CprE 488 – Embedded Systems Design

Lecture 5 – Embedded Operating Systems

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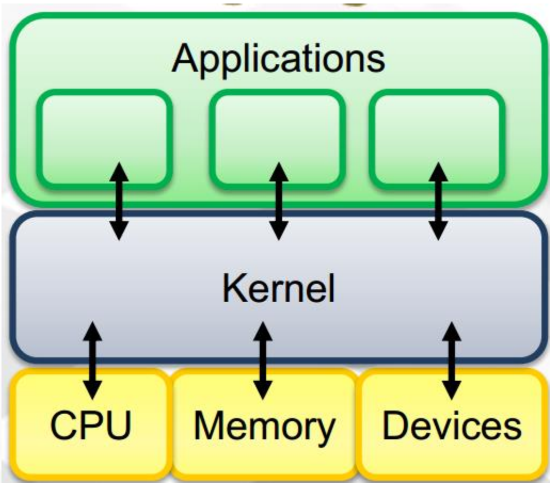
...the Linux philosophy is "laugh in the face of danger". Oops. Wrong one. "Do it yourself". That's it. – Linux Torvalds

Motivation

- We have already run into some limitations of the standalone process model:
  - Single application, growing in complexity quickly
  - Lots of polling loops, deep nested 'if' statements
- We could continue in this direction, but a modern Operating System (OS) provides streamlined mechanisms for:
  - Preemptive multitasking
  - Device drivers
  - Memory management
  - File systems



- It would be insane to try to cover all the major issues involved in embedded OS in a single lecture

This Week's Topic

- Embedded Operating System features
  - Processes and scheduling
    - Context switching
    - Scheduler policies
    - Real-Time Operating Systems (RTOS)
  - Atomic operations
  - Inter-processes communication
  - Virtual memory
  - Examples along the way:
    - Linux, POSIX, freeRTOS.org
    - ARM architecture support
- Reading: Wolf chapter 6, 3.5

Reactive Systems

- Respond to external events:
  - Engine controller
  - Seat belt monitor
- Requires real-time response:
  - System architecture
  - Program implementation
- May require a chain reaction among multiple processors

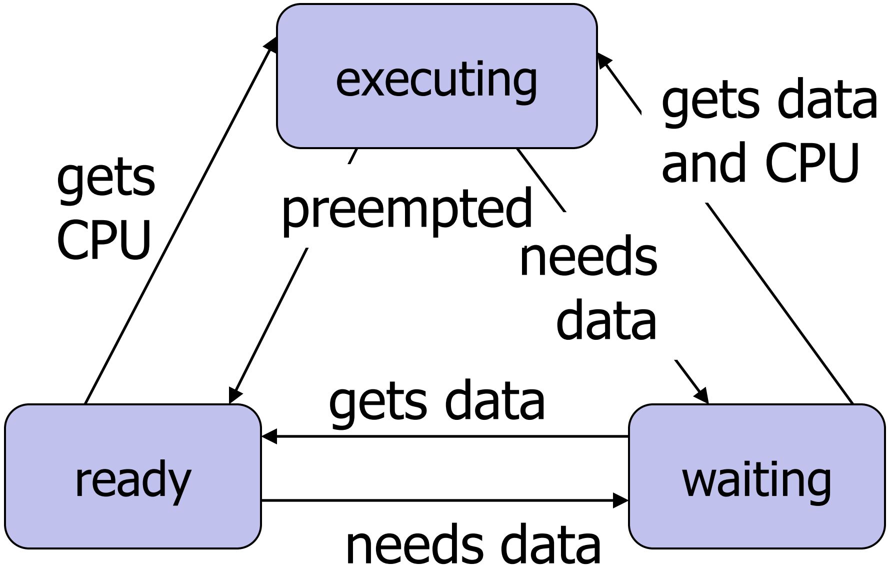
Tasks and Processes

- A task is a functional description of a connected set of operations
- Task can also mean a collection of processes

- A process is a unique execution of a program
  - Several copies of a program may run simultaneously or at different times
- A process has its own state:
  - registers
  - memory
- The operating system manages processes

Process State

- A process can be in one of three states:
  - executing on the CPU
  - ready to run
  - waiting for data

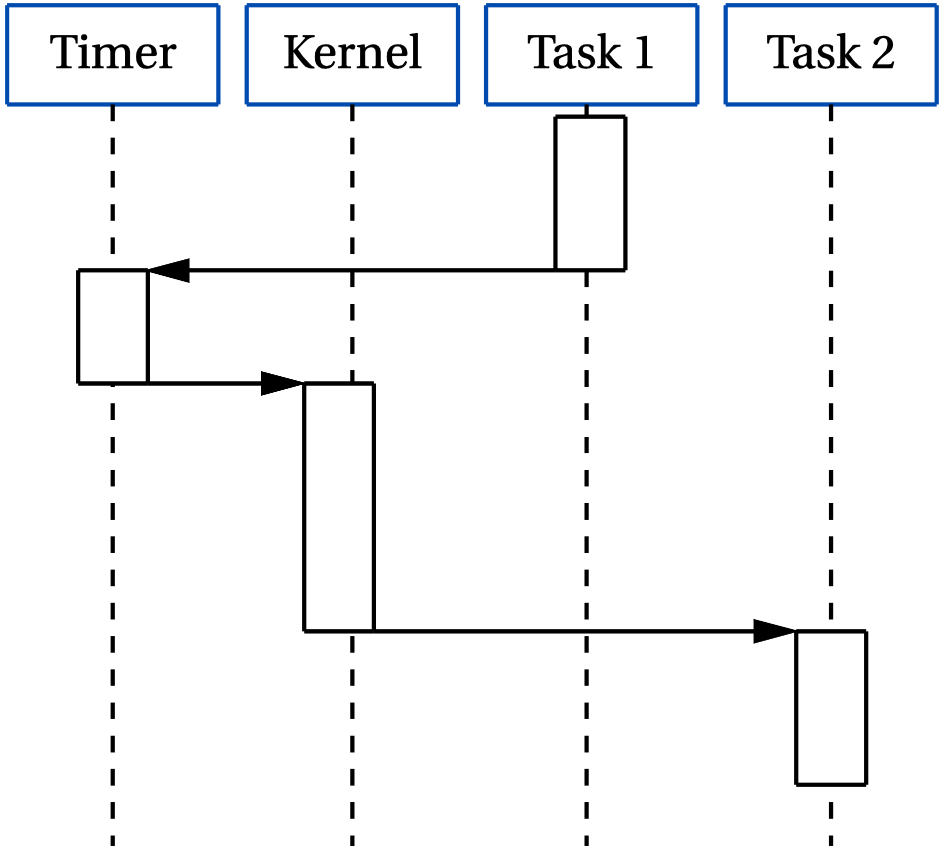


Embedded vs. General-Purpose Scheduling

- Workstations try to avoid starving processes of CPU access
  - Fairness == access to CPU
- Embedded systems must meet deadlines
  - Low-priority processes may not run for a long time

Preemptive Scheduling

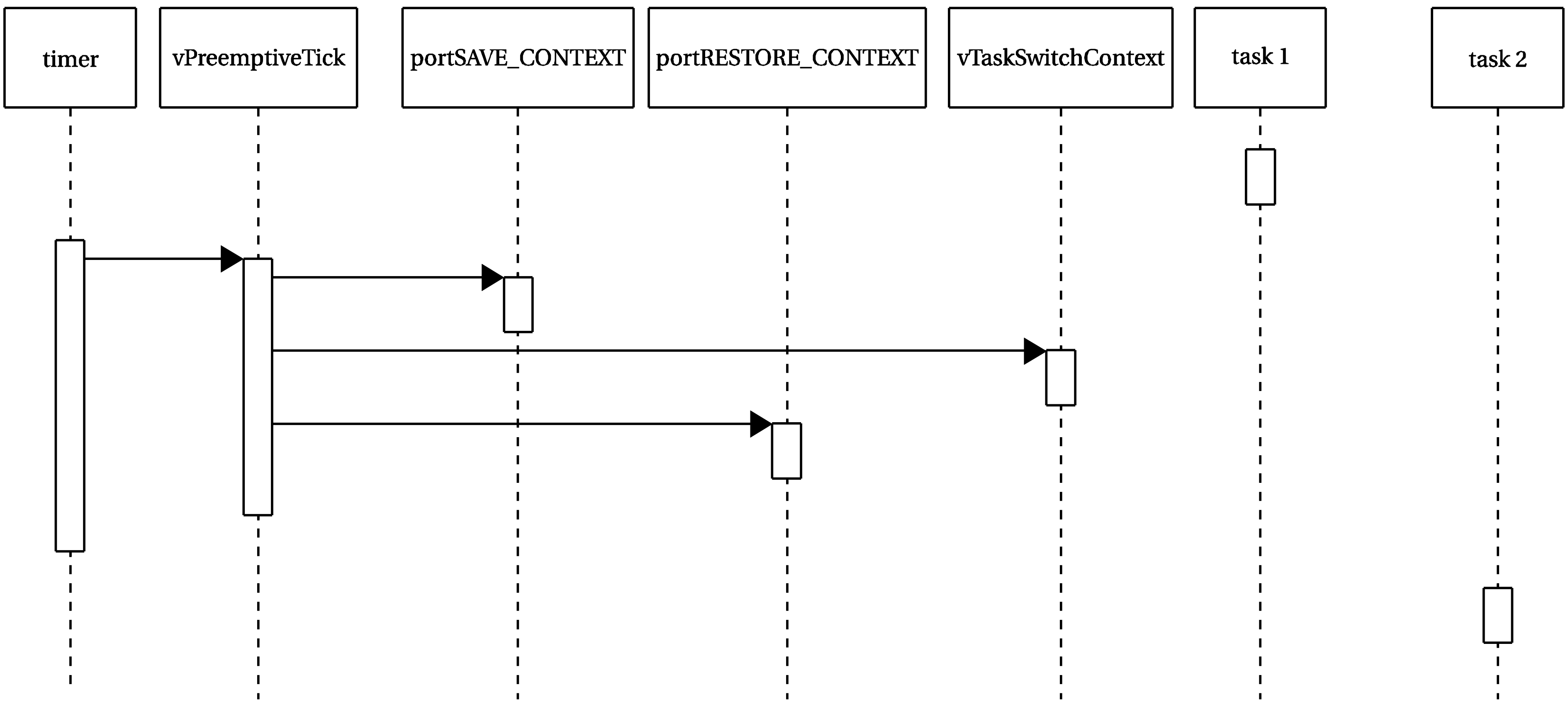
- Timer interrupt gives CPU to kernel
  - Time quantum is smallest increment of CPU scheduling time
- Kernel decides what task runs next
- Kernel performs context switch to new context



Context Switching

- Set of registers that define a process's state is its context
  - Stored in a record
- Context switch moves the CPU from one process's context to another
- Context switching code is usually assembly code
  - Restoring context is particularly tricky

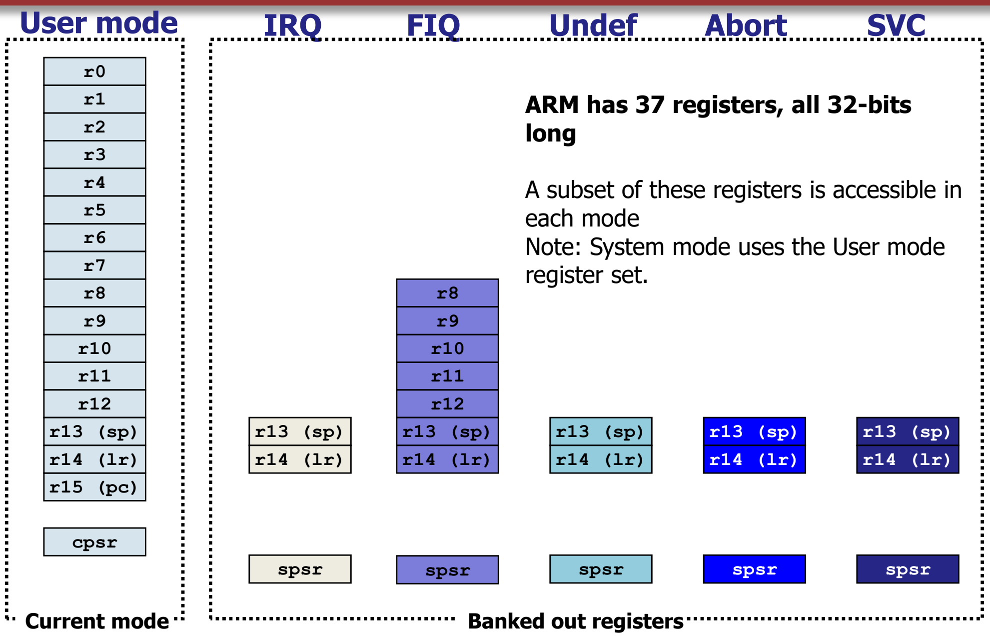
freeRTOS.org Context Switch



freeRTOS.org Timer Handler

```
void vPreemptiveTick( void ) {
   /* Save the context of the current task. */
   portSAVE_CONTEXT();
   /* Increment the tick count - this may wake a task. */
   vTaskIncrementTick();
   /* Find the highest priority task that is ready to run. */
   vTaskSwitchContext();
   /* End the interrupt in the AIC. */
   AT91C_BASE_AIC->AIC_EOICR = AT91C_BASE_PITC->PITC_PIVR;
   portRESTORE_CONTEXT();
}
```

ARM Context Switch




```
STM      sp, {R0-lr}^         ; Dump user registers above R13.
MRS      R0, SPSR             ; Pick up the user status
STMDB    sp, {R0, lr}         ; and dump with return address below.
LDR      sp, [R12], #4        ; Load next process info pointer.
CMP      sp, #0               ; If it is zero, it is invalid
LDMDBNE  sp, {R0, lr}         ; Pick up status and return address.
MSRNE    SPSR_cxsf, R0        ; Restore the status.
LDMNE    sp, {R0-lr}^         ; Get the rest of the registers
NOP                           ; and return and restore CPSR.
SUBSNE pc, lr, #4             ; Insert "no next process code" here.
```

Real-Time Systems

- What is a real-time system?
- Which of the following is real-time?
  - A program that processes 100 video frames per second?
  - A program that that process 1 video frame per 10 seconds?

- A better name
  - "Get things done on time" Systems
- They are about getting things done **on time**, not getting things done fast

Real-Time Systems: Key Terms/Concepts

- Task
  - Cost: time for processor to complete task without interruptions
  - Release time: when task is ready to be run
  - Deadline: time by which task needs to completed
  - Period: time between release times
- Task-set schedule: order in which tasks are allocated the CPU
- Scheduling policy (algorithm): means by which (i.e. rules followed) to create a task-set schedule

Scheduling: Period vs Aperiodic

- Periodic process: executes on every period
- Aperiodic process: executes on demand
- Analyzing aperiodic process sets is harder---must consider worst-case combinations of process activations

Timing Requirements on Processes

- Period: interval between process activations
- Initiation interval: reciprocal of period
- Initiation time: time at which process becomes ready
- Deadline: time at which process must finish

- What happens if a process doesn't finish by its deadline?
  - Hard deadline: system fails if missed
  - Soft deadline: user may notice, but system doesn't necessarily fail

Priority-driven Scheduling

- Each process has a priority
- CPU goes to highest-priority process that is ready
- Priorities determine scheduling policy:
  - Fixed (Static) priority
  - Time-varying (Dynamic) priorities

Priority-driven Scheduling Example

- Rules:
  - Each process has a fixed priority (1 highest)
  - Highest-priority ready process gets CPU
  - Process will not self stop (i.e. block) until done or is preempted by a high priority process
- Processes
  - P1: priority 1, execution time 10, release time 15
  - P2: priority 2, execution time 30, release time 0
  - P3: priority 3, execution time 20, release time 18

Priority-driven Scheduling Example (cont.)

P1: priority 1, execution time 10, release time 15

P2: priority 2, execution time 30, release time 0

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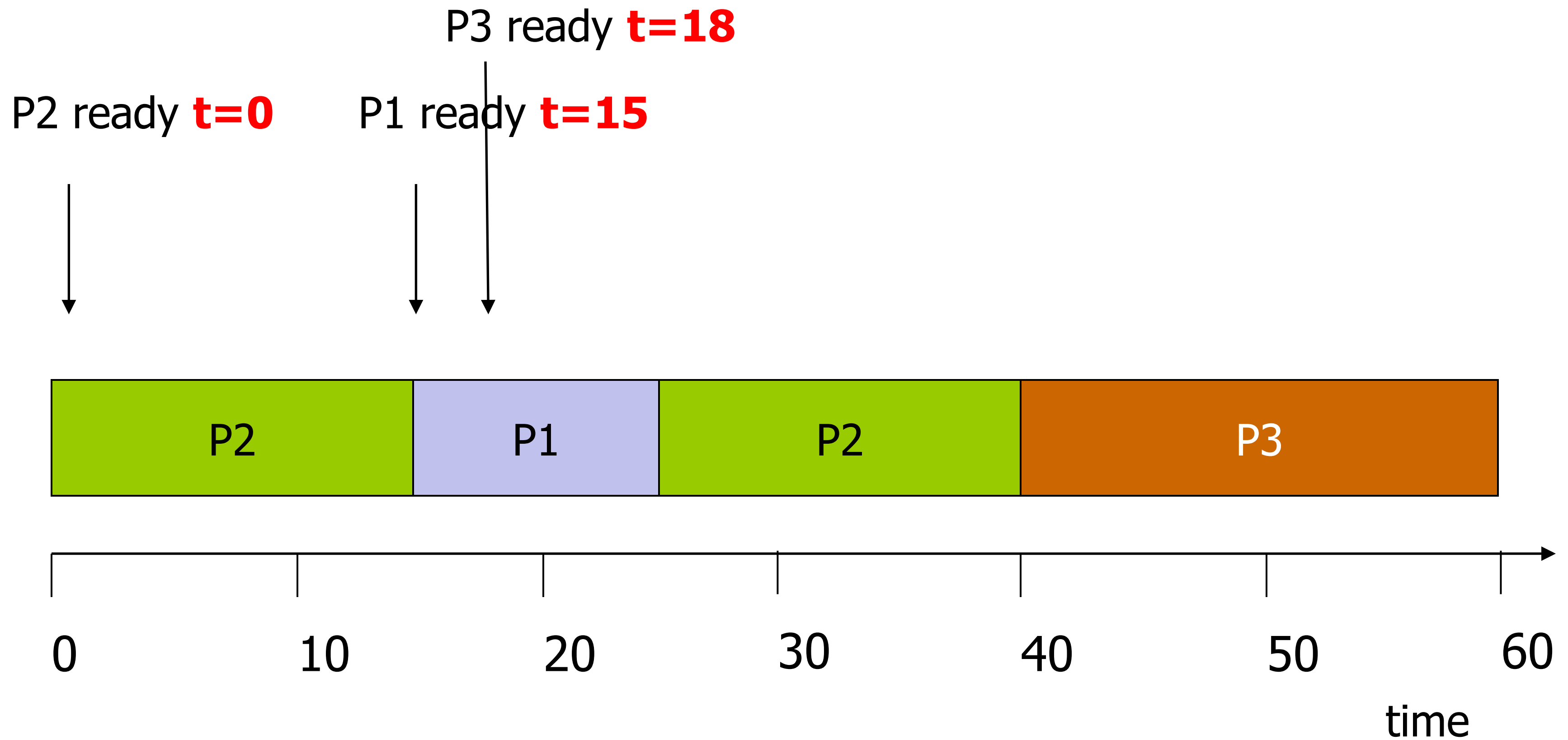

The Scheduling Problem

- Can we meet all deadlines?
  - Must be able to meet deadlines in all cases
- How much CPU horsepower do we need to meet our deadlines?

CPU Utilization

- T1: PPM update
  - Cost = 1 ms
  - Deadline = 3 ms
  - Period = 3 ms
- What is the CPU utilization of T1?

$$\boldsymbol{Task\_CPU\_Utilization = \frac{Task\_Cost}{Task\_Period}}$$

Scheduling Example (no preemption)

- T1: PPM update
  - Cost = 1 ms
  - Deadline = 3 ms
  - Period = 3 ms
- T2: Video processing
  - Cost = 1 ms
  - Deadline = 6 ms
  - Period = 6 ms
- T3: Check Sensors
  - Cost = 6 ms
  - Deadline = 12 ms
  - Period = 12 ms

- What rules to follow for scheduling
  - Let's say that the more often a Task needs to run, the higher the priority (allow NO preemption)
  - Is there a release pattern that can cause a task to miss a deadline?

Scheduling Example (no preemption)

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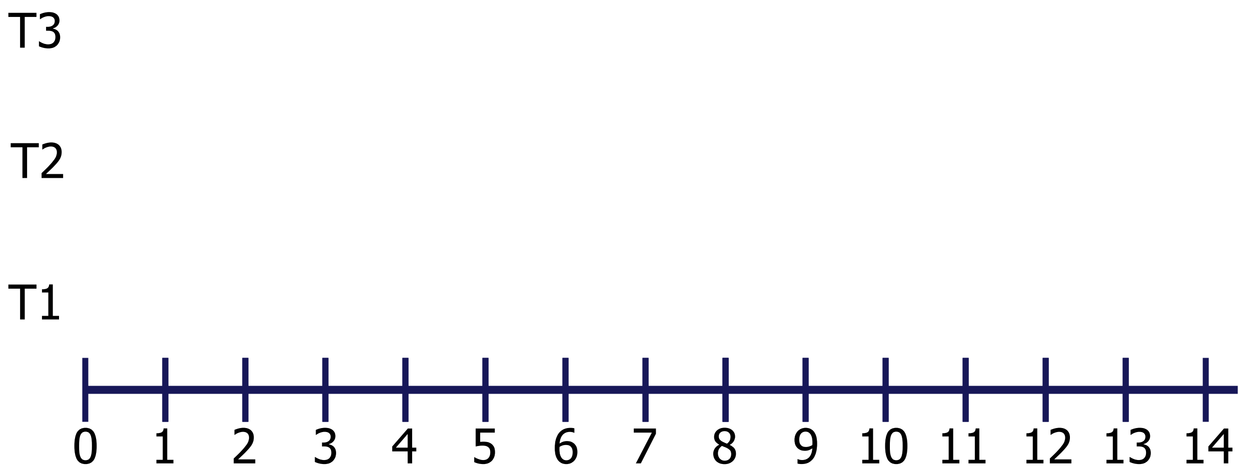

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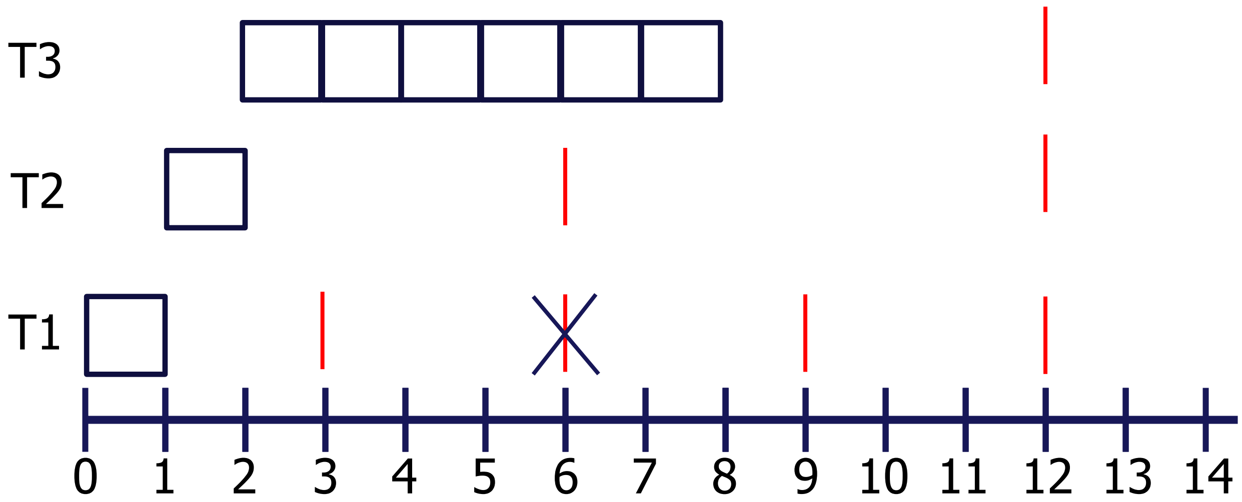

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Scheduling Example (with preemption)

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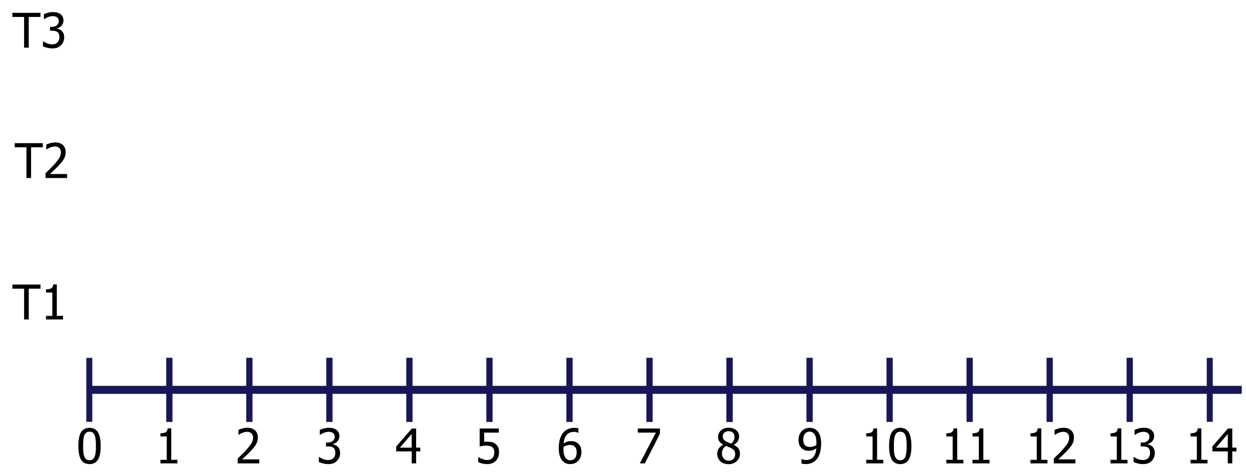

- What rules to follow for scheduling
  - Let's say that the more often a task needs to run, the higher the priority (allow preemption)
  - Draw out schedule and see if we miss a deadline

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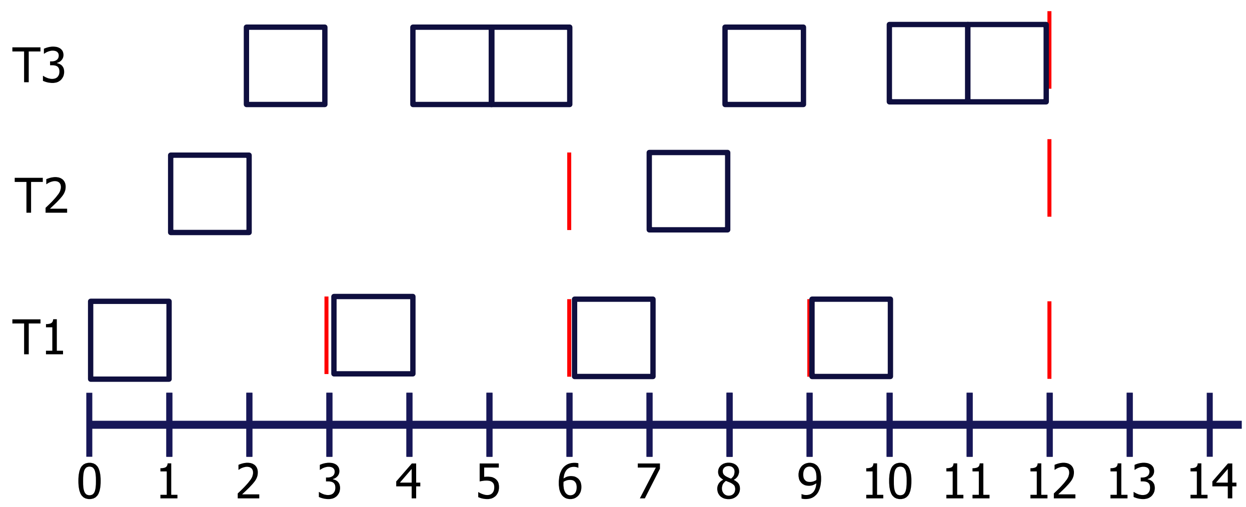

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  - Let's say that the more often a task needs to run, the higher the priority (allow preemption)
  - Draw out schedule and see if we miss a deadline

Scheduling Metrics

- How do we evaluate a scheduling policy:
  - Ability to satisfy all deadlines (Feasibility)
  - Often a trade-off between:
    - Task set CPU utilization (i.e., time doing "useful" work)
    - Scheduling overhead (time to make scheduling decision)

Scheduling Metrics: Feasibility

- For previous preemption example
  - How long do we have to draw out the schedule before we know we will never miss a deadline?
  - What if we had 3 tasks with period 3ms, 4ms, and 7ms?
  - For a general task set, how long do we have to draw out the schedule?

Scheduling Metrics: Feasibility

- For previous preemption example
  - How long do we have to draw out the schedule before we know we will never miss a deadline?
  - What if we had 3 tasks with period 3ms, 4ms, and 7ms? **Answer: 84 ms**
  - For a general task set, how long do we have to draw out the schedule? **Answer: Lowest common multiple** of Task periods (a task set's ***Hyper Period***). This is the time it takes before all Tasks release times synchronize after time = 0

- Is there a better way to determine is feasible (i.e. schedule using a given policy)? Yes! **RMA / RMS**

Rate Monotonic Scheduling (RMS)

- RMS (Liu and Layland [1973]): widely-used, analyzable scheduling policy
- Analysis is known as Rate Monotonic Analysis (RMA)
  - All processes run on single CPU
  - Zero context switch time
  - No data dependencies between processes
  - Process execution time is constant
  - Process deadline is at end of its period
  - Highest-priority ready process runs
  - Processes with lower periods have higher priority

RMS Priorities

- RMS gives an **optimal** (fixed/static) priority assignment:
  - Shortest-period process gets highest priority
  - Priority inversely proportional to period
  - Break ties arbitrarily
- No fixed-priority scheme does better:
  - In other words, if RMS does not give you a feasible schedule, then no static priority assignment approach can

RMS CPU Utilization

- CPU utilization for a Task set of **n** tasks:

$$CPU\ Utilization\ of\ Task\ Set = \sum_{i=1}^{n}\left(\frac{Cost_i}{Period_i}\right) = \sum_{i=1}^{n}(CPU\_Utilization\_Task_i)$$

- **For RMS**: Independent of number of tasks in the set, RMS is guaranteed to give a feasible scheduled if CPU Utilization is less than 69%:
  - If the Task set Utilization <= 69%, then RMS is guaranteed to meet all deadlines
  - If Utilization > 69%, then must draw schedule for the Lowest Common Multiple (LCM) of the Task set periods.
  - Positive: Quick way to determine Feasibility
  - Negative: Gives up about 30% of CPU Utilization

Earliest-Deadline-First Scheduling

- EDF: dynamic priority scheduling scheme
  - Process closest to its deadline has highest priority
  - Must recalculate process priorities at every timer interrupt

- EDF <u>guaranteed</u> to give a feasible schedule, if a Task-set's CPU utilization is less than or equal to 100%

Scheduling Example (First try RMS)

- T1: PPM update
  - Cost = 1 ms
  - Deadline = 3 ms
  - Period = 3 ms
- T2: Video processing
  - Cost = 2 ms
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Task-set CPU Utilization: 4/12 + 6/12 + 2/12 = 12/12 = 100%

Hyper-Period = 12

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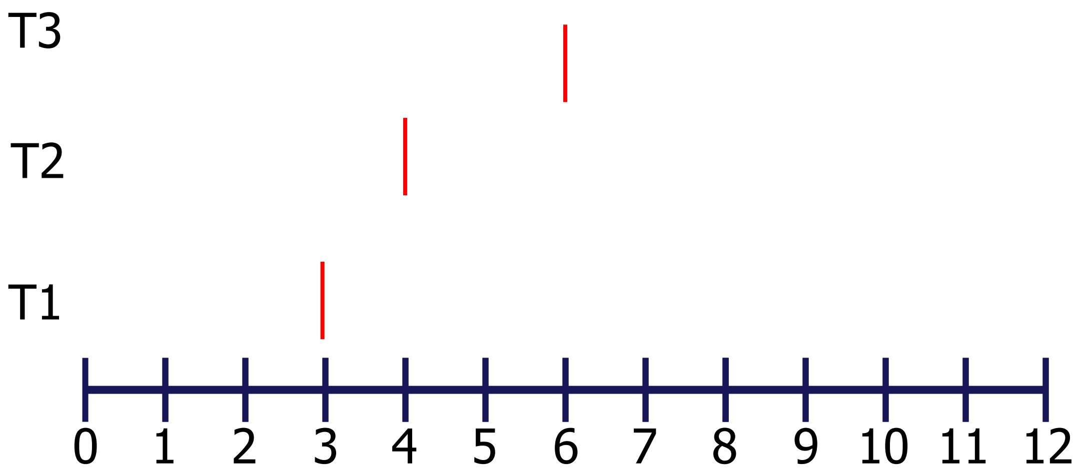

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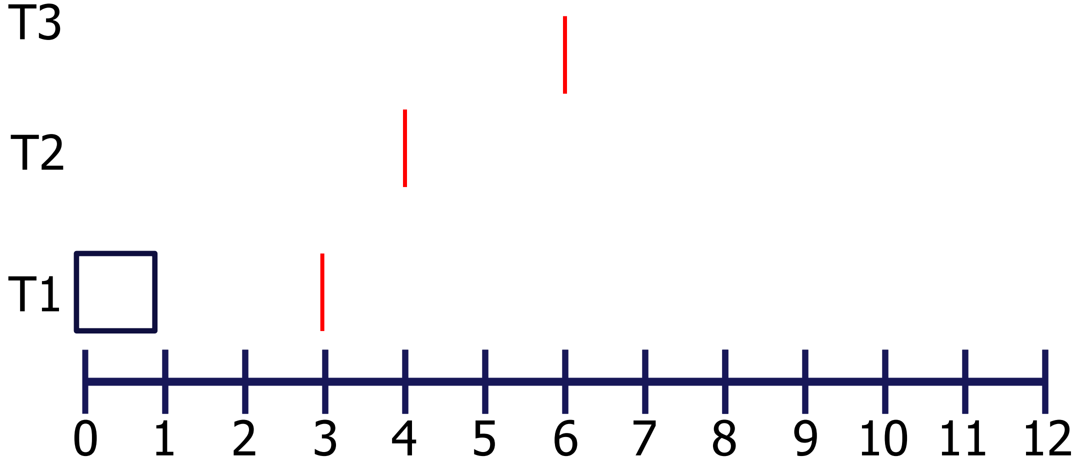

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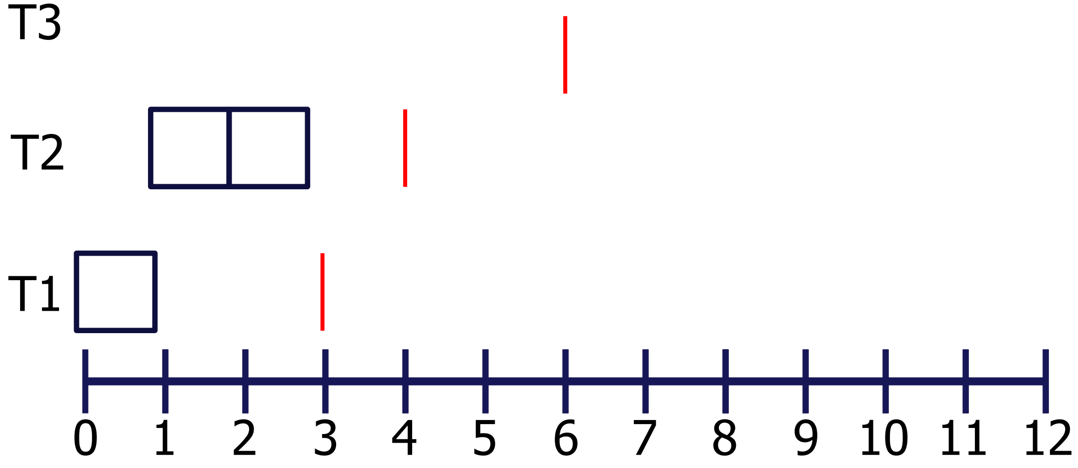

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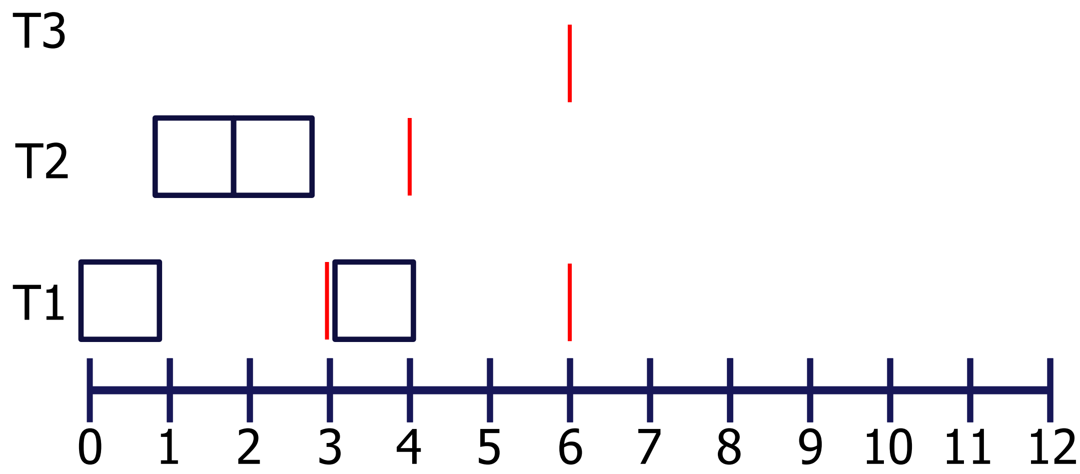

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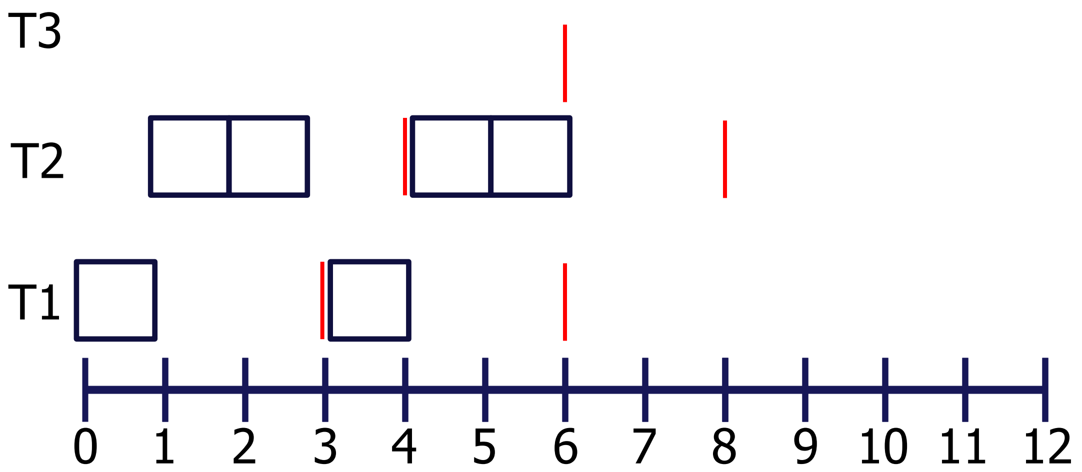

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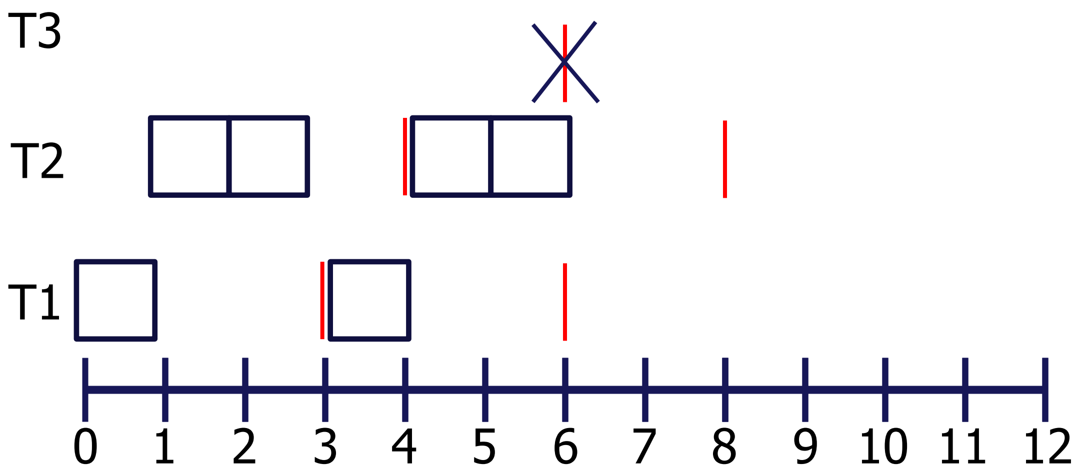

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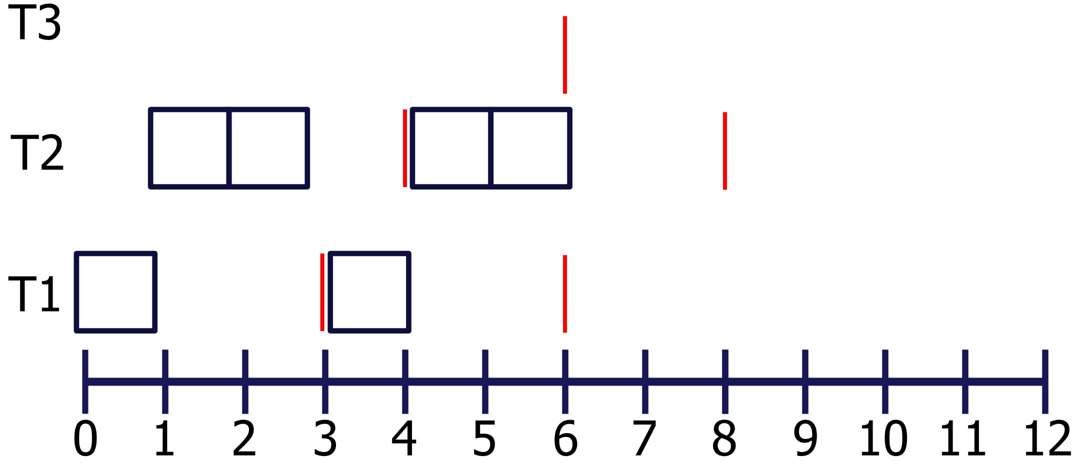

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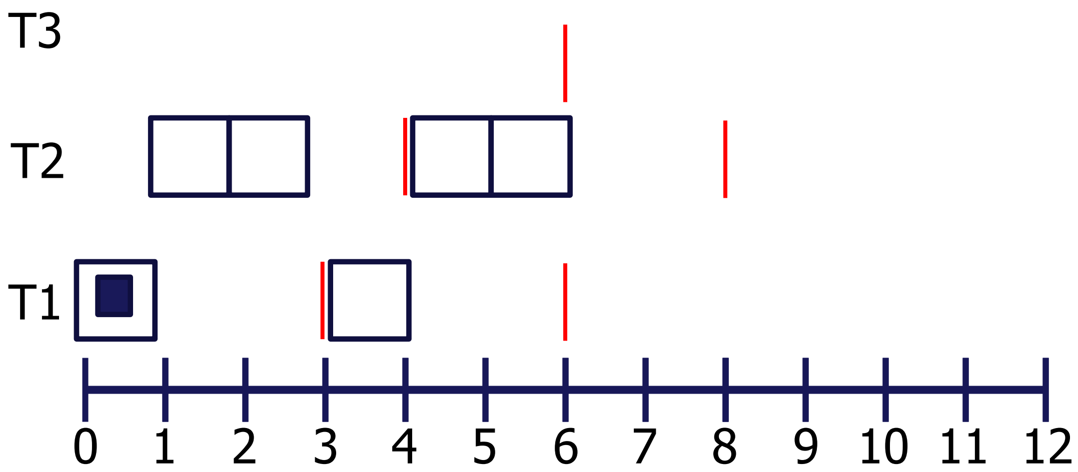

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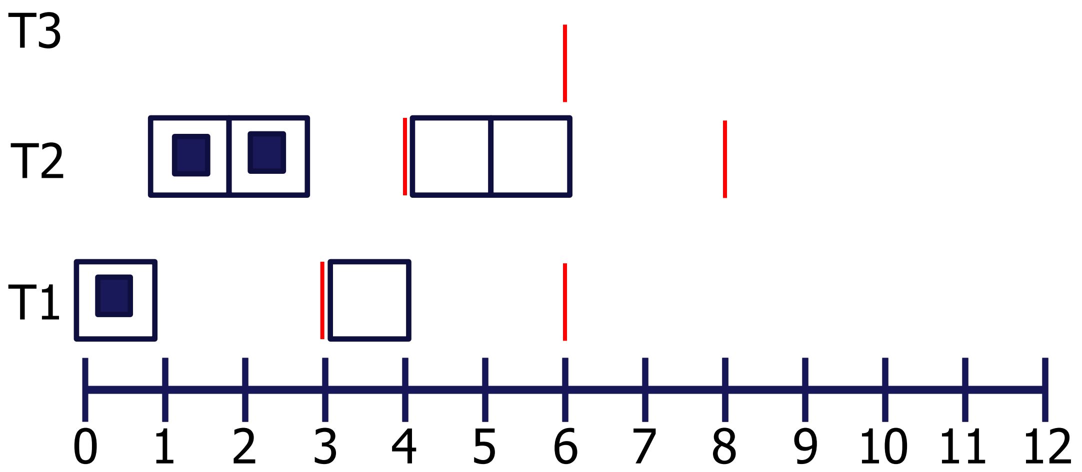

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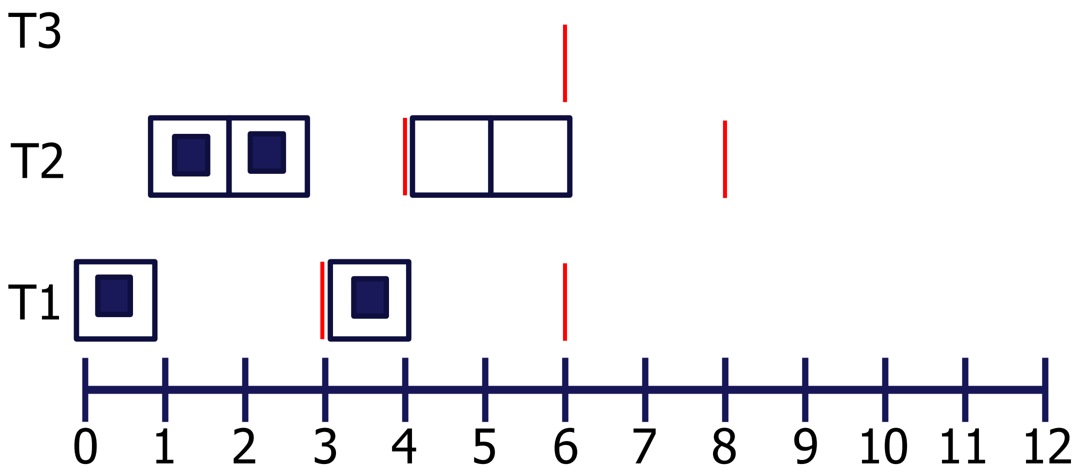

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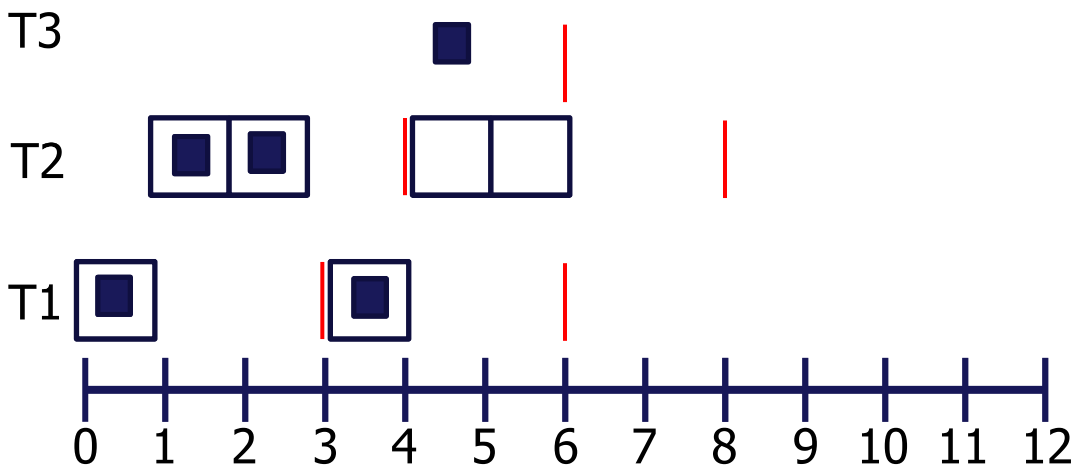

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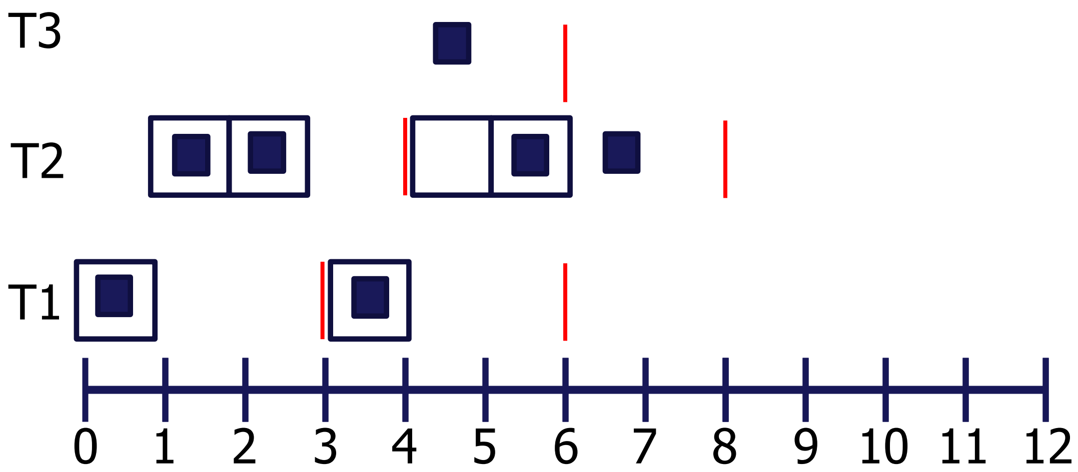

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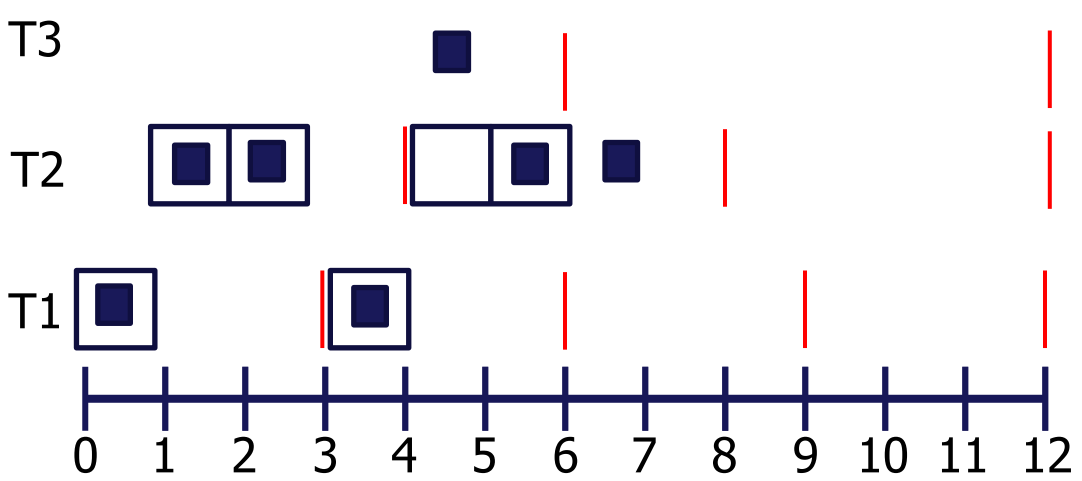

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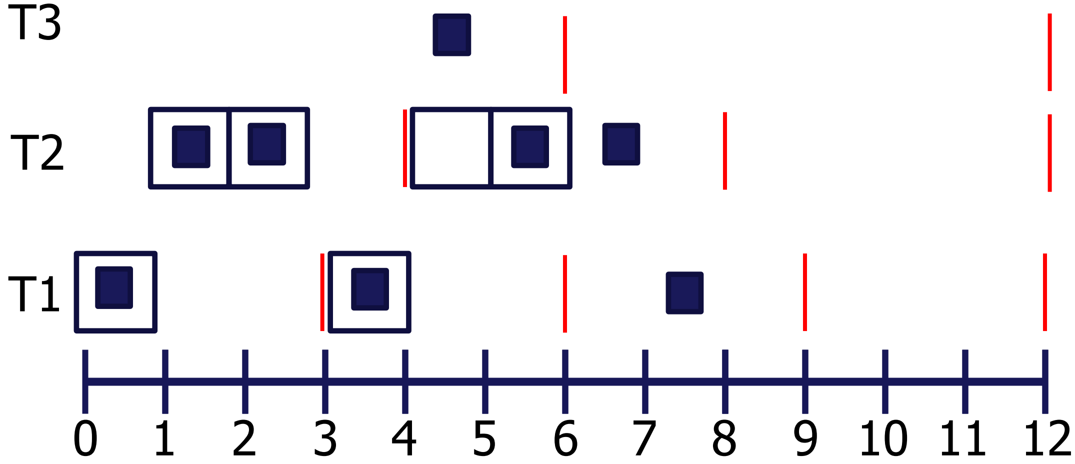
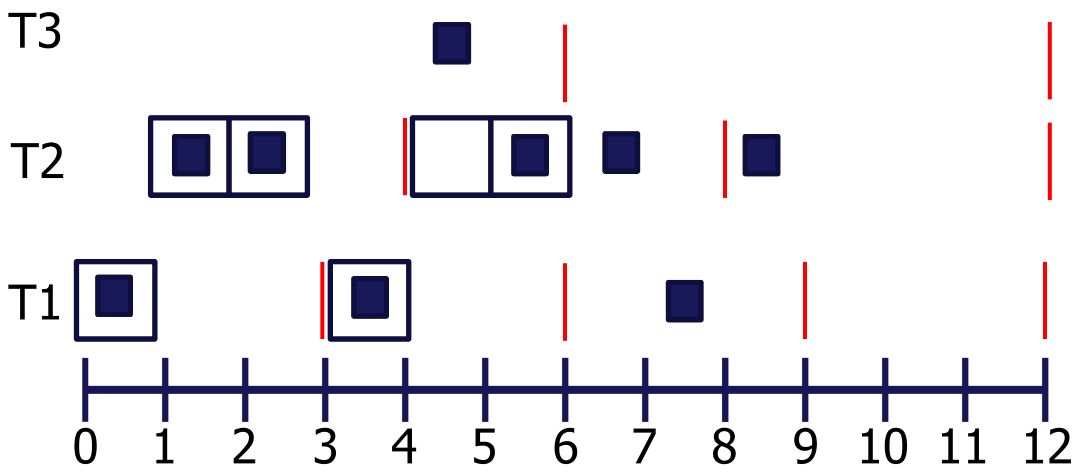


Task-set CPU Utilization: 4/12 + 6/12 + 2/12 = 12/12 = 100%

Hyper-Period = 12

Scheduling Example (Now try EDF)

- T1: PPM update
  - Cost = 1 ms
  - Deadline = 3 ms
  - Period = 3 ms
- T2: Video processing
  - Cost = 2 ms
  - Deadline = 4 ms
  - Period = 4 ms
- T3: Check Sensors
  - Cost = 1 ms
  - Deadline = 6 ms
  - Period = 6 ms



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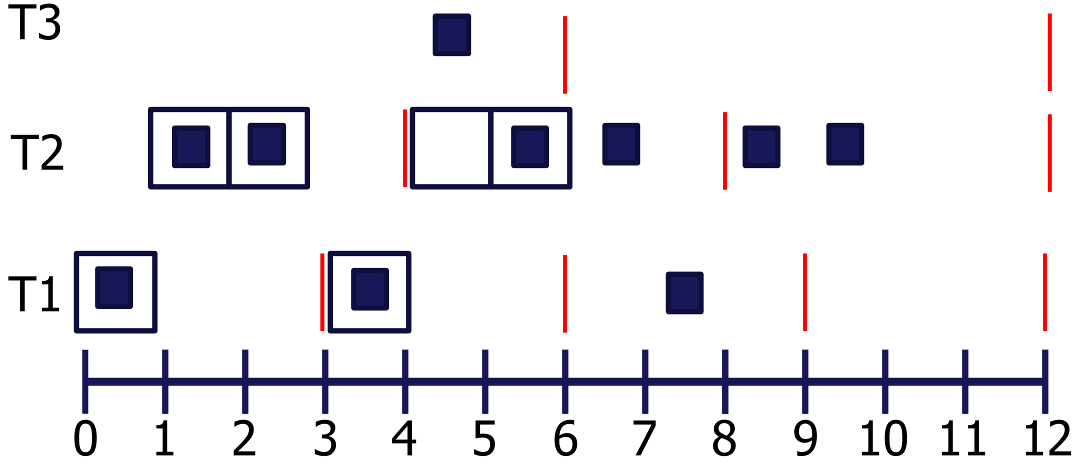

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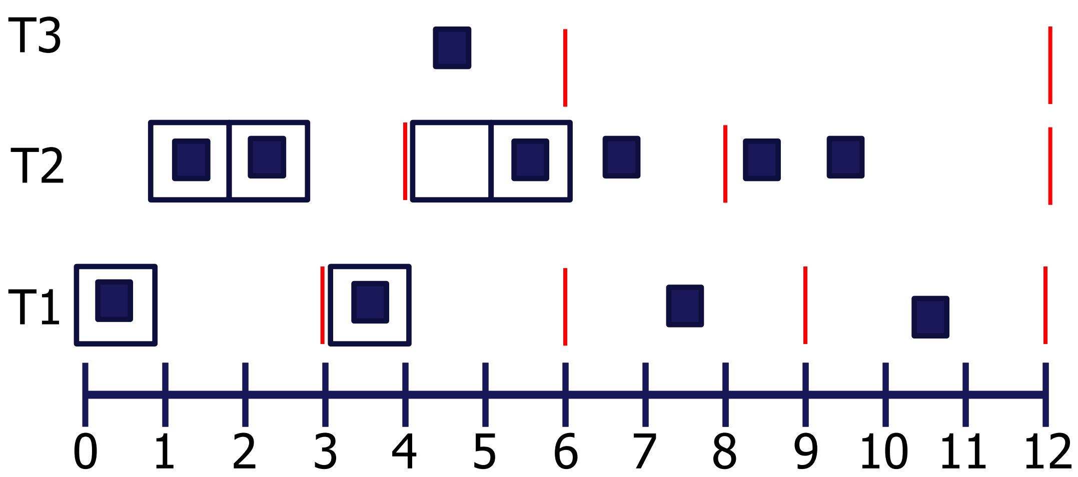

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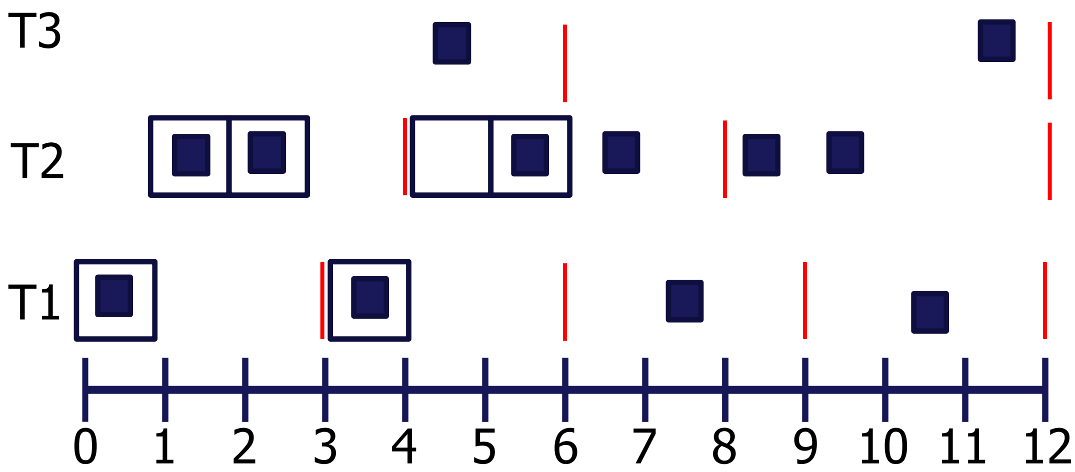

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Scheduling Metrics

- How do we evaluate a scheduling policy:
  - Ability to satisfy all deadlines (Feasibility)
  - Often a trade-off between:
    - Task set CPU utilization (i.e., time doing "useful" work)
    - Scheduling overhead (time to make scheduling decision)

EDF Implementation

- On each timer interrupt:
  - Compute time to deadline for each task
  - Choose process closest to deadline
- Generally considered too expensive to use in practice
  - EDF guarantees meeting all task deadlines if task set CPU utilization is less than or equal to 100%, but a major underlining assumption is that updating priorities at each timer interrupt take zero CPU time.
    - For fine grain timer ticks (i.e., short time between timer interrupts), the overhead for re-computing priorities can easily cost more CPU time than the task set!!
- **Note for RMS**: If task periods of a task set are "**Harmonic**" (i.e., period of each task is a multiple of each task with a smaller period), then RMS is **guaranteed** to schedule a task set with up to **100%** utilization

Scheduling Concerns

- **Task Context Switching Time**: Both EDF and RMS assume zero time for task context switching. In a real system one must be careful that indeed the time for context switching is MUCH smaller than the period of the tasks in the system. This can be a little tricky to account for in a real system.
  - Non-zero context switch time can push limits of a tight schedule
  - Hard to calculate effects---depends on order of context switches
  - In practice, OS context switch overhead is often small (hundreds of clock cycles) relative to many common task periods (10's ms – sec's)
    - Some microcontrollers (e.g. ARM), have special instructions, and hardware mechanisms to help keep context switch time small.
- What if your set of processes is not schedulable?
  - Change deadlines in requirements
  - Reduce execution times of processes
  - Get a faster CPU

Fixed Priority Concern: Priority Inversion

- **Priority inversion**: low-priority process keeps high-priority process from running. Thus the low-priority task indirectly acts as though it is a high-priority process.
  - This can happen if a low-priority process has a lock (control) of a resource that a higher priority process needs.
  - Can cause deadlock
- Example from Textbook, chapter 6
  - Assume three processes, with P1 highest priority, P2 next highest, and P3 lowest priority.
    - 1) P3 takes control of resource A (e.g. a Network card)
    - 2) P2 then preempts P3, while P3 still has control of resource A
    - 3) P1 preempts P2, and runs until it needs resource A, then blocks
    - 4) P2 run to completion, since P1 is no longer ready to run
    - 5) P3 runs until it releases control of resource A
    - 6) Now P1 can stop blocking on resource A and run

Solving Priority Inversion

- **Priority Inheritance**: Have process inherit the priority of the highest process that may ever need a given System resource, while using System resource.
  - Assume three processes, with P1 highest priority, P2 next highest, and P3 lowest priority. Now use Priority Inheritance.
    - 1) P3 takes control of resource A (e.g. a Network card)
      - Since P1 may need resource A, give P3 the priority level of P1
    - 2) P2 becomes ready, but will not preempt P3
    - 3) P3 finishes with resource A, and has it priority set back to its original level.
    - 4) P2 can now preempt P3, and P2 runs until
    - 3) P1 preempts P2, and P1 runs to completion
    - 4) P2 run to completion, assuming P1 does not restart
    - 5) P3 runs to completion, assuming P1 or P2 do not restart
  - Note: can still have deadlock occur.
- **Priority Ceilings** (summary of idea): Process can only enter a critical section of code (e.g. lock a resource), if no other higher priority process has locked a resource that it may need.
  - Solves deadlock issue: But a more complex protocol.

Acknowledgments

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