Processing Enhancement and Virtualization for Cyber-Physical Computations

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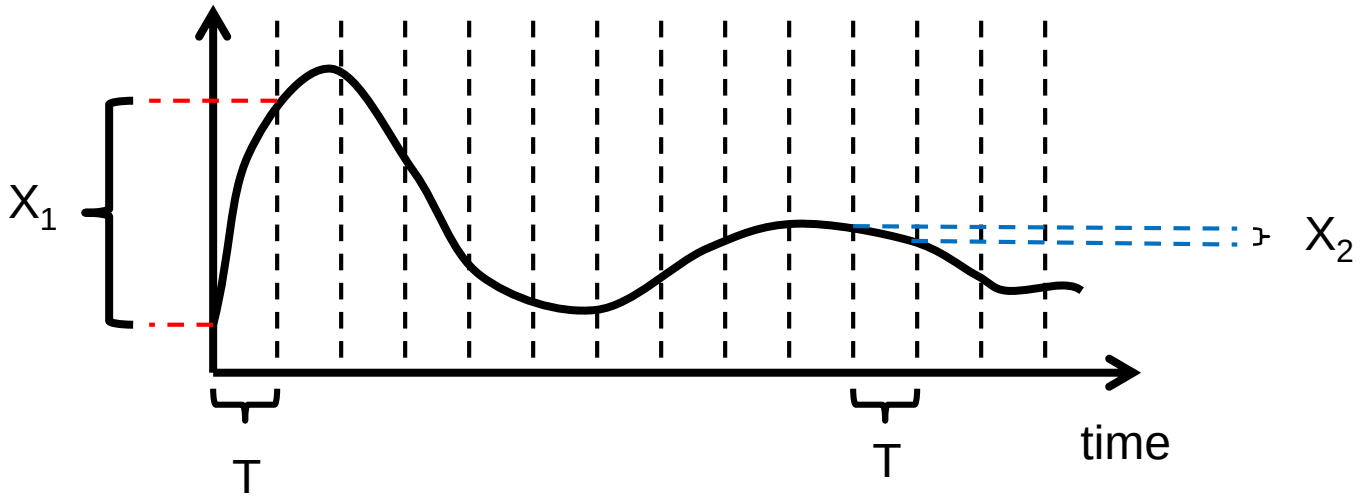
DM19-0388

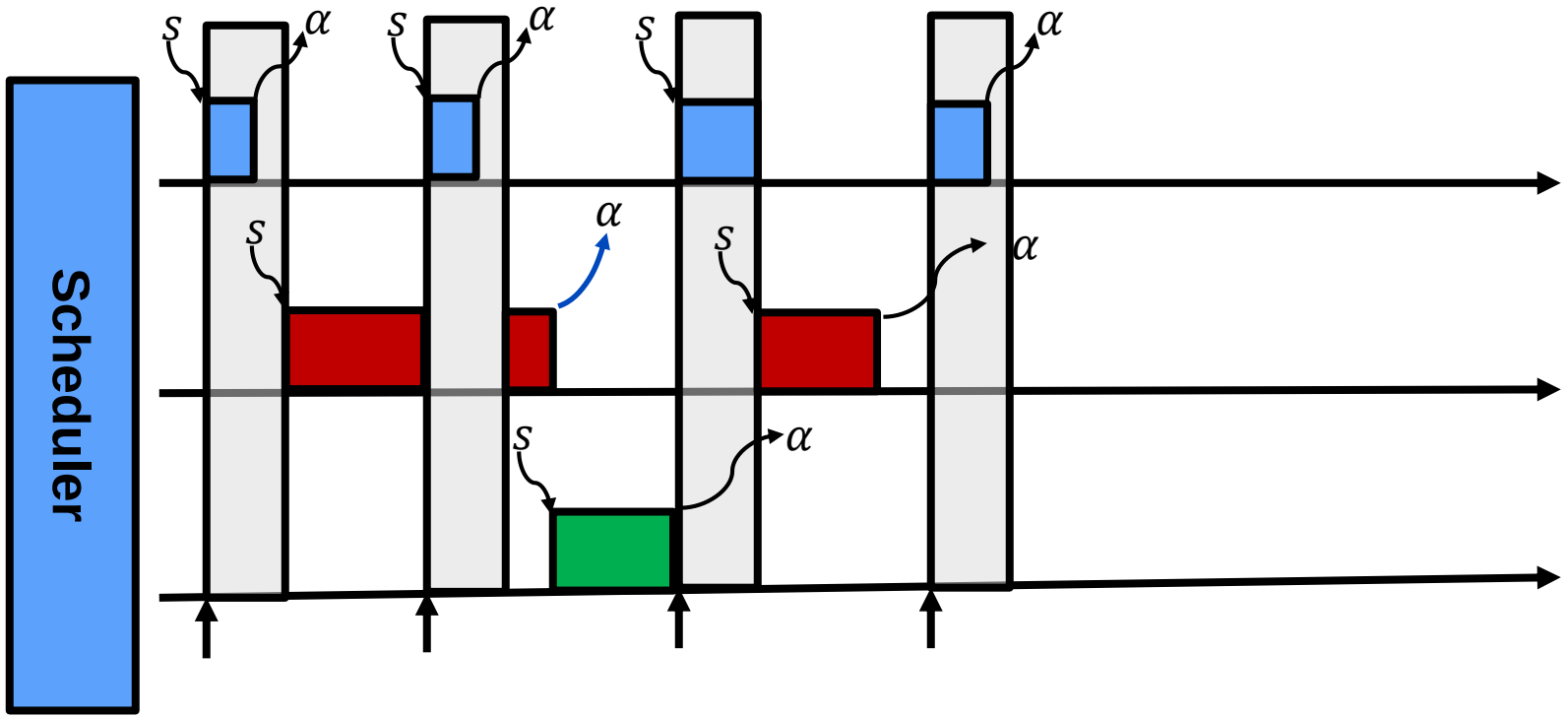
Synchronize cyber processes with physical processes

Traditionally done by fixing a “sampling” period



Drawbacks:
Variation in the evolution of physical process can be large ($X_1 >> X_2$)
Need to force minimum period
Pessimistic resource utilization for guaranteed deadlines

Processing Budget



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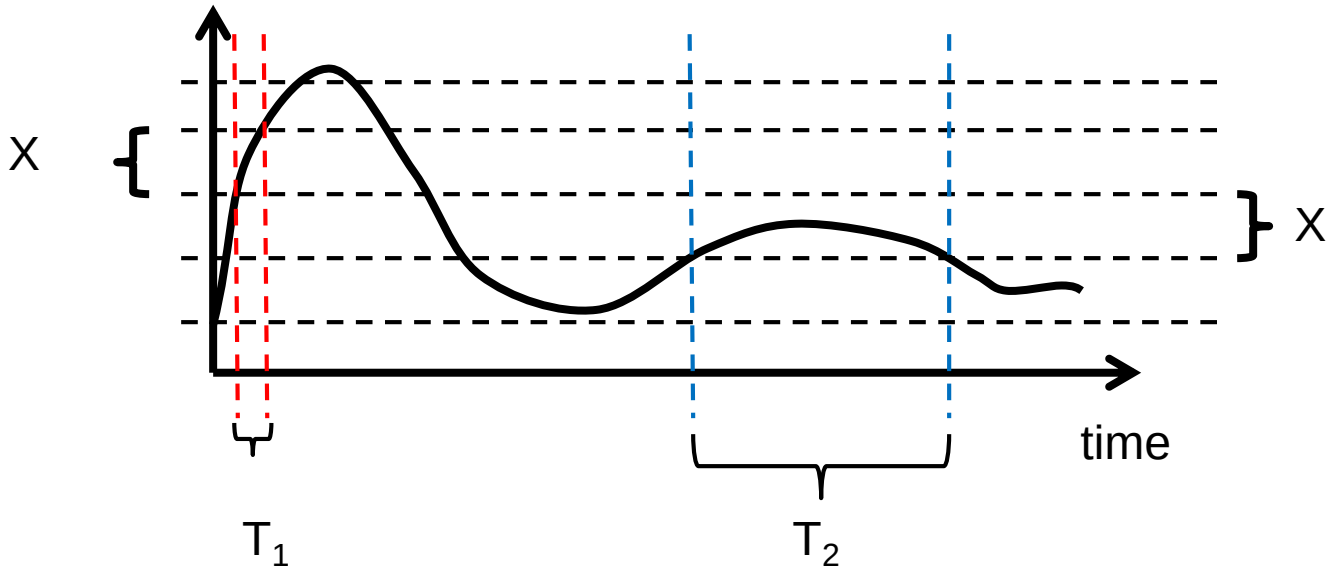
Synchronize cyber processes with physical processes

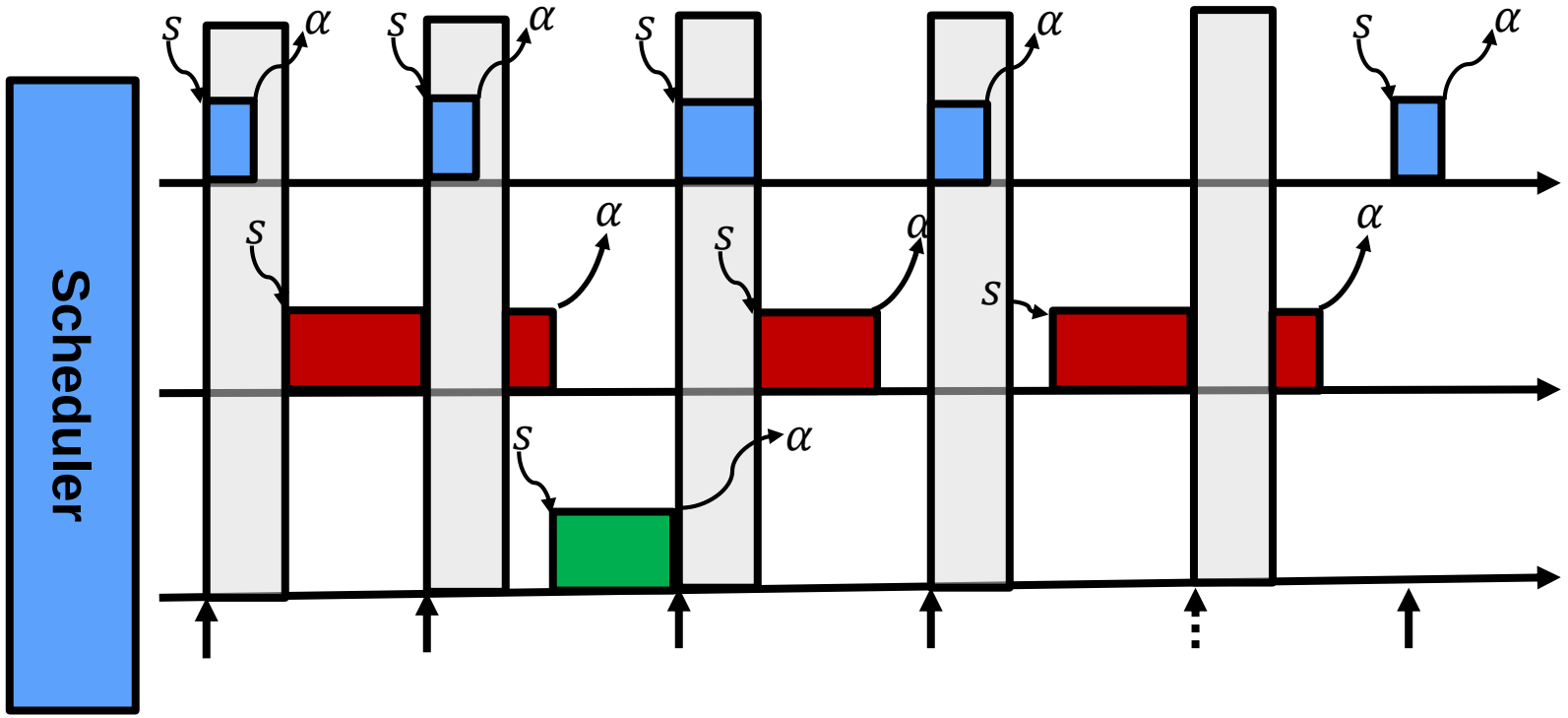
Approach: Let the physical process drive the computation



Alternative approaches:
Event-based control
Self-triggered control

Improved resource utilization for guaranteed deadlines

Processing Budget Non-Periodic Arrivals



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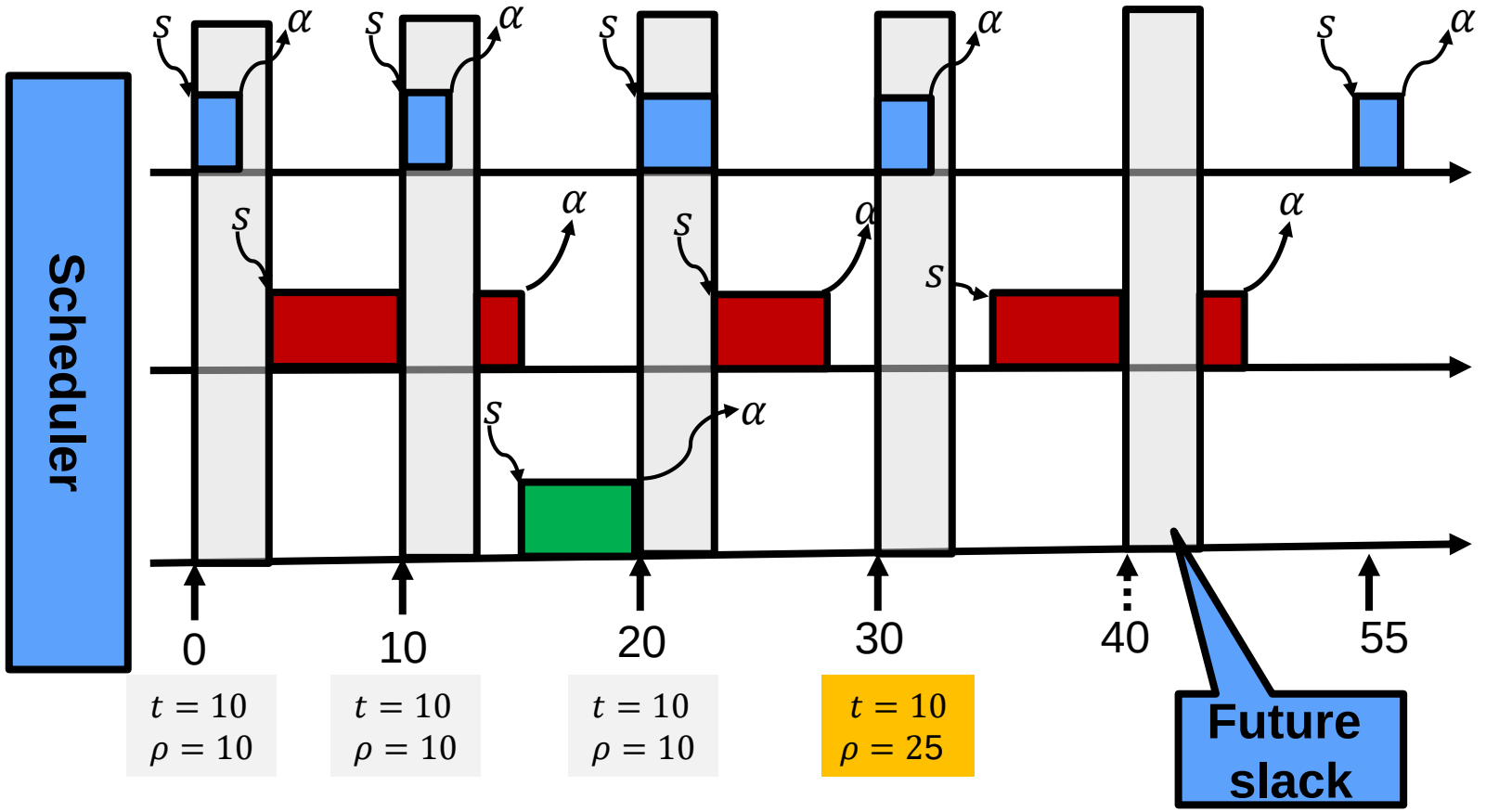
Temporal-Physical Clocks

Infinite sequence of temporal-physical ticks:

- $\psi = (t, \rho)$
  - t : traditional minimum inter-arrival time for a task (fixed at design time)
  - ρ: physical tick that defines time to the next job arrival (driven by physical evolution)
    - Can change every tick
    - $\rho \geq t$

- At design time:
  - t = T is used for schedulability : $U = \sum_i \frac{C_i}{T_i} < bound$

Recover Future Slack



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Synchronizing different cyber processes

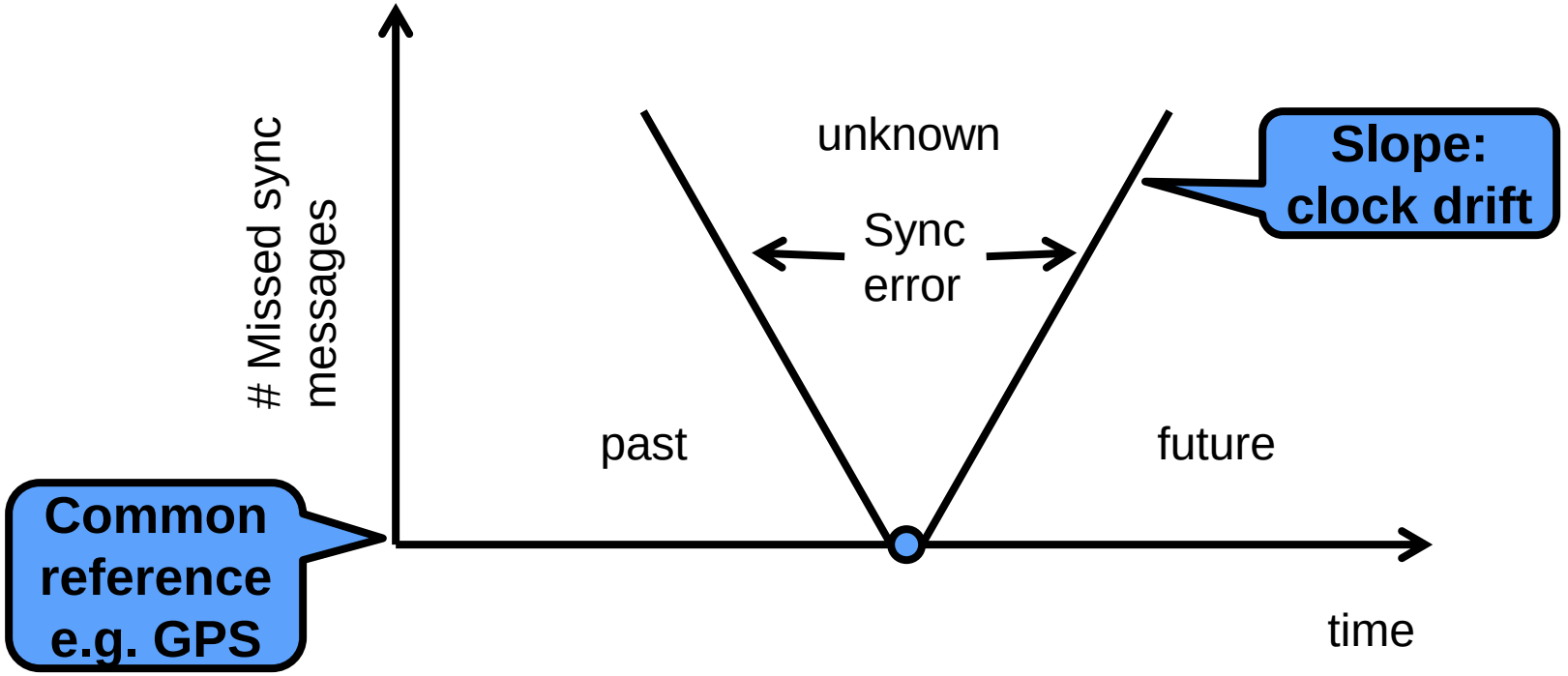
Using a “common” clock

- Common reference (e.g. GPS)
- Synchronized local clocks (e.g. NTP)
- Logical clocks

Reliability needs to be taken into account

- Loss of satellite signals (GPS)
- Synchronization message loss (NTP)
- Synchronization message delays (logical clocks)

Synchronized cyber-clock accuracy

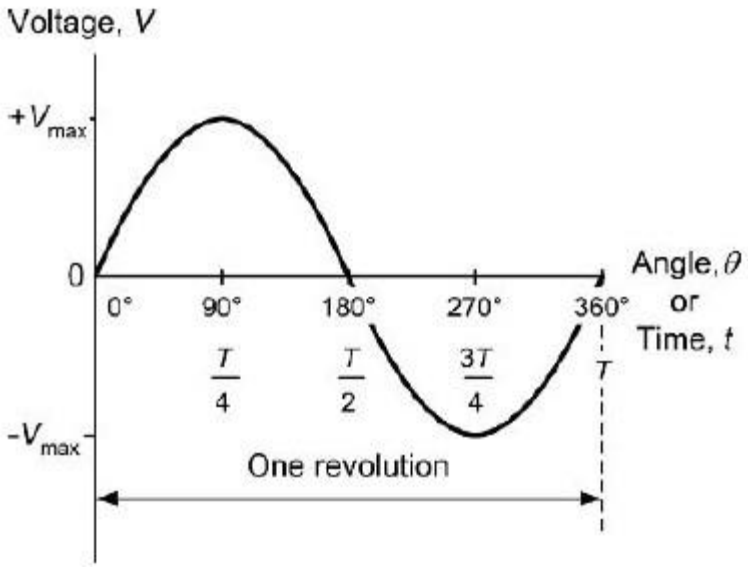


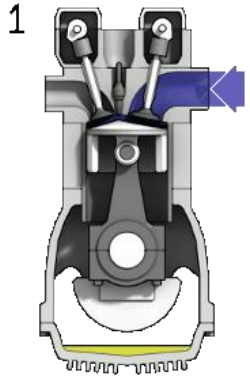
From the loss of the common reference
every time we miss a sync message the sync error increases

Common physical processes in CPS

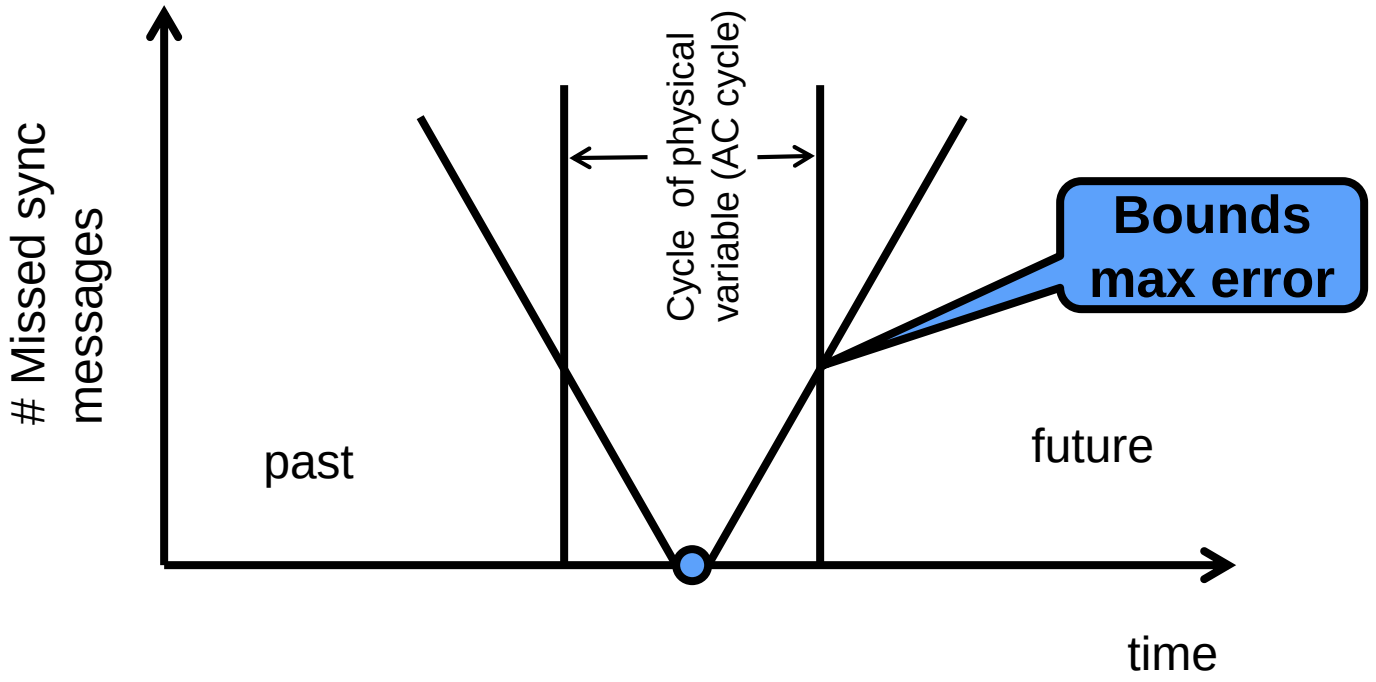
In a CPS cyber processes may observe a common physical process (physical variable)

- AC cycle in the smart grid
- Crankshaft angle in an engine

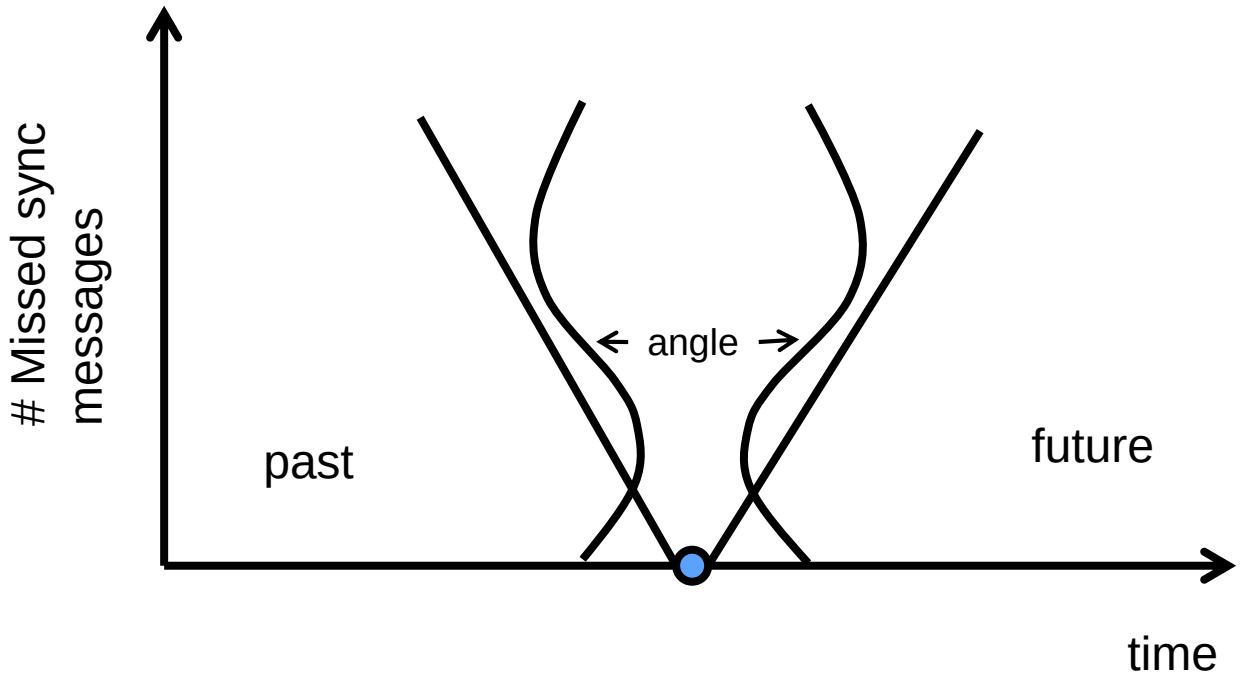


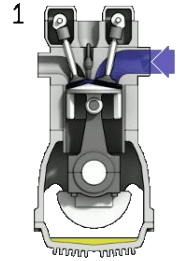


Combining sync clocks with physical variable



Physical process with variable cycles

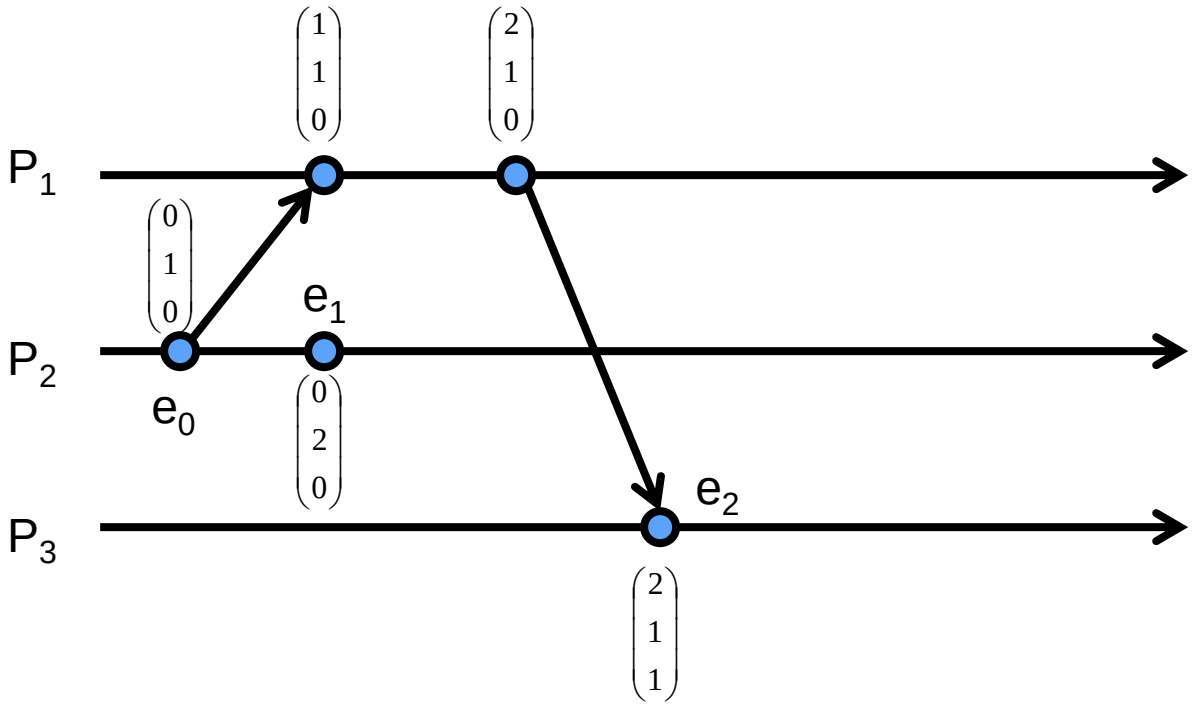




In CPS time is frequently a proxy for physical variable
Hence, cyber processes only require sync with physical variable

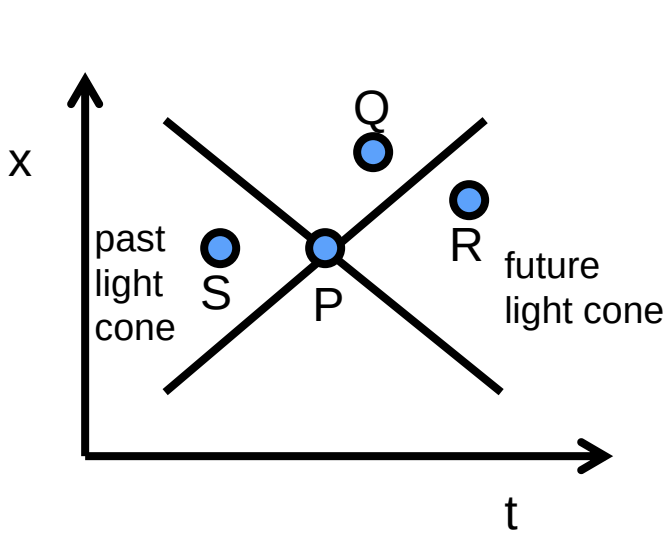
E.g. open/close valves sync with fuel injection

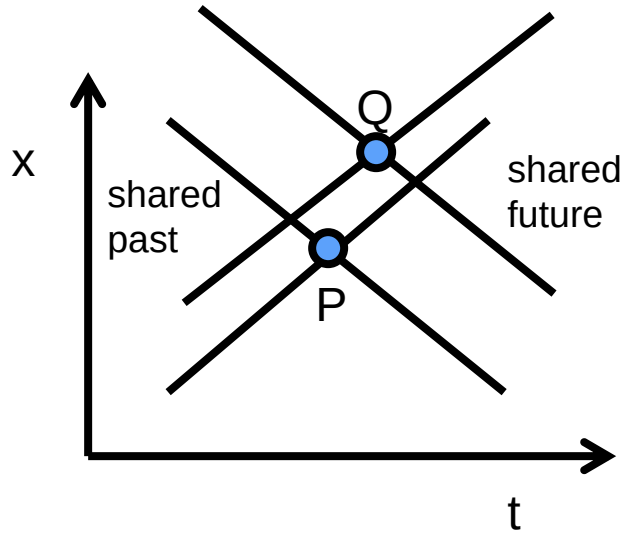
Logical (vector) clocks can also complement sync



But they are also sensitive to “missed” syncs

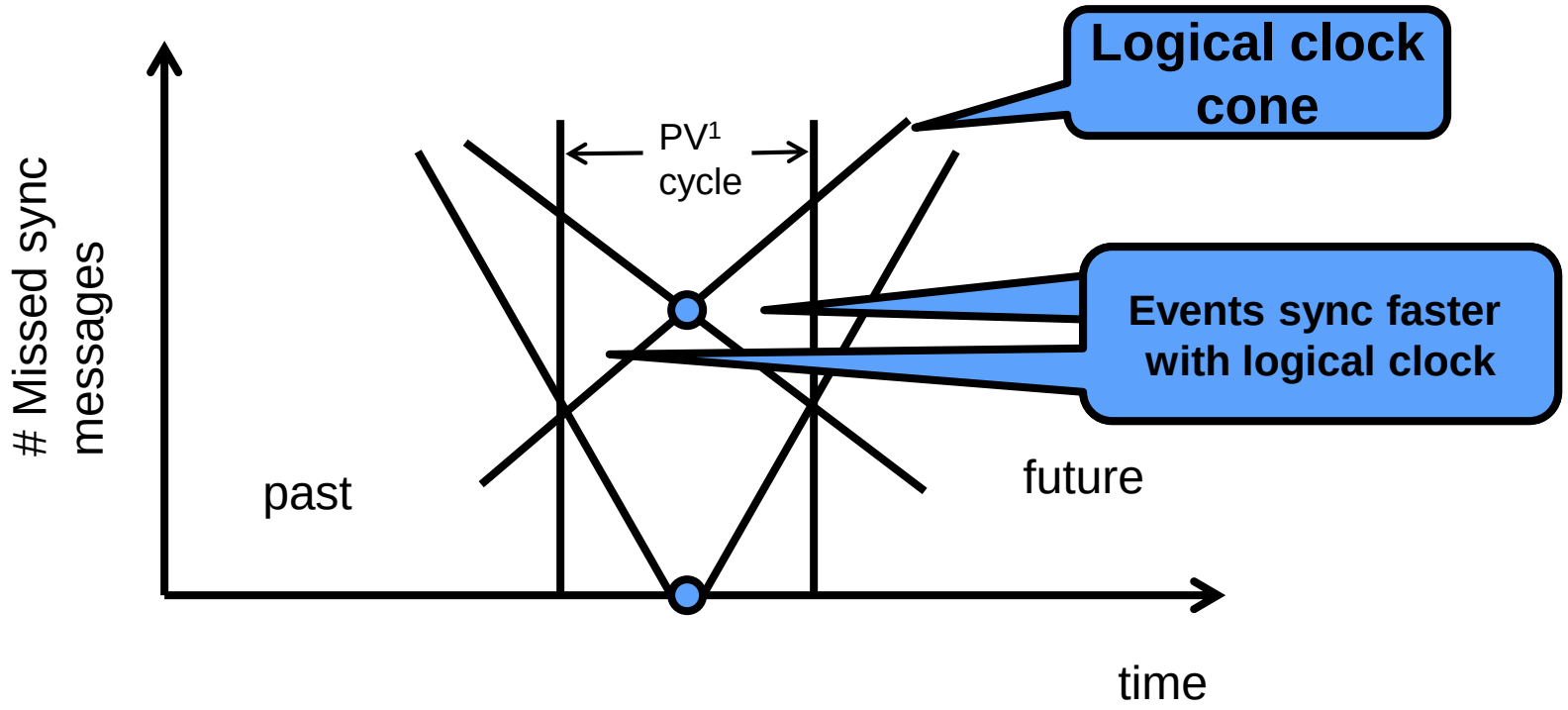
Mattern related vector clocks to Minkowski's spacetime





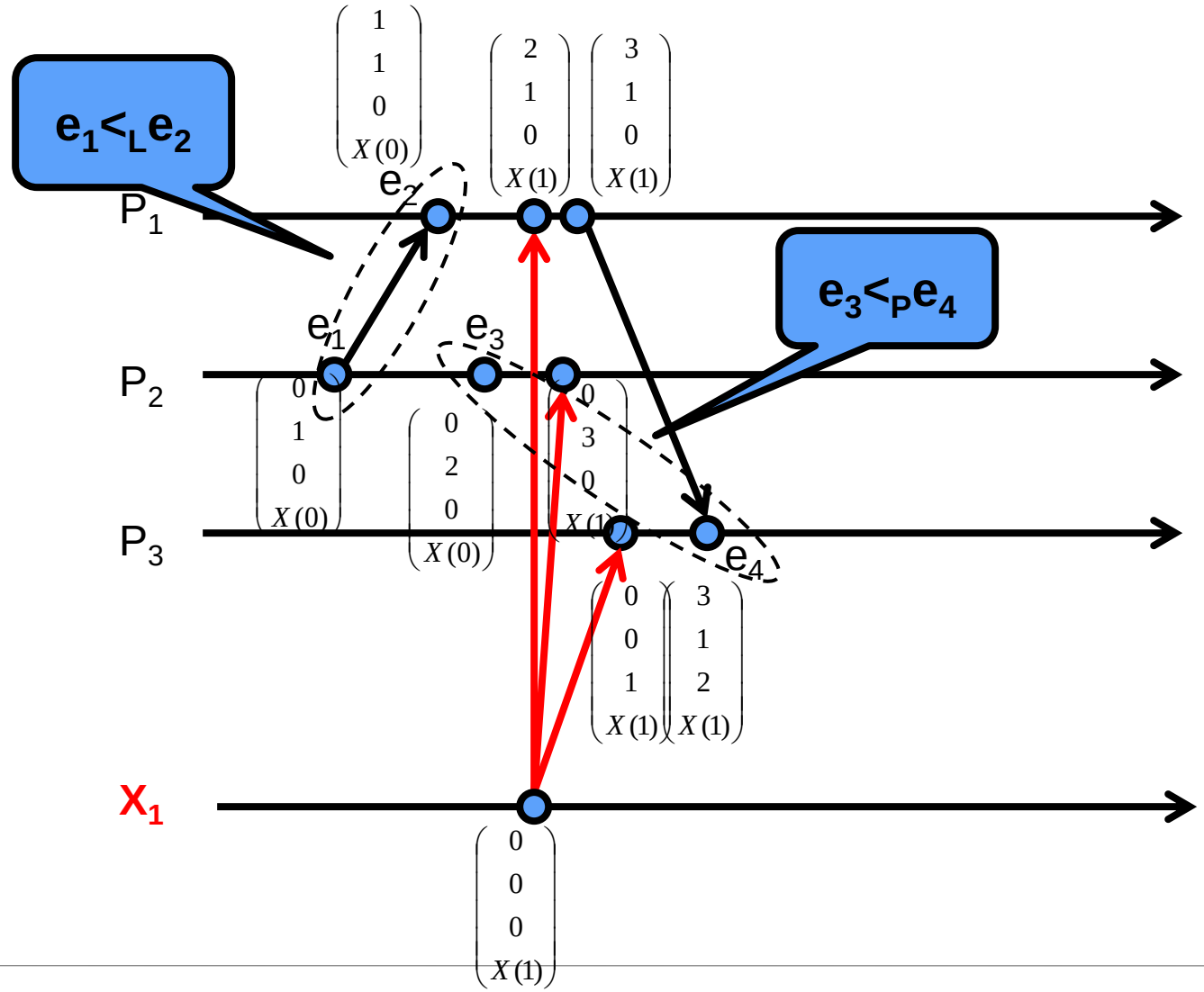
In CPS "x" can also be related to a physical variable (and back to time)

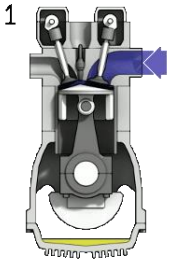
Mixed Physical and Cyber Clocks



[1]PV: physical variable

Logical + Physical Clock





Distributed Physical-Temporal Clocks

Add maximum instantaneous speed of change of physical variable x.

- $\hat{\dot{x}}$

Distributed Physical-Temporal Tick:

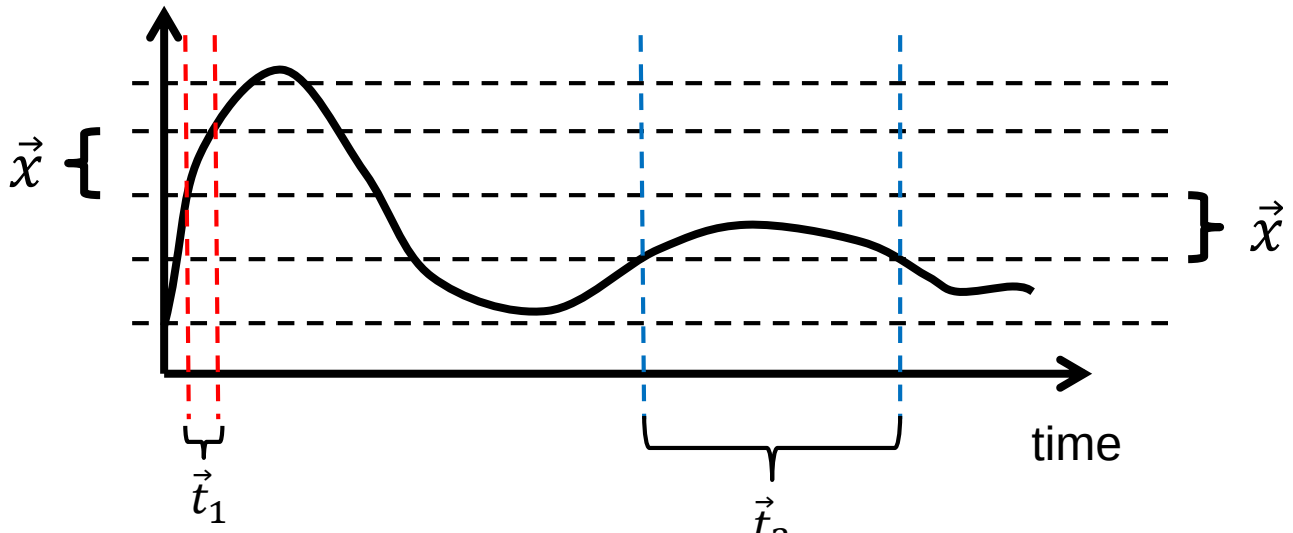
- $\delta\psi = (t, \rho, \hat{\dot{x}})$

Bounding maximum physical disagreement

- Given maximum disagreement bound: $\vec{x}$
- Calculate maximum out of sync interval:
  - $\vec{t} = \frac{\vec{x}}{\hat{\dot{x}}}$

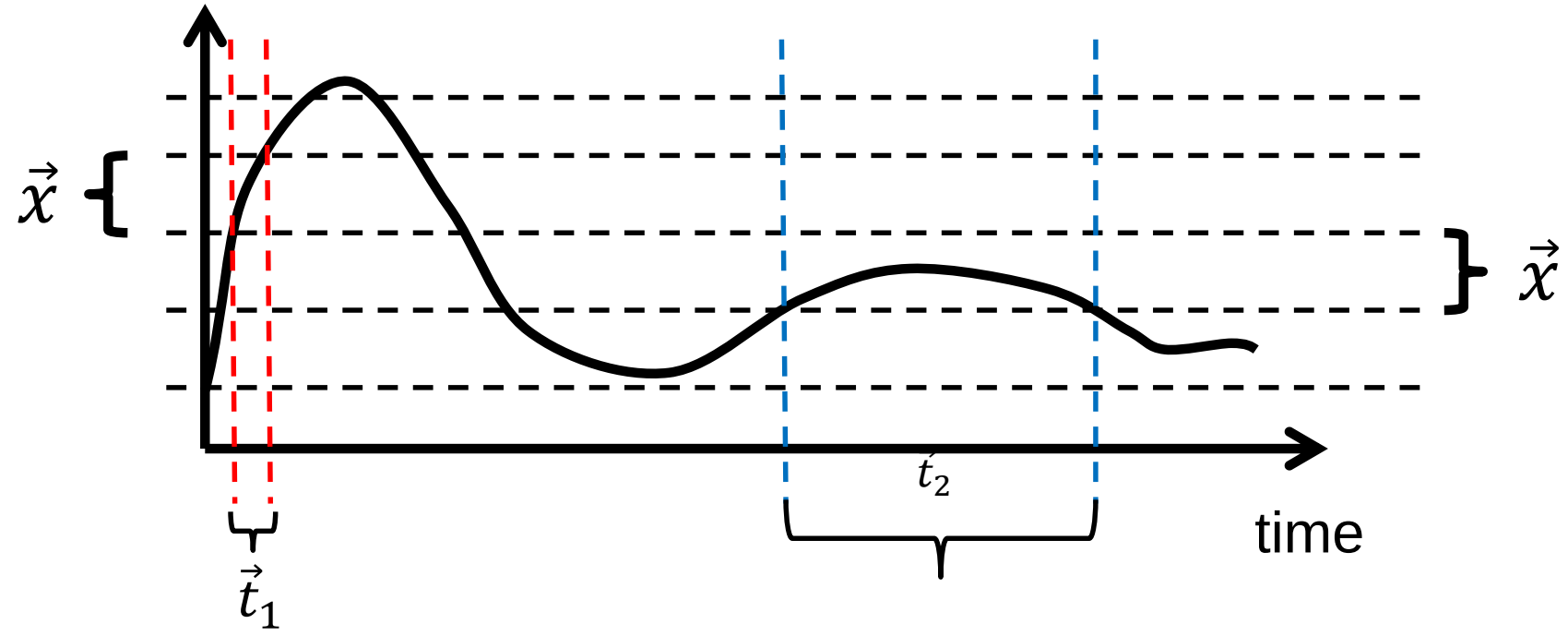
Use $\vec{t}$ to adaptively timeout and take corrective actions

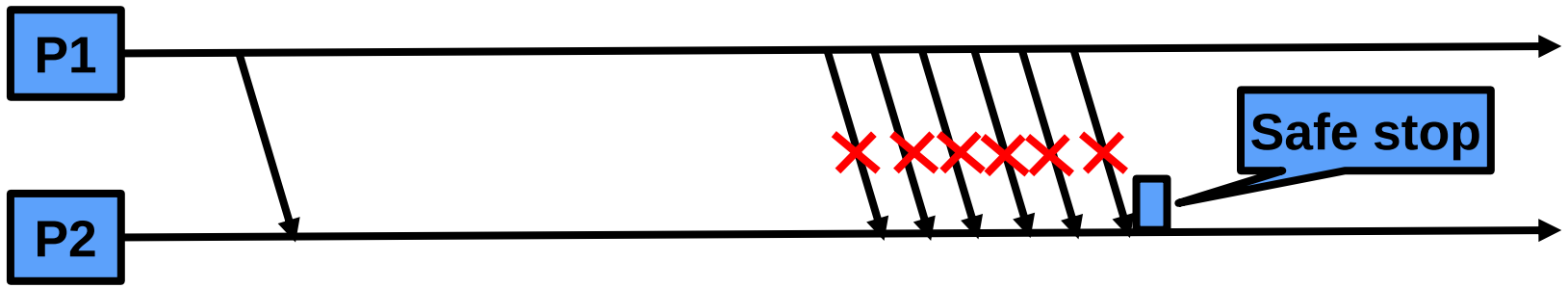
Physical Tick



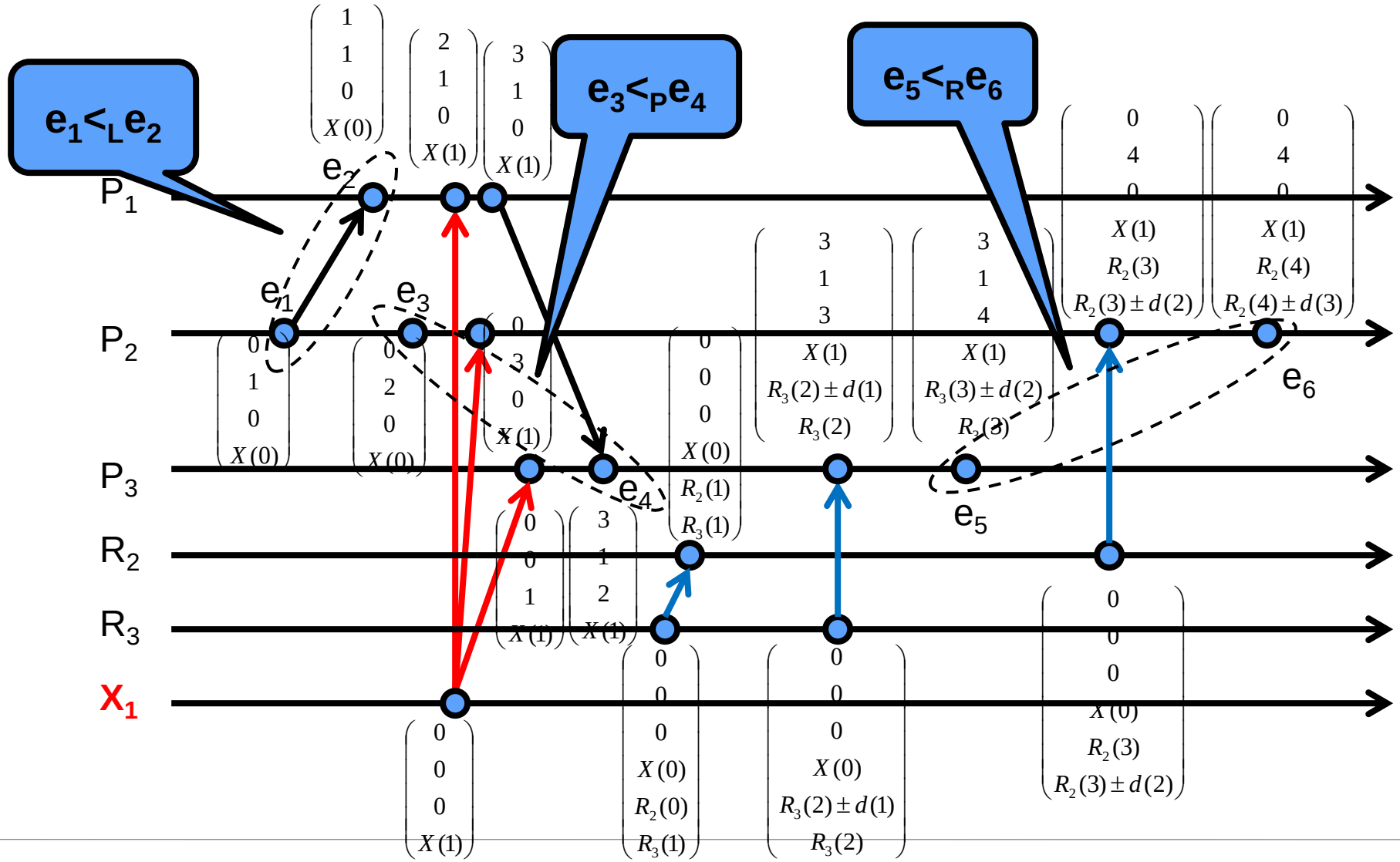
$$\hat{\dot{x}} = \frac{\vec{x}}{\vec{t}_1} \qquad \hat{\dot{x}} = \frac{\vec{x}}{\vec{t}_2}$$

Dynamic Timeout and Safe Stop

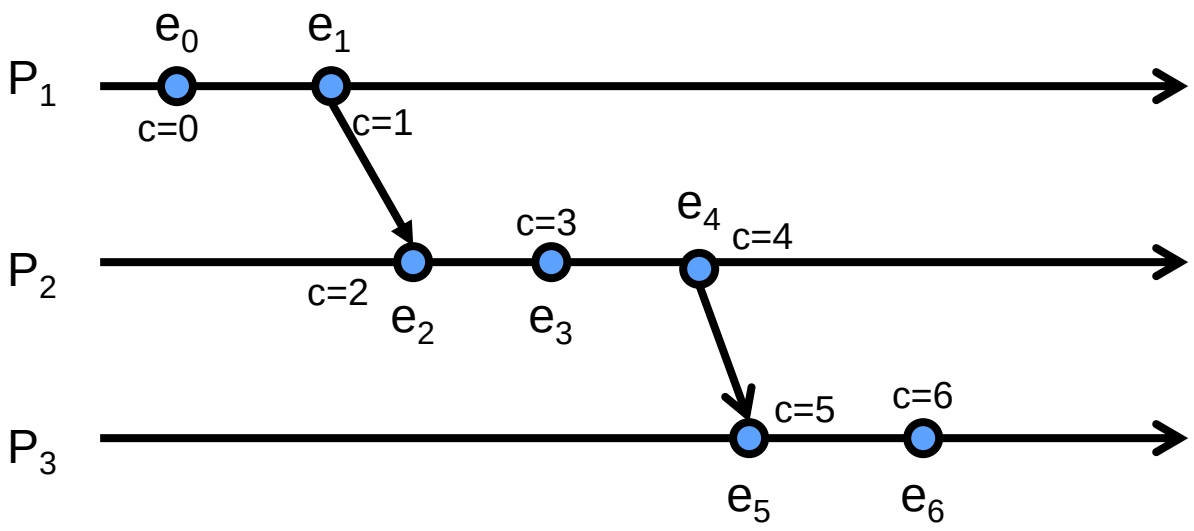




Logical + Physical Clock + Real-time clock



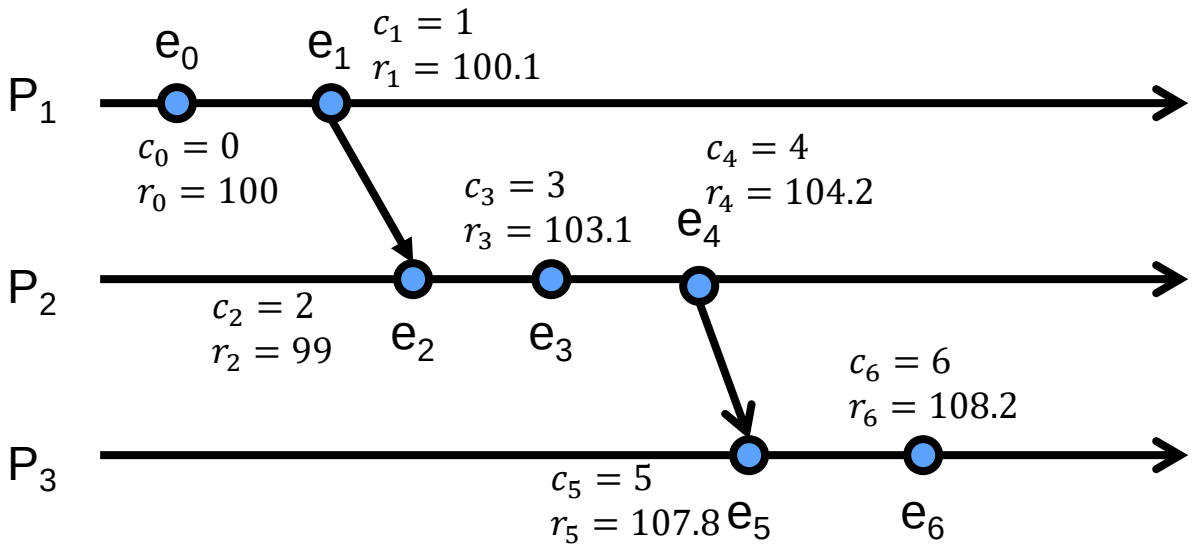
Traditional Virtual Clocks



e_i occurred before e_j if clock at e_i smaller than at e_j

BUT: No physical time relationship

Incorporating Physical Time



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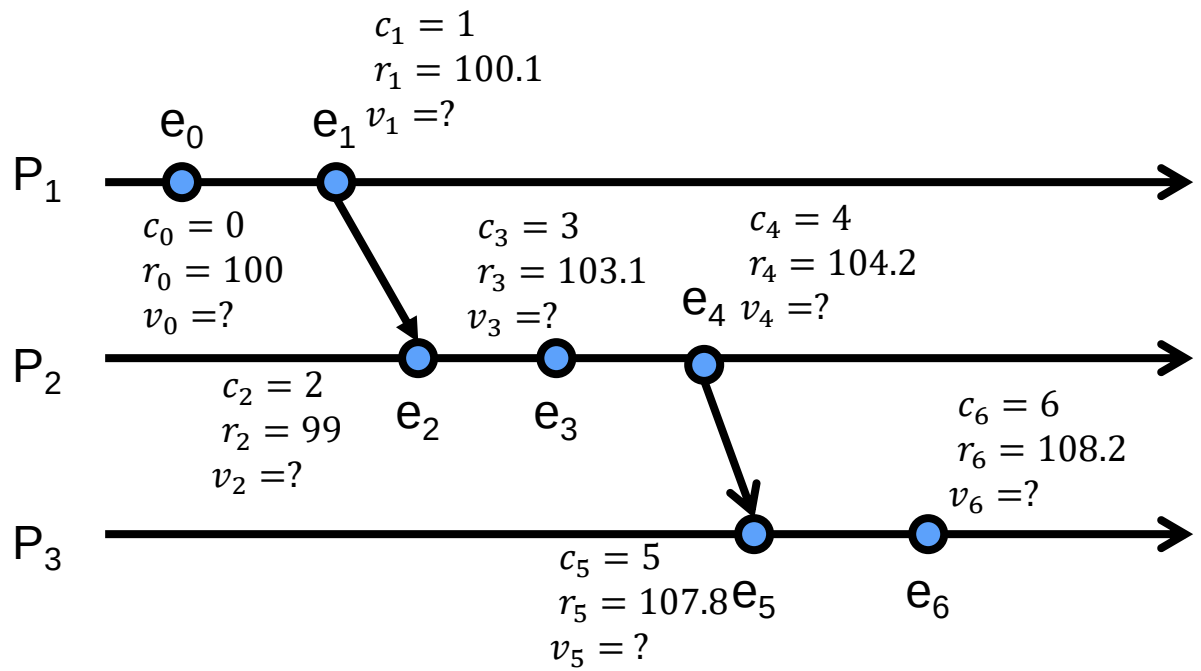
Incorporating Physical Time



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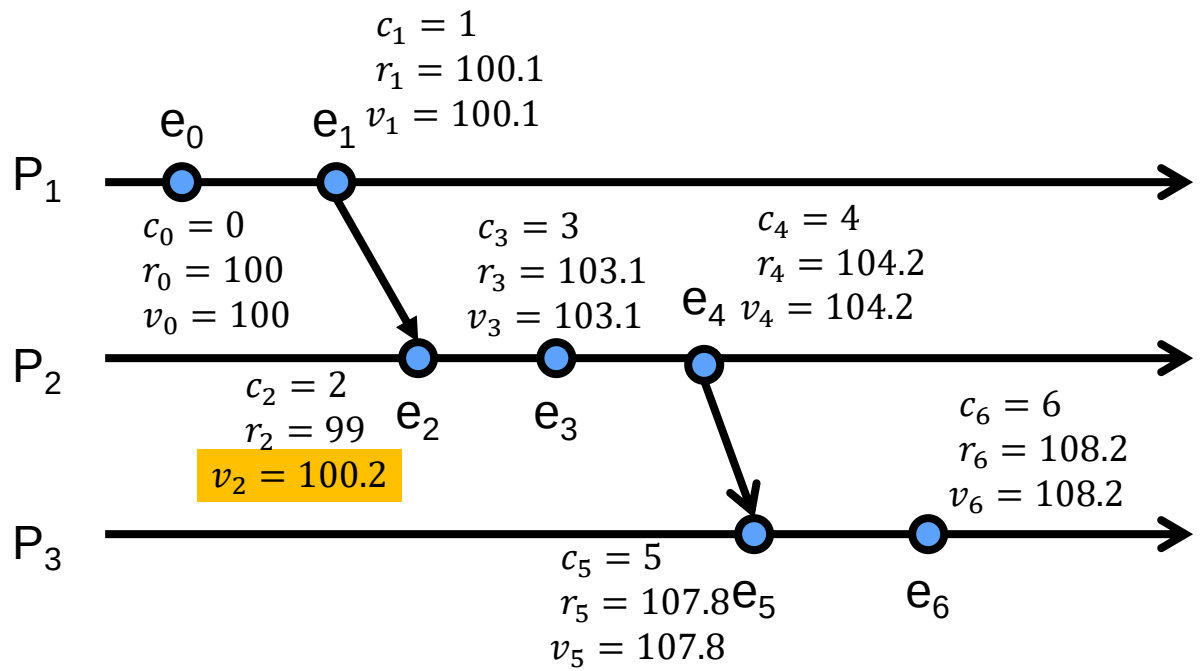
Incorporating Physical Time



Minimize:

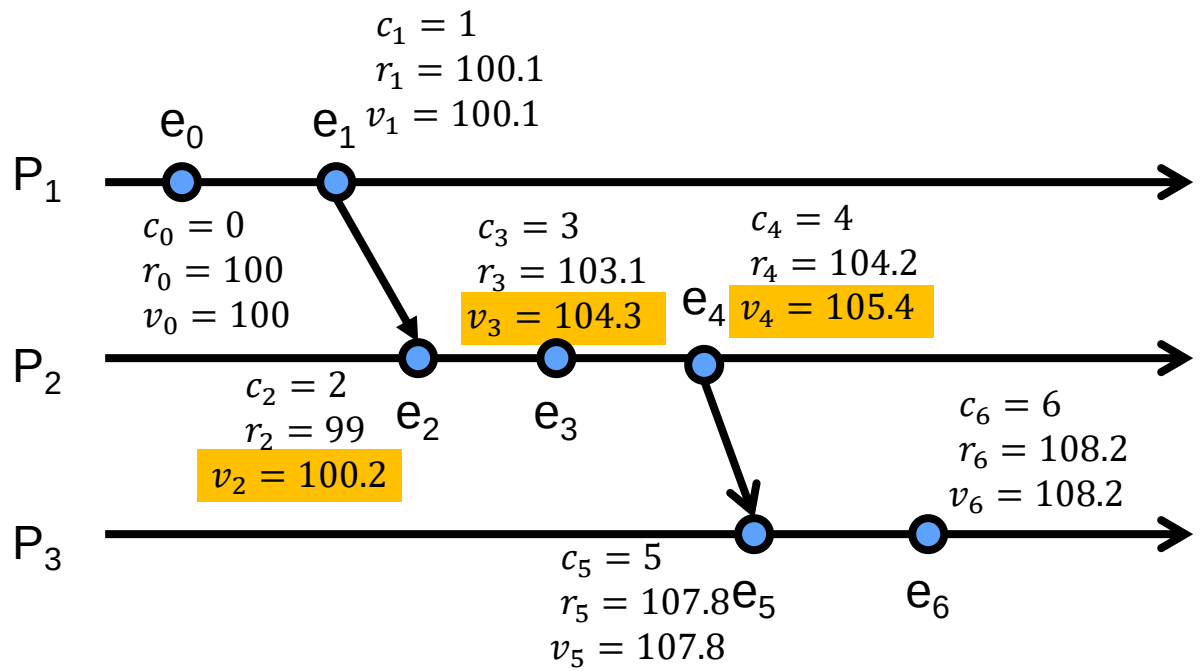
$$\max_i |v_i - r_i|$$

Subject to:

respecting event ordering

e_i occurred before e_j if clock at e_i smaller than at e_j

Incorporating Physical Time



Minimize:

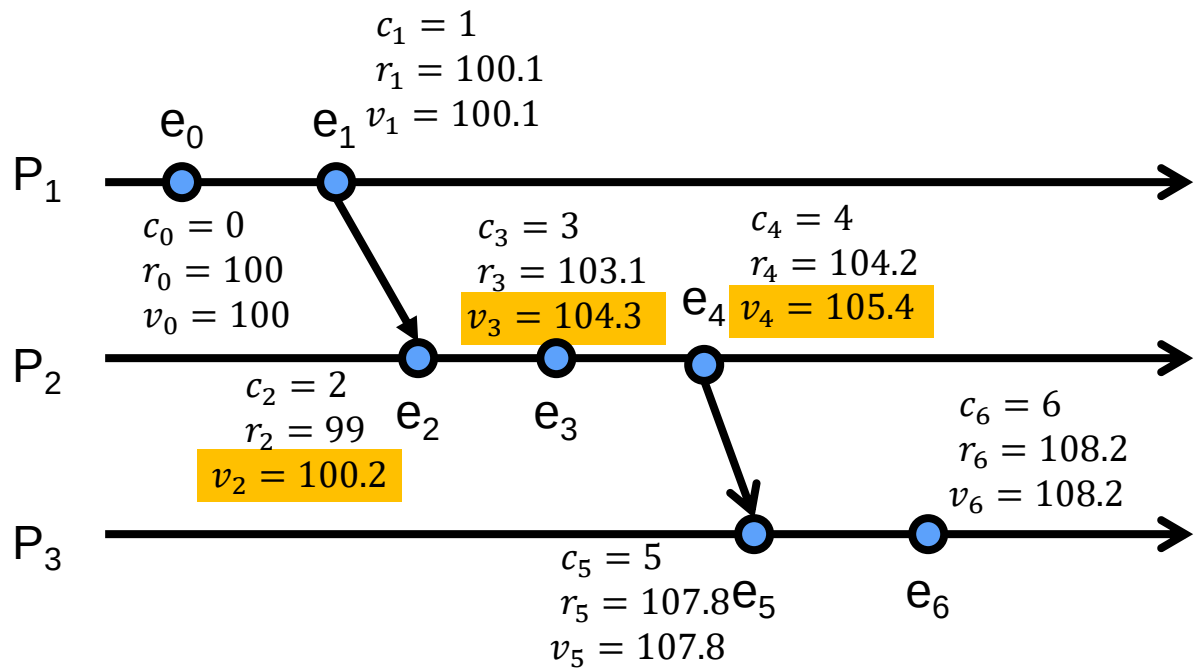
$$\max_{p \in \{1..m\}} \max_{e_i, e_j \in p} |(v_i - v_j) - (r_i - r_j)|$$

Subject to:

respecting event ordering

e_i occurred before e_j if clock at e_i smaller than at e_j

Incorporating Physical Time



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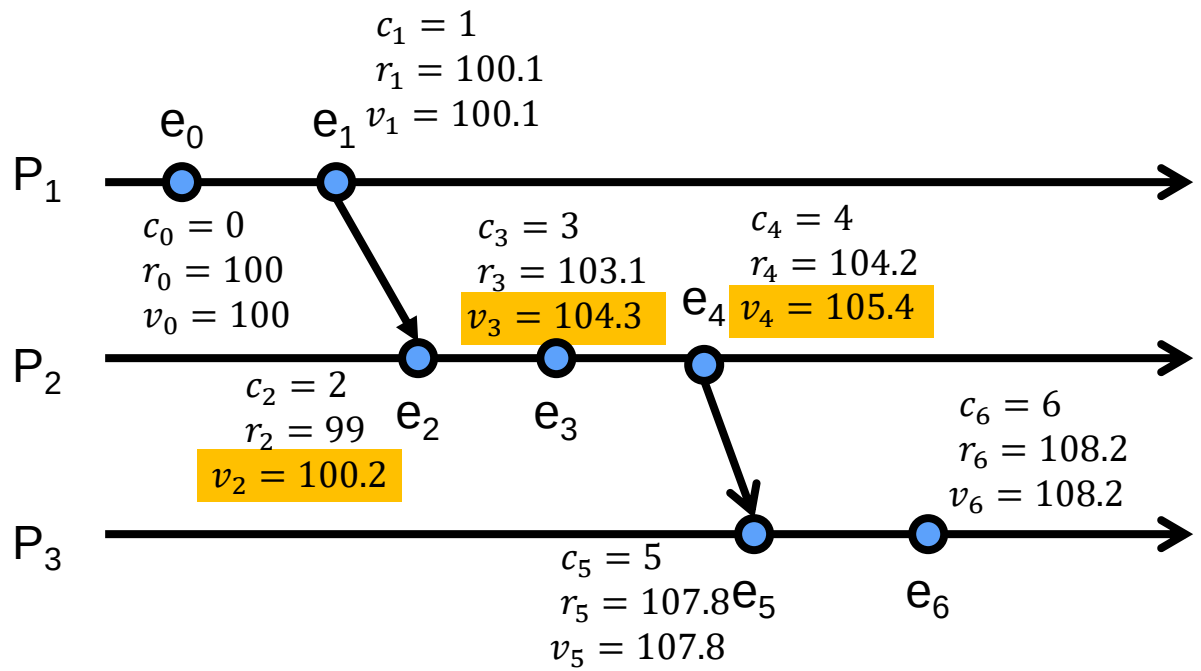

Minimize:

$$\max_{p \in \{1..m\}} \max_{e_i, e_j \in p} \left| \frac{(v_i - v_j) - (r_i - r_j)}{(r_i - r_j)} \right|$$

Subject to:

respecting event ordering

e_i occurred before e_j if clock at e_i smaller than at e_j

Concluding Remarks

Resource Optimization

- Exploiting new non-periodic control algorithms to minimize resource consumption

Distributed Agreement Optimization

- Exploit knowledge of physical state to minimize synchronization

Deriving Physical Timestamps from Agreement

- Assigning timestamps to events such that timestamps can be used to find event order and the timestamps mimic physical time.