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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Scheduling in FreeRTOS
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** $\tau_i$:
  - A job is released exactly and periodically by a period $T_i$
  - A phase $\phi_i$ indicates when the first job is released
  - A relative deadline $D_i$ for each job from task $\tau_i$
  - $(\phi_i, C_i, T_i, D_i)$ is the specification of periodic task $\tau_i$, where $C_i$ is the worst-case execution time.
- **Sporadic Task** $\tau_i$:
  - $T_i$ is the minimal time between any two consecutive job releases
  - A relative deadline $D_i$ for each job from task $\tau_i$
  - $(C_i, T_i, D_i)$ is the specification of sporadic task $\tau_i$, 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 \( \tau_1 \) and \( \tau_2 \). 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:
  \[ U(T) := \sum_{\tau_i \in T} \frac{C_i}{T_i} \]

A task system \( T \) 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, \( U(T) \) is an upper bound on utilization for \( A \), denoted \( U_{ub}(T, A) \).

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

\[ U_{lub}(A) = \min_T U_{ub}(T, A) \]
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 \( n\left(2^{\frac{1}{n}} - 1\right)\). In other words,

\[
U_{lub}(RM, n) = n\left(2^{\frac{1}{n}} - 1\right) \geq 0.693.
\]

<table>
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<th>( n )</th>
<th>( U_{lub}(RM, n) )</th>
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<td>6</td>
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<td>8</td>
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<tr>
<td>10</td>
<td>0.717</td>
<td>( \infty )</td>
<td>0.693 = ln2</td>
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</table>
Least Upper Bound

RM Bound

Least Upper Bound

n

0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
0.82
0.84
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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Scheduling Approaches and Analysis

Lists in FreeRTOS

Scheduling in FreeRTOS
Task Priority and Ready List

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

```c
pxReadyTaskLists[0]
```

```
uxNumberOfItems = 3
```

```
pxIndex
```

```
xListEnd
```

```
xItemValue = 0xffffffff
```

```
pxNext
```

```
xPrevious
```

```
pvOwner
```

```
pvContainer
```

```
TCB: Task A
```

```
structure xListItem
```

```
xItemValue = 0
```

```
pxNext
```

```
xPrevious
```

```
pvOwner
```

```
pvContainer
```

```
TCB: Task B
```

```
pxCurrentTCB
```

```
structure xListItem
```

```
xItemValue = 0
```

```
pxNext
```

```
xPrevious
```

```
pvOwner
```

```
pvContainer
```

```
TCB: Task C
```

```
structure xListItem
```

```
xItemValue = 0
```

```
pxNext
```

```
xPrevious
```

```
pvOwner
```

```
pvContainer
```

[http://aosabook.org/en/freertos.html]
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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Scheduling in FreeRTOS
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.

```c
#define prvAddTaskToReadyQueue( pxTCB )
2 if( ( pxTCB )->uxPriority > uxTopReadyPriority )
3 { 
4 uxTopReadyPriority = ( pxTCB )->uxPriority;
5 } 
6 vListInsertEnd( ( xList * ) &pxReadyTasksLists[ ( pxTCB ← )→uxPriority ] ), & ( pxTCB )→xGenericListItem )
```

![Diagram showing the ready queue with tasks and priorities]
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 ≥ 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

```c
/* 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

- \texttt{vTaskPrioritySet(pxTask, uxNewPriority)}: set the priority of a task
  - It may cause a context switch
- \texttt{uxTaskPriorityGet(pxTask)}: get the priority of a task
- \texttt{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.
- \texttt{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

Create Task

- xTaskCreate

Suspended

- vTaskSuspend

Ready

- vTaskResume
- vTaskSuspend
- vTaskIncrementTick

Running

- vTaskDelay
- vTaskDelayUntil

Blocked

- vTaskDelay

Deleted