CS 5372
Specification and Design of Real-Time Systems

Lecture 8: Exceptions, Interrupts, Signals

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Issues

- Exceptions vs. interrupts
- Programmable interrupt controller
- Interrupt processing sequence
- Interrupt priorities
- VxWorks and interrupt handling
- ISR restrictions
- Signals: concept and operations
- POSIX signal API
- Reentrancy
- Exception handling (Ada/C++/C)
- Using error messages

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Exceptions and Signals

- There is need in a microprocessor system to detect and handle exceptional situations that may change the flow of the program control
- Such situations can be caused by:
  - external hardware **interrupts** handled by ISR
  - error event **exceptions** (zero-divide, overflow, bus or address error, illegal instruction)
  - program event **exceptions** (trap or breakpoint instruction, signal generation)
- Operating system implements selected ISR sending **signals** - the kernel calls *sigInit()* routine at initialization

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Interrupt Processing

- **Interrupts** are triggered by external hardware inputs
- Interrupts allow devices to notify the CPU that some event has occurred
- Interrupt processing sequence saves the current context and loads PC with starting address of a user-defined and installed **Interrupt Service Routine**
  - **(ISR)** is kept in the interrupt pointer table in predefined memory locations
- Return from ISR restores saved context to continue execution of the interrupted program sequence
- ISR runs at interrupt time: it is ***not*** a task
- On-board timers are a common source of interrupts - using them requires understanding interrupts

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Exception Overview

- An **exception** is an unplanned event generated internally by the CPU (trap or breakpoint instruction, divide by zero, floating point or integer overflow, illegal instruction, or address error)
- VxWorks, as any operating system, installs exception handlers at system startup
- When hardware detects an exception a user-defined exception handler is invoked (if exists)
- A VxWorks exception handler may in turn communicate with a user tasks by signaling semaphore, sending message, generating signal, etc.
- Conceptually, asynchronous interrupts and synchronous exceptions are handled in the same manner

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Programmable Interrupt Controller (PIC)

- Interrupts are prioritized based on the classifications
- Most systems have more than one source of interrupt and the sources are prioritized
- PIC is implementation dependent and it serves two main functions:
  - Prioritizing multiple interrupt sources for CPU
  - Offloading the core CPU with the processing required to determine interrupt exact source
- Interrupt Table:
  - Priority – interrupt source priority
  - Vector Address – address of the ISR
  - IRQ – interrupt number
  - Max Frequency – defines time constraint

{Li, Chapter 10, Fig 10.1}

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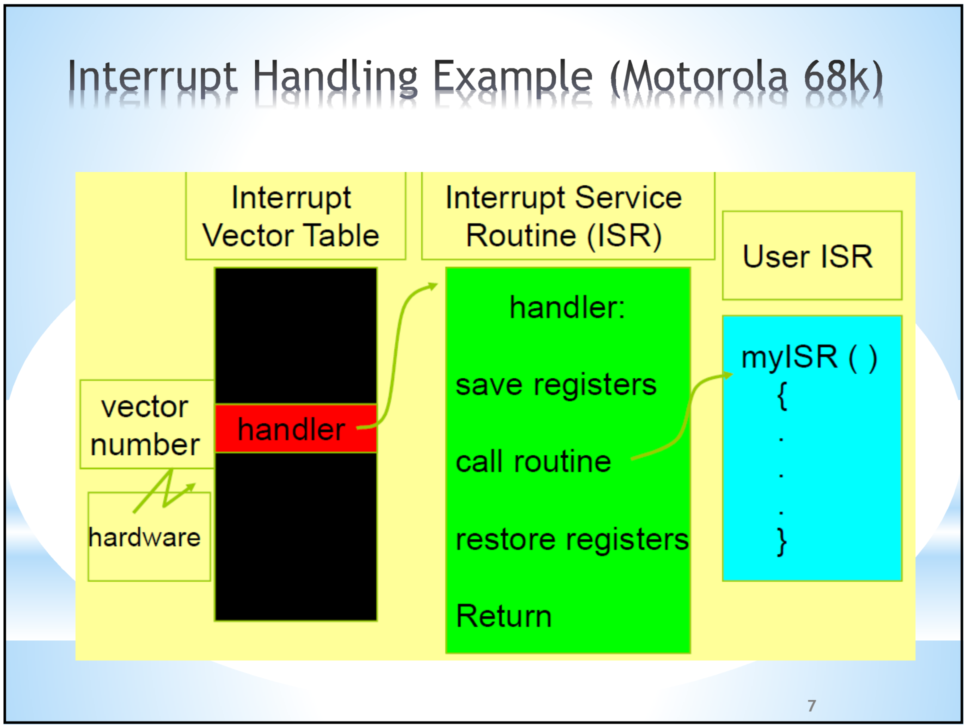
Interrupt Handling Example (Motorola 68k)
Interrupt Vector Table
Interrupt Service Routine (ISR)
User ISR
handler:
save registers
call routine
restore registers
Return
mylSR ( )
{
.
.
.
}
vector number
handler
hardware
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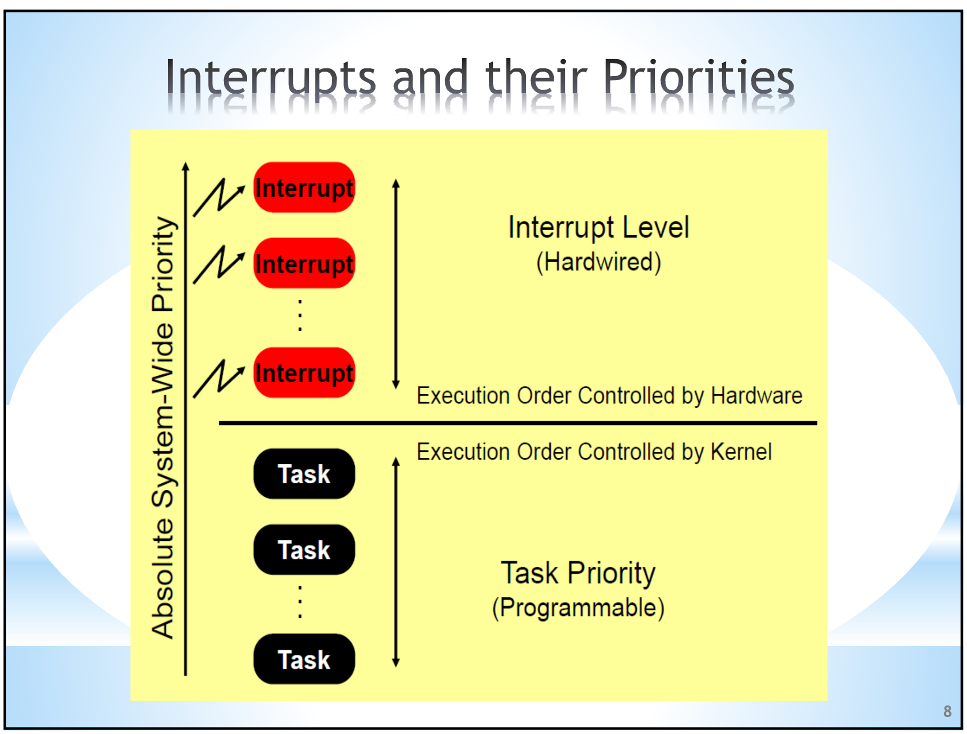
Interrupts and their Priorities
Absolute System-Wide Priority
Interrupt
Interrupt
Interrupt
Interrupt Level
(Hardwired)
Execution Order Controlled by Hardware
Execution Order Controlled by Kernel
Task
Task
Task
Task Priority
(Programmable)
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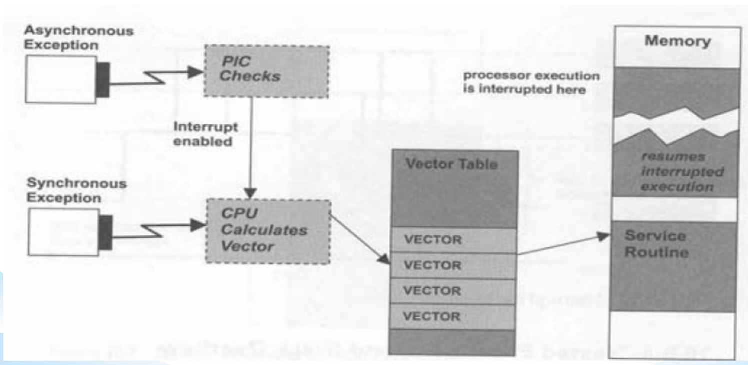
Interrupt Stack

- Most architectures use a single dedicated interrupt stack allocated at system start-up
- The interrupt stack size is controlled by the macro *ISR_STACK_SIZE*; default value defined in **configAll.h**



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Hardware Interrupt Handling (1)

- Interrupts are critical in RTS providing links between applications and the controlled hardware
- A system device event can trigger a hardware interrupt and the application must respond to this interrupt within specific determined time constraints
- When an interrupt occurs, it changes the state of the processor causing exception and allowing a user-defined routine to execute in response
- The fastest way to deal with hardware interrupts is running ISR in a special hardware context not involving the overhead associated with a conventional kernel controlled task context switch
- The time between the interrupt generation and the time when the system responds to this interrupt is called **interrupt latency**

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Hardware Interrupt Handling (2)

- Designing an application to handle interrupts requires writting interrupt service routines to handle events
- VxWorks provides routines to support handling hardware interrupts (see sigLib.h):
  - *intConnect( ):* connect a C routine to an interrupt vector !!!
    - Takes: VOIDFUNCPTR * vector (interrupt vector to attach to), VOIDFUNCPTR routine (routine to be called, int (parameters for routine)
  - *intContext( ):*
    - returns TRUE only if the current execution state is in interrupt context and not in a task context
  - *intLock( ), intUnlock( ):* disable/enable interrupts
  - *intVecBaseSet/Get( ):* set/get the vector base address
  - *intVecSet/Get( ):* set/get an exception vector
- **ISR code does not run in the normal task context**
  - it has no task control block and all ISR share a single stack
- ISR must be short, fast, and not invoke functions which may cause **blocking** of the caller

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intConnect() operation

Wrapper build by *intConnect()*:

save registers
set-up stack
invoke routine
restore registers
restore stack
exit

ISR

myISR
{
int val;
…
…

/ deal with hardware */*
…
}

intConnect (INUM_TO_IVEC(someIntNum), myISR, someVal);

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ISR to Task-Level Code Communication (Allowed???)

- Shared Memory and Ring Buffers:
  - ISR can share variables with task-level code
- Semaphores:
  - ISR can give semaphores (except for mutual-exclusion semaphores) but not take it
- Message Queues:
  - ISR can send messages to message queues for tasks to receive (if the queue is full, the message is discarded) but not receive it
- Pipes:
  - ISR can write messages to pipes that tasks can read; tasks and ISR can write to the same pipes
- Signals:
  - ISR can send "signal" to tasks, causing asynchronous scheduling of their signal handlers

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ISR Restrictions

- No tasks can run until ISR has completed
- ISR's can't block (it is non-reentrant):
  - Can't call ***semTake()***
  - Can't call ***malloc()*** (uses semaphores)
  - Can't call I/O system routines (e.g. ***printf()***)
- The ***Programmer's Guide*** gives a list of routines which are callable at interrupt time (some on next slide)
- Typical ISR functions:
  - Reads and writes memory-mapped I/O registers
  - Communicates information to a task by:
    - Writing to memory
    - Making non-blocking writes to a message queue
    - Giving a binary or counting semaphore

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Examples of Routines Callable from ISR

- ***errnoLib***: *errnoGet(), errnoSet()*
- ***intLib***: *intContext(), intCount(), intVecSet(), intVecGet()*
- ***intArchLib***: *intLock(), intUnlock()*
- ***logLib***: *logMsg()*
- ***msgQLib***: *msgQSend()*
- ***pipeDrv***: *write()*
- ***semLib***: *semGive()* (except mutex), *semFlush( )*
- ***sigLib***: *kill()*
- ***taskLib***: *taskSuspend(), taskResume(), taskPrioritySet(), taskPriorityGet(), taskIdVerify(), taskIdDefault(), taskIsReady(), taskIsSuspended(), taskTcb()*
- ***tickLib***: *tickAnnounce(), tickSet(), tickGet()*
- ***wdLib***: *wdStart(), wdCancel()*

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ISR Guidelines

- Keep ISR short:
  - It does delay lower and equal priority interrupts
  - It does delay all tasks
  - It is hard to debug
- Avoid using floating-point operations in an ISR
  - they may be too slow
  - must call ***fppSave( )*** and ***fppRestore( )***
- Try to off-load less critical and/or longer in duration work to application tasks running under kernel control

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Debugging ISR

- To log diagnostic information to the console at interrupt time:
  - ***logMsg ("foo = %d\n", foo, 0, 0, 0, 0, 0);***
  - Sends a request to ***tLogTask*** to do a ***printf( )*** for us
- Similar to ***printf( )***, with the following caveats:
  - Arguments must be four bytes
  - Format string plus six additional arguments
- Use a debugging strategy which provides system-level debugging:
  - WDB agent
  - Emulator

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Signals - Concept

- Signals are software representation of interrupts defined inside the operating system and thus they are primary means to notify task about events
- Receiving task must have established a **signal handler** to catch the signal and respond
  - default exception handler shall handle the exception - in most cases the task shall be suspended and a message is logged on the console
  - Handler is a function that is bound to (or triggered by) the specific signal (handler is an application software version of the Interrupt Service Routine (ISR)
- Signals are, typically, used for error and exception handling (not for a general inter-task communication)

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Signals - Basic Terms

- A signal is ***generated*** when the event that causes the signal occurs
- A signal is ***delivered*** when a task or a process takes action based on that signal.
- The ***lifetime*** of a signal is the interval between its generation and its delivery
- A signal that has been generated but not yet delivered is ***pending*** (there may be a considerable time between signal generation and signal delivery)
- A task can block some or all signals with a signal mask, to protect itself from diversions while it executes a critical section of code
- The exchange of signals provides a means for communication between tasks *(NOTE: message queues, shared memory, and semaphores provide facilities that are generally more suitable for inter-task communication)*

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Selected Signals (signal.h)

#define SIGINT	2	/* interrupt */
#define SIGQUIT	3	/* quit */
#define SIGILL	4	/* illegal instruction */
#define SIGTRAP	5	/* trace trap */
#define SIGABRT	6	/* used by abort */
#define SIGFPE	8	/* floating point exception */
#define SIGKILL	9	/* kill */
#define SIGBUS	10	/* bus error */
#define SIGSEGV	11	/* segmentation violation */
#define SIGALRM	14	/* alarm clock */
#define SIGTERM	15	/* software termination */
#define SIGUSR1	30	/* user defined signal 1 */
#define SIGUSR2	31	/* user defined signal 2 */
#define SIGRTMIN	23	/* Realtime signal min */
#define SIGRTMAX	29	/* Realtime signal max */

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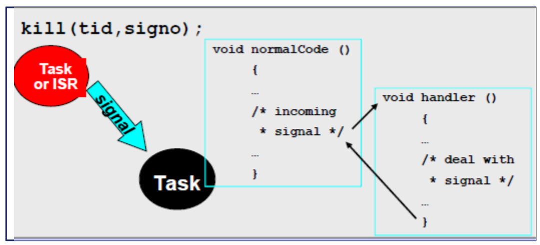
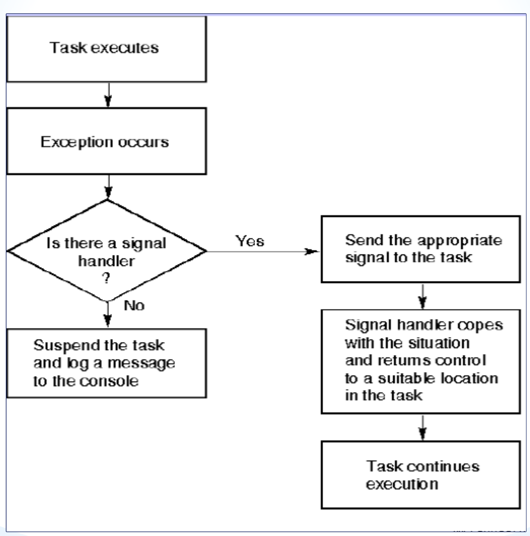
Signals - Operations

- An exception in application - when the computer detects an error caused by code that is currently executing (processing cannot continue past the exception point unless the software or a user takes a remedial action)
- **In response to the exception**, **the system** software stops the current thread of program execution and **generates an appropriate signal**



Typical Exception Handling



Kernel Signals (1)

- The Wind kernel supports both BSD 4.3 and standardized POSIX signal interface
- Examples of few POSIX1003.1b signal routines from the *sigLib* library (check *signal.h, sigLib.h*):
  - *signal():* specify the handler associated with a signal
  - *kill(), raise(), sigqueue():* send a signal to a task
  - *sigaction():* examine or set a signal hander for a signal
  - *sigprocmask():* examine and/or change the signal mask
  - *sigwaitinfo():* wait for signal
- Signals are analogous to hardware interrupts – the basic signal facility provides a set of 31 signals
- Signal binding using *signal(), sigvec( ), sigaction( )*

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Important Caveats

- Signals are ***not*** recommended for general inter-task communication
- A signal:
  - May be handled at too high a priority if it arrives during a priority inheritance
  - Disrupts a task's normal execution order. (It is better to create two tasks than to multiplex processing in one task via signals)
  - Can cause reentrancy problems between a task running its signal handler and the same task running its normal code
  - Can be used to tell a task to shut itself down
- **sigLib** contains both POSIX and BSD UNIX interfaces (do not mix them)

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Signal Handler

- To register a signal handler we may use:

  signal (signo, handler)

  signo signal number

  handler routine to invoke when signal arrives

  returns the installed signal handler (or ***SIG_ERR***)
- The signal handler is declared as follows:

  void sigHandler (int sig); ***/* signal number */***
- When signal is detected, the offending task will be suspended and a message is logged to the console
- Exception signal handlers typically call:
  - **exit()** to terminate the task,
  - **taskRestart()** to restart the task, or
  - **longjmp()** to resume execution at location saved by **setjmp()**

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Signals and Exceptions

- Hardware exceptions include bus error, address error, divide by zero, floating point overflow, etc.
- Some signals correspond to exceptions (e.g. ***SIGSEGV*** corresponds to a bus error on a 68k)

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Example: sending and handling signals (VxWorks)

```
/* install handlers to intercept signals */
   for(sigNo=0; sigNo<32; sigNo++)
      signal(sigNo, sigHandler);
  ...
/* sending all 32 signals to the task
   specified by taskID*/
 sigNo = 1;
 while(1)
    {
      kill(taskID, sigNo++);
         /* you may use raise(sigNo) */
     if(sigNo>31) break;
        /* limit with 32 signals */
     taskDelay(sysClkRateGet()/4);
        /* delay 250 msec */
}
```

```
/* handling signals #30 and #31 */

 void sigHandler(int sigNo)
{
logMsg ("%d \n", sigNo, 0, 0, 0, 0, 0);
      switch (sigNo)
      {
          case 30:
             /* respond to signal #30 */
             break;
          case 31:
             /* respond to signal #31 */
             break;
          default:
              printf("\n other signal \n");
       }
}
```

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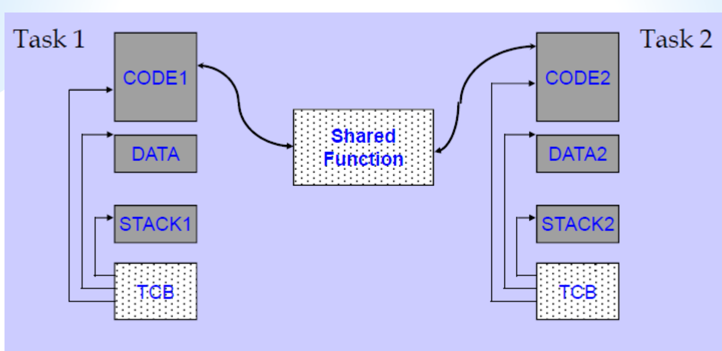
Reentrancy: Sharing Code Between Tasks



Reentrancy is critical in code that may be called by more than one task

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Example: exception handler (VxWorks)

```
/* install an exception handler first */
    excHookAdd((FUNCPTR) excHandler);

/* handler code */
void excHandler(void)
{
    logMsg("\n EXCEPTION - RESTART !\n",0,0,0,0,0,0);
    taskRestart(0);
}
```

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Exception Implementation – C++

```
// the code
    try
       { // any block of code }
          catch(<exception_class>)
          { // perform exception handling }
            // function generating exception
             throw(<exception_class>)
```

C++ provides a *try* block associated with *catch* and allows for *throw* calls

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Exception Implementation - C

```
/* here is where we need to return - handler
        setjmp(jmp_buff);

/* here the exception will be caught
        longjmp(jmp_buff, arg)
```

Handling exceptions in C is cumbersome and requires preserving the program status by *setjmp* and use *longjmp* to implement exception

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Error Messages

- VxWorks uses an error symbol table (**statSymTbl**) to convert error numbers to error messages
- To obtain the error string corresponding to errno:

```
{
  char errStr [NAME_MAX];
  strerror_r (errno, errStr);
  ...
}
```

- To print the error message associated with an error number to the WindSh console:

  printErrno(0x110001)
  - *0x110001 = S_memLib_NOT_ENOUGH_MEMORY*
  - *value = 0 = 0x0*

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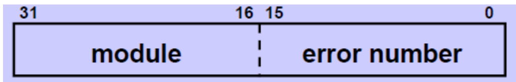
Interpreting errno

- VxWorks uses the 32-bit value **errno** as follows:
  - **module error numbers** are defined in **vwModNum.h**
  - Each module defines its own error numbers in its header file
  - For example, an **errno** of 0x110001 would be:
    - Module number 0x11 (defined in **vwModNum.h** to be **memLib**) and
    - Error number 0x01 (defined in **memLib.h** to be “not enough memory”)

- VxWorks allows to create user-defined error codes



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EXAMPLE: Setting errno

Lowest level routine to detect an error sets **errno** and returns ***ERROR***:

```
STATUS reactorOK( )
  {
  coreTemp = checkCoreTemp( );
  if ( coreTemp >= maxCoreSafeTemp)
         {
                 errno = S_rctorLib_TEMP_DANGER_ZONE;
                 return (ERROR);
         }
         ...
  if ( corePressure <= minContainmentPressure )
         {
                 errno = S_rctorLib_LEAK_POSSIBLE;
                 return (ERROR)
         }
                 ...
  }
```

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EXAMPLE: Examining errno

Examine **errno** to find out why a routine failed

```
if ( reactorOk( ) == ERROR )
{switch (errno)
  {
  case  S_rctorLib_TEMP_DANGER_ZONE:
        moveControlRods(0x0f, 0);
        break;
  case  S_rctorLib_TEMP_CRITICAL_ZONE:
        logMsg("Run!");
        break;
  case S_rctorLib_LEAK_POSSIBLE:
        checkVessel( );
        break;
  default:
        startEmergProc( );
  }
}
```

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Summary

- Exceptions, Signals and Interrupts are means for providing information allowing the program to branch
- Interrupts are handled by hardware
- Signals are RTOS implementation of interrupts
- Interrupt Service Routines have a limited context:
  - No Blocking
  - No I/O system calls
- Using signals for exception handling:
  - *signal( )*
  - *exit( )*
  - *taskRestart( )*
  - *longjmp( )*

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