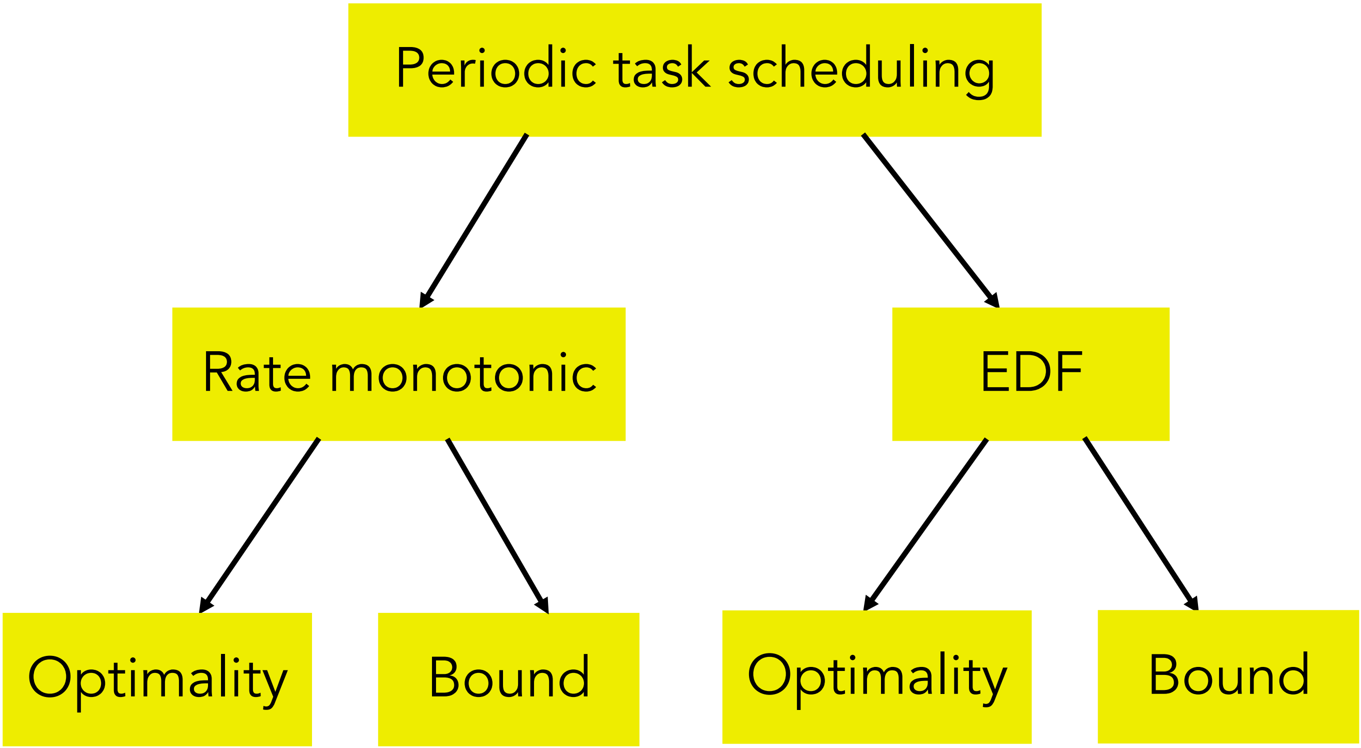
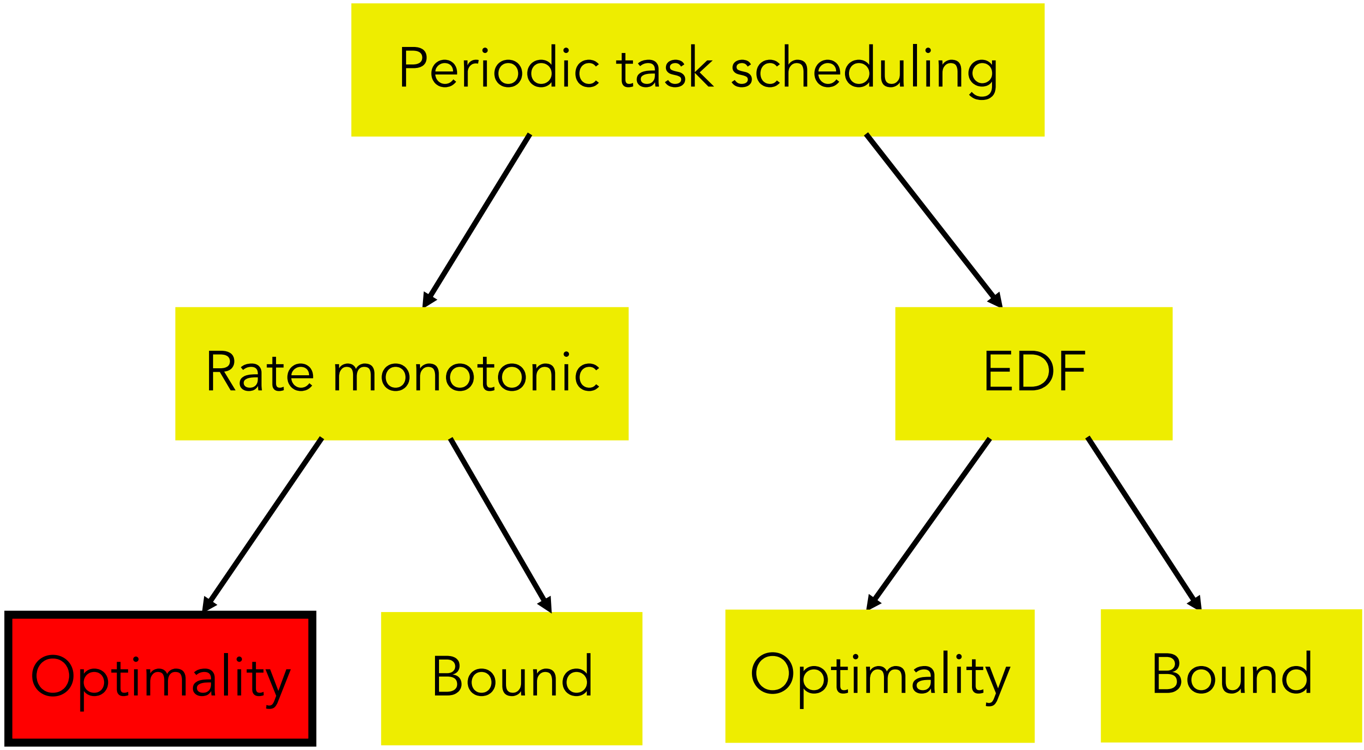
Periodic task scheduling

Optimality of rate monotonic scheduling (among static priority policies)
Utilization bound for EDF
Optimality of EDF (among dynamic priority policies)
Tick-driven scheduling (OS issues)

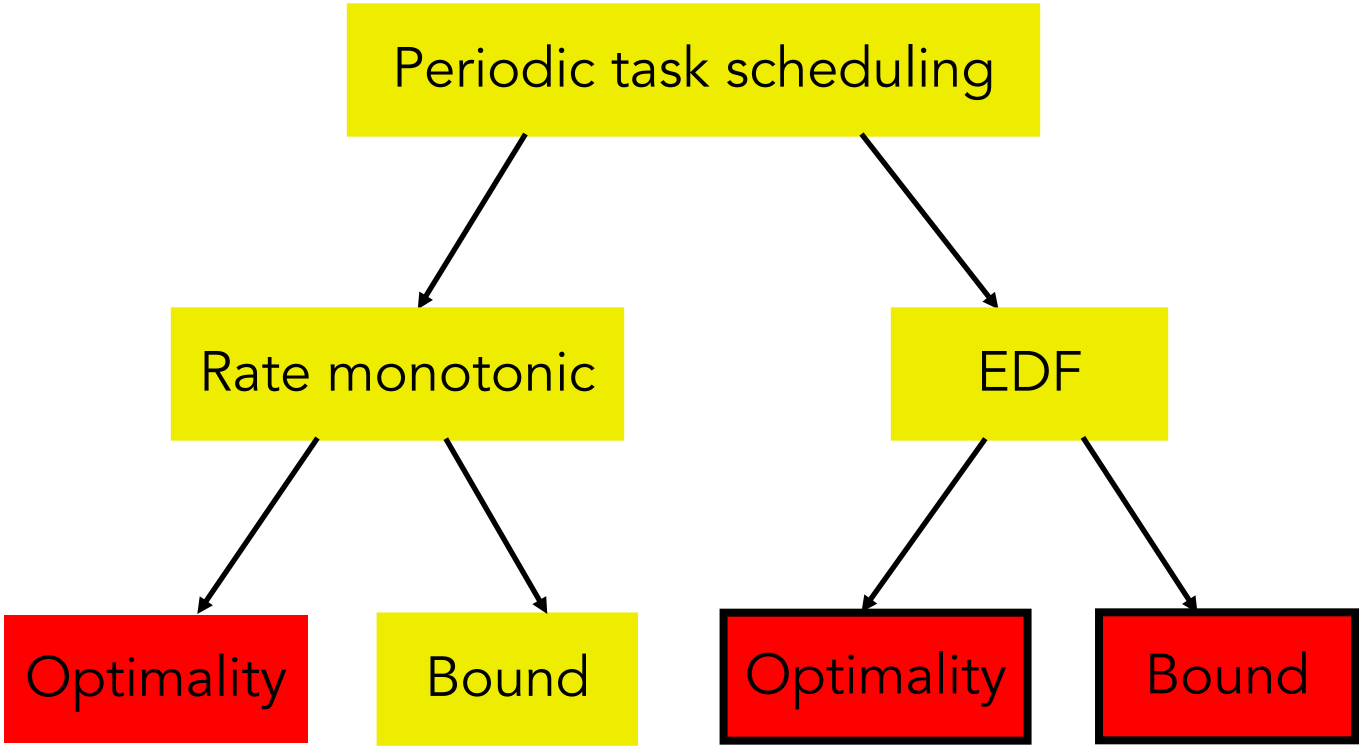
Lecture outline



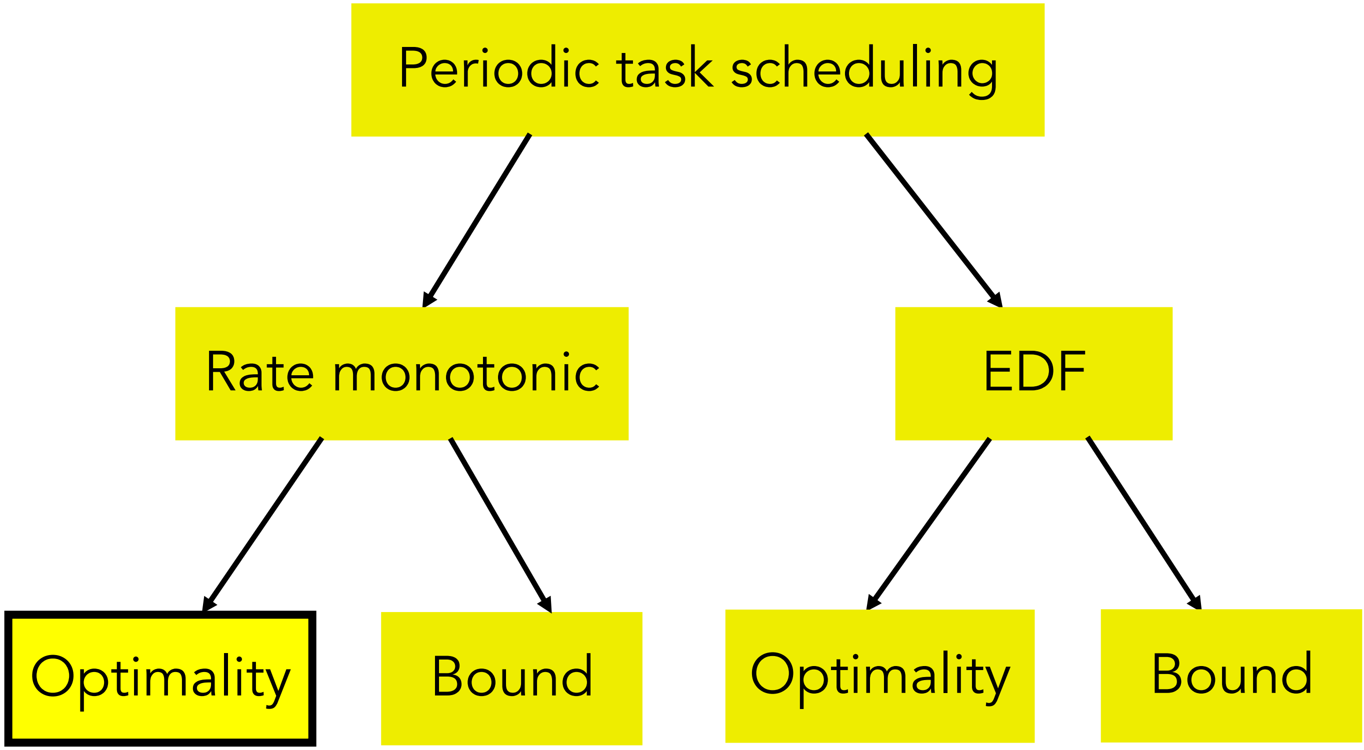
Lecture outline



Lecture outline



Next



Periodic task scheduling
Rate monotonic
EDF
Optimality
Bound
Optimality
Bound

Rate monotonic scheduling

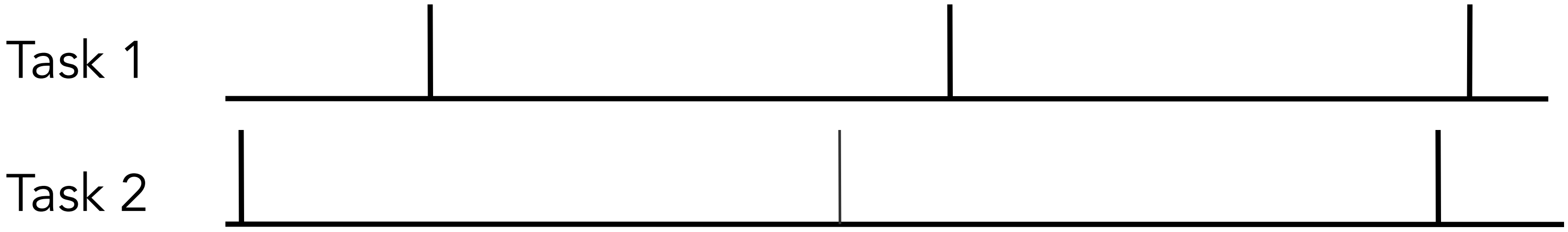
- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
    - Optimality (Trial #1):

Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
    - Optimality (Trial #1): If any other fixed-priority scheduling policy can meet deadlines, so can RM.

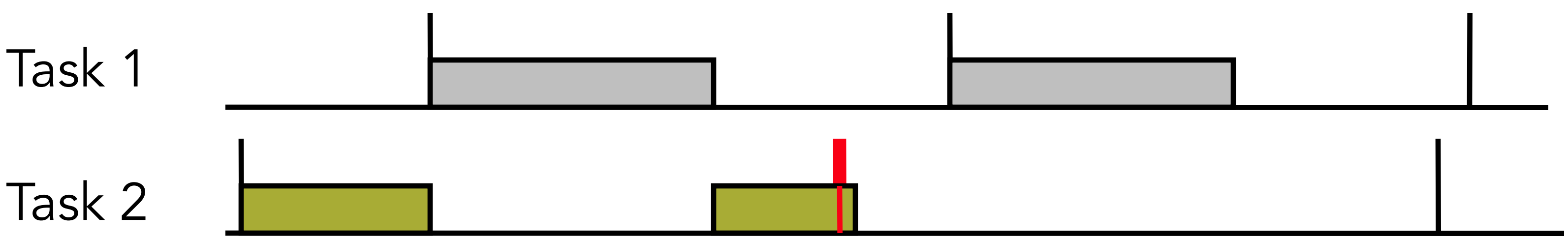
Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
    - Optimality (Trial #1): If any other fixed-priority scheduling policy can meet deadlines, so can RM



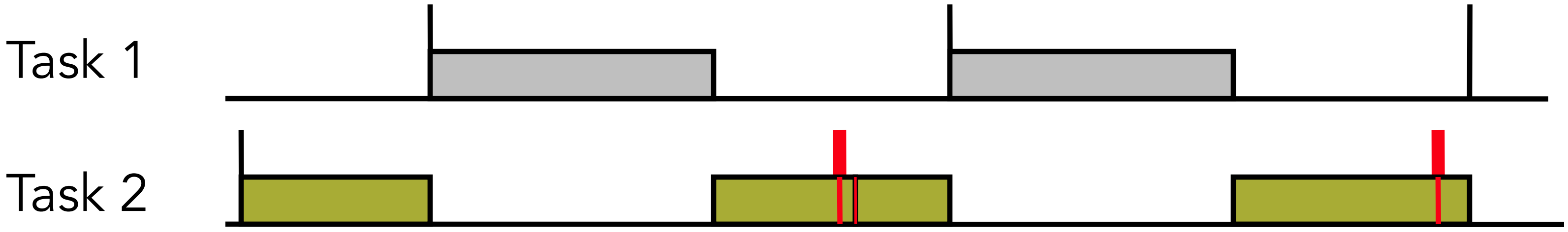
Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
  - Optimality (Trial #1): If any other fixed-priority scheduling policy can meet deadlines, so can RM



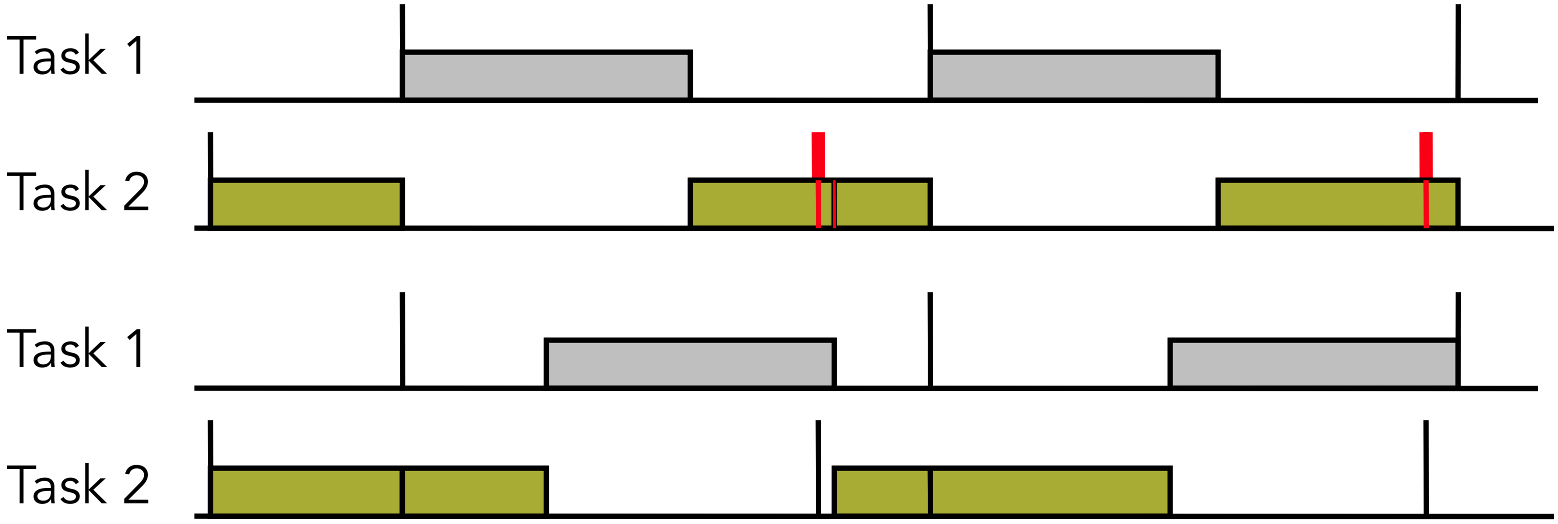
Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
  - Optimality (Trial #1): If any other fixed-priority scheduling policy can meet deadlines, so can RM



Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
  - Optimality (Trial #1): If any other fixed-priority scheduling policy can meet deadlines, so can RM



Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
  - Optimality (Trial #2): If any other fixed-priority scheduling policy can meet deadlines in the worst case scenario, so can RM.
- How do we prove it?

Rate monotonic scheduling

- Rate monotonic scheduling is the optimal fixed-priority (or static-priority) scheduling policy for periodic tasks.
    - Optimality (Trial #2): If any other fixed-priority scheduling policy can meet deadlines in the worst case scenario, so can RM.
- How do we prove it?
    - Consider the worst case scenario
    - Show that if someone else can schedule then RM can

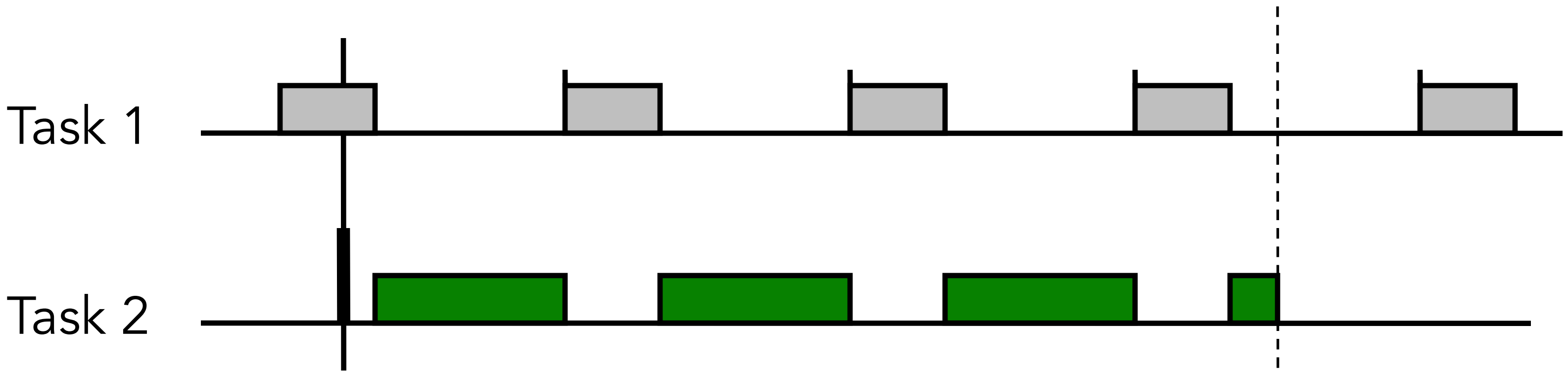
The worst-case scenario

- **Q:** When does a periodic task, *T*, experience the maximum delay?
  - Which arrival time produces the largest *response time* for *T*?
- **A:** When it arrives together with all the higher-priority tasks (critical instant)
  - Liu and Layland

- Idea for the proof
  - If some higher-priority task does not arrive together with *T*, aligning the arrival times can only increase the completion time of *T*.

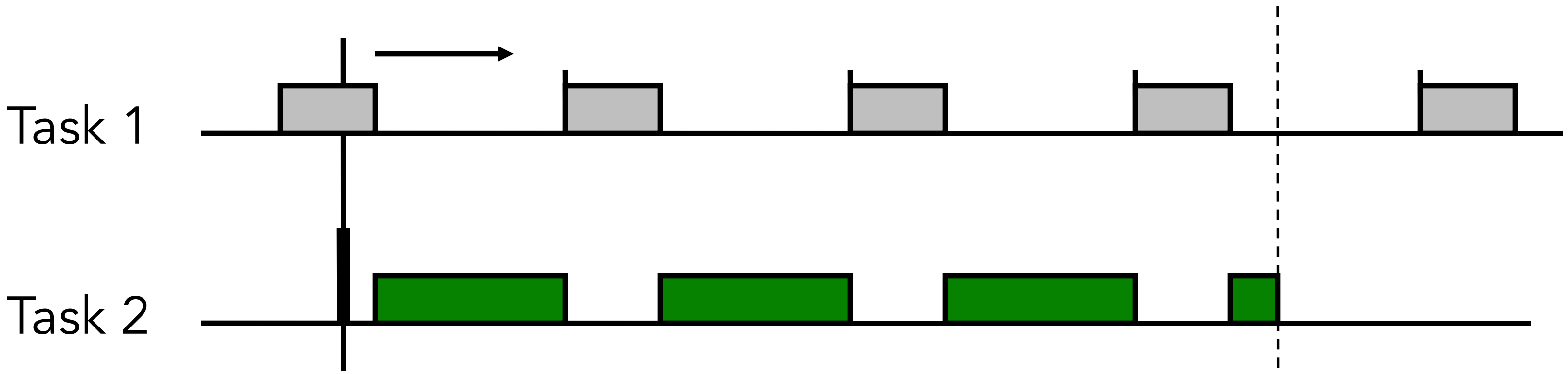
Critical instant theorem

Critical Instant: Proof (Case 1)



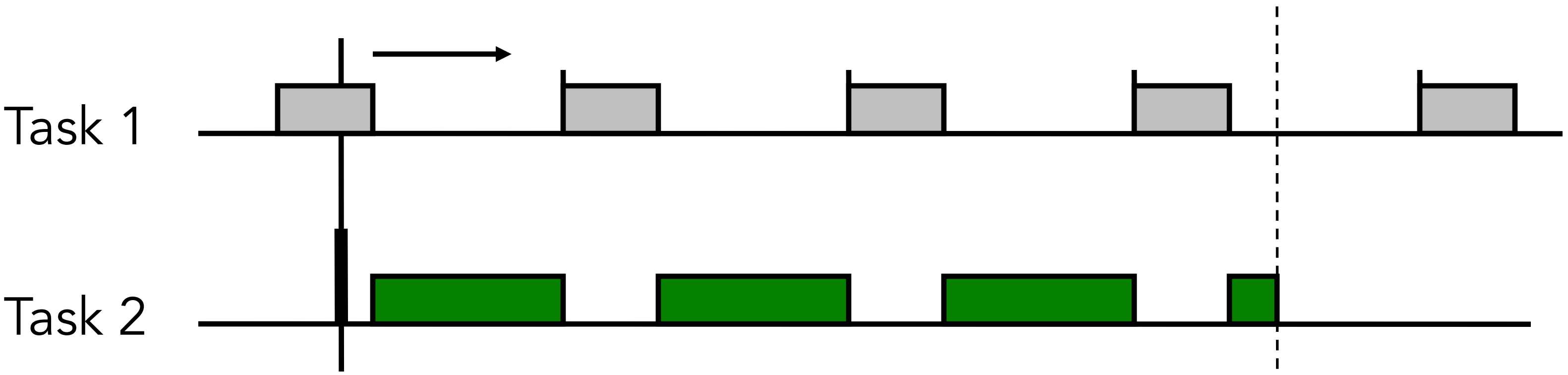
Case 1: Higher priority task 1 is running when task 2 arrives.

Critical Instant: Proof

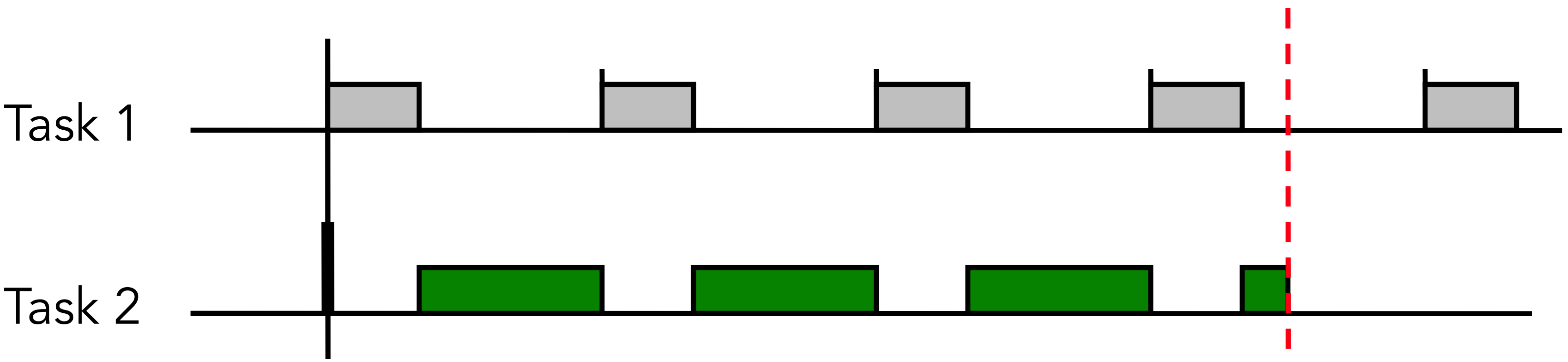


Case 1: higher priority task 1 is running when task 2 arrives
→ shifting task 1 right will increase completion time of 2

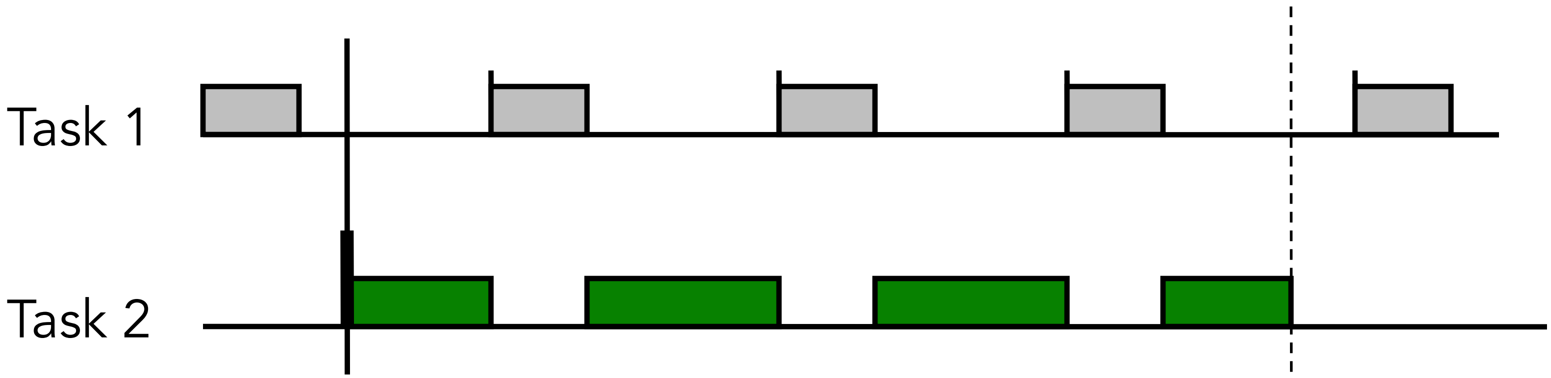
Critical Instant: Proof



Case 1: higher priority task 1 is running when task 2 arrives
→ shifting task 1 right will increase completion time of 2

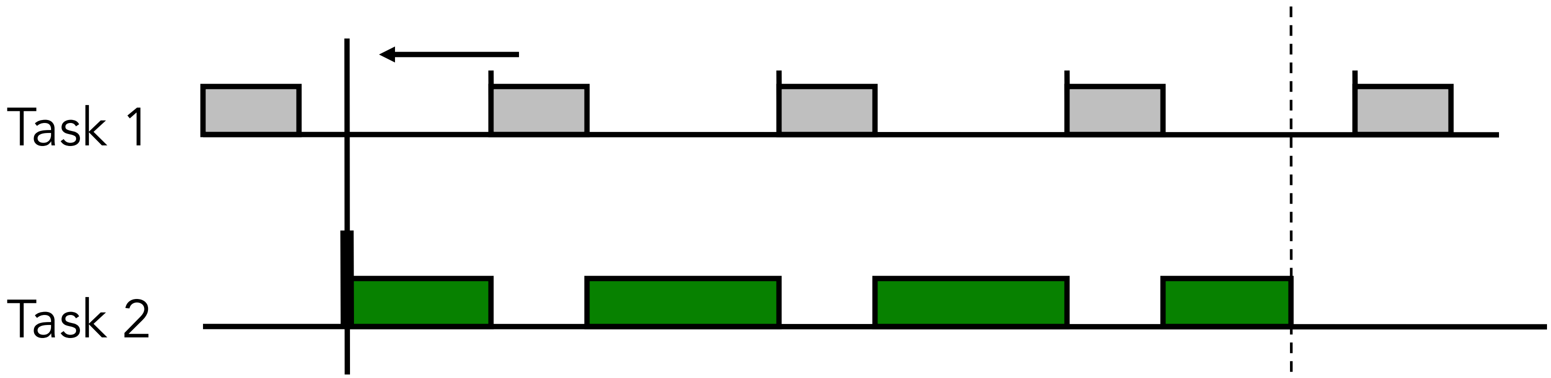


Critical Instant: Proof (Case 2)



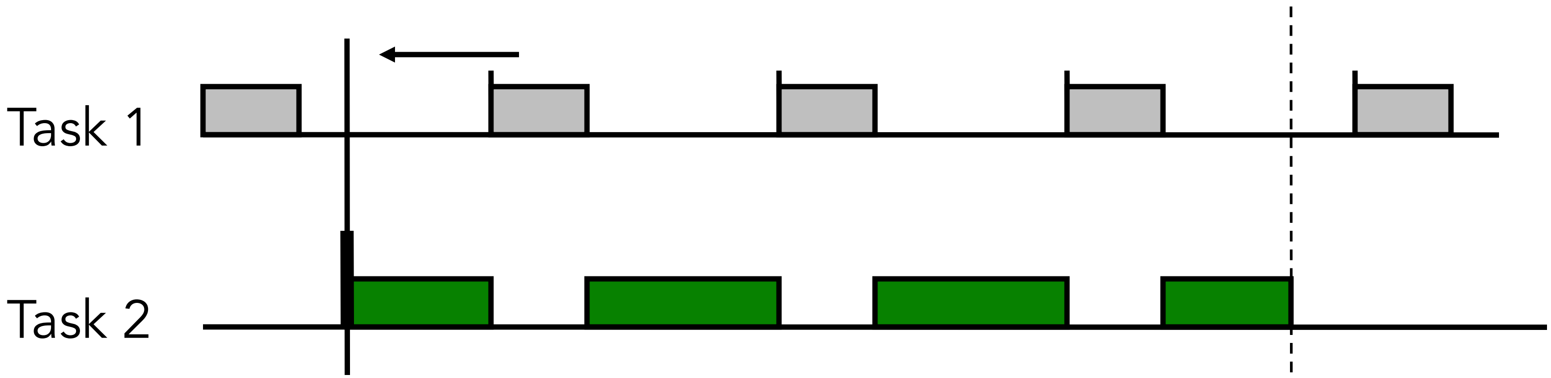
Case 2: processor is idle when task 2 arrives

Critical Instant: Proof (Case 2)

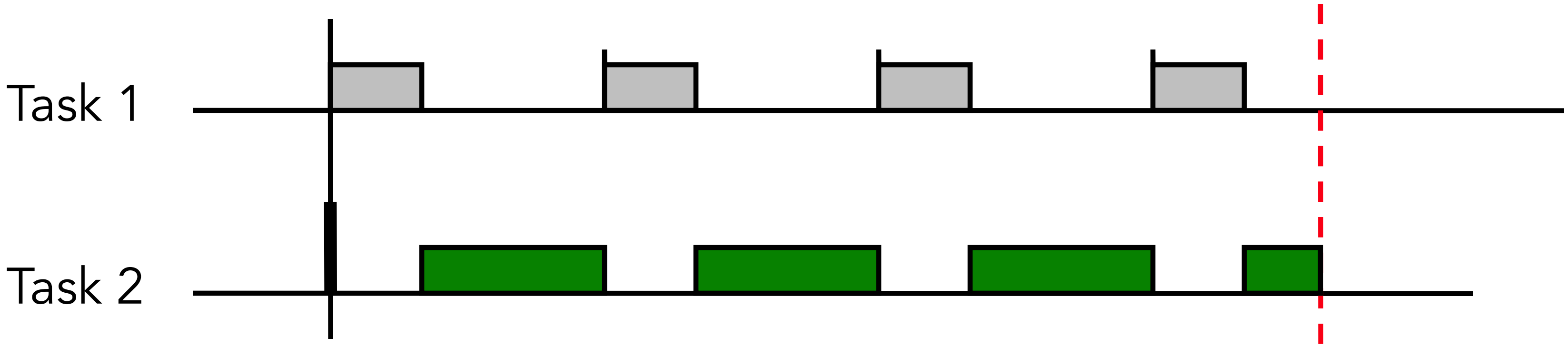


Case 2: processor is idle when task 2 arrives
→ shifting task 1 left cannot decrease completion time of 2

Critical Instant: Proof (Case 2)



Case 2: processor is idle when task 2 arrives
→ shifting task 1 left cannot decrease completion time of task 2



Critical Instant: Remarks

- ***All analyses hereafter will assume the critical instant theorem in effect***
- *Why is it important to identify the critical instant?*
  - *Characterizes the worst case scenario when a task experiences the max delay (remember the pitfall of trial #1 in proving RM optimality earlier?)*
  - *For task schedulability, need to reason only about the feasibility of the job arriving at the critical instant*

Critical Instant: Remarks

- If task **phases** are **not all** 0, does there always exist a point of simultaneous release? Can you come up with a counterexample?
  - It does not necessarily exist in this case and a simple counterexample of 3 tasks exists
- If not, then how easy it is to determine whether a point of simultaneous release exists for non-zero phase task sets?
  - An algorithm exists! (naïve approach takes exponential time, however)

Critical Instant: Remarks

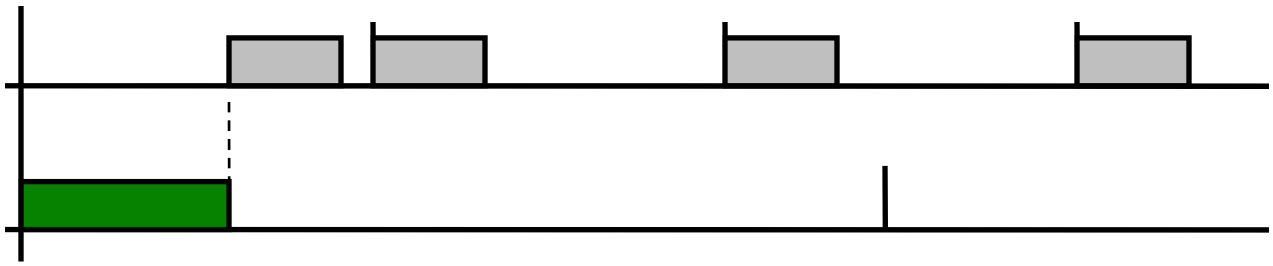
- Are *rate* (and later *deadline*) monotonic optimal if a simultaneous release does not exist?
  - **No.** You can construct a counterexample.
- What about EDF?
  - **Hint:** study the proof of optimality of EDF later and see whether the critical instant theorem was used.
- Does the critical instant theorem still hold in **non-preemptive** scheduling? (Assuming a simultaneous release exists)
  - **No.** The response time of a job that is not released together with higher priority jobs might be larger than that of a job whose release time is aligned with the release time of jobs of all the higher priority tasks (can you come up with an example?)

Assumptions

- All scheduling is preemptive
- A simultaneous release exists even if tasks have non-zero phases
  - And thus critical instant theorem assumed
- Implicit deadlines (deadline = period)
- A task does not suspend itself (on I/O, for instance)
- All tasks in a task set are *independent* (there are no precedence relations and no resource constraints.)
- All overheads in the kernel are assumed to be zero (context switching and others)

Optimality of the RM policy

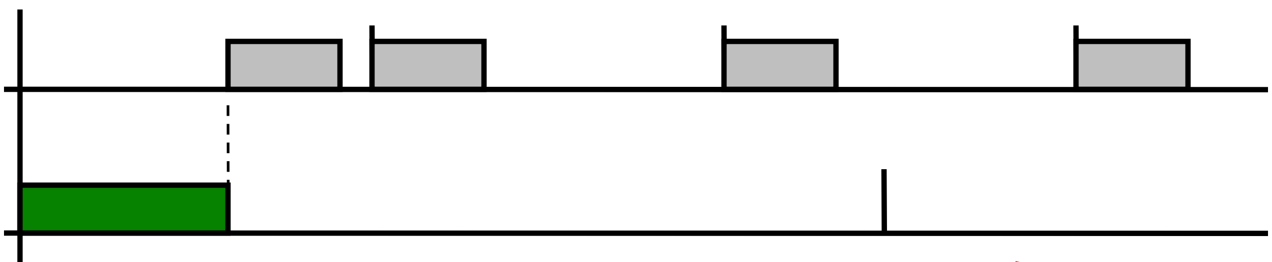
- If any other fixed-priority policy can meet deadlines so can RM



Policy X meets deadlines?

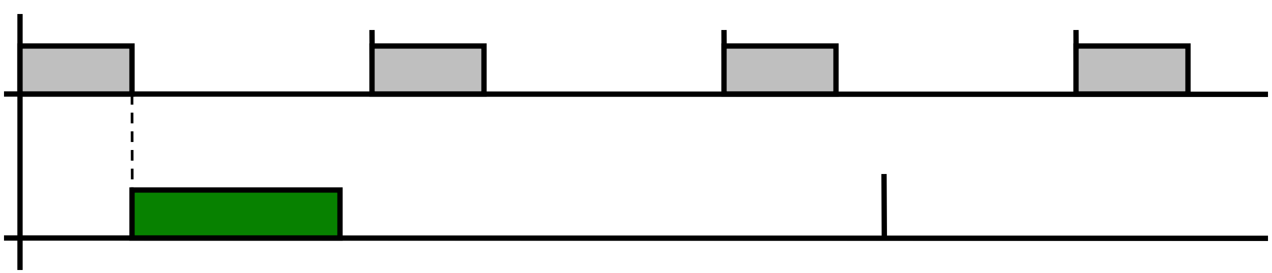
Optimality of the RM policy

- If any other policy can meet deadlines so can RM

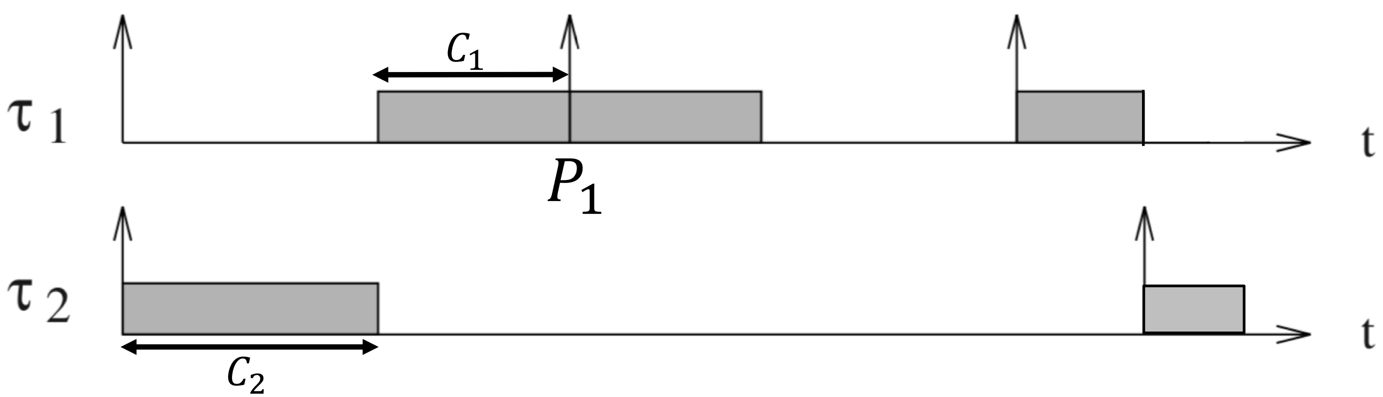


Policy X meets deadlines? YES

→ RM meets deadlines



Optimality of the RM policy: Proof



Two tasks scheduled not according to RM

For feasibility in a non-RM policy, we need $C_1 + C_2 \leq P_1$ to hold at critical instant

Why?

Optimality of the RM policy: Proof

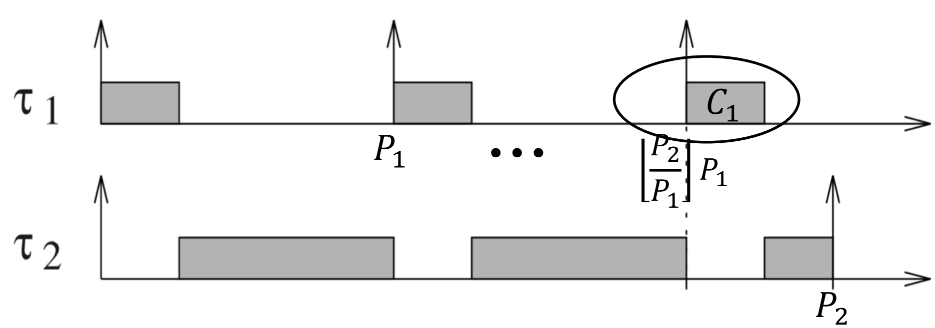
For feasibility in a non-RM policy, we need $C_1 + C_2 \leq P_1$ to hold at critical instant

- Now **exchange priorities** of tasks to make it into an RM assignment
- Plan:
  - identify all possible cases
  - In each case derive feasibility condition
  - Show that if $C_1 + C_2 \leq P_1$ then derived feasibility condition in RM holds

Optimality of the RM policy: Case 1

For feasibility in a non-RM policy, we need $C_1 + C_2 \leq P_1$ to hold at critical instant

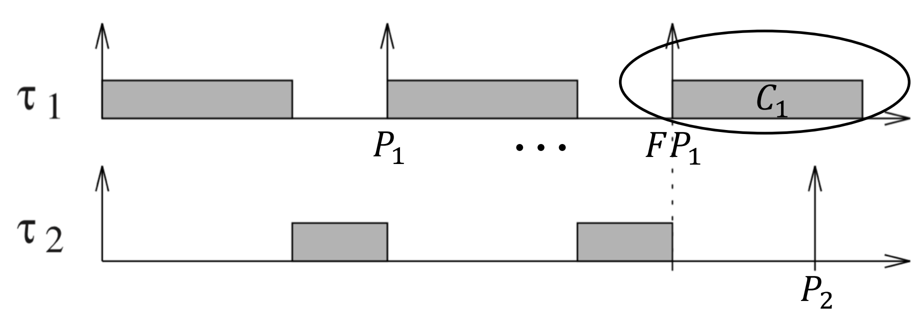
- **Case 1:** computation time of τ_1 is short enough that all its *requests* are completed before the second request of τ_2
  - Number of periods P_1 **entirely contained** in P_2 is $\left\lfloor \frac{P_2}{P_1} \right\rfloor$ → Let $F = \left\lfloor \frac{P_2}{P_1} \right\rfloor$
  - **Case 1** translates to $\boldsymbol{C_1 + FP_1 \leq P_2}$
  - **Feasibility:** All computation *requested* by τ_1 during P_2, in addition to C_2, should be completed by P_2
  - $(F+1)C_1 + C_2 \leq P_2 \qquad (*)$
  - Need to show that $C_1 + C_2 \leq P_1$ implies $(*)$



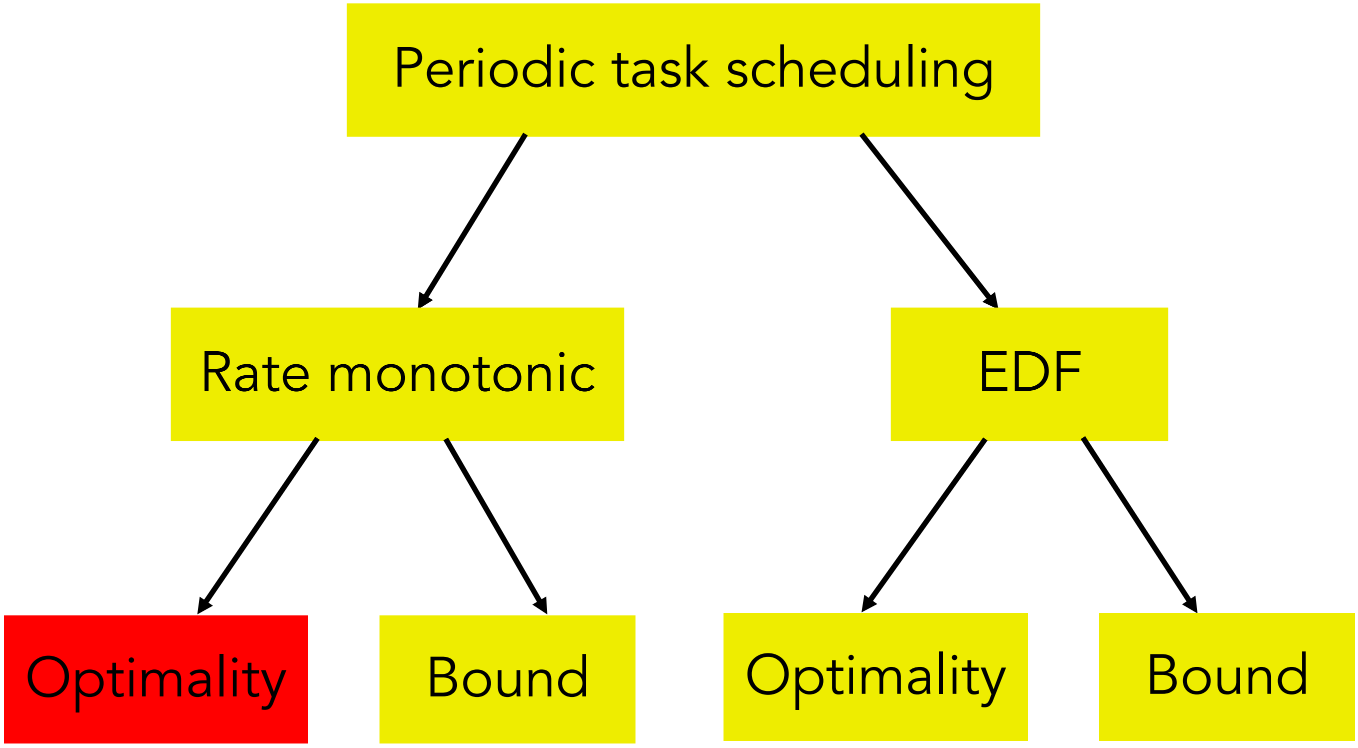
Optimality of the RM policy: Case 2

For feasibility in a non-RM policy, we need $C_1 + C_2 \leq P_1$ to hold at critical instant

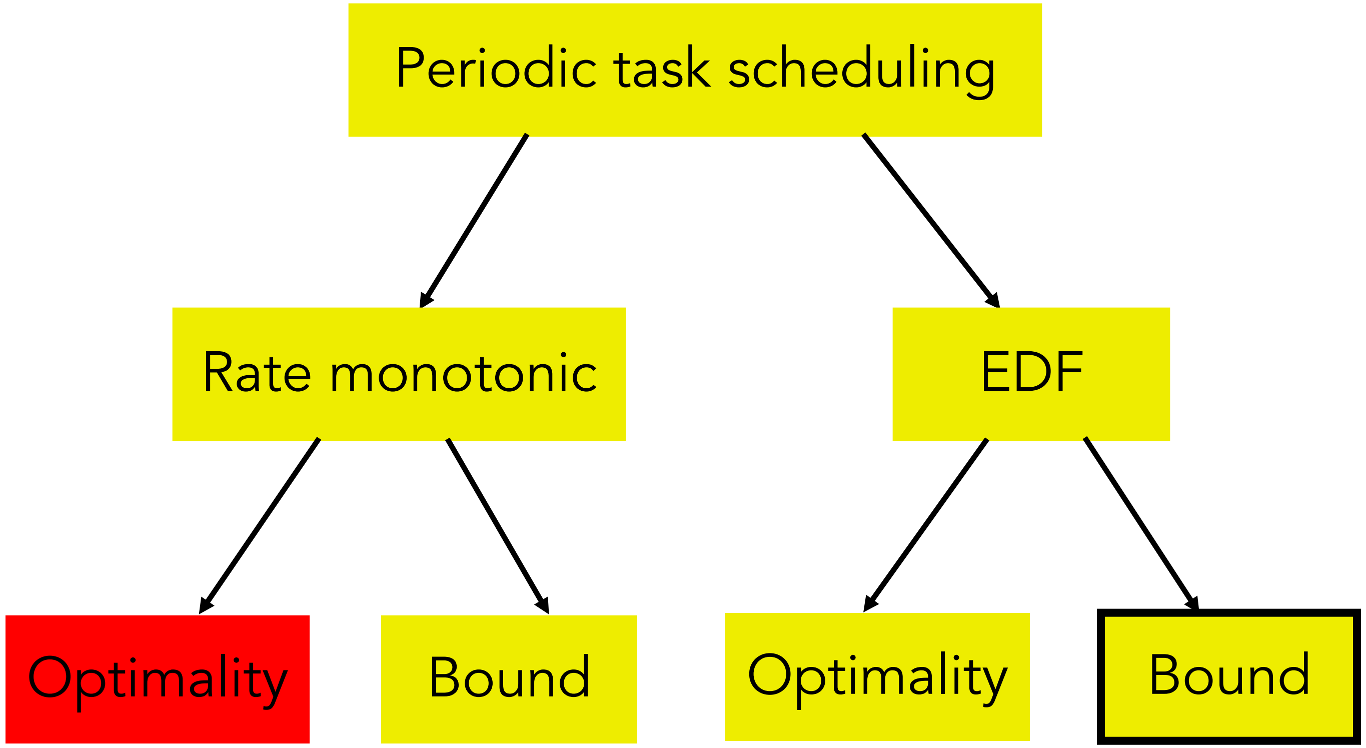
- **Case 2:** computation time of τ_1 is long enough to overlap with the second request of τ_2
  - **Case 2 translates to $\boldsymbol{C_1 + FP_1 \geq P_2}$**
  - **Feasibility condition:** $FC_1 + C_2 \leq FP_1$ $\quad (**)$ $\quad$ Why?
    - For feasibility τ_2 must finish before the start of the (FP_1)-th request of τ_1 because τ_1 has higher priority than τ_2 so τ_1 will occupy the processor until P_2 by the condition in **case 2** and thus P_2 cannot execute in $[FP_1, P_1]$
  - Need to show that $C_1 + C_2 \leq P_1$ implies $(**)$



What have we achieved?



Next

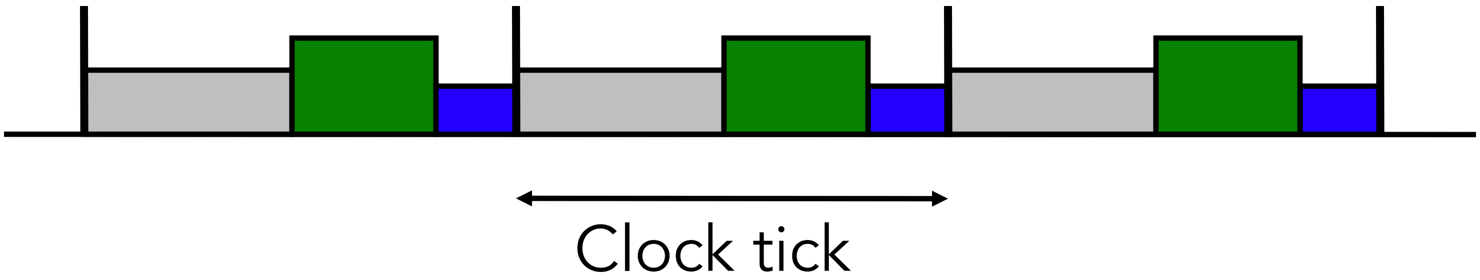

Periodic task scheduling
Rate monotonic
EDF
Optimality
Bound
Optimality
Bound

Utilization bound for EDF

- Why is it 100%?
- Consider a task set where:

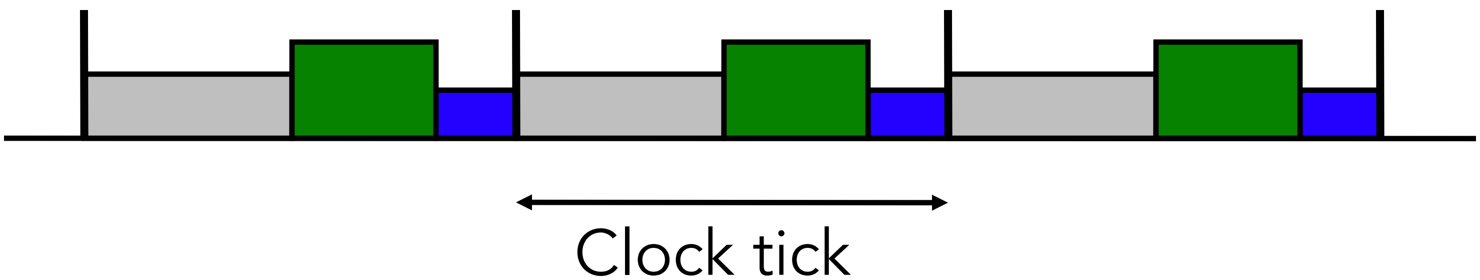
$$\sum_i \frac{c_i}{P_i} = 1$$

- Imagine a policy that reserves for each task i a fraction u_i of each clock tick, where u_i = C_i / P_i



Utilization bound for EDF

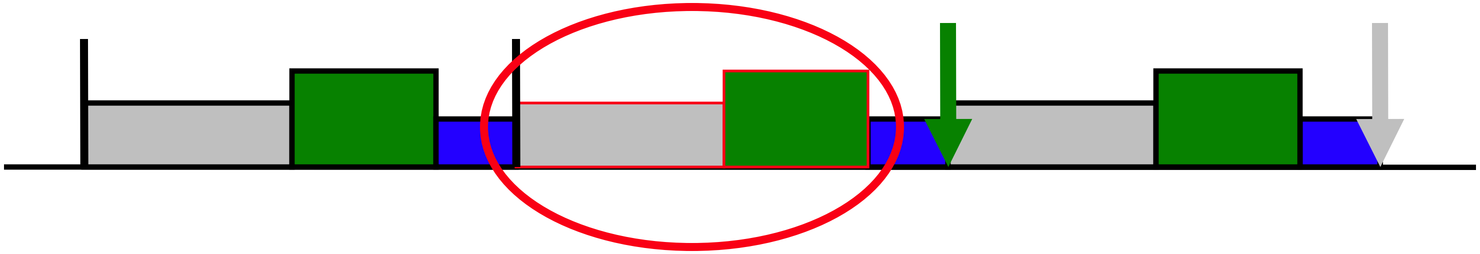
- Imagine a policy that reserves for each task i a fraction u_i of each time unit, where $u_i = C_i \,/ P_i$



- This policy meets all deadlines, because within each period P_i it reserves for task i a total time
  - Time given to T_i in its period = $u_i P_i = (C_i \,/ P_i)\; P_i = C_i$ (i.e., enough to finish)

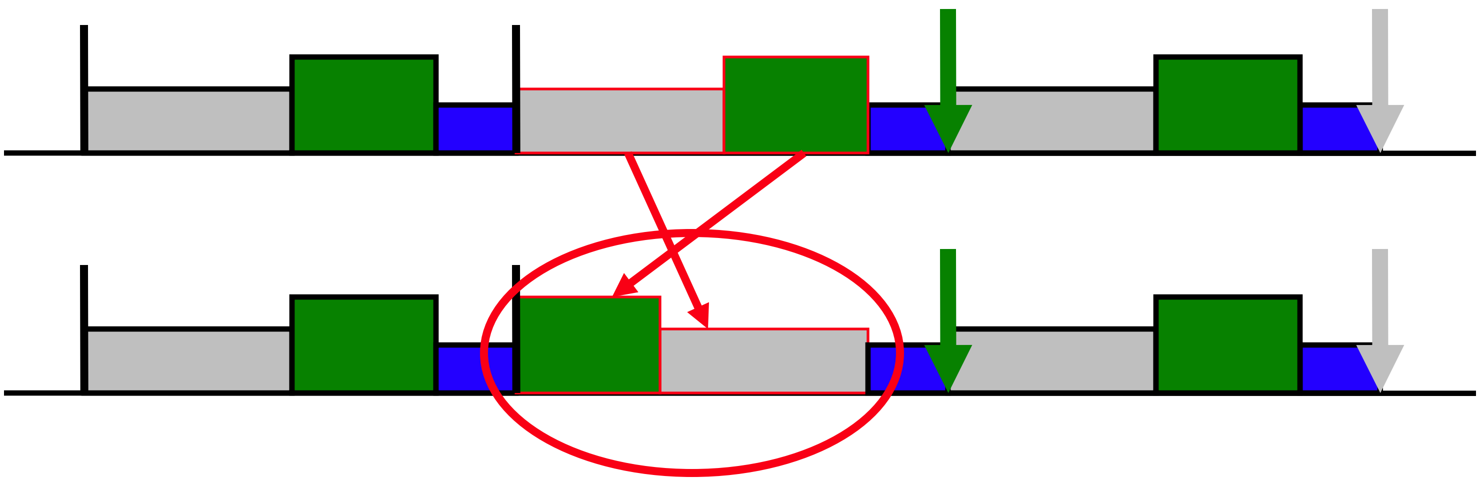
Utilization bound for EDF

- Pick any two execution chunks that are not in EDF order and swap them



Utilization bound for EDF

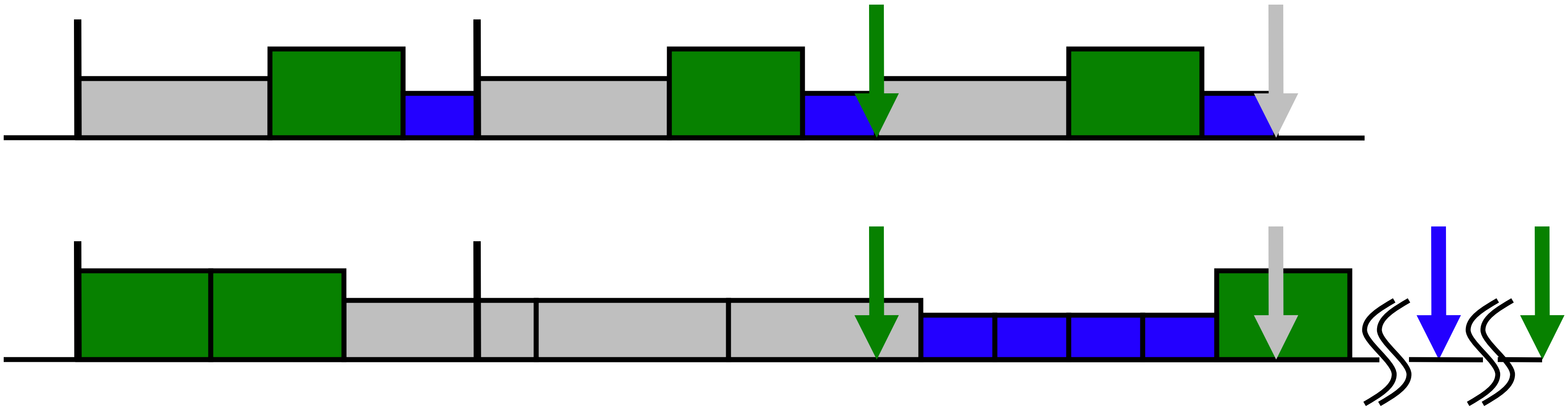
- Pick any two execution chunks that are not in EDF order and swap them



- Still meets deadlines!

Utilization bound for EDF

- Pick any two execution chunks that are not in EDF order and swap them

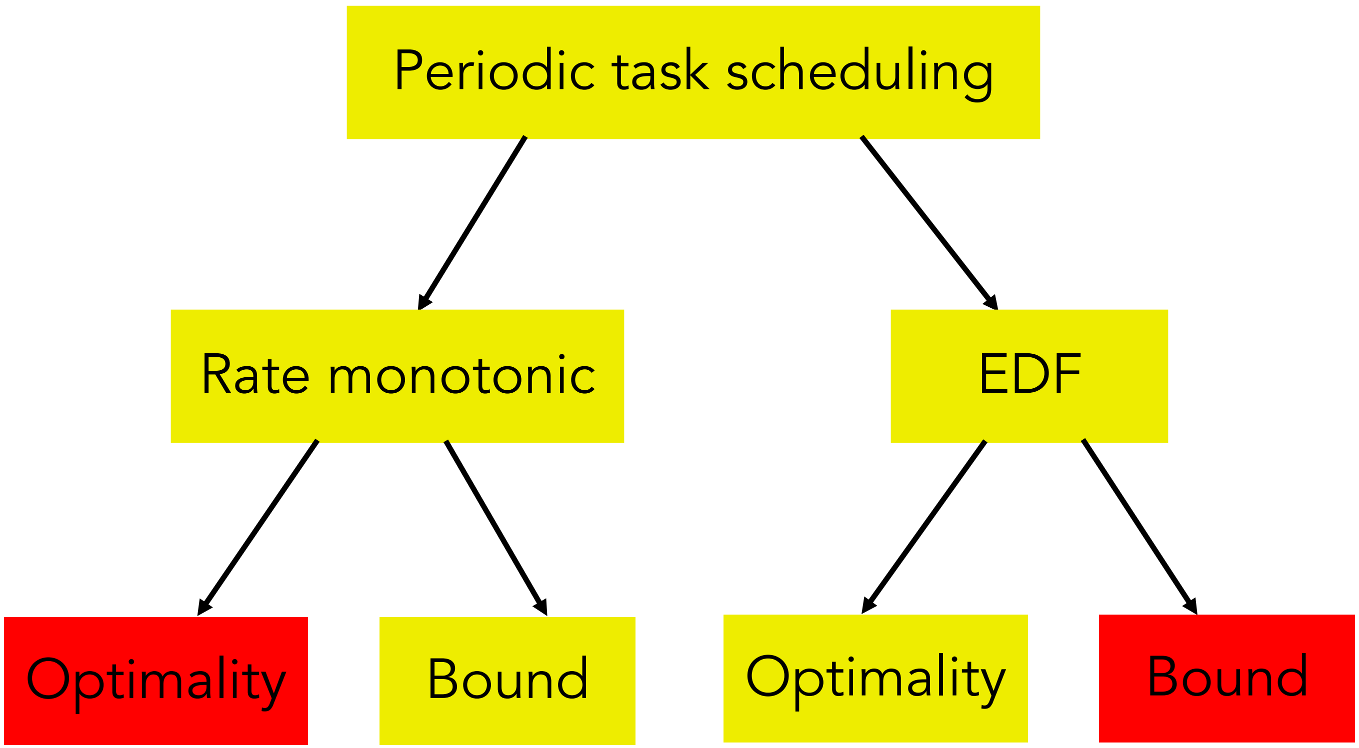


- Still meets deadlines!
- Repeat swap until all in EDF order
  - → EDF meets deadlines

Utilization bound for EDF

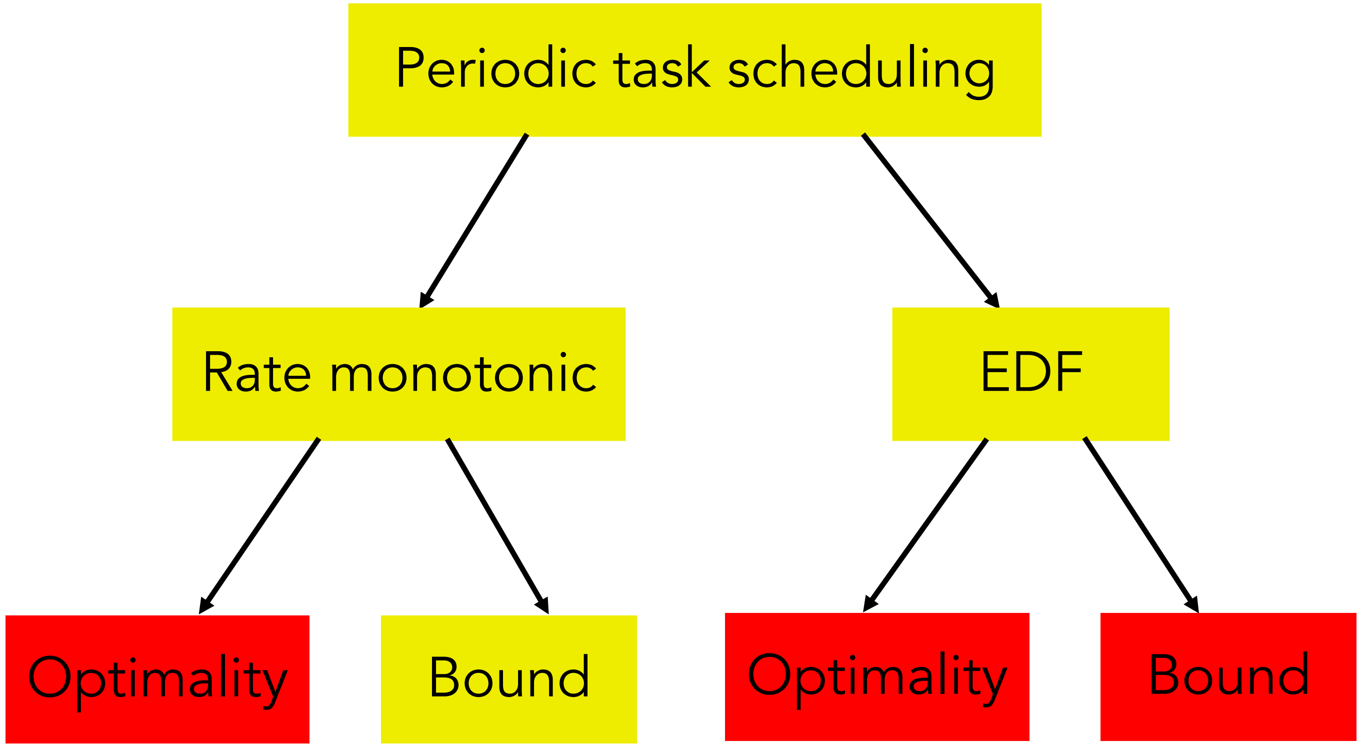
- Why does this prove that the utilization bound of EDF is 1?
  - Intuitively, must also show that for every instance I with utilization factor U, if I is feasible under EDF, then every instance I' with utilization $U' < U$ is also feasible
  - This is not needed! Previous argument follows for any $U \leq 1$, not necessarily $U = 1$
  - Consequences:
    - EDF is optimal!
    - EDF is able to schedule every task set who utilization is 1 or less

Next



Periodic task scheduling
Rate monotonic
EDF
Optimality
Bound
Optimality
Bound

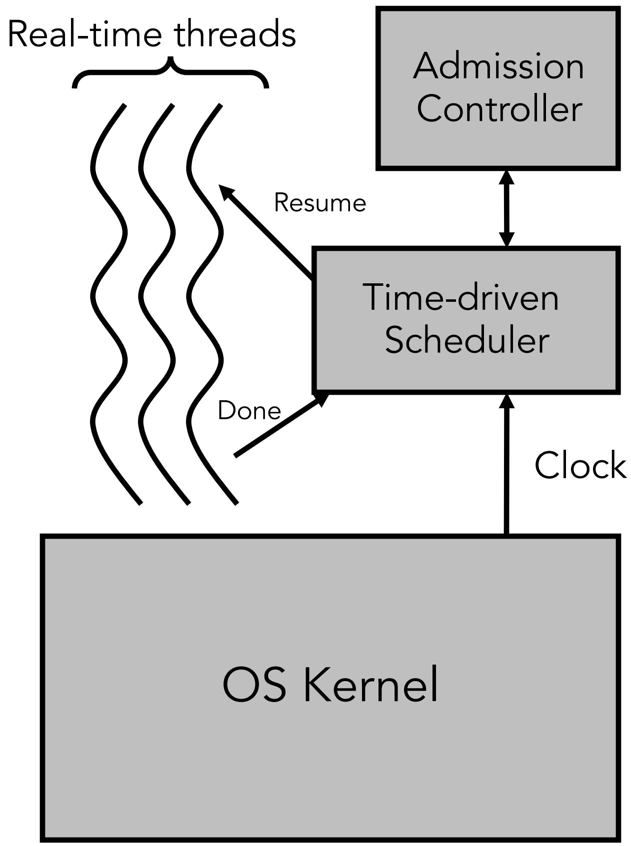
Next



Periodic task scheduling
Rate monotonic
EDF
Optimality
Bound
Optimality
Bound

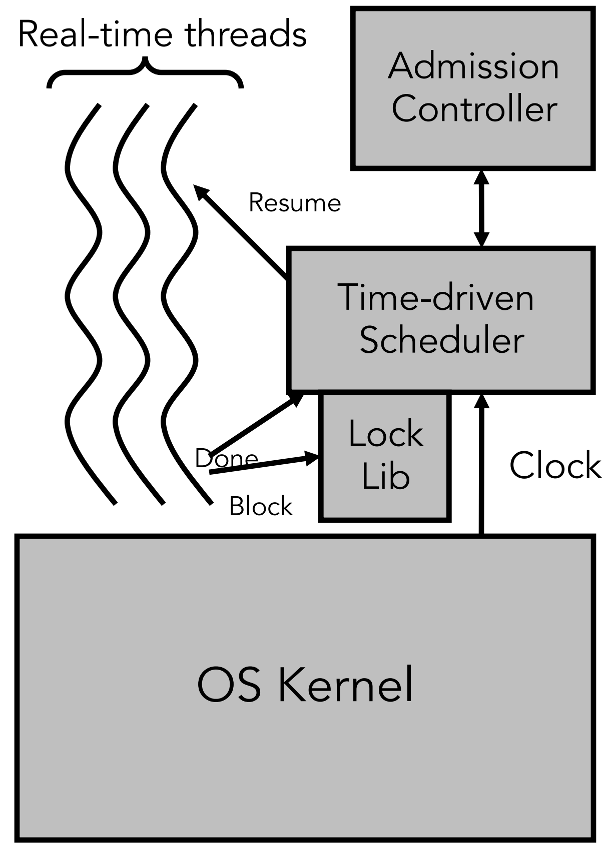
Tick-based scheduling within an OS

- A real-time library for periodic tasks on Linux or Windows
  - There is need to provide approximate real-time guarantees on common operating systems (as opposed to specialized real-time OSes)
  - A high-priority "real-time" thread pool is created and maintained
  - A higher-priority scheduler is invoked periodically by timer-ticks to check for periodic invocation times of real-time threads. The scheduler resumes threads whose arrival times have come.
  - Resumed threads execute one invocation then block.
  - Scheduling is preemptive
  - The scheduler can implement arbitrary scheduling policies including EDF, RM, etc.
  - An admission controller is responsible for spawning new periodic threads if the new task set can meet its deadlines.



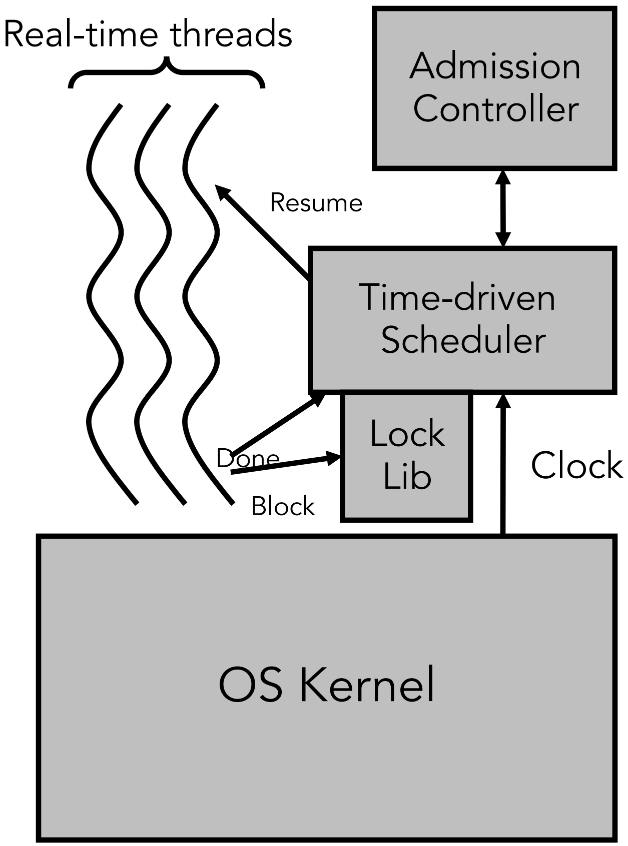
Tick-based scheduling within an OS

- A real-time library for periodic tasks on Linux or Windows
  - There is need to provide approximate real-time guarantees on common operating systems (as opposed to specialized real-time OSes)
  - A high-priority "real-time" thread pool is created and maintained
  - A higher-priority scheduler is invoked periodically by timer-ticks to check for periodic invocation times of real-time threads. The scheduler resumes threads whose arrival times have come.
  - Resumed threads execute one invocation then block.
  - Scheduling is preemptive
  - The scheduler can implement arbitrary scheduling policies including EDF, RM, etc.
  - An admission controller is responsible for spawning new periodic threads if the new task set can meet its deadlines.
  - Scheduler implements wrappers for blocking primitives

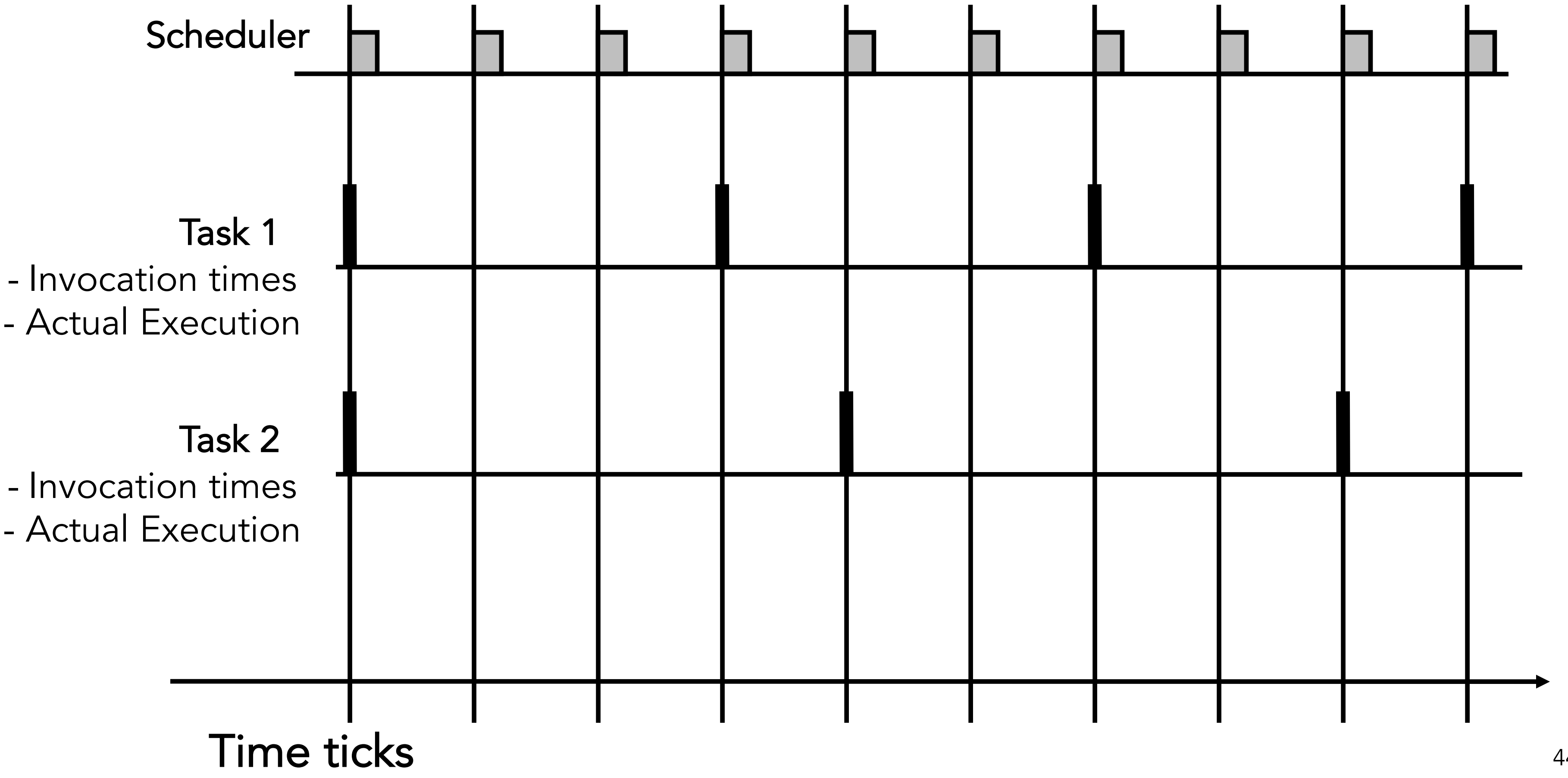


The time-driven scheduler

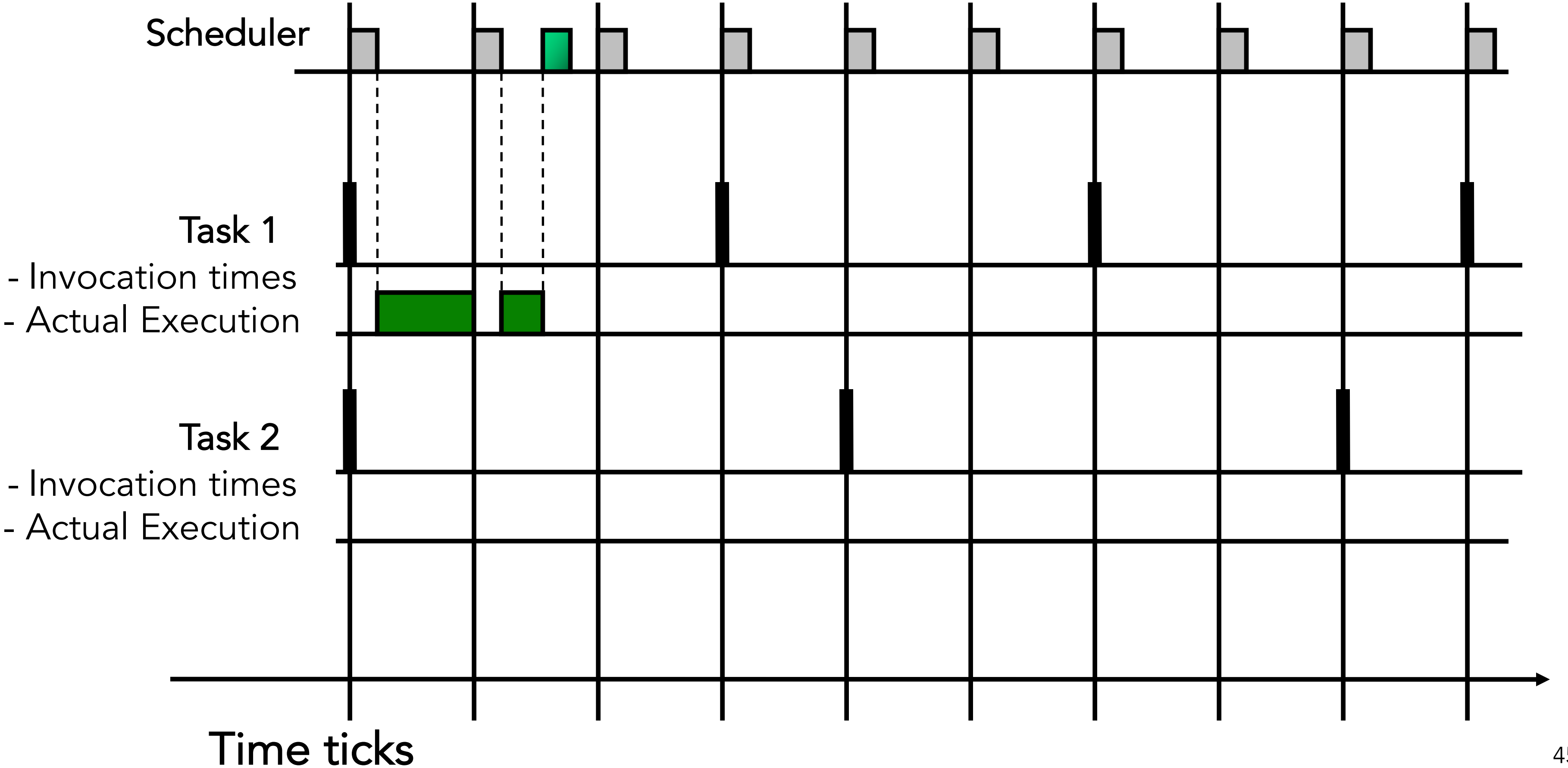
- /* N is the number of periodic tasks */
- For i=1 to N
-     if (current_time = next_arrival_time of task i)
-             put task i in ready_queue
- /* ready_queue is a priority queue that implements
-     the desired scheduling policy. */
- Inspect top task from ready queue, call it j
- If (a task is running and its priority is higher than priority of j) return
- Else resume task j (and put the running task into the ready queue if applicable); return



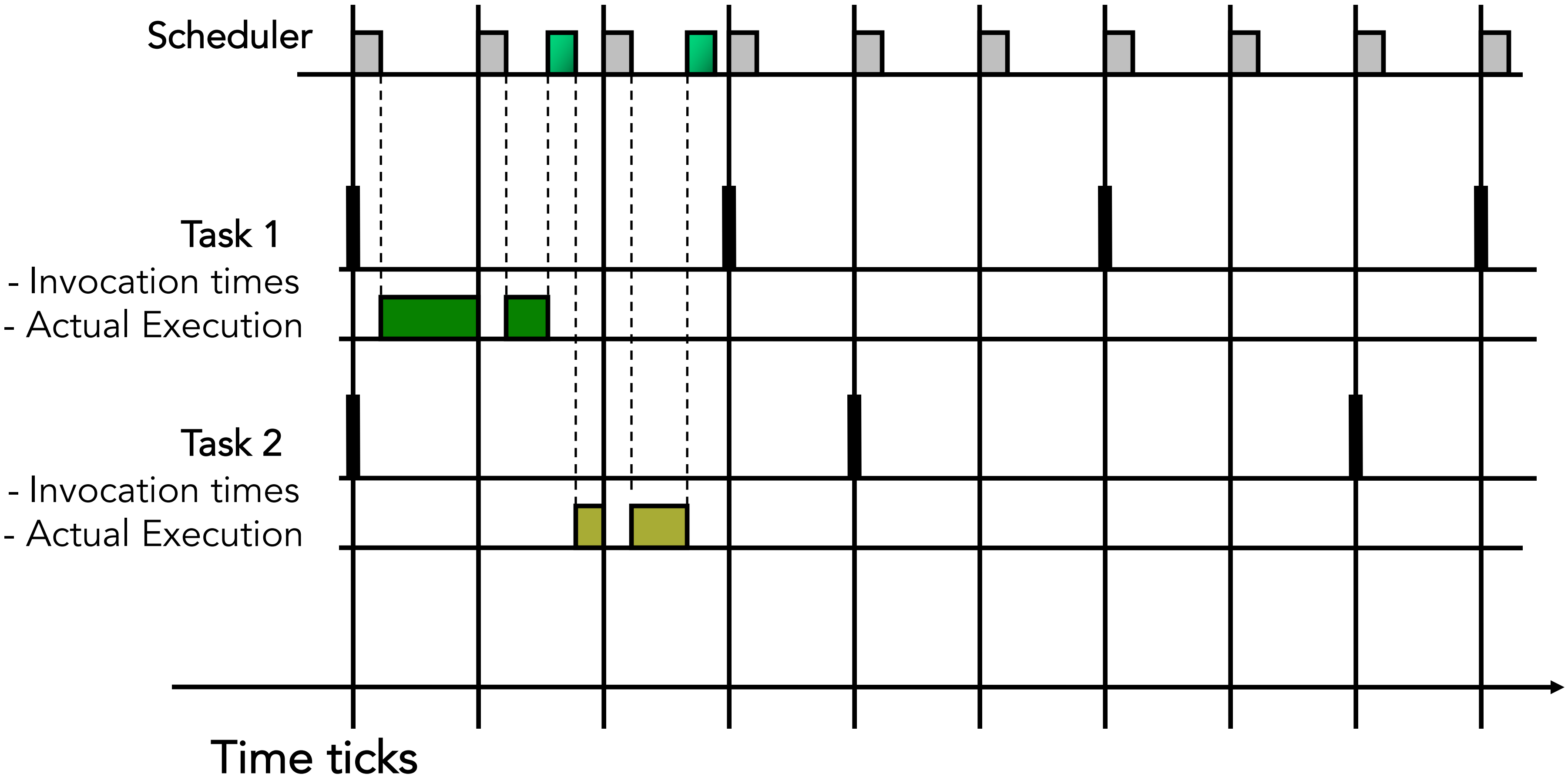
An example schedule



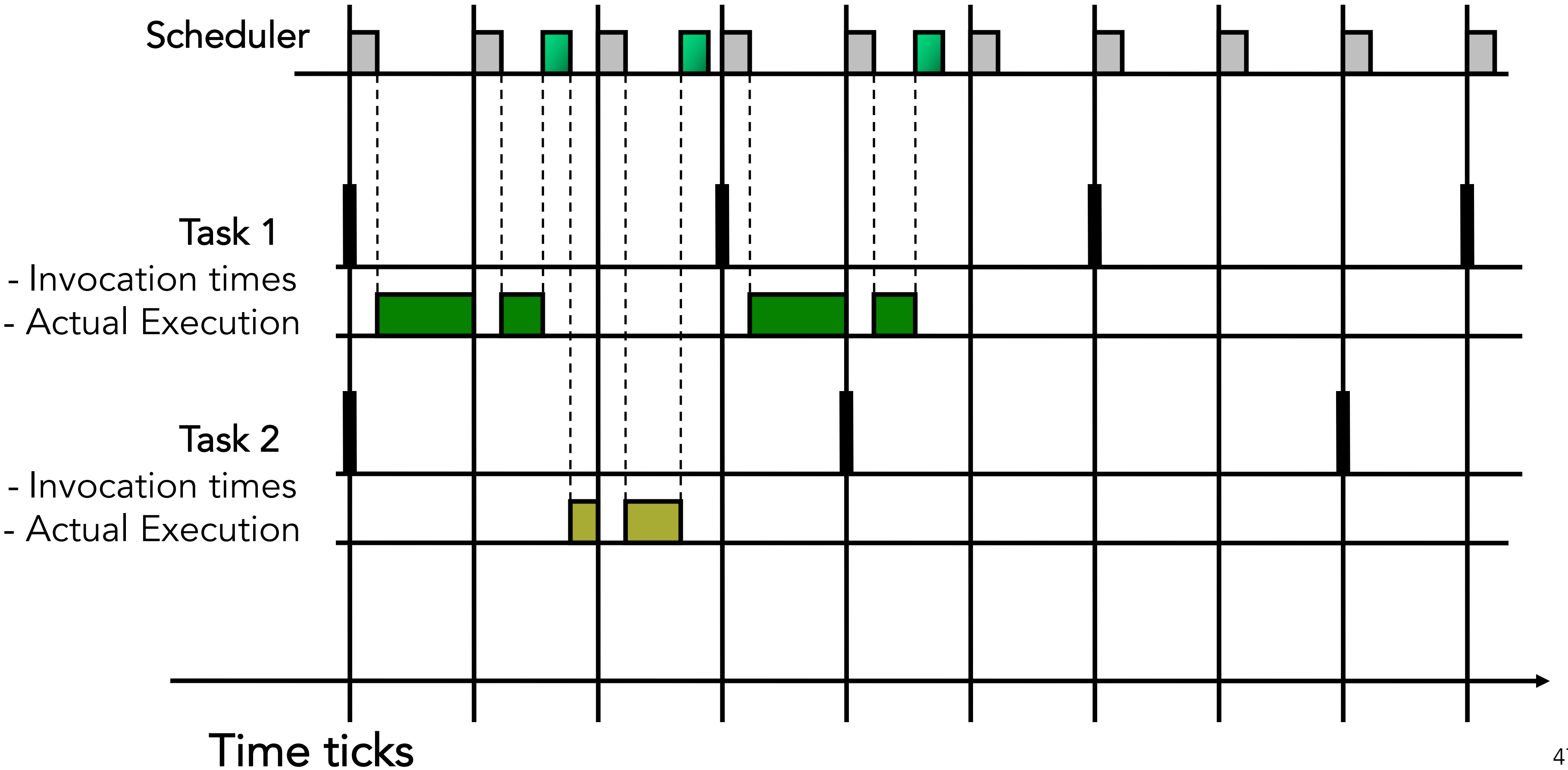
An example schedule



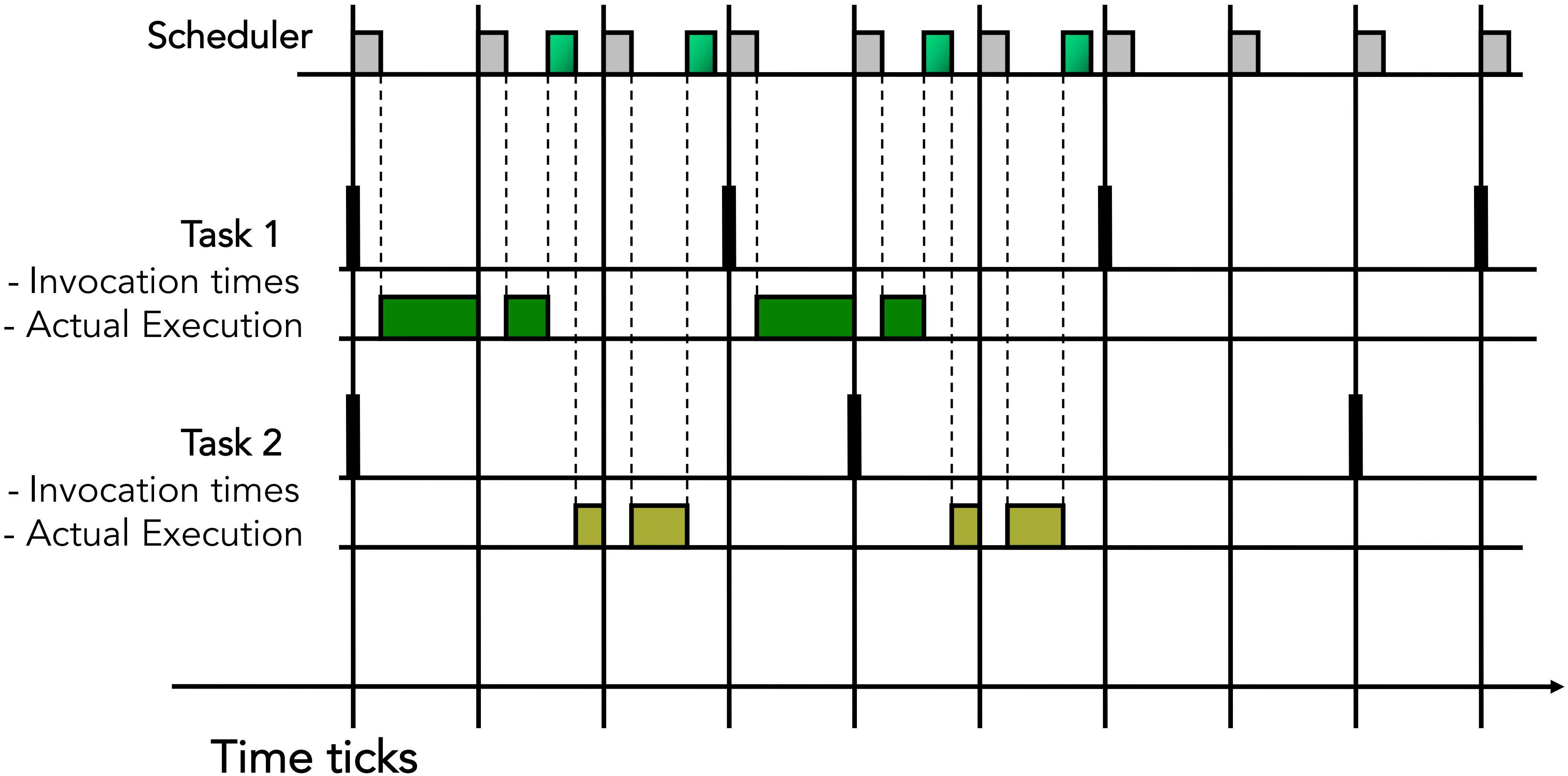
An example schedule



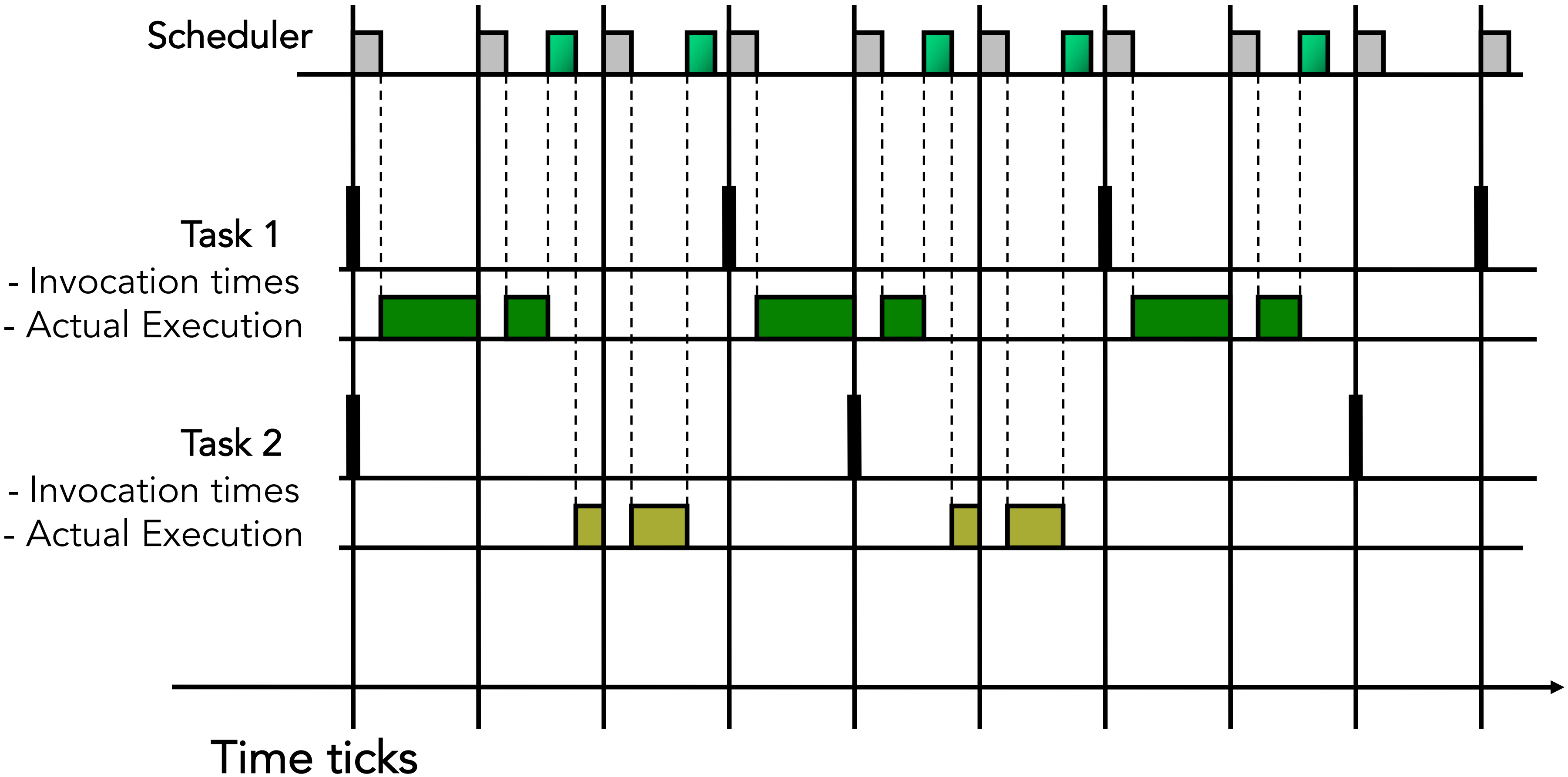
An example schedule



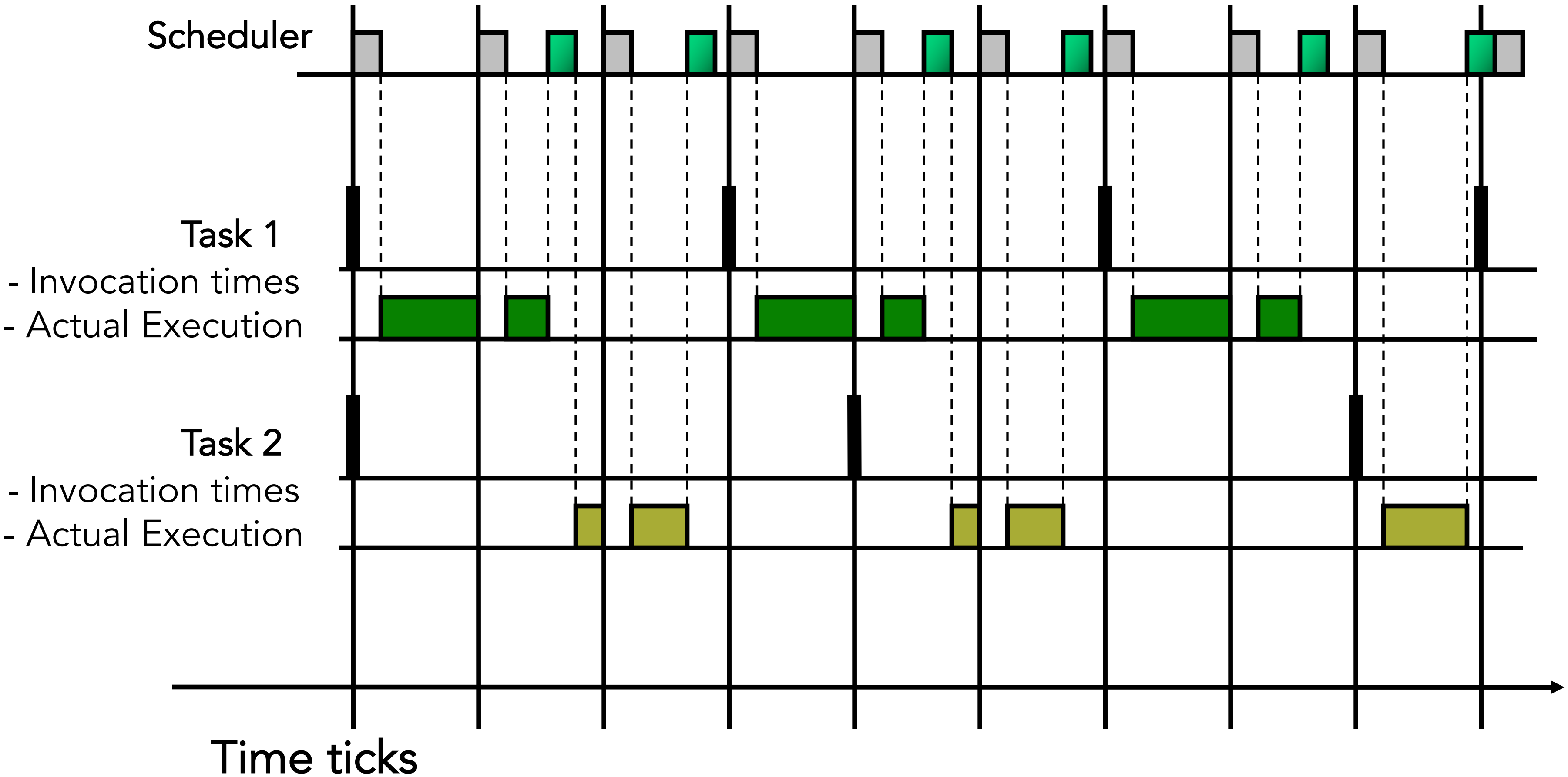
An example schedule



An example schedule

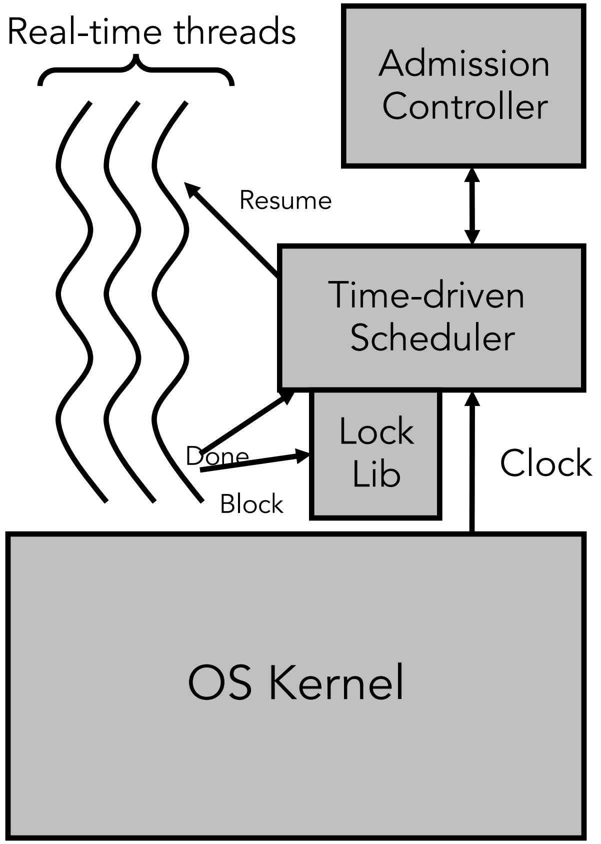


An example schedule



Admission controller

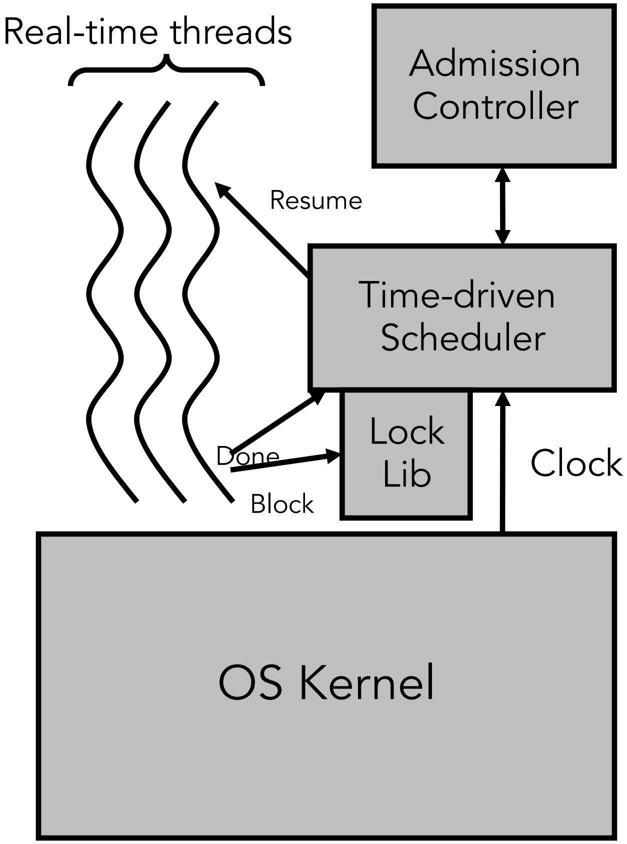
- Implements schedulability analysis
  - If $U+C_{new}/P_{new} < U_{bound}$ admit task
  - Must account for various practical overheads. How?
  - Examples of overhead:
    - How to account for the overhead of running the time-driven scheduler on every time-tick?
    - How to account for the overhead of running the scheduler after task termination?
- If new task admitted
  - $U = U + C_{new}/P_{new}$
  - Create a new thread
  - Register it with the scheduler



Library with lock primitives

- Lock (S) {
- Check if semaphore S = locked
- If locked
- enqueue running tasks in semaphore queue
- Else
- let semaphore = locked
- }

- Unlock (S) {
- If semaphore queue empty then
- semaphore = unlocked
- Else
- Resume highest-priority waiting task
- }



Problem: some threads may execute blocking OS calls (e.g., disk or network read/write and block without calling your lock/unlock!)