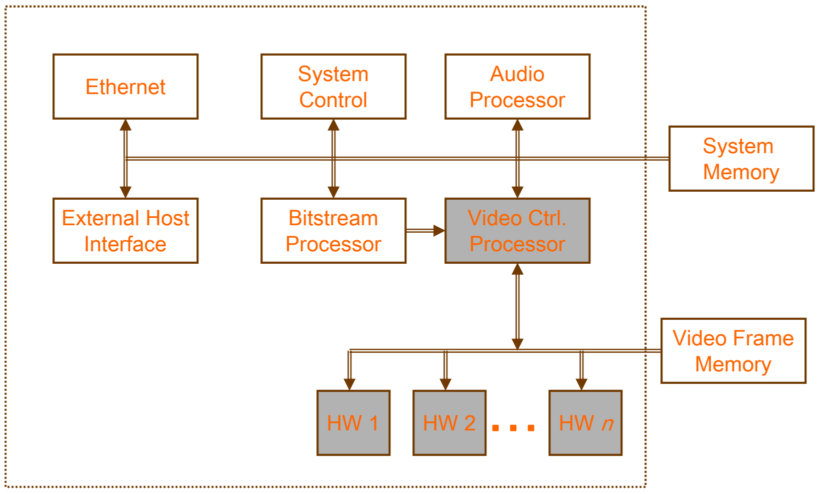
Unit-Level Hardware/Software Integration

- 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 hardware resources or hardware interrupts
  - Reassess resource requirements

Subsystem Software Integration

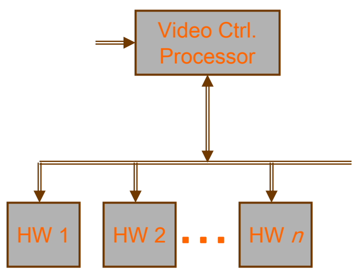
- Typically addresses specific functionality in comparative isolation
- May cover a single processor and the hardware resources it manages directly
- First opportunity to test and debug HAL with application software
- Provides basis for evaluating performance estimates at the subsystem level
  - Reflects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

Subsystem Decomposition Example: Media Processor



▨ := Subsystem of interest

Subsystem Decomposition Example: Media Processor



- 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 Focus

- 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

Multiprocessor and Multitasking 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 still difficult without synchronized single-stepping

Advanced Multiprocessing Debug Issues

- 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

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