## HiRTOS: A Multi-Core RTOS written in SPARK Ada

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### Topics

- HiRTOS Design Overview
- HiRTOS Thread Scheduler
- HiRTOS Separation Kernel
- Porting HiRTOS to a New Platform
- Future Work

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### What is HiRTOS?

- HiRTOS: *High-Integrity* RTOS
  - SPARK Ada
  - HiRTOS targets deeply embedded software applications that run in small single-core and multi-core embedded platforms
  - HiRTOS won the "2023 Alire Embedded Crate of the Year" award
- HiRTOS is available for download as two Alire crates:
  - HiRTOS kernel at <u>https://alire.ada.dev/crates/hirtos</u>
  - HiRTOS separation kernel at
- https://alire.ada.dev/crates/hirtos\_separation\_kernel HiRTOS code is available in GitHub at https://github.com/jgrivera67/HiRTOS

A small real-time operating system kernel and separation kernel written in

## HiRTOS Design Overview

- In a multi-core platform, there is one HiRTOS instance per CPU. • Each HiRTOS instance is independent of each other. No resources are
  - shared between CPUs.
  - No communication/synchronization between CPU cores is supported by HiRTOS.
- Mutexes and condition variables are the only synchronization primitives in HiRTOS
  - Other synchronization primitives such as semaphores, event flags and message queues can be implemented on top of mutexes and condition variables.
- HiRTOS mutexes support both priority inheritance and priority ceiling protocols.

## HiRTOS Design Overview (2)

- HiRTOS condition variables can also be waited on while having interrupts disabled, not just while holding a mutex.
  - This prevents missing "thread wakeups", when signaling condition variables from interrupt service routines. (Semaphore not needed)
- HiRTOS atomic levels can be used to disable the thread scheduler or to disable interrupts at and below a given priority or to disable all interrupts.
- Threads are bound to the CPU core in which they were created, for the lifetime of the thread.
  - No thread migration between CPU cores is supported

## HiRTOS Design Overview (3)

- All RTOS objects such as threads, mutexes and condition variables are allocated internally by HiRTOS from statically allocated internal object arrays
  - Once allocated, RTOS objects cannot be deallocated
  - RTOS object handles provided to application code are just indices into these internal object arrays.
- All application threads run in unprivileged mode by default.
- In unprivileged mode, a thread can only access its own stack.
- To access global variables or MMIO space, application threads must explicitly request permission to HiRTOS.

## HiRTOS Design Overview (4)

### • HiRTOS pointer-less data structures

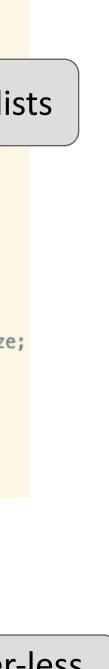
Arrays of RTOS objects

Arrays of nodes for linked lists of the corresponding type

ty	<pre>pe HiRTOS_Cpu_Instance_Type is limited record</pre>	
	Initialized : Boolean	:= False;
	Last_Chance_Handler_Running : Boolean	:= False;
	Tick_Timer_Thread_Work_Requested : Boolean	:= False v
	Cpu_Id : Cpu_Core_Id_Type;	
	<pre>Thread_Scheduler_State : Thread_Scheduler_State_Type</pre>	:=
	Thread_Scheduler_Stopped;	
	Current_Atomic_Level : Atomic_Level_Type := Atomic_	mic_Level
	<pre>Current_Cpu_Execution_Mode : Cpu_Execution_Mode_Type</pre>	:= Cpu_Exe
	Current_Thread_Id : Thread_Id_Type := Inv	/alid_Threa
	Timer_Ticks_Since_Boot : Timer_Ticks_Count_Typ	e := 0;
	<pre>Idle_Thread_Id : Thread_Id_Type := Inv</pre>	/alid_Threa
	Tick_Timer_Thread_Id : Thread_Id_Type := Inv	/alid_Threa
	<pre>Interrupt_Stack_Base_Address : System.Address := Sys</pre>	tem.Null_/
	<pre>Interrupt_Stack_End_Address := System.Address := Sys</pre>	tem.Null_/
	<pre>Next_Free_Thread_Id : Atomic_Counter_Type :=</pre>	
	Atomic_Counter_Initializer (Cpu_Register_Type (Thr	read_Id_Typ
	<pre>Next_Free_Mutex_Id : Atomic_Counter_Type :=</pre>	
	Atomic_Counter_Initializer (Cpu_Register_Type (Mut	ex_Id_Type
	<pre>Next_Free_Condvar_Id : Atomic_Counter_Type :=</pre>	
	Atomic_Counter_Initializer (Cpu_Register_Type (Cor	dvar_Id_Ty
	<pre>Next_Free_Timer_Id : Atomic_Counter_Type :=</pre>	
	Atomic_Counter_Initializer (Cpu_Register_Type (Tim	ner_Id_Type
	<pre>Interrupt_Nesting_Level_Stack : Interrupt_Nesting_Lev</pre>	/el_Stack_1
	Runnable_Threads_Queue : Thread_Priority_Queue	_Type;
	Timer_Wheel : Timer_Wheel_Type;	
ſ	Thread_Instances : Thread_Array_Type;	
	<pre>Mutex_Instances : Mutex_Array_Type;</pre>	
$\left\{ \right\}$	Condvar_Instances : Condvar_Array_Type;	
	<pre>Timer_Instances : Timer_Array_Type;</pre>	
	<pre>Thread_Queues_Nodes : Thread_Queue_Package.List_Node</pre>	es_Type;
$\left\{ \right.$	<pre>Mutex_Lists_Nodes : Mutex_List_Package.List_Nodes_</pre>	Type;
L	Timer_Lists_Nodes : Timer_List_Package.List_Nodes_	Туре;
en	d record with	
	<pre>Alignment =&gt; HiRTOS_Cpu_Arch_Parameters.Cache_Line_Si</pre>	<pre>ze_Bytes;</pre>

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package Thread\_Queue\_Package is new Generic\_Linked\_List (List\_Id\_Type => Thread\_Priority\_Type, Null\_List\_Id => Invalid\_Thread\_Priority, pointer-less linked lists Element\_Id\_Type => Thread\_Id\_Type, with Atomic; Null\_Element\_Id => Invalid\_Thread\_Id); package Mutex\_List\_Package is new Generic\_Linked\_List (List\_Id\_Type => Thread\_Id\_Type, l None; Executing\_Reset\_Handler; Null\_List\_Id => Invalid\_Thread\_Id, pointer-less linked lists read\_Id; Element\_Id\_Type => Mutex\_Id\_Type, Null\_Element\_Id => Invalid\_Mutex\_Id); read\_Id; read\_Id; type Per\_Priority\_Thread\_Queues\_Array\_Type is \_Address; array (Valid\_Thread\_Priority\_Type) of Thread\_Queue\_Package.List\_Anchor\_Type; \_Address; First); type Boolean\_Bit\_Map\_Type is array (Valid\_Thread\_Priority\_Type) of Boolean with Component\_Size => 1, Size => HiRTOS\_Cpu\_Arch\_Interface.Cpu\_Register\_Type'Size; /pe'First)); type Thread\_Priority\_Queue\_Type is record \_Type'First)); Non\_Empty\_Thread\_Queues\_Map : Boolean\_Bit\_Map\_Type := [others => False]; Thread\_Queues\_Array : Per\_Priority\_Thread\_Queues\_Array\_Type; /pe'First)); end record; <\_Type; package Timer\_List\_Package is new Generic\_Linked\_List => Timer\_Wheel\_Spoke\_Index\_Type, (List\_Id\_Type => Invalid\_Timer\_Wheel\_Spoke\_Index, Null\_List\_Id Element\_Id\_Type => Timer\_Id\_Type, pointer-less => Invalid\_Timer\_Id); Null\_Element\_Id linked lists



## HiRTOS Design Overview (5)

### HiRTOS pointer-less linked lists

```
generic
   type List_Id_Type is private;
   Null_List_Id : List_Id_Type;
   type Element_Id_Type is range <>;
   Null_Element_Id : Element_Id_Type;
package Generic_Linked_List with
  SPARK Mode => On
is
   type List_Node_Type is limited private;
   type List_Anchor_Type is private;
   type List_Nodes_Type is limited private;
Backing storage for all the linked lists (pairs of
"next/prev" injective functions) of a given type
```

### private

```
type List_Anchor_Type is record
      List_Id : List_Id_Type := Null_List_Id;
      Head : Element_Id_Type := Null_Element_Id;
      Tail : Element_Id_Type := Null_Element_Id;
      Length : Natural := 0;
   end record with
     Type_Invariant =>
      (if List_Anchor_Type.Length = 0 then
         (List_Anchor_Type.Head = Null_Element_Id
          and then List_Anchor_Type.Tail = Null_Element_Id)
       else
         (List_Anchor_Type.Head /= Null_Element_Id
          and then List_Anchor_Type.Tail /= Null_Element_Id
          and then
          (if List_Anchor_Type.Head = List_Anchor_Type.Tail then
             List_Anchor_Type.Length = 1
           else List_Anchor_Type.Length > 1)));
type List_Node_Type is limited record
  Next_Element_Id : Element_Id_Type := Null_Element_Id;
  Prev_Element_Id : Element_Id_Type := Null_Element_Id;
  Containing_List_Id : List_Id_Type := Null_List_Id;
end record;
pragma Compile_Time_Error
 (Null_Element_Id /= Element_Id_Type'Last,
  "Null_element_Id has the wrong value");
subtype Valid_Element_Id_Type is
 Element_Id_Type range Element_Id_Type'First .. Element_Id_Type'Last - 1;
   NOTE: The same element cannot be in more than one list. So,
— the maximal set of nodes that we need is `Valid_Element_Id_Type`
type List_Nodes_Type is array (Valid_Element_Id_Type) of List_Node_Type;
```

### **HiRTOS Supported Platforms**

### ARM Fixed Virtual Platform (FVP) Simulator for ARMv8-R (ARM) Cortex-R52 processor with 4 cores)

FVP terminal_0	∧ _ □ × 🕅 🛣 FVP terminal_1 ∧ _ □ 3	
Thread 1 (id 2, prio 30): Period 500ms, Last run at 2492s 492808us, Wakeups 4921 Thread 2 (id 3, prio 28): Period 1000ms, Last run at 2492s 493025us, Wakeups 2464	Thread 1 (id 2, prio 30): Period 500ms, Last run at 2492s 521698us, Wakeups 4921	
Thread 2 (id 3, prio 29): Period 1000ms, Last run at 2492s 493025us, Wakeups 2461 Thread 3 (id 4, prio 28): Period 1500ms, Last run at 2492s 493277us, Wakeups 1641	l	
Thread 5 (id 6, prio 26): Period 2500ms, Last run at 2492s 493494us, Wakeups 985	Thread 5 (id 6, prio 26): Period 2500ms, Last run at 2492s 522384us, Wakeups 985	
Thread 6 (id 7, prio 25): Period 3000ms, Last run at 2492s 493803us, Wakeups 821 Thread 4 (id 5, prio 27): Period 2000ms, Last run at 2482s 508508us, Wakeups 1234	Thread 6 (id 7, prio 25): Period 3000ms, Last run at 2492s 522694us, Wakeups 821	
Thread 4 (id 5, prio 27): Period 2000ms, Last run at 2492s 509509us, Wakeups 1231 Thread 8 (id 9, prio 23): Period 4000ms. Last run at 2492s 510520us. Wakeups 616	l Thread 4 (id 5, prio 27): Period 2000ms, Last run at 2492s 538404us, Wakeups 1231 Thread 8 (id 9, prio 23): Period 4000ms, Last run at 2492s 539418us, Wakeups 616	
Thread 1 (id 2, prio 30): Period 500ms, Last run at 2492s 999301us, Wakeups 4922	Thread 1 (id 2, prio 30): Period 500ms, Last run at 2493s 28160us, Wakeups 4922	
Thread 7 (1d 8, prio 24): Period 3500ms, Last run at 2493s 313us, Wakeups 704 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2493s 506030us, Wakeups 4923	Thread 7 (id 8, prio 24): Period 3500ms, Last run at 2493s 29175us, Wakeups 704 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2493s 534865us, Wakeups 4923	
Thread 2 (id 3, prio 29): Period 1000ms, Last run at 2493s 506247us, Wakeups 2462		
Thread 1 (id 2, prio 30): Period 500ms, Last run at 2494s 12571us, Wakeups 4924 Thread 3 (id 4, prio 28): Period 1500me, Last run at 2484a 12787us, Wakeups 1642	Thread 1 (id 2, prio 30): Period 500ms, Last run at 2494s 41448us, Wakeups 4924 Thread 7 (id 4, prio 38): Period 4500ms, Last run at 2494s 44664us, Wakeups 4642	
Thread 3 (id 4, prio 28): Period 1500ms, Last run at 2494s 12787us, Wakeups 1642 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2494s 519079us, Wakeups 4925	Thread 3 (id 4, prio 28): Period 1500ms, Last run at 2494s 41664us, Wakeups 1642 Thread 1 (id 2. prio 30): Period 500ms. Last run at 2494s 548177us. Wakeups 4925	
Thread 2 (id 3, prio 29): Period 1000mś, Last run at 2494s 519296uś, Wakeups 2463	Thread 2 (id 3, prio 29): Period 1000mś, Last run at 2494s 548394uś, Wakeups 2463	
Thread 4 (id 5, prio 27): Period 2000ms, Last run at 2494s 535792us, Wakeups 1232 Thread 1 (id 2. prio 30): Period 500ms. Last run at 2495s 25580us. Wakeups 4926	2 Thread 4 (id 5, prio 27): Period 2000ms, Last run at 2494s 564892us, Wakeups 1232 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2495s 54796us, Wakeups 4926	
Thread 5 (id 6, prio 26): Period 2500ms, Last run at 2495s 26086us, Wakeups 986	Thread 5 (id 6, prio 26): Period 2500ms, Last run at 2495s 55304us, Wakeups 986	
Thread 1 (id 2, prio 30): Period 500ms, Last run at 2495s 532172us, Wakeups 4927 Thread 2 (id 3, prio 20): Period 4000ms, Last run at 2495s 532380us, Wakeups 2464	Thread 1 (id 2, prio 30): Period 500ms, Last run at 2495s 561344us, Wakeups 4927	
Thread 2 (id 3, prio 29): Period 1000ms, Last run at 2495s 532389us, Wakeups 2464 Thread 3 (id 4. prio 28): Period 1500ms. Last run at 2495s 532630us. Wakeups 1643		
Thread 6 (id 7, prio 25): Period 3000ms, Last run at 2495s 533167us, Wakeups 822	Thread 6 (id 7, prio 25): Period 3000ms, Last run at 2495s 562340us, Wakeups 822	
Thread 1 (id 2, prio 30): Period 500ms, Last run at 2496s 38967us, Wakeups 4928	Thread 1 (id 2, prio 30): Period 500ms, Last run at 2496s 67912us, Wakeups 4928	
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## HiRTOS Supported Platforms (2)

### ARM Cortex-R52-SMP Renode Simulator configuration (2 cores)

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H	HiRTOS > sample_apps > h	ello partitions
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FVP ARMv8-R Hel	lo running on CPU scheduler started	n May 24 2024 at 14:50:48) 0 (built on May 21 2024 at 11:36:04)
		d 500ms, Last run at 0s 6000us, Wakeups 1
		d 1000ms, Last run at 0s 6200us, Wakeups
Thread 3 (id 4	, prio 28): Perio	d 1500ms, Last run at 0s 6500us, Wakeups
Thread 4 (id 5	, prio 27): Perio	d 2000ms, Last run at 0s 6700us, Wakeups
Thread 5 (id 6	, prio 26): Perio	d 2500ms, Last run at 0s 7000us, Wakeups
Thread 6 (id 7	, prio 25): Perio	d 3000ms, Last run at 0s 7200us, Wakeups
Thread 7 (id 8	, prio 24): Perio	d 3500ms, Last run at 0s 7500us, Wakeups
Thread 8 (id 9	, prio 23): Perio	d 4000ms, Last run at 0s 7700us, Wakeups
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Thread 1 (id 2	, prio 30): Perio	d 500ms, Last run at 1s 5900us, Wakeups 3
Thread 2 (id 3	, prio 29): Perio	d 1000ms, Last run at 1s 6100us, Wakeups
		d 500ms, Last run at 1s 505900us, Wakeups
Thread 3 (id 4	, prio 28): Perio	d 1500ms, Last run at 1s 506400us, Wakeup
Thread 1 (id 2	, prio 30): Perio	d 500ms, Last run at 2s 5900us, Wakeups 5
Thread 2 (id 3	, prio 29): Perio	d 1000ms, Last run at 2s 6100us, Wakeups
Thread 4 (id 5	, prio 27): Perio	d 2000ms, Last run at 2s 6400us, Wakeups
Thread 1 (id 2	, prio 30): Perio	d 500ms, Last run at 2s 505900us, Wakeups
Thread 5 (id 6	, prio 26): Perio	d 2500ms, Last run at 2s 506900us, Wakeup
Thread 1 (id 2	, prio 30): Perio	d 500ms, Last run at 3s 5900us, Wakeups 7
Thread 2 (id 3	, prio 29): Perio	d 1000ms, Last run at 3s 6100us, Wakeups
Thread 3 (id 4	, prio 28): Perio	d 1500ms, Last run at 3s 6400us, Wakeups
Thread 6 (id 7	, prio 25): Perio	d 3000ms, Last run at 3s 6900us, Wakeups
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1 1 1 1 1 1 1 1 1 1 1 2 2 4 5 2 4 3 2 6 5 2 4 3 2 6 5 2 4 3 2 6 5 2 4 3 2 6 5 2 4 5 2 1 1 1 1 1 1 1 1 1 1 1 1 1	<pre>HiRTOS running on CPU 1 (built on May 24 2024 at 14:50:48) FVP ARMv8-R Hello running on CPU 1 (built on May 21 2024 at 11:36:04) HiRTOS: Thread scheduler started HiRTOS: Timer thread started Thread 1 (id 2, prio 30): Period 500ms, Last run at 0s 6200us, Wakeups 1 Thread 2 (id 3, prio 29): Period 1000ms, Last run at 0s 6400us, Wakeups 1 Thread 3 (id 4, prio 28): Period 1500ms, Last run at 0s 6700us, Wakeups 1 Thread 4 (id 5, prio 27): Period 2000ms, Last run at 0s 6700us, Wakeups 1 Thread 5 (id 6, prio 26): Period 2500ms, Last run at 0s 7200us, Wakeups 1 Thread 6 (id 7, prio 25): Period 3000ms, Last run at 0s 7400us, Wakeups 1 Thread 6 (id 7, prio 25): Period 3000ms, Last run at 0s 7400us, Wakeups 1 Thread 7 (id 8, prio 24): Period 3500ms, Last run at 0s 7000us, Wakeups 1 Thread 8 (id 9, prio 23): Period 4000ms, Last run at 0s 7000us, Wakeups 1 HiRTOS: Idle thread started Thread 1 (id 2, prio 30): Period 500ms, Last run at 1s 6100us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 1s 6000us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 1s 6000us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 1s 6000us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 1s 506600us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2s 60100us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2s 60100us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2s 60100us, Wakeups 2 Thread 1 (id 2, prio 30): Period 500ms, Last run at 2s 60100us, Wakeups 4 Thread 3 (id 4, prio 28): Period 1000ms, Last run at 2s 60100us, Wakeups 4 Thread 5 (id 6, prio 26): Period 2500ms, Last run at 2s 60100us, Wakeups 6 Thread 5 (id 6, prio 26): Period 500ms, Last run at 2s 60100us, Wakeups 7 Thread 1 (id 2, prio 30): Period 500ms, Last run at 3s 6100us, Wakeups 7 Thread 5 (id 6, prio 28): Period 1000ms, Last run at 3s 6100us, Wakeups 7 Thread 1 (id 2, prio 30): Period 500ms, Last run at 3s 6010us, Wakeups 3 Thread 6 (id 7, prio 28): Period 1000ms, Last run</pre>
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### HiRTOS Supported Platforms (3)

### RISC-V-based ESP32-C3 board (single-core)

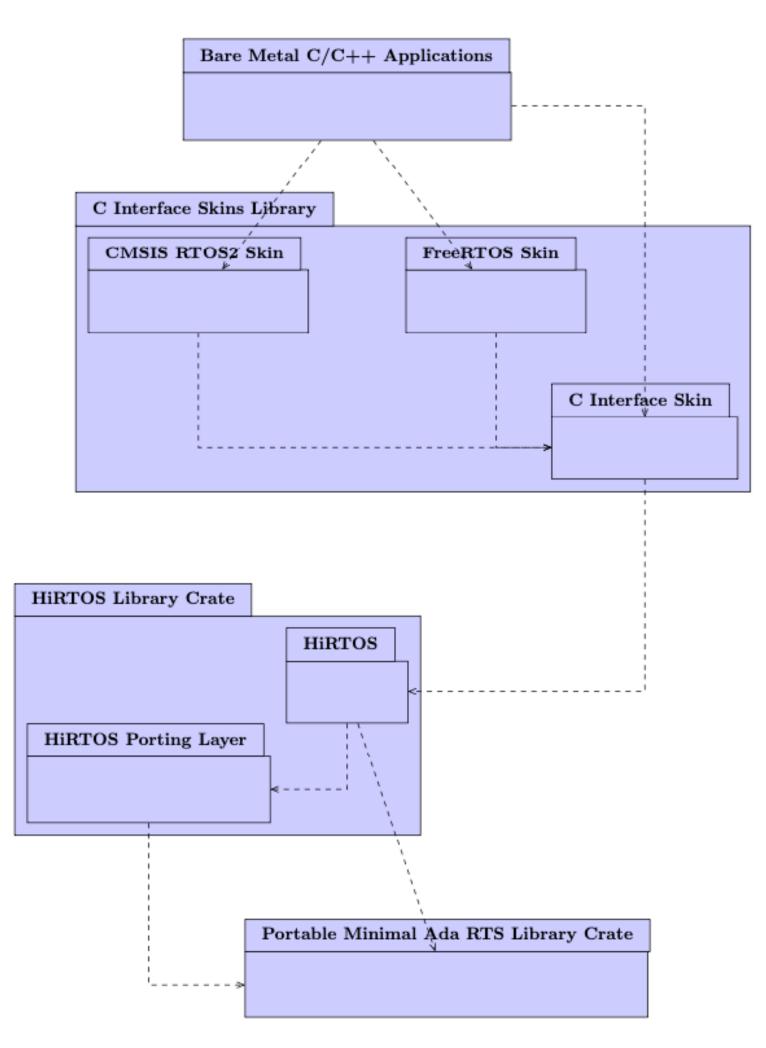
0000034ABF5D0E50	Thread	2	(id	3,	prio	29):
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0000034ABF64CEB0	Thread	3	(id	4,	prio	28):
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0000034ABF6C5090	Thread	2	(id	З,	prio	29):
0000034ABF6C8F10	Thread	4	(id	5,	prio	27):
0000034ABF6CF0B8	Thread	7	(id	8,	prio	24):
0000034ABF73D270	Thread	1	(id	2,	prio	30):
0000034ABF7B7390	Thread	1	(id	2,	prio	30):
0000034ABF7B92D0	Thread	2	(id	3,	prio	29):
0000034ABF7BB210	Thread	3	(id	4,	prio	28):
0000034ABF7BF090	Thread	5	(id	6,	prio	26):
0000034ABF7C0FD0	Thread	6	(id	7,	prio	25):
0000034ABF8314B0	Thread	1	(id	2,	prio	30):
0000034ABF8AB5D0	Thread	1	(id	2,	prio	30):
0000034ABF8AD510	Thread	2	(id	З,	prio	29):
0000034ABF8B1390	Thread	4	(id	5,	prio	27):
0000034ABF8C1178	Thread			9,	prio	23):
0000034ABF9256F0	Thread	1	(id	2,	prio	30):
0000034ABF929570				4,	prio	
0000034ABF99F810	Thread	1	(id	2,	prio	30):
0000034ABF9A1750						
0000034ABFA19930						
0000034ABFA21630						
0000034ABFA25898	Thread	7	(id	8,	prio	24):
0000034ABFA93A50	Thread	1	(id	2,	prio	30):
0000034ABFA95990						
0000034ABFA978D0	Thread	3	(id	4,	prio	28):
0000034ABFA99810						
0000034ABFA9D690						
0000034ABFB0DB70	Thread	1	(id	2,	prio	30):

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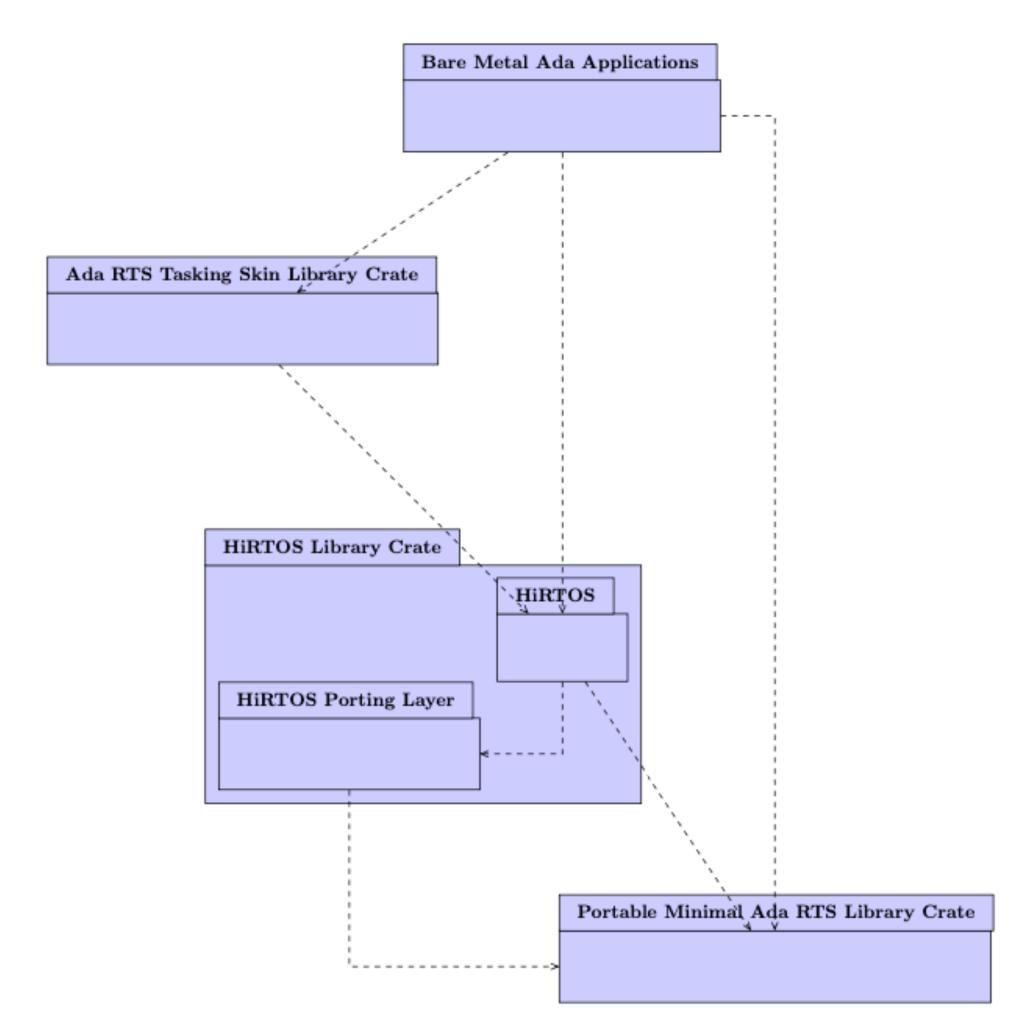
Period 1000ms, Last run at 1005h 1573s 12470us, Wakeups 3619574 Period 500ms, Last run at 1005h 1573s 504468us, Wakeups 7239148 Period 1500ms, Last run at 1005h 1573s 520470us, Wakeups 2413050 Period 500ms, Last run at 1005h 1574s 4468us, Wakeups 7239149 Period 1000ms, Last run at 1005h 1574s 12471us, Wakeups 3619575 Period 2000ms, Last run at 1005h 1574s 28471us, Wakeups 1809788 Period 3500ms, Last run at 1005h 1574s 53470us, Wakeups 1034165 Period 500ms, Last run at 1005h 1574s 504468us, Wakeups 7239150 Period 500ms, Last run at 1005h 1575s 4471us, Wakeups 7239151 Period 1000ms, Last run at 1005h 1575s 12471us, Wakeups 3619576 Period 1500ms, Last run at 1005h 1575s 20471us, Wakeups 2413051 Period 2500ms, Last run at 1005h 1575s 36471us, Wakeups 1447831 Period 3000ms, Last run at 1005h 1575s 44470us, Wakeups 1206526 Period 500ms, Last run at 1005h 1575s 504468us, Wakeups 7239152 Period 500ms, Last run at 1005h 1576s 4468us, Wakeups 7239153 Period 1000ms, Last run at 1005h 1576s 12470us, Wakeups 3619577 Period 2000ms, Last run at 1005h 1576s 28471us, Wakeups 1809789 Period 4000ms, Last run at 1005h 1576s 93470us, Wakeups 904895 Period 500ms, Last run at 1005h 1576s 504468us, Wakeups 7239154 Period 1500ms, Last run at 1005h 1576s 520470us, Wakeups 2413052 Period 500ms, Last run at 1005h 1577s 4469us, Wakeups 7239155 Period 1000ms, Last run at 1005h 1577s 12470us, Wakeups 3619578 Period 500ms, Last run at 1005h 1577s 504469us, Wakeups 7239156 Period 2500ms, Last run at 1005h 1577s 536470us, Wakeups 1447832 Period 3500ms, Last run at 1005h 1577s 553470us, Wakeups 1034166 Period 500ms, Last run at 1005h 1578s 4468us, Wakeups 7239157 Period 1000ms, Last run at 1005h 1578s 12471us, Wakeups 3619579 Period 1500ms, Last run at 1005h 1578s 20473us, Wakeups 2413053 Period 2000ms, Last run at 1005h 1578s 28470us, Wakeups 1809790 Period 3000ms, Last run at 1005h 1578s 44472us, Wakeups 1206527 Period 500ms, Last run at 1005h 1578s 504468us, Wakeups 7239158

### **HiRTOS Usage Architecture Vision**

• Using HiRTOS from C/C++

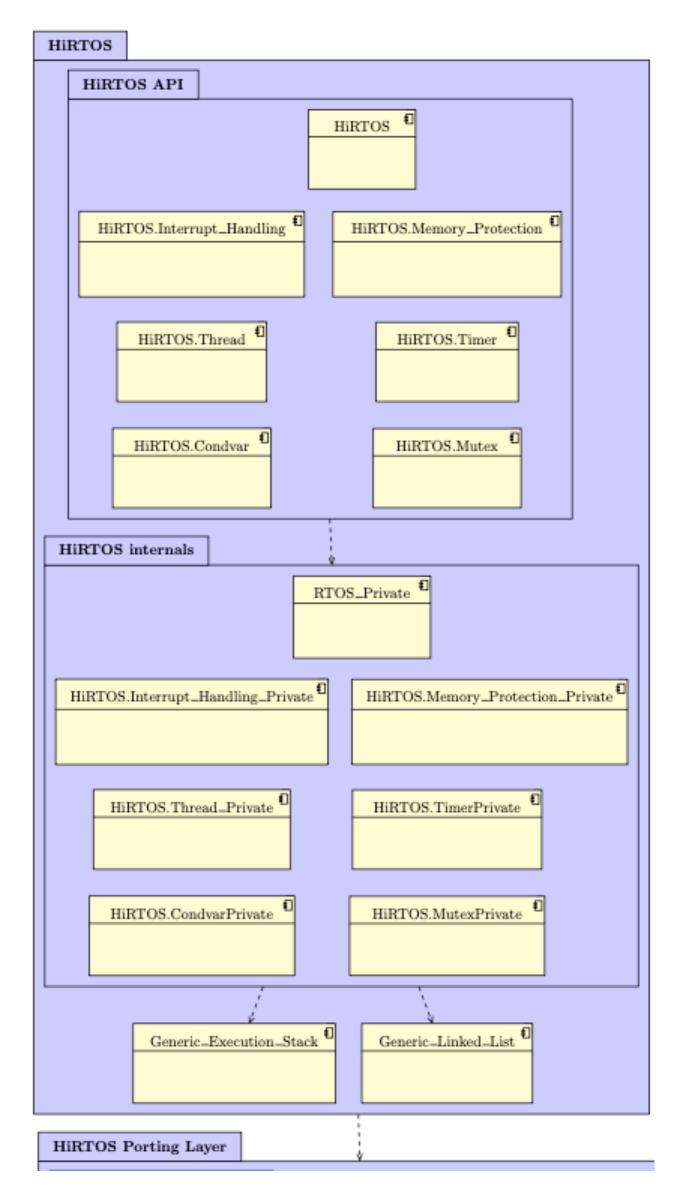


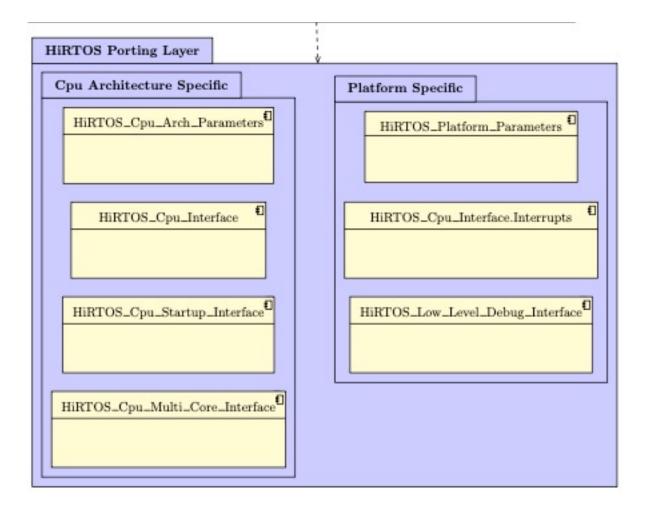
Using HiRTOS from Ada





### HiRTOS Code Architecture

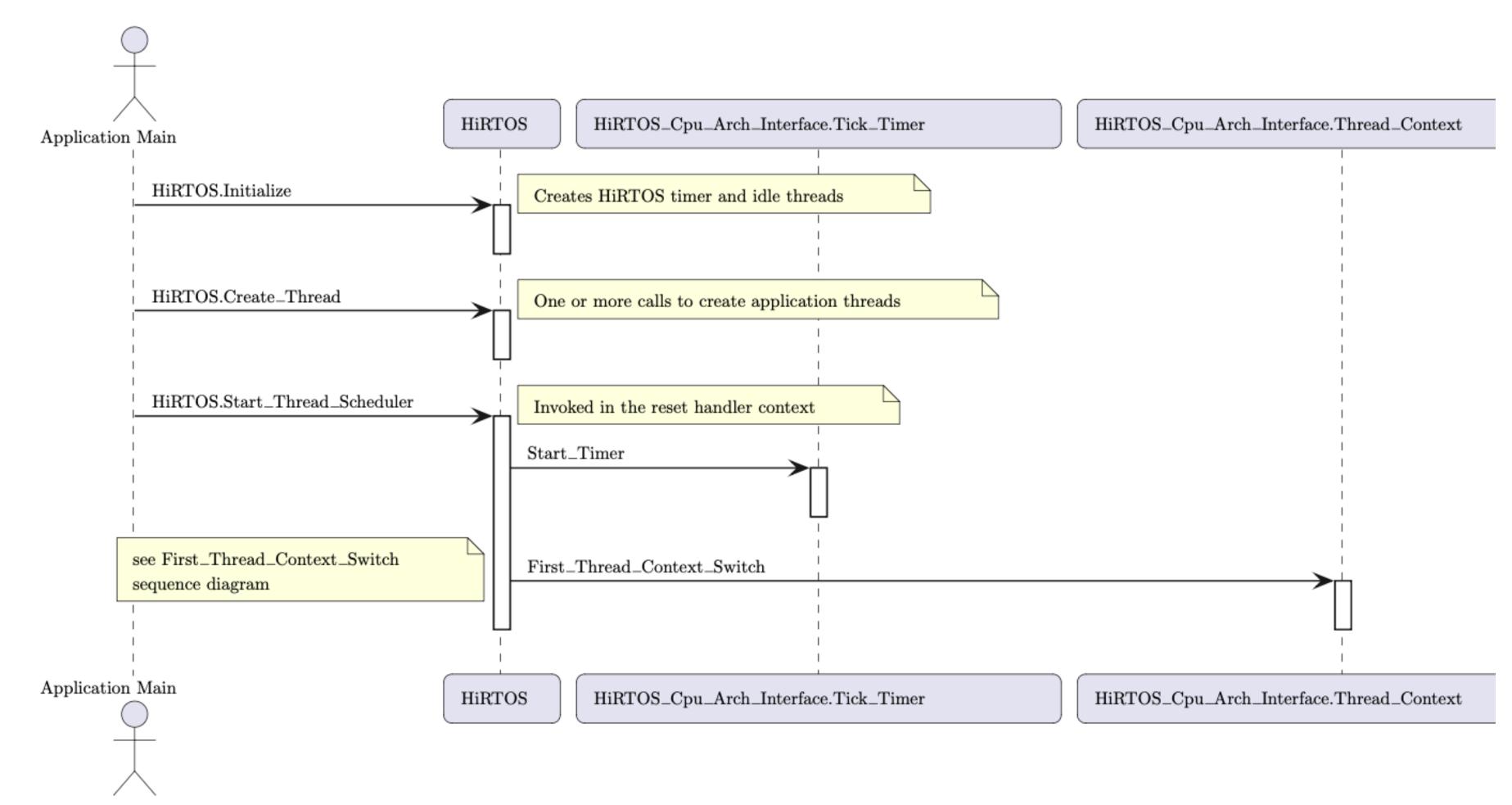






### **HiRTOS Thread Scheduler**

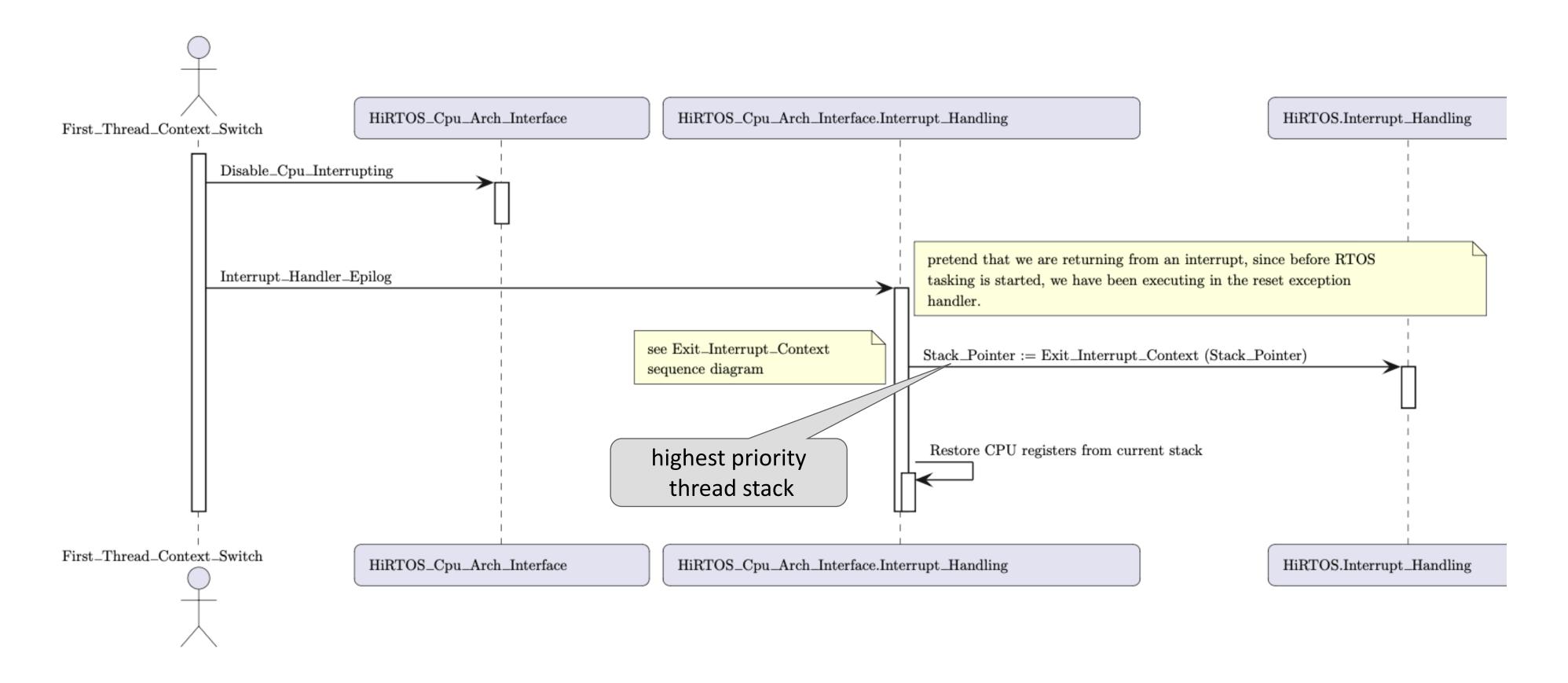
### HIRTOS Thread Scheduler Initialization





## HiRTOS Thread Scheduler (2)

### • HIRTOS Thread Scheduler Initialization (cont.)





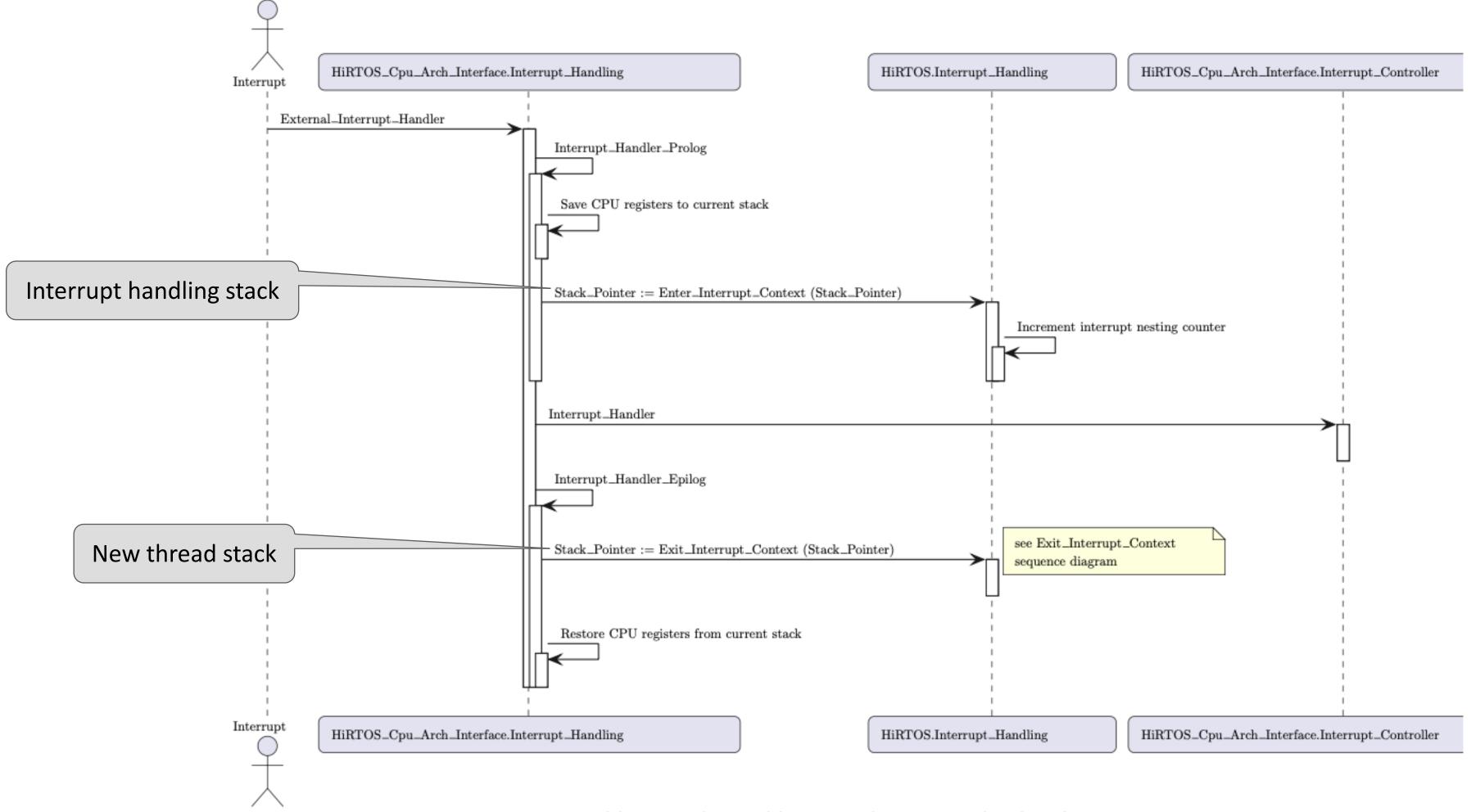
## HiRTOS Thread Scheduler (3)

- Asynchronous Thread Context Switch
  - In HiRTOS, thread preemption is implemented by invoking the thread scheduler on the exit path of an interrupt handler.
  - When an interrupt fires while a thread is running, the executing thread's CPU context is saved on thread's stack by the interrupt handler prolog.
  - Then, before calling the actual interrupt handler, the stack is switched to the interrupt handling stack. After the interrupt handler returns, the interrupt handler epilog invokes the HiRTOS thread scheduler, to select the highest priority runnable thread.
  - Then, if the newly selected thread is different from the one that was running before the interrupt, the extended context of the old thread is saved and the extended context of the new thread is restored.



### HiRTOS Thread Scheduler (4)

Asynchronous Thread Context Switch (cont.)

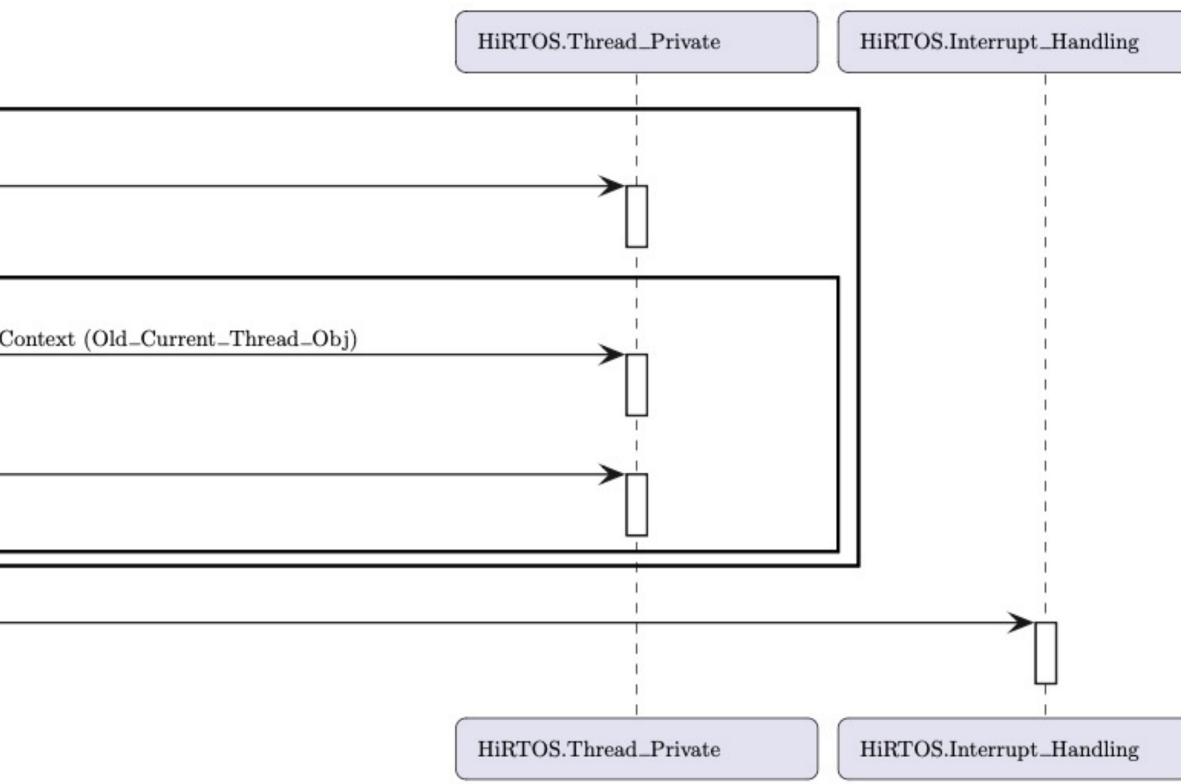




## HiRTOS Thread Scheduler (5)

Asynchronous Thread Context Switch (cont.)

	(	
	Exit_Interrupt.	Context
	opt [C	$urrent\_Interrupt\_Nesting\_Counter = 1]$
I		Run_Thread_Scheduler
l	opt	$New_Current_Thread_Id /= Old_Current_Thread_Id$
l		[Old_Current_Thread_Id /= Invalid_Thread_Id] Save_Thread_Extended_C
		Restore_Thread_Extended_Context (New_Current_Thread_Obj)
l		
		Decrement interrupt nesting counter
		$\square$
	Exit_Interrupt	_Context
	/	





## HiRTOS Thread Scheduler (6)

- In HiRTOS, a synchronous thread context switch occurs when: • A thread calls HiRTOS.Condvar.Wait

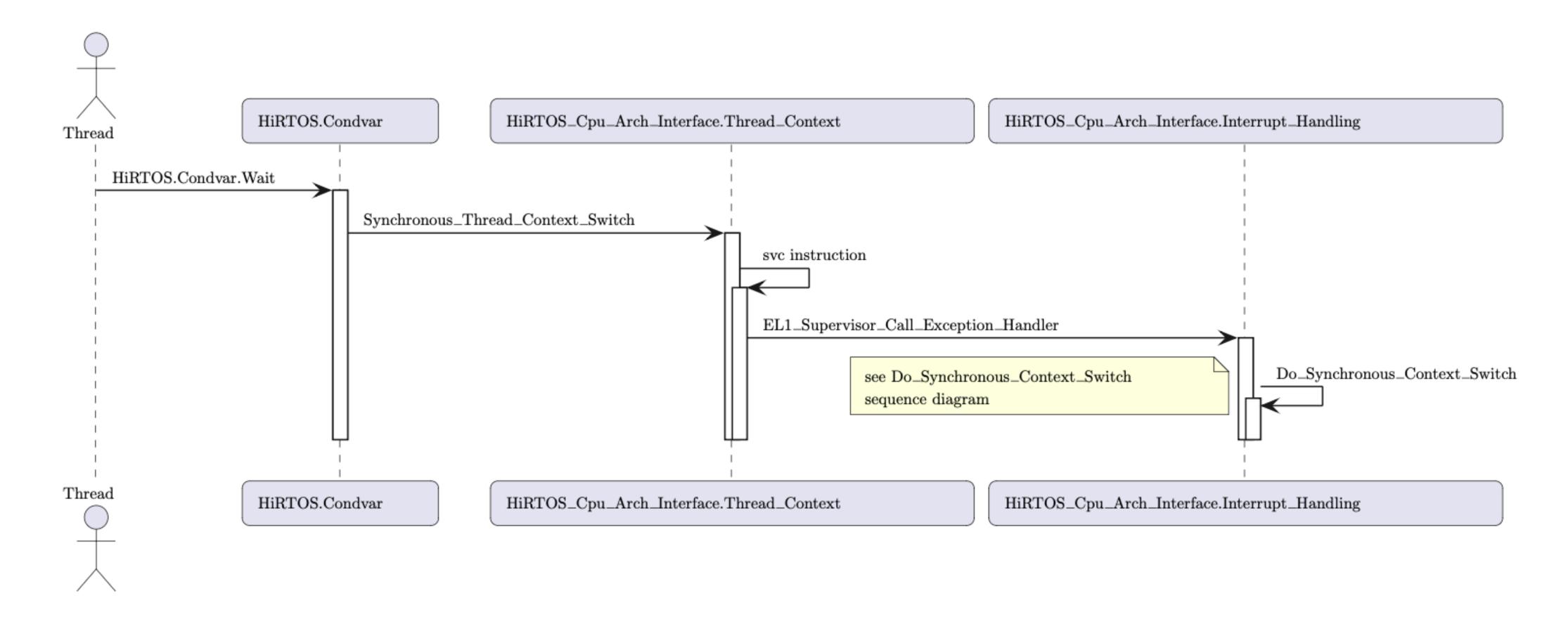
  - A thread calls HiRTOS.Condvar.Signal or HiRTOS.Condvar.Broadcast, and there are threads waiting on the condition variable
  - A thread calls HiRTOS. Mutex. Acquire and the mutex is not available
  - A thread calls HiRTOs. Mutex. Release and there are threads waiting to acquire the mutex
  - A thread calls HiRTOS.Thread.Thread\_Delay\_Until (which calls HiRTOS.Condvar.Wait)

  - A thread calls HiRTOS. Thread. Suspend Current Thread • A thread calls HiRTOS.Thread.Resume Thread A thread calls HiRTOS.Restore \_Atomic \_Level and the old atomic level is
  - Atomic Level None



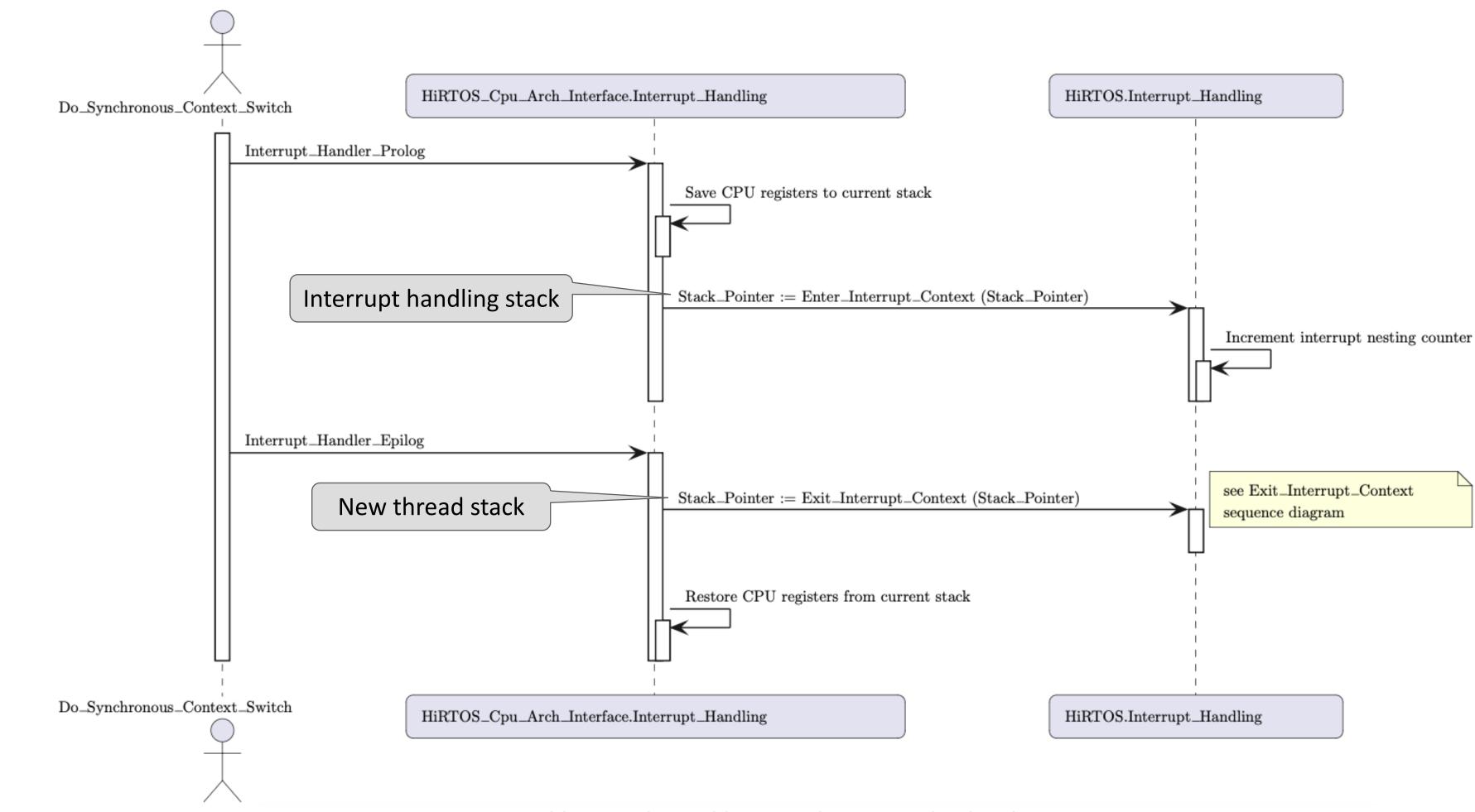
## HiRTOS Thread Scheduler (7)

Synchronous Thread Context Switch



## HiRTOS Thread Scheduler (8)

Synchronous Thread Context Switch (cont.)



### **HiRTOS Separation Kernel Overview**

- A separation kernel can be seen as an RTOS that schedules partitions instead of threads
  - CPU needs to support hypervisor privilege mode and two-stage memory protection
- A partition is a spatial and temporal separation/isolation unit on which a bare-metal or RTOS-based application runs.
- Each partition consists of one or more address ranges covering disjoint portions of RAM and MMIO space that only that partition can access
- HiRTOS uses the hypervisor-controlled MPU to enforce isolation between partitions "address spaces"
- Each partition can only use the supervisor-controlled MPU within its own address space



## **HiRTOS Separation Kernel Overview (2)**

- Each partition also has its own interrupt vector table and its own set of physical interrupts.
  - Physical peripherals can be assigned to individual partitions (discrete device) assignment).
  - No device virtualization is supported.
- In a multi-core platform, there is one separation kernel instance per CPU Core.

  - Each instance is independent of each other. No resources are shared. The CPU core is time-sliced among the partitions running on the same separation kernel instance.
  - Partitions are bound to the CPU core in which they were created. Partitions are created at boot time before starting the partition scheduler on the corresponding CPU core. Partitions cannot be destroyed or terminated.



### HiRTOS Separation Kernel Overview (3)

- The separation kernel code itself runs in hypervisor privilege mode.
- All partitions run at a privilege lower than hypervisor mode. Partitions can communicate with the separation kernel via hypervisor calls
- Inter-partition communication is not supported yet • A shared-memory-based mailbox mechanism could be provided in the
  - future

# HiRTOS Separation Kernel Running on ARM FVP Simulator for ARMv8-R

X	FVP terminal_0	~ _ O X	FVP terminal_1	^ _ O X
Partition 1: Thread 3 Partition 2: Thread 1 Partition 2: Thread 2 Partition 2: Thread 3 Partition 1: Thread 3 Partition 1: Thread 6 Partition 1: Thread 6 Partition 1: Thread 4 Partition 1: Thread 8 Partition 2: Thread 8 Partition 2: Thread 8 Partition 1: Thread 1 Partition 2: Thread 1 Partition 2: Thread 1 Partition 2: Thread 1 Partition 2: Thread 1 Partition 1: Thread 3 Partition 2: Thread 1	<pre>(id 3, prio 29): Period 1000ms, Last run at 24s 420546us, Wakeups 13 (id 4, prio 28): Period 1500ms, Last run at 24s 420817us, Wakeups 9 (id 2, prio 30): Period 500ms, Last run at 24s 430326us, Wakeups 25 (id 3, prio 29): Period 1000ms, Last run at 24s 430554us, Wakeups 13 (id 4, prio 28): Period 1500ms, Last run at 24s 430822us, Wakeups 9 (id 7, prio 25): Period 3000ms, Last run at 24s 431366us, Wakeups 5 (id 7, prio 25): Period 3000ms, Last run at 24s 441367us, Wakeups 5 (id 7, prio 25): Period 2000ms, Last run at 24s 457107us, Wakeups 7 (id 9, prio 27): Period 2000ms, Last run at 24s 458120us, Wakeups 7 (id 9, prio 23): Period 2000ms, Last run at 24s 458120us, Wakeups 7 (id 9, prio 23): Period 2000ms, Last run at 24s 468125us, Wakeups 7 (id 9, prio 23): Period 2000ms, Last run at 24s 468125us, Wakeups 7 (id 9, prio 23): Period 500ms, Last run at 25s 438931us, Wakeups 26 (id 6, prio 26): Period 500ms, Last run at 25s 438931us, Wakeups 26 (id 6, prio 26): Period 2500ms, Last run at 25s 448928us, Wakeups 26 (id 6, prio 26): Period 2500ms, Last run at 25s 4489434us, Wakeups 26 (id 7, prio 30): Period 500ms, Last run at 25s 4489434us, Wakeups 27 (id 3, prio 29): Period 500ms, Last run at 26s 457714us, Wakeups 14 (id 2, prio 30): Period 500ms, Last run at 26s 457714us, Wakeups 14 (id 2, prio 30): Period 500ms, Last run at 26s 467737us, Wakeups 14 (id 2, prio 30): Period 500ms, Last run at 27s 476096us, Wakeups 28 (id 4, prio 28): Period 1000ms, Last run at 27s 476095us, Wakeups 28 (id 4, prio 28): Period 1500ms, Last run at 27s 476095us, Wakeups 28 (id 4, prio 28): Period 1500ms, Last run at 27s 476095us, Wakeups 28 (id 4, prio 28): Period 1500ms, Last run at 27s 486601us, Wakeups 10 (id 2, prio 30): Period 500ms, Last run at 27s 486601us, Wakeups 10 (id 2, prio 28): Period 1500ms, Last run at 27s 486601us, Wakeups 10 (id 2, prio 28): Period 1500ms, Last run at 27s 486601us, Wakeups 10 (id 4, prio 28): Period 1500ms, Last run at 27s 486601us, Wakeups 10</pre>		Partition 1: Thread 2 (id 3, prio 29): Period 1000ms, Last run at 24s 420869us, Wakeups 13 Partition 1: Thread 3 (id 4, prio 28): Period 1500ms, Last run at 24s 420663us, Wakeups 9 Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Last run at 24s 430663us, Wakeups 25 Partition 2: Thread 2 (id 3, prio 29): Period 1000ms, Last run at 24s 430683us, Wakeups 13 Partition 2: Thread 3 (id 4, prio 28): Period 1000ms, Last run at 24s 430687us, Wakeups 9 Partition 2: Thread 6 (id 7, prio 25): Period 3000ms, Last run at 24s 431671us, Wakeups 5 Partition 1: Thread 6 (id 7, prio 25): Period 3000ms, Last run at 24s 431671us, Wakeups 5 Partition 2: Thread 6 (id 7, prio 25): Period 3000ms, Last run at 24s 457430us, Wakeups 7 Partition 1: Thread 4 (id 5, prio 27): Period 2000ms, Last run at 24s 457430us, Wakeups 7 Partition 2: Thread 8 (id 9, prio 23): Period 4000ms, Last run at 24s 458451us, Wakeups 7 Partition 2: Thread 8 (id 9, prio 23): Period 2000ms, Last run at 24s 468457us, Wakeups 7 Partition 2: Thread 8 (id 9, prio 23): Period 2000ms, Last run at 24s 468457us, Wakeups 7 Partition 2: Thread 8 (id 9, prio 23): Period 500ms, Last run at 25s 439260us, Wakeups 26 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 25s 449238us, Wakeups 6 Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Last run at 25s 449746us, Wakeups 6 Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Last run at 25s 449746us, Wakeups 27 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 25s 449746us, Wakeups 27 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 26s 458076us, Wakeups 14 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 26s 458078us, Wakeups 14 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 26s 468078us, Wakeups 27 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 27s 476428us, Wakeups 28 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 27s 476428us, Wakeups 28 Partition 1: Thread 3 (id 4, prio 28): Period 1500ms, Last run at	
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	↑ON BOOTSW 18 ■■■■■■■ ▶ I ▶ I Total Instr: 638,898,479	Total Time:	2m Ø6s Grab mouse: LeftCtrl+LeftAlt	
X	FVP terminal_2	^ _ 🗆 X	FVP terminal_3	^ _ O X
Partition 1: Thread 2	(id 3. prio 29): Period 1000ms, Last run at 24s 421057us, Wakeups 13		Partition 1: Thread 2 (id 3, prio 29): Period 1000ms, Last run at 24s 420892us, Wakeups 13	

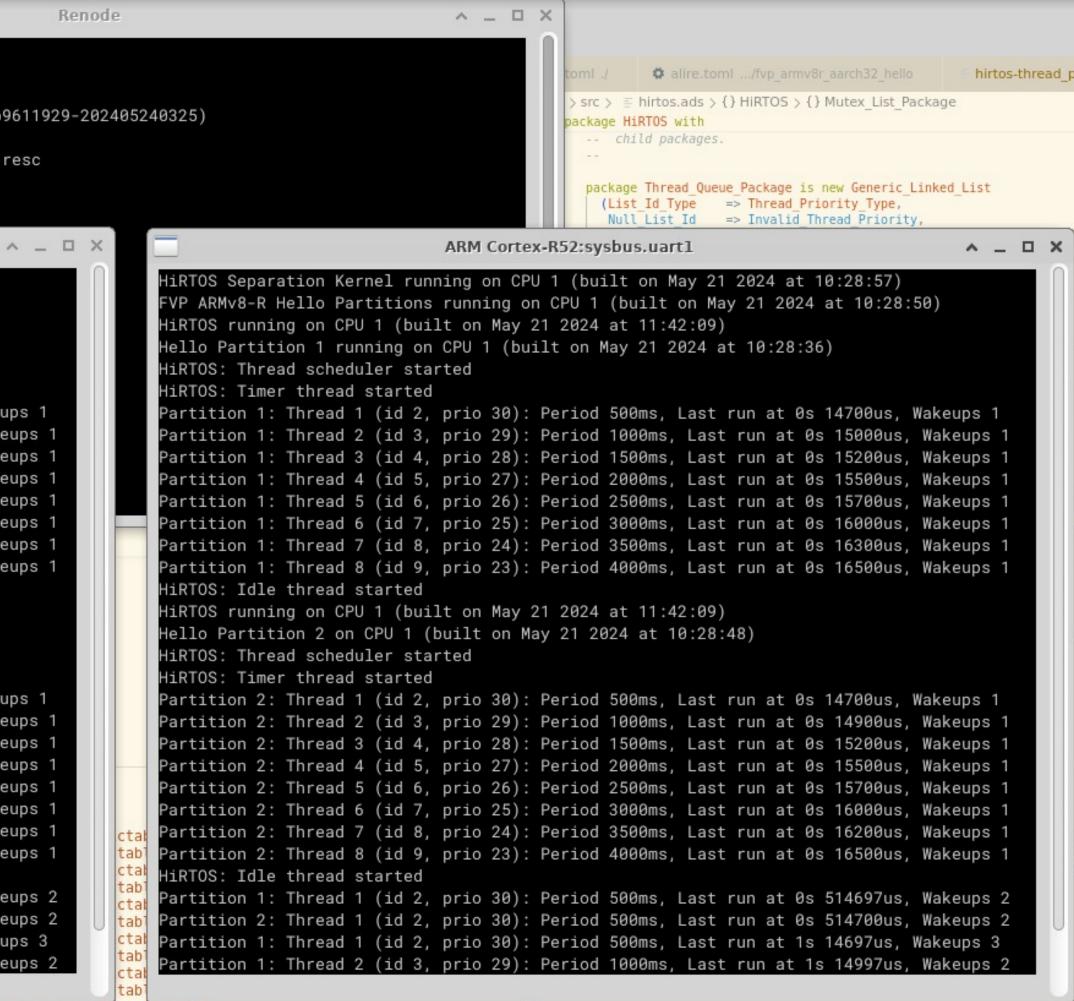
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	Fast Models -	CLCD AEMv8R	Base BaseR FVP	~ _ ×	
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Partition 1: Thread 2 (id 3, prio 29): Period 1000ms, Partition 1: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 2 (id 3, prio 29): Period 1000ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 1: Thread 6 (id 7, prio 25): Period 3000ms, Partition 2: Thread 6 (id 7, prio 25): Period 3000ms, Partition 1: Thread 6 (id 7, prio 25): Period 3000ms, Partition 1: Thread 6 (id 9, prio 27): Period 2000ms, Partition 1: Thread 8 (id 9, prio 23): Period 4000ms, Partition 2: Thread 8 (id 9, prio 23): Period 4000ms, Partition 2: Thread 8 (id 9, prio 23): Period 2000ms, Partition 2: Thread 8 (id 9, prio 23): Period 4000ms, Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Partition 1: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Partition 2: Thread 3 (id 4, prio 28): Period 1500ms,	Last run at 24s 421327us, Wakeups 9 Last run at 24s 430833us, Wakeups 25 Last run at 24s 431060us, Wakeups 13 Last run at 24s 431331us, Wakeups 9 Last run at 24s 431866us, Wakeups 5 Last run at 24s 441870us, Wakeups 5 Last run at 24s 457617us, Wakeups 7 Last run at 24s 458630us, Wakeups 4 Last run at 24s 468628us, Wakeups 7 Last run at 24s 468628us, Wakeups 4 Last run at 25s 439427us, Wakeups 26 Last run at 25s 439937us, Wakeups 26 Last run at 25s 449926us, Wakeups 26 Last run at 25s 449926us, Wakeups 26 Last run at 26s 458032us, Wakeups 27 Last run at 26s 458032us, Wakeups 14 Last run at 26s 458032us, Wakeups 14 Last run at 26s 468014us, Wakeups 14 Last run at 27s 476614us, Wakeups 28 Last run at 27s 476614us, Wakeups 28 Last run at 27s 477122us, Wakeups 20		Partition 1: Thr Partition 2: Thr Partition 2: Thr Partition 2: Thr Partition 2: Thr Partition 1: Thr Partition 1: Thr Partition 1: Thr Partition 2: Thr Partition 2: Thr Partition 1: Thr	ead 2 (id 3, prio 29): Period 1000ms, Last run at 24s 420892us, Wakeups 13 ead 3 (id 4, prio 28): Period 1500ms, Last run at 24s 430662us, Wakeups 9 ead 1 (id 2, prio 30): Period 500ms, Last run at 24s 430662us, Wakeups 25 ead 2 (id 3, prio 29): Period 1000ms, Last run at 24s 430890us, Wakeups 13 ead 3 (id 4, prio 28): Period 1500ms, Last run at 24s 431159us, Wakeups 9 ead 6 (id 7, prio 25): Period 3000ms, Last run at 24s 431179us, Wakeups 5 ead 6 (id 7, prio 25): Period 3000ms, Last run at 24s 441698us, Wakeups 5 ead 6 (id 7, prio 25): Period 2000ms, Last run at 24s 4457444us, Wakeups 7 ead 8 (id 9, prio 27): Period 2000ms, Last run at 24s 457444us, Wakeups 7 ead 8 (id 9, prio 23): Period 2000ms, Last run at 24s 458456us, Wakeups 4 ead 4 (id 5, prio 27): Period 2000ms, Last run at 24s 458456us, Wakeups 4 ead 4 (id 5, prio 27): Period 2000ms, Last run at 24s 468461us, Wakeups 7 ead 8 (id 9, prio 23): Period 4000ms, Last run at 24s 468461us, Wakeups 4 ead 1 (id 2, prio 30): Period 500ms, Last run at 25s 439257us, Wakeups 26 ead 5 (id 6, prio 26): Period 2500ms, Last run at 25s 449758us, Wakeups 26 ead 5 (id 6, prio 26): Period 500ms, Last run at 25s 449758us, Wakeups 26 ead 5 (id 6, prio 26): Period 500ms, Last run at 25s 449758us, Wakeups 27 ead 2 (id 3, prio 29): Period 1000ms, Last run at 26s 457846us, Wakeups 27 ead 2 (id 3, prio 29): Period 1000ms, Last run at 26s 458073us, Wakeups 14 ead 1 (id 2, prio 30): Period 500ms, Last run at 26s 468078us, Wakeups 14 ead 1 (id 2, prio 30): Period 1000ms, Last run at 27s 476437us, Wakeups 28 ead 3 (id 4, prio 28): Period 1500ms, Last run at 27s 476437us, Wakeups 28 ead 3 (id 4, prio 28): Period 1500ms, Last run at 27s 486430us, Wakeups 28 ead 3 (id 4, prio 28): Period 1500ms, Last run at 27s 486430us, Wakeups 28 ead 3 (id 4, prio 28): Period 1500ms, Last run at 27s 486430us, Wakeups 28 ead 3 (id 4, prio 28): Period 1500ms, Last run at 27s 486430us, Wakeups 28 ead 3 (id 4, prio 28): Period 1500ms, Last run at 27s 486430us, Wakeups 10 ead 1 (id 2, prio 30): Period 500ms	



### HiRTOS Separation Kernel Running on Renode Simulator Configured for ARMv8-R

Edit Selection View Go Run T	erminal Help	
EXPLORER ····	• alire.toml/hello_partitions	RENODE
✓ OPEN EDITORS	HiRTOS > sample_apps > hell	
GROUP 3 alire.toml sample_apps/fvp_arm alire.toml sample_apps/esp32 c	11 everytables = ["hell	Renode, version 1.15.0.6166 (b96 (monitor) i \$CWD/./cortex-r52.re
GROUP 4 W HIRTOS.tex doc 9+, M	12 13 [[depends-on]] 14 hirtos_separation_k	Starting emulation (ARM Cortex-R52)
	ARM Cortex-R52:sysbus.u	art0 ^

HiRTOS Separation Kernel running on CPU 0 (built on May 21 2024 at 10:28:57) FVP ARMv8-R Hello Partitions running on CPU 0 (built on May 21 2024 at 10:28:50) HiRTOS running on CPU 0 (built on May 21 2024 at 11:42:09) Hello Partition 1 running on CPU 0 (built on May 21 2024 at 10:28:36) HiRTOS: Thread scheduler started HiRTOS: Timer thread started Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 0s 14600us, Wakeups 1 Partition 1: Thread 2 (id 3, prio 29): Period 1000ms, Last run at 0s 14900us, Wakeups 1 Partition 1: Thread 3 (id 4, prio 28): Period 1500ms, Last run at 0s 15100us, Wakeups 1 Partition 1: Thread 4 (id 5, prio 27): Period 2000ms, Last run at 0s 15400us, Wakeups 1 Partition 1: Thread 5 (id 6, prio 26): Period 2500ms, Last run at 0s 15600us, Wakeups 1 Partition 1: Thread 6 (id 7, prio 25): Period 3000ms, Last run at 0s 15900us, Wakeups 1 Partition 1: Thread 7 (id 8, prio 24): Period 3500ms, Last run at 0s 16200us, Wakeups 1 Partition 1: Thread 8 (id 9, prio 23): Period 4000ms, Last run at 0s 16400us, Wakeups 1 HiRTOS: Idle thread started HiRTOS running on CPU 0 (built on May 21 2024 at 11:42:09) Hello Partition 2 on CPU 0 (built on May 21 2024 at 10:28:48) HiRTOS: Thread scheduler started HiRTOS: Timer thread started Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Last run at 0s 14600us, Wakeups 1 Partition 2: Thread 2 (id 3, prio 29): Period 1000ms, Last run at 0s 14800us, Wakeups 1 Partition 2: Thread 3 (id 4, prio 28): Period 1500ms, Last run at 0s 15100us, Wakeups 1 Partition 2: Thread 4 (id 5, prio 27): Period 2000ms, Last run at 0s 15300us, Wakeups 1 Partition 2: Thread 5 (id 6, prio 26): Period 2500ms, Last run at 0s 15600us, Wakeups 1 Partition 2: Thread 6 (id 7, prio 25): Period 3000ms, Last run at 0s 15800us, Wakeups 1 Partition 2: Thread 7 (id 8, prio 24): Period 3500ms, Last run at 0s 16100us, Wakeups 1 Partition 2: Thread 8 (id 9, prio 23): Period 4000ms, Last run at 0s 16400us, Wakeups 1 HiRTOS: Idle thread started Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 0s 514500us, Wakeups 2 Partition 2: Thread 1 (id 2, prio 30): Period 500ms, Last run at 0s 514500us, Wakeups 2 Partition 1: Thread 1 (id 2, prio 30): Period 500ms, Last run at 1s 14500us, Wakeups 3 Partition 1: Thread 2 (id 3, prio 29): Period 1000ms, Last run at 1s 14800us, Wakeups 2





## Porting HiRTOS to a new platform

- Implement CPU-architecture-specific interfaces for the new CPU architecture, including:
  - Startup code
  - Interrupt handling prolog and epilog code
  - Interrupt controller driver
  - CPU-architecture-specific timer driver (if available)
  - Memory protection unit (MPU) driver
- Implement platform-specific interfaces for the new SoC or board, including:
  - UART driver
  - External timer driver (if needed)
  - Platform-specific hardware initialization

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### Future Work

- Change the idle thread to be a "safety patrol" thread to check
- separation kernel
- Port HiRTOS to other embedded CPU architectures such as ARMv7-M, ARMv8-M, 64-bit ARMv8-R and 64-bit RISC-V
- Port The HiRTOS separation kernel to RISC-V platforms with Hypervisor mode
- Do Formal Verification of HiRTOS code using gnatprove

safety invariants and liveness properties during spare CPU cycles Add inter-core communication functionality to the HiRTOS kernel Add inter-partition communication functionality to the HiRTOS

