SYSC 5701

Operating System Methods for Real-Time Applications

Access Control: PCP

Winter 2014

Resource-Sharing Dependencies

- A job cannot proceed (is blocked) because of resource-sharing synchronization
- Resource-sharing requires mutually exclusive access to the resource
- Can cause priority inversions

Resources

- serially reusable "units" of resource
  - eg. binary semaphore has one unit
    - counting semaphore has *count* units
- grant mutually exclusive right to access a unit
- once a unit is granted to a job, must not be reused by other jobs until released
- Recall management of mutual exclusion "unit" in monitors!

Access to Resources

- job requests resource(s)
  → job "*locks*" the resource(s)
- lock is managed by o/s (kernel)
- if resource(s) not available job is blocked
- eventually, job is granted the resource(s) and is unblocked
- when finished with resource(s)
  → job "*unlocks*" resource(s) for reuse

Access (more)

related material from earlier in course:

- **semaphores, IPC**
- **monitors**
- **critical sections**
- **mutual exclusion**

semaphores, IPC and monitors: constructs to enable programs to control locking and unlocking of resources

critical sections: parts of programs that require locking

mutual exclusion: the desired effect

Result: task can have interdependencies when accessing resources

Access Control Protocol

- **resource conflict:**

  two jobs require same resource type

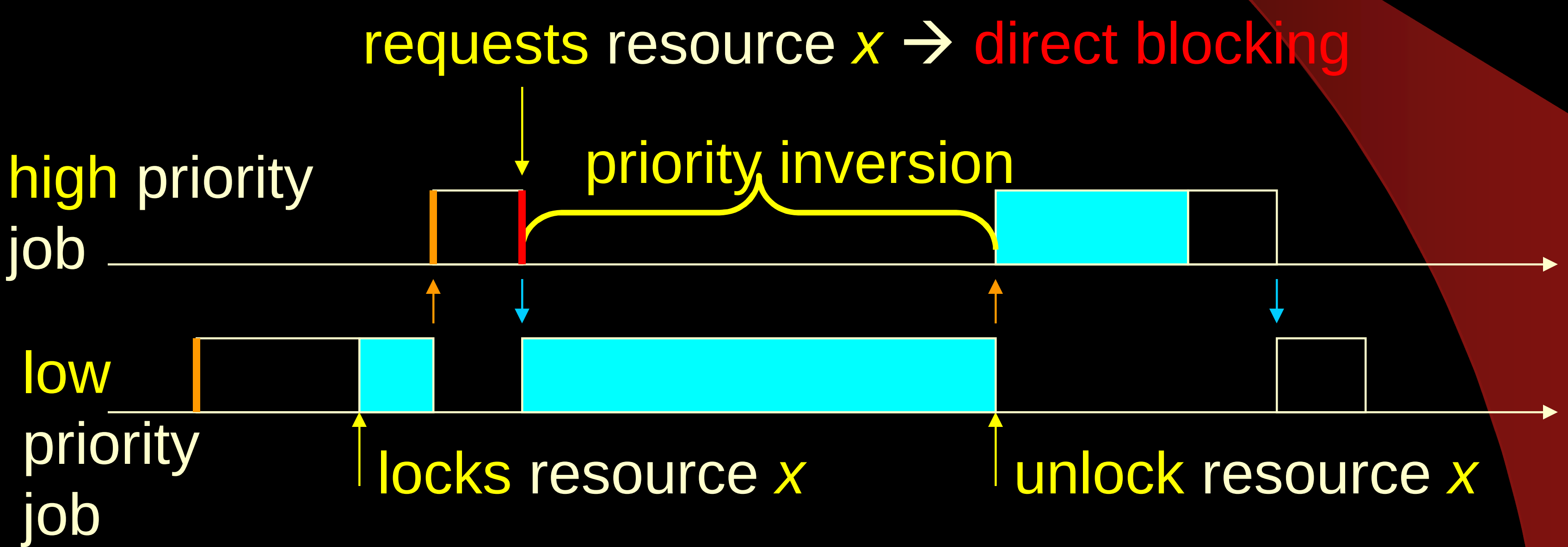
  - **jobs must contend for the resource**

- **access control protocol: set of rules for**

1. **granting resources**
2. **scheduling jobs requesting resources**

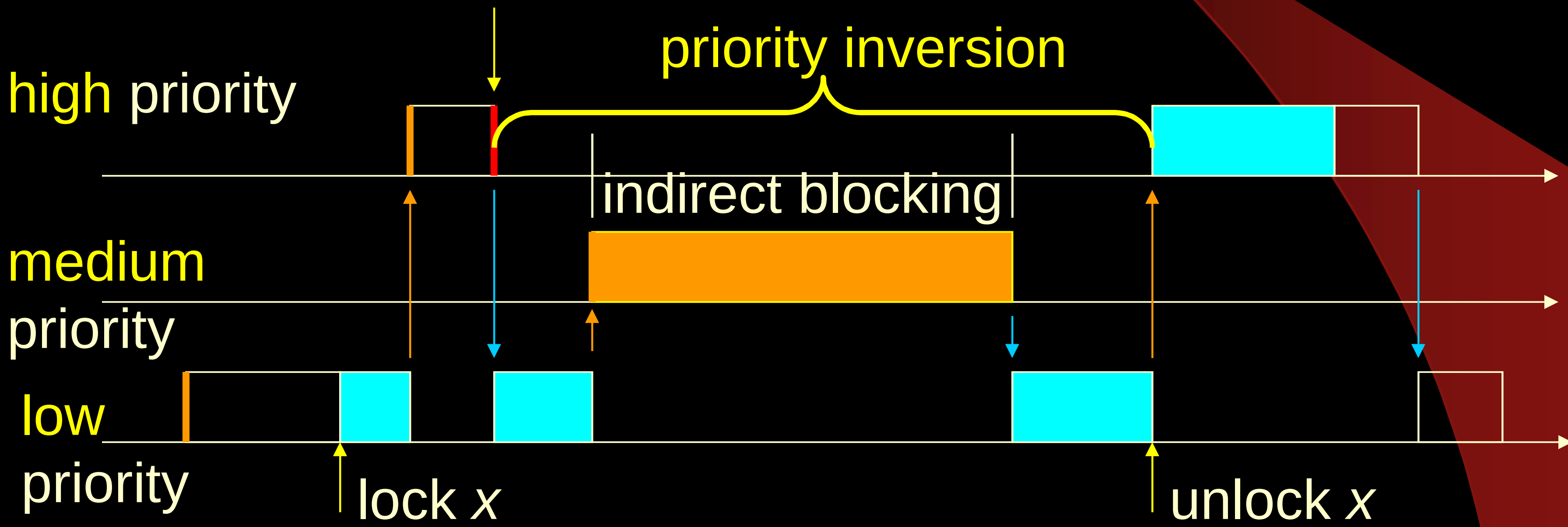
Priority Inversion

- a higher priority job is prevented from executing by a lower priority job
  - the priority relationship is inverted!



Unbounded Priority Inversion

- **duration of priority inversion is not a function of the time for low priority job to execute the relevant critical section**



Worst Case Job Response Time

- preemption time: delay due to higher priority job
- execution time: time to do job's work
- blocking time: time spent blocked
  - hopefully, blocking time is a simple function of delays while lower-priority jobs execute critical sections
    - if not, then difficult to compute (unbounded)

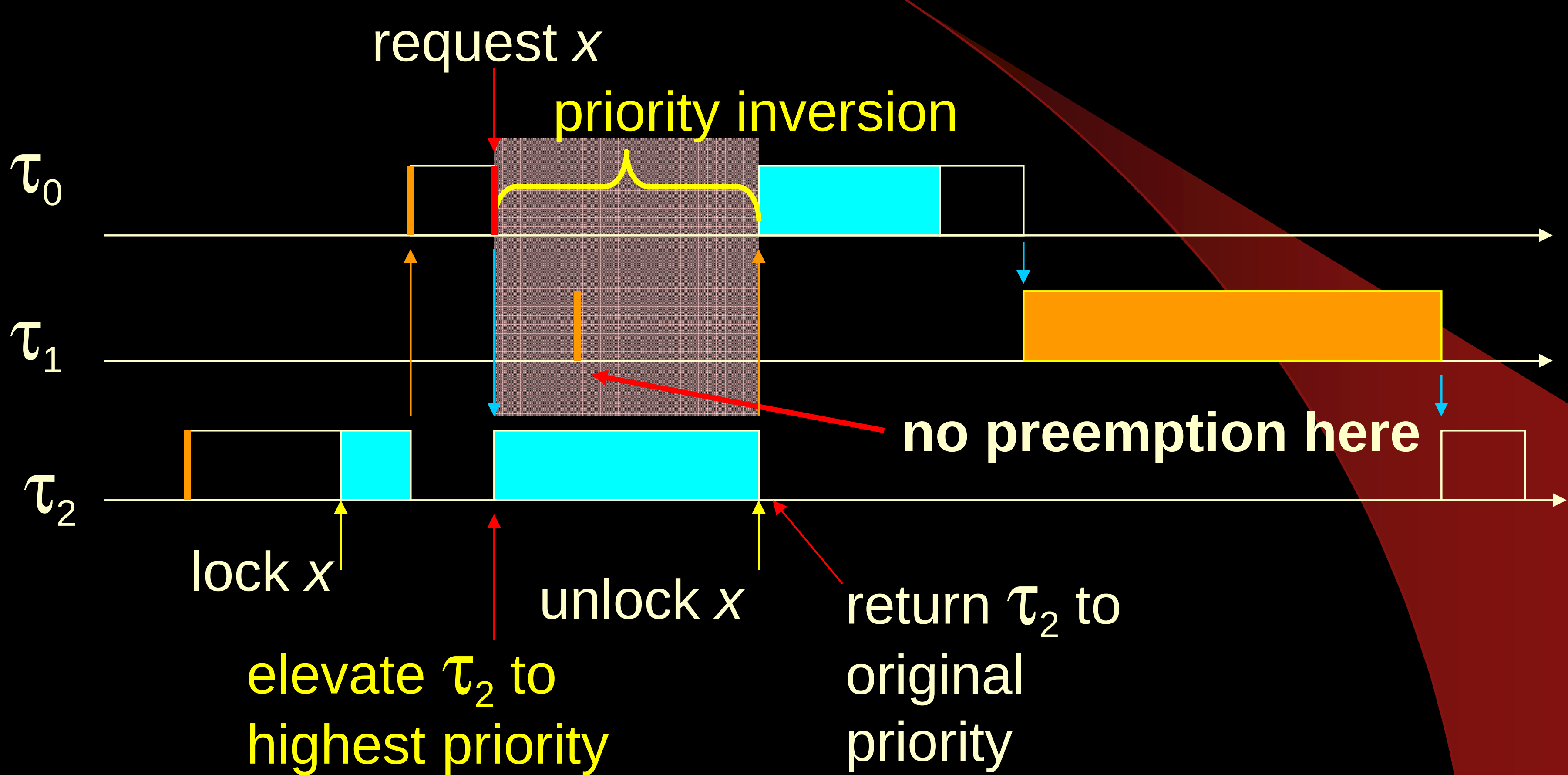
Avoiding Unbounded Priority Inversion

1. **disable preemption**
2. **priority inheritance protocol**
3. **priority ceiling protocol**

Disable All Preemption

- **disable preemption during critical sections**
- **effectively elevate job in critical section to highest priority (cannot be preempted)**
- **priority elevation only needed when higher-priority jobs are requesting the relevant critical section – in other cases, the lower priority job should be preemptable by higher-priority jobs**
- **OK if critical sections are <u>very short</u> relative to shortest deadlines**

Disable Preemption for Unbounded PI Example



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Variation on Disable Preemption: Priority Ceiling Emulation

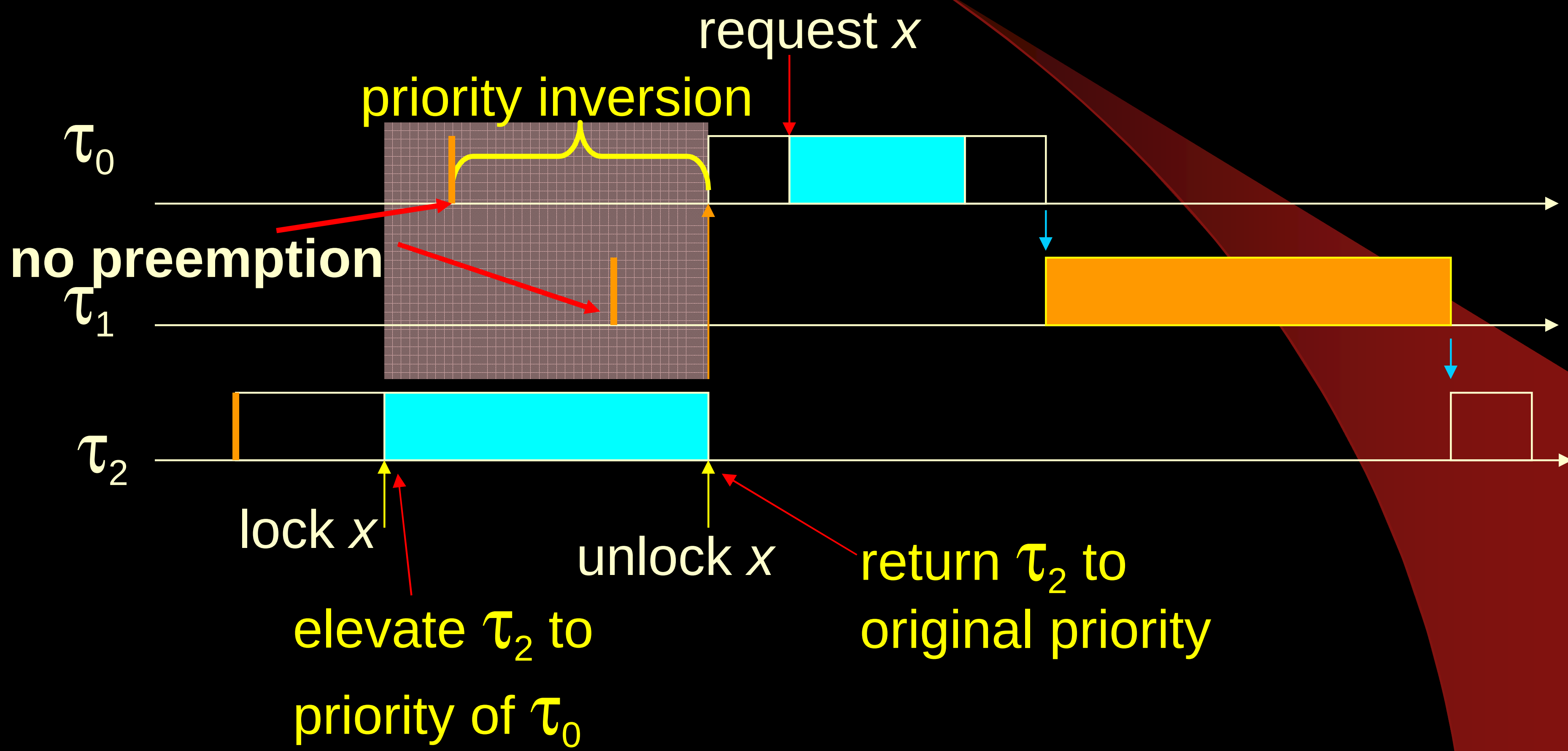
Priority Ceiling:

- the **priority ceiling** of resource R_i is the highest priority of all jobs that require access to R_i at any time during their operation
- denote $\Pi(R_i)$
- Q: do any jobs with priority higher than $\Pi(R_i)$ access R_i ?

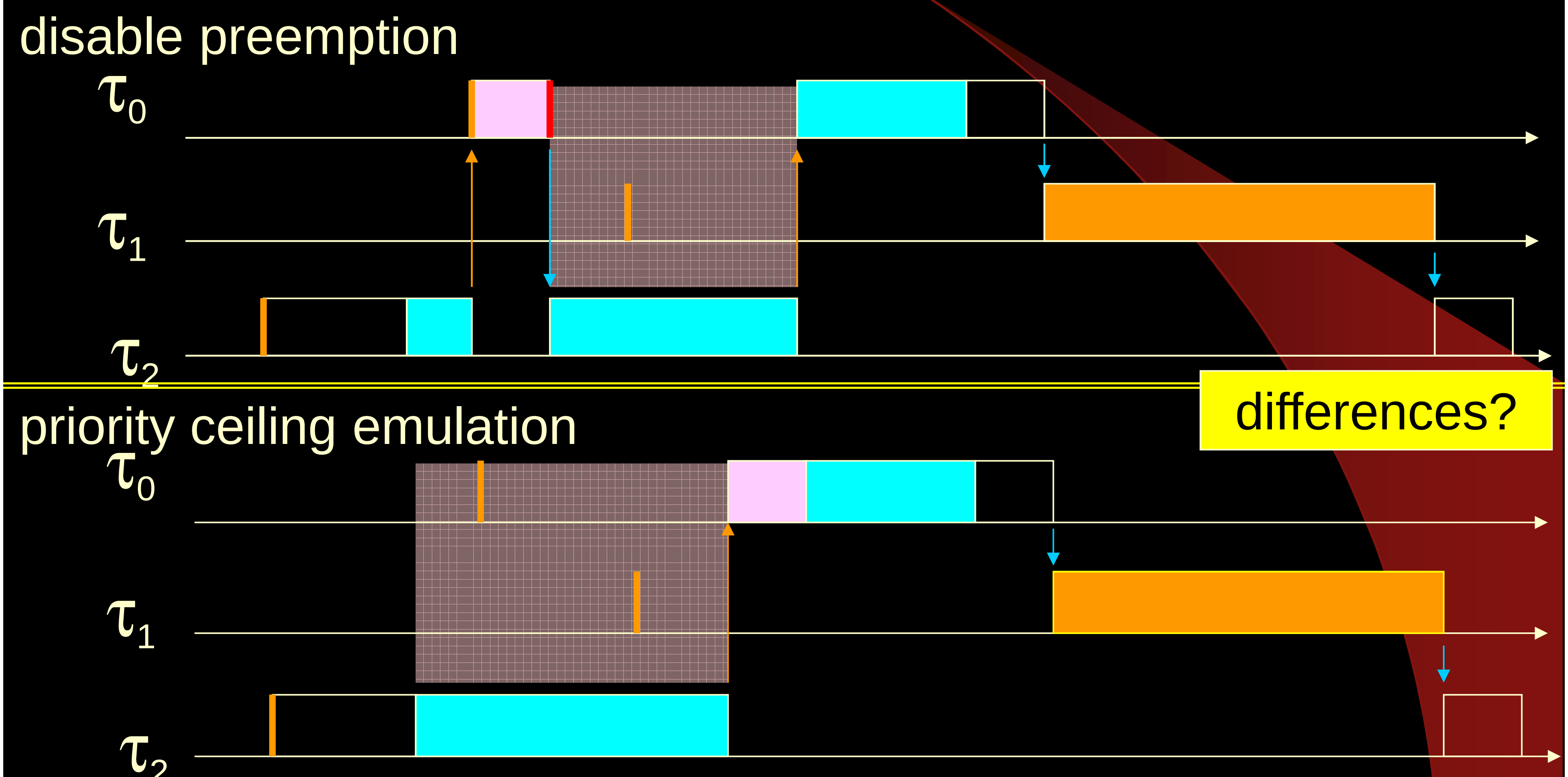
Priority Ceiling Emulation

- in critical section, job runs at priority = priority ceiling for the resource
  - i.e. no job that <u>might</u> request access to the resource is able to run!
- job in critical section disables all jobs that <u>might</u> access critical section
- at end of critical section, job returns to original priority
- jobs at priority higher than the ceiling are still eligible to run

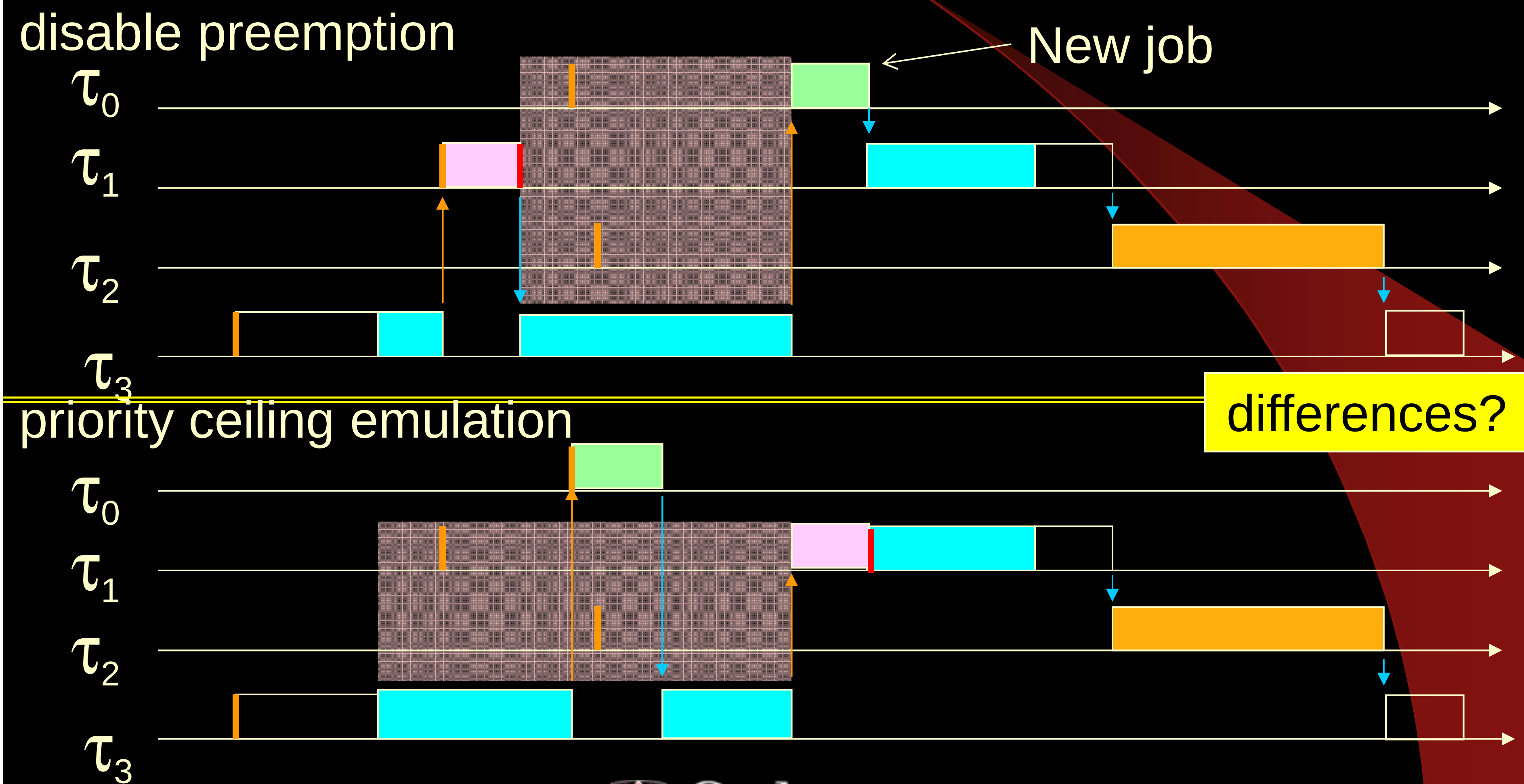
Priority Ceiling Emulation for Unbounded PI Example



Priority Ceiling Emulation vs. Disable Preemption Example 1



Priority Ceiling Emulation vs. Disable Preemption Example 2



Basic Priority Inheritance Protocol

- while a job_{low} is holding any resource: raise its priority to the highest priority of any job **requesting** any resource held by job_{low}
- **dynamic** → raise at time higher priority job requests the resource
- when unlock a resource: assign job_{low} the higher of (1) its original priority, or (2) the highest priority of a job requesting a resource held by job_{low}

Lowering Priority Scenario

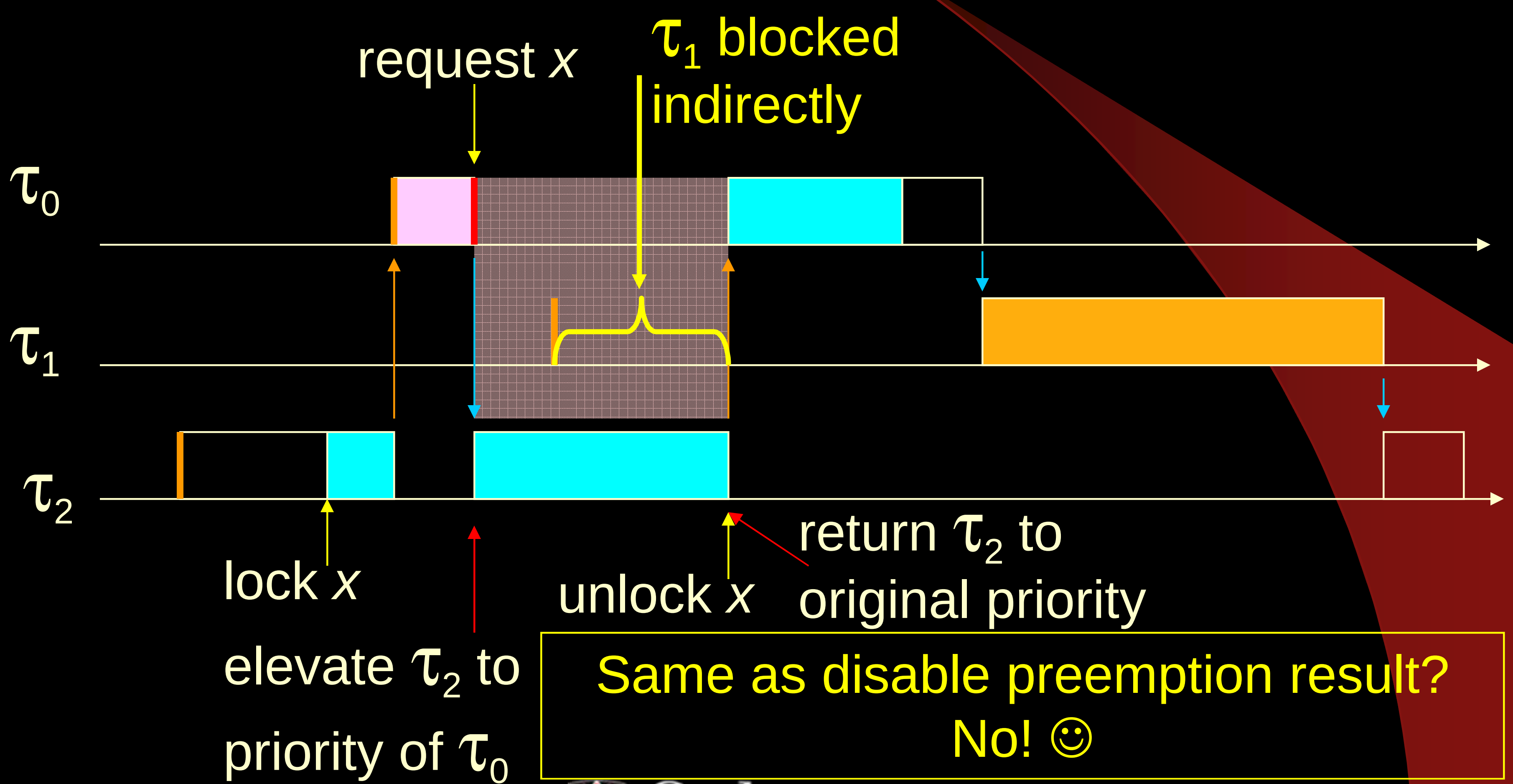
- Suppose job_{low} holds resource 1 and it is then requested by job with priority τ_2

  → raise job_{low} to priority τ_2
- Now job_{low} acquires resource 2 and it is then requested by job with priority τ_1

  → raise job_{low} to priority τ_1
- Now job_{low} releases resource 1

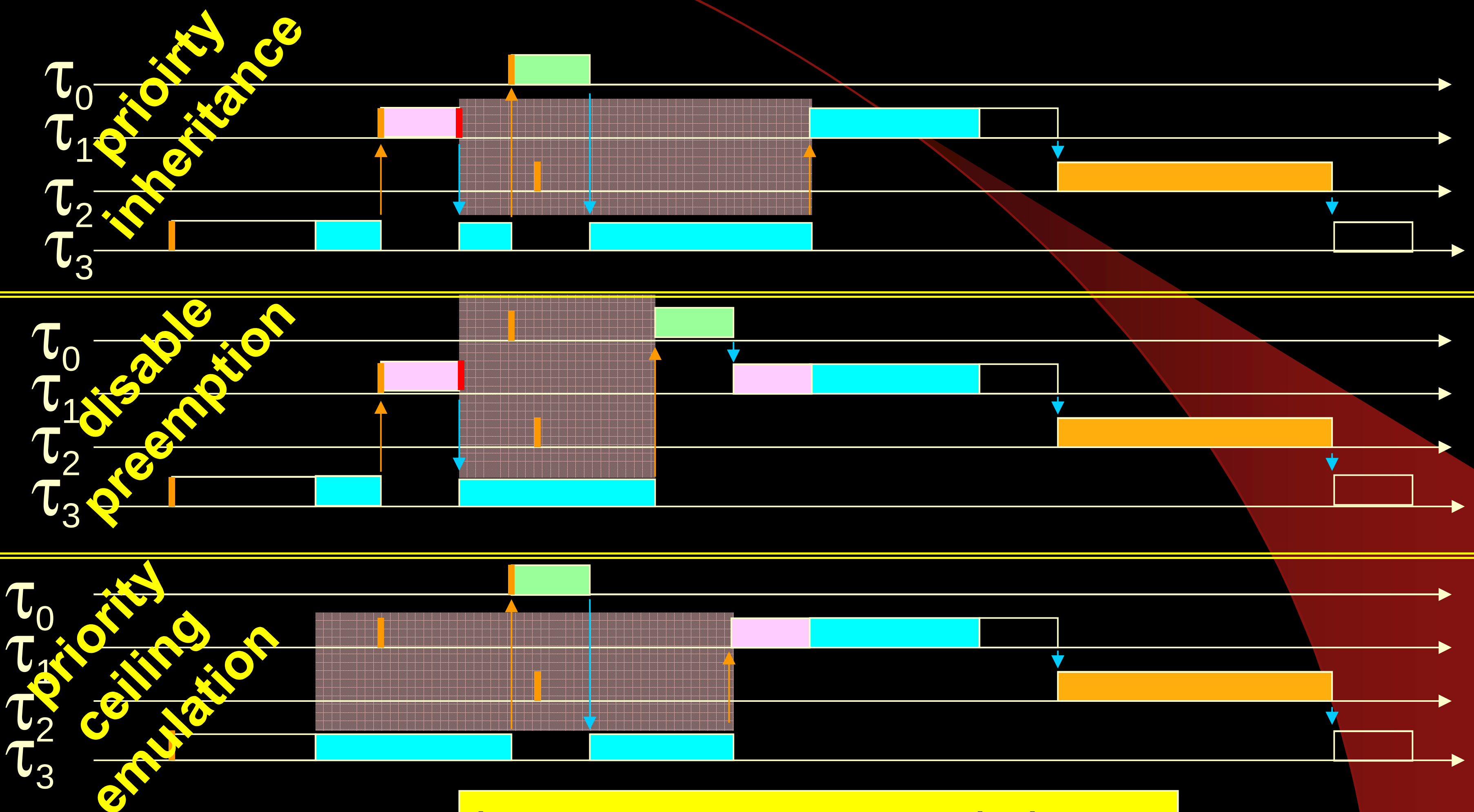
  → what should be priority of job_{low} now?
  - How does this fit with the rule on previous slide?

Basic Priority Inheritance for Unbounded PI Example



Same as disable preemption result?
No! ☺

What about All Three?



how many context switches?

response times?

blocking?

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Is Blocking a Function of Time to Execute Critical Sections?

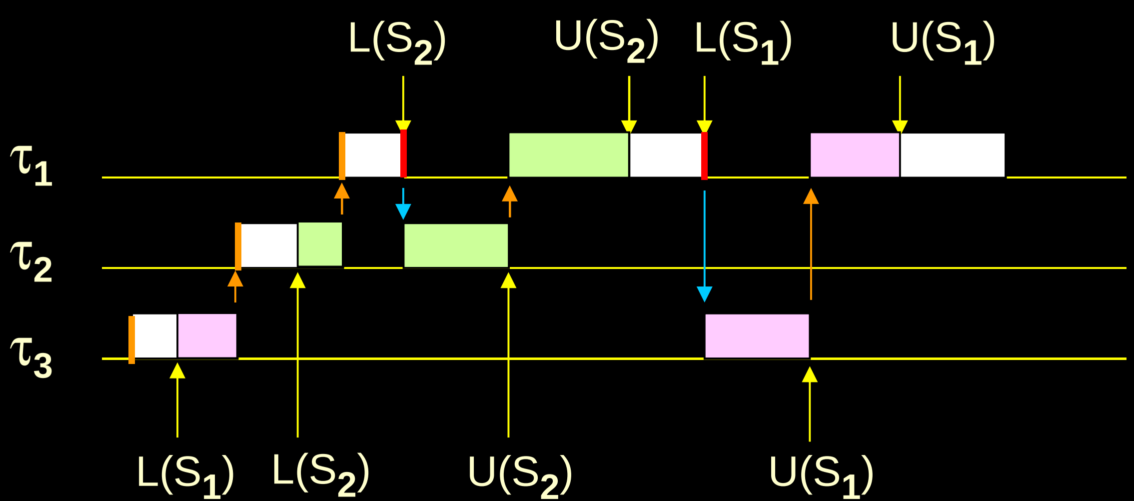
- suppose *m* critical sections accessed by task τ
- job of τ can be blocked directly, at most, m times
  - not counting indirect blocking!
- if *n* tasks at lower priority than τ
  - job of τ can be blocked, at most, at one critical section in each of the n tasks
  - blocking time is bounded, ☺ but ... may suffer from "chain blocking" – blocks each time attempt to access a critical section

Chain Blocking Example

τ_1 : $L(S_2)$ $U(S_2)$ $L(S_1)$ $U(S_1)$

τ_2 : $L(S_2)$ $U(S_2)$

τ_3 : $L(S_1)$ $U(S_1)$



τ_1 blocked each time it tries to access a critical section

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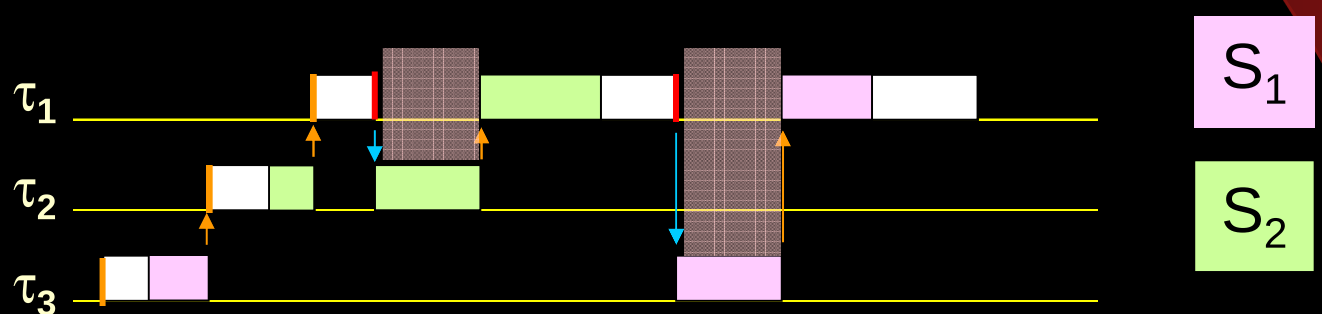
Chain Blocking for Disable Preemption & Priority Inheritance?

- **still a problem!**
- **previous example:**



Same behaviour for both? WHY?

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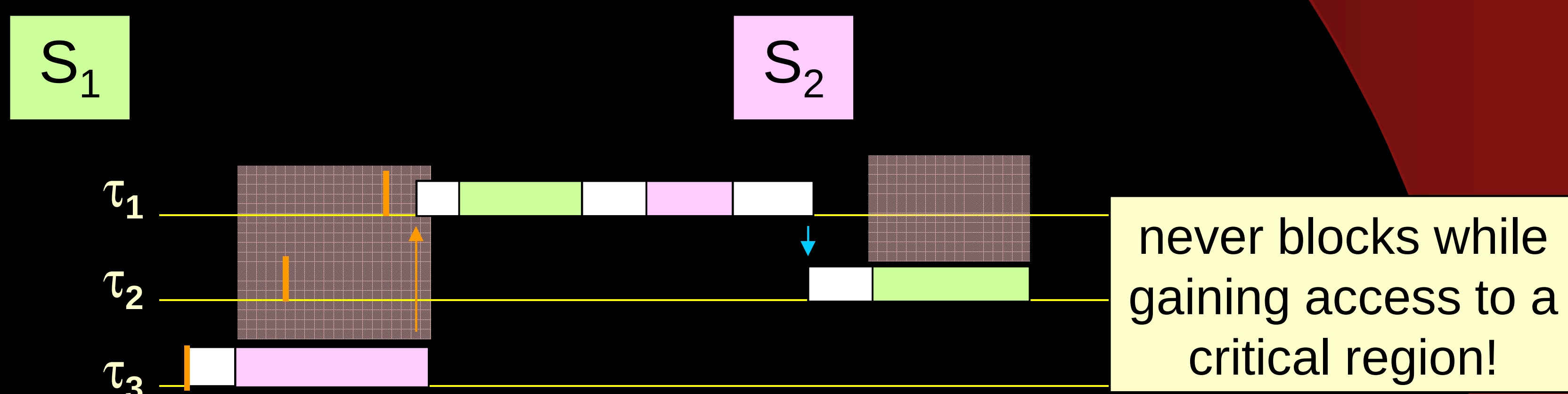
Chain Blocking for Priority Ceiling Emulation?

- never blocks on request!
- resource always available (GOOD!) … **WHY?**
- for previous example:

$\Pi(S_1) = \pi(\tau_1)$ $\Pi(S_2) = \pi(\tau_1)$



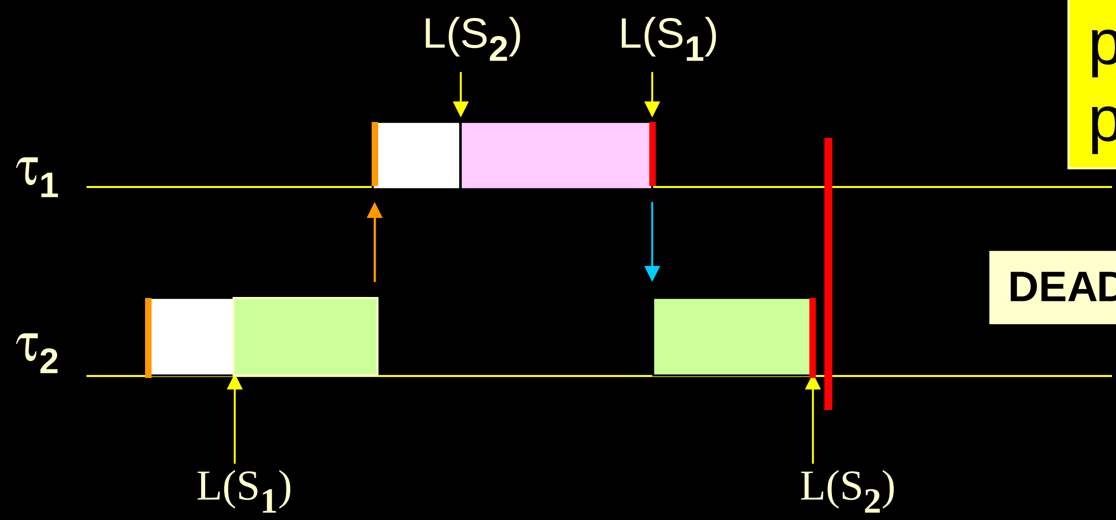
Potential Deadlock

- loop of tasks blocked waiting for each other

τ_1 : $L(S_2)$ $L(S_1)$ $U(S_1)$ $U(S_2)$

τ_2 : $L(S_1)$ $L(S_2)$ $U(S_2)$ $U(S_1)$

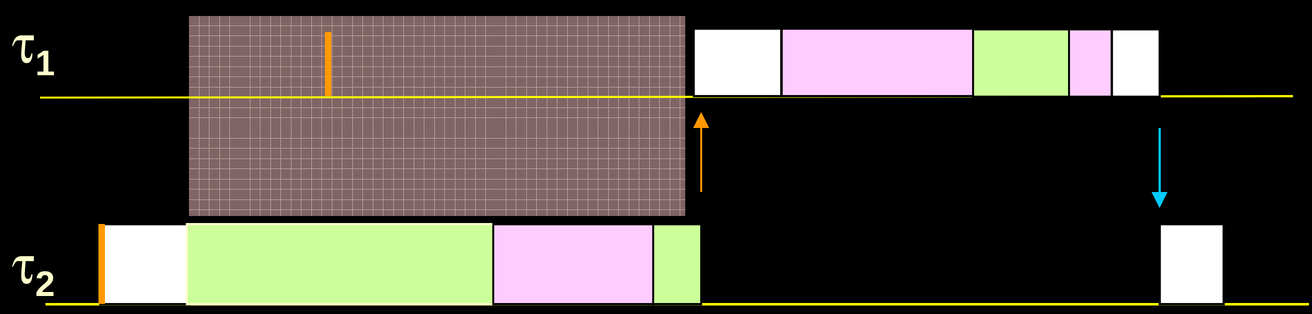
problem for disable preemption & priority inheritance



DEADLOCK!

Deadlock for Priority Ceiling Emulation?

- no!
- resource always available **WHY?**



No DEADLOCK!

Performance vs. Penalty

- **priority ceiling emulation looks "best" in terms of performance**
  - **penalty? → may delay higher priority jobs even though no conflict would occur**
    - **→ unnecessary priority inversion!**
- **disable preemption & priority inheritance**
  - **only elevate priority when a conflict occurs → avoids unnecessary priority inversion**

Basic Priority Ceiling Protocol

- **combine priority ceiling emulation with priority inheritance protocol**
  - ✓ **priority ceiling**
  - ✓ **inheritance only when conflict**

meaning of "conflict" is key!

- **current priority ceiling: $\hat{\Pi}(t)$**

  highest priority ceiling of <u>all</u> resources <u>currently in use</u>

Basic Priority Ceiling Protocol Rules

Scheduling Rule:

- **job released at <u>assigned</u> priority**
- **preemptive and priority driven at job's current priority**

Allocation Rule: when J requests R at time t

- **if R already locked – request denied and J blocked**

Allocation Rule (con't)

if **R** is free:

i. if priority of **J** at **t** > $\hat{\Pi}(t)$, allocate **R** to **J**

- J does not access any of the held resources!

ii. else: if **J** is the job holding the resource(s) whose priority ceiling = $\Pi(t)$, allocate **R** to **J**

- Not possible for different jobs to hold resources with same priority ceiling! (see i. and iii.)

iii. otherwise: request denied and **J** is blocked

Allocation Rule (paraphrasing)

- a job <u>cannot</u> acquire a resource unless its priority is higher than the ceilings of all other resources currently acquired by other jobs
- if priority higher than ceilings, then job will not request access to any of the other active resources (by the definition of a ceiling!)
- when request denied and job is blocked, higher priority jobs <u>might still be able to acquire resource</u>! (deny access ≠ FIFO blocking)

Priority-Inheritance Rule

- while a job_{low} is holding any resource: raise its priority to the highest priority of any job **requesting** any resource held by job_{low}
- **dynamic**: at time **t** when a job **J** becomes blocked, the job J_{low} which blocks **J** inherits the current priority of **J**
- J_{low} executes at inherited priority until **t′** when it releases every resource whose priority ceiling is greater or equal to the inherited priority
- at **t′**: priority of J_{low} falls to the higher of (1) its original priority, or (2) the priority of the highest job requesting one of the resources still held by J_{low}

Lowering Priority Scenario

- Suppose job_{low} holds resource 1 with priority ceiling π_3 which is then requested by job with priority π_4 (rules?)
  → raise job_{low} to priority π_4
- Now job_{low} acquires resource 2 with priority ceiling π_1 which is then requested by job with priority π_2 (rules?)
  → raise job_{low} to priority π_2
- Now job_{low} releases resource 1
  → what should be priority of job_{low} now? (rules?)
- Now job_{low} releases resource 2
  → what should be priority of job_{low} now? (rules?)
- What if resources released in other order? (rules?)

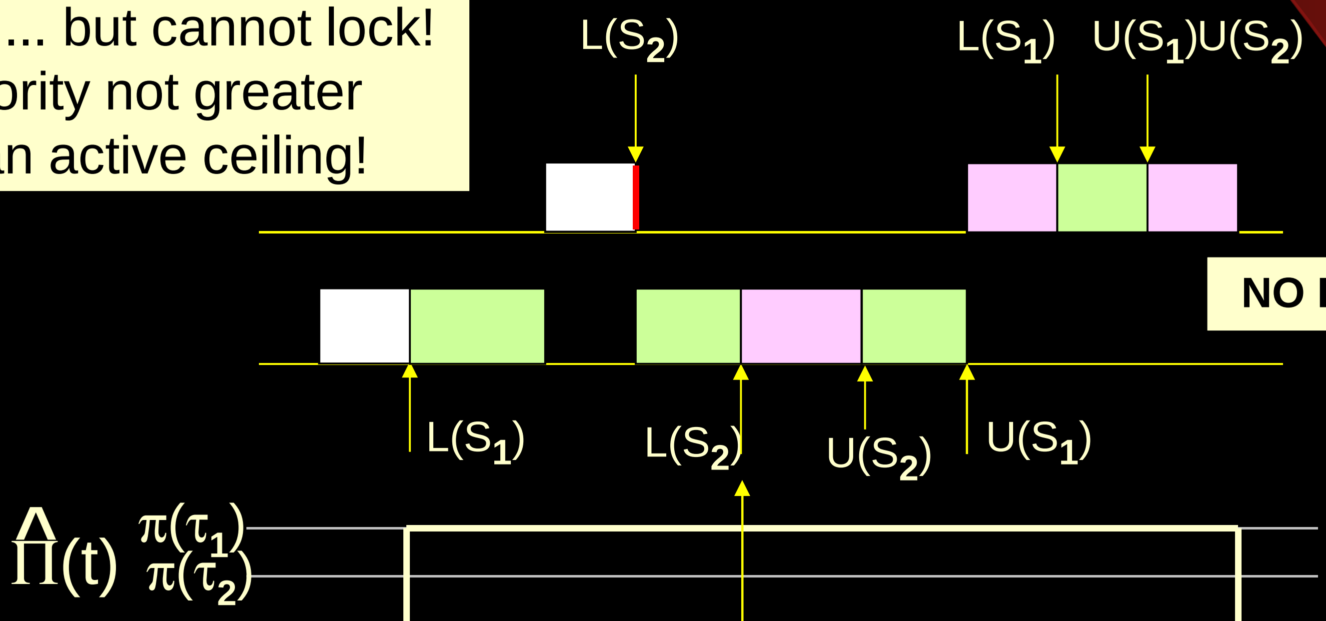
Recall Previous Deadlock Example

τ_1 : $L(S_2)$ $L(S_1)$ $U(S_1)$ $U(S_2)$

τ_2 : $L(S_1)$ $L(S_2)$ $U(S_2)$ $U(S_1)$

$$\Pi(S_1) = \pi(\tau_1) \qquad \Pi(S_2) = \pi(\tau_1)$$

try ... but cannot lock!
priority not greater
than active ceiling!



NO DEADLOCK

why can τ_2 lock S_2?

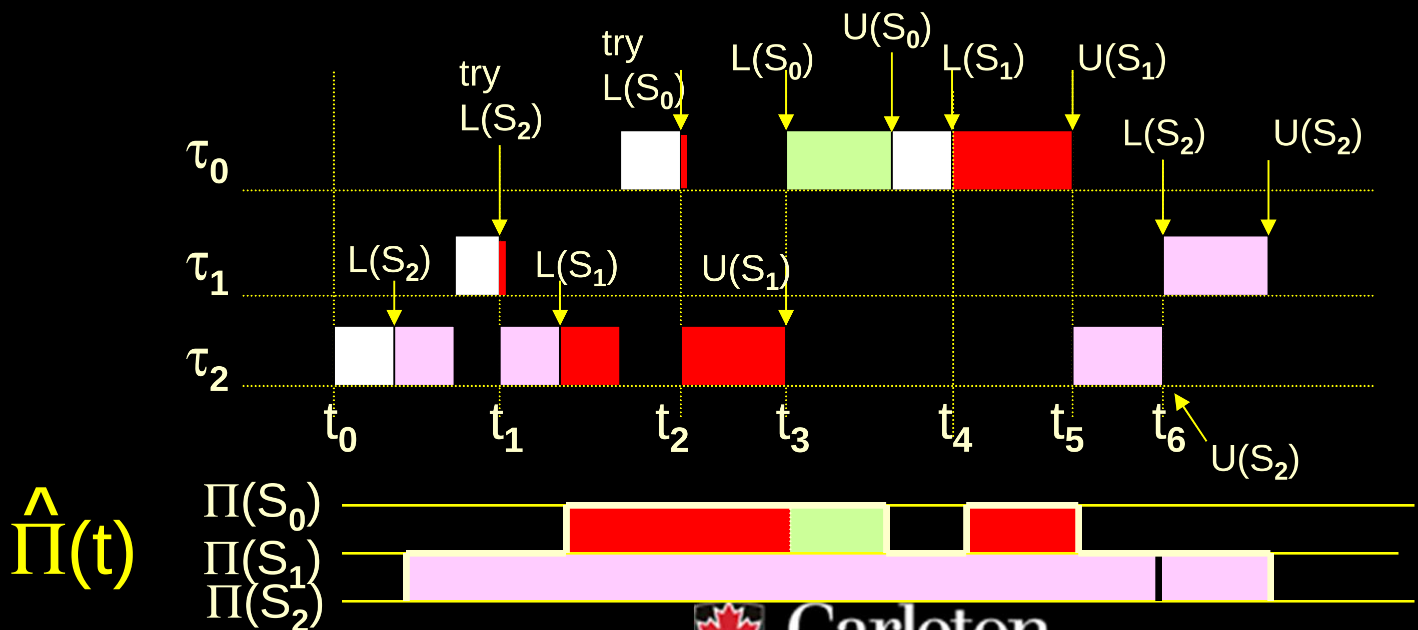
Another Example

τ_0 : $L(S_0)$ $U(S_0)$ $L(S_1)$ $U(S_1)$

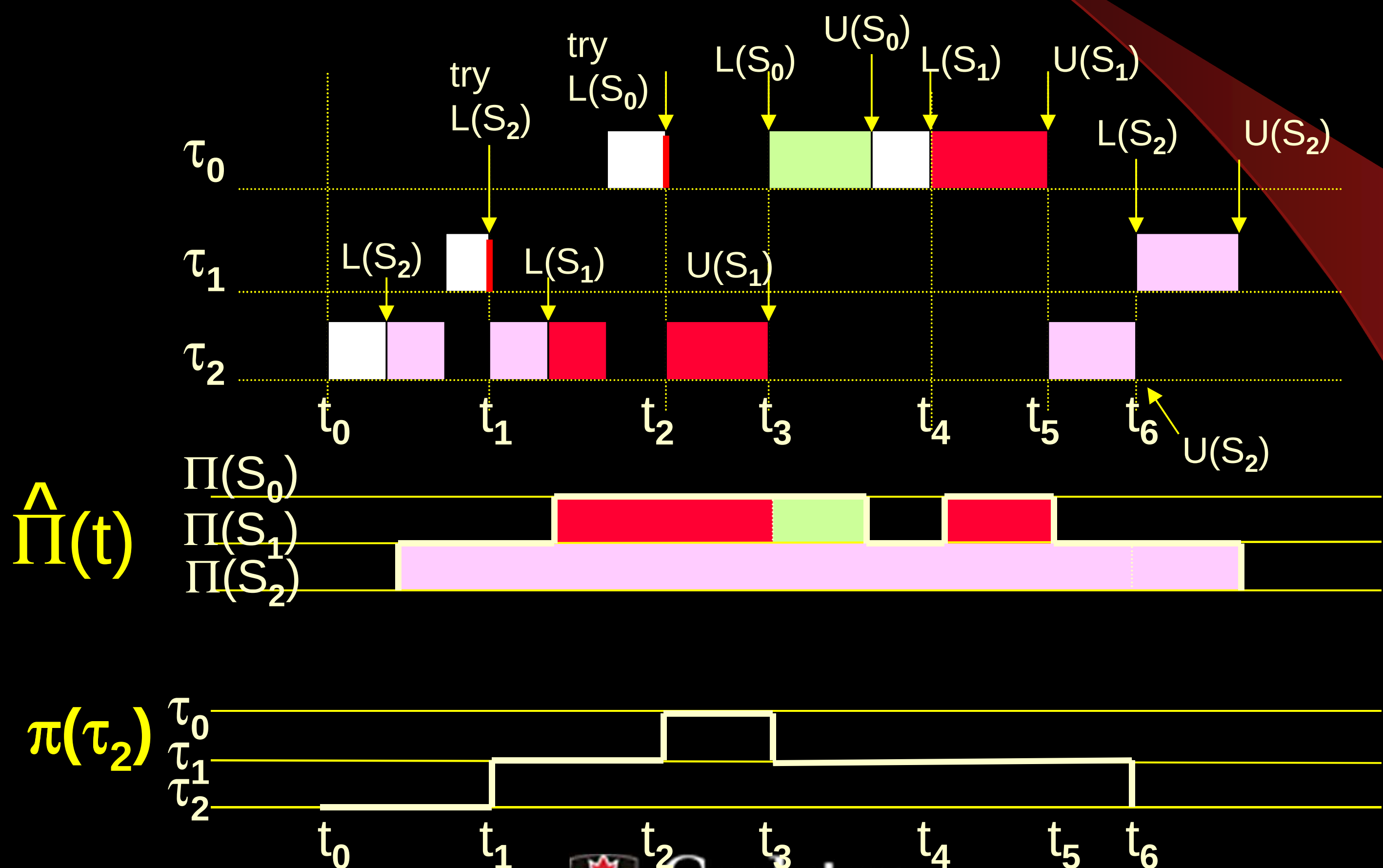
τ_1 : $L(S_2)$ $U(S_2)$

τ_2 : $L(S_2)$ $L(S_1)$ $U(S_1)$ $U(S_2)$

$\Pi(S_0) = \pi(\tau_0)$ $\Pi(S_1) = \pi(\tau_0)$ $\Pi(S_2) = \pi(\tau_1)$



Priority Inheritance in Example



Behaviour

- t_0 : $\pi(\tau_2) = \tau_2$
- t_1 : $\Pi(S_2) = \pi(\tau_1)$ $\therefore$ block, bump τ_2 to $\pi(\tau_1)$
- t_2 : $\Pi(S_1) = \pi(\tau_0)$ $\therefore$ block, bump τ_2 to $\pi(\tau_0)$
- t_3 : $\pi(\tau_2)$ returns to $\pi(\tau_1)$, τ_0 resumes
- t_4 : S_1 free, only other active resource is S_2

  $\Pi(S_2) = \pi(\tau_1) \rightarrow \hat{\Pi}(t_4)$ and $\pi(\tau_0) > \hat{\Pi}(t_4)$

  $\therefore$ allocate S_1 to τ_0
- t_5 τ_2 resumes
- t_6 : $\pi(\tau_2)$ returns to $\pi(\tau_2)$, τ_1 resumes

Points Seen in Example

- **a job is blocked by a (possibly nested) critical section of <u>at most</u> one lower priority job**
- **ceiling blocking occurs – a job is prevented from entering a critical section by ceiling of an active resource → not because the requested resource was busy !**
  - **e.g. t_2: τ_0 is blocked even though S_0 is free**

Properties of Basic Priority Ceiling Protocol

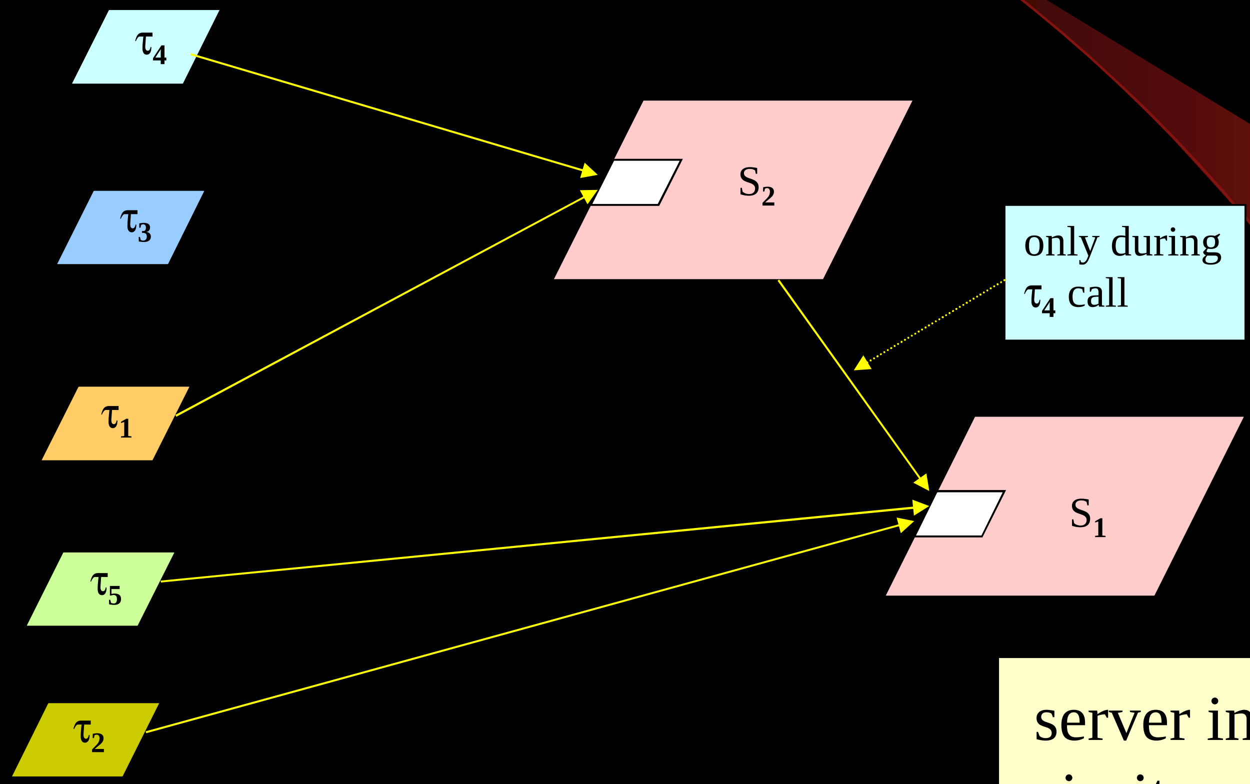
- no deadlock !
- job blocks in at most one critical section
  - blocking is bounded
  - no chain blocking → shorter blocking bound than Priority Inheritance Protocol
- once acquire first resource, all resources needed will be available when requested

Implementation of Basic Priority Ceiling Protocol

- don't need "lock" queues (e.g. semaphore queue)
- maintain queue of tasks that are ready-to-run or blocked – maintain in priority order
- task at head is current task
- need list of active resources – ordered by ceiling priority (includes task that locked the resource, and highest priority of any task blocked waiting for the resource)
- *lock* and *unlock* manipulate queue and list
- need analysis of critical section use – establish priority ceilings prior to run-time

Why is a single queue sufficient?

Example Using Client / Server (similar to Liu text)

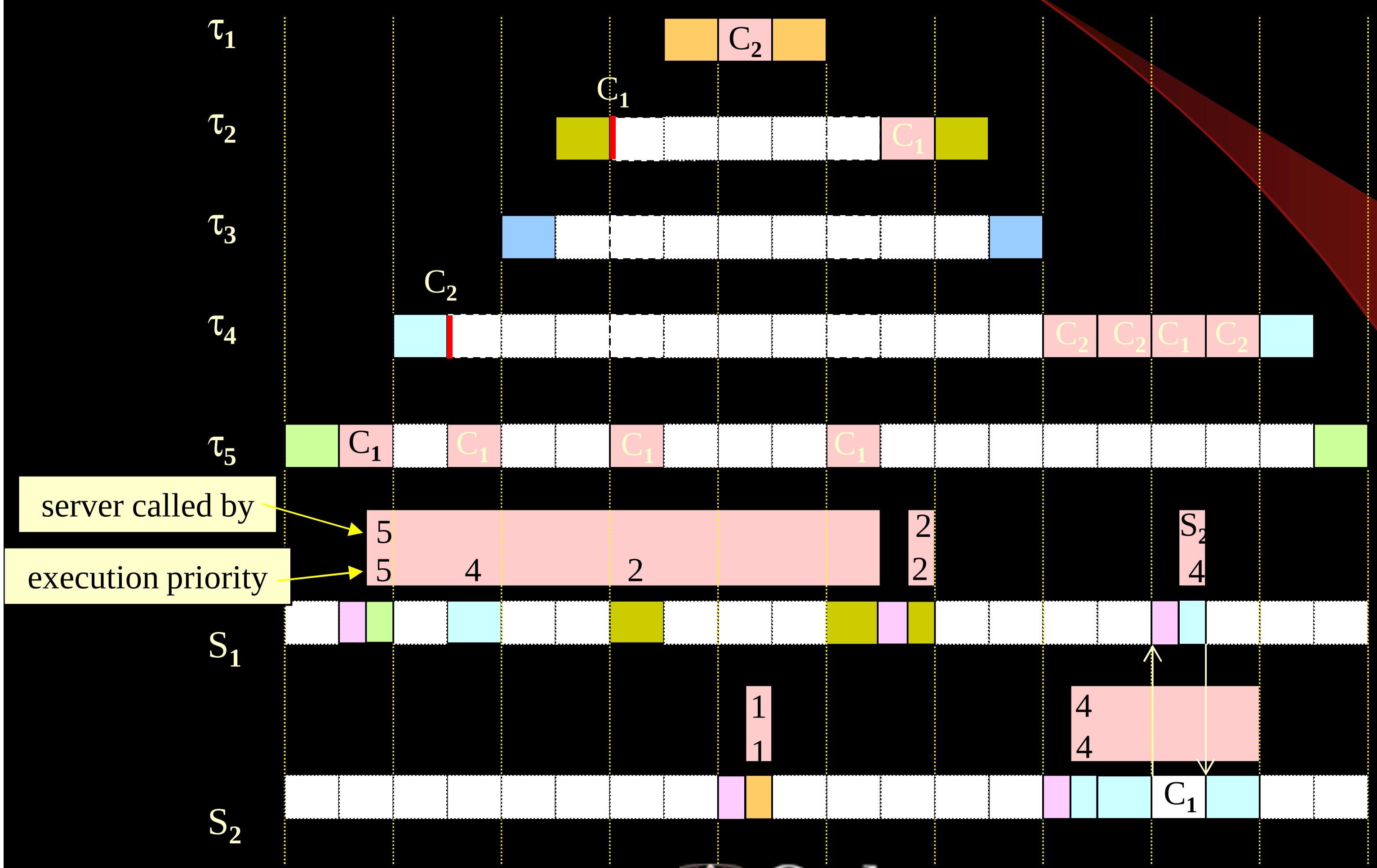


server inherits priority of caller

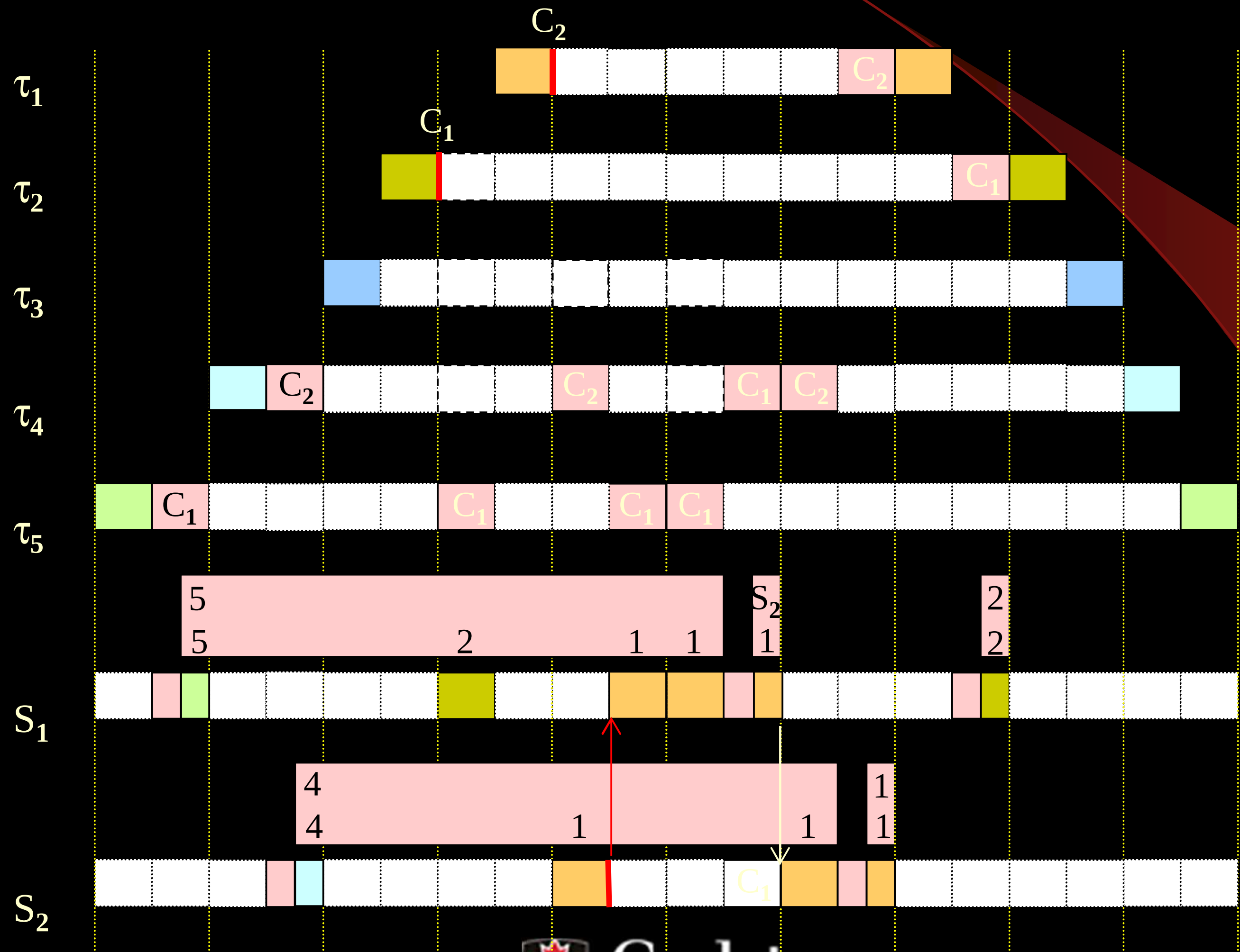
Ceilings in Example

- Ceiling(S_1) = max {τ_2 , τ_4 , τ_5 } (τ_4 indirect)
  = Priority(τ_2)
- Ceiling(S_2) = max {τ_1 , τ_4 }
  = Priority(τ_1)
- τ_3 does not access servers

Basic Priority Ceiling Protocol Behaviour



Basic Priority Inheritance Same Example



Response Comparison