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Real-Time Systems Programming with GNAT and OpenRavenscar

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Overview

- High Integrity Systems and the Ravenscar profile
- The OpenRavenscar project
- The OpenRavenscar kernel
  - Integration with GNAT
  - Kernel interface
  - Design issues
  - Other components
- The OpenRavenscar tool set
- Developing real-time systems with OpenRavenscar
- Lessons learned and future work

High Integrity Systems

- Systems with strong safety and reliability requirements
  - static and dynamic analysis required according to different certification standards
- Ada is the language of choice for HIS
  - careful design
  - annex H: Safety and security
  - ISO/IEC TR 15942:2000. *Guide for the use of the Ada programming language in High Integrity Systems*
- A *safe subset* of the language is often used
  - traditional approach: no tasking (e.g. SPARK)
  - more recently: safe tasking profile (Ravenscar)

The Ravenscar Profile

- Ada tasking subset for high-integrity applications
- Defined at IRTAW 8 (Ravenscar, UK, 1997)
- Revised at
  - IRTAW 9 (Tallahassee, Florida, 1999)
  - IRTAW10 (Las Navas del Marqués, Spain, 2000)
- Strategy
  - remove constructs with
    - » high overhead
    - » non-predictable behaviour
  - allow
    - » timing analysis
    - » small, fast, reliable runtime system

Ravenscar tasking model

- Static tasks and protected types/objects at the library level
- Protected objects with at most one entry with a simple barrier
  - no more than one task queued on an entry
- Synchronous task control
- Real-time package and delay until statement
- FIFO within priorities and ceiling locking scheduling
- Protected procedure interrupt handlers

Model enforced by pragma restrictions at compile time

(except for task termination and entry queue)

Forbidden features

- Task hierarchies
- Protected object hierarchies
- Dynamic POs and tasks
- Task entries
- Protected types with more than one entry
- Complex barriers
- More than one task in one entry queue
- Requeue
- ATC
- Select statement
- Abort
- Dynamic priorities
- Calendar package
- Relative delays
- Asynchronous task control
- User-defined task attributes

Supported features

- Library level tasks and POs
- Task discriminants
- Task identifiers
- FIFO within priority and Ceiling Locking policies
- Real-Time package
- Delay until statements
- Protected procedures as interrupt handlers
- Synchronous task control
- Atomic and Volatile pragmas
- Count Attribute (but not within entry barriers)

Ravenscar profile restrictions

Standard in Ada 95

No_Task_Hierarchy
No_Abort_Statements
No_Task_Allocators
No_Dynamic_Priorities
No_Asynchronous_Control
Max_Task_Entries => 0
Max_Protected_Entries => 1
Max_Asynchronous_Select_Nesting => 0
Max_Tasks => N

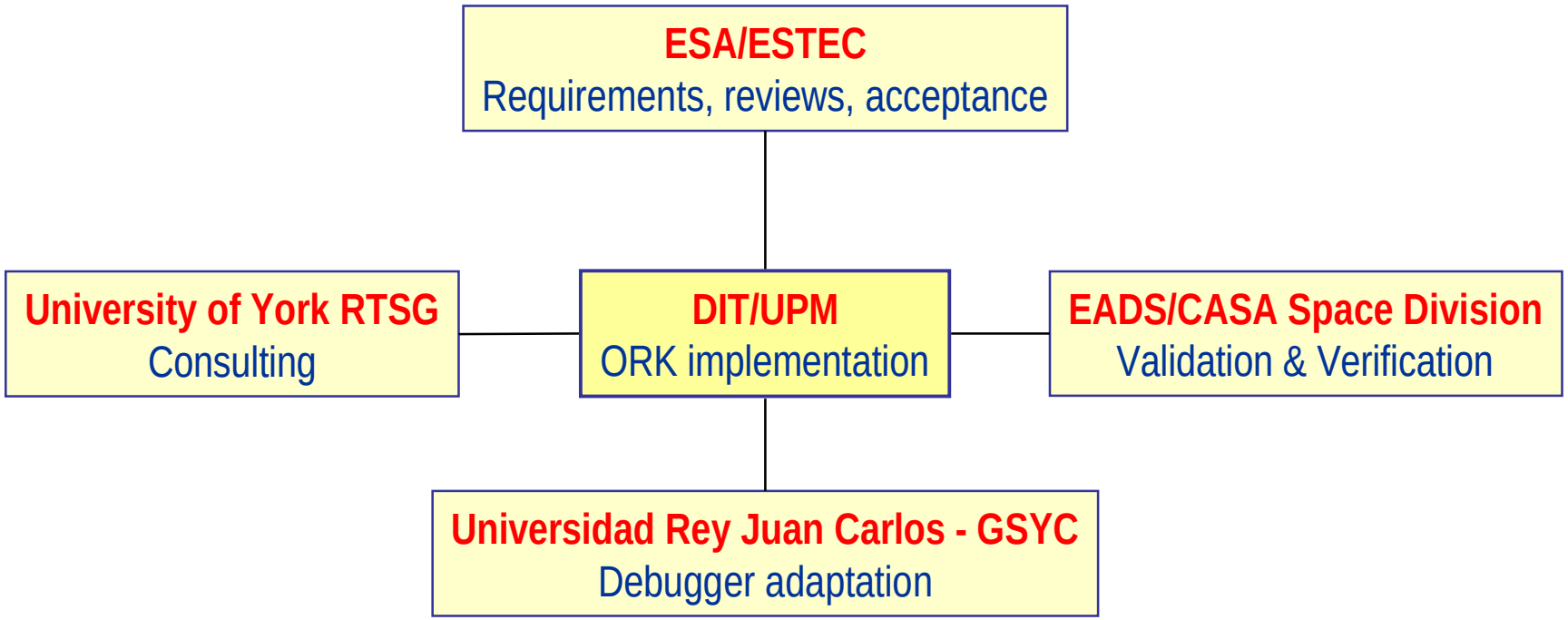
Proposed

Simple_Barrier_Variables
Max_Entry_Queue_Depth => 1
No_Calendar
No_Relative_Delay
No_Protected_Type_Allocators
No_Local_Protected_Objects
No_Requeue
No_Select_Statements
No_Task_Attributes
No_Task_Termination

The Open Ravenscar project

- Ravenscar profile-compliant runtime for GNAT
  - GNAT based cross-compilation system for ERC-32 (SPARC V7)
  - distributed as free software (GPL)
- Launched and funded by ESA/ESTEC
  - programme on software development tools for ERC32
    - » commercial tools
    - » open-source tools
- Time frame
  - Phase 1: October 1999 - June 2000 GNAT/ORK 2.1
  - Phase 2: November 2000-May 2001

The ORK consortium



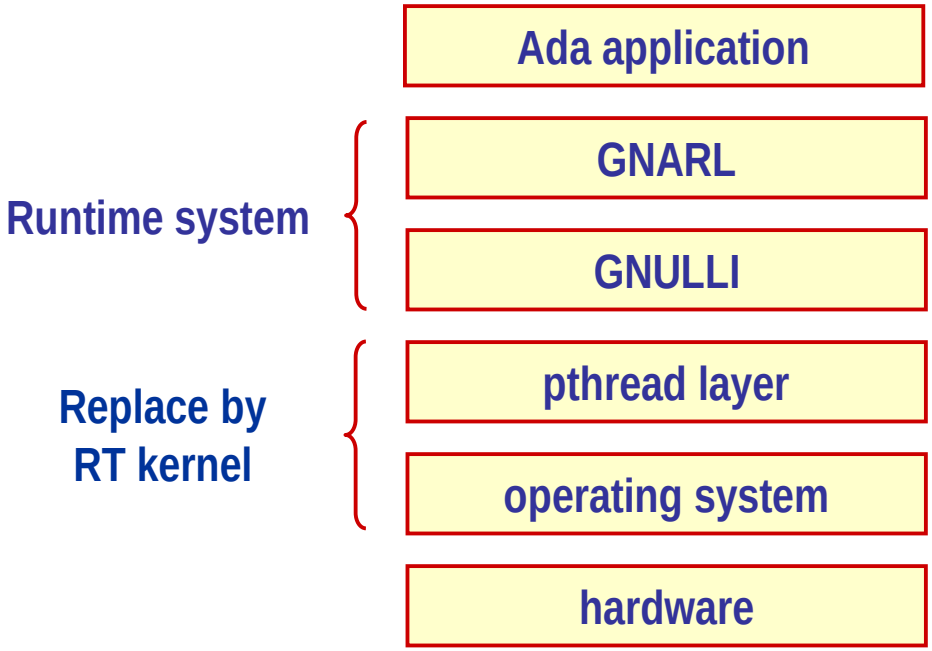
ORK inputs

- **GNARL**
  - running on pthreads
  - Ravenscar restricted tasking selected by a pragma
- **JTK** (José's Tasking Kernel)
  - internal DIT/UPM development
  - running on bare ix86
  - full Ada tasking with GNAT

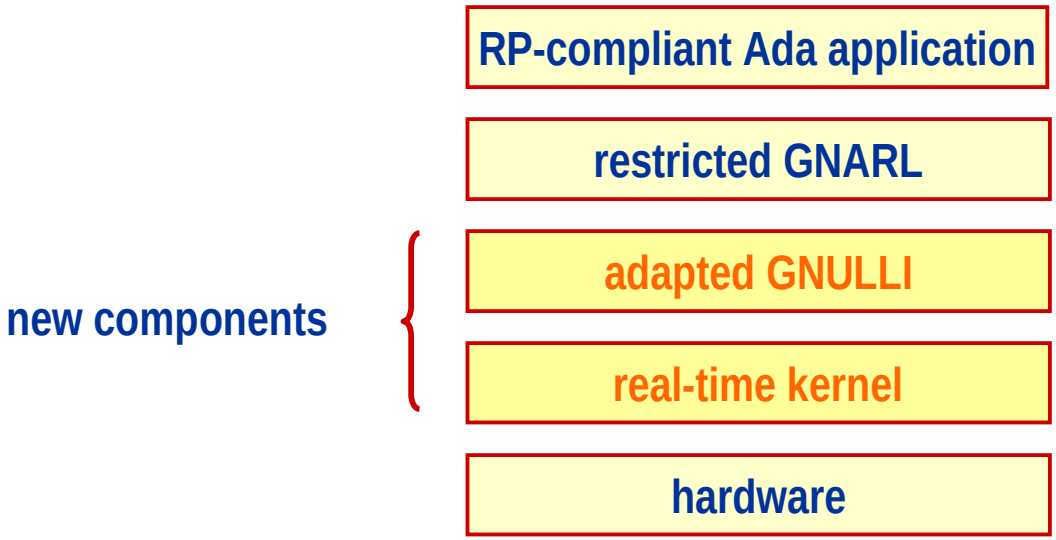
GNAT support for the Ravenscar Profile

- All RP restrictions implemented
  - compile-time checking possible for most of them
- Standard RTS (GNARL & GNULL) not adapted to RP
  - dynamic storage, task entries, etc. in RTS
  - complex dependencies between RTS packages
- Special pragma Ravenscar
  - selects all RP restrictions (and two additional ones)
  - selects a restricted RTS
    - » simplified tasking support
    - » no support for interrupt handlers
- Little support for cross-compilation
  - special versions of libraries required (newlib)

GNAT Run-Time Architecture



Initial Open Ravenscar Architecture



The Open Ravenscar Real-Time Kernel (ORK)

- A special-purpose real-time kernel providing support for RP-compliant programs compiled with GNAT
  - initial implementation for ERC-32
- No need for pthreads interface
  - pthreads duplicate much of the Ada 95 tasking functionality
  - almost direct implementation of GNULL interface possible
- Small, robust, efficient implementation possible
  - opens the way to HIS certification

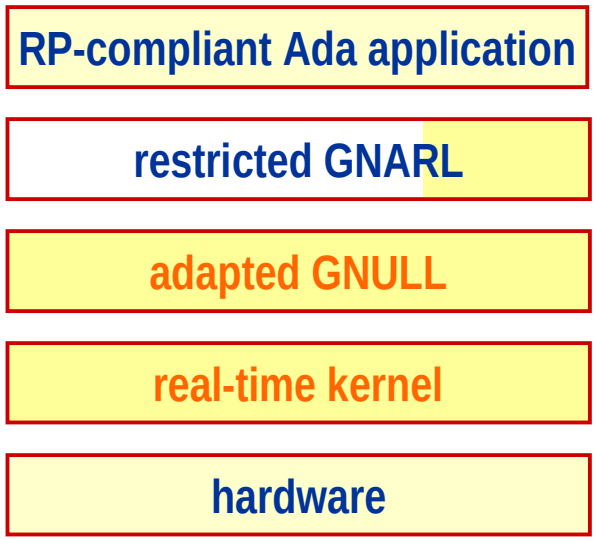
Design decisions (1)

- Code in Ada as far as possible
  - safe sequential Ada subset used
- Keep GNARL unmodified
  - but some GNARL packages had to be changed
- Take advantage of RP restrictions to simplify the implementation
- Careful implementation of kernel primitives to provide effective timing analysis

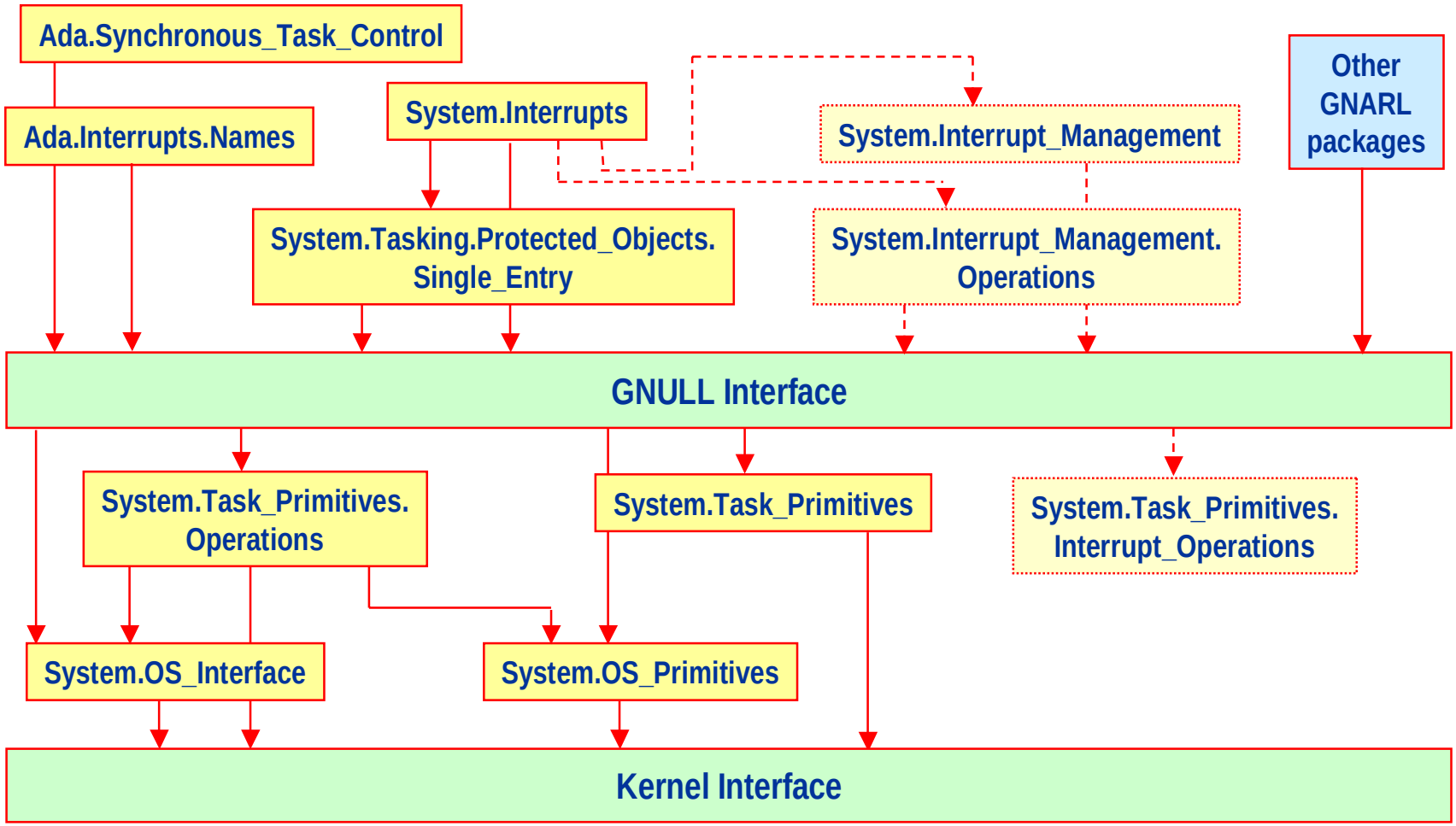
Design decisions (2)

- Allow implementation of device drivers at application level
  - GNARL interrupt support had to be redesigned
- Effective real-time support
  - fine-granularity clock
- Isolate target dependencies to allow easy retargeting
- Include configuration support for hardware and kernel parameters

Actual Open Ravenscar Architecture

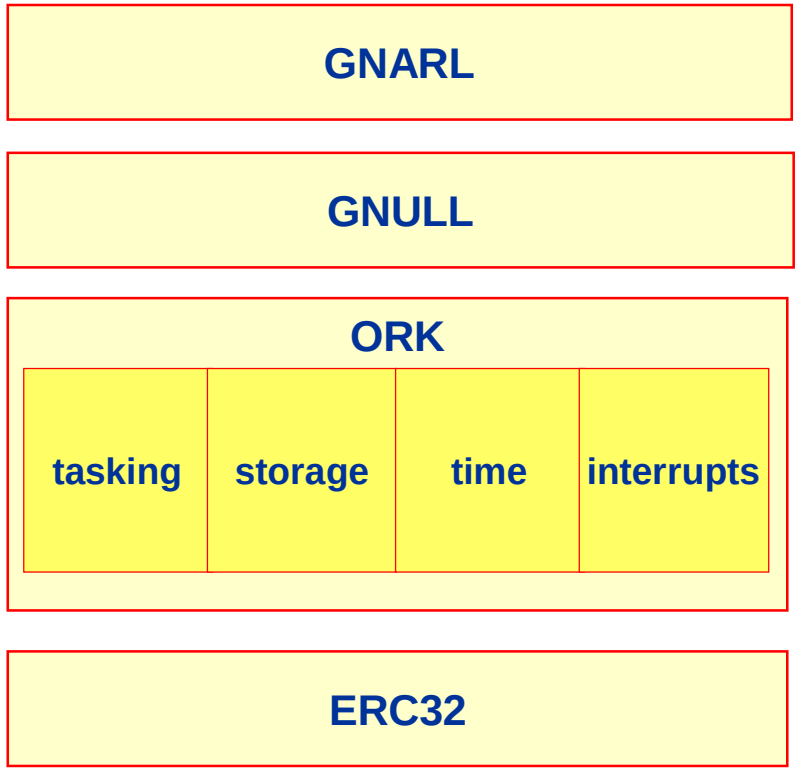


GNARL / ORK interfaces

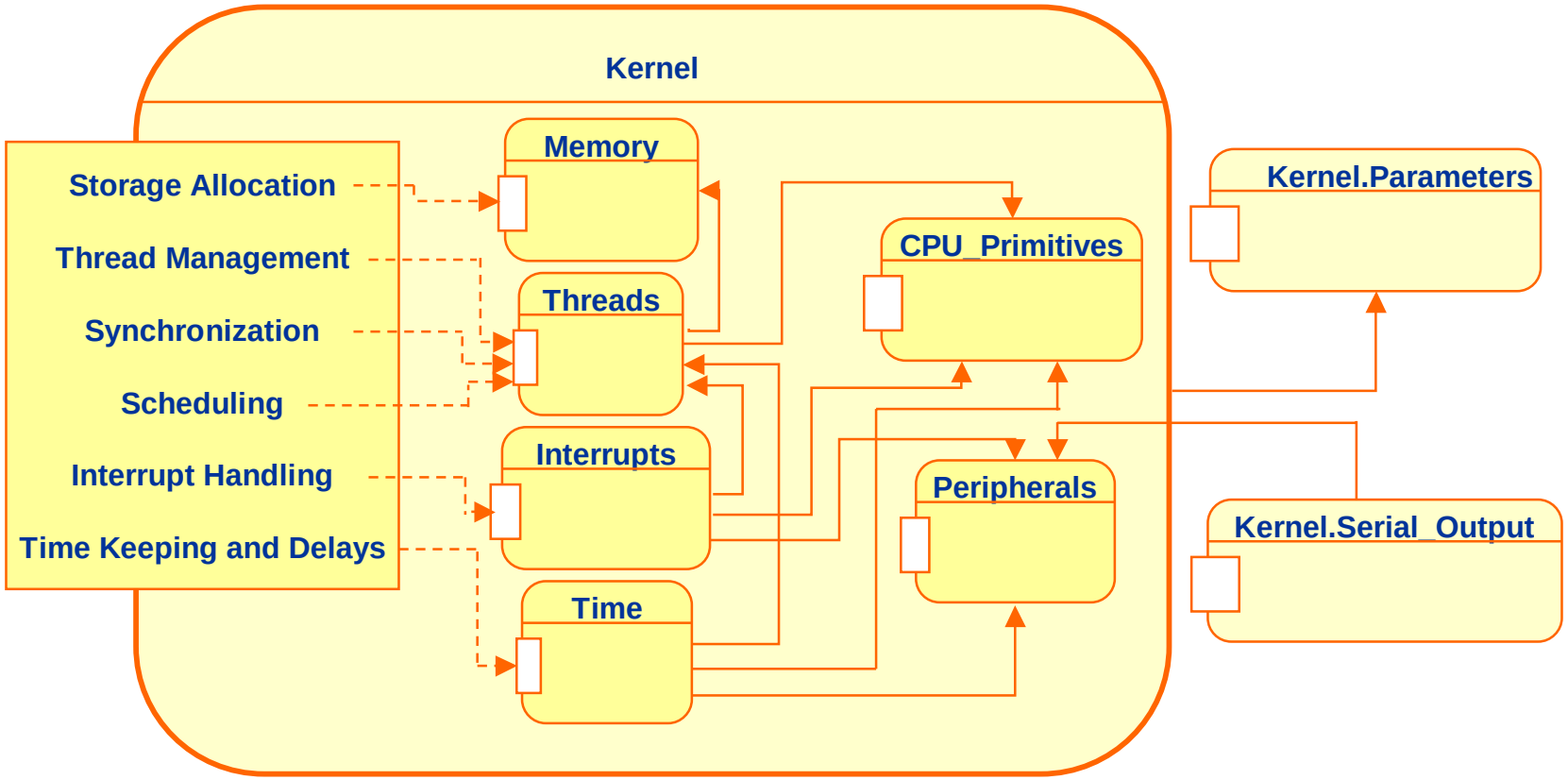


ORK functionality

- Task management
- Task synchronization
- Scheduling
- Storage allocation
- Time-keeping and delays
- Interrupt handling



ORK architecture



Thread management

- Threads are created only at start-up
  - storage management simplified
- Threads do not terminate
  - user-defined procedure called if a thread attempts to terminate
  - default : raise Program_Error
- FIFO within priorities dispatching
  - ready queue: priority-ordered double linked queue
- Thread-safe kernel
  - monolithic monitor, interrupts disabled
  - no separate kernel and user modes

Thread syncronization

- Mutexes
  - ceiling locking (immediate ceiling priority inheritance)
  - direct implementation of mutual exclusion
    - » by raising priority to ceiling priority
  - need to detect calls to potentially blocking operations
    - » raise Program_Error
- Condition variables
  - condition variables with at most one waiting thread
    - » raise Program_Error or user-defined procedure
  - no queues required
- Almost direct implementation of GNULLI operations
  - no need for all pthreads complexity

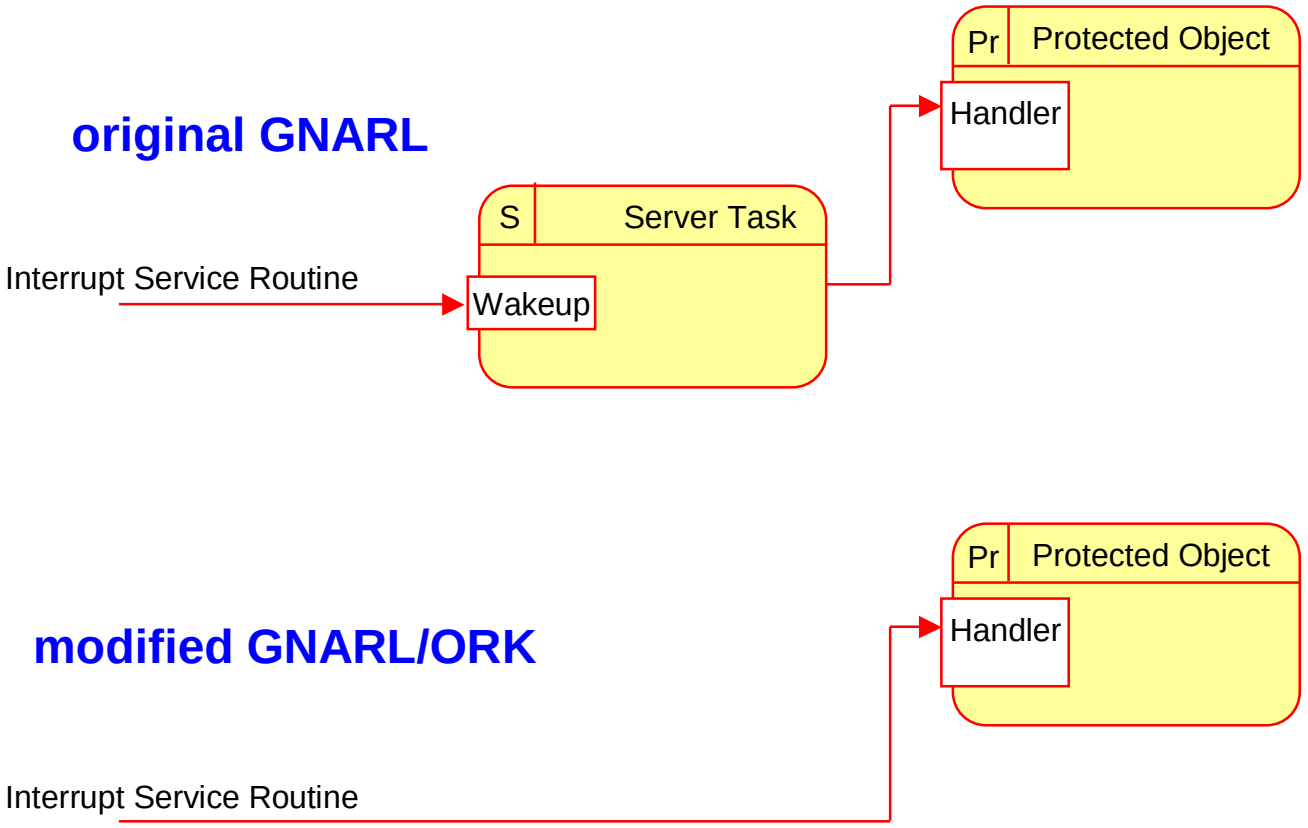
Storage management

- Provides initial storage allocation for TCBs and stacks
  - pre-allocated TCB space
  - task space based on pragma Storage_Size
  - no storage allocation after start-up
  - no de-allocation
- Application code does not use storage pools
  - problems with some GNARL packages
- Thread stack limits are protected for improved safety
  - forbidden blocks between adjacent stacks

Interrupt handlers (1)

- Only protected handlers supported
  - direct attachment of hardware interrupts to protected handlers
  - no need for POSIX signals
- Interrupt support in GNARL redesigned
  - simpler implementation
  - no service tasks
  - special interrupt stack

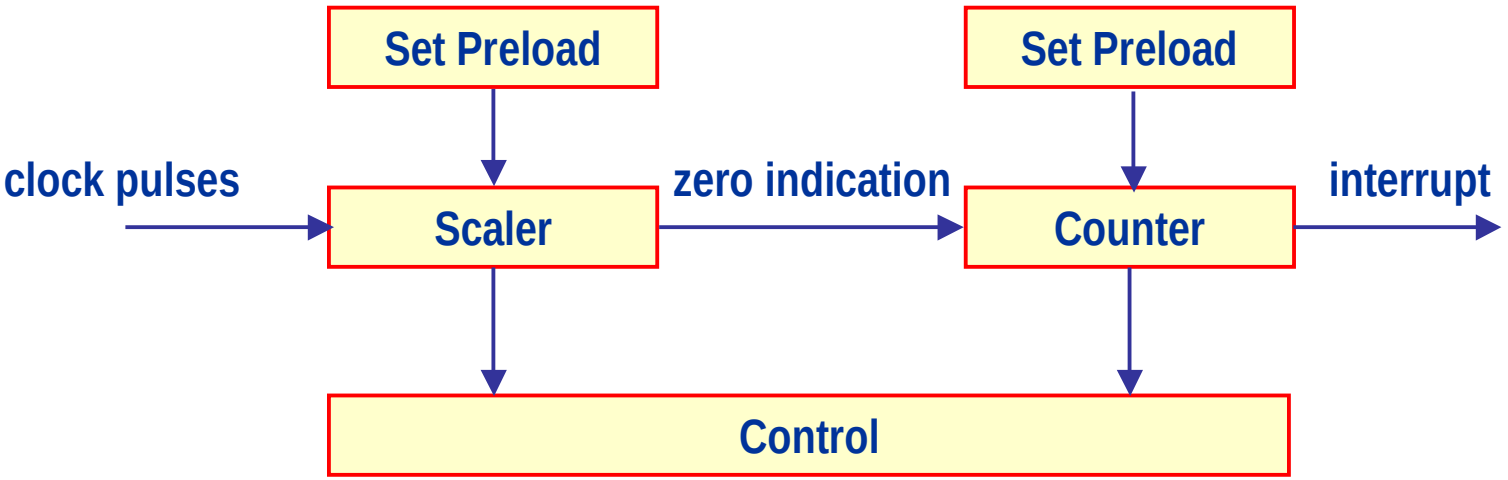
Interrupt handlers (2)



Time management

- Monotonic clock
  - integer nanoseconds from system start-up
  - high resolution tick
    - » equal to the hardware clock period (100 ns on 10MHz ERC32)
  - efficient timekeeping
    - » clock interrupts only every 1s
- Efficient absolute delays
  - alarm-clock model
  - delayed queue implemented as a single-linked list ordered by wake-up time
  - no cancellation
  - all delayed tasks made ready at once

High-resolution tick



The Open Ravenscar tool set (1)

Cross-compilation system

- Based on GNAT 3.13
- Development platform : PC GNU/Linux
  - Solaris coming soon
- Execution platform
  - ERC32-based computer
  - TSIM ERC32 simulator
- Components
  - sparc-ork-gcc, sparc-ork-gnatbind, sparc-ork-gnatlink
  - sparc-ork-gnatmake
  - other gnat & binutils tools

The Open Ravenscar tool set (2)

Debugging tools

- GDB 4.17 & DDD 3.2 for GNU/Linux
  - scripts added for enhanced tasking support

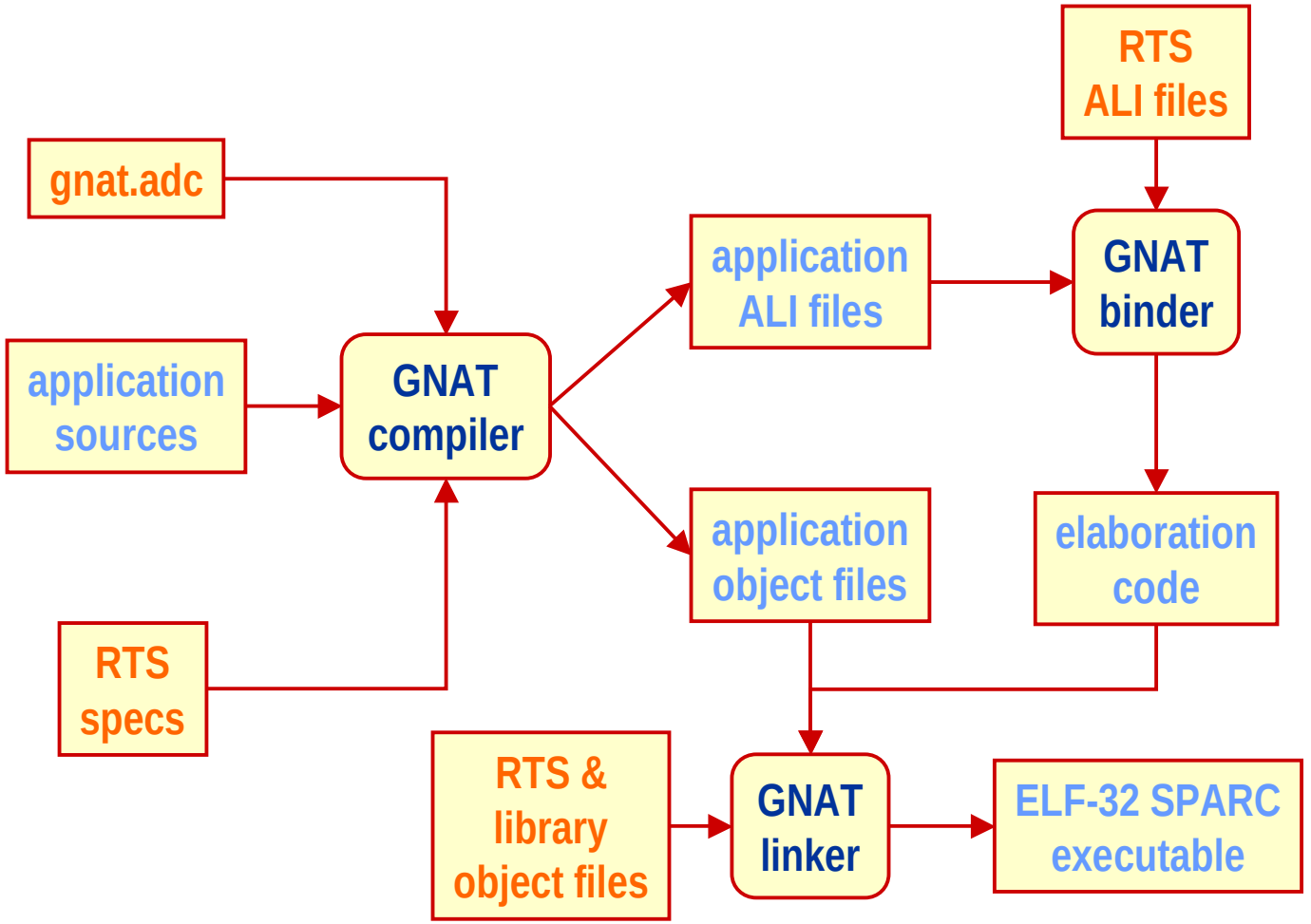
TSIM Simulator

- Not part of Open Ravenscar
  - distributed by ESA/ESTEC
- Allows debugging on development platform before going to the actual target hardware

Developing with Open Ravenscar

- Write a Ravenscar profile-compliant program
  - a special gnat.adc file is required
- Compile and link with sparc-ork-gnat
  - most RP violations checked at compile-time
  - result is an ELF executable file
- Debug the program
  - on the development platform:
    - » TSIM and GDB/DDD
  - on the target platform:
    - » download and remote debugging monitor (not yet available)
- Make a PROM
    - » tools not yet available

GNAT/Open Ravenscar compilation process



GNAT configuration file

```
-- file gnat.adc

pragma Ravenscar;

pragma Restrictions (Max Tasks => N);
-- N must be equal to the number of tasks of the
-- application

-- other restrictions can be declared here

pragma Task Dispatching Policy (FIFO Within Priorities);
pragma Locking Policy (Ceiling Locking);
```

Compile time and run time checks

- Most Ravenscar Profile restrictions checked at compile time
- Two restrictions checked at run time
  - No_Task_Termination
    - » call a user-defined procedure (default silent)
  - Max_Entry_Queue_Depth => 1
    - » raise Program_Error

Configuring ORK

- Configurable parameters in Kernel.Parameters
  - Maximum number of threads
  - Amount of memory available in the target board
  - Amount of memory space reserved for thread stacks
  - Size of the interrupt stack
  - Priority range
  - Clock frequency
  - Clock interrupt period
- Interrupt names and other parameters defined in **System.OS_Interface** (and **Ada.Interrupts.Names)**
- Requires re-building the kernel from sources

Kernel metrics (ERC32 at 10 MHz)

◆ Size of kernel sources (statements)	1361	Ada
	478	assembly code
	82	C
◆ Size of kernel binary code	15	KB (with vector table)
◆ Minimum program size	94	KB (no tasks)
	133	KB (with tasks)
◆ Context switch time	85	µs
◆ Interrupt latency	295	µs

Conclusions

- It is feasible to build new, simpler kernels for GNAT
  - GNULL concept and interface very useful
  - but reducing the memory footprint requires rewriting most of GNARL
  - it is possible to use a safe sequential subset of Ada for the kernel itself
- Certification of applications will require more effort
  - especially in upper GNARL layers

Current and future work

- Porting a reusable component framework (OBOSS) to GNAT/ORK
- Test on real hardware
  - board monitor & loader to be written
- Integrate in ESA Software Engineering Environment
  - generate RP-compliant code from HRT-HOOD designs
  - integrate timing analysis tools
- Improve integration with GNAT and prune GNARL of unused code

The ORK team

ORK development (DIT/UPM)

- Juan Antonio de la Puente
- Juan Zamorano
- José Ruiz
- Ramón Fernández
- Rodrigo García

ORK validation (EADS CASA)

- Jesús Borruel
- Juan Carlos Morcuende

GDB/DDD adaptation (URJC)

- Jesús González-Barahona
- Vicente Matellán
- Andrés Arias
- Juan Manuel Dodero

RP consultants (U York)

- Andy Wellings
- Alan Burns

Availability

source and binaries for PC GNU/Linux available on

http:www.openravenscar.org

current version is 2.1