CS 5372
Specification and Design of Real-Time Systems

Lecture 3: Concurrency & Tasking

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What is Concurrency

- Real time systems interact asynchronously with external entities and must cope with multiple threads of control and react to events - the executing programs need to share the CPU
- **Concurrency** in a computer application is when two or more sequential programs execute "*at the same time*" resulting in two or more sequences of machine instructions (executed one-after-another or interleaving on a CPU)
- Concurrency is implemented on either **operating system level** or **programming language level**

NOTE: *when concurrency is implemented on multiple processors - we define it as* ***distributed*** *or* ***parallel computing***

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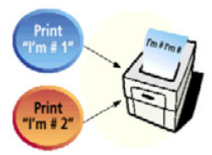
Task - Definition

- **Task**: a step-by-step complete sequence of instructions, *spawned for execution*, with a defined execution time designed to fulfill one of the system functions
- Each task may be executed **concurrently** with other tasks
- Each task is a separate *non-dormant* programming construct (implemented as a **process** or a **thread**) with its own execution sequence and the context (program counter, registers, memory, stack, etc.)



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Patterns of Task Interactions (in Concurrent Problems)

- **Independent**: the tasks operate on separate parts of a problem, requiring no interaction
- **Competing**: the tasks require use of the same resource (CPU, shared data, display, file, peripheral)
- **Cooperating**: the tasks operate on common problem parts (overlapping at a few well defined points) and cooperate with each other at these points to solve the problem

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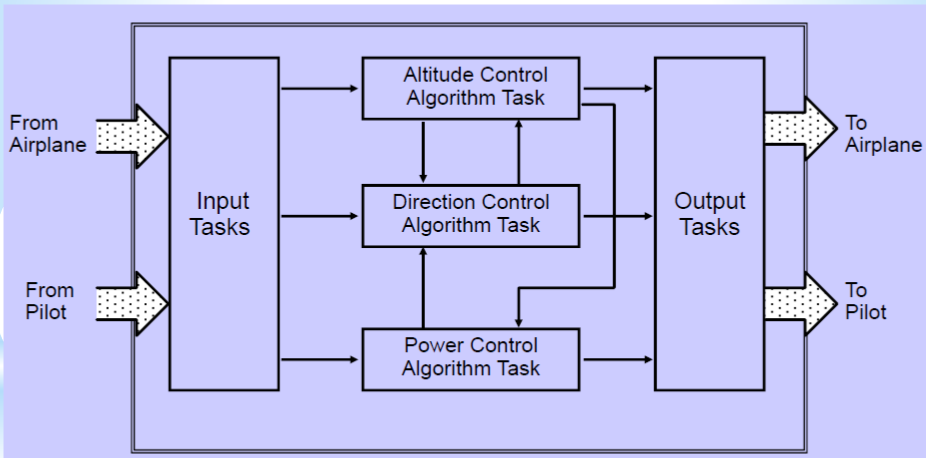
Example: Concurrent Application Design



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Rationale for Concurrency
CYCLIC EXECUTIVE

- Four tasks require specific time
- Execute all tasks in a sequence of one loop
- Event E3, that must be handled by T3, occurs when T4 starts execution

```
loop
    T1(200 ms)
    T2(300 ms)
    T3(100 ms)
    T4(400 ms)
end loop
```

What is the required response time?

400+200+300+100 = **1000 ms**

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Rationale for Concurrency
ROUND-ROBIN

- Execute each task in a separate loop
- Assign each task 50 ms time slice

loop T1(200 ms) end loop

loop T2(300 ms) end loop

loop T3(100 ms) end loop

loop T4(400 ms) end loop

- Event E3, that must be handled by T3, occurs when T4 starts execution

What is the required response time?

The T3 response takes two time slices
50 + 50 + 50 + 50 + 50 + 50 + 50 + 50 = **400 ms**

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Rationale for Concurrency
NON-PREEMPTIVE PRIORITY

- Schedule task Ti for execution when activated by event Ei
- Lower number task has a higher priority
- When event Ei occurs **complete currently executing task** and schedule the Ti (according to its priority)

loop T1(200 ms) end loop

loop T2(300 ms) end loop

loop T3(100 ms) end loop

loop T4(400 ms) end loop

- Event E3, that must be handled by T3, occurs when T4 starts execution

What is the required response time?

400+100= **500 ms**

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Rationale for Concurrency
PREEMPTIVE PRIORITY

- Schedule task Ti for execution when activated by event Ei
- Lower number task has a higher priority
- When event Ei occurs and currently executing task Tj (j > i), interrupt Tj and execute Ti

loop T1(200 ms) end loop

loop T2(300 ms) end loop

loop T3(100 ms) end loop

loop T4(400 ms) end loop

- Event E3, that must be handled by T3, occurs during execution of T4

What is the required response time?

100 = **100 ms**

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Concurrency Implications

- Concurrently executed programs imply sharing of resources - they require **synchronization** and **communication** facilities
- **Synchronization** - we want to execute concurrent components of program "in step"
- **Communication** - we want to pass data between concurrent program components (but only at the appropriate time)

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Concurrency - Potential Problems

- **Deadlock** - a task is blocked waiting for a resource that shall never be available (e.g. due to a circular wait of more than one tasks)
- **Livelock** - a task executes an idle loop waiting for a condition that will never happen (e.g., the task that is to set this condition is not doing so)
- **Non-reentrant Code** - the interrupted code may have corrupted data upon resuming its execution (due to overwriting data on subsequent code invocations)

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Concurrency - Potential Problems (2)

- **Race condition** - different results are obtained depending upon which task will execute a specific instruction first
- **Mutual exclusion violation** - two tasks have access to shared data (or resource) at the same time which may lead to data corruption, operation on corrupted data, or resource contention and malfunction
- **Priority Inversion** – tasks of lower priority execute while task of higher priority waits for execution
  - (Can you think of a way this might happen?)

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Ordering and Determinism

- **Sequential** programs are totally ordered - we can always determine which statement will be executed next (the steps of an algorithm are always performed in a **well defined** order)
- For **concurrent** programs the next statement to be executed is much harder to determine - it could be from any of the executing concurrently processes
- The order of the activities involved in the execution of an algorithm can only be **partially defined**

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Example: Non-Determinism

- The order or execution of a set of concurrent processes cannot be predetermined

P1	P2
N:= N-1	N:= N+1

Assuming N is initialized to 3
What is the final value of N ?
Pick one: 1, 2, 3, 4, 5,…

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Example: Non-Determinism (cont)

P1	P2
N:= N-1	N:= N+1

P1:
P11: fetch N
P12: decrease N by 1
P13: store N

P2:
P21: fetch N
P22: increase N by 1
P23: store N

Case 1	p11	p12	p13	p21	p22	p23
N	3	2	2	2	3	3
Case 2	p11	p21	P12	p22	p13	p23
N	3	3	2	4	2	4
Case 3	p11	p21	p22	p23	p12	p13
N	3	3	4	4	2	2

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Task Implementation Operating System Level

- **As a process** – executing program with its data and context
  - a “heavy” separate executing programming construct
  - scalability and modularity
  - good protection via operating system
  - time penalty on process overhead
- **As a thread -** unit of work executing sequentially
  - a “light” programming construct executing within a process
  - fast creation and communication
  - common data area
  - sensitive to data corruption

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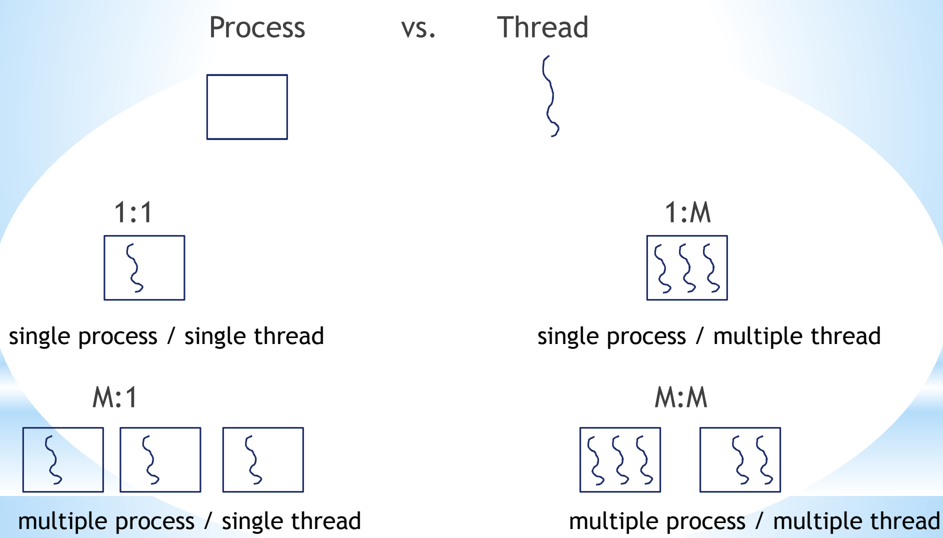
Process vs. Thread



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Task Activation

- **Periodic Activation**
  - defined time interval between two consecutive activation events
  - must be completed before the next activation

```
begin loop
    { body of task }
    delay period
end

        OR

begin loop
    wait for time point
    {body of task}
end
```

- **Sporadic Activation**
  - triggered by an asynchronous event
  - must be completed within a defined time limit

```
begin loop
    wait for event
    { body of task }
end
```

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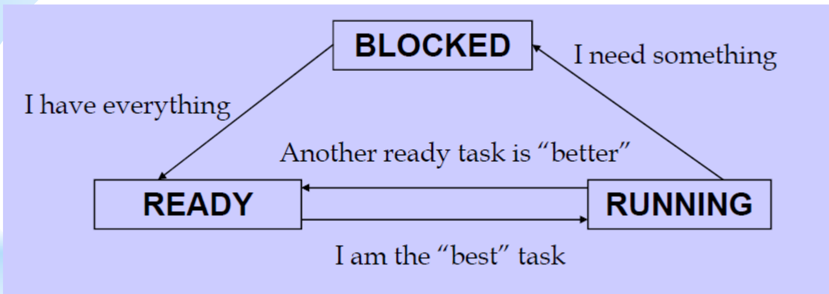
Task States – a Simple Approach

- RUNNING: Executing with access to CPU
- READY: has everything it needs (but no CPU)
- BLOCKED: waiting for something (to be ready)



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Two Common Task Scheduling Mechanisms

- **Preemptive Priority** Scheduling
  - Kernel schedules the tasks according to task priority and scheduling options
  - Kernel preempts a low priority task to execute a higher priority task when the latter is ready
- **Round-Robin** Scheduling
  - A time-slice is defined with each task is assigned time processor for duration defined by the time slice
  - Upon time-slice expiration the next task is assigned to processor

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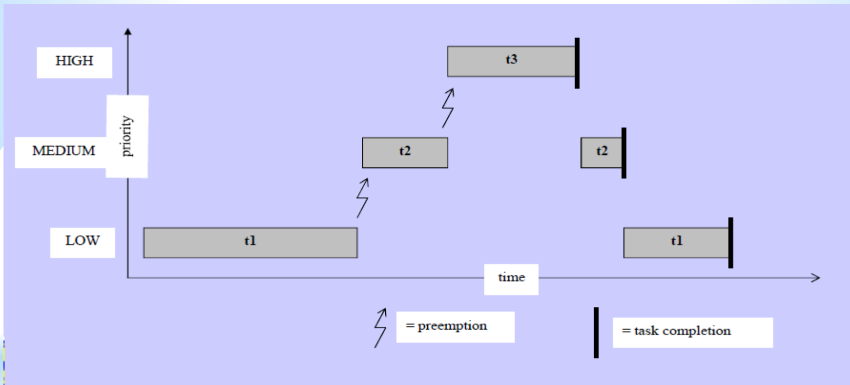
Example: Preemptive Priority

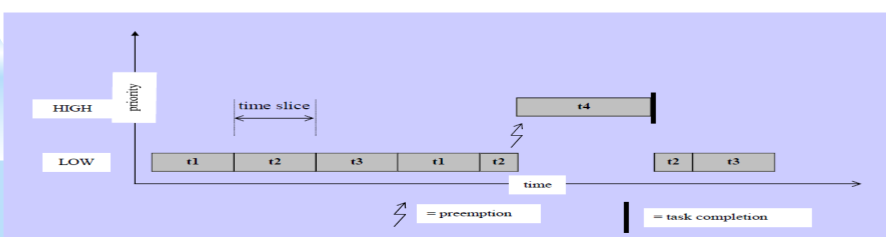
- Context switch occurs when a higher priority task is ready to run



From WRS vxWorks and Workbench Documentation

Example: Round-Robin with Time-Slicing

- To allow ***equal priority*** tasks to preempt each other, time slicing must be turned on:
  - *kernelTimeSlice(ticks)*
  - If **ticks** = 0, time slicing is turned off
- Priority scheduling always takes precedence
- Round-robin only applies to tasks of the same priority
- Priority-based rescheduling can happen any time at the pre-emption point
- Round-robin rescheduling can only happen at specific clock tick defined by the time slice



Multitasking

- Mechanism by which an application reacts to multiple discrete real-world events creating the appearance of many threads of execution running concurrently
- Kernel interleaves the task execution on the basis of a scheduling algorithm
- All real-time kernels provide multitasking environment (e.g.: VxWorks ***wind)***

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Multitasking Kernel

- The ***wind*** kernel is that part of VxWorks which directly manages tasks
- Allocates the CPU to tasks according to the VxWorks scheduling algorithm (to be discussed)
- Uses **Task Control Blocks** (**TCB**s) to keep track of tasks
  - One per task
  - Declared as ***WIND_TCB*** data structure in **taskLib.h**
  - RTOS controls information about state, task priority, delay timer breakpoint list, error status, I/O redirections, etc.
  - CPU context information: PC, CPU registers, FPU registers

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Types of Context Switches

- Synchronous context switches occur because the executing task:
  - pends, delays, or suspends itself
  - makes a higher priority task ready to run
  - (less frequently) lowers its own priority, or exits
- Asynchronous context switches occur when an ISR:
  - makes a higher priority task ready to run
  - (less frequently) suspends the current task or lowers its priority

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When does context switch occur ?

- Under the control of kernel at specified preemption points (usually the real clock time tick):
  - when the task completes
  - when the task becomes pending, delayed, or suspended
  - when the task time slice expires
- Under the control of hardware (after the completion of currently executing instruction) as a response to an interrupt/exception

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How does context switch happen?

- The created task is placed on the ready queue (in the priority order)
- The first task from the ready queue starts execution
- When the software context switch occurs, the next task from ready queue shall execute
- When the interrupt occurs, the ISR (interrupt service routine) executes in the hardware context
- Context switch time (μsec range) may be critical for a real-time system performance

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Detailed Insight into Task States

- **NON-EXISTING** - not yet created (or terminated)
- **DORMANT** - created but not yet activated (or completed but not yet terminated)
- **RUNNING** - executing with access to processor
- **INTERRUPTED** - when system responds to hardware interrupt
- **READY** - ready to execute
- **PENDING or BLOCKED** - waiting for a resource which is not available
- **DELAYED or WAITING** - waiting on a delay or timer to expire
- **SUSPENDED** - stopped for debugging or other purpose (not able to execute - *may be used with READY, PENDING, or DELAYED*)

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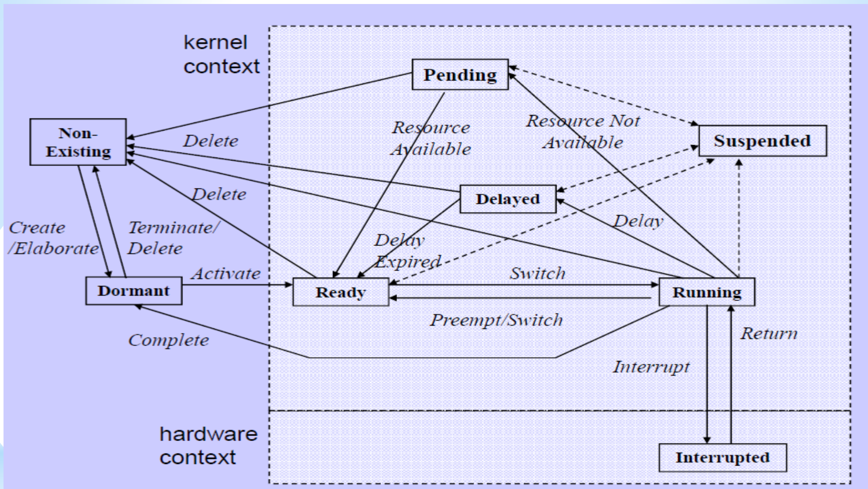
Task State Transitions



Kernel maintains the current state of each task using queues for:
Delayed; Ready; Pending; Suspended

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Many vs. Few Tasks

- Benefits of many tasks:
  - faster response time
  - cohesion and modularity
  - Encapsulation
- Benefits of few tasks:
  - data sharing
  - easy communication and synchronization
  - less memory
  - less switching

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Task Creation, Activation and Termination

- Distinction between:
  - **creation** - elaboration of a declaration of code segment,
  - **activation** - explicit or implicit operation resulting in the actual execution of a task
- Activation can be by:
  - continuing execution of the activating task (UNIX fork, Ada task)
  - executing specific list of statements concurrently (Occam cobegin-coend)
- Process termination can be **explicit** (UNIX kill, Ada abort) or **implicit** via completion
- In some cases the completed task can still not terminate until (because) it has active dependent tasks

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Task Actions

- Task can:
  - spawn another task
  - delete another task
  - protect itself from other tasks
  - delete itself (exit)
  - suspend another task
  - resume another
  - restart another task
  - delay another task

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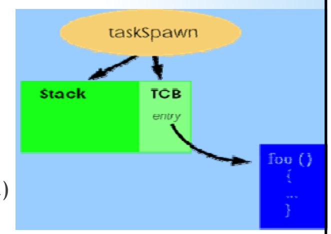
Creating VxWorks Task taskLib.h

- *int taskSpawn (name, priority, options, stackSize, entryPt, arg1, …, arg10)*

  name Task name, if ***NULL*** gives a default name
  priority Task priority 0-255 (0 highest)
  options Task options e.g. ***VX_UNBREAKABLE***
  stackSize Size of stack to be allocated in bytes
  entryPt Address of code to start executing (initial PC)
  arg1, ..., **arg10** Up to 10 arguments to entry-point routine



- Returns a task id or ***ERROR*** if unsuccessful

Example:
newTid = taskSpawn("tMyTask", 150, 0, 20000, myRoutine, arg1, arg2, 0,0,0,0,0,0,0,0)

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VxWorks Task Control

- Task Creation and Activation
  - *taskSpawn/ taskCreate/ taskActivate*
- Task Names and ID
  - *taskName: get name from ID*
  - *taskNameToId: get tid from name*
  - *taskIdSelf: gets ID of calling task*
  - *taskIdVerify: verify that ID is valid*
- TaskOptions
  - *taskOptionsGet/ taskOptionsSet: get or set task options*
- Task Information
  - *taskIdListGet/ taskInfoGet*
  - *taskPriorityGet*
  - *taskRegsGet/ taskRegsSet*
  - *taskIsReady/ taskIsSuspended*

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VxWorks Task Control (Cont.)

- Control round-robin scheduling
  - *kernelTimeSlice(N)*
  - N is the slice duration - number of clock ticks (0 – no time slicing)
- Change priority of task
  - *taskPrioritySet(N)*. N is the new priority (0-255)
- Disable/enable task rescheduling
  - *taskLock*/*taskUnlock*. Function to disable/enable context switching
- Disable/enable interrupts
  - *intLock*/*intUnlock*. Function to disable/enable interrupts

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VxWorks Task Control (Cont.)

- Task Deletion (BIG RED FLAG)
  - *taskDelete(tid)*
  - *taskDelete(0) ???*
  - *exit*. (Same as taskDelete (0)) but code is still stored in TCB
- Task Control
  - *taskSuspend*/*taskResume*
  - *taskDelay(number of ticks)*
  - *taskRestart*. Task is reinitialized with original arguments and *tid*

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VxWorks Task ID's and Names

- Uniquely assigned by kernel when task is created
- May be reused after task exits
- A task ID of zero refers to task making call (self)
- Relevant **taskLib** routines:
  - **taskIdSelf( )** Get ID of calling task
  - **taskIdListGet( )** Array with ID's of all existing tasks
  - **taskIdVerify( )** Verify a task ID is valid
- Task names provided for human convenience
  - Typically used only from the shell (during development)
  - Within programs, use task IDs
- By convention, task names start with a "t" followed by an integer

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Task Priorities and Stack

- Range from **0** (**highest**) to **255** (**lowest**)
- Timing requirements rather than hazy ideas about task importance should govern priorities (theory exists)
- One can manipulate priorities dynamically (not recommended)
  - ***taskPriorityGet (tid, &priority)***
  - ***taskPrioritySet (tid, priority)***
- Task stack allocated from system memory pool when task created
  - Task stack has fixed size after creation
  - The kernel reserves space from the stack, making the stack space actually available slightly less than the stack space requested
  - Exceeding stack size ("stack crash") causes unpredictable system behavior

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VxWorks Task Creation and Options

- During time critical code, task creation can be unacceptably time consuming
- To reduce creation time, a task can be spawned with the ***VX_NO_STACK_FILL*** option bit set
- Alternatively, spawn a task at system start-up which blocks immediately, and waits to be made ready when needed
- Can be bitwise or'ed together when the task is created:
- ***VX_FP_TASK*** Add floating point support
- ***VX_NO_STACK_FILL*** Don't fill stack with 0xee
- ***VX_UNBREAKABLE*** Disable breakpoints
- ***VX_DEALLOC_STACK*** Deallocate stack and TCB at exit
  - Use **taskOptionsGet( )** to inquire about a tasks options
  - Use **taskOptionsSet( )** to set or unset a task option

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VxWorks Task Deletion and Restart

- ***taskDelete (tid).*** Deleting specified task
  - De-allocating the TCB and stack: ***exit (code)***
  - does not return global resources, i.e. allocated memory and open file descriptors
  - the same as ***taskDelete(0)*** except code is stored in the tasks TCB before the task is terminated
  - can be examined postmortem if ***VX_DEALLOC_STACK*** is off
- ***taskRestart (tid).*** Task is reinitialized with original arguments and *tid*
  - The stack is reset and cleared
  - Global resources used by the task are not reset
  - Global and static variables do not get reset
  - file descriptors will be left open
  - any memory allocated by the task will not be freed at restart

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VxWorks Task Suspend/Resume and Delay

- ***taskSuspend (tid).*** Makes task ineligible to execute (safest to have a task suspend itself)
- ***taskResume (tid)*** removes suspension
  - ***taskSuspend( )*** and ***taskResume( )*** used for debugging and development purposes
- To delay a task for a specified number of system clock ticks: ***STATUS taskDelay (tics)***

  To poll every 1/5 second:

```
FOREVER
    {
        taskDelay (sysClkRateGet( ) / 5)
        ...
    }
```

- Only accurate if clock rate is a multiple of five ticks/second
- Use ***sysClkRateSet( )*** to change the clock rate

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Lab Work

- **Task Basics**
- **Task Control**
- **Task Delay**

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Group Quiz

Upcoming Tasks

Lab 1: Due by class time on Thursday 09/25

Reading Assignment: Chapter 6 (Semaphores)