Konfigurierbare Systemsoftware (KSS)

VL 6 – Generative Programming: The Sloth Approach

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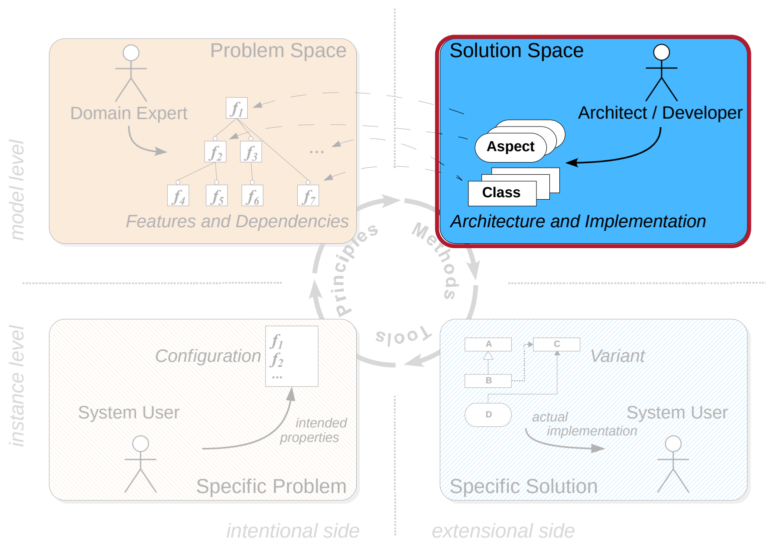
About this Lecture



Implementation Techniques: Classification

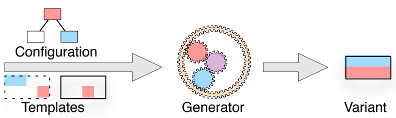
- Decompositional Approaches

  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches

  - Language-based composition mechanisms (typed)
  - OOP, **AOP**, Templates

- Generative Approaches



  - Metamodel-based generation of components (typed)
  - MDD, C++ TMP, generators

Implementation Techniques: Classification

- Decompositional Approaches

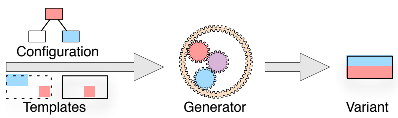
  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches

> *“I'd rather write programs to write programs than write programs.”*
>
> Dick Sites (DEC)

composition
ed)
plates

- Generative Approaches



  - Metamodel-based generation of components (typed)
  - MDD, C++ TMP, generators

Agenda

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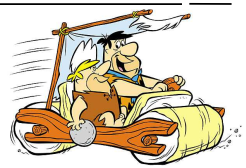
The OSEK Family of Automotive OS Standards

- **1995** OSEK OS (OSEK/VDX) [8]
- **2001** OSEKtime (OSEK/VDX) [10]
- **2005** AUTOSAR OS (AUTOSAR) [1]



- **OSEK OS** ↦ "Offene Systeme und deren Schnittstellen für die Elektronik in Kraftfahrzeugen"
  - **statically configured**, event-triggered real-time OS
- **OSEKtime**
  - **statically configured**, time-triggered real-time OS
  - can optionally be extended with OSEK OS (to run in slack time)
- **AUTOSAR OS** ↦ "Automotive Open System Architecture"
  - **statically configured**, event-triggered real-time OS
  - real superset of OSEK OS ⇝ backwards compatible
  - additional time-triggered abstractions (schedule tables, timing protection)
  - intended as a successor for both OSEK OS and OSEKtime

OSEK OS: Abstractions [8]

- Control flows
  - `Task`: software-triggered control flow (strictly priority-based scheduling)
    - Basic Task (BT) — run-to-completion task with strictly stack-based activation and termination
    - Extended Task (ET) — may suspend and resume execution (↦ coroutine)
  - `ISR`: hardware-triggered control flow (hardware-defined scheduling)
    - Cat 1 ISR (ISR1) — runs below the kernel, may not invoke system services (↦ prologue without epilogue)
    - Cat 2 ISR (ISR2) — synchronized with kernel, may invoke system services (↦ epilogue without prologue)
  - `Hook`: OS–triggered signal/exception handler
    - `ErrorHook` — invoked in case of a syscall error
    - `StartupHook` — invoked at system boot time
    - ...

OSEK OS: Abstractions [8] (Cont'd)

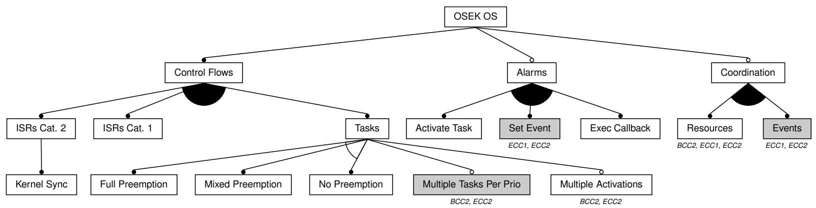
- Coordination and synchronization
  - `Resource`: mutual exclusion between well-defined set of tasks
    - stack-based priority ceiling protocol ([11]):
      `GetResource()` ⇝ priority is raised to that of highest participating task
    - pre-defined `RES_SCHED` has highest priority (⇝ blocks preemption)
    - implementation-optional: task set may also include cat 2 ISRs
  - `Event`: condition variable on which ETs may block
    - part of a task's context
  - `Alarm`: asynchronous trigger by HW/SW counter
    - may execute a callback, activate a task, or set an event on expiry

OSEK OS: System Services (Excerpt)

- `Task`-related services
  - `ActivateTask(`*task*`)` ⇝ *task* is active (↦ ready), counted
  - `TerminateTask()` ⇝ running task is terminated
  - `Schedule()` ⇝ active task with highest priority is running
  - `ChainTask(`*task*`)` ↦ atomic { `ActivateTask(`*task*`)` / `TerminateTask()` }
- `Resource`-related services
  - `GetResource(`*res*`)` ⇝ current task has *res* ceiling priority
  - `ReleaseResource(`*res*`)` ⇝ current task has previous priority
- `Event`-related services (extended tasks only!)
  - `SetEvent(`*task*`, `*mask*`)` ⇝ events in *mask* for *task* are set
  - `ClearEvent(`*mask*`)` ⇝ events in *mask* for current task are unset
  - `WaitEvent(`*mask*`)` ⇝ current task blocks until event from *mask* has been set
- `Alarm`-related services
  - `SetAbsAlarm(`*alarm*`, ...)` ⇝ arms *alarm* with absolute offset
  - `SetRelAlarm(`*alarm*`, ...)` ⇝ arms *alarm* with relative offset

OSEK OS: Conformance Classes [8]

- OSEK offers predefined tailorability by four **conformance classes**
  - **BCC1** only basic tasks, limited to one activation request per task and one task per priority, while all tasks have different priorities
  - **BCC2** like BCC1, plus more than one task per priority possible and multiple requesting of task activation allowed
  - **ECC1** like BCC1, plus extended tasks
  - **ECC2** like ECC1, plus more than one task per priority possible and multiple requesting of task activation allowed for basic tasks
- The OSEK feature diagram



OSEK OS: System Specification with OIL [9]

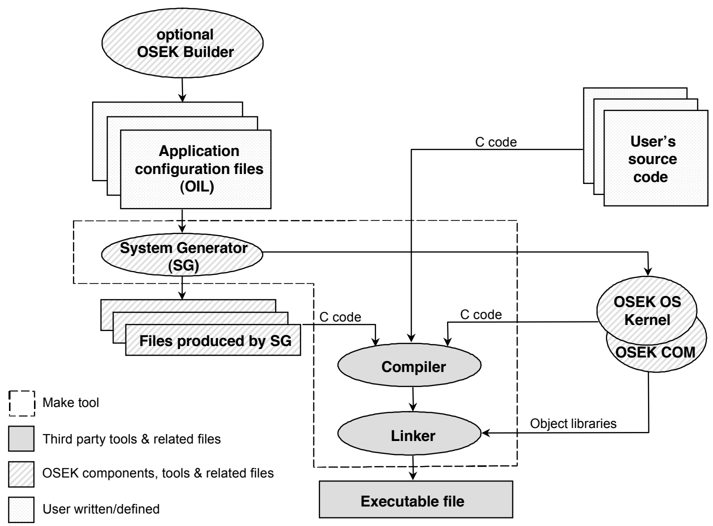
- An OSEK OS instance is configured **completely statically**
  - all general OS features (hooks, ...)
  - all instances of OS abstractions (tasks, ...)
  - all relationships between OS abstractions
  - described in a domain-specific language (DSL)
- OIL: The OSEK Implementation Language
  - standard types and attributes (`TASK`, `ISR`, ...)
  - vendor/plattform-specific *attributes* (ISR source, priority, triggering)
  - task types and conformance class is deduced

OIL File for Example System (BCC1)

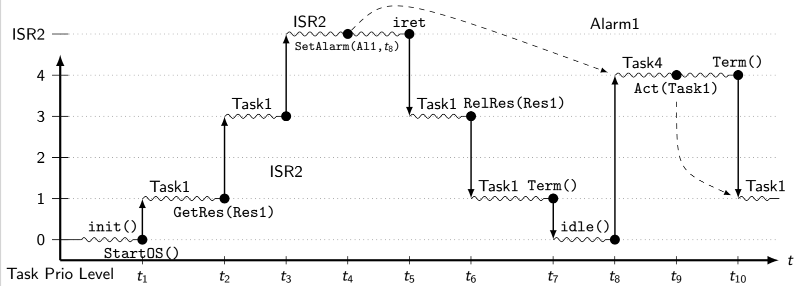
- Three basic tasks: `Task1`, `Task3`, `Task4`
- Category 2 ISR: `ISR2` (platform-spec. source/priority)
- `Task1` and `Task3` use resource `Res1` ⇝ ceiling pri = 3
- Alarm `Alarm1` triggers `Task4` on expiry

```
...
OS ExampleOS {
  STATUS       = STANDARD;
  STARTUPHOOK  = TRUE;
};
TASK Task1 {
  PRIORITY     = 1;
  AUTOSTART    = TRUE;
  RESOURCE     = Res1;
};
TASK Task3 {
  PRIORITY     = 3;
  AUTOSTART    = FALSE;
  RESOURCE     = Res1;
};
TASK Task4 {
  PRIORITY     = 4;
  AUTOSTART    = FALSE;
};
RESOURCE Res1 {
  RESOURCEPROPERTY = STANDARD;
};
ISR ISR2 {
  CATEGORY     = 2;
  PRIORITY     = 2;
};
ALARM Alarm1 {
  COUNTER      = Timer1;
  ACTION       = ACTIVATETASK {
    TASK       = Task4;
  };
  AUTOSTART    = FALSE;
};
```

OSEK OS: System Generation [9, p. 5]



OSEK OS: Example Control Flow



- Basic tasks behave much like IRQ handlers (on a system with support for IRQ priority levels)
  - priority-based dispatching with run-to-completion
  - LIFO, all control flows can be executed on a single shared stack
- So why not dispatch tasks as ISRs?
  - ⇝ Let the hardware do all scheduling!
  - ⇝ Let's be a SLOTH!

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"SLOTH: Threads as Interrupts" [5]

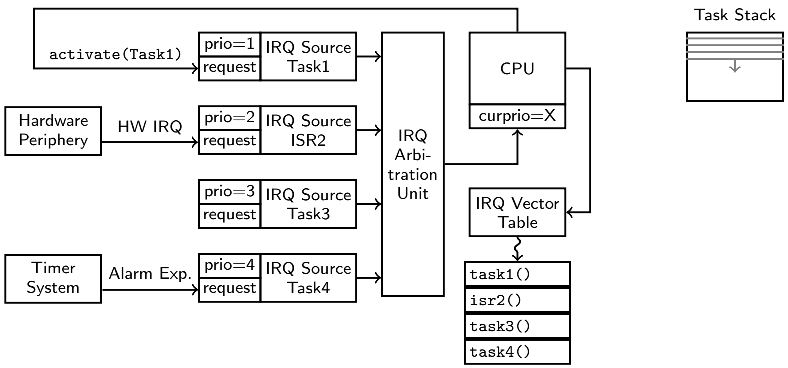
- **Idea: threads are interrupt handlers, synchronous thread activation is IRQ**

Paper title of [5] is a pun to the approach taken by SOLARIS: "Interrupts as Threads", ACM OSR (1995) [7]

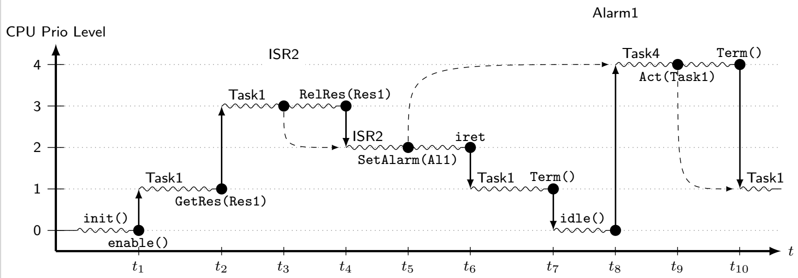
- Let interrupt subsystem do the scheduling and dispatching work
- Applicable to priority-based real-time systems
- Advantage: small, fast kernel with unified control-flow abstraction

Sloth Design

- IRQ system must support priorities and software triggering



Sloth: Example Control-Flow



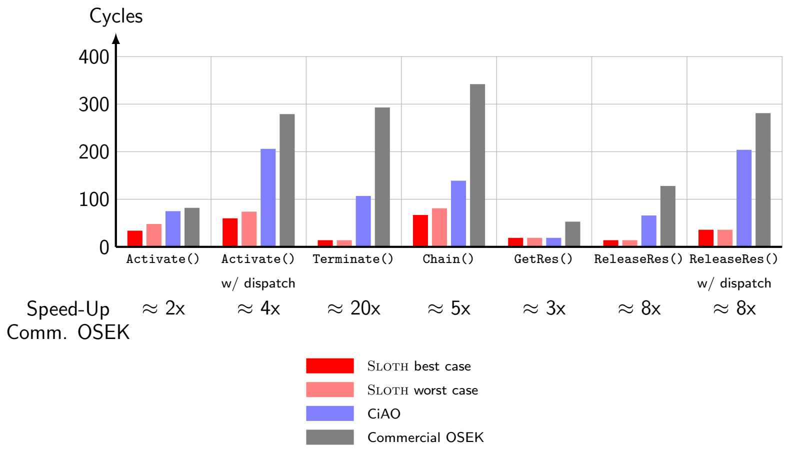
Sloth: Qualitative Results

- Concise kernel design and implementation
  - < 200 LoC, < 700 bytes code memory, very little RAM
- Single control-flow abstraction for tasks, ISRs (1/2), callbacks
  - Handling oblivious to how it was triggered (by hardware or software)
- Unified priority space for tasks and ISRs
  - No rate-monotonic priority inversion [2, 3]
- Straight-forward synchronization by altering CPU priority
  - Resources with ceiling priority (also for ISRs!)
  - Non-preemptive sections with `RES_SCHEDULER` (highest task priority)
  - Kernel synchronization with highest task/cat.-2-ISR priority

Performance Evaluation: Methodology

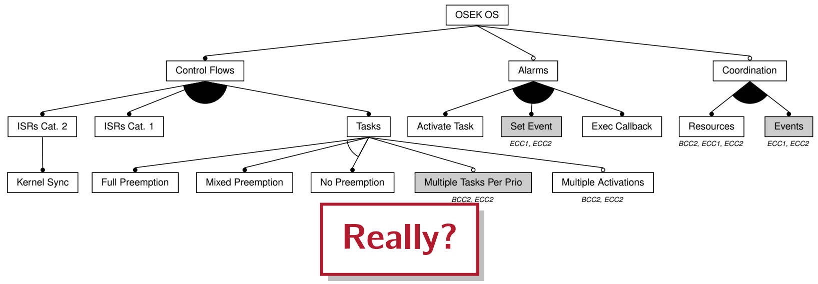
- Reference implementation for Infineon TriCore
  - 32-bit load/store architecture
  - Interrupt controller: 256 priority levels, about 200 IRQ sources with memory-mapped registers
  - Meanwhile also implementations for ARM Cortex-M3 (SAM3U) and x86
- Evaluation of task-related system calls:
  - Task activation
  - Task termination
  - Task acquiring/releasing resource
- Comparison with commercial OSEK implementation and CiAO
- Two numbers for Sloth: best case, worst case
  - Depending on number of tasks and system frequency

Performance Evaluation: Results



Limitations of the Sloth Approach

- No extended tasks (that is, events, ↦ OSEK ECC1 / ECC2)
  ↩ **impossible with stack-based IRQ execution model**
- No multiple tasks per priority (↦ OSEK BCC2 / ECC2)
  ↩ execution order has to be the same as activation order



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Control Flows in Embedded Systems

	Activation Event	Sched./Disp.	Semantics
ISRs	HW	by HW	RTC
Threads	SW	by OS	Blocking
Sloth [5]	HW or SW	by HW	RTC
Sleepy Sloth [6]	HW or SW	by HW	RTC or Blocking

(RTC: Run-to-Completion)

SLEEPY SLOTH: Main Goal and Challenge

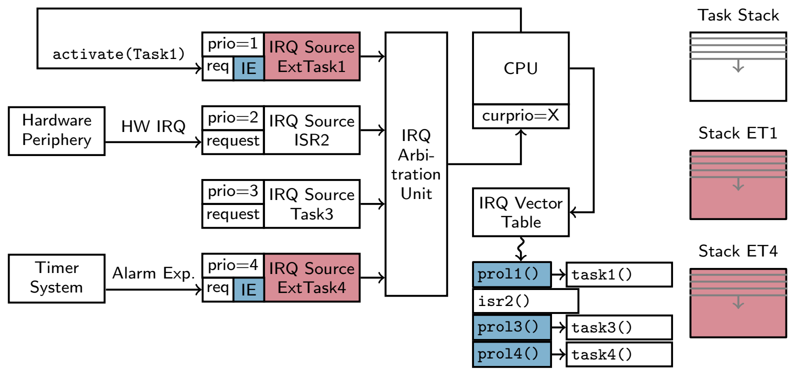
Main Goal

Support extended blocking tasks (with stacks of their own), while preserving SLOTH's latency benefits by having threads run as ISRs

Main Challenge

IRQ controllers do not support suspension and re-activation of ISRs

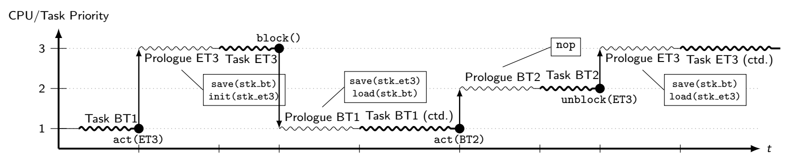
SLEEPY SLOTH Design: Task Prologues and Stacks

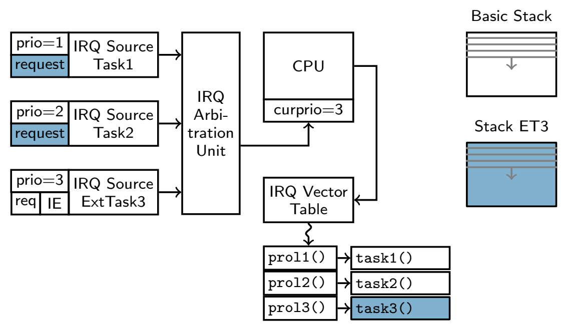


SLEEPY SLOTH: Dispatching and Rescheduling

- Task prologue: switch stacks if necessary
  - Switch *basic task* ↪ *basic task* omits stack switch
  - On job start: initialize stack
  - On job resume: restore stack
- Task termination: task with next-highest priority needs to run
  - Yield CPU by setting priority to zero
  - (Prologue of *next* task performs the stack switch)
- Task blocking: take task out of "ready list"
  - Disable task's IRQ source
  - Yield CPU by setting priority to zero
- Task unblocking: put task back into "ready list"
  - Re-enable task's IRQ source
  - Re-trigger task's IRQ source by setting its pending bit

SLEEPY SLOTH: Example Control Flow

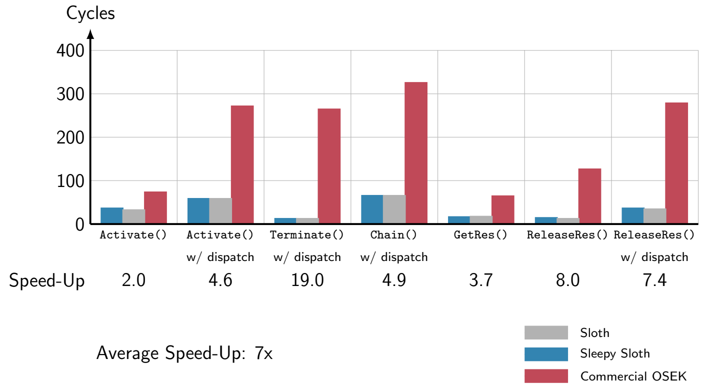




Sleepy Sloth: Evaluation

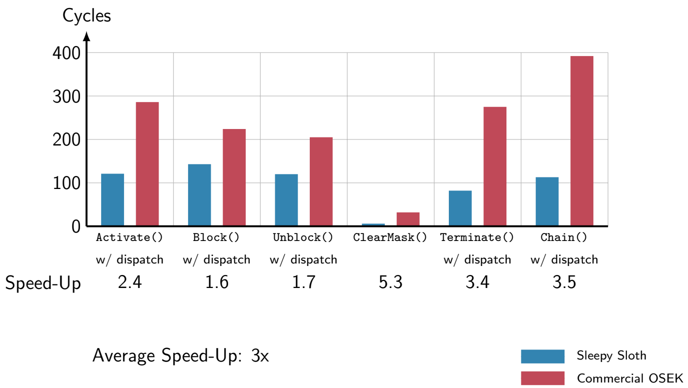
- Reference implementation on Infineon TriCore microcontroller
- Measurements: system call latencies in 3 system configurations, compared to a leading commercial OSEK implementation
  1. Only basic run-to-completion tasks
  2. Only extended blocking tasks
  3. Both basic and extended tasks

Evaluation: Only Basic Tasks



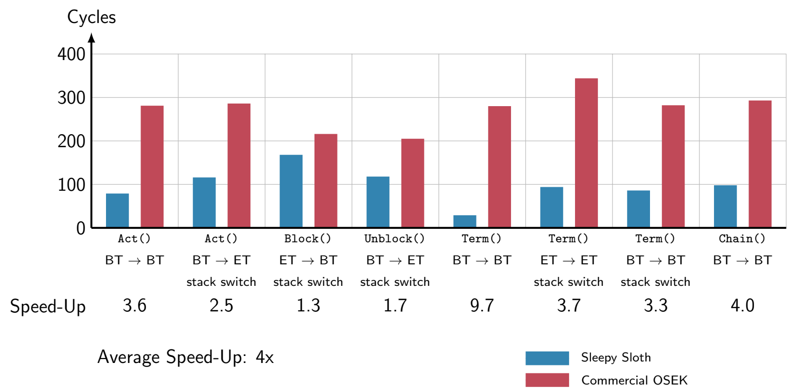
- Sleepy Sloth outperforms commercial kernel with SW scheduler
- Sleepy Sloth as fast as original Sloth

Evaluation: Only Extended Tasks



- Still faster than commercial kernel with SW scheduler
- Sleepy Sloth: Extended switches slower than basic switches

Evaluation: Extended *and* Basic Tasks



- Basic switches in a mixed system only slightly slower than in purely basic system

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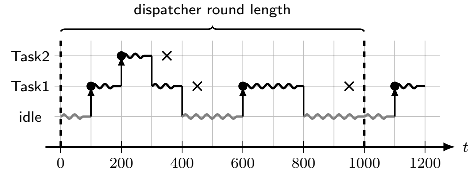
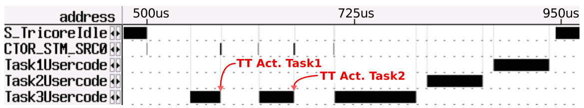
Sloth on Time: Time-Triggered Laziness [4]

- **Idea: use hardware timer arrays to implement schedule tables**
- TC1796 GPTA: 256 timer cells, routable to 96 interrupt sources
  - use for task activation, deadline monitoring, execution time budgeting, time synchronization, and schedule table control
- Sloth on Time implements OSEKtime [10] and AUTOSAR OS schedule tables [1]
  - combinable with Sloth or Sleepy Sloth for mixed-mode systems
  - up to 170x lower latencies compared to commercial implementations

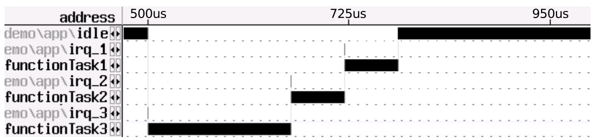


Qualitative Evaluation: AUTOSAR

Commercial AUTOSAR: **Priority inversion** with time-triggered activation (2,075 cycles each)



Sloth on Time: avoids this *by design!*

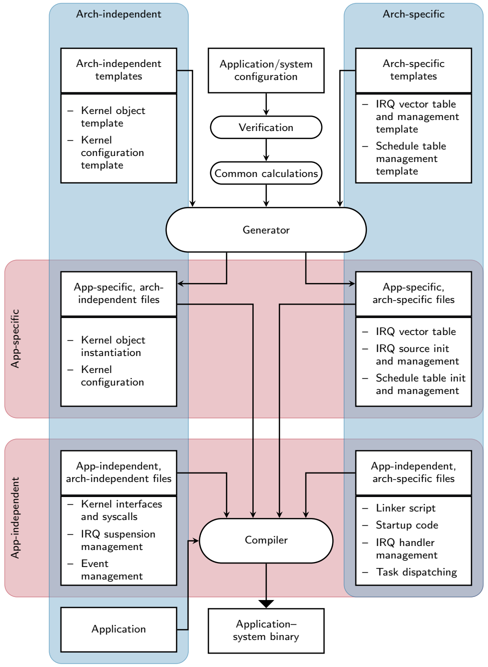


> *Interrupts are perhaps the biggest cause of priority inversion in real-time systems, causing the system to not meet all of its timing requirements.*
>
> Stewart 1999: "*Twenty-Five Most Common Mistakes with Real-Time Software Development*" [12]

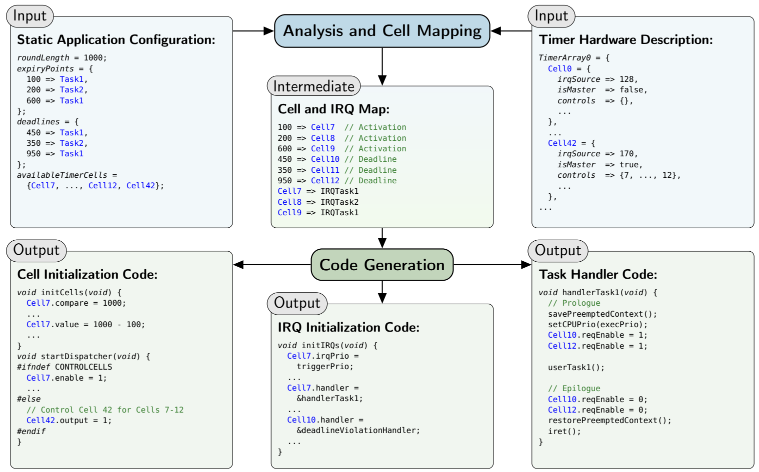
Agenda

SLOTH∗ Generation

- Two generation dimensions
  - Architecture
  - Application
- Generator is implemented in Perl
  - Templates
  - Configuration



SLOTH ON TIME Generation



Agenda

Summary: The SLOTH∗ Approach

- Exploit standard interrupt/timer hardware to delegate core OS functionality to hardware
  - scheduling and dispatching of control flows
  - OS needs to be tailored to application *and* hardware platform
    - ⇝ generative approach is necessary
- Benefits
  - tremendous latency reductions, very low memory footprints
  - unified control flow abstraction
    - hardware/software-triggered, blocking/run-to-completion
    - no need to distinguish between tasks and ISRs
    - no rate-monotonic priority inversion
    - reduces complexity
  - less work for the OS developer :-)

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[2] Luis E. Leyva-del Foyo, Pedro Mejia-Alvarez, and Dionisio de Niz. "Integrated Task and Interrupt Management for Real-Time Systems". In: *Transactions on Embedded Computing Systems* 11.2 (July 2012), 32:1–32:31. ISSN: 1539-9087. DOI: `10.1145/2220336.2220344`. URL: `http://doi.acm.org/10.1145/2220336.2220344`.

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[12] David B. Stewart. "Twenty-Five Most Common Mistakes with Real-Time Software Development". In: *Proceedings of the 1999 Embedded Systems Conference (ESC '99)*. 1999.