

## Evolving real-time systems using hierarchical scheduling and concurrency analysis

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### Abstract

*We have developed a new way to look at real-time and embedded software: as a collection of execution environments created by a hierarchy of schedulers. Common schedulers include those that run interrupts, bottom-half handlers, threads, and events. We have created algorithms for deriving response times, scheduling overheads, and blocking terms for tasks in systems containing multiple execution environments. We have also created task scheduler logic, a formalism that permits checking systems for race conditions and other errors. Concurrency analysis of low-level software is challenging because there are typically several kinds of locks, such as thread mutexes and disabling interrupts, and groups of cooperating tasks may need to acquire some, all, or none of the available types of locks to create correct software. Our high-level goal is to create systems that are evolvable: they are easier to modify in response to changing requirements than are systems created using traditional techniques. We have applied our approach to two case studies in evolving software for networked sensor nodes.*

### 1. Introduction

By focusing on a single abstraction for concurrency, such as events or threads, traditional models for real-time and embedded software ignore a great deal of the richness and complexity that is present in actual systems. For example, in a typical embedded system based on an off-the-shelf real-time operating system (RTOS),

- interrupts are prioritized by a preemptive scheduler that is implemented in hardware,
- bottom-half handlers (a.k.a. tasklets, software interrupts, or deferred procedure calls) are scheduled non-preemptively in software,
- threads are scheduled preemptively by the RTOS, and

- lightweight events are run by schedulers implemented within individual OS-supported threads.

Each of these schedulers creates a unique execution environment — a context for running code that has particular performance characteristics and restrictions on actions that can be taken inside it. Furthermore, each pair of interacting execution environments has rules that need to be followed to implement mutual exclusion between tasks running in them.

Multiple execution environments exist because developers can exploit their diverse properties by mapping each task to an appropriate environment. For example, interrupt handlers incur very little overhead but provide an inconvenient programming model: blocking is not permitted and long-running interrupts unnecessarily delay other tasks. Threads, on the other hand, are more flexible and can block, but incur more time and space overhead.

The concurrency structure of a system is largely determined by the execution environments that it supports and by the way that tasks are mapped to these environments. For example, consider a pair of cooperating tasks. If both tasks are mapped to an event-driven execution environment then the tasks are mutually atomic — they run to completion with respect to each other, regardless of whatever preemption occurs in other parts of the system. On the other hand, if the tasks are mapped to separate threads, then the tasks can potentially preempt the other; they must each acquire a mutex before accessing any shared resources. Finally, if one task is mapped to a thread and the other is mapped to an interrupt handler, then the preemption relation is asymmetrical — the interrupt can preempt the thread, but not vice versa. In this case, the thread must disable interrupts when accessing a resource shared by the two tasks, but the interrupt does not need to take any special action.

Systems tend to evolve over time as features and requirements accumulate, and as the underlying platform changes to accommodate newer and better hardware. Also, all too often systems are designed in an exploratory way where code is initially structured in a simple, apparently adequate way, and then it is generalized several times before an en-

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