Compositional Schedulability Analysis

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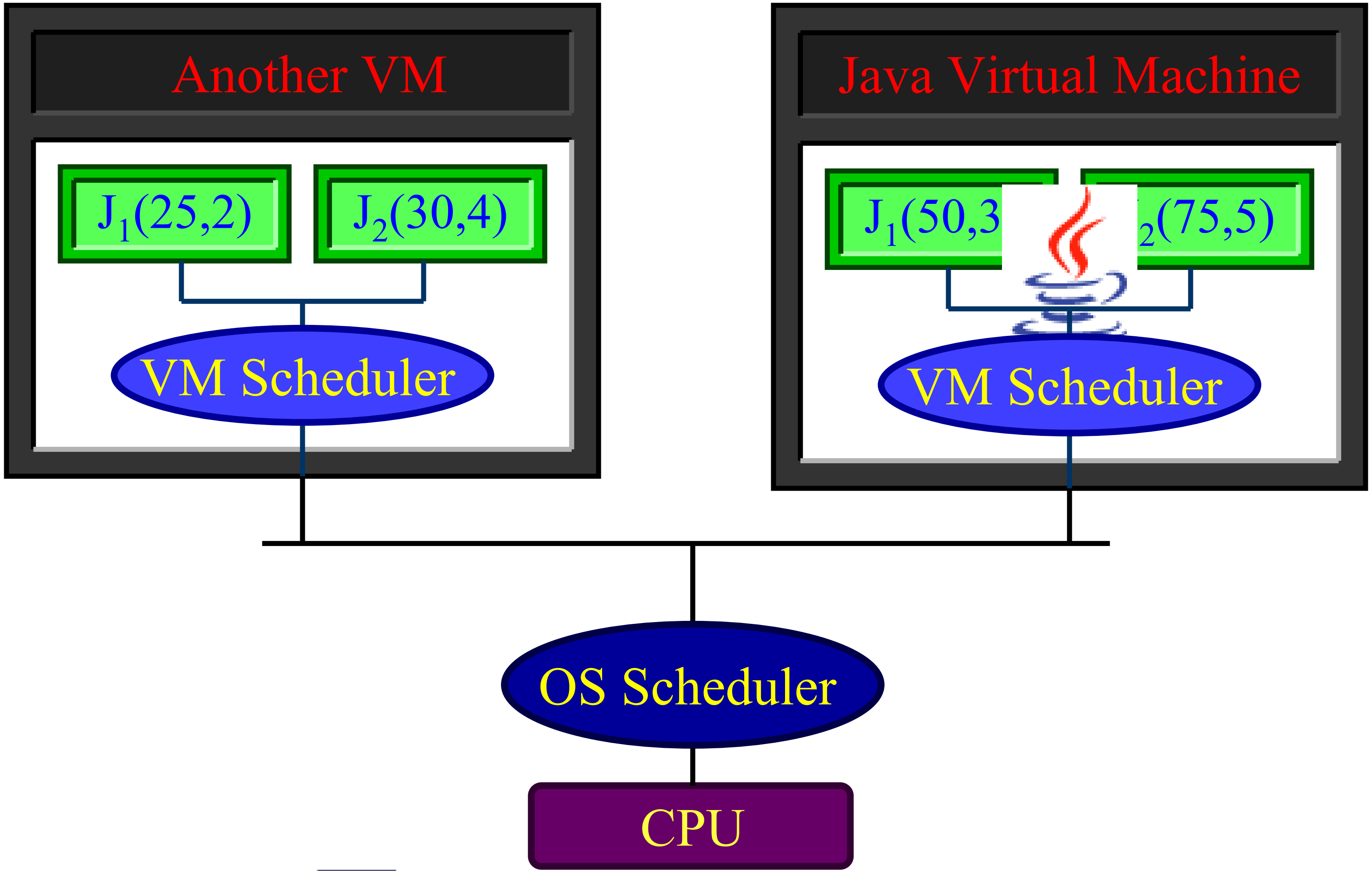
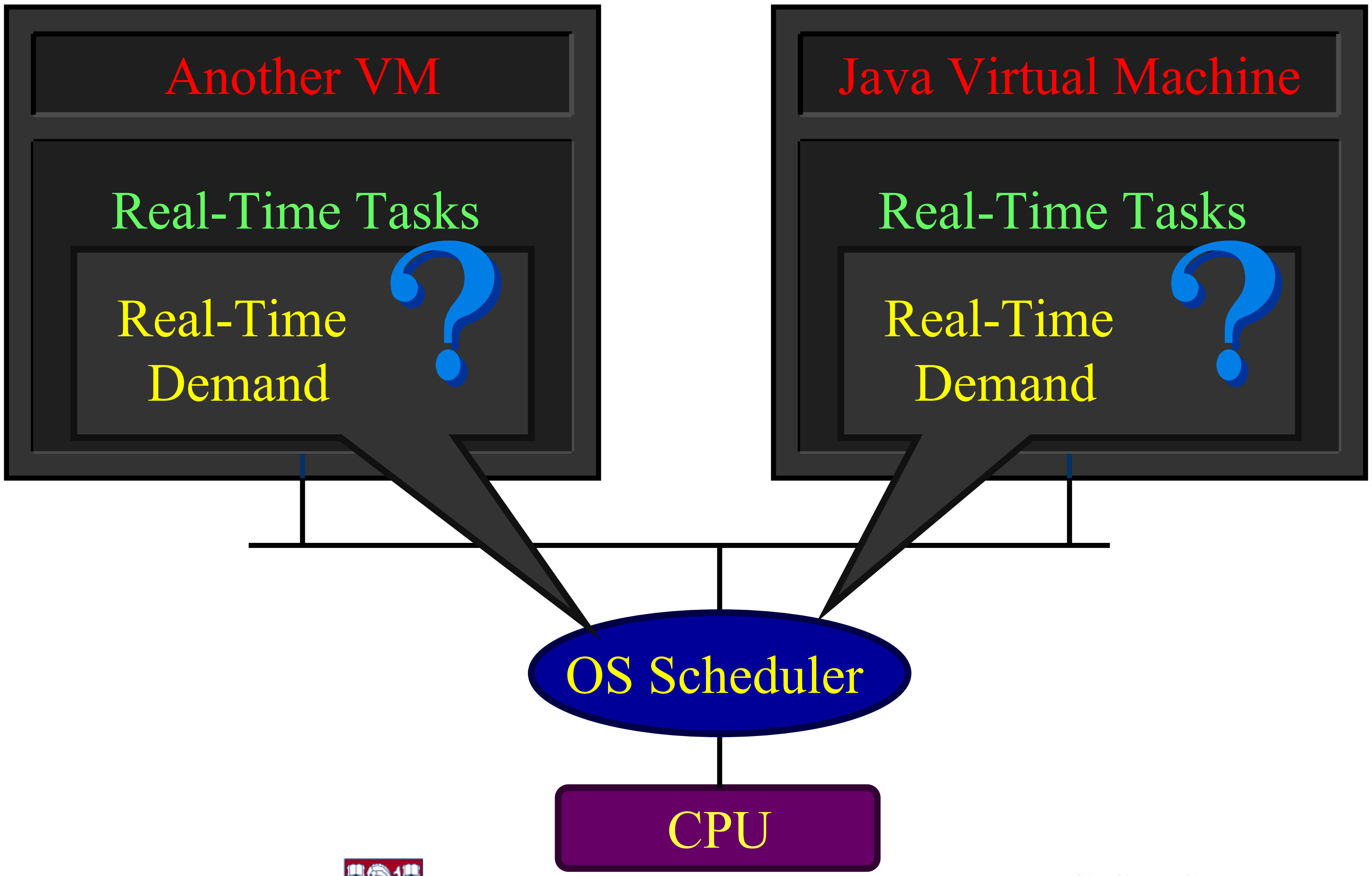
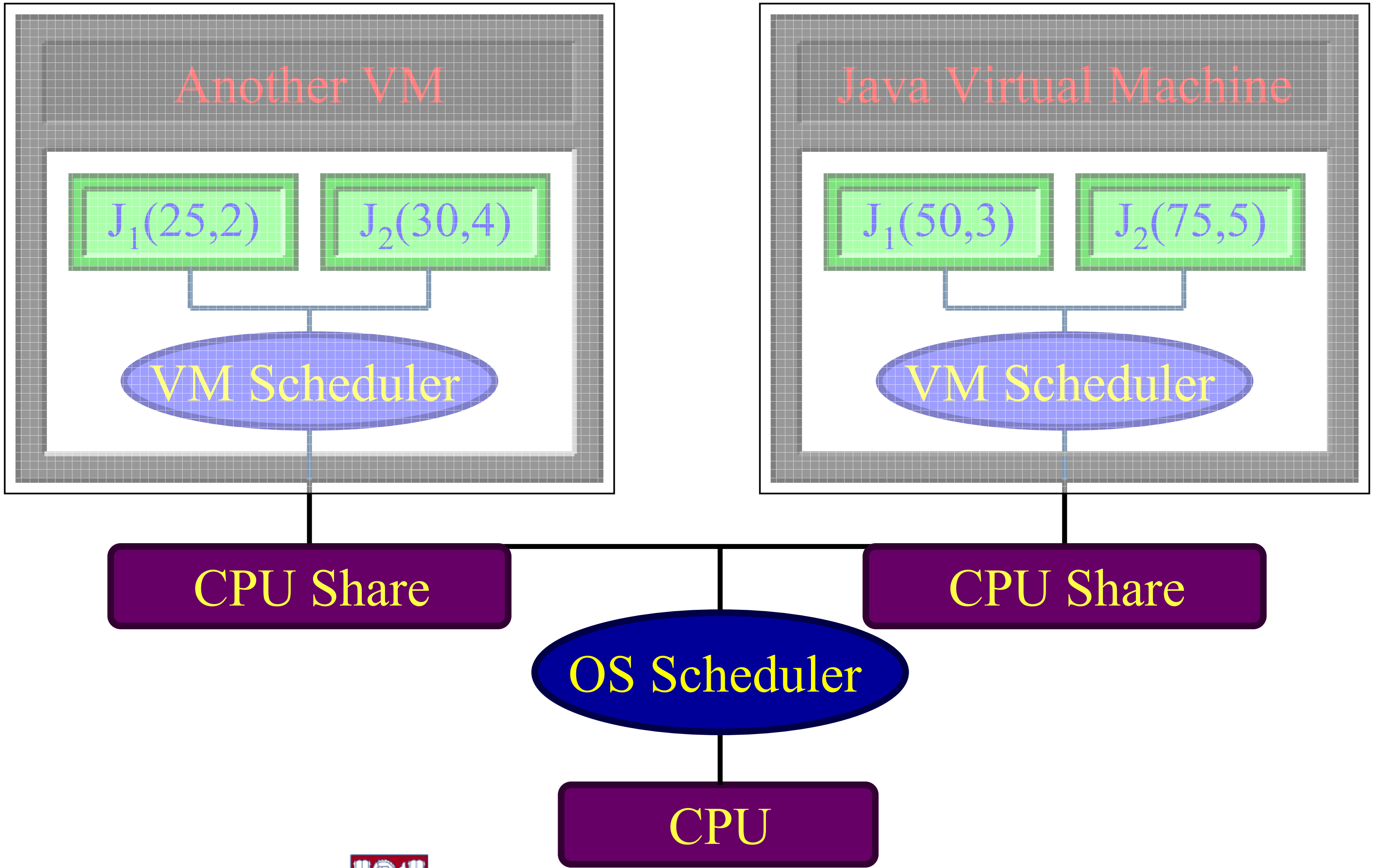
Motivating Example



Component Abstraction



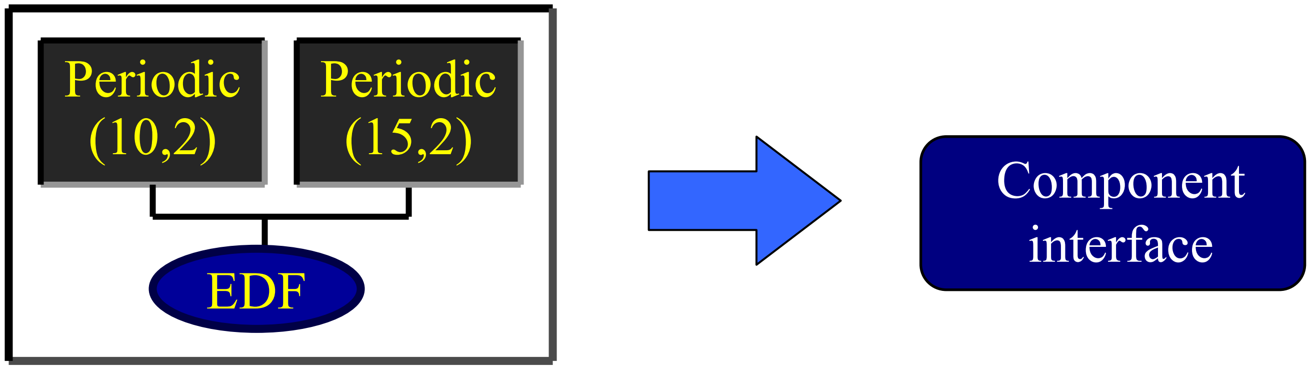
Component Abstraction



The CSA Problem Statement

Two Problems: Abstraction & Composition

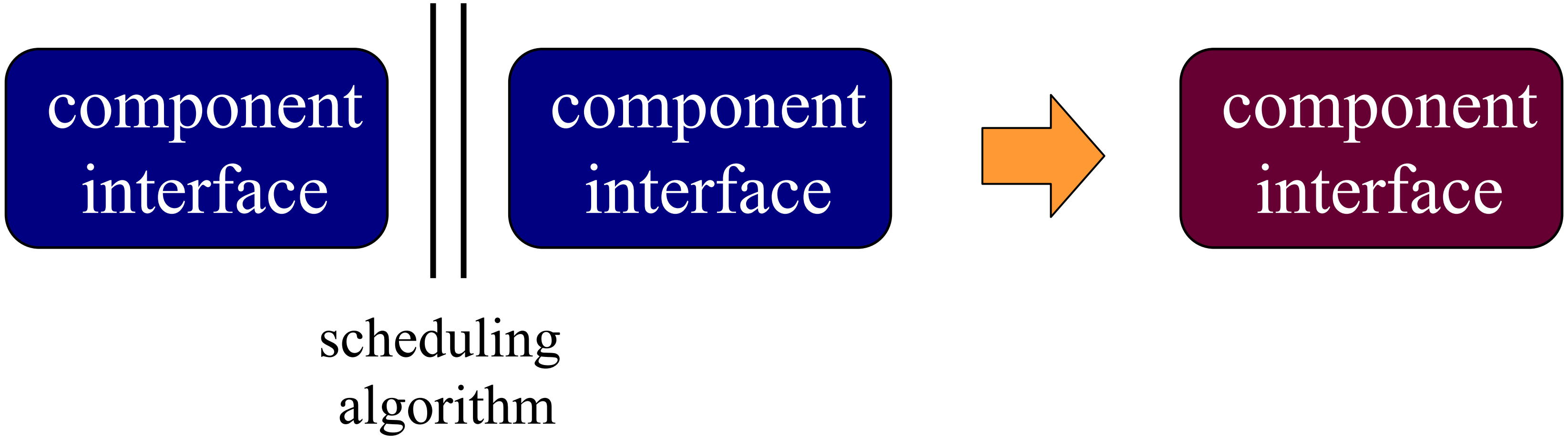
- *Abstraction Problem:* abstracts the real-time requirements of component (application) with *interface*



- Compute the minimum real-time requirements necessary for guaranteeing the schedulability of a component

Two Problems: Abstraction & Composition

- *Composition Problem:* composes component-level properties into system-level (or next-level component) properties



Compositionality

- Compositionality:
  - system-level properties can be established by composing independently analyzed component-level properties
- Compositional reasoning based on assume/guarantee paradigm
  - components are combined to form a system such that properties established at the component-level still hold at the system level.
- Compositional schedulability analysis using the demand/supply bounds
  - Establish the system-level timing properties by combining component-level timing properties through interfaces

Resource Satisfiability Analysis

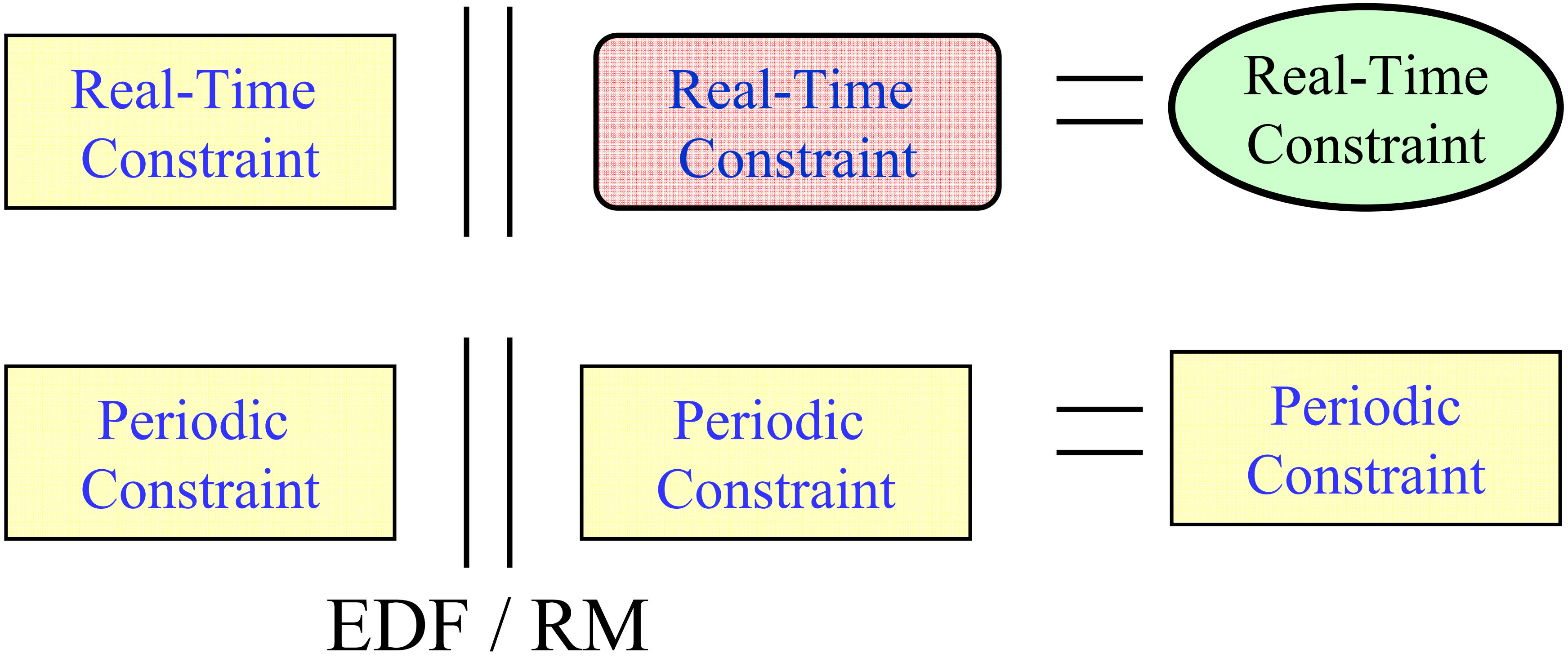
- Given a task set and a resource model, resource satisfiability analysis is to determine if, for every time,

resource demand, which a task set needs under a scheduling algorithm	≤	(minimum possible) resource supply

Resource Demand Models

Real-time demand composition

- Combine real-time requirements of multiple tasks into real-time requirement of a single task



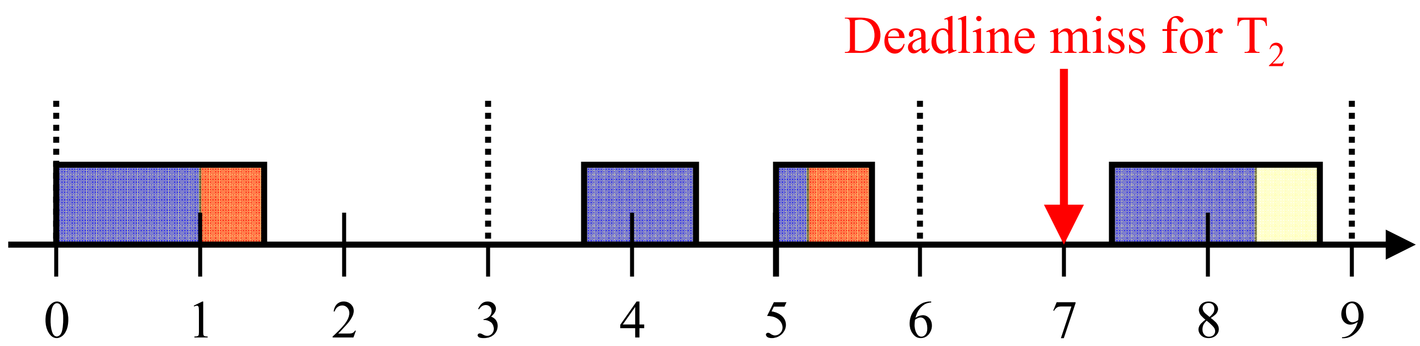
Non-composable periodic models?

- What are right abstraction levels for real-time components?
- (execution time, period)
- P1 = (p1,e1); e.g., (3,1)
- P2 = (p2,e2); e.g., (7,1)
- What is P1 || P2?
  - (LCM(p1,p2), e1*n1 + e2*n2); e.g., (21,10) where n1*p1 = n2*p2 = LCM(p1,p2)
- What is the problem?
  - beh(P1) || beh(P2) = beh(P1||P2)?
- Can we do
  - (P1 || P2) || P3 = P || P3, where P = P1 || P2?

Simple Observation (1)

- Given a task group G such that
  - Scheduling algorithm : EDF
  - A set of periodic tasks : { $T_1(3,1)$, $T_2(7,1)$ },

  model the timing requirements of the task group with a periodic task model
- G (3, 1.43) based on utilization does not work !!

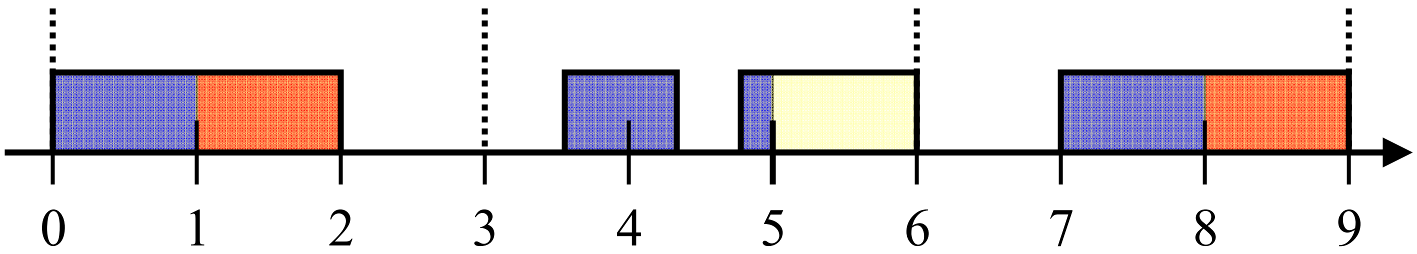


Simple Observation (2)

- Given a task group G such that
  - Scheduling algorithm : EDF
  - A set of periodic tasks : { $T_1(3,1)$, $T_2(7,1)$ },

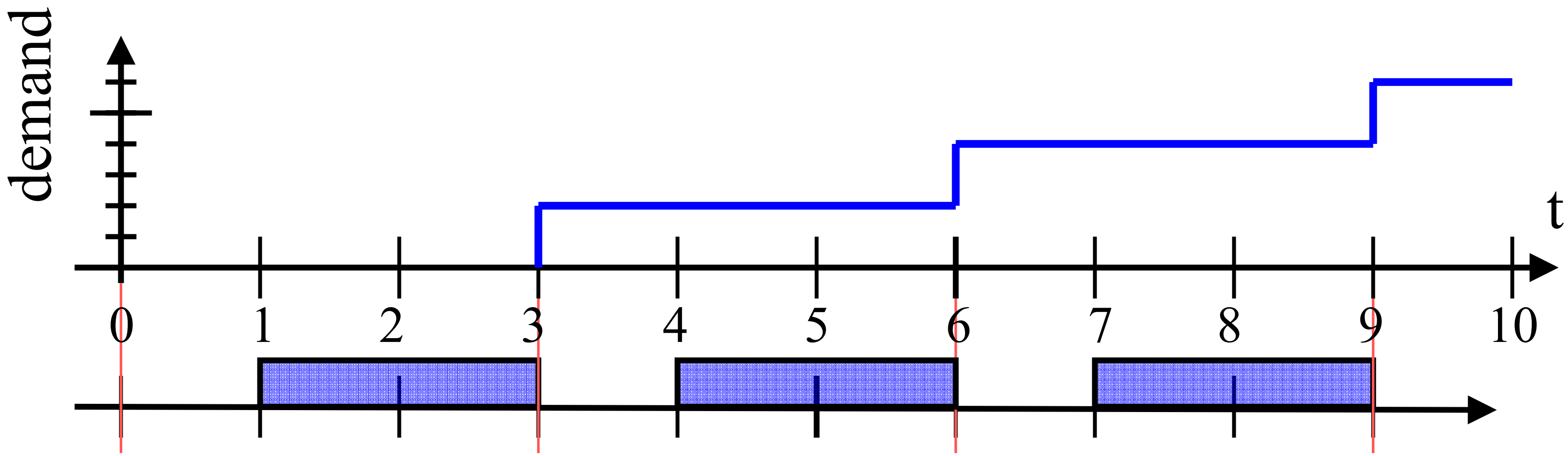
  model the timing requirements of the task group with a periodic task model

- G (3, 2.01) works !!



Resource Demand Bound

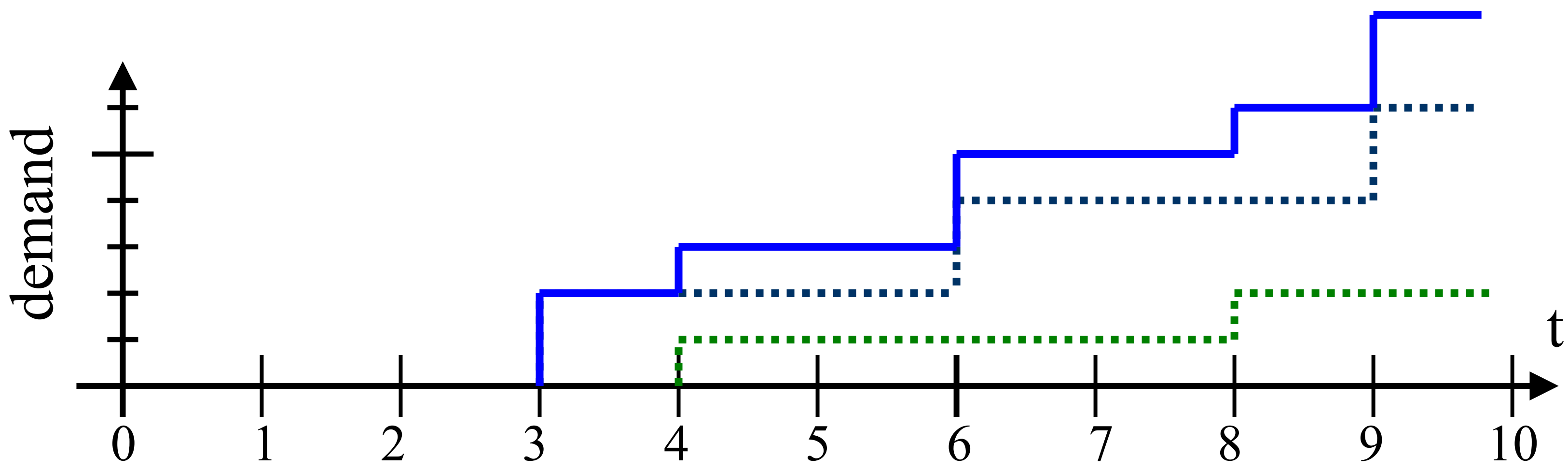
- Resource demand bound during an interval of length t
  - dbf(W,A,t) computes the maximum possible resource demand that W requires under algorithm A during a time interval of length t
- Periodic task model T(p,e) [Liu & Layland, '73]
  - characterizes the periodic behavior of resource demand with period p and execution time e
  - Ex: T(3,2)



Demand Bound - EDF

- For a periodic workload set *W* = {Ti(pi,ei)},
  - dbf (*W*,*A*,*t*) for EDF algorithm [Baruah et al.,'90]

$$\mathrm{dbf}\,(\mathrm{W},\mathrm{EDF},\mathrm{t}) = \sum_{T_i \in W} \left\lfloor \frac{t}{p_i} \right\rfloor \cdot e_i$$



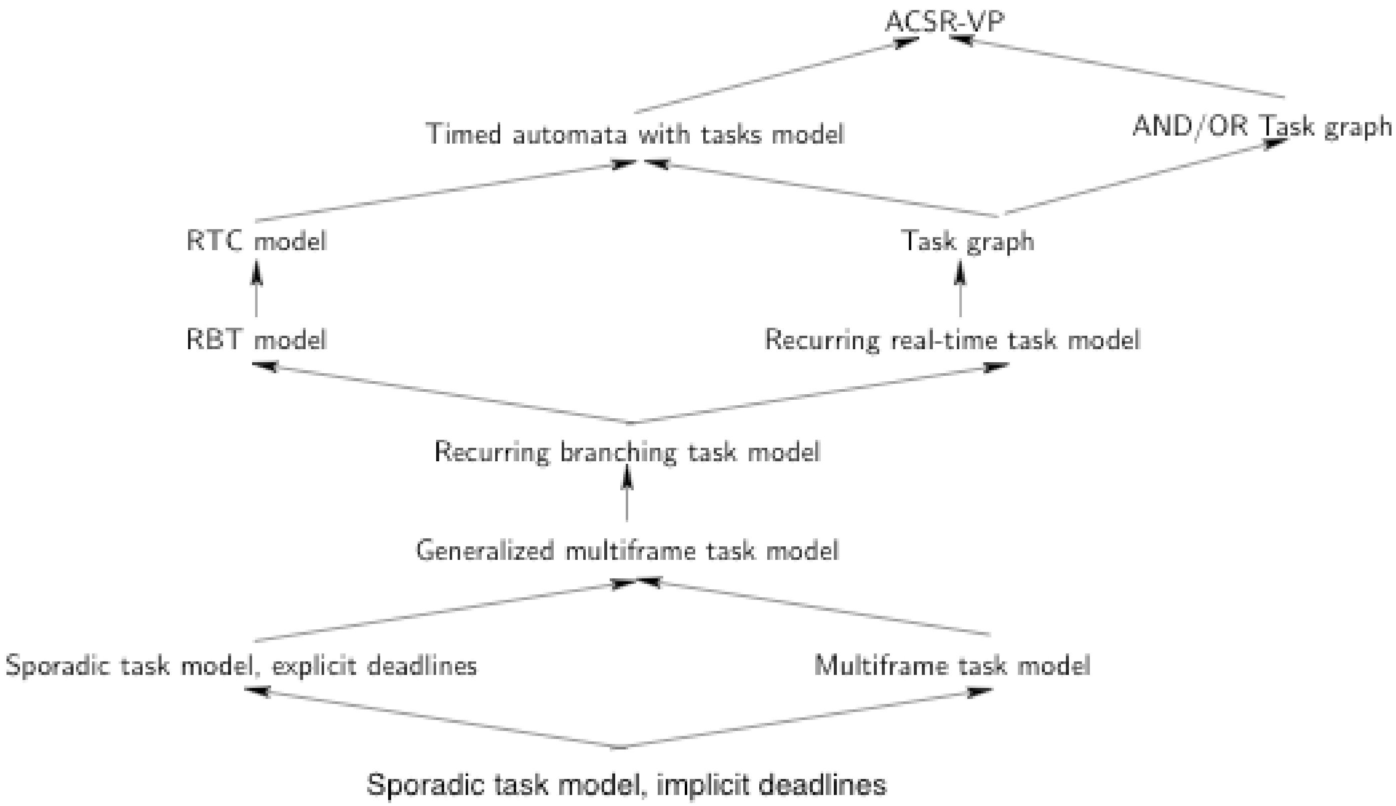
ACSR

$$T_1 = \{(cpu, 1)\} : \emptyset : T_1$$

$$T_2 = \{(cpu, 1)\} : \emptyset : T_2$$
$$+\emptyset : \{(cpu, 1)\} : \emptyset : T_2$$

$$T_3 = \{(cpu, 1)\} : \emptyset : \emptyset : T_3$$
$$+\emptyset : \{(cpu, 1)\} : \emptyset : T_3$$
$$+\emptyset : \emptyset : \{(cpu, 1)\} : T_3$$

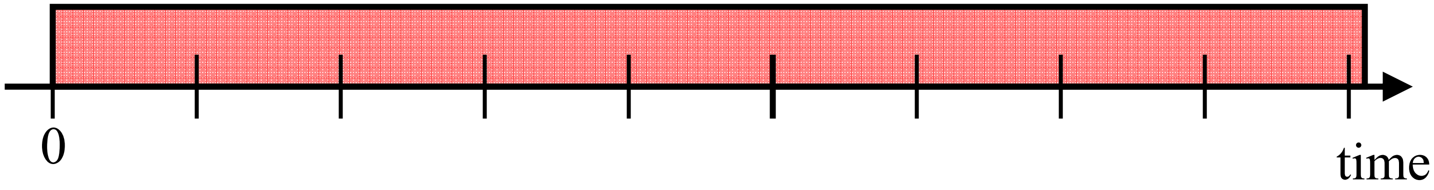
Task (resource demand) representations



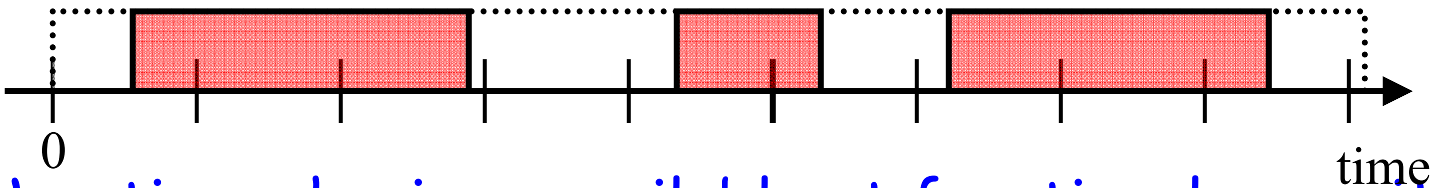
Resource Supply Models

Resource Modeling

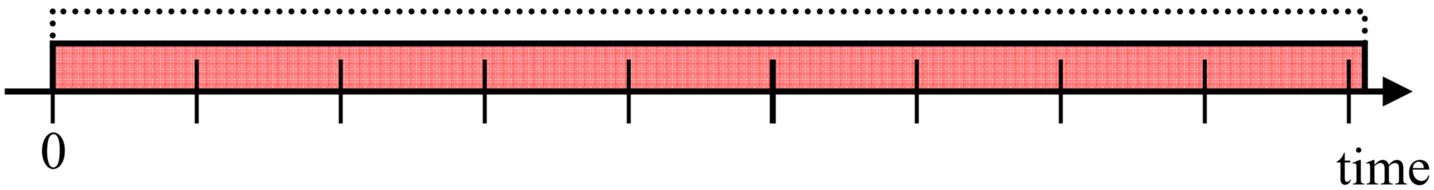
- Dedicated resource : always available at full capacity



- Shared resource : not a dedicated resource
  - Time-sharing : available at some times

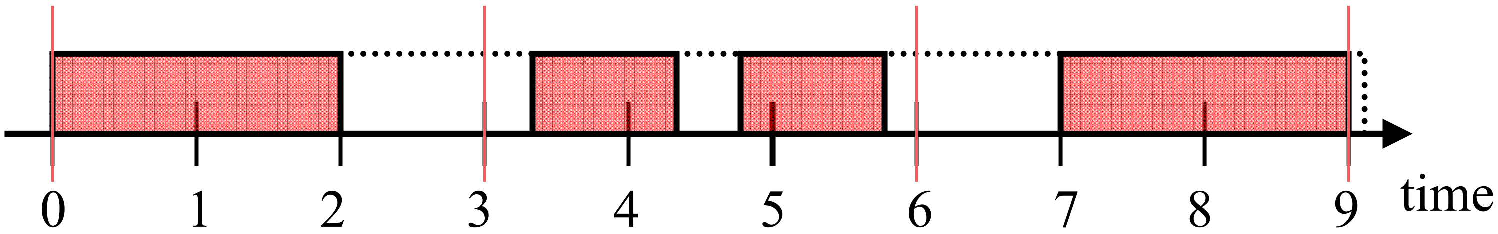


  - Non-time-sharing : available at fractional capacity



Resource Modeling

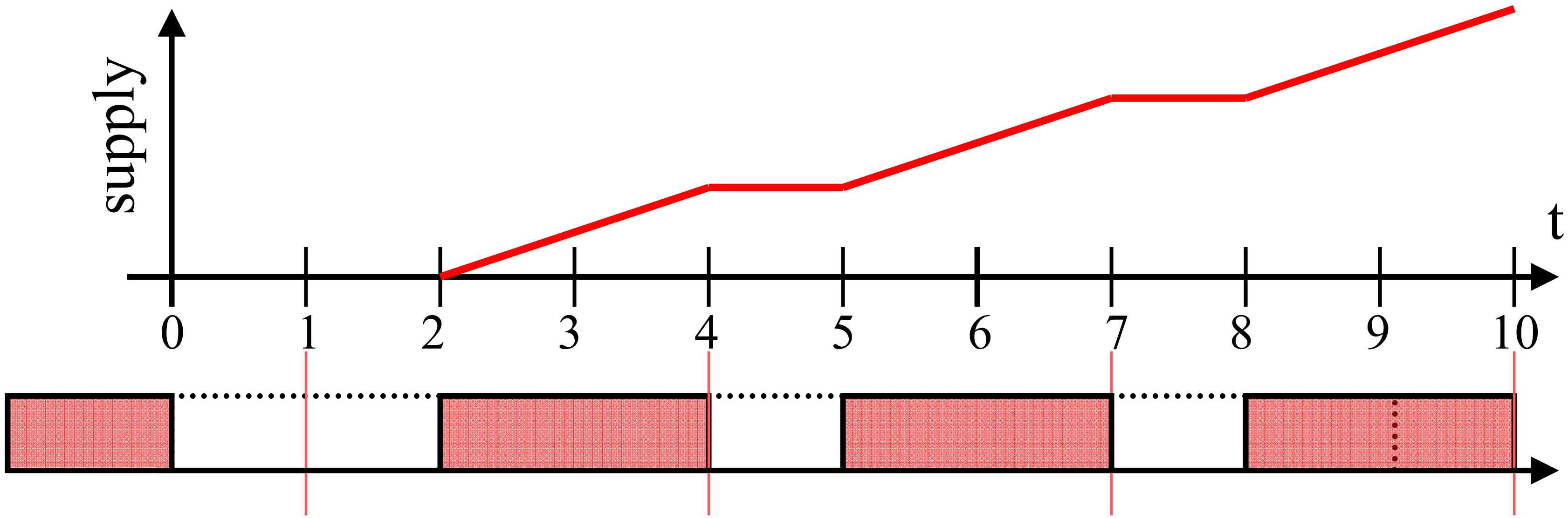
- Time-sharing resources
  - Bounded-delay resource model [Mok et al., '01] characterizes a time-sharing resource w.r.t. a non-time- sharing resource
  - Periodic resource model $\Gamma(\Pi,\Theta)$ [Shin & Lee, RTSS '03] characterizes periodic resource allocations
  - EDP model [Easwaran et all, RTSS 07]



Resource Supply Bound

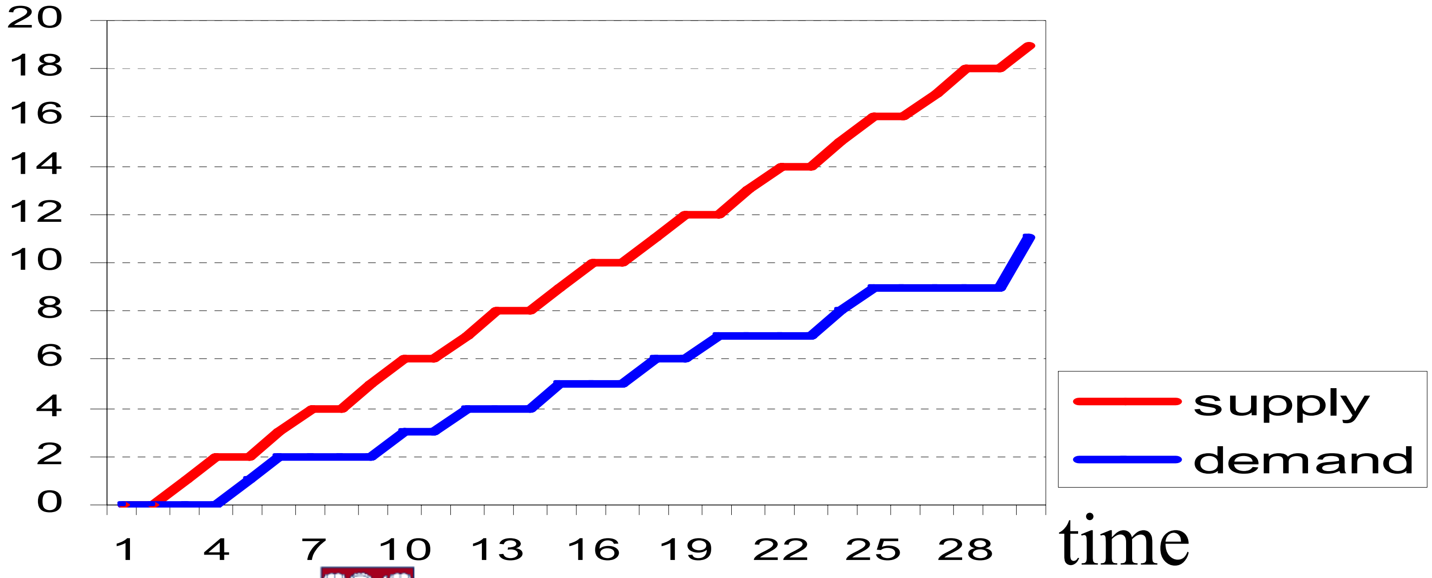
- Resource supply during an interval of length t
  - $sbf_R(t)$: the minimum possible resource supply by resource R over all intervals of length t

- For a single periodic resource model, i.e., Γ(3,2)
  - we can identify the worst-case resource allocation



Schedulability Condition - EDF

- A periodic workload set W is schedulable under a scheduling algorithm A over a periodic resource model $\Gamma(\Pi, \Theta)$ if and only if $\forall t > 0 \quad \mathrm{dbf}(W, EDF, t) \leq \mathrm{sbf}_\Gamma(t)$
  - A = EDF



EDP resource model based Interfaces

- Explicit Deadline Periodic resource
- Specification: $\Omega = (\Pi, \Theta, \Delta)$
  - Explicit deadline Δ
  - Θ resource units in Δ time units
  - Repeat supply every Π time units

EDP supply bound function (sbf_Ω)

- $sbf_\Omega(t)$

$$sbf_\Omega(\mathrm{t}) = y\Theta + \max\{0, t - (\Pi + \Delta - 2\Theta) - y\Pi\}$$

$$where \quad y = \left\lfloor \frac{t - (\Delta - \Theta)}{\Pi} \right\rfloor, \; t \geq \Delta - \Theta$$

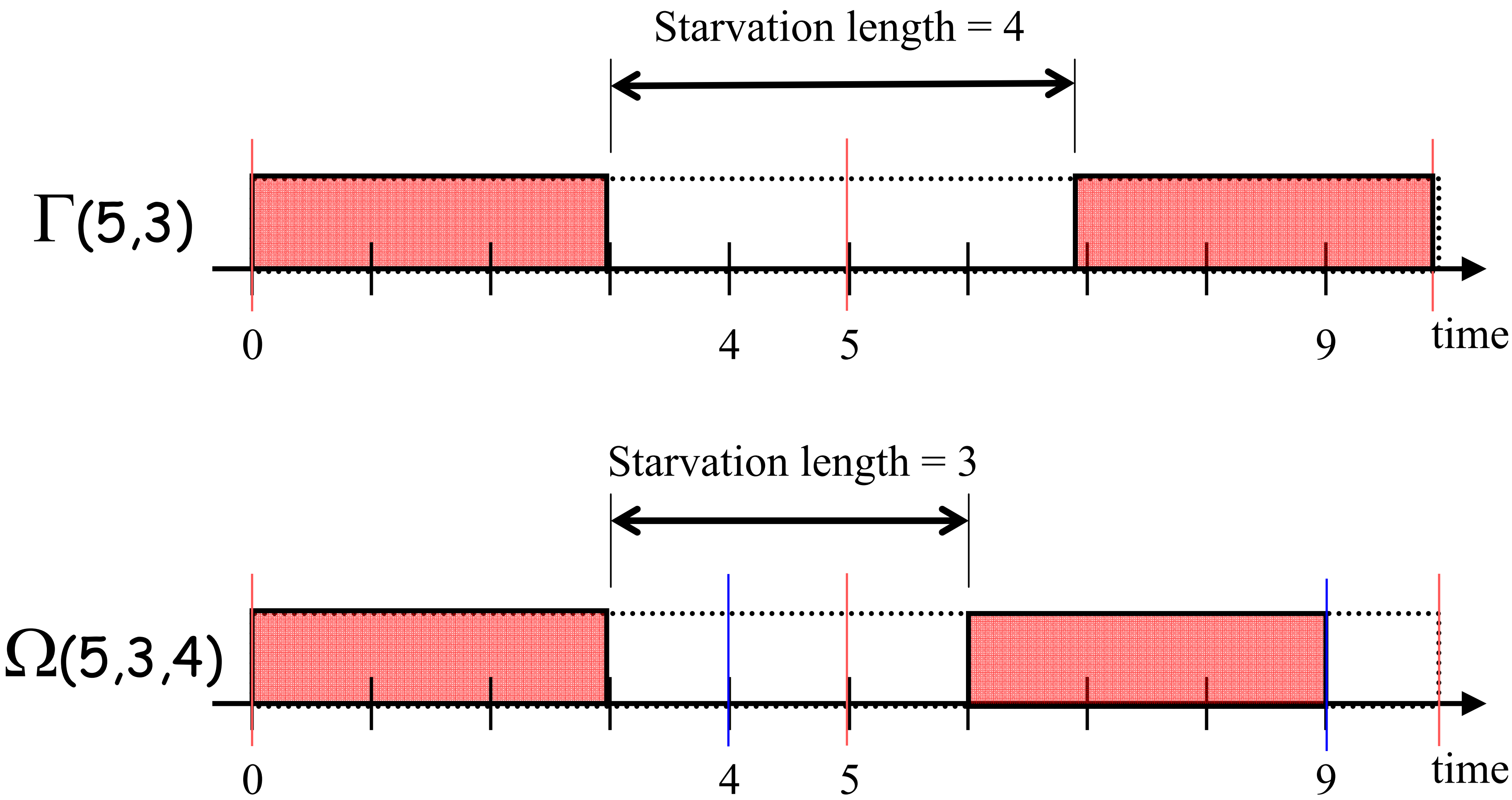
- $lsbf_\Omega(t)$

$$lsbf_\Omega(\mathrm{t}) = \frac{\Theta}{\Pi}(t - \underbrace{(\Pi + \Delta - 2\Theta)})$$

Bandwidth

Starvation length

Supply bound function (sbf_{Ω})



ACSR+ for supply partition specification

$$S_1 = \{(cpu, \_)\} : \emptyset : S_1$$

$$S_2 = \{(cpu, \_)\} : \emptyset : S_2 \oplus \emptyset : \{(cpu, -)\} : S_2$$

$$T_1 = \{(cpu, 1)\} : \emptyset : T_1$$

$$T_2 = \{(cpu, 1)\} : \emptyset : T_2$$
$$+\emptyset : \{(cpu, 1)\} : \emptyset : T_2$$

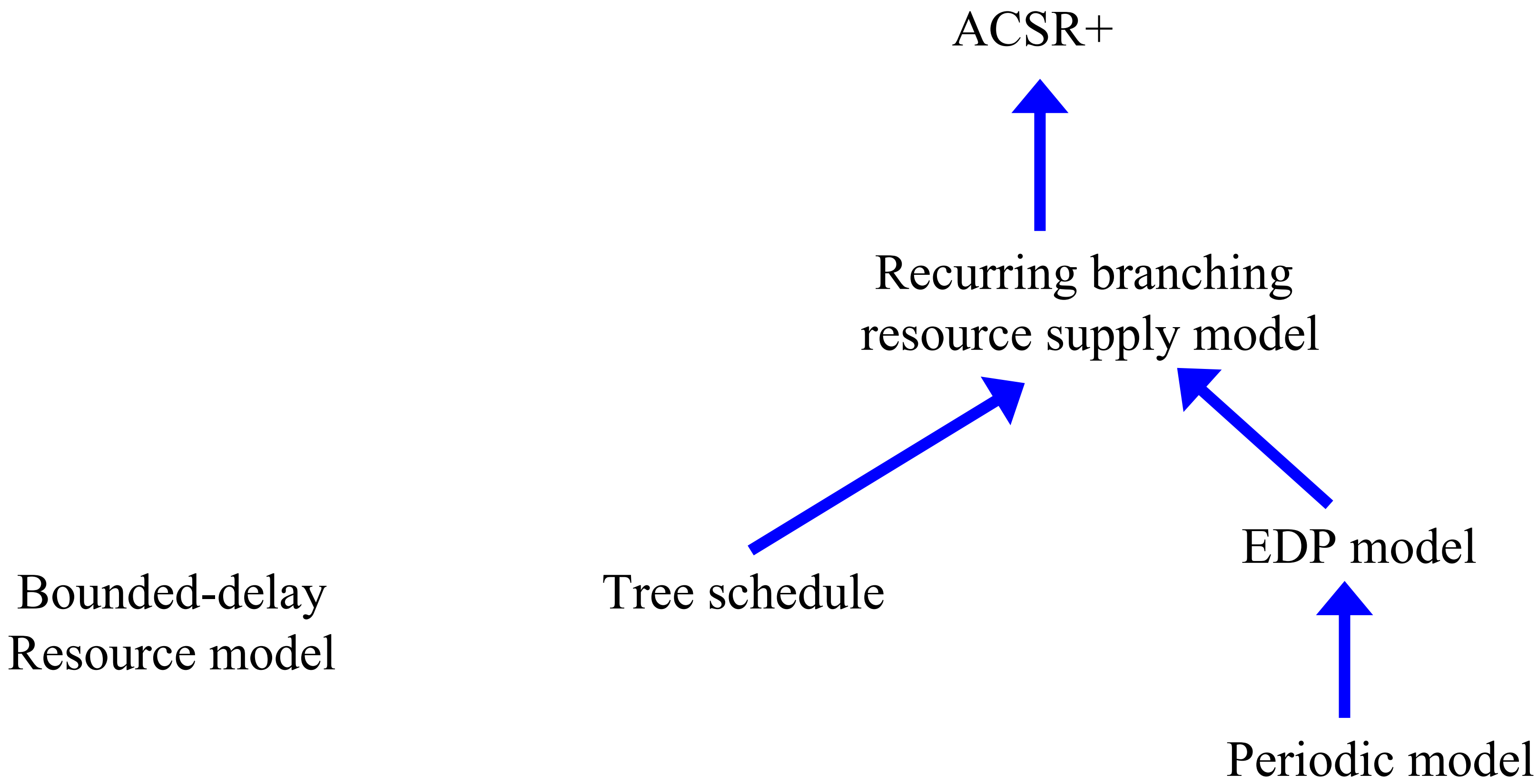
Notion of “schedulable under”

(1) T_1 is schedulable under S_1

(2) T_2 is schedulable under S_2

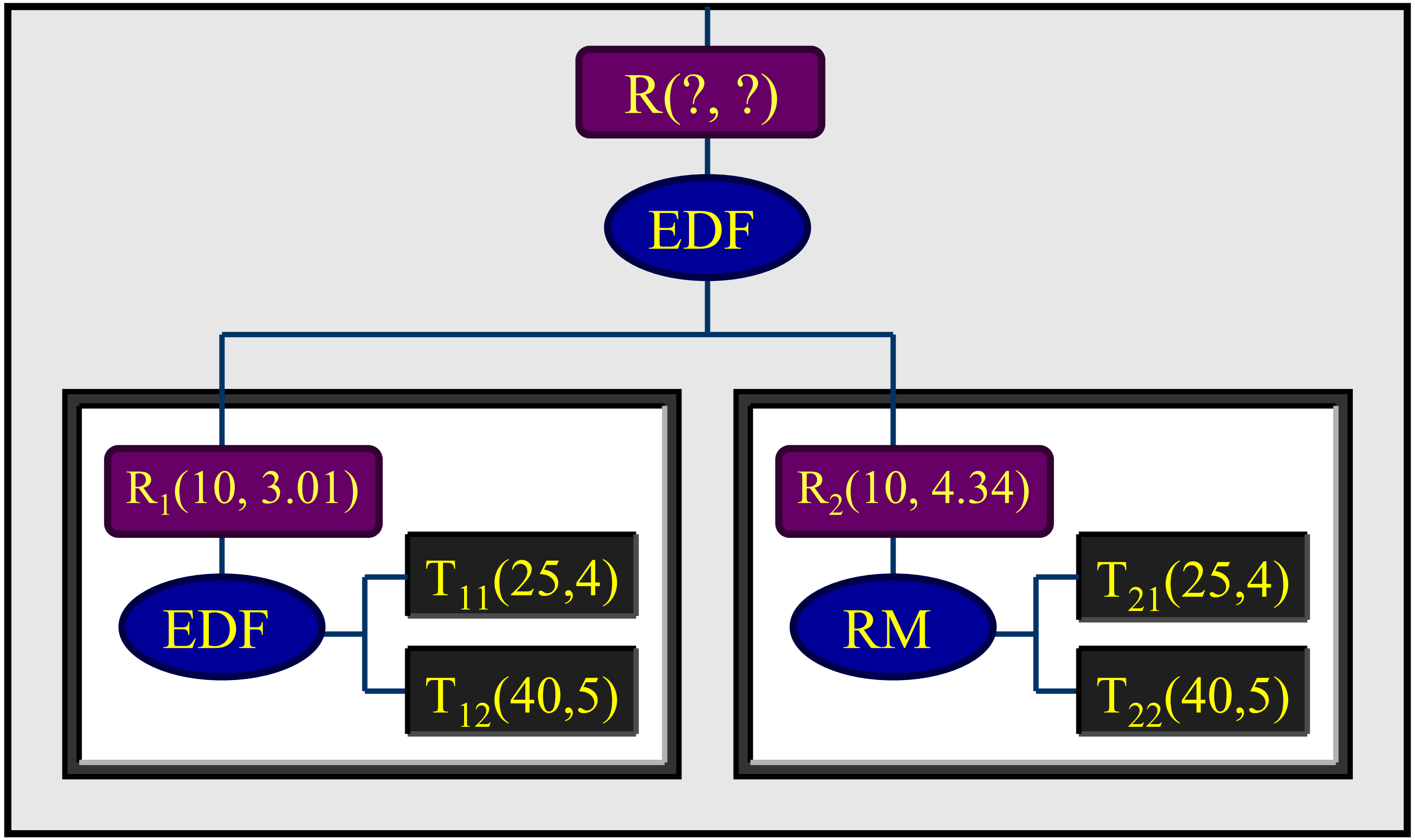
(3) T_1 is not schedulable under S_2

Resource Supply Models

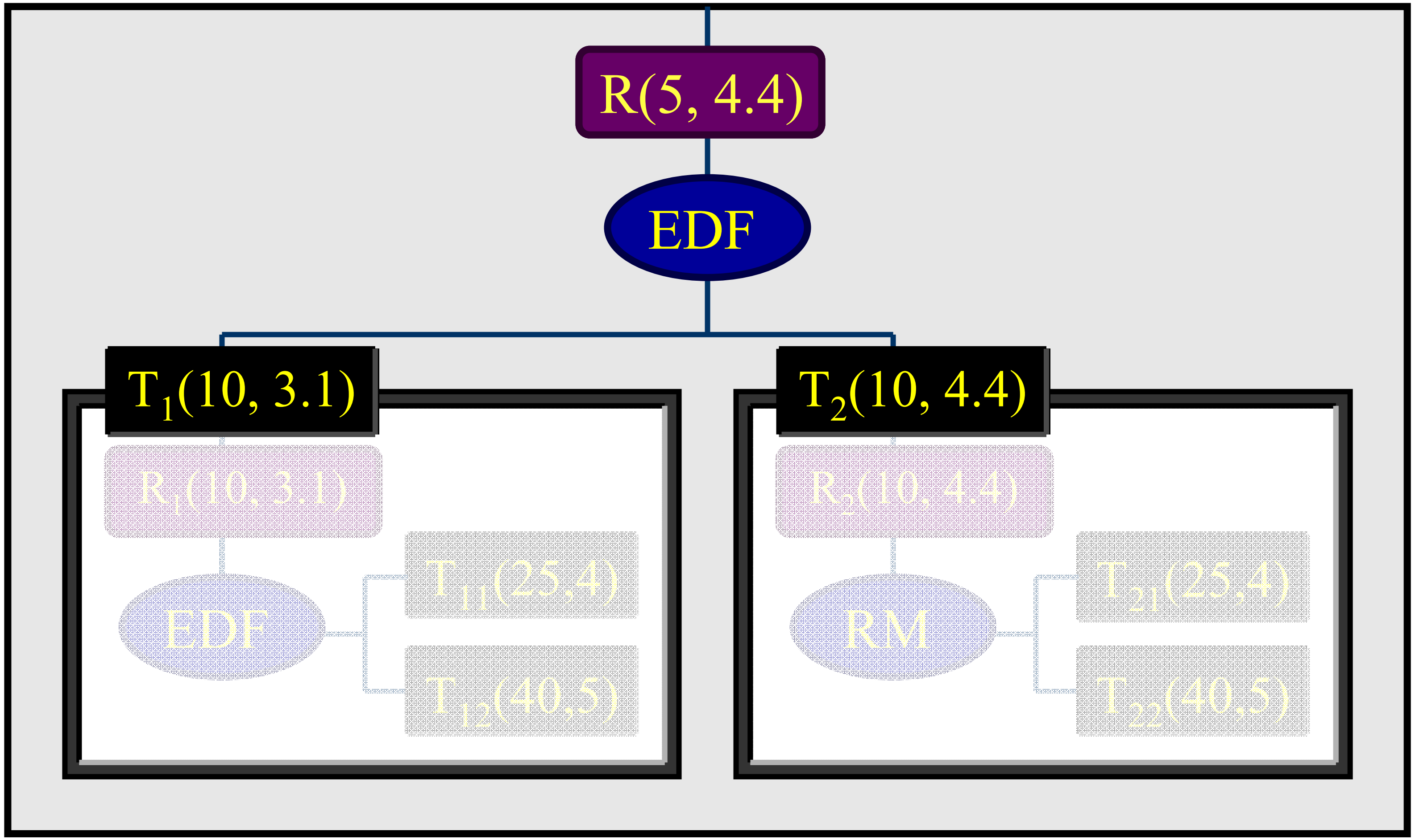


Compositional Schedulability Analysis

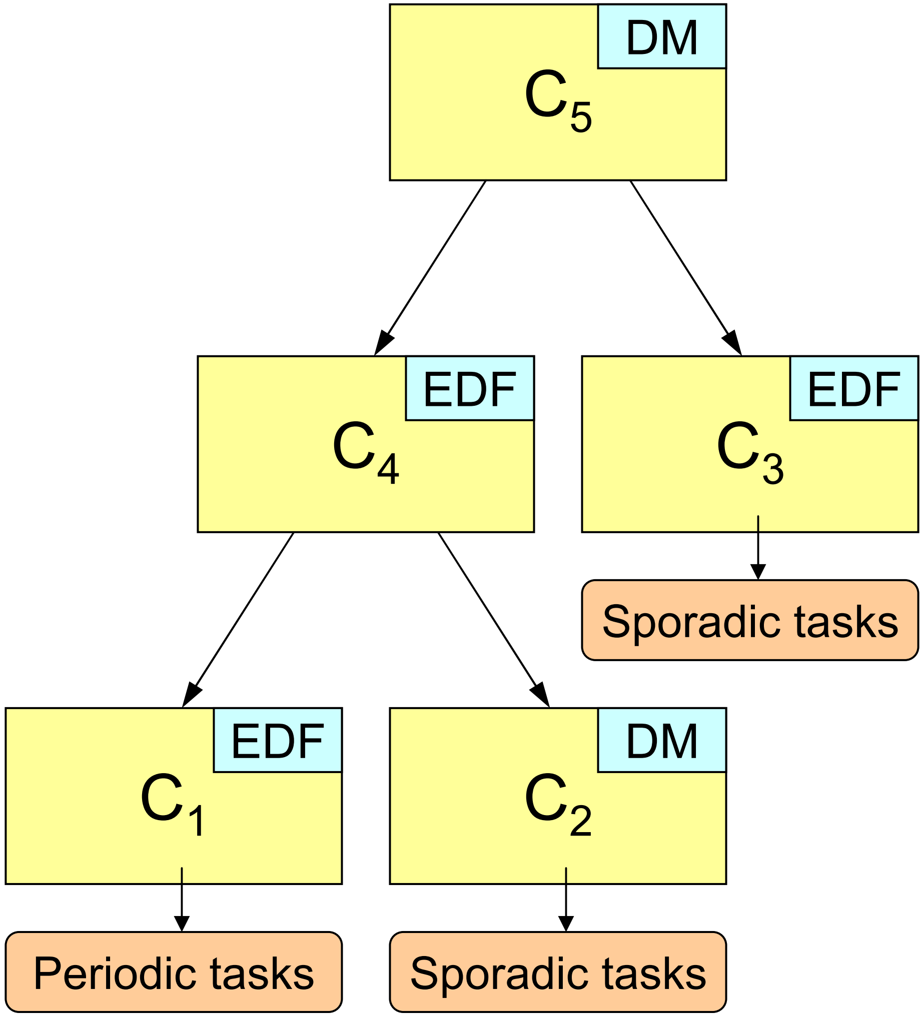
Component Abstraction



Compositional Real-Time Guarantees



Hierarchical Scheduling Framework



- Resource allocation from parent to child
- Notations
  - Leaf → C_1, C_2, C_3
  - Non-leaf → C_4, C_5
  - Root → C_5

ARINC 653 → Two-level hierarchical framework

Compositional Schedulability Analysis (CSA)

- Assume/Guarantee reasoning
  - Let C_R be a system configuration: Component C is running on resource R.
  - Let supply(C_R) be the residual supply of R after C; I.e., supply to the rest of the system.
  - If
    - C1 guarantees schedulability assuming demand(C1) <= supply(C2_R)
    - C2 guarantees schedulability assuming demand(C2) <= supply(C1_R)
  - Then,
    - C1 || C2 guarantees schedulability in (C1 || C2)_R

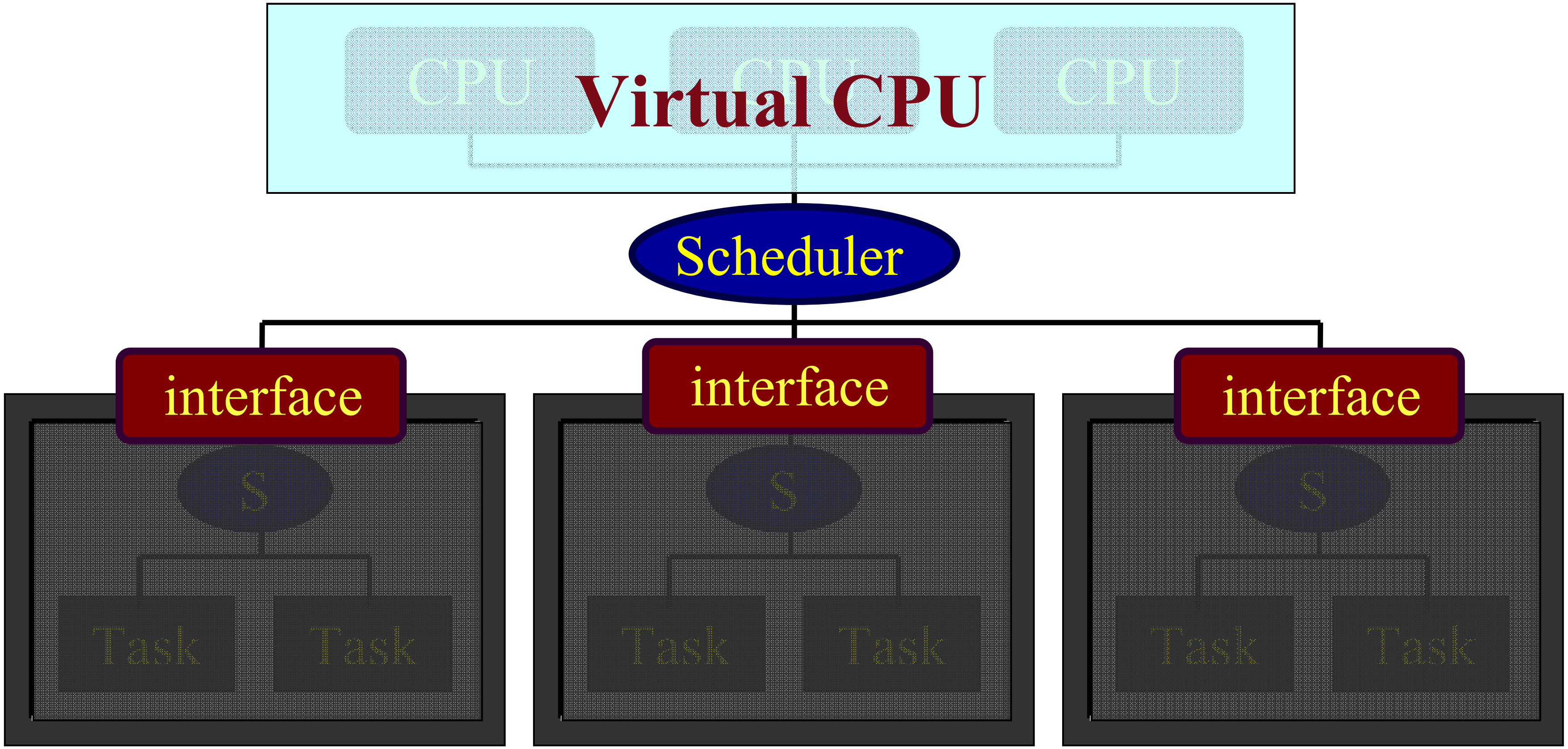
Questions on CSA

- Dbf/sbf bounds
  - Associativity
  - Minimum bounds on hierarchical scheduling
- ACSR/ACSR+
  - Non-deterministic supply alternatives
  - Definition and characterization of "schedulable under"
    - Given demand process T and supply partition S, when T schedulable with respect to S.
    - Relation to Linear Logic?

Hierarchical Scheduling Framework for Virtual Clustering of Multiprocessors

Multicore Processor Virtualization

1. Compositional analysis of hierarchical multiprocessor real-time systems, through component interfaces
2. Using virtualization to develop new component interface for multiprocessor platforms



Multiprocessor Embedded Systems

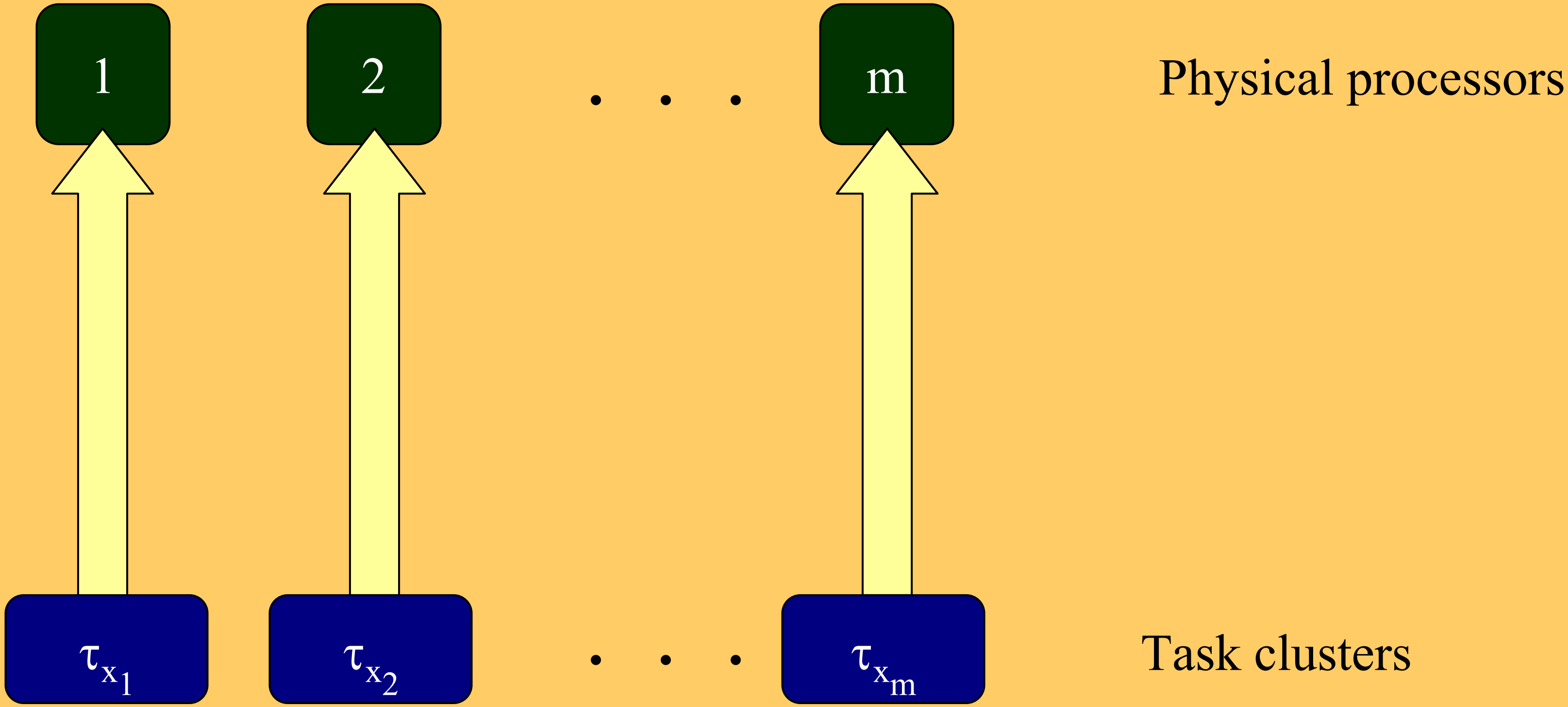
- Why consider multiprocessors
  - Better tradeoff between computational power and costs (energy,fabrication)
  - Ability to exploit inherent concurrency in embedded software
- Problem Statement
  - Constrained deadline sporadic task model

    $\tau = \{\tau_1, \ldots, \tau_n\}$, where each $\tau_i = (T_i, C_i, D_i)$ with $C_i <= D_i <= T_i$

    C_i units must be supplied non-concurrently
  - Identical, unit-capacity multiprocessor platform

    m processors
  - How can they be scheduled?

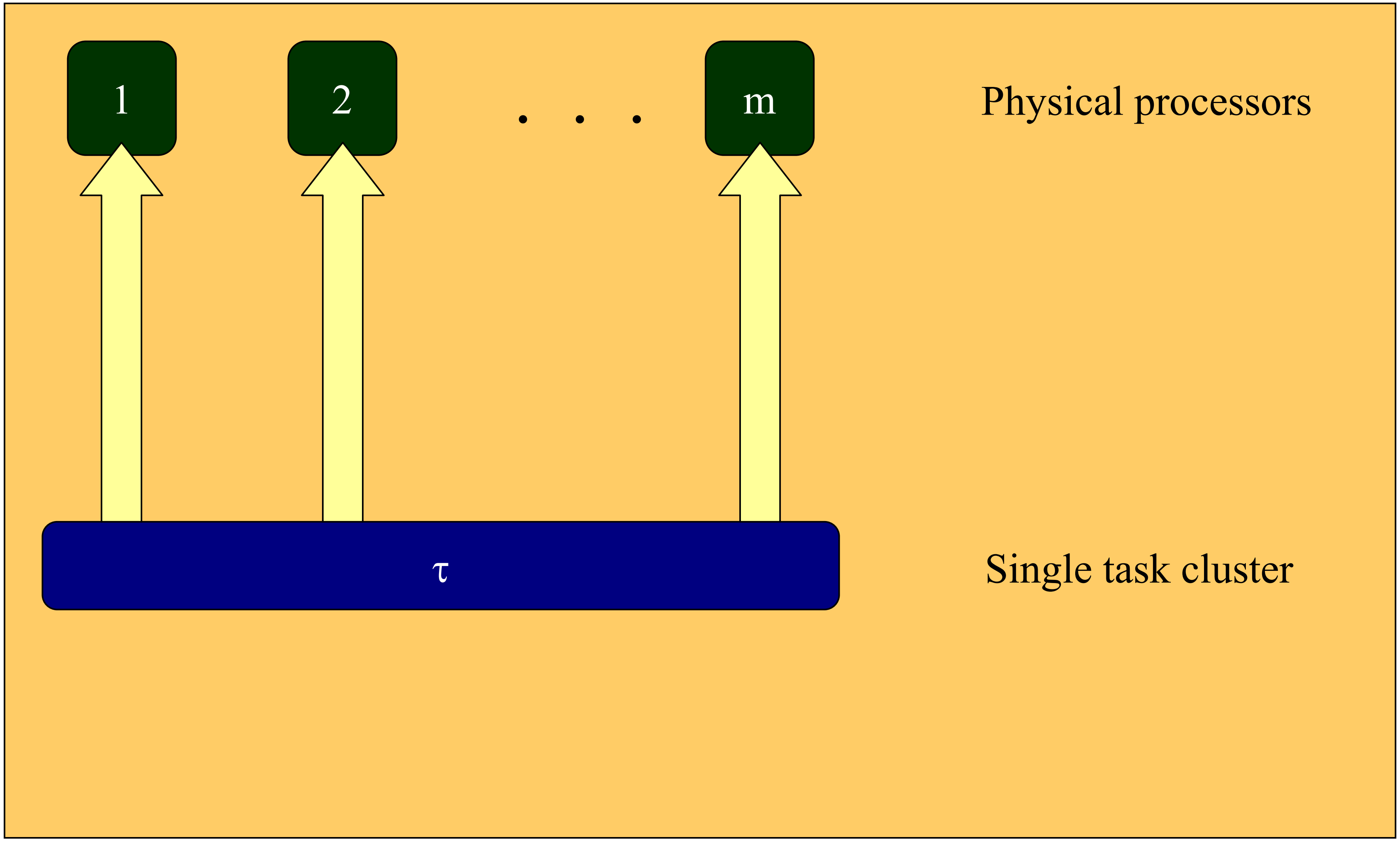
Partitioned Scheduling



$$\tau_{x_1} \cup \tau_{x_2} \ldots \cup \tau_{x_m} = \tau$$

$$\tau_{x_i} \cap \tau_{x_j} = \phi \text{ for all i and j}$$

Global Scheduling



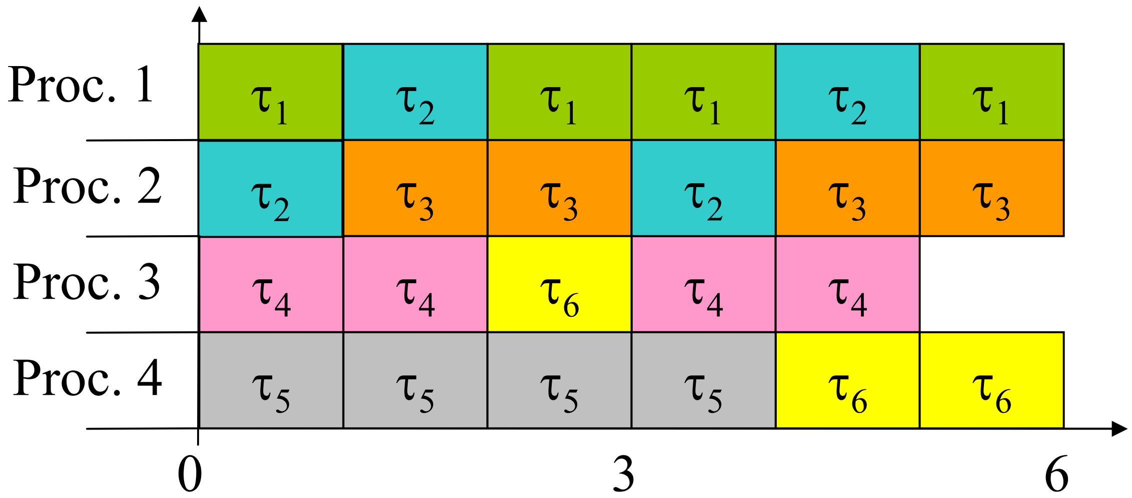
Motivation for Virtual Clustering

- Task set and number of processors

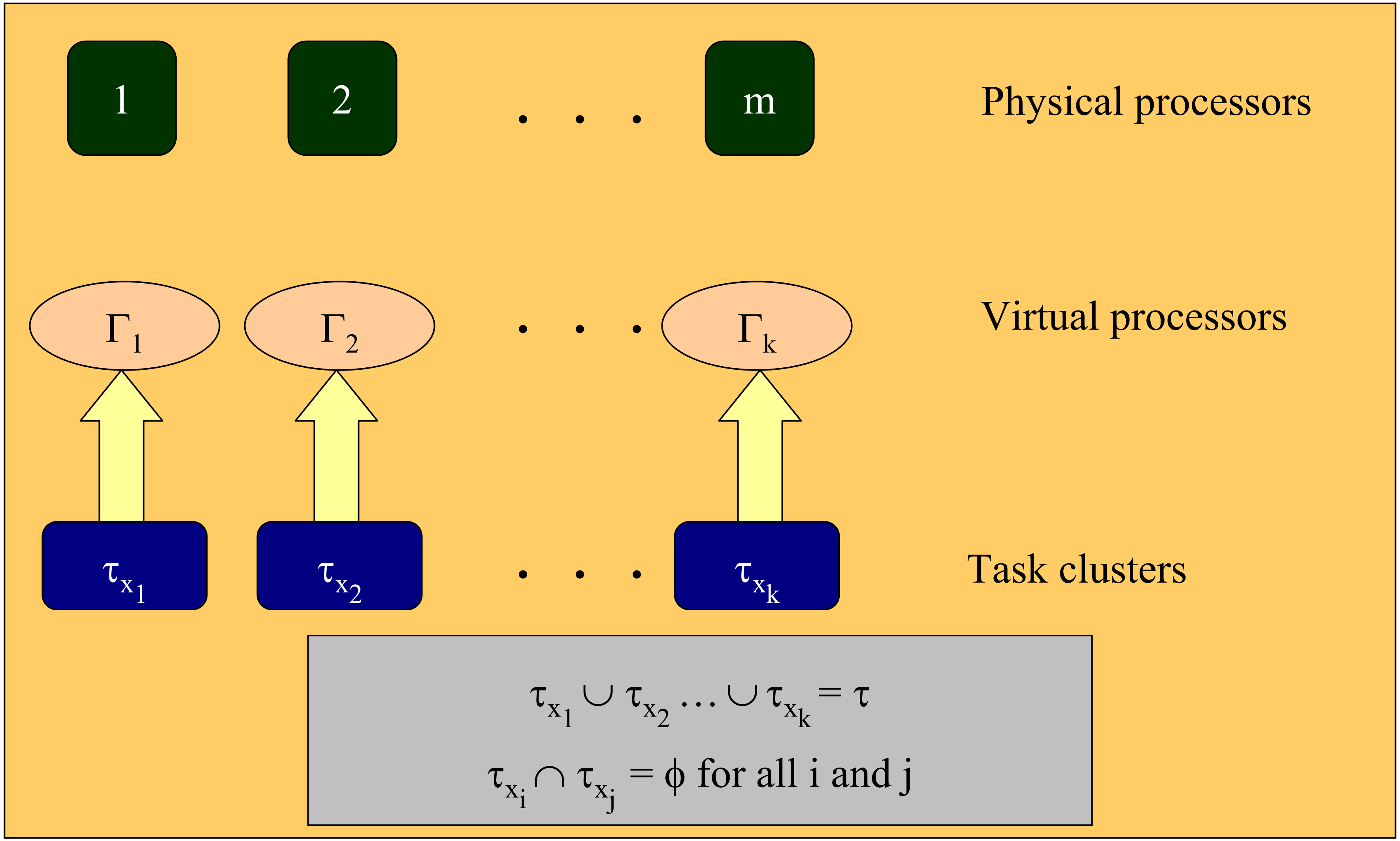
  $\tau_1=\tau_2=\tau_3=\tau_4=(3,2,3)$, $\tau_5=(6,4,6)$, and $\tau_6=(6,3,6)$, m=4
- Schedule under clustered scheduling

  τ_1, τ_2, τ_3 scheduled on processors 1 and 2

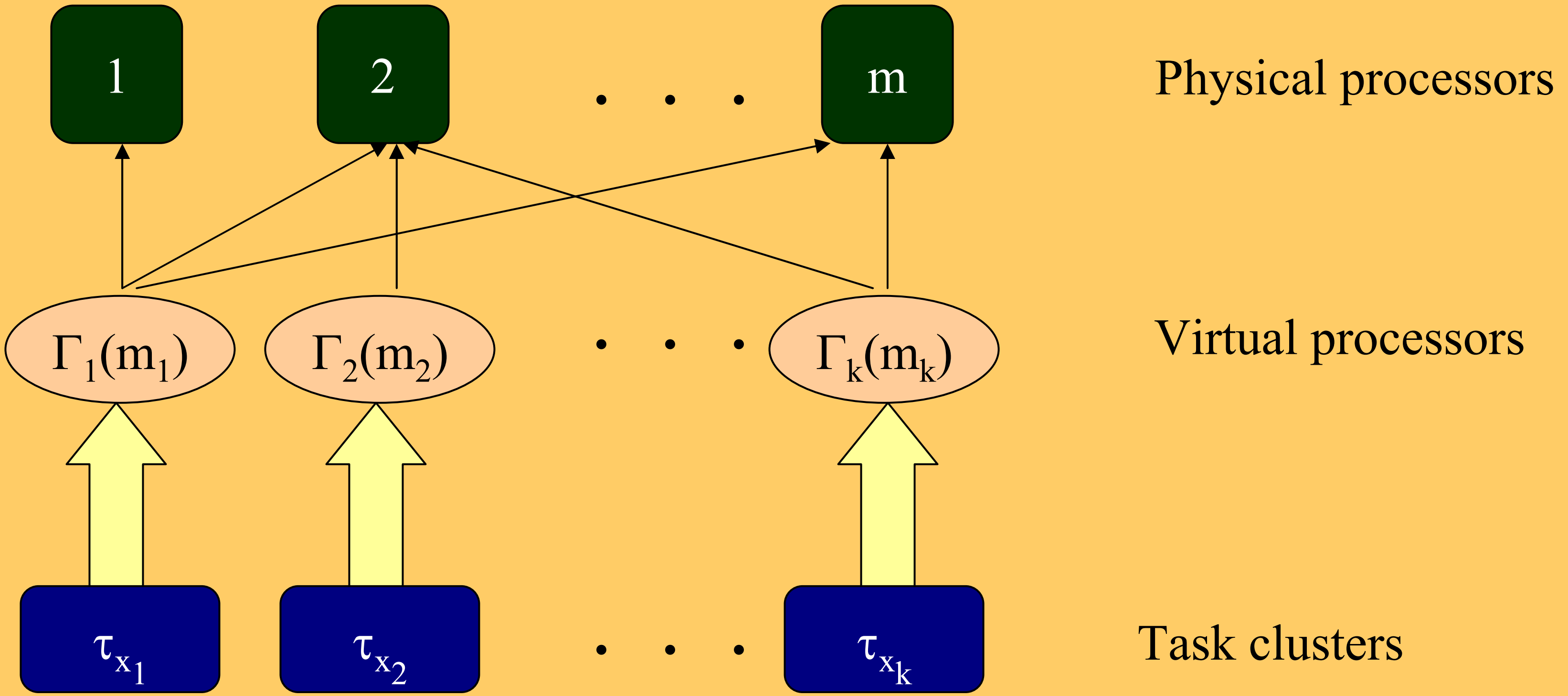
  τ_4, τ_5, τ_6 scheduled on processors 3 and 4



Virtual Clustering Interface

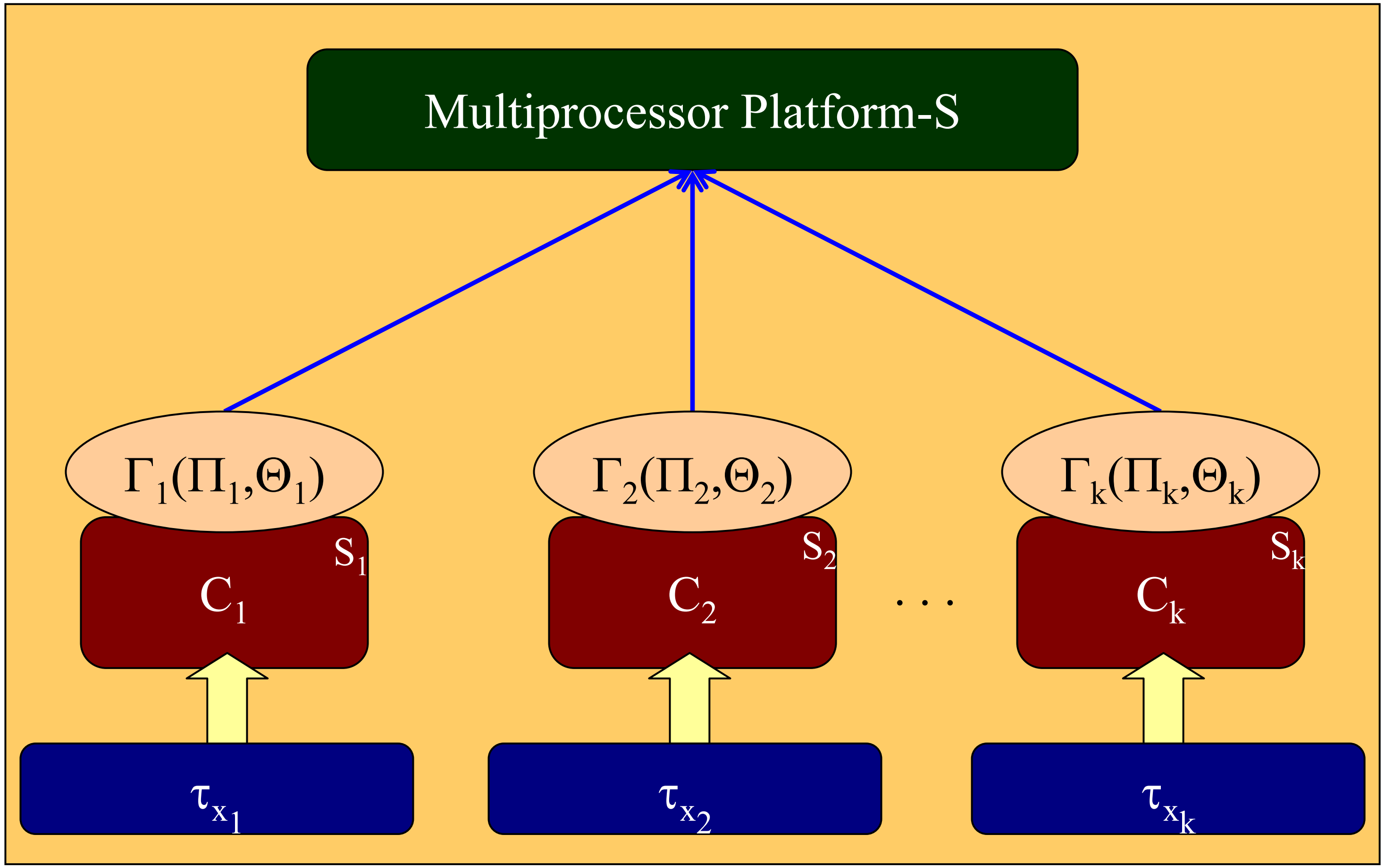


Virtual Clustering Interface

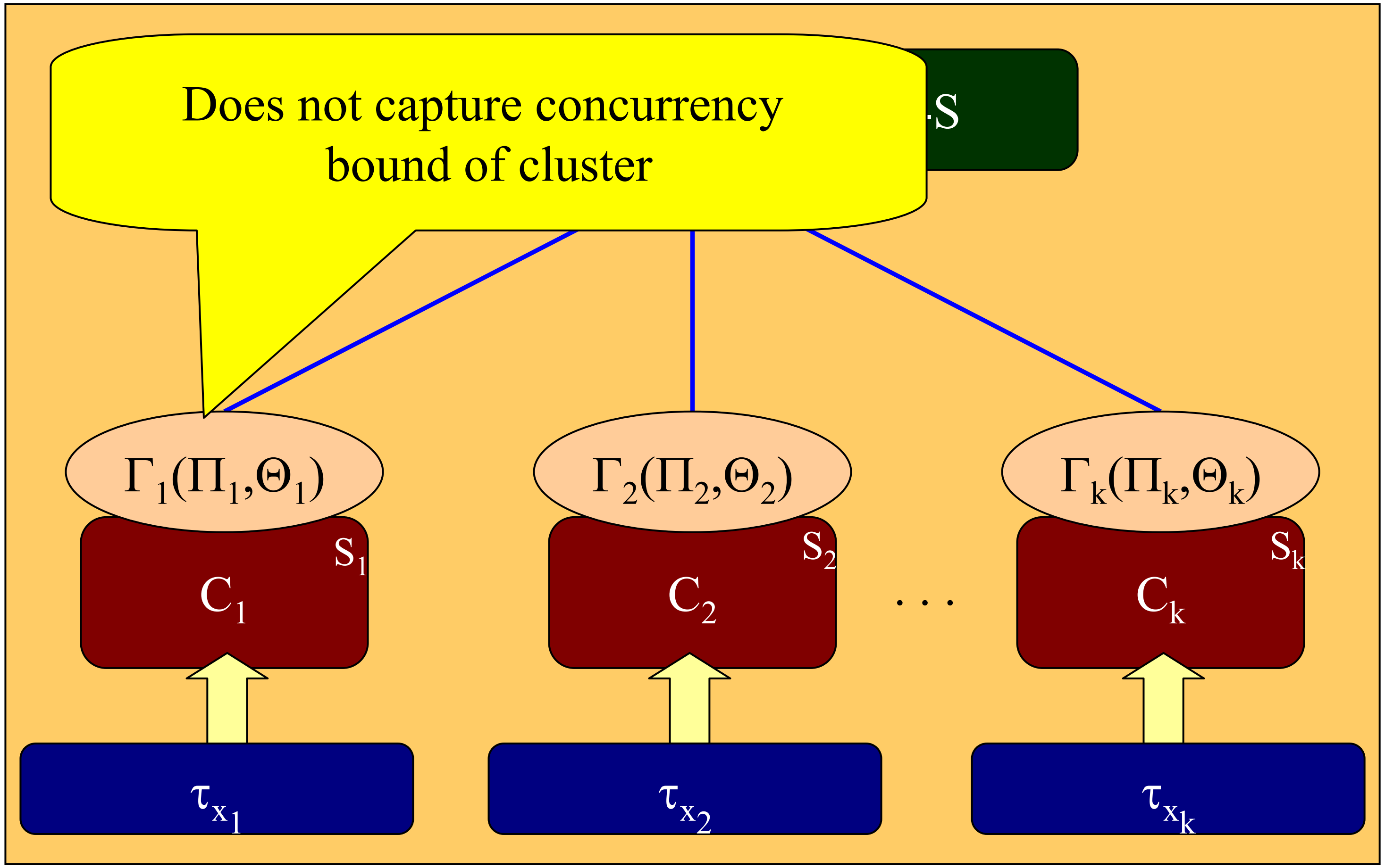


For each Γ_i, m_i ($\le m$) is maximum number of physical processors that can be assigned to Γ_i at any instant

Multiprocessor Periodic Resource (MPR) model



Multiprocessor Periodic Resource (MPR) model



Multiprocessor Periodic Resource (MPR) model

- $\Gamma = (\Pi, \Theta, m')$
  - Θ units of resource guaranteed in every Π units of time, with amount of concurrency at most m' in any time slot

- Why MPR model?
  - Periodicity enables transformation of resource model to tasks that can be used by various inter-cluster schedulers (schedulers at higher level)

Virtual Cluster based Interface

1. Split task set τ into clusters $\tau_{x_1}, \ldots, \tau_{x_k}$
   - We assume that clusters are given
2. Abstract cluster τ_{x_i} into MPR model Γ_i
   - Solution for global EDF intra-cluster interface
   - Present sufficient schedulability condition and minimize overhead of Γ_i
3. Transform each Γ_i into periodic tasks
   - Enables inter-cluster scheduler to schedule Γ_i
   - Preserves concurrency bound of Γ_i

Conclusions

- Interface framework for real-time system based on hierarchical schedulability analysis
  - Independent implementation of components
  - Interface-based component composition
  - Virtual clustering for multiprocessors
- Other issues
  - Task blocking due to synchronization
  - Context switch overheads
- Applications
  - ARINC 653
  - Automotive SAE J2056/Class C Vehicle Communication Requirements
  - Real-Time Virtual Machines (esp. multicore processors)

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Related work

- Much work on hierarchical scheduling
  - Provide schedulability conditions that are needed for instantiation
  - Serves as the basis for abstraction
    - Shin and Lee, '03 '04, Easwaran et al., '06
- Real-time interface frameworks
  - Henzinger and Matic, '06
  - Wandeler and Thiele, '06

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Questions?

Thank You!