Task Scheduling

(slides are based on Prof. Dr. Jian-Jia Chen and http://www.freertos.org)

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Outline

Scheduling Approaches and Analysis

Lists in FreeRTOS

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Fundamentals (Recall)

- Problem:
  - A concrete quest described by a set of input parameters and a set of constraints to be satisfied.
  - A **feasible solution** is to find a solution that meets all the required constraints.
    - In real-time systems: A schedule of real-time tasks is **feasible** if all the tasks meet their deadlines.
  - An **optimal solution** is to a solution with the "best" objective function (defined by the problem) among all feasible solutions.

- Algorithm:
  - Logical procedure to solve a certain problem
  - Informally specified a sequence of elementary steps that an "execution machine" must follow to solve the problem
  - Implemented in a formal programming language (Program)
  - In real-time systems: **Optimal algorithm** is an algorithm that is able to find a feasible schedule.

Recurrent Tasks (Recall)

- When jobs (usually with the same computation requirement) are released recurrently, these jobs can be modeled by a recurrent task
- Periodic Task τ_i:
  - A job is released exactly and periodically by a period T_i
  - A phase ϕ_i indicates when the first job is released
  - A relative deadline D_i for each job from task τ_i
  - (ϕ_i, C_i, T_i, D_i) is the specification of periodic task τ_i, where C_i is the worst-case execution time.
- Sporadic Task τ_i:
  - T_i is the minimal time between any two consecutive job releases
  - A relative deadline D_i for each job from task τ_i
  - (C_i, T_i, D_i) is the specification of sporadic task τ_i, where C_i is the worst-case execution time.

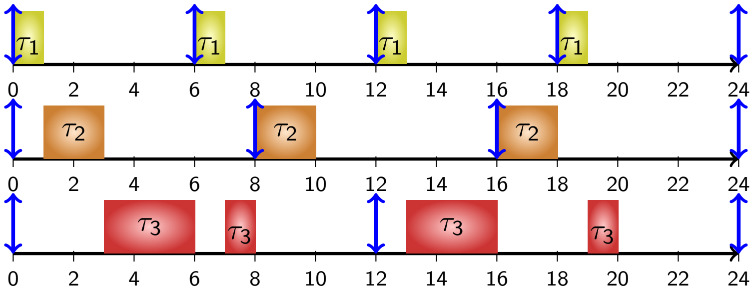
Scheduling Algorithms

- Static-Priority Scheduling
  - Different jobs of a task are assigned the same priority
- Dynamic-priority Scheduling
  - Different jobs of the same task may be assigned different priorities

Rate-Monotonic (RM) Scheduling (Liu and Layland, 1973)

Priority Definition: A task with a smaller period has higher priority, in which ties are broken arbitrarily.

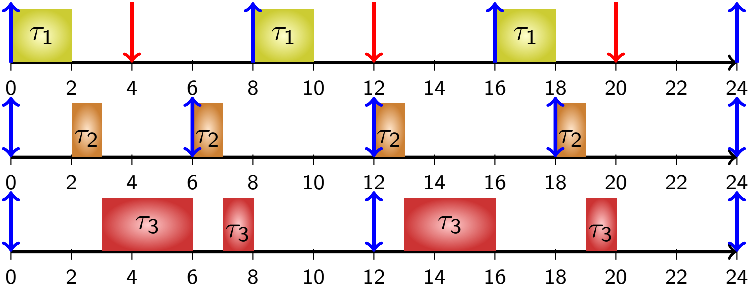
Example Schedule: $\tau_1 = (1, 6, 6)$, $\tau_2 = (2, 8, 8), \tau_3 = (4, 12, 12)$.



Deadline-Monotonic (DM) Scheduling (Leung and Whitehead)

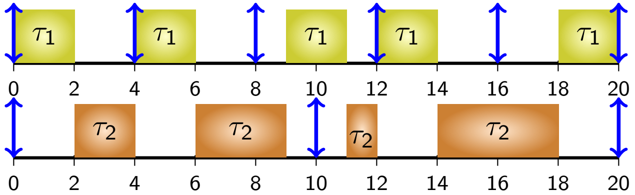
Priority Definition: A task with a smaller relative deadline has higher priority, in which ties are broken arbitrarily.

Example Schedule: $\tau_1 = (2, 8, 4)$, $\tau_2 = (1, 6, 6)$, $\tau_3 = (4, 12, 12)$.



Optimality (or not) of RM and DM

Example Schedule: $\tau_1 = (2, 4, 4)$, $\tau_2 = (5, 10, 10)$



The above system is schedulable.
However, a deadline will be missed, regardless of how we choose to (statically) prioritize τ_1 and τ_2. Therefore, no static-priority scheme is optimal for scheduling periodic tasks.

Corollary

Neither RM nor DM is optimal.

Utilization-Based Schedulability Test

- Task utilization:

$$u_i := \frac{C_i}{T_i}$$

- System (total) utilization:

$$U(\mathbf{T}) := \sum_{\tau_i \in \mathbf{T}} \frac{C_i}{T_i}$$

A task system $\mathbf{T}$ fully utilizes the processor under scheduling algorithm A if any increase in execution time (of any task) causes A to miss a deadline. In this case, $U(\mathbf{T})$ is an **upper bound** on utilization for A, denoted $U_{ub}(\mathbf{T}, A)$.

$U_{lub}(A)$ is the **least upper bound** for algorithm A:

$$U_{lub}(A) = \min_{\mathbf{T}} U_{ub}(\mathbf{T}, A)$$

Liu and Layland Bound

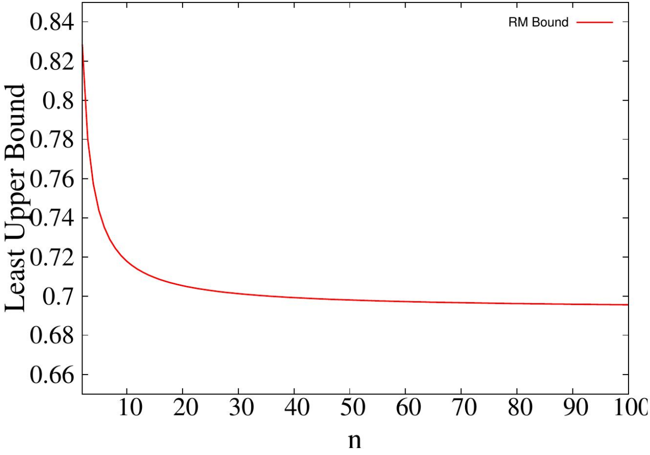
Theorem

[Liu and Layland] A set of n independent, preemptable periodic tasks with relative deadlines equal to their respective periods can be scheduled on a processor according to the RM algorithm if its total utilization U is at most $n(2^{\frac{1}{n}} - 1)$. In other words,

$$U_{lub}(RM, n) = n(2^{\frac{1}{n}} - 1) \geq 0.693.$$

n	$U_{lub}(RM, n)$	n	$U_{lub}(RM, n)$
2	0.828	3	0.779
4	0.756	5	0.743
6	0.734	7	0.728
8	0.724	9	0.720
10	0.717	∞	$0.693 = ln2$

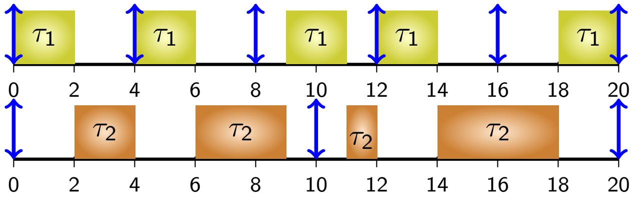
Least Upper Bound



Earliest-Deadline-First (EDF) Scheduling

At any moment, the system executes the job with the **earliest absolute deadline** among the jobs in the ready queue.

Example Schedule: $\tau_1 = (2, 4, 4)$, $\tau_2 = (5, 10, 10)$



Optimality and Schedulability of EDF

Theorem

Liu and Layland: A task set **T** of independent, preemptable, periodic tasks with relative deadlines equal to their periods can be feasibly scheduled (under EDF) on one processor if and only if its total utilization U is at most one.

Note: EDF is optimal for timing satisfactions on uniprocessor systems.

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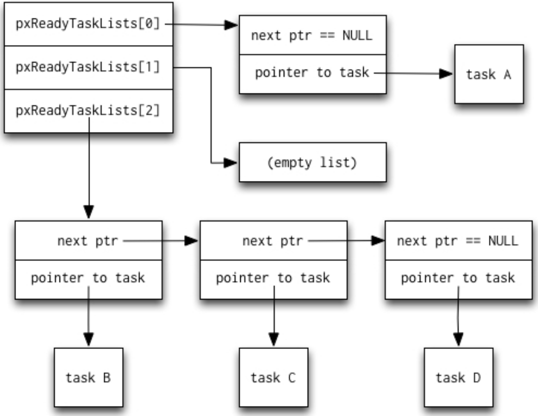
Lists in FreeRTOS

Scheduling in FreeRTOS

Task Priority and Ready List

- An array of task lists
  - static xList pxReadyTasksLists[configMAX_PRIORITIES];
    /* Prioritised ready tasks. */



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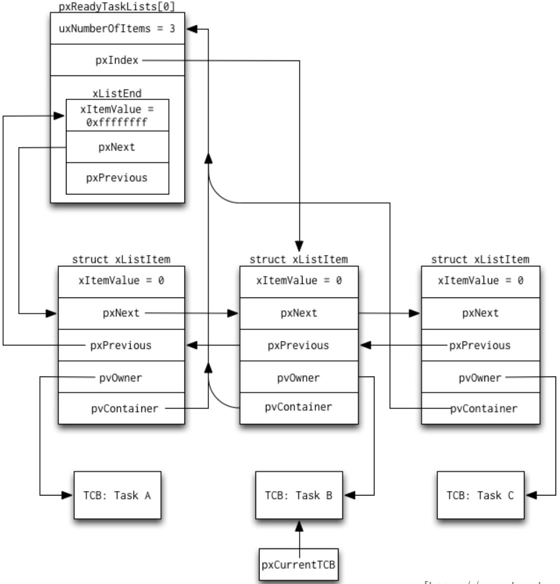
Overview of Ready Task Lists



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Lists in FreeRTOS (list.c)

- xListItem is a data structure for an element in double linked lists
- void vListInsertEnd(xList *pxList, xListItem *pxNewListItem)
  - insert an item pxNewListItem to the end of the list pxList
- void vListInsert(xList *pxList, xListItem *pxNewListItem)
  - insert an item pxNewListItem to the list pxList in a sorted (increasing) order
- void vListRemove(xListItem *pxItemToRemove)
  - remove the item pxItemToRemove from its associated list

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xPortStartScheduler() and vPortStartFirstTask()

- The implementation of xPortStartScheduler() is hardware dependent
  - Start the timer that generates the tick Interrupt Service Routine (ISR)
  - This function does not return until an executing task calls vTaskEndScheduler()
  - At least one task should be created via a call to xTaskCreate() before calling vTaskStartScheduler()
  - The idle task is created automatically
  - Run the first task by running vPortStartFirstTask().
- The implementation of xPortStartFirstTask() is also hardware dependent
  - Locate the stack of the first task
  - Enable the interrupts (as they were disabled)
  - Run from the pointer of the stack

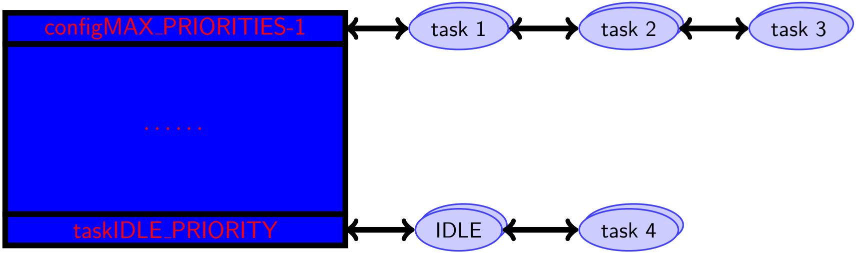
Ready Queue and Scheduling

- A ready queue maintains the TCB pointers of the tasks that are ready to be executed.
- The scheduler then selects the highest-priority job (task instance) in the ready queue for execution
- (Static-priority) fixed-priority scheduling
  - FreeRTOS uses fixed-priority (static-priority) scheduling
  - A task has a default priority value, defined when the task is created by using xTaskCreate()
  - All the instances of the task will then use the same priority for executing
  - If there are multiple task instances in the ready queue with the same priority, they share the processor and FreeRTOS uses a shared scheme to run these tasks

Ready Queue in FreeRTOS

- FreeRTOS uses multiple ready lists: one at each priority level.

```
#define prvAddTaskToReadyQueue( pxTCB ) \
if( ( pxTCB )->uxPriority > uxTopReadyPriority ) \
{ \
uxTopReadyPriority = ( pxTCB )->uxPriority; \
} \
vListInsertEnd( ( xList * ) &( pxReadyTasksLists[ ( pxTCB )->uxPriority ] ), &( ( pxTCB )->xGenericListItem ) )
```



Context Switching

- What is a context switch
  - The computing process of storing and restoring state of a CPU
  - Not for free
- When to switch
  - Multitasking
  - Interrupt handling
  - User and kernel mode change

Scheduler (in Context Switch - vTaskSwitchContext())

- System periodic tick interrupt calls vTaskSwitchContext()
- vTaskSwitchContext() function
  - Selects the task with the highest priority in the ready list
    - uxTopReadyPriority $\geq$ the highest priority in the ready list
  - pxCurrentTCB holds a pointer to the TCB of the selected task
  - Returns the hardware-dependent code that starts running that task

```
...
/* Find the highest priority queue that contains ready tasks. */
while( listLIST_IS_EMPTY( &( pxReadyTasksLists[ uxTopReadyPriority ] ) ) )
{
  configASSERT( uxTopReadyPriority );
  --uxTopReadyPriority;
}
/* listGET_OWNER_OF_NEXT_ENTRY walks through the list, so the tasks of
the same priority get an equal share of the processor time. */
...

listGET_OWNER_OF_NEXT_ENTRY( pxCurrentTCB, &( pxReadyTasksLists
[ uxTopReadyPriority ] ) );
...
```

[http://aosabook.org/en/freertos.html]

Other Misc

- vTaskPrioritySet(pxTask, uxNewPriority): set the priority of a task
  - It may cause a context switch
- uxTaskPriorityGet(pxTask) : get the priority of a task
- vDeleteTask(pxTaskToDelete): delete a task
  - The task is just removed from the ready queue, blocked queue after the call. The memory recycling is done by the idle task.
- vTaskIncrementTick(void)
  - Called by the portable layer each time a tick interrupt occurs
  - Increments the tick
  - Checks to see if the new tick value will cause any tasks to be unblocked

Summary: Task Management Functions

Creation

- xTaskCreate
- vTaskDelete

Control

- vTaskDelay
- vTaskDelayUntil
- uxTaskPriorityGet
- vTaskPrioritySet
- vTaskSuspend
- vTaskResume
- xTaskResumeFromISR

Utilities

- xTaskGetTickCount
- uxTaskGetNumberOfTasks
- vTaskList
- vTaskGetRunTimeStats
- vTaskStartTrace
- ulTaskEndTrace
- uxTaskGetStackHighWaterMark
- vTaskSetApplicationTaskTag
- xTaskGetApplicationTaskTag
- xTaskCallApplicationTaskHook

States of A Task