Debugging Applications that use TI-RTOS Technical Overview

Agenda

- **30 Second Advertisement / TI-RTOS History**
- Stack Overflow
- Device Exception
- Memory Mismanagement

30 Second Advertisement

Since we know there a number of customers that will not want to use an RTOS for various reasons. Here's some key point to remember:

- **TI-RTOS is developed and supported by TI:** If you write your own little scheduler, you have to write it, maintain it, port it if you move to a new device, etc. Is your job to deliver a smaller scheduler or a real product on time?
- **Includes Power Management:** For the low power devices, TI has power management included in TI-RTOS. Look at the device's power management…it is hard. Do you really want to deliver a power manager (and power aware drivers) or a real product on time?
- **Portable:** Want to move to another device? Hope you factored this in when you wrote their own little scheduler and drivers.
- **Scalable**: Want to add system-level functionality into the application? Hope you factored this in when you wrote their own little scheduler and drivers.
- **Don't want to learn an RTOS**: TI-RTOS's kernel has "standard" OS components: Tasks, interrupts, semaphore, queues, etc. It also supports POSIX (also called Pthreads).
- **Overhead**: Yes, TI-RTOS takes space. So does your little scheduler. What is the threshold (other than "smaller")? For the smallest CC1310 device (32KB flash), TI-RTOS can be set-up to only use ~3KB (~6KB with full Power Management) of the flash and this still includes almost all the kernel's functionality. Note: CC13xx/CC26xx has the kernel's .text in ROM.
- **Debugging Facilities**: Hey this is a good lead-in…

TI-RTOS History

First let's look at the history of the RTOSes that have been developed and supported by Texas Instruments:

- **DSP/BIOS**: 1999-current. RTOS that is available for C2xxx, MSP430, C54xx, C55xx, and C6xxx devices. Currently in maintenance-mode only. Available as a stand-alone product.
- **TI-RTOS**: 2008-current. Started as SYS/BIOS and was re-branded to TI-RTOS in 2014. TI-RTOS is available for C2xxx, MSP43x, C6xxx, CortexA and CortexM devices. Active development of new features is ongoing. Currently running on millions of devices (e.g. IoT, automotive, industrial, etc.).

Use the following to determine the best way to obtain TI-RTOS.

- **SimpleLink Devices** (CC13xx, CC26xx, CC32xx, and MSP432): Bundled in SimpleLink SDKs.
- **Processor Devices** (Sitara, C6xxx, etc.): Bundled in Processors SDKs.
- **TM4C, MSP430 and Concerto (M3 + C28) Devices**: Stand-alone TI-RTOS product.
- **Non-Concerto C2000 Devices**: Stand-alone SYS/BIOS product.

SimpleLink Specific Items

1. The majority of SimpleLink SDK examples can easily use different kernel projects
   - The **“release” kernel project** optimizes for size and performance instead of debug features. This is the default kernel project for most examples.
   - The **“debug” kernel project** enables many of the debug features that will be discussed in this presentation. Please refer to the SimpleLink SDK User Guide for more details on what is enabled and how to use it.
2. The SimpleLink SDK examples ship a Runtime Object View (ROV) dashboard. This can be used to quickly populate the tool with common views. For more details please refer to: https://training.ti.com/runtime-object-view and http://processors.wiki.ti.com/index.php/Runtime_Object_View_(ROV)

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- **Stack Overflow**
- Device Exception
- Memory Mismanagement

Stacks Overflow

Stacks are used to place information like local data storage, return state, parameter passing, etc. Stacks grow as more subroutines are called. Finding a “good” value for the stack size is important. If you make it too large, you waste memory. Worse though is if you make it too small…

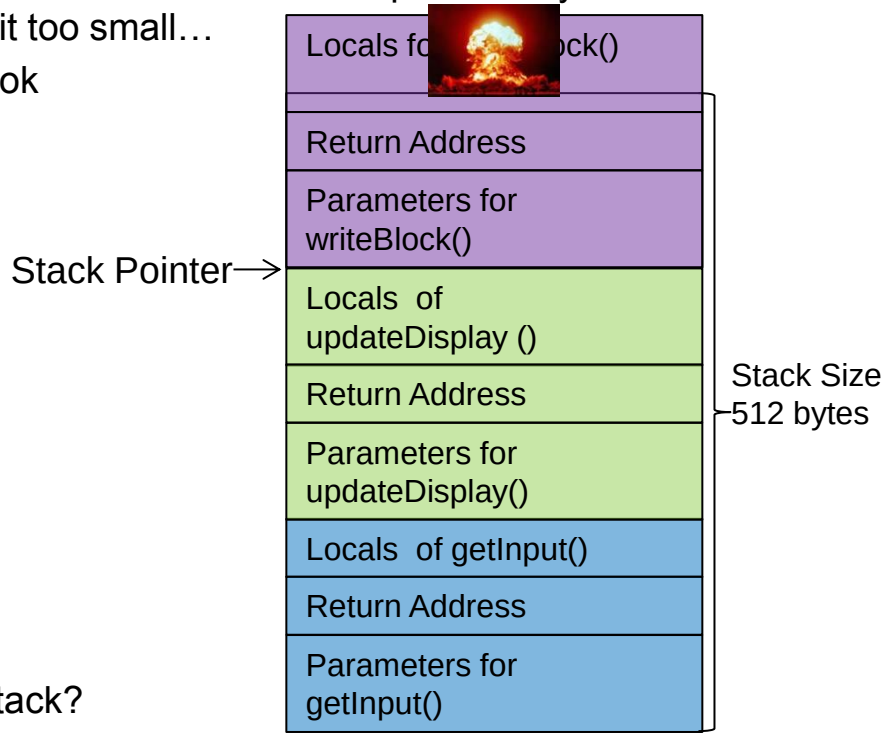
Here’s code executing and let’s see what the stack might look like before the calling `writeBlock()` in `updateDisplay()`.

```
void getInput(int foo, int bar)
{
    …
     retVal = updateDisplay(buffer, BASE_X, BASE_Y);

int updateDisplay(char *bitmap, int x, int y)
{
     …
     writeBlock(&bitmap[i], xoffset, yoffset);

int writeBlock(char *block int x, int y)
{
     char tempBuf[256];
```

What’s going to happen when tempBuf is placed onto the stack?



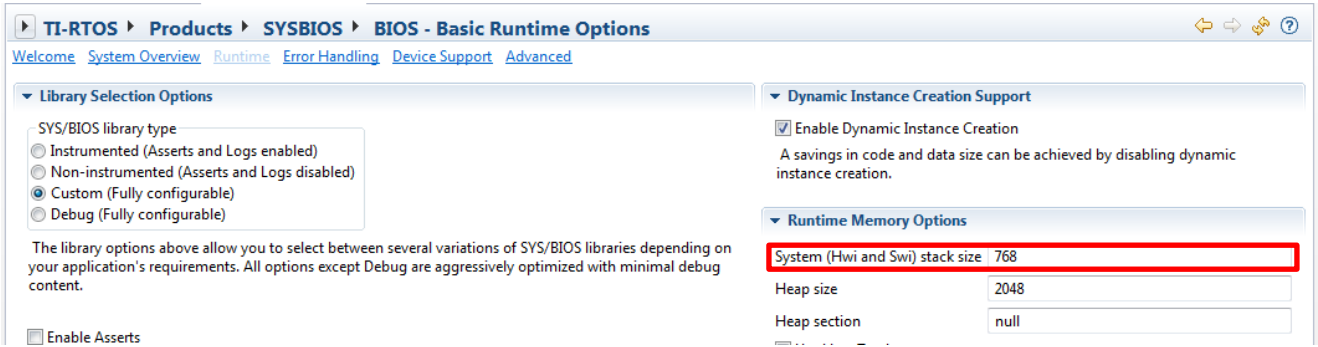
Stacks in TI-RTOS

With TI-RTOS there are two different types of stacks

System Stack: Hardware Interrupts (Hwi) and Software Interrupts (Swi) use a single system stack. The size of this stack is configurable via the .cfg file (with IAR, you set it in the linker file).

```
Program.stack = 768;
```

Or graphically



Task Stack: Each Task has it's own stack. The size of this stack is specified when you create a task.

Peak Usage of Stacks in TI-RTOS

The kernel will initialize the stacks with 0xBE values if the initStackFlags are set to true in the .cfg file (the default is true).

```
var Task = xdc.useModule('ti.sysbios.knl.Task');
var halHwi = xdc.useModule('ti.sysbios.hal.Hwi');
Task.initStackFlag = true;
halHwi.initStackFlag = true;
```

If you set these to false, you save ~160 bytes of code* and booting is slightly faster.
If you use true, you can get the peak usage in RTOS Object Viewer (ROV) in CCS and IAR.

Task Detailed

address	label	priority	mode	fxn	arg0	arg1	stackPeak	stackSize	stackBase	curCoreId	affinity	blockedOn
0x2000a2c8	ti.sysbios.knl.Task.IdleTask	0	Running	ti_sysbios_knl_Idle_loop__E	0x0	0x0	288	512	0x20009290	n/a	n/a	
0x20000318	Console	1	Blocked	consoleThread	0x0	0x0	580	1024	0x20000390	n/a	n/a	Semaphore: 0x20000b08
0x200007d0	Temperature	2	Blocked	temperatureThread	0x0	0x0	560	560	0x20008400	n/a	n/a	Semaphore: 0x200009d8

Hwi Module

address	options	activeInterrupt	pendingInterrupt	exception	hwiStackPeak	hwiStackSize	hwiStackBase
0x2000a370	Hwi.autoNestingSupport = true	0	0	none	552	1024	0x2003fc00

It looks like the stack for the Temperature task is too small!

* Used SimpleLink SDK's Empty example for CC3220SF

Runtime Checking of Stacks in TI-RTOS

The kernel will perform runtime checks if desired.

```
var Task = xdc.useModule('ti.sysbios.knl.Task');
var halHwi = xdc.useModule('ti.sysbios.hal.Hwi');
Task.checkStackFlag = true;
halHwi.checkStackFlag = true;
```

If you set these to **false**, you save ~200 bytes of code.
If you use **true**:

- Whenever there a task context switch, the kernel will check the stack peaks of the new and old tasks to make sure it is still 0xBE. If it is not, an error* is raised.
- If the Idle task executes, it will call the “ti_sysbios_hal_Hwi_checkStack” function to make sure the system stack is ok. If the stack is blown, an error* is raised.

* Refer to the xdc.runtime.Error module for details on how to plug in an Error handler.

Stacks: Recommendations

For new development, it's recommended you enable both the initialization of the stack and the runtime checking.

```
Task.initStackFlag = true;
halHwi.initStackFlag = true;

Task.checkStackFlag = true;
halHwi.checkStackFlag = true;
```

Once you have the application to a stable point, you can then turn them off if you are tight on space or need to squeeze out a tiny bit more performance. If these are not a concern, you can leave them enabled and plug in an Error* handler that can act accordingly if the stacks are blown (e.g. dump memory to be analyzed later and restart the device).

* Refer to the xdc.runtime.Error module for details on how to plug in an Error handler.

Additional Techniques to Size Stacks

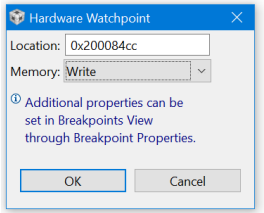
Hardware Watchpoints: HW watchpoints in CCS are great for seeing what caused the stack peak. You can run the application and determine the stack peak with ROV.

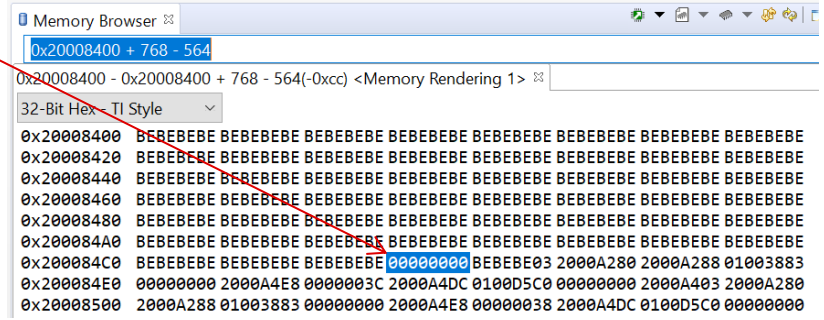
Task Detailed

address	label	priority	mode	fxn	arg0	arg1	stackPeak	stackSize	stackBase	curCoreId	affinity	blockedOn
0x2000a2c8	ti.sysbios.knl.Task.IdleTask	0	Running	ti_sysbios_knl_Idle_loop__E	0x0	0x0	304	512	0x20009290	n/a	n/a	
0x20000318	Console	1	Blocked	consoleThread	0x0	0x0	580	1024	0x20000390	n/a	n/a	Semaphore: 0x20000b08
0x200007d0	Temperature	2	Blocked	temperatureThread	0x0	0x0	564	768	0x20008400	n/a	n/a	Semaphore: 0x200009d8

If you look at the memory, you can see the peak

Then simply set a HW Watchpoint for a write to that address.





Restart the application. It will be hit quickly (since you have stack initialization turned on). The next time you hit the breakpoint, you can look at the call stack to see what caused the peak. Please note: the quality of the call task trace is dependent on the device, the symbols compiler options you have enabled/disabled, and compiler toolchain.

Additional Techniques to Size Stacks

Call_graph: Call_graph analyzes stacks based on a .out file (i.e. statically determined as opposed to runtime). This can be useful in trying to find places that use a large amount of stack space. Here is a write-up: http://processors.wiki.ti.com/index.php/Code_Generation_Tools_XML_Processing_Scripts

The call_graph tool does not work through function pointers and assembly that is not instrumented for it. For example, below shows UART_write being 8 bytes, where in reality it is more since it calls UARTMSP432_write via a function pointer.

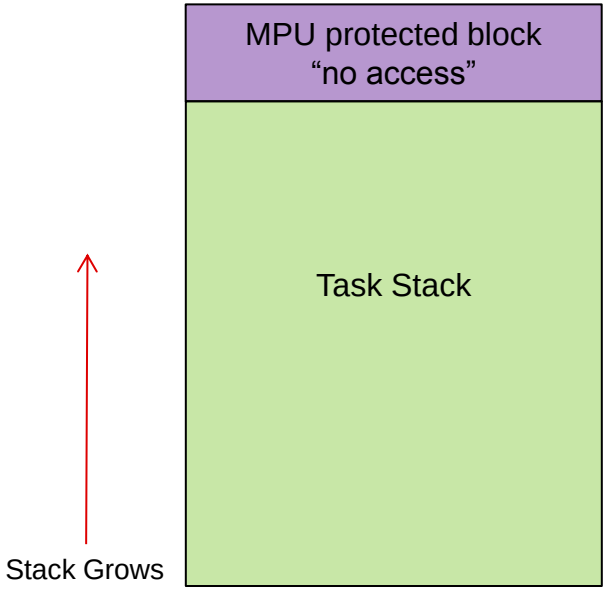
```
consoleFxn : wcs = 320
|  malloc : wcs = 120
|  |  <repeat ...>
|  free : wcs = 0
|  |  <repeat ...>
|  simpleConsole : wcs = 296
|  |  UARTUtils_getHandle : wcs = 8
|  |  UART_read : wcs = 8
|  |  UART_write : wcs = 8
|  |  ti_sysbios_heaps_HeapTrack_printTask__E : wcs = 256
|  |  |  ti_sysbios_heaps_HeapTrack_Object__first__S : wcs = 0
|  |  |  ti_sysbios_heaps_HeapTrack_Object__get__S : wcs = 0
|  |  |  ti_sysbios_heaps_HeapTrack_Object__next__S : wcs = 0
|  |  |  ti_sysbios_heaps_HeapTrack_printTrack__I : wcs = 216
|  |  |  |  ti_sysbios_knl_Task_Handle__label__S : wcs = 16
|  |  |  |  |  xdc_runtime_Core_assignLabel__I : wcs = 8
|  |  |  |  |  |  xdc_runtime_Text_cordText__E : wcs = 0
|  |  |  |  xdc_runtime_System_printf__E : wcs = 168
|  |  |  |  |  <repeat ...>
|  |  ti_sysbios_knl_Task_self__E : wcs = 0
|  |  ti_sysbios_knl_Task_sleep__E : wcs = 168
```

```
UARTMSP432_write : wcs = 208
|  HwiP_disable : wcs = 0
|  |  <repeat ...>
|  ( HwiP_restore
     ti_sysbios_family_arm_m3_Hwi_restoreFxn__E ) : wcs = 0
|  Power_setConstraint : wcs = 16
|  |  <repeat ...>
|  SemaphoreP_pend : wcs = 184
|  |  ti_sysbios_knl_Semaphore_pend__E : wcs = 176
|  |  |  ti_sysbios_knl_Clock_addI__E : wcs = 16
|  |  |  |  ti_sysbios_knl_Queue_put__E : wcs = 0
|  |  |  ti_sysbios_knl_Task_blockI__E : wcs = 32
|  |  |  ti_sysbios_knl_Task_restore__E : wcs = 80
|  |  |  |  <repeat ...>
|  UART_clearInterruptFlag : wcs = 0
|  UART_disableInterrupt : wcs = 8
|  UART_enableInterrupt : wcs = 0
```

Additional Techniques to Catch Stack Overflow

Memory Protection Unit (MPU) Module

There is a MPU module in the TI-RTOS kernel for selected ARM Cortex-A and Cortex-M devices. You can have a small region (e.g. 32 bytes) at the top of the stack where its attributes are no-access. If the stack grows into the protected region an exception occurs.



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- **Device Exception**
- Memory Mismanagement

Exceptions

What is an exception?

Really short-story…not a good thing!

Short-story…a condition that the device cannot handle. For example, bus error, executing an unknown instruction, etc.

TI-RTOS supports exception handling for the ARM and C64+ devices. For this presentation, we are going to focus on the exception handling for the MCU (M3, M4, M4F) devices.

Exceptions

We are going to look at what happens when the following code is executed on the MSP-EXP432E401Y board. Note: line 73 in the `mainThread()` is going to cause an exception!

```
56 void *mainThread(void *arg0)
57 {
58     /* 1 second delay */
59     uint32_t time = 1;
60
61     /* Call driver init functions */
62     GPIO_init();
63
64     /* Configure the LED pin */
65     GPIO_setConfig(Board_GPIO_LED0, GPIO_CFG_OUT_STD | GPIO_CFG_OUT_LOW);
66
67     /* Turn on user LED */
68     GPIO_write(Board_GPIO_LED0, Board_GPIO_LED_ON);
69
70     while (1) {
71         sleep(time);
72         GPIO_toggle(Board_GPIO_LED0);
73         asm("    .word 0x4567f123");
74     }
75 }
76
```

Let's look and see how TI-RTOS can help debug when an exception occurs…

Exception Handler

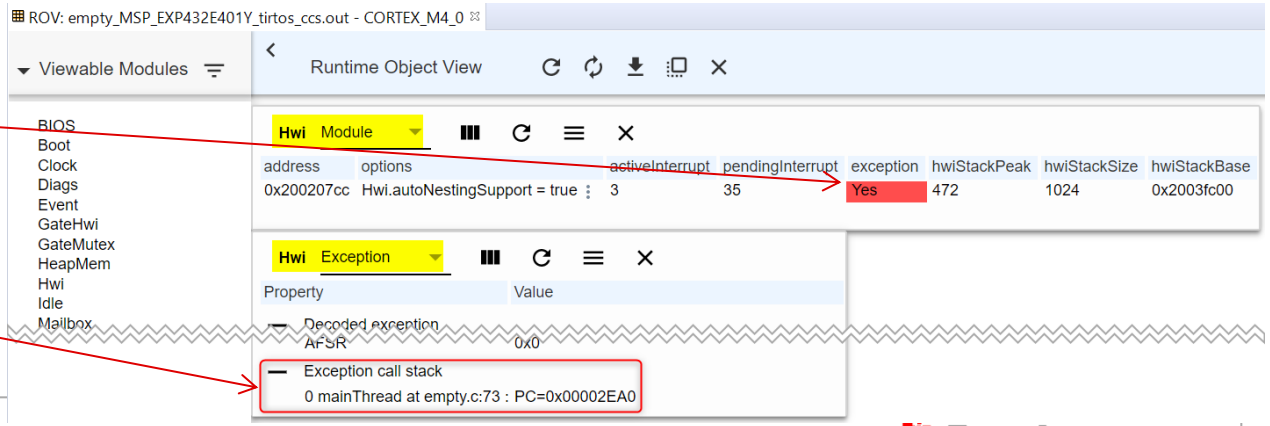
When an exception occurs, the device jumps to the exception handler. TI-RTOS allows different types of handlers for exceptions to be plugged in:

- User supplied Handler
- TI-RTOS Spin loop Handler
- TI-RTOS “Minimal” Exception Decoding Handler
- TI-RTOS Enhanced Exception Decoding Handler

The next slides will show how to select which exception handler to use and its benefits.

Before that, please note that regardless of the handler, the exception shows up in ROV and the back trace with

- file name
- function name
- line number



Exceptions: User Supplied Handler

User Supplied: If you want to be master of your domain and supply the exception handler yourself, you can set the following and your handler is called (instead of going into the spin-loop).

```
var m3Hwi = xdc.useModule('ti.sysbios.family.arm.m3.Hwi');
m3Hwi.excHandlerFunc = "&myExceptionHandler";
```

Here is some pseudo-code for the user supplied handler

```
Void myExceptionHandler(UInt *excStack, UInt lr)
{
    // do stuff like write RAM to flash, flash LEDS, phone home, etc.
    // reset device
```

Benefits

- You're in charge.
- You still know you have an exception from ROV and the back trace*.

* Please note, the quality of the back trace is dependent on the device, the symbols compiler options you have enabled/disabled, and compiler toolchain.

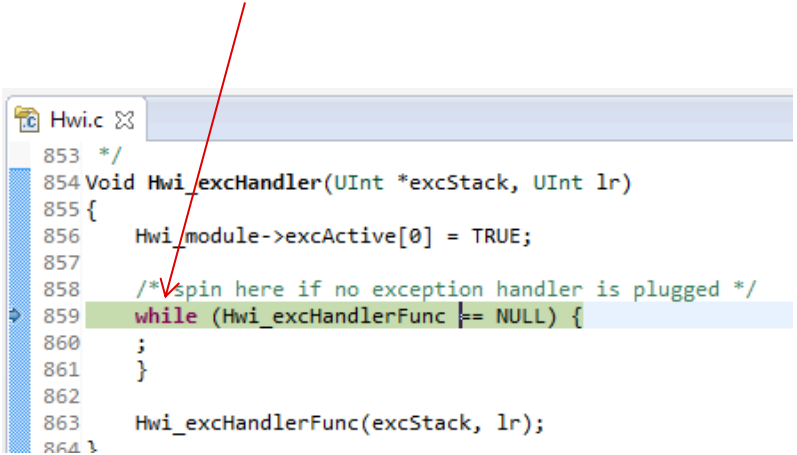
Exceptions: TI-RTOS Spin Loop Handler

TI-RTOS Spin Loop Handler: You can configure TI-RTOS to use a spin-loop handler instead

```
var m3Hwi = xdc.useModule('ti.sysbios.family.arm.m3.Hwi');
m3Hwi.excHandlerFunc = null;
```

Benefits

- You still know you have an exception from ROV and the back trace.
- Smallest footprint for the handlers
- If you halt the target, you will be in the spin-loop



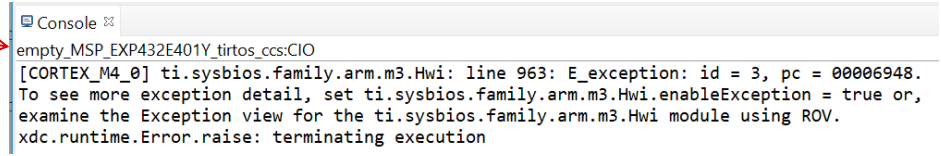
Exceptions: TI-RTOS Minimal Exception Decoding Handler

TI-RTOS Minimal Exception Decoding Handler: If you disable the enhanced exception handling and use the TI-RTOS minimal handler instead.

```
var m3Hwi = xdc.useModule('ti.sysbios.family.arm.m3.Hwi');
m3Hwi.enableException = false;  //true for enhanced
```

Benefits

- ROV decodes the exception and give a back trace*.
- The CCS Console will have some information (if the application configures the xdc.runtime.System output to CCS Console).



- You can set excHookFunc to execute before decoding.
  (refer to the Additional Details slide at the end for more details)
- However, slightly larger footprint when compared to the spin-loop (~420 bytes more).

* Again please note, the quality of the back trace is dependent on the device, thesymbols compiler options you have enabled/disabled, and compiler toolchain.

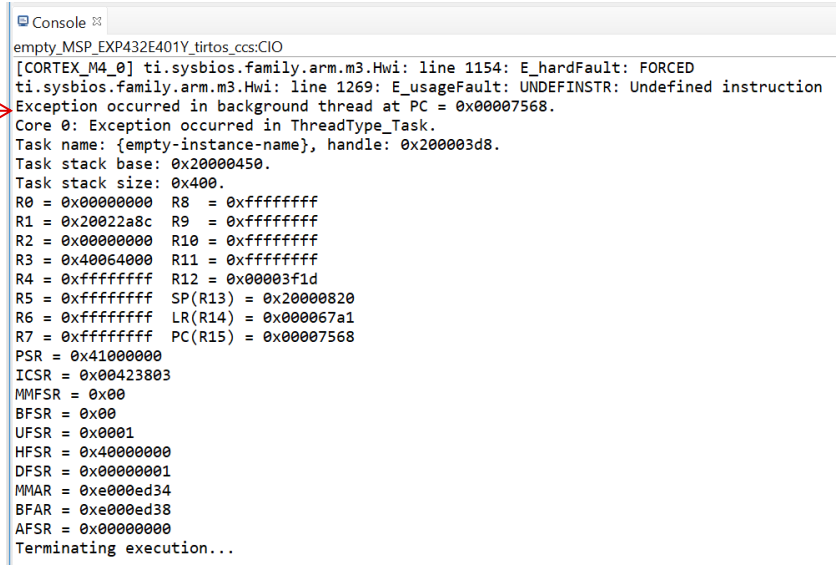
Exceptions: TI-RTOS Enhanced Exception Decoding Handler

TI-RTOS Enhanced Exception Decoding Handler: If you accept the default configuration (shown below), you get the TI-RTOS enhanced exception decoder.

```
var m3Hwi = xdc.useModule('ti.sysbios.family.arm.m3.Hwi');
m3Hwi.enableException = true;
```

Benefits

- ROV decodes the exception and give a back trace.
- The CCS Console will have more information (if the application configures the xdc.runtime.System output to CCS Console).
- You can set excHookFunc to execute before decoding. (refer to the Additional Details slide at the end for more details)
- However, ~6K larger footprint when compared to the “minimal”.



Exceptions: Handlers Summary

You have several options with TI-RTOS for handling exceptions

- User supplied Handler
- TI-RTOS Spin loop Handler
- TI-RTOS “Minimal” Exception Decoding Handler
- TI-RTOS Enhanced Exception Decoding Handler

Handler	ROV	CCS Console	ExcHookFunc
User Supplied	Decoded & Back Trace	Up to user code	Not Available
Spin-loop	Decoded & Back Trace	Nothing	Not Available
Minimal Decoder	Decoded & Back Trace	Notification	Available
Enhanced Decoder	Decoded & Back Trace	Decoded and Registers	Available

More Exception Information…

excHookFunc: For the enhanced and minimal TI-RTOS decoding exception handlers, you can plug in a function that will be called during the handling of the exception. This gives you an opportunity to perform any needed actions. Refer to the ti.sysbios.family.arm.M3.Hwi module for more details.

More Exception Details: There is more information about exceptions here: http://processors.wiki.ti.com/index.php/SYS/BIOS_FAQs#4_Exception_Dump_Decoding_Using_the_CCS_Register_View

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Memory Allocation

Doing dynamic memory allocation in an embedded device has its risks. TI-RTOS offers a way to easily add a smart heap on top of the system/default heap. This heap is called **HeapTrack**. It helps with the following areas

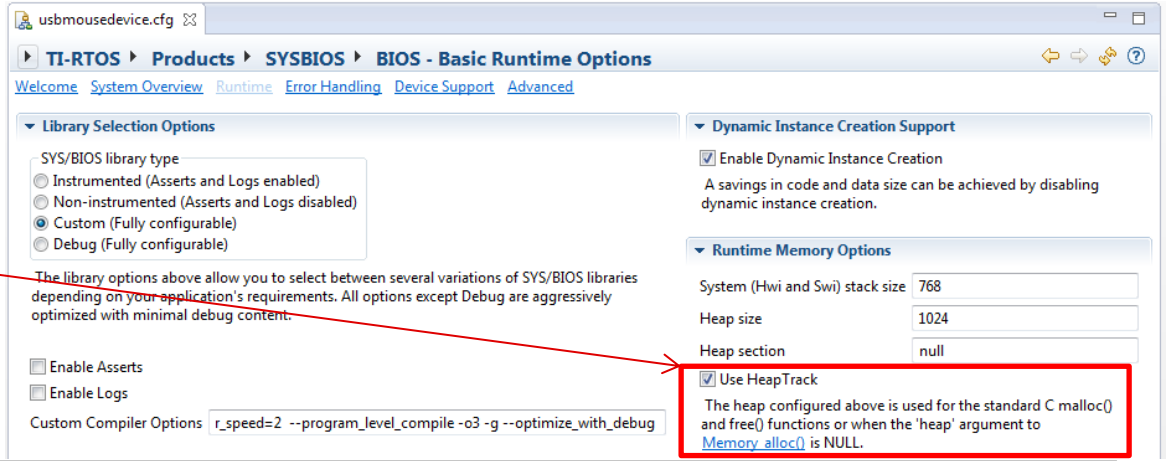
- **Over-writing the end of allocated buffers**
- **Freeing the same block twice**
- **Memory leaks**
- **Sizing the heap**

To enable **HeapTrack**, simply set the following in the .cfg file:

```
BIOS.heapTrackEnabled = true;
```

Or graphically

Or use the “Debug” Kernel Project.



Memory Allocation: HeapTrack Details

For every memory allocation from the system heap, HeapTrack adds this small structure at the end of the allocated block.

```
struct Tracker {
    UInt32 scribble;    // = 0xa5a5a5a5 when in use
    Queue_Elem queElem; // next and prev pointers
    SizeT size;
    UInt32 tick;
    Task_Handle taskHandle;
}
```

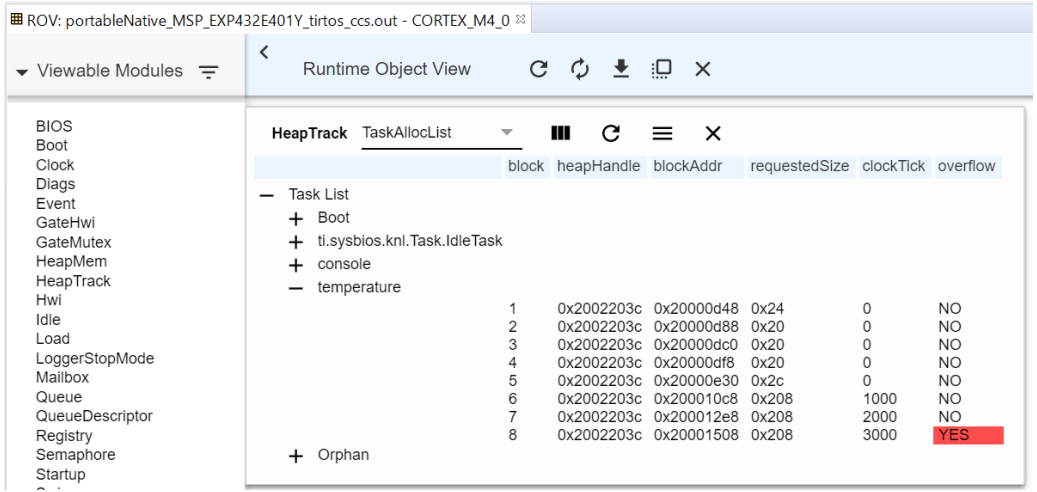
Note: this may require you to slightly increase the size of your system heap since a little extra memory is used for every allocated block.

This structure is analyzed both during via ROV and runtime execution…

Memory Allocation: HeapTrack ROV

HeapTrack in ROV displays all the allocated blocks by the task that allocated the blocks and by the heap. Here are the things that HeapTrack in ROV helps find

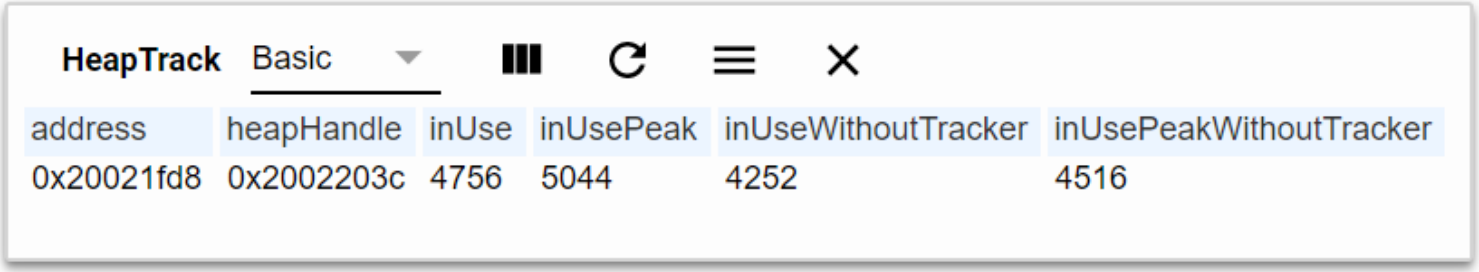
- **Writing past the block**: If the block has a corrupted scribble word, it is denoted with red. Note: the runtime check only happens when freeing the block. ROV shows it when it is still allocated.



- **Memory Leak**: By looking at the timestamp and Task owner, you generally can spot memory leaks pretty easily. For example, above you see “temperature” task is allocating blocks of 0x208 bytes every second. This might be fine, but should be checked to make sure it is not a leak.

Memory Allocation: HeapTrack ROV [cont.]

- **Peaks**: You can see the high-watermark for the heap also (both with and without the Tracker struct). This information can be used to optimize the size of your heaps.



address	heapHandle	inUse	inUsePeak	inUseWithoutTracker	inUsePeakWithoutTracker
0x20021fd8	0x2002203c	4756	5044	4252	4516

Memory Allocation: HeapTrack Runtime

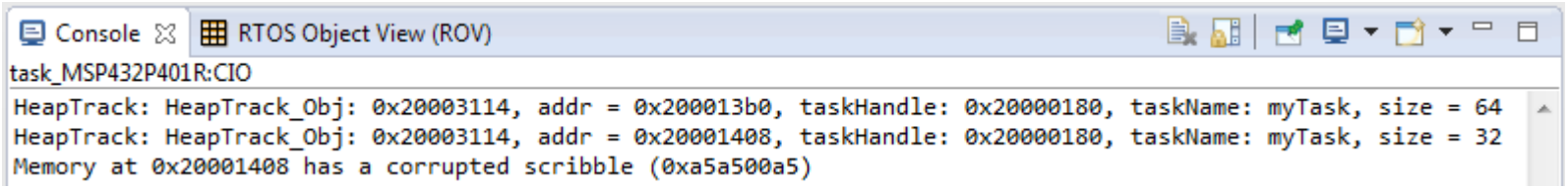
When the allocated block is freed, the following two checks are done if kernel asserts are enabled.

- **Double free**: In free, an assert checks to see that you are not trying to free a free block.
- **Writing past the block**: In the free, an assert check makes sure the scribble word is valid. If you accidently write past the end of the block, the scribble gets corrupted.

HeapTrack has a **two APIs that can be called by the applicatio**n to output (via System_printf) the allocated blocks.

```
Void HeapTrack_printHeap(HeapTrack_Object *obj);
Void HeapTrack_printTask(Task_Handle task);
```

Here is an example of the HeapTrack_printTask output. The task has allocated two blocks of size 64 and 32. The application has overwritten the scribble word (on purpose☺). This is shown in the output.



Memory Allocation: Recommendations

You can quickly enable **HeapTrack** and run your application. Then using ROV and/or runtime checks you can quickly find

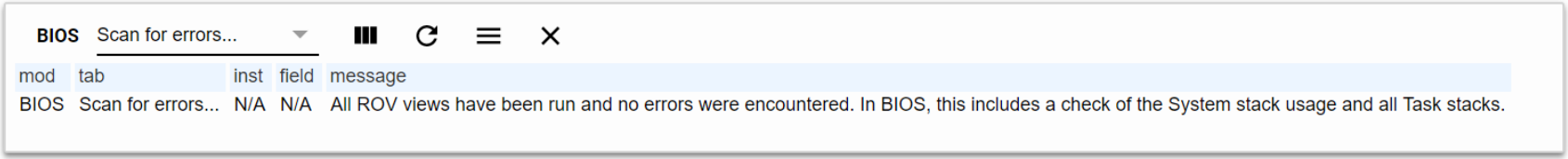
- **Over-writing the end of allocated buffers**
- **Freeing the same block twice**
- **Memory leaks**
- **Sizing the heap properly**

After the problem is fixed, simply turn **HeapTrack** off to minimize the slight performance and size impact.

Recommendation Summary

So…something weird is going on with your application. Here are some easy steps to do…

1. **Check System and Task stack peaks in ROV or "Scan for Errors…":** A quick and easy way to see if there are any issues detected is select "BIOS->Scan for errors…" in ROV. Stack overflows will show up here as well as Hwi and Task.



2. **Use the Debug Kernel Project** which will
   - Turn on TI-RTOS "Enhanced" Exception Handling.
   - Enable HeapTrack if you have a dynamic allocation.
   - Enable some other features to give more meaningful data (e.g. names instead of addresses).

Resources

- **www.ti.com Web Page**
  - www.ti.com/tool/ti-rtos
- **e2e Forum - TI-RTOS Forum**:
  - http://e2e.ti.com/support/embedded/tirtos/default.aspx
- **Additional Training & Support Resources**
  - **Main Product Page**: http://processors.wiki.ti.com/index.php/TI-RTOS
  - **TI-RTOS online training**: https://training.ti.com/ti-rtos-workshop-series
  - **SimpleLink Academy Labs**: http://www.ti.com/wireless-connectivity/simplelink-solutions/overview/simplelink-academy.html
  - **Support direct link** (includes Apps projects, extended release notes, FAQ, training, etc.) http://processors.wiki.ti.com/index.php/TI-RTOS_Support
- **Download page**
  - http://software-dl.ti.com/dsps/dsps_public_sw/sdo_sb/targetcontent/tirtos/index.html

Thank you