ARTIST2 Summer School 2008 in Europe
Autrans (near Grenoble), France
September 8-12, 2008

Feedback Performance Control of Distributed Computing Systems:

A Real-time Perspective

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University of Illinois

Feedback Performance Control of Distributed Computing Systems

- Feedback control has been a great success story in performance management of engineering and physical artifacts.
- It is time to advance a branch of theory that addresses feedback control of distributed ***software*** systems!

Why Feedback Control of Software?

- **Claim 1:** In 10 years, most computing innovation will be focused on *distributed systems that interact with the physical world*
- **Claim 2:** They will operate under *increased uncertainty*
- **Claim 3:** They will be burdened with *increased autonomy*

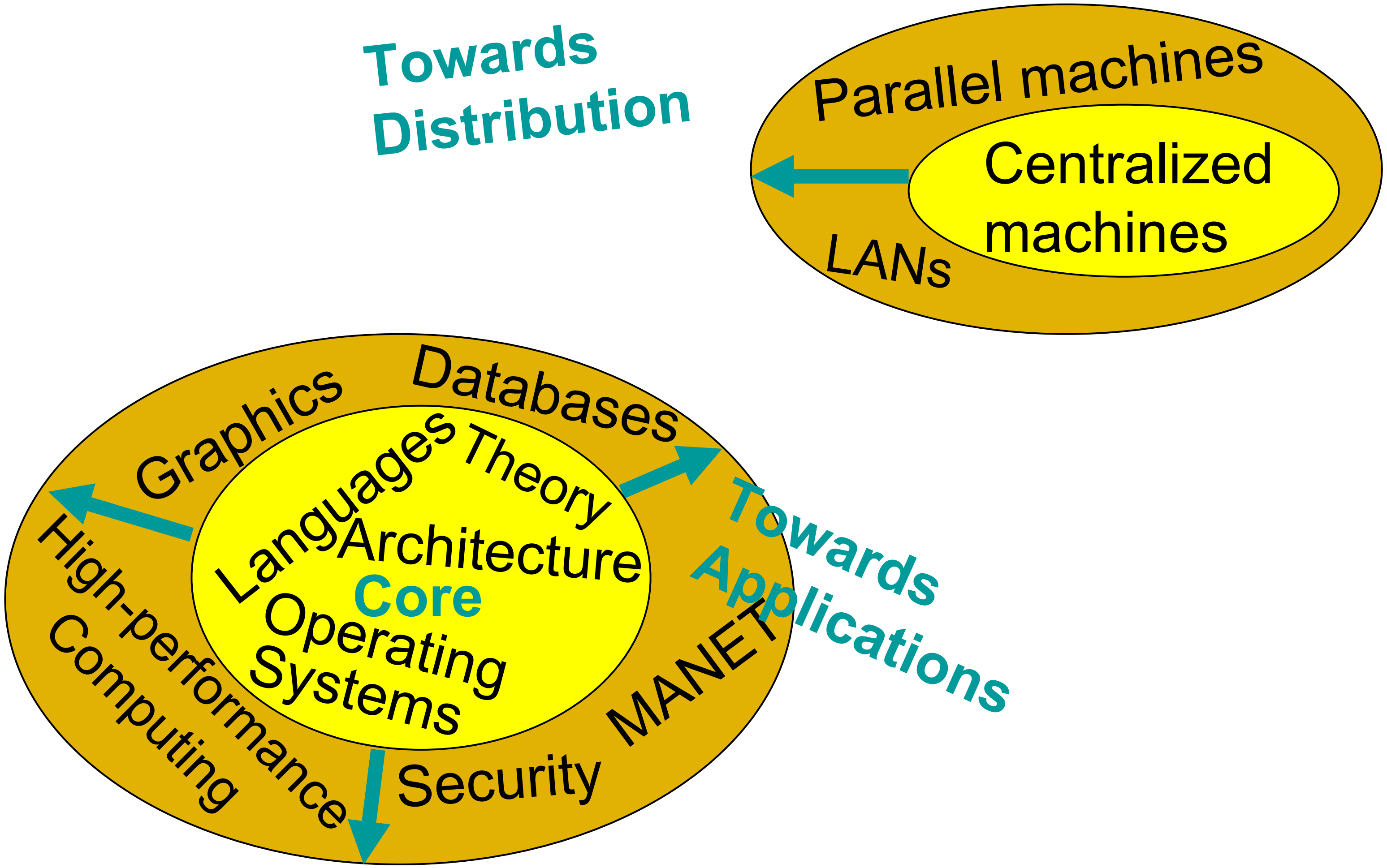
Where is Computer Science Research Going?

The beginning:

Centralized machines

Languages
Theory
Architecture
Core
Operating Systems

Where is Computer Science Research Going?



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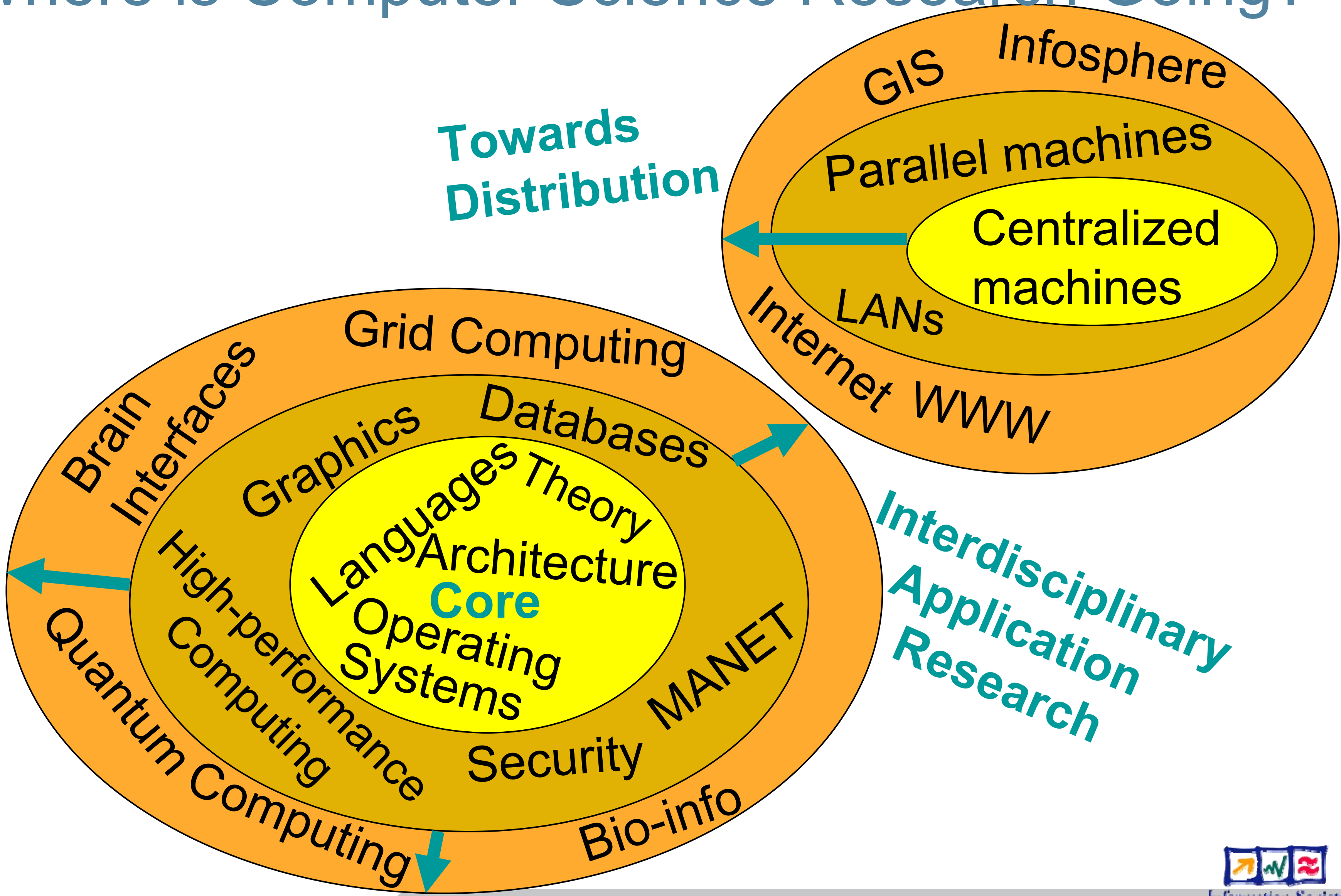

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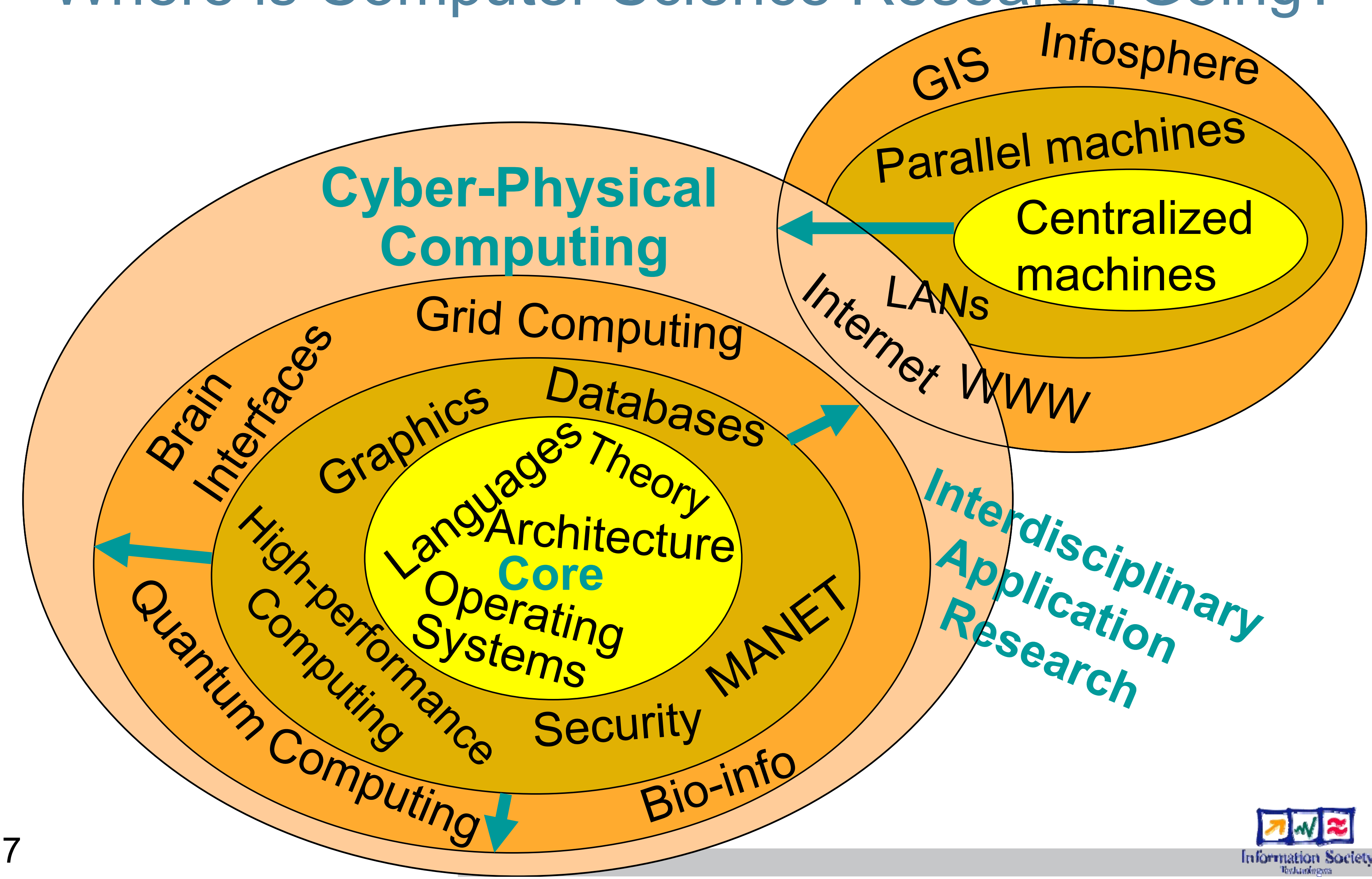

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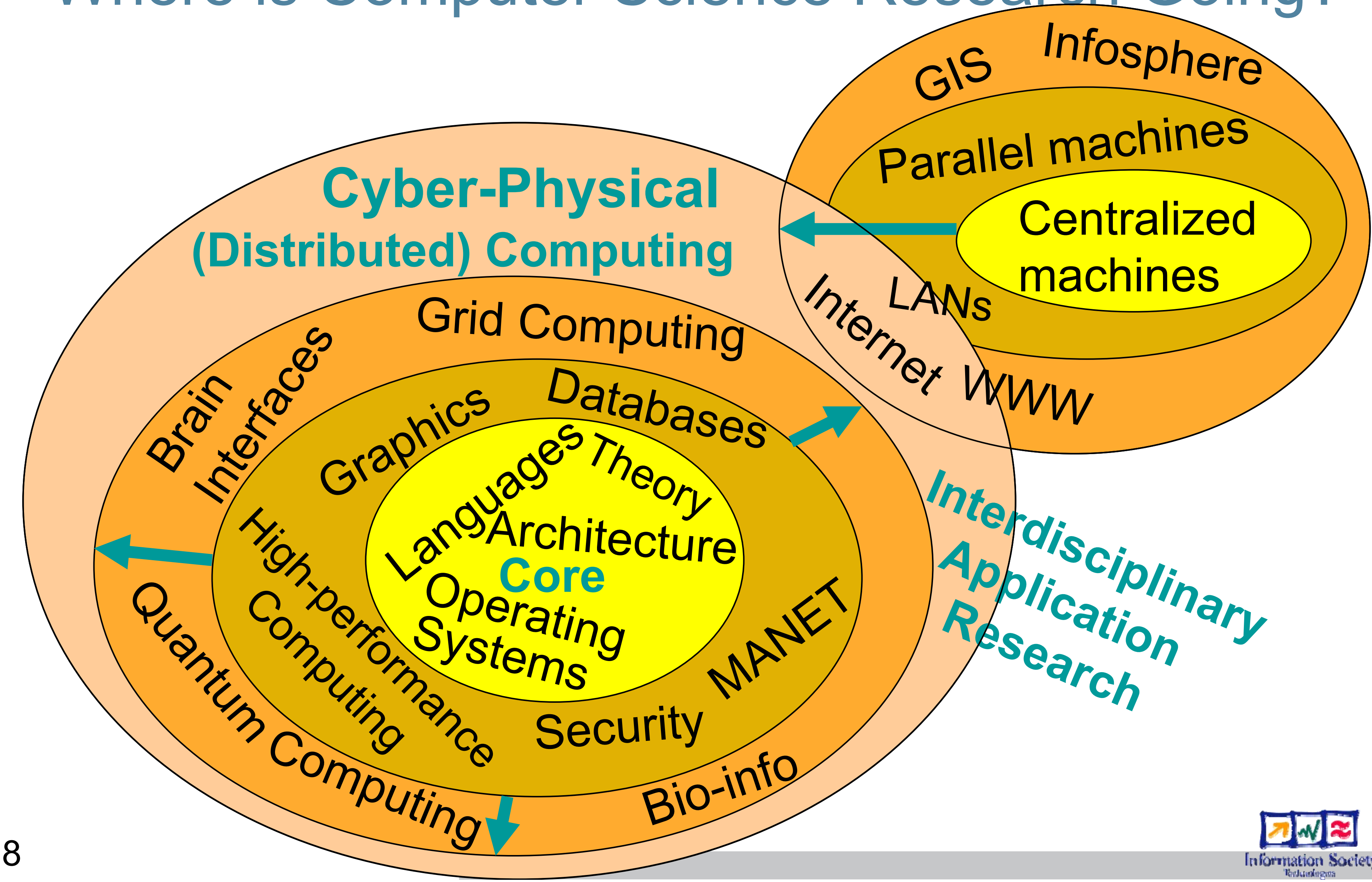

Where is Computer Science Research Going?

Claim 1: In 10 years, most computing innovation will be focused on *distributed systems that interact with the physical world*

Cyber-Physical Distributed Systems

For example:

In the US, the **Presidential Counsel of Advisors in Science and Technology** named systems that interact with the physical world the

#1 Research Priority in the US

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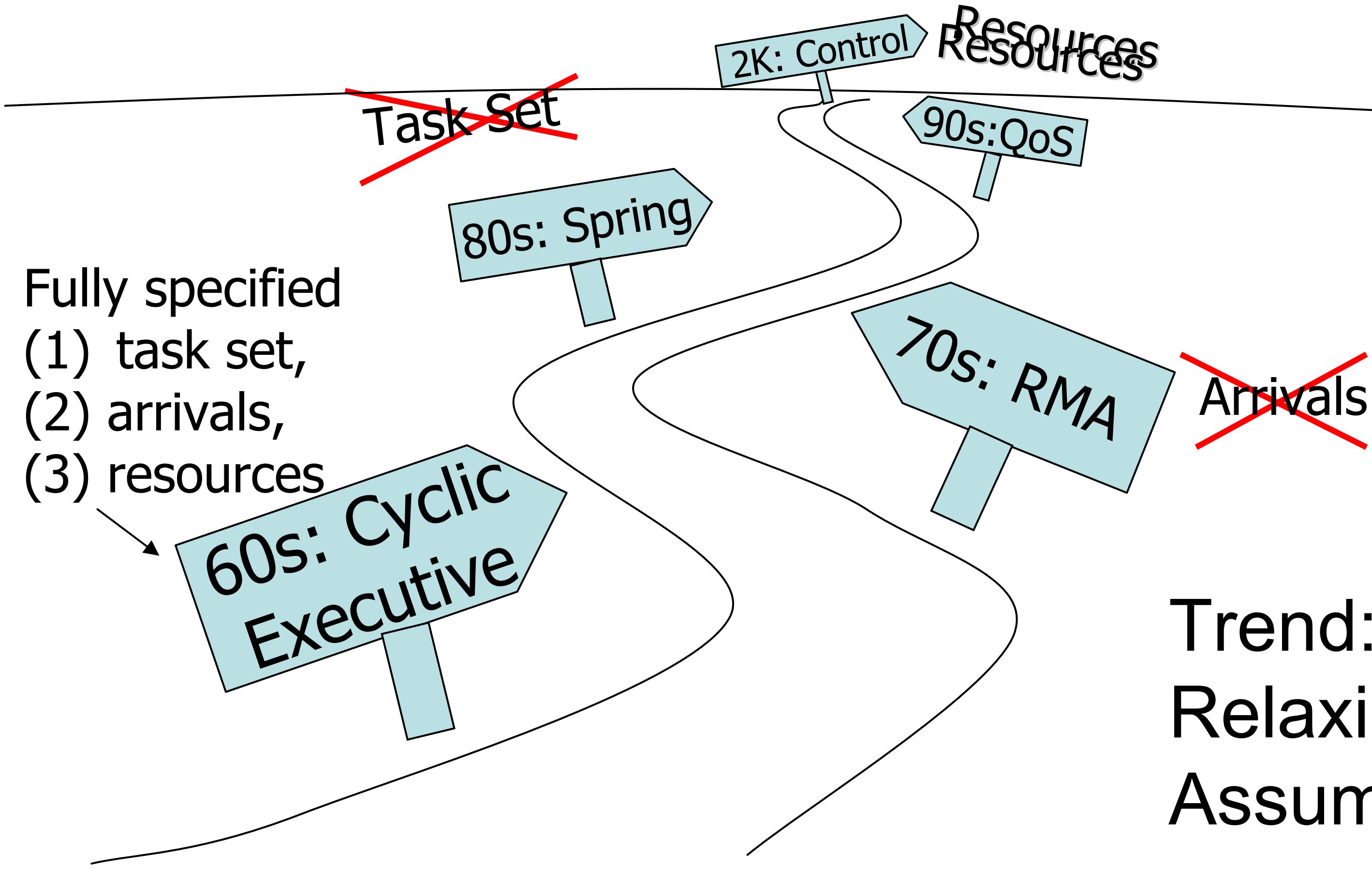
The Mounting Uncertainty

- Larger (distributed) systems
- Higher connectivity and interactive complexity
- Increasingly data-centric nature
  - Time it takes to execute is driven by data
  - Worst case is too pessimistic or unbounded
- More complex sensing at higher-level of abstractions
  - Data mining engines to convert data to actionable information
- Increasingly hybrid nature
  - Fusion of digital, analog, social, and biological models to understand overall behavior

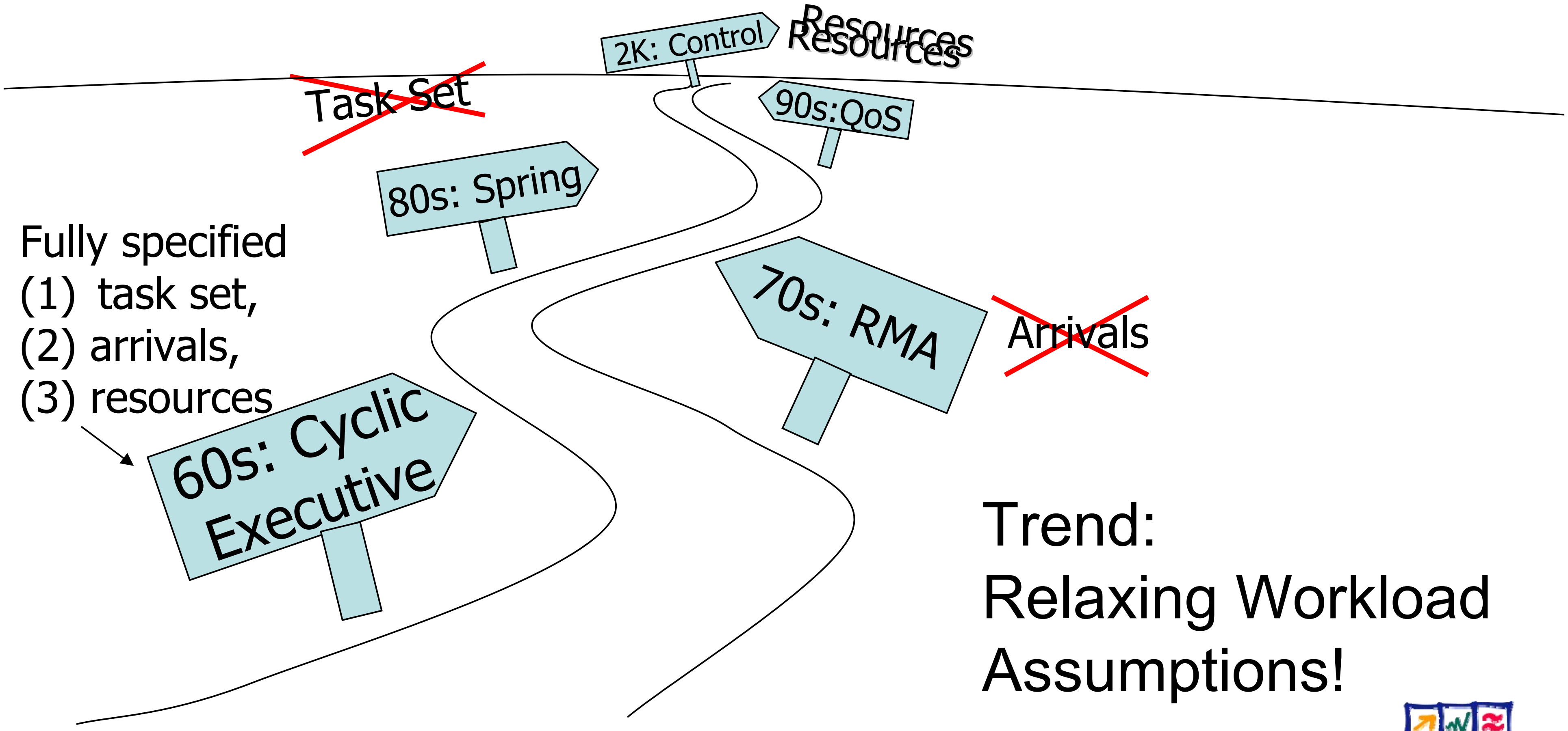
Evidence by Example:
The Real-Time Scheduling Theory Roadmap



Trend:
Relaxing Workload Assumptions!

Evidence by Example: The Real-Time Scheduling Theory Roadmap

Claim 2: A significant challenge will be one of providing *guarantees under uncertainty*



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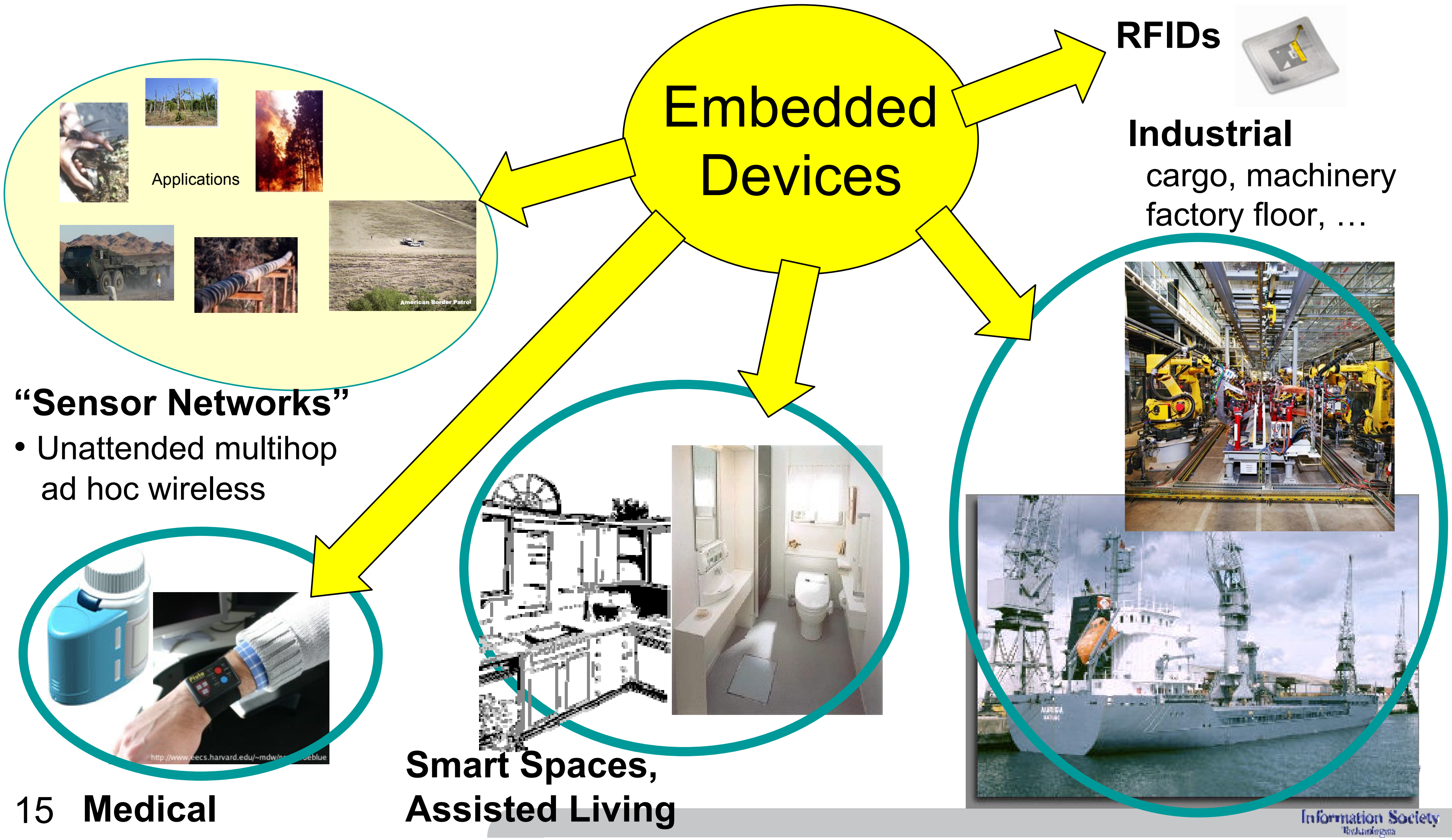
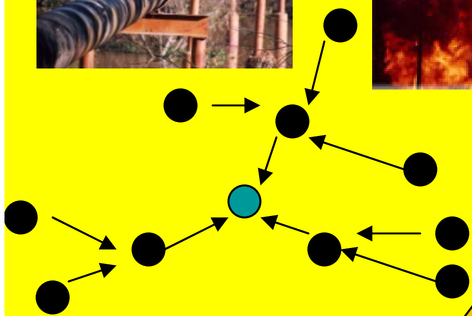
Factor #1: Device Proliferation (By Moore's Law)



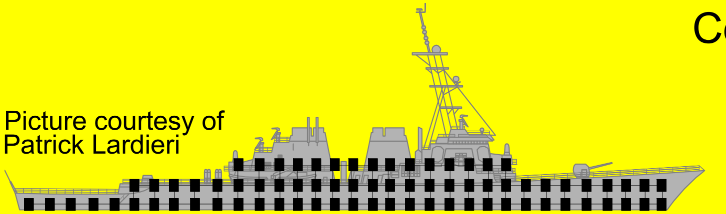
Information Society Technologies

Factor #2: Integration at Scale (Isolation costs!)

- Low end: ubiquitous embedded devices
  - Large-scale networked embedded systems
  - Seamless integration with a physical environment
- High end: complex systems with global integration
  - Examples: Global Information Grid, Total Ship Computing Environment



World Wide Sensor Web
(Feng Zhao)



Picture courtesy of
Patrick Lardieri

Total Ship Computing Environment
(TSCE)

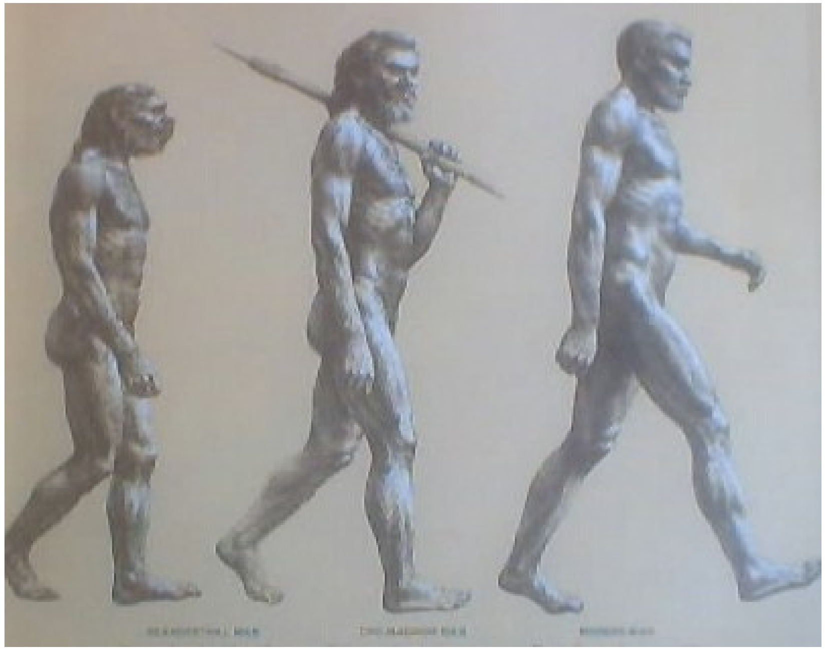
Global Information Grid

Future Combat System
(Rob Gold)

Integration and Scaling Challenges

Low End — High End

Factor #3: Biological Evolution



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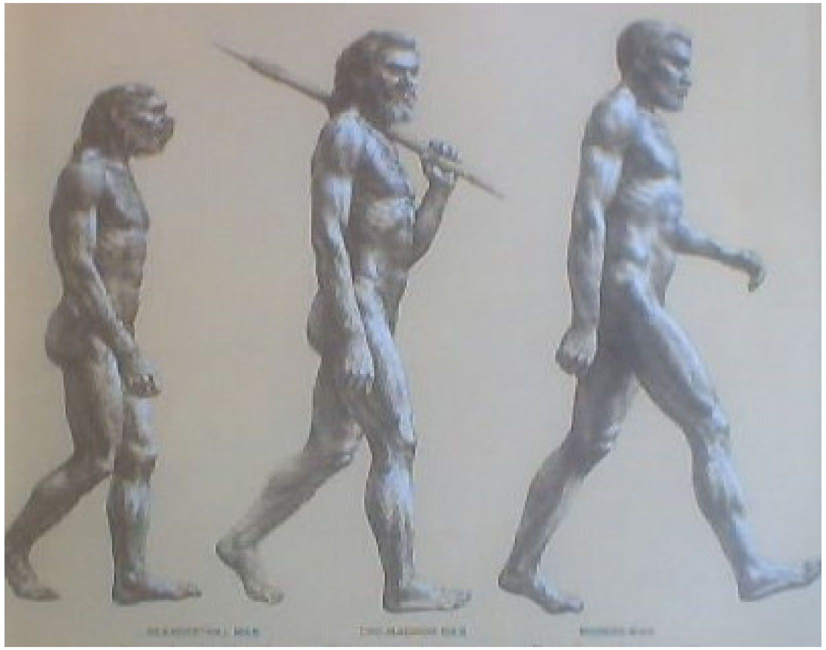
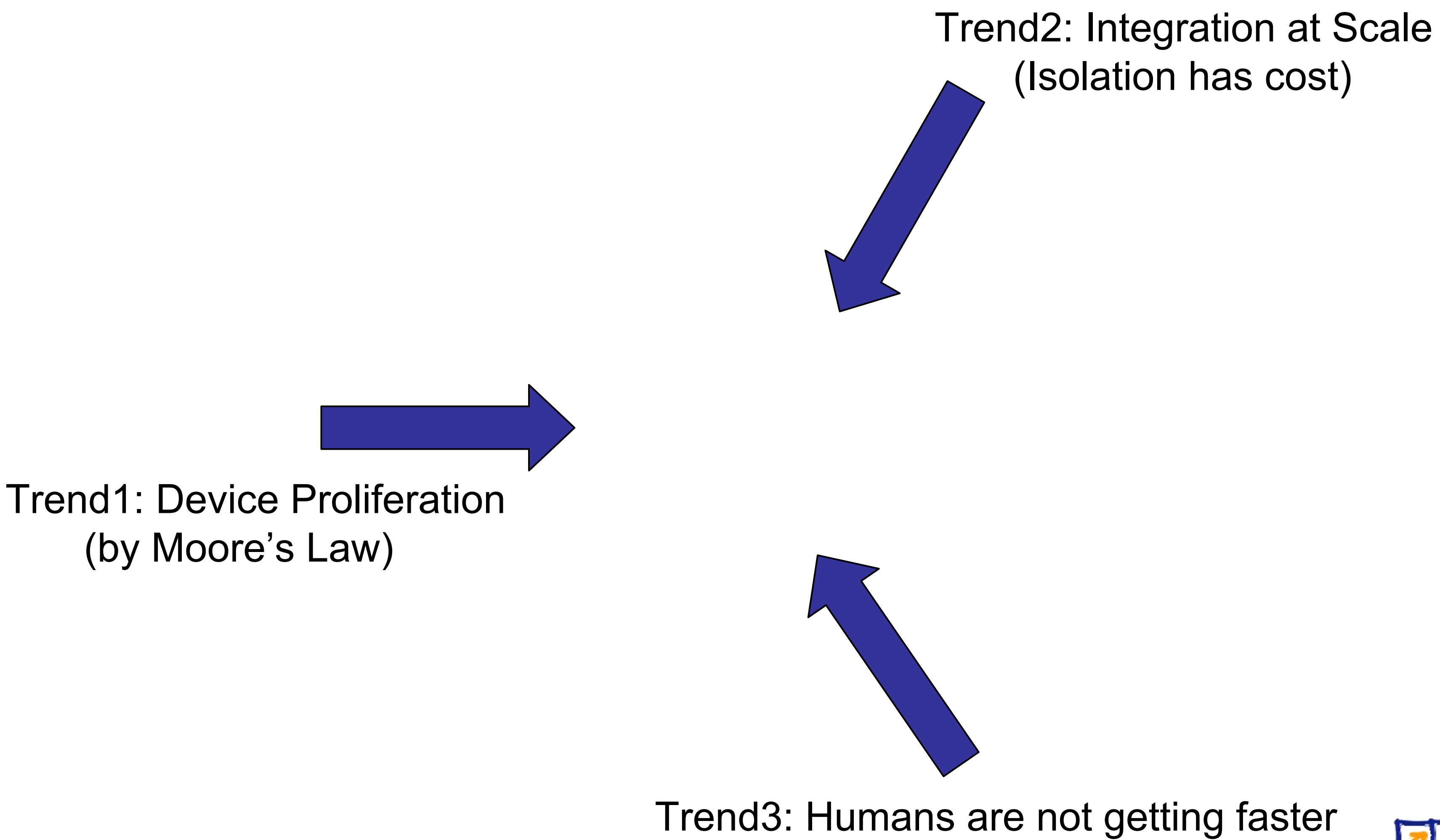


- **It's too slow!**
  - The exponential proliferation of data sources (afforded by Moore's Law) is ***not*** matched by a corresponding increase in human ability to consume information!

Confluence of Trends
The Overarching Challenge



Confluence of Trends
The Overarching Challenge

Trend2: Integration at Scale
(Isolation has cost)

Core Challenge:
Autonomous Distributed Systems
of Embedded Devices

Trend1: Device Proliferation
(by Moore's Law)

Trend3: Humans are not getting faster

Confluence of Trends

The Overarching Challenge

Trend2: Integration at Scale
(Isolation has cost)

Self-regulating
Self-tuning
Self-healing
Self…

Core Challenge:
Autonomous Distributed Systems
of Embedded Devices

Trend1: Device Proliferation
(by Moore's Law)

… and interacting
with the physical
world

Trend3: Humans are not getting faster

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- **Claim 1:** In 10 years, most computing innovation will be focused on *distributed systems that interact with the physical world*
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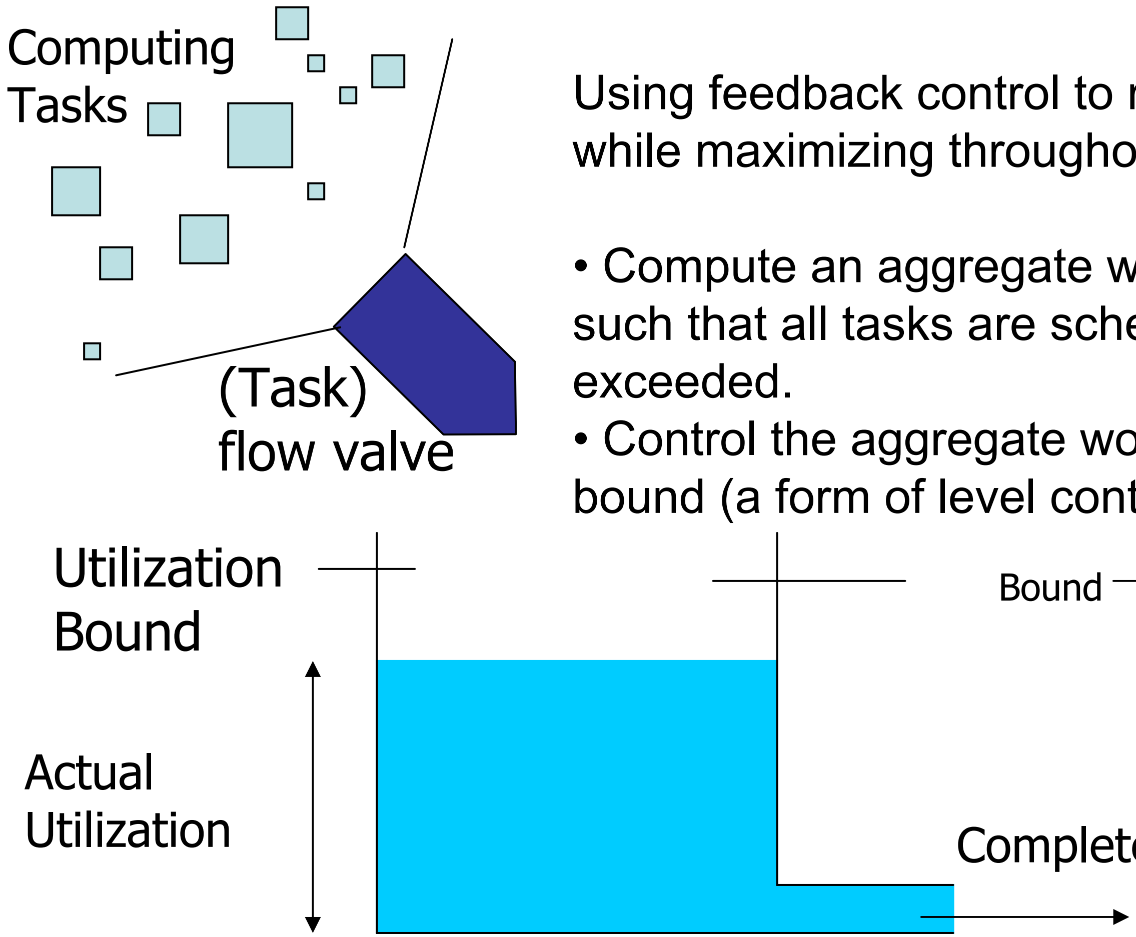
Examples

- Distributed vehicular traffic control algorithms for mass (e.g., city scale) evacuation in disaster scenarios
  - Hundreds of thousands of vehicles
  - Poor communication infrastructure (mostly vehicle to vehicle communication)
  - Complex time-varying underlying topology (accidents, gridlock, obstructions, …)
  - Need for personalized directions to balance load, optimize throughput, etc.
- Large energy-optimal data centers
  - Tens of thousands of machines
  - Hundreds of performance management knobs, including computing and cooling
  - Time-varying demand on multiple time scales
  - Need to minimize energy (cost) while meeting service-level agreements
- Utility optimizing wireless ad hoc networks

Feedback Performance Control of Distributed Software Systems

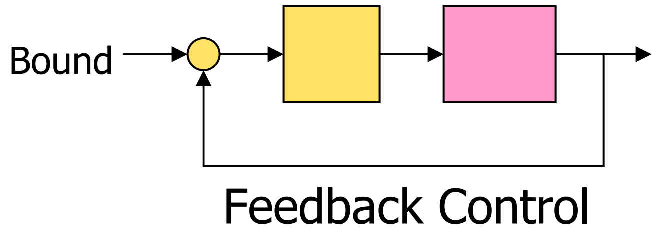
- Software performance optimization is a **resource management problem**
  - Resource allocation and scheduling are adjusted dynamically in response to external stimuli to optimize an objective while meeting constraints
- A key challenge: **bridge the levels of abstraction**
  - Software: tasks, priorities, deadlines, queues, arrival times, precedence constraints, …
  - Control: state variables, deviations, dynamic models, stability conditions, …
- A key challenge: **formulate and solve a control problem**

Bridging the Levels of Abstraction: An Example

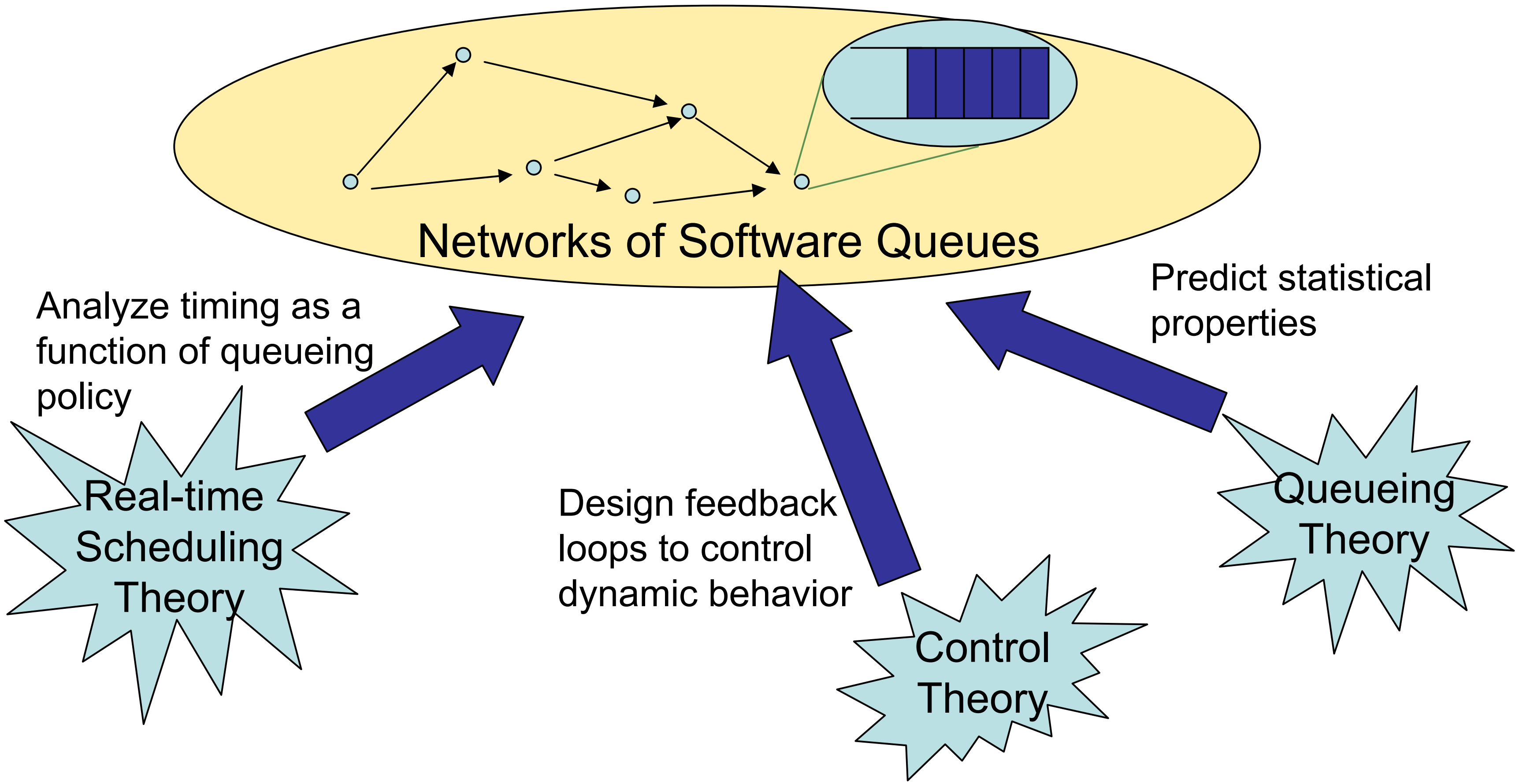


Using feedback control to remove deadline misses while maximizing throughout:

• Compute an aggregate workload or utilization bound such that all tasks are schedulable if bound is not exceeded.
• Control the aggregate workload not to exceed the bound (a form of level control).

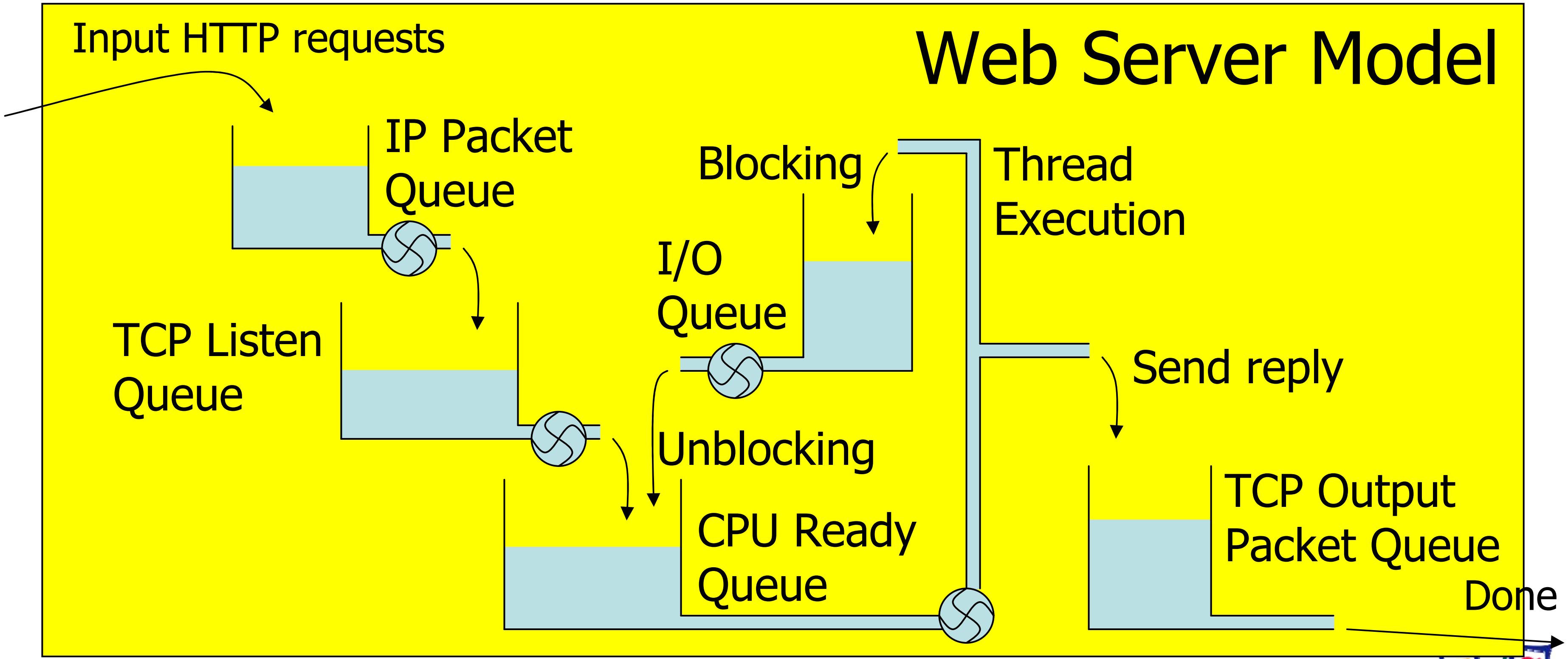


Software Queues: A Unifying Construct in Software Performance Control

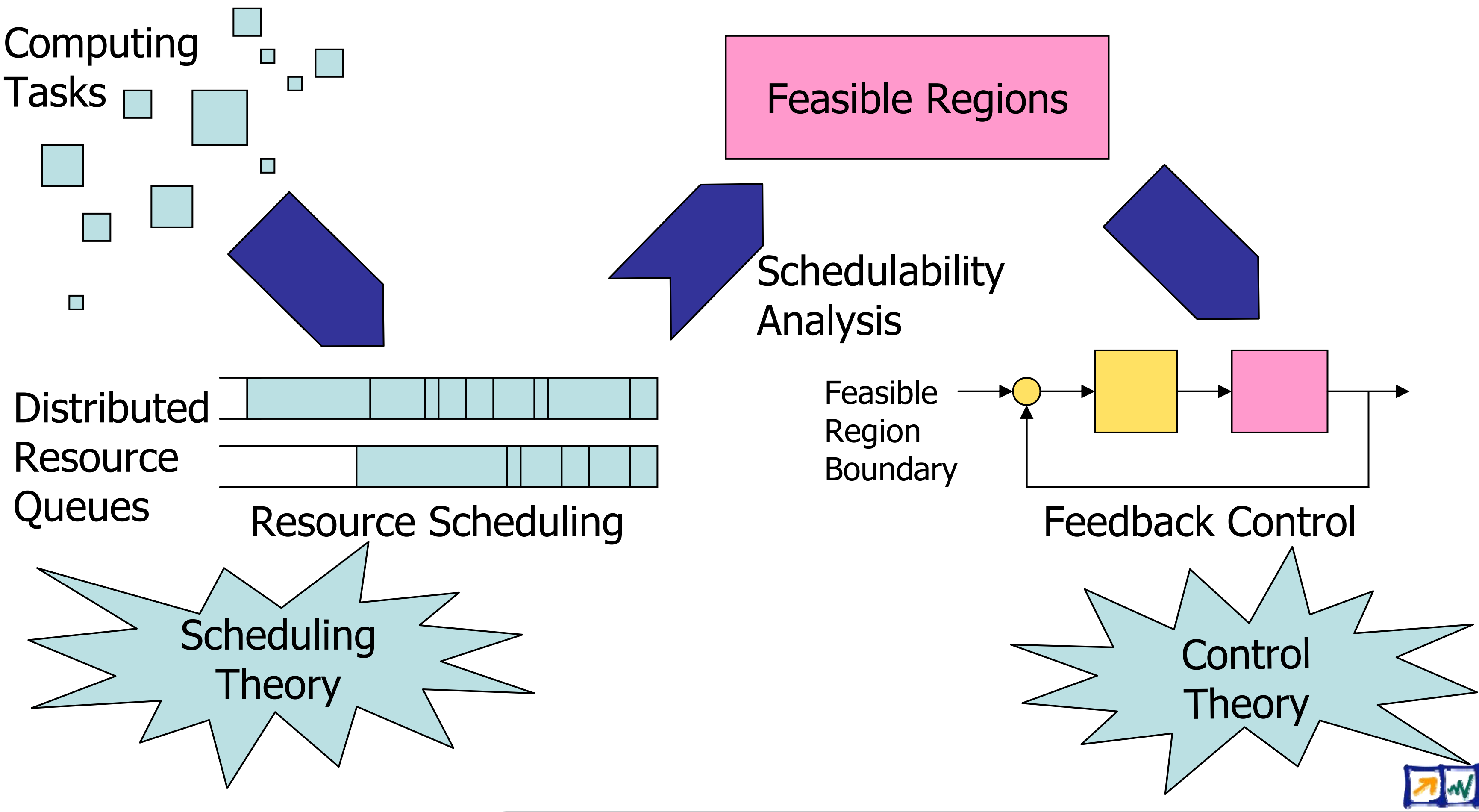


Example: A Web Server Model

Why web servers can be modeled by difference equations!

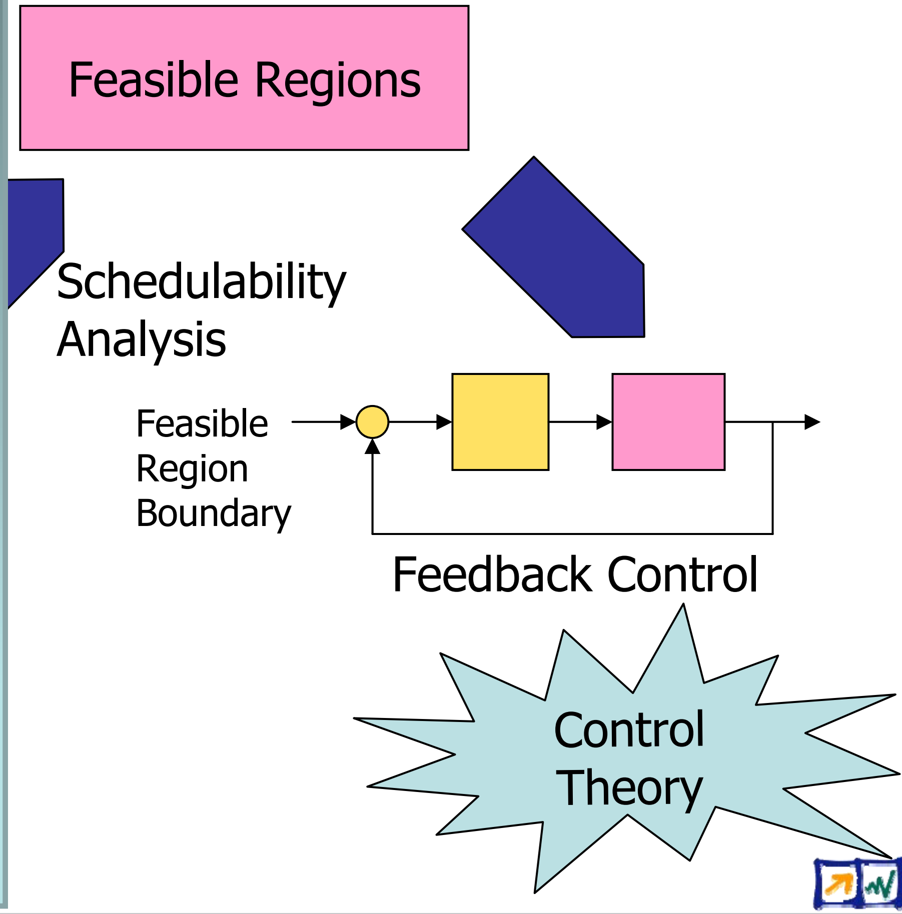


Distributed Software Performance Control



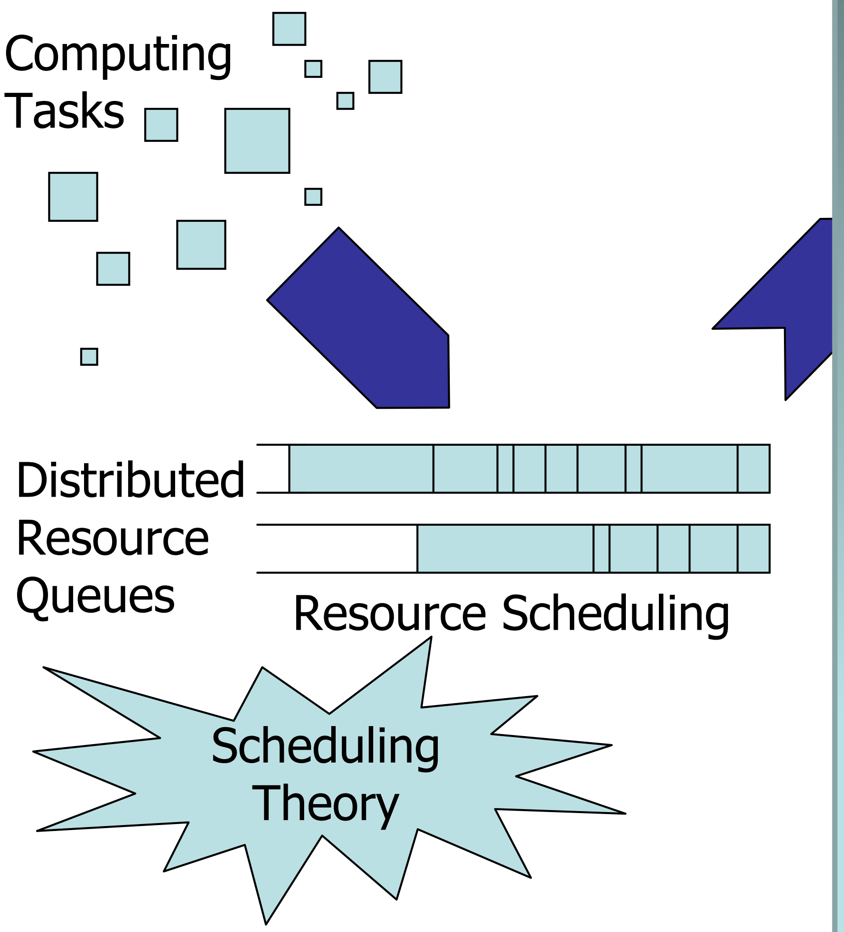
Distributed Software Performance Control

Part I: Bridge the abstractions: low-level metrics → queue state



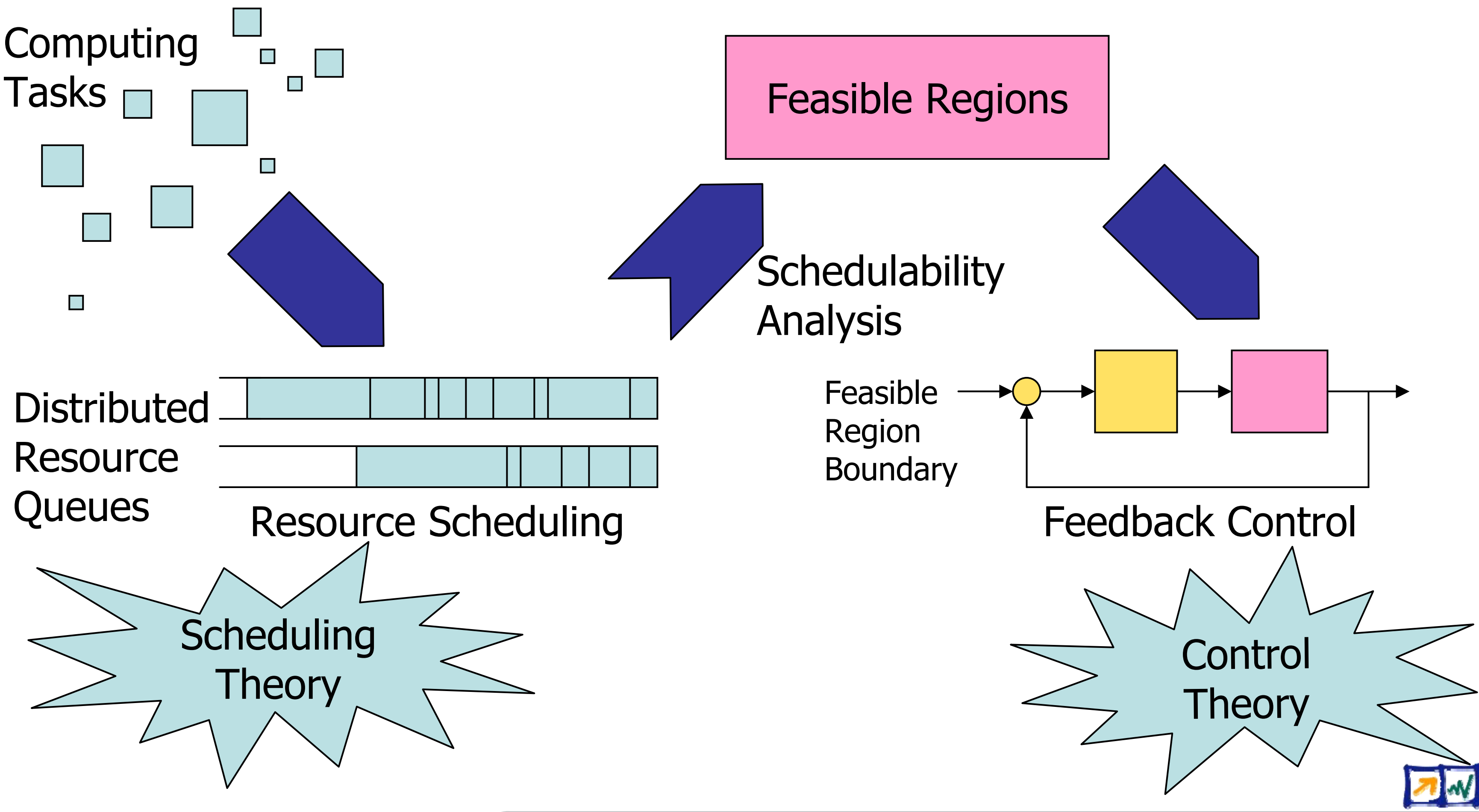
Distributed Software Performance Control

Part II: Formulate and solve a (queue state) control problem



Bridging the Abstractions: A Schedulability Study

Requirements on meeting deadlines → utilization (queue state) → performance control



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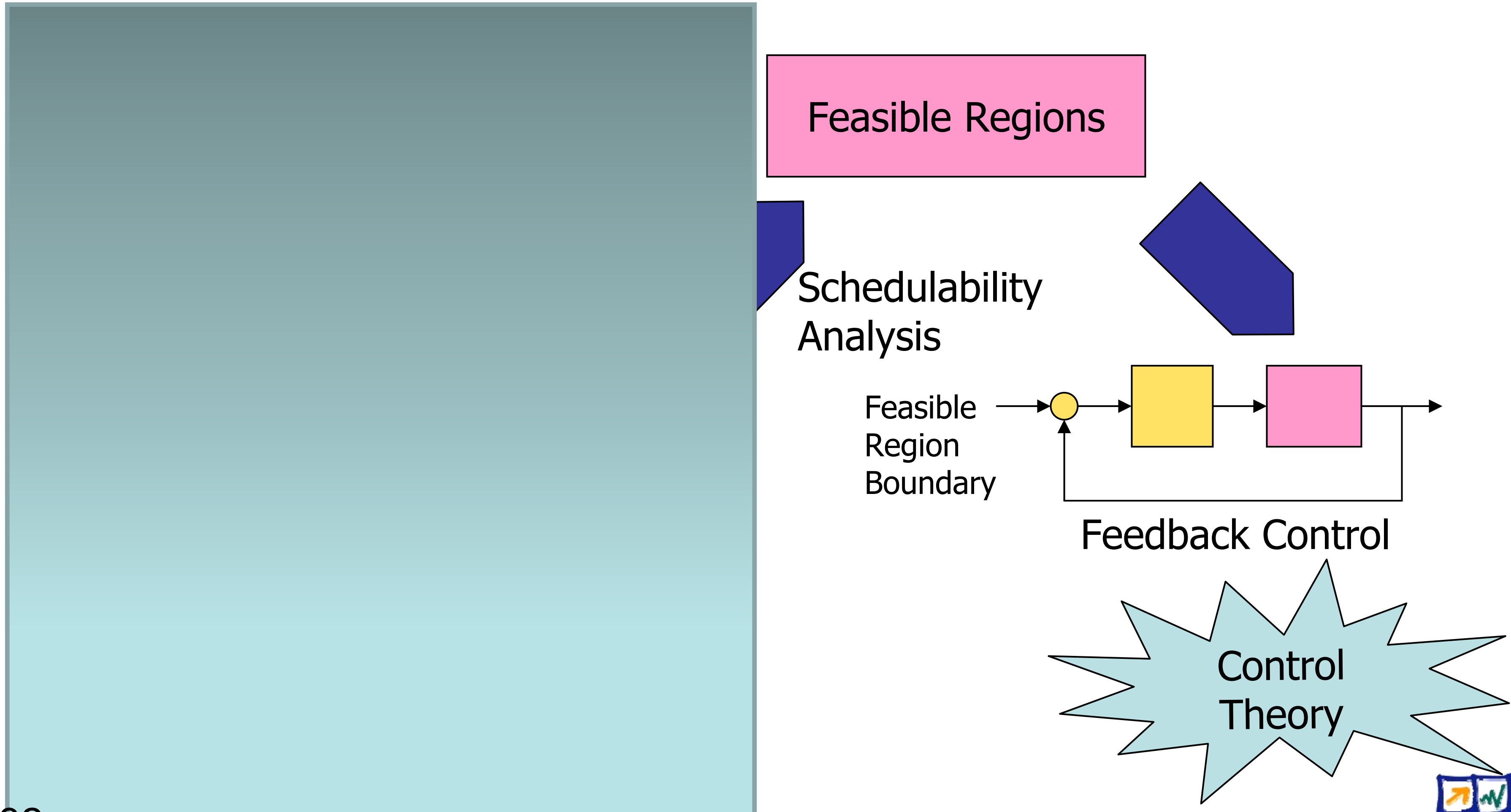

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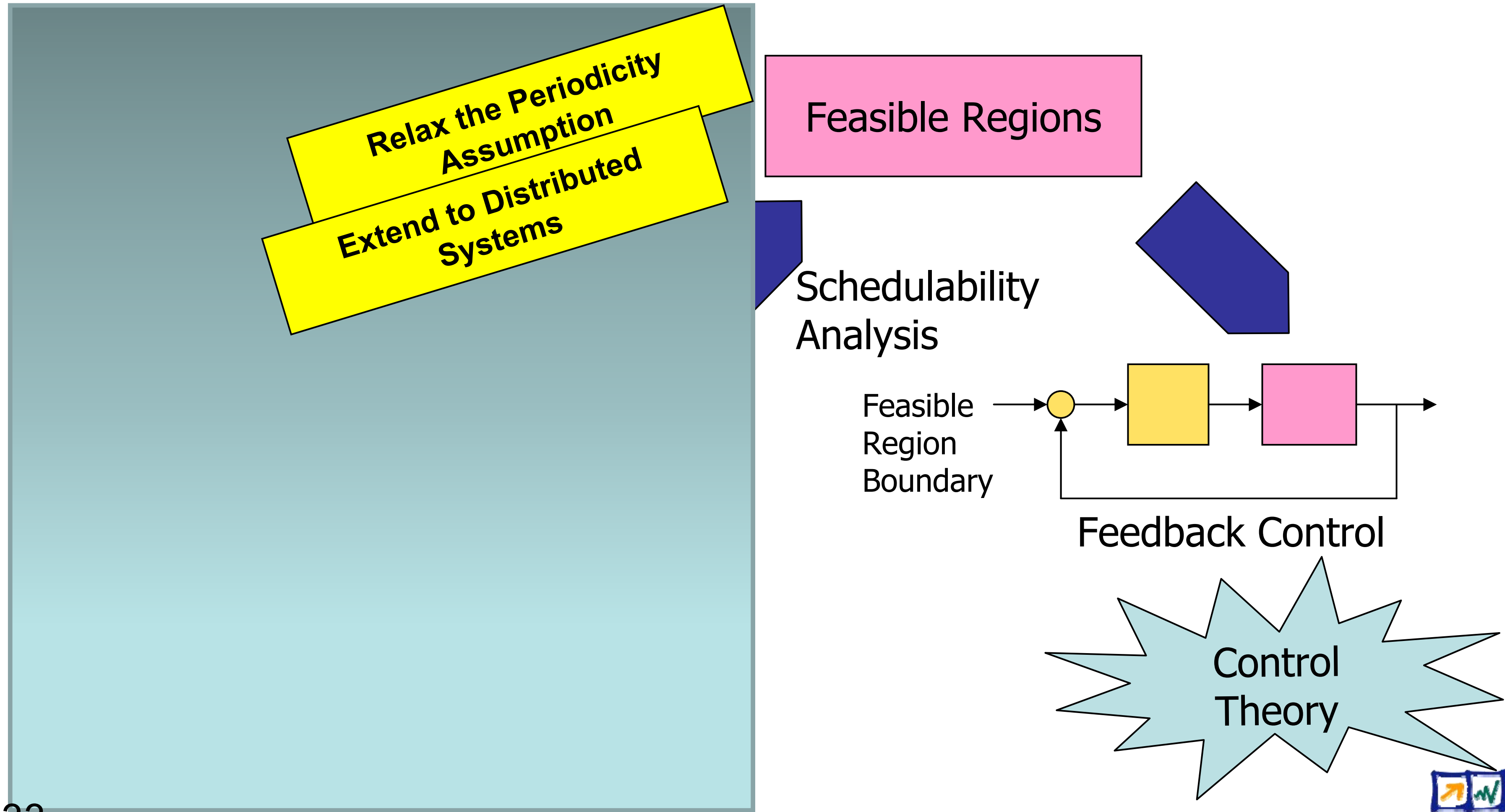
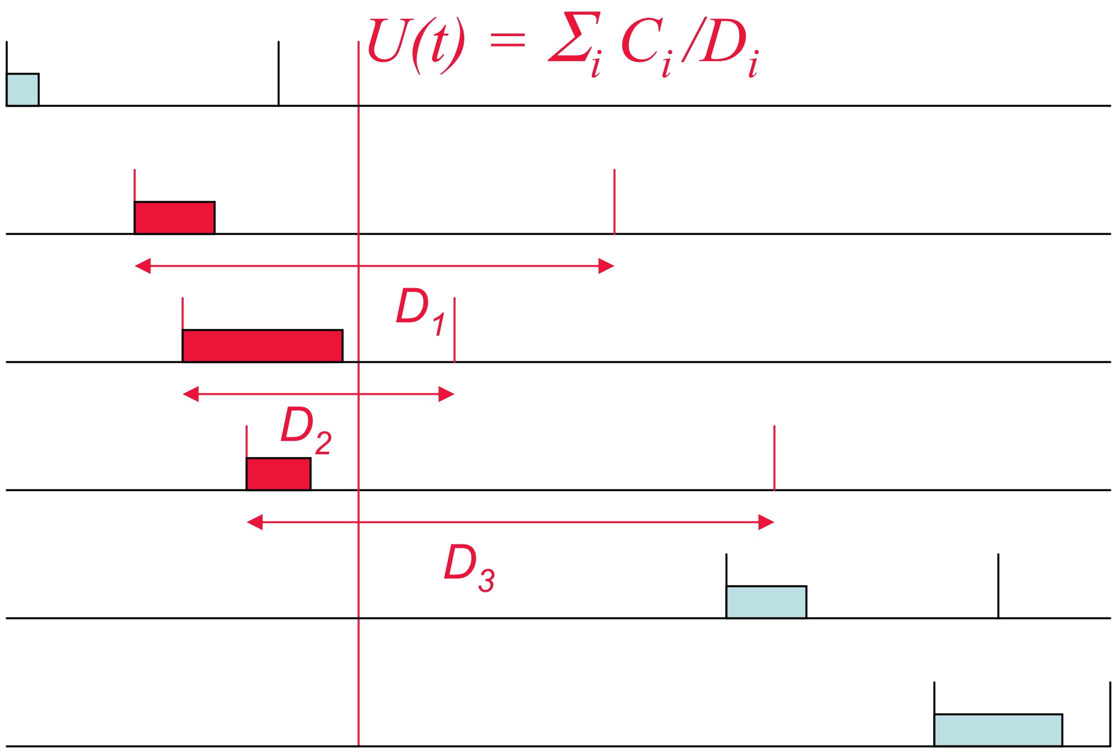


Relaxing the Periodicity Assumption

- Is there a utilization bound such that a system of aperiodic tasks arriving at arbitrary time instances meets all deadlines as long as the bound is not exceeded?
- If so, this bound would make a good control set point.

Aperiodic Tasks and *Instantaneous* Utilization

- Instantaneous utilization $U(t)$ is a function of time, t
- $U(t)$ is defined over the *current* invocations



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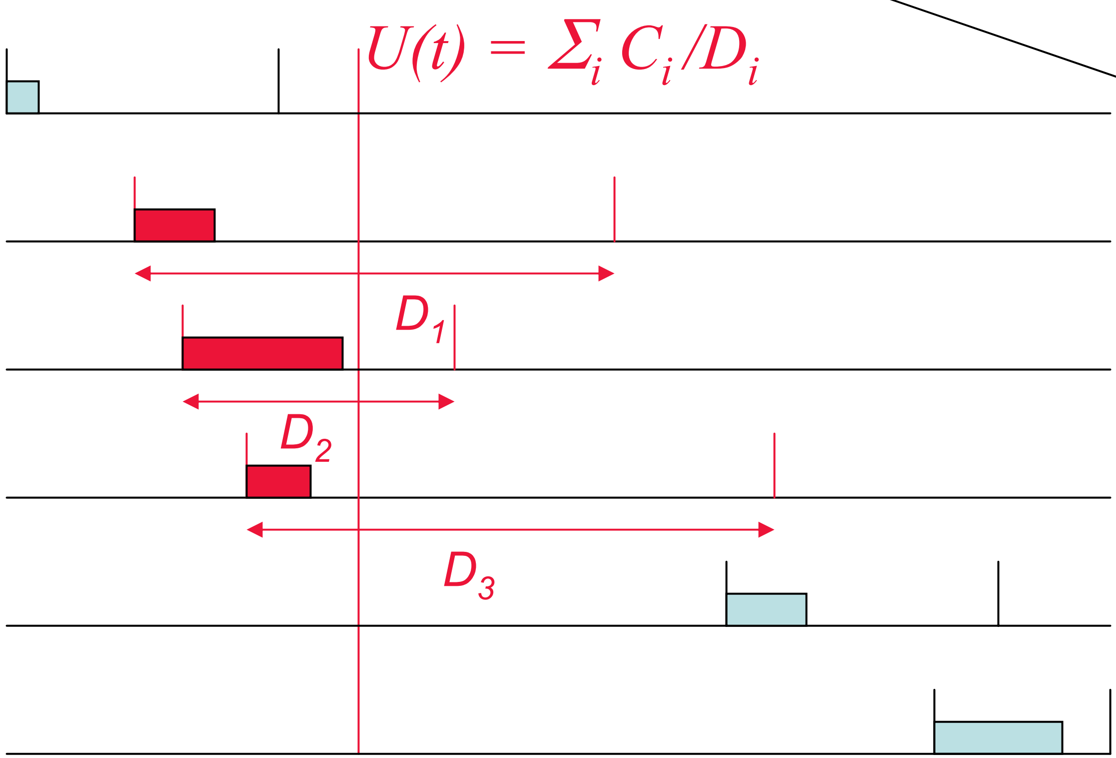
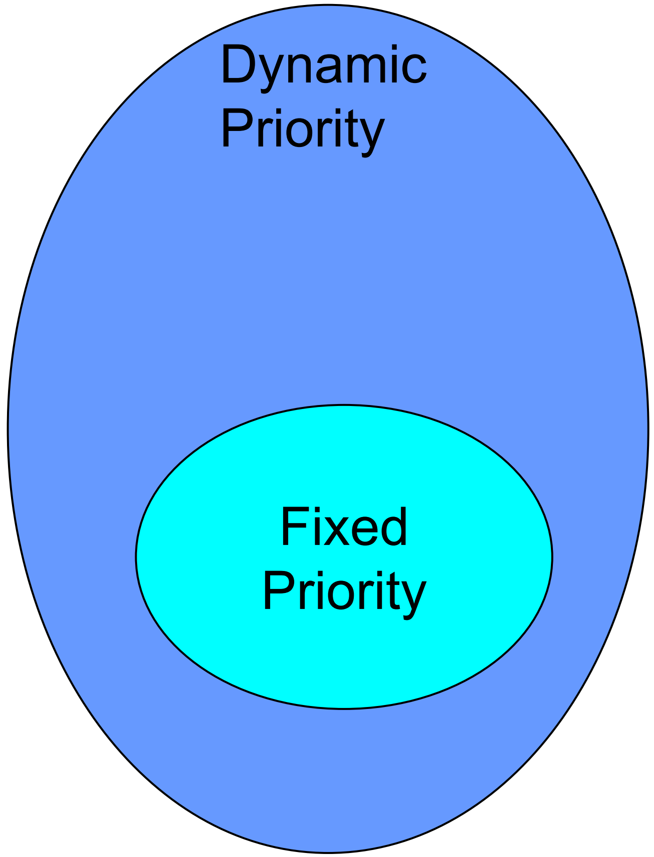


Arrived but deadline has not expired

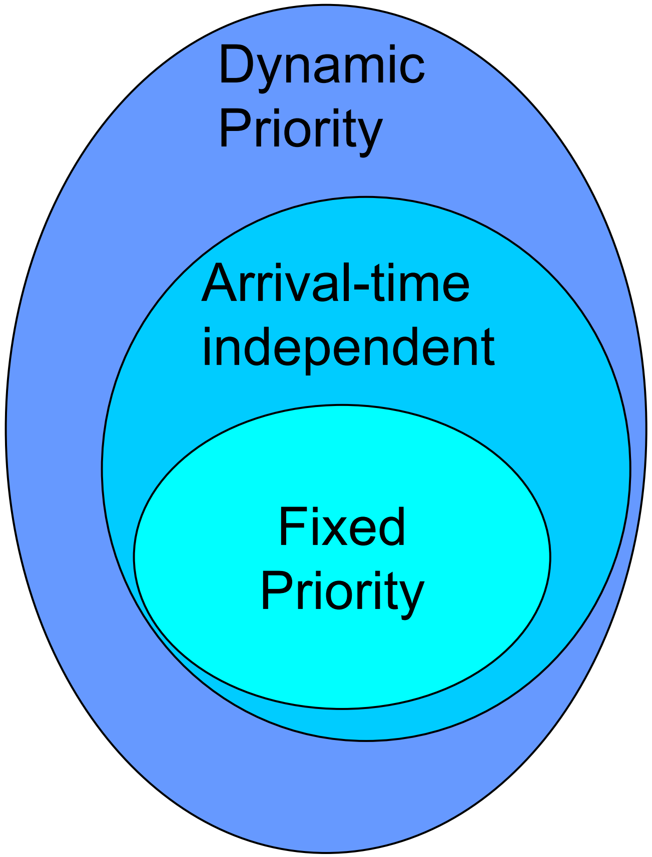
Fixed versus Dynamic Priority Scheduling

- ***Fixed-priority scheduling:***
  - All invocations of a task have same priority
- ***Dynamic-priority scheduling:***
  - Invocation priorities may not be the same
- ***What about Aperiodic Tasks?***
  - Equivalent for fixed priority scheduling?



Arrival-Time-Independent Scheduling

- ***Fixed-priority scheduling:***
  - All invocations of a task have same priority
- ***Dynamic-priority scheduling:***
  - Invocation priorities may not be the same
- ***Arrival-time-independent scheduling:***
  - Invocation priorities are not a function of invocation arrival times



Why Arrival-Time Independent Scheduling?

- Easy to implement on current non-real-time operating systems with fixed-priority support (e.g., UNIX, the #1 OS for web servers)
  - Requires a finite number of priority levels
  - Priorities are statically assigned to threads

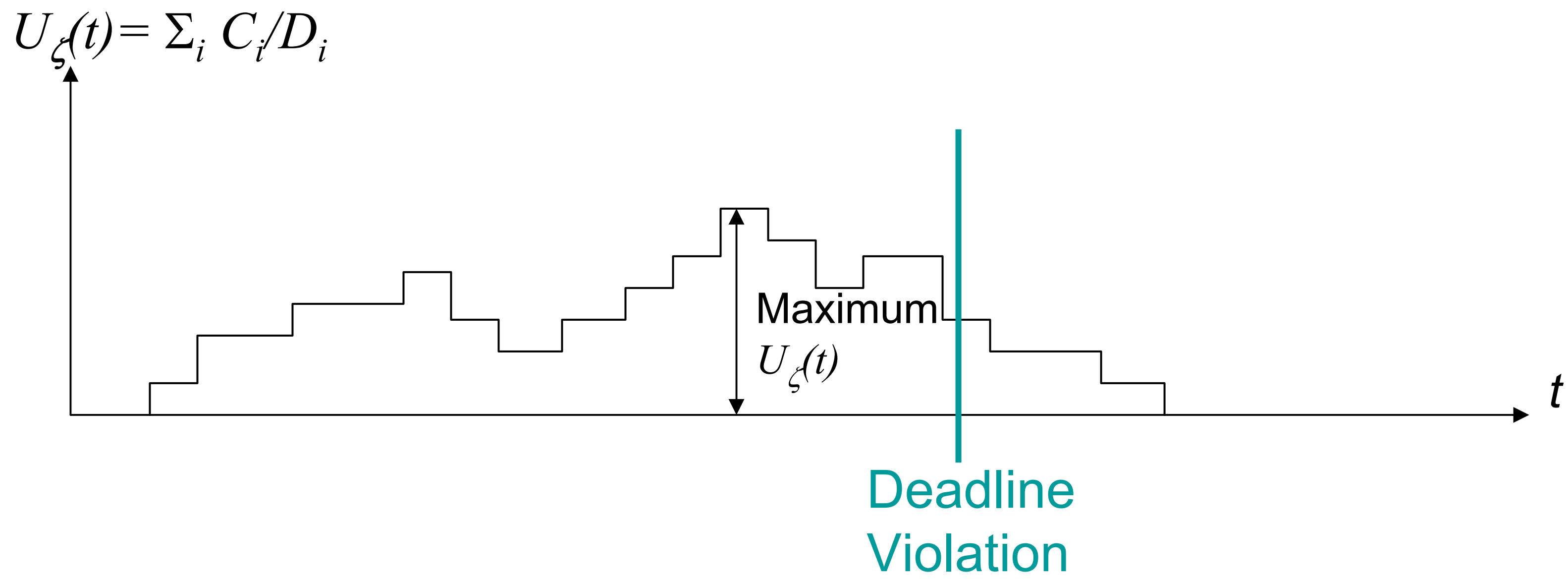
A Sense of Optimality

- A scheduling policy is optimal in a class if it maximizes the schedulable utilization bound among all policies in the class
- "Backward Compatibility":
  - Rate monotonic is the optimal fixed-priority policy (for periodic tasks)
  - EDF is optimal dynamic-priority policy
  - ***New:*** Deadline monotonic is the optimal arrival-time independent policy

Deriving a Utilization Bound for Aperiodic Tasks

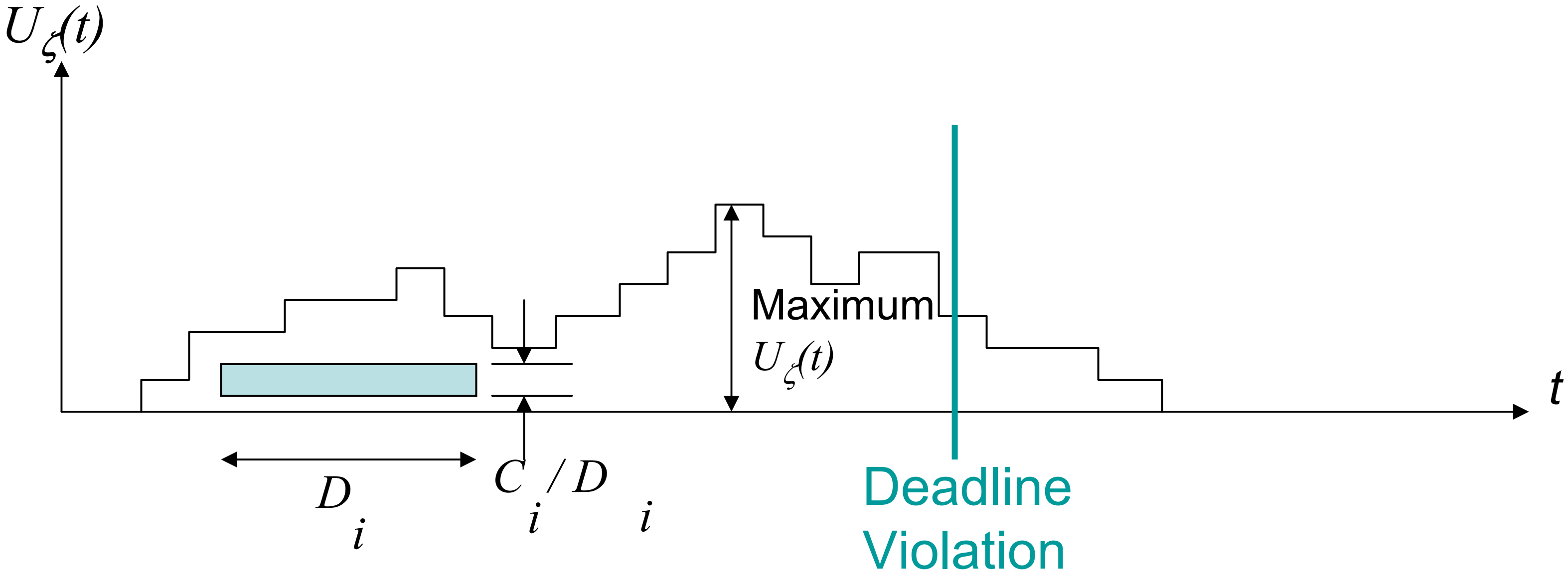
Main idea:

- **Minimize**, over all arrival patterns ζ, the maximum $U_\zeta(t)$ that precedes a deadline violation



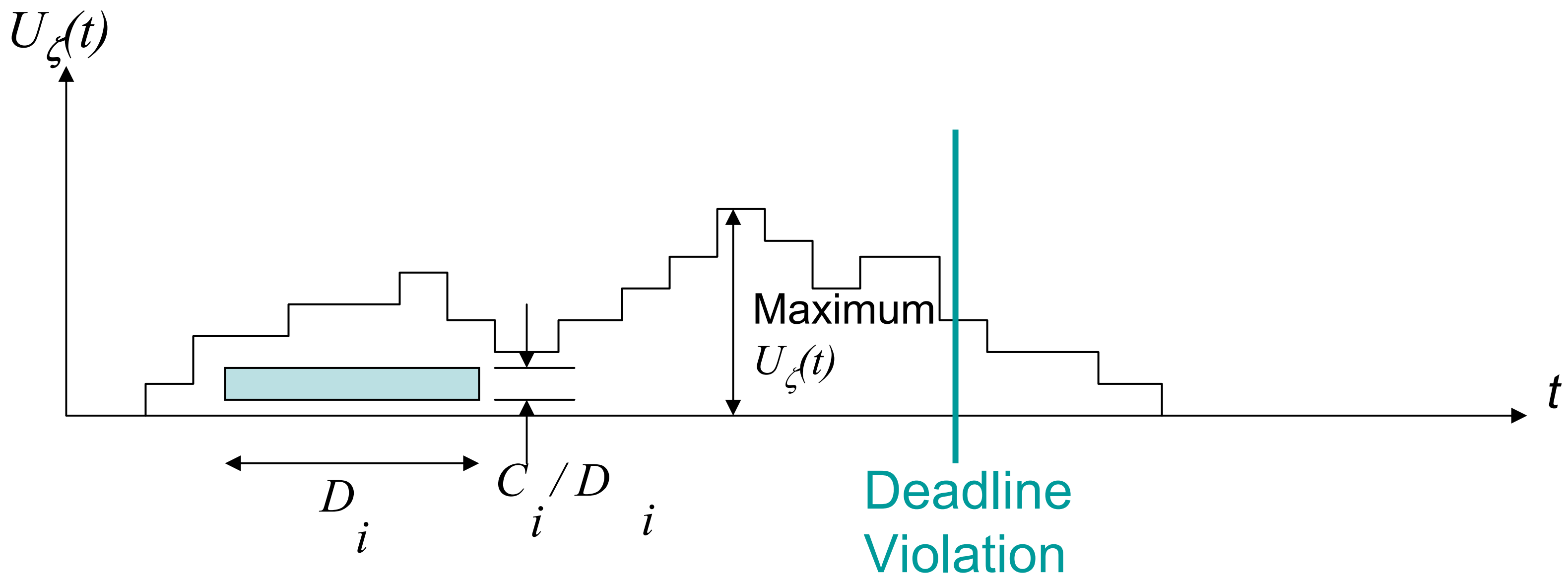
Quick-and-Dirty Derivation

- Observe that each task i contributes C_i to the area under the $U_\varsigma(t)$ curve – see figure below.



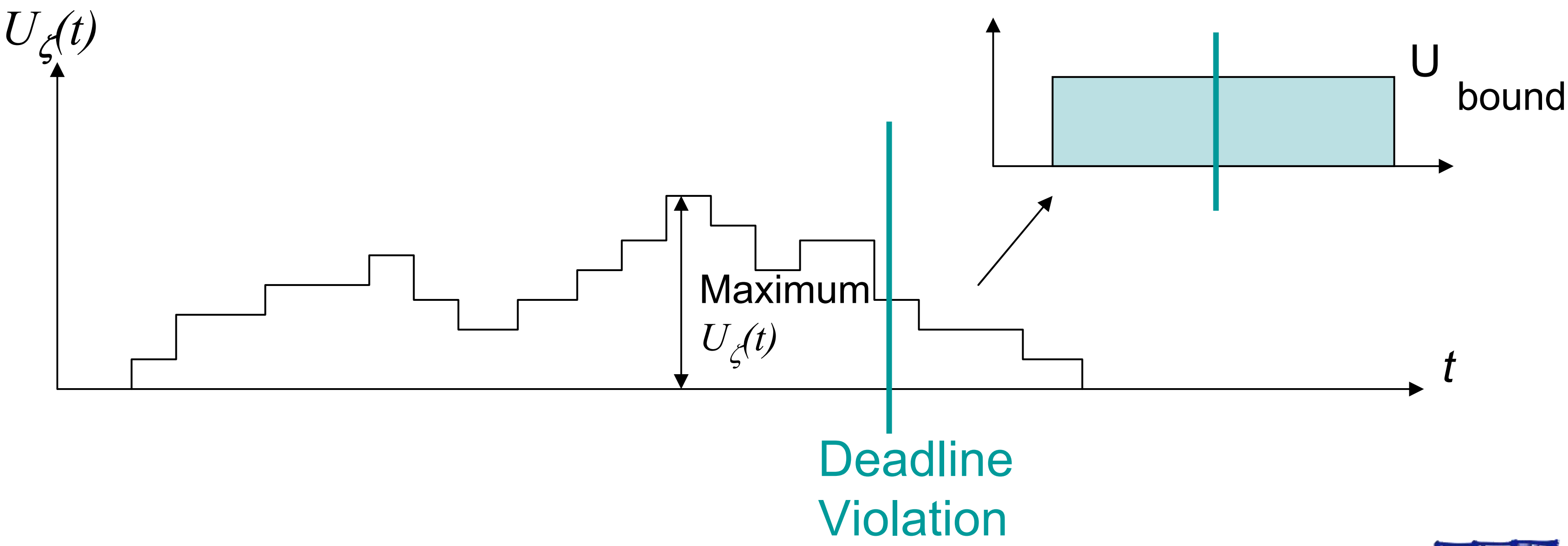
Corollary

- The total area under the $U_\zeta(t)$ curve is $\Sigma\, C_i$ carried over all arrived tasks



A Geometric Interpretation

- **Minimize**, the sum $\Sigma\, C_i$ across all unschedulable patterns. Say minimum is **C**$_{min}$
- Minimize curve hight while area = **C**$_{min}$



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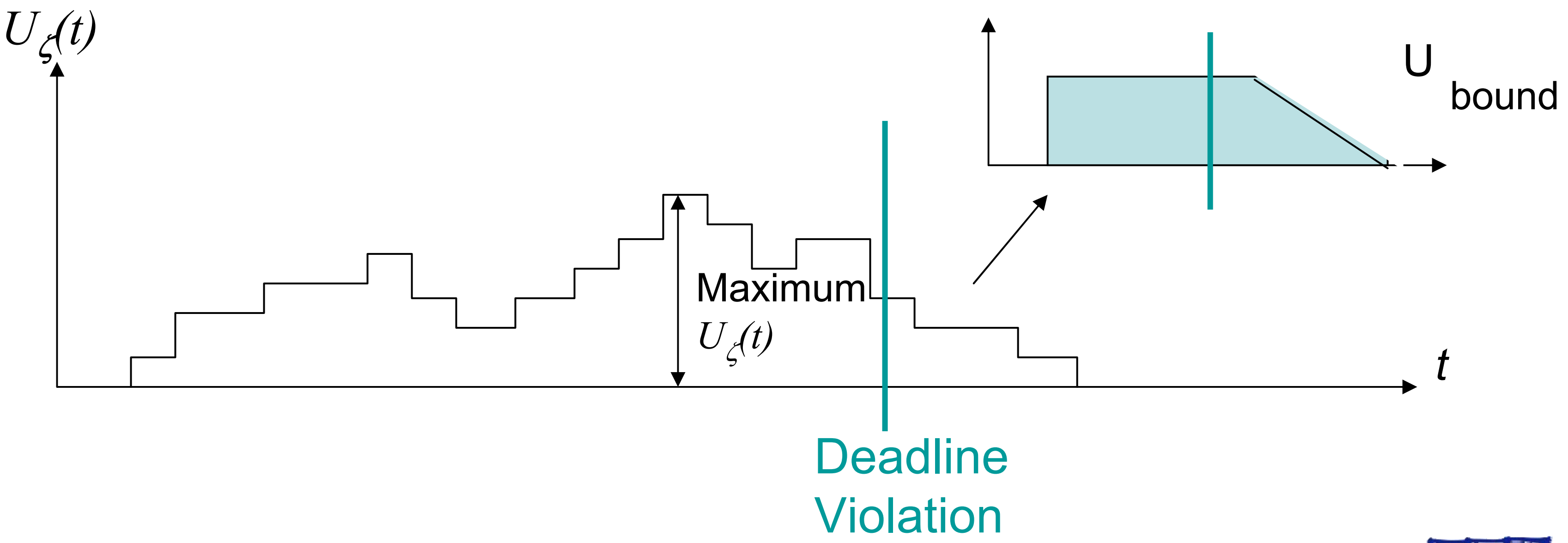

Main Result

- A set of aperiodic tasks is schedulable using an optimal fixed-priority policy if:

$$U(t) \leq \frac{1}{1+\sqrt{\frac{1}{2}}}$$

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$$U(t) \leq \frac{1}{1+\sqrt{\frac{1}{2}}}$$

58.6%

More Main Results

- A set of *n* recurrent tasks is schedulable using an optimal arrival-time-independent policy if:

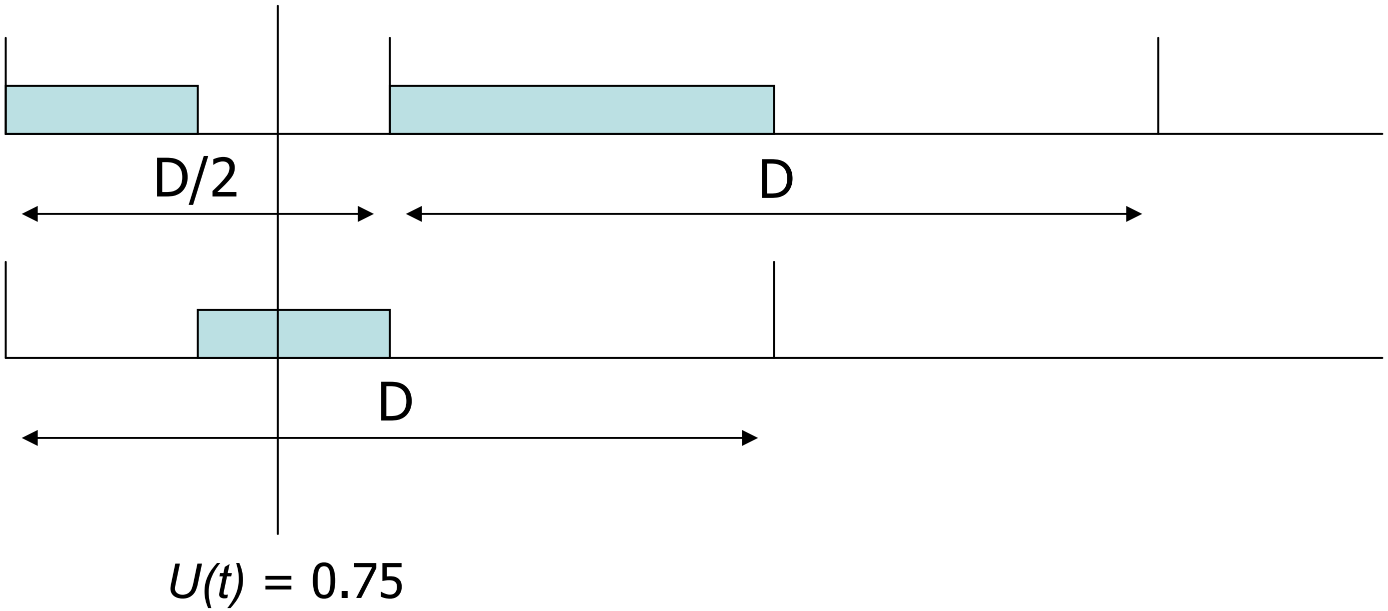
$$U(t) \leq \tfrac{1}{2} + \tfrac{1}{2n} \qquad n < 3$$

$$U(t) \leq \frac{1}{1 + \sqrt{\tfrac{1}{2}\left(1 - \tfrac{1}{n-1}\right)}} \qquad n \geq 3$$

- This bound is tight

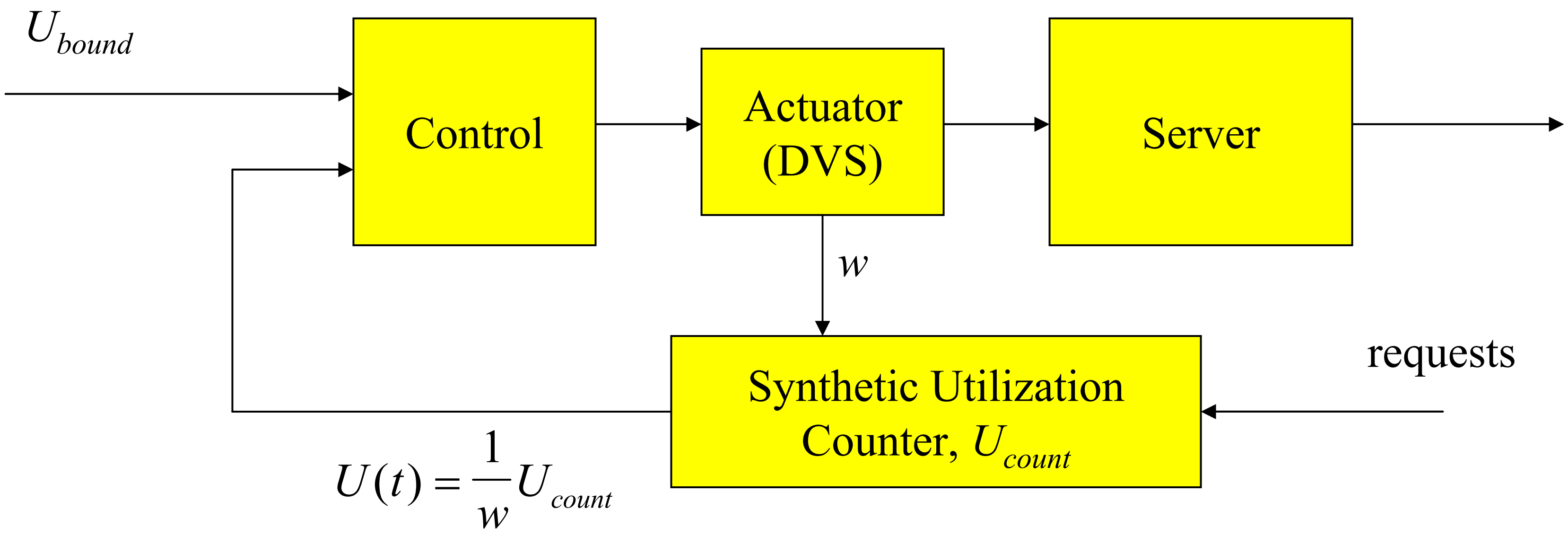
Example of Tightness

- Consider n=2



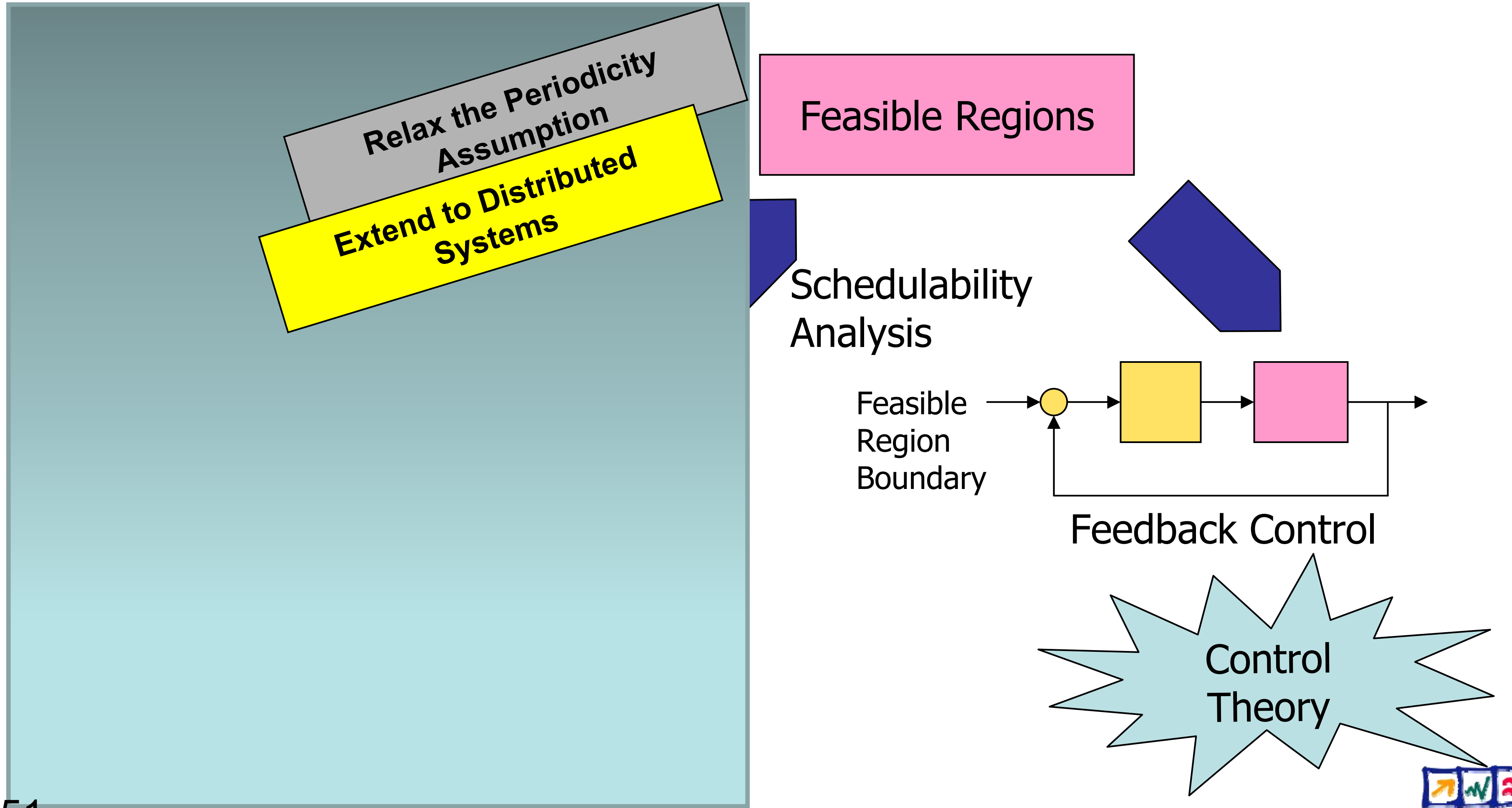
Utilization Control

- Controller scales CPU speed, *w*, to the slowest value that keeps measured instantaneous utilization below the bound



Bridging the Abstractions

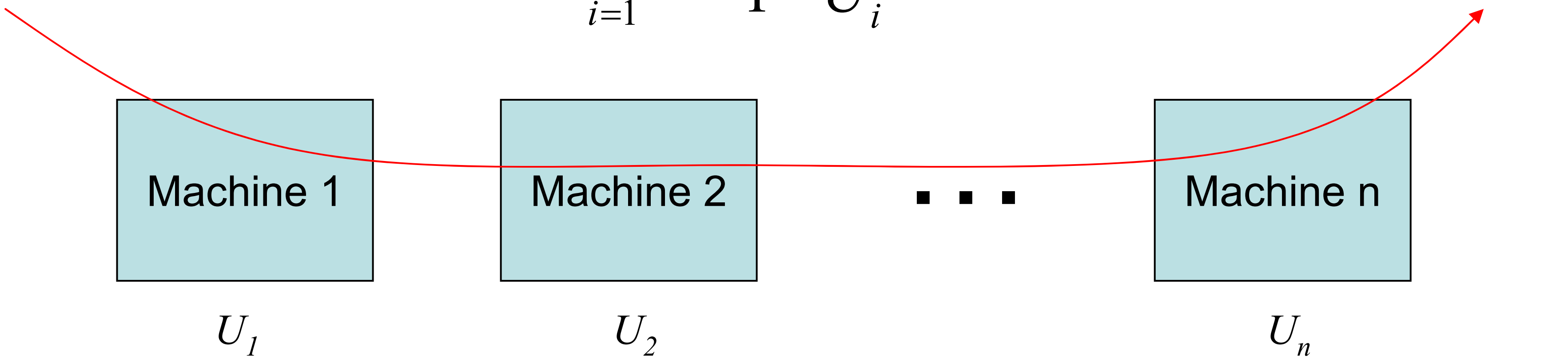
Transform fine-grained performance requirements into aggregate state variables that are easy to control



Main Results in Schedulability of Multistage Execution

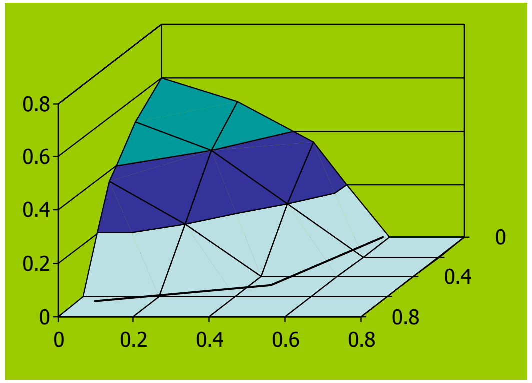
- Let U_1, U_2, …, U_n be the utilization values of n machines
- The end-to-end deadline of a task T traversing the n-machine path is met if:

$$\sum_{i=1}^{n} \frac{U_i(1-U_i/2)}{1-U_i} \leq 1$$



Main Results in Schedulability of Multistage Execution

- A Multidimensional utilization bound



$$\sum_{i=1}^{n} \frac{U_i(1-U_i/2)}{1-U_i} \leq 1$$

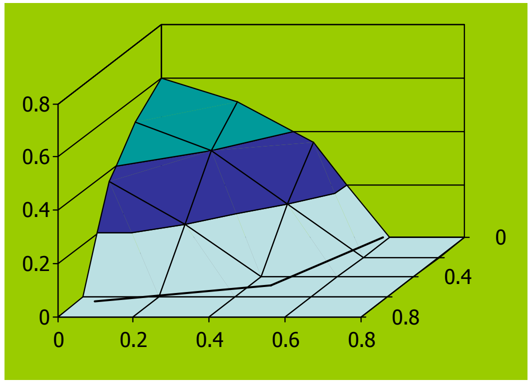
Task T

Machine 1   Machine 2   . . .   Machine n

U_1 U_2 U_n

Main Results in Schedulability of Multistage Execution

- A Multidimensional utilization bound

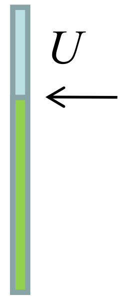


$$\sum_{i=1}^{n} \frac{U_i(1-U_i/2)}{1-U_i} \le 1$$

Reduces to

$$U(t) \le \frac{1}{1+\sqrt{\frac{1}{2}}}$$

for a single stage



Task T

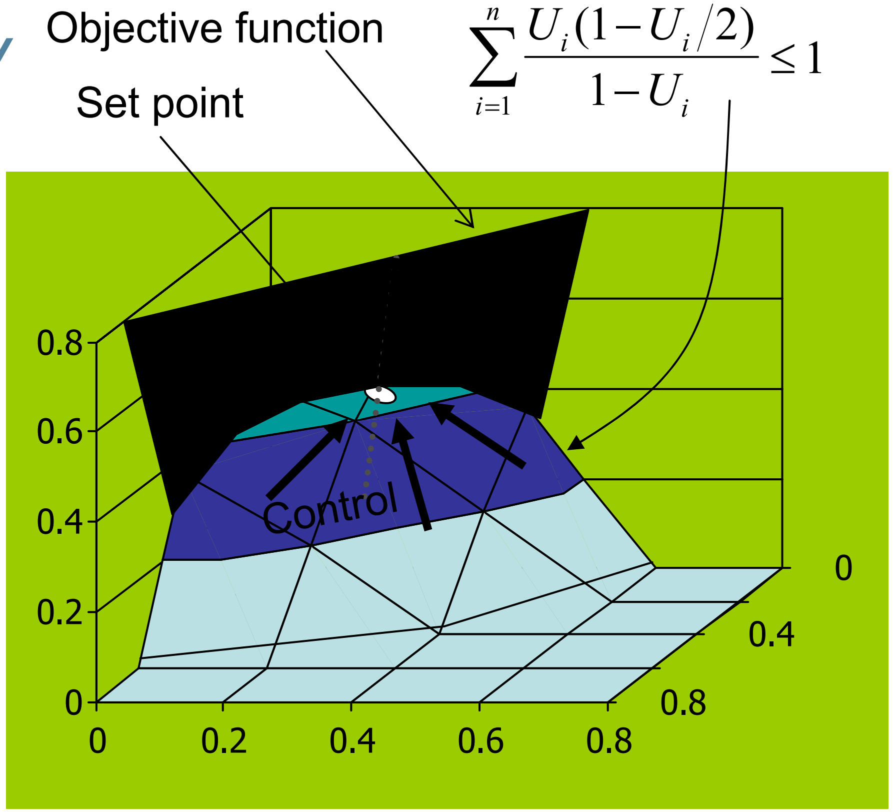
Machine 1	Machine 2	. . .	Machine n
U_1	U_2		U_n

Optimization Subject to Schedulability Constraints

- *Intersect the schedulability surface of the system with objective function*
- *Find optimal point on intersection curve*
- *Use run-time feedback control to measure and correct performance dynamically to reach optimal.*

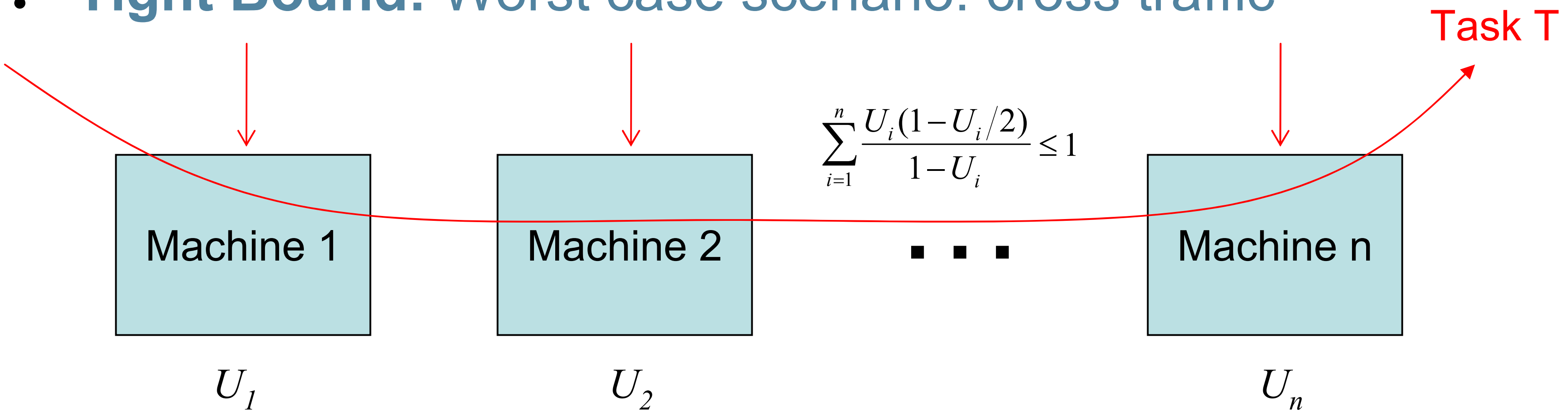
Schedulability surface

$$\sum_{i=1}^{n} \frac{U_i(1-U_i/2)}{1-U_i} \leq 1$$



Main Results in Schedulability of Multistage Execution

- **Tight Bound!** Worst case scenario: cross traffic



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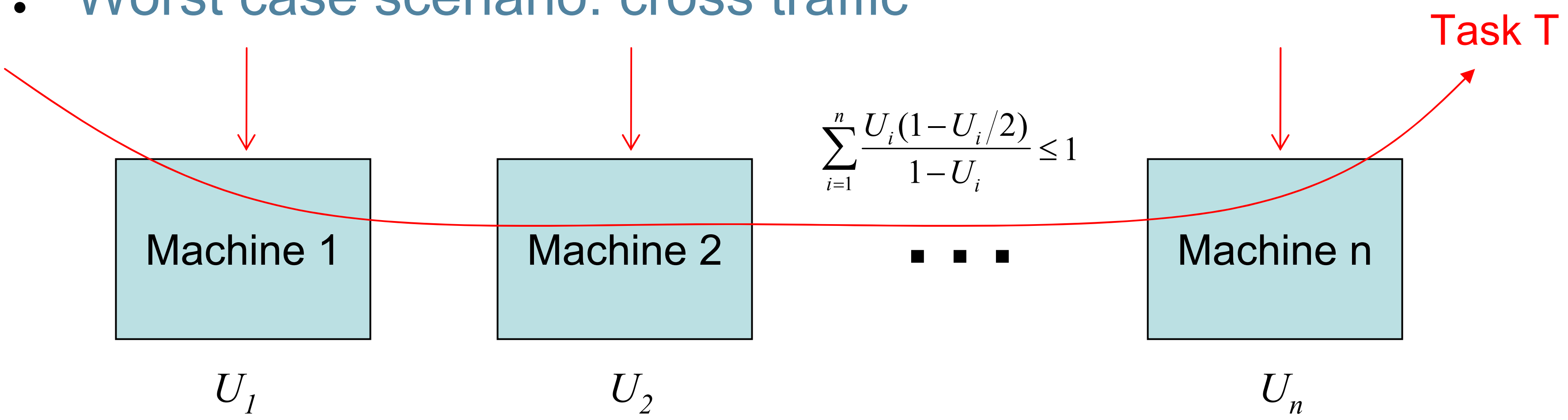
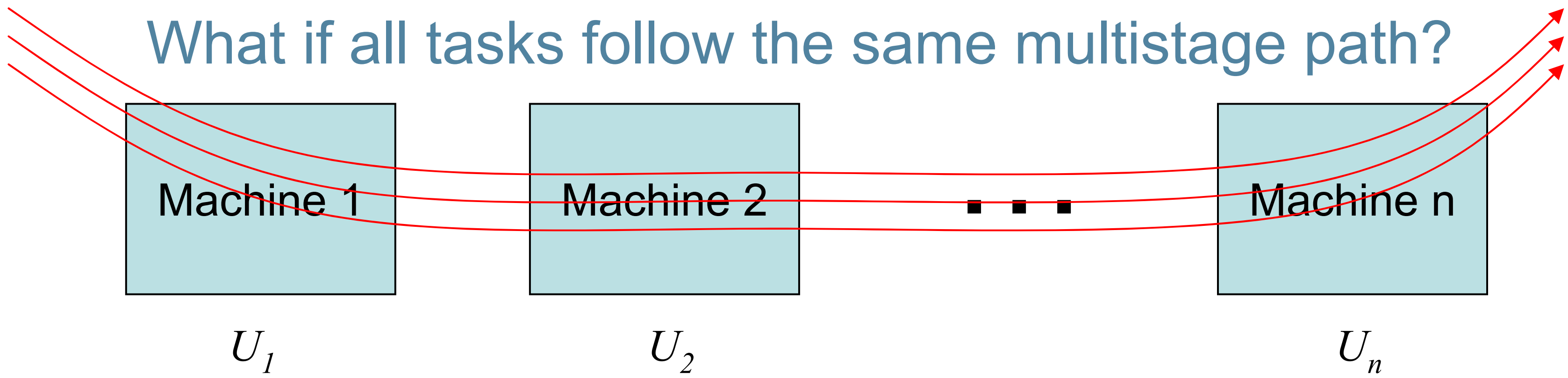


$$\sum_{i=1}^{n} \frac{U_i(1-U_i/2)}{1-U_i} \le 1$$

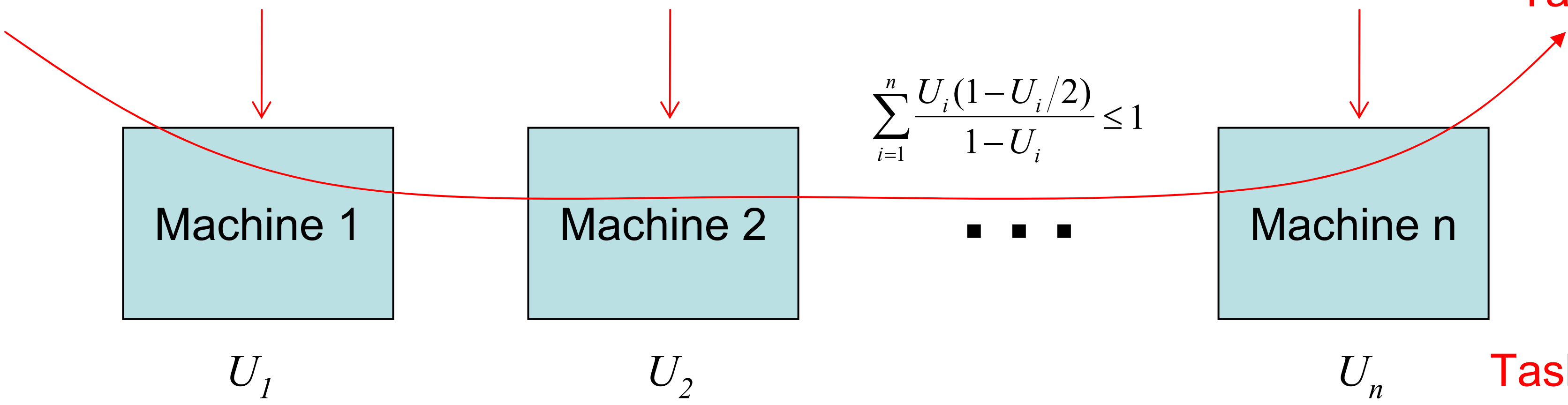
What if all tasks follow the same multistage path?



Main Results in Schedulability of Multistage Execution

- Worst case scenario: cross traffic

Task T

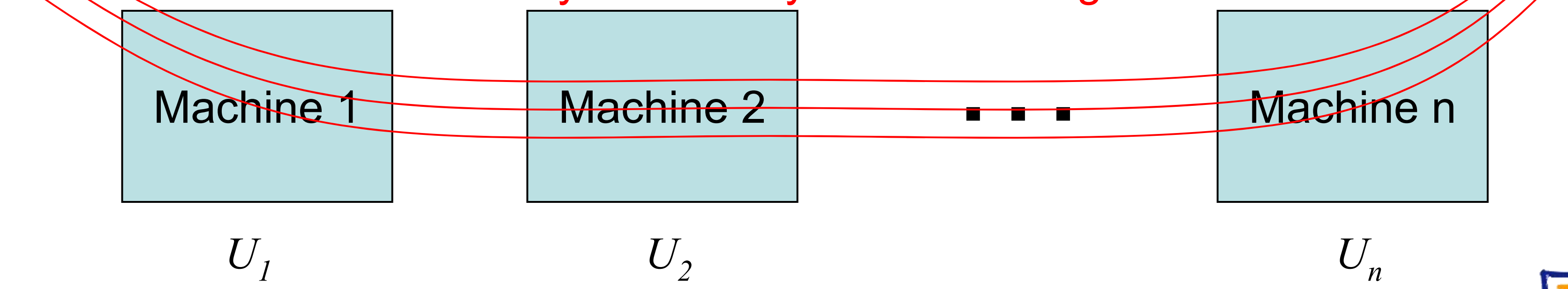


$$\sum_{i=1}^{n} \frac{U_i(1-U_i/2)}{1-U_i} \le 1$$

Task T
and others

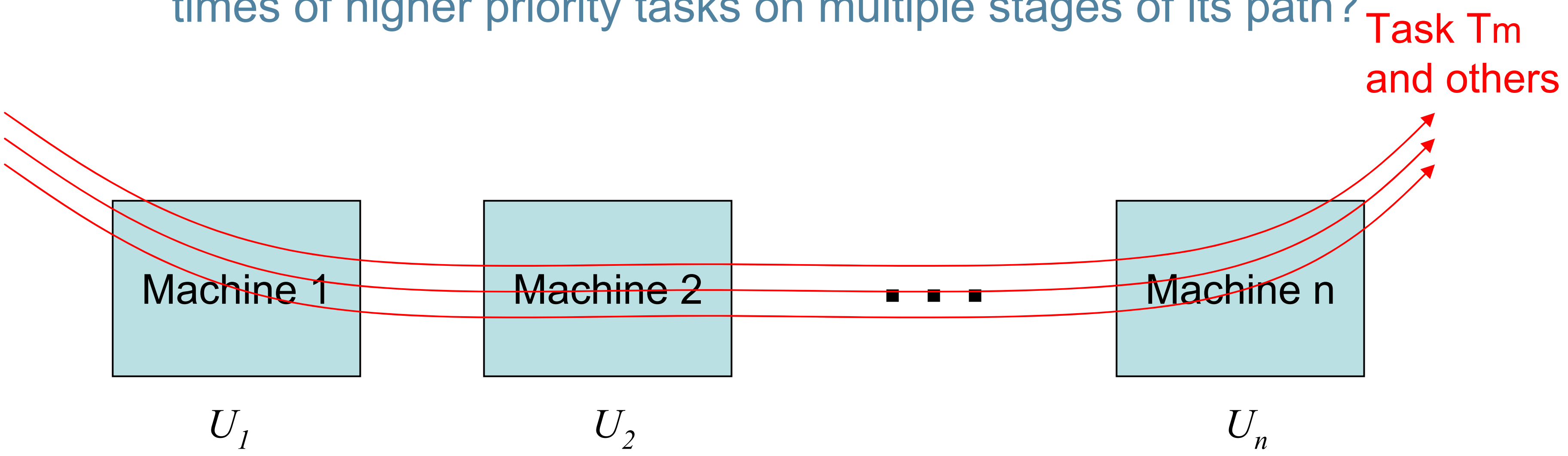
What if all tasks follow the same multistage path?

Better schedulability! Adversary has fewer degrees of freedom!



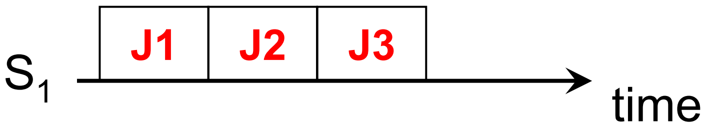
Main Results in Schedulability of Multistage Execution

- A fundamental question:
  - How does delay of a low priority task Tm depend on execution times of higher priority tasks on multiple stages of its path?



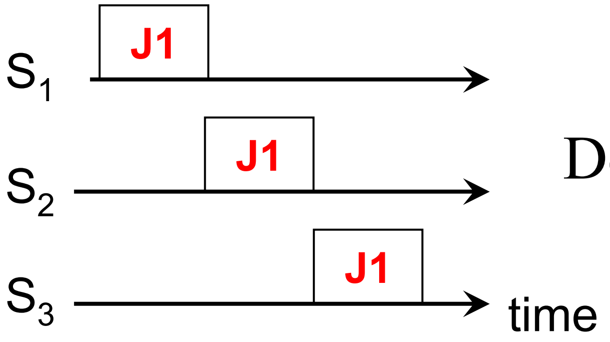
Delay Composition in Pipelined Execution

Many jobs, one stage



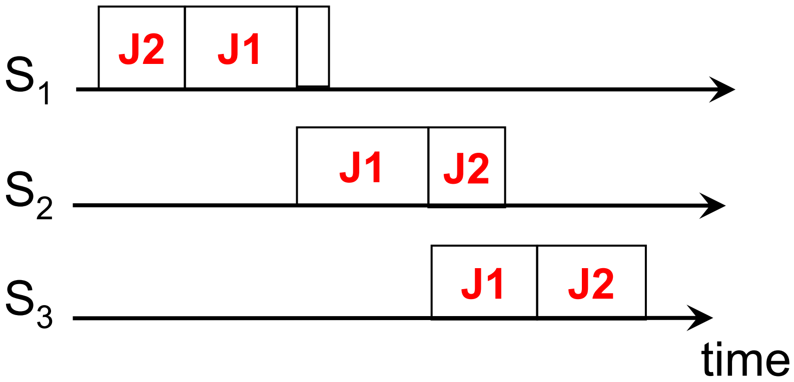
$$\text{Delay} = \sum_{i \in jobs} C_{i,1}$$

Many stages, one job



$$\text{Delay} = \sum_{j \in stages} C_{1,j}$$

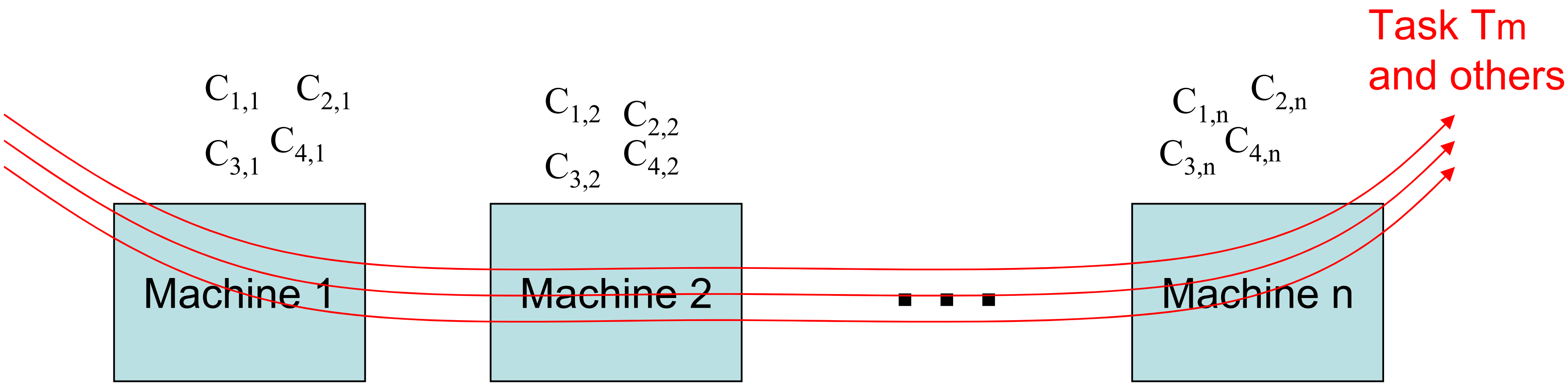
Many jobs, many stages



$$\text{Is Delay} = \sum_{i \in jobs} \sum_{j \in stages} C_{i,j} \,?$$

$$\text{Is Delay} < \sum_{i \in jobs} \sum_{j \in stages} C_{i,j} \,?$$

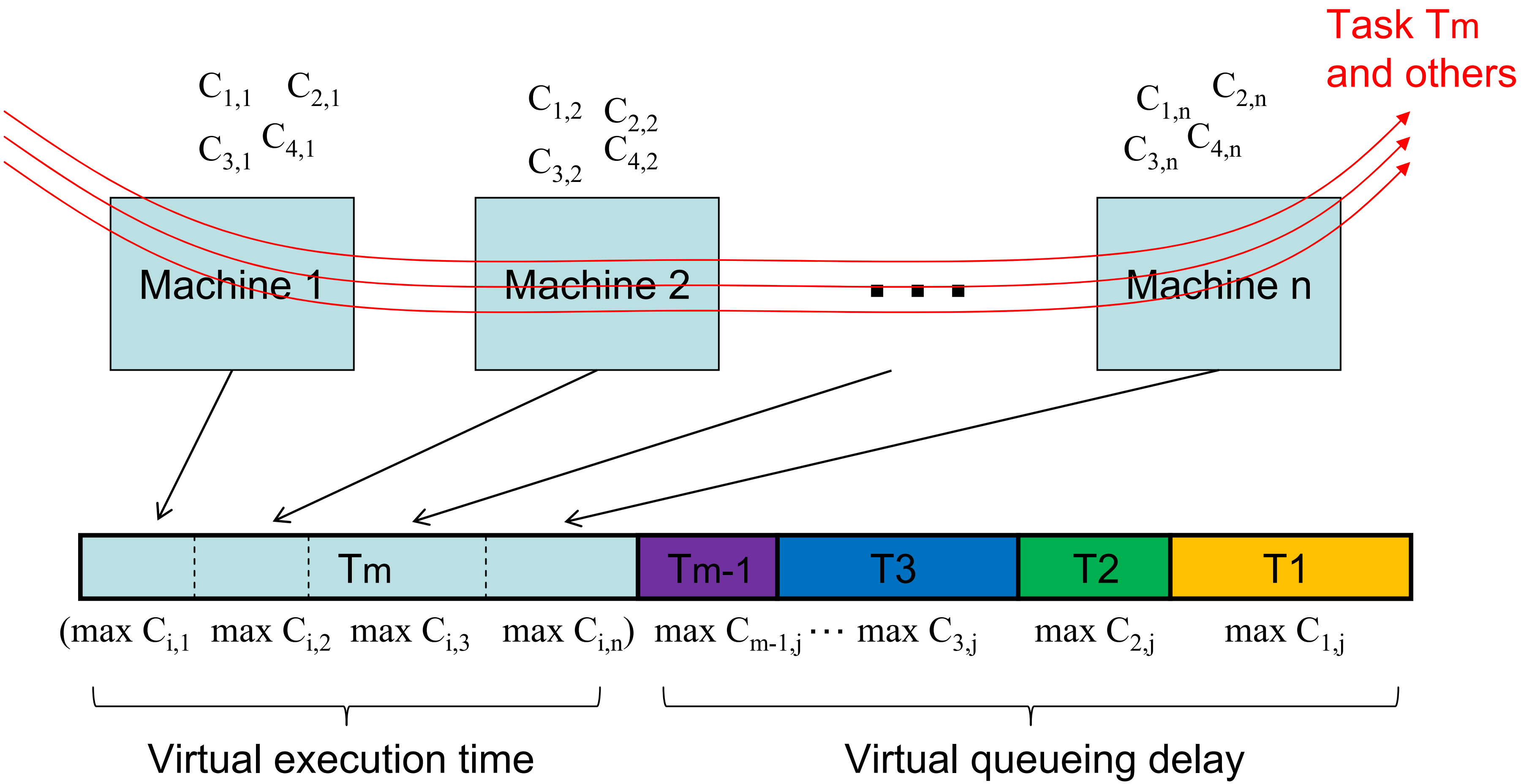
Delay Composition in Pipelined Execution



$$\text{Delay} \leq \sum_{\text{all stages}} \max_{\substack{\text{higher}\\ \text{priority}\\ \text{jobs}}} C_{i,j} + \sum_{\substack{\text{higher}\\ \text{priority}\\ \text{jobs}}} \max_{\text{all stages}} C_{i,j}$$

$$\begin{matrix} C_{1,1} & C_{2,1} & C_{3,1} & C_{4,1} \\ C_{1,2} & C_{2,2} & C_{3,2} & C_{4,2} \\ C_{1,3} & C_{2,3} & C_{3,3} & C_{4,3} \\ C_{1,4} & C_{2,4} & C_{3,4} & C_{4,4} \end{matrix}$$

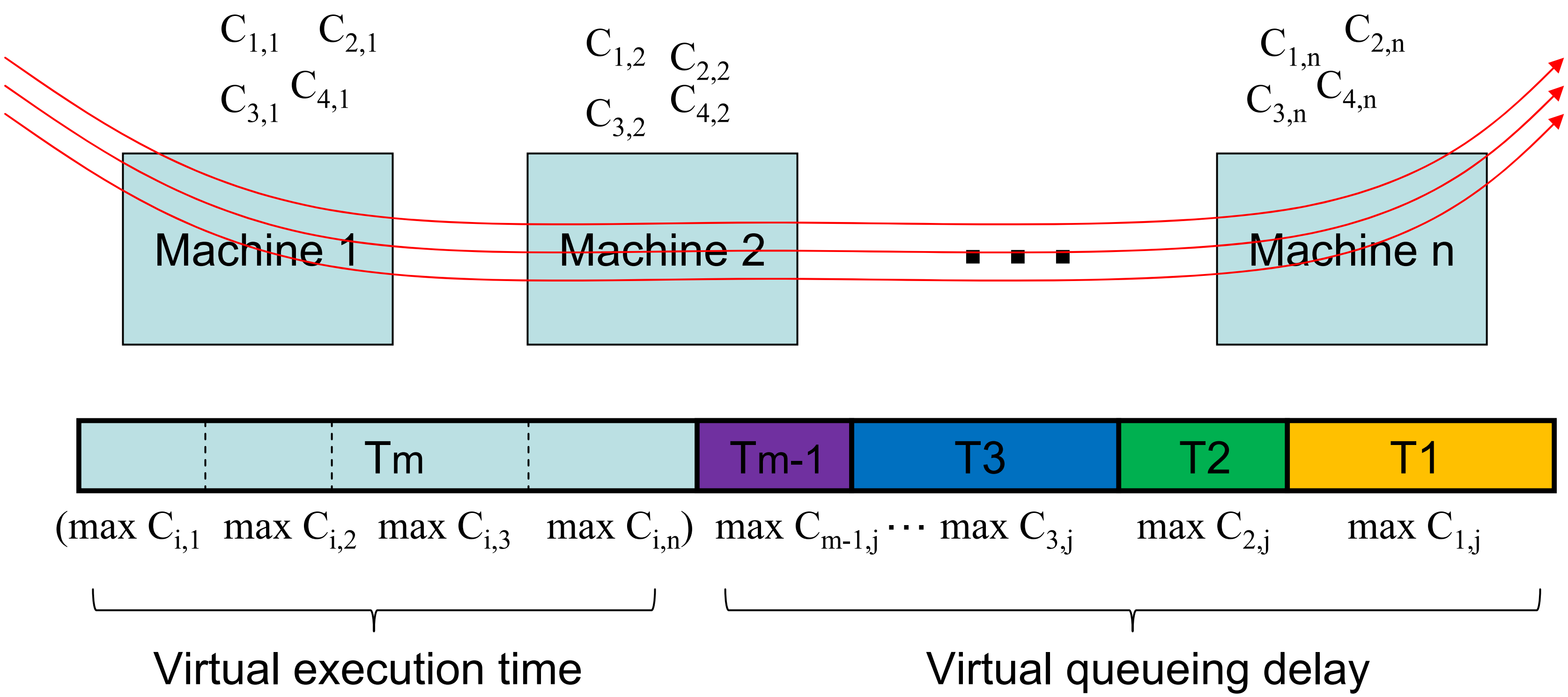
Delay Composition in Pipelined Execution



$$\text{Delay} \le \sum_{\text{allstages}} \max_{\text{jobs}} C_{i,j} + \sum_{\text{jobs}} \max_{\text{allstages}} C_{i,j}$$

Properties

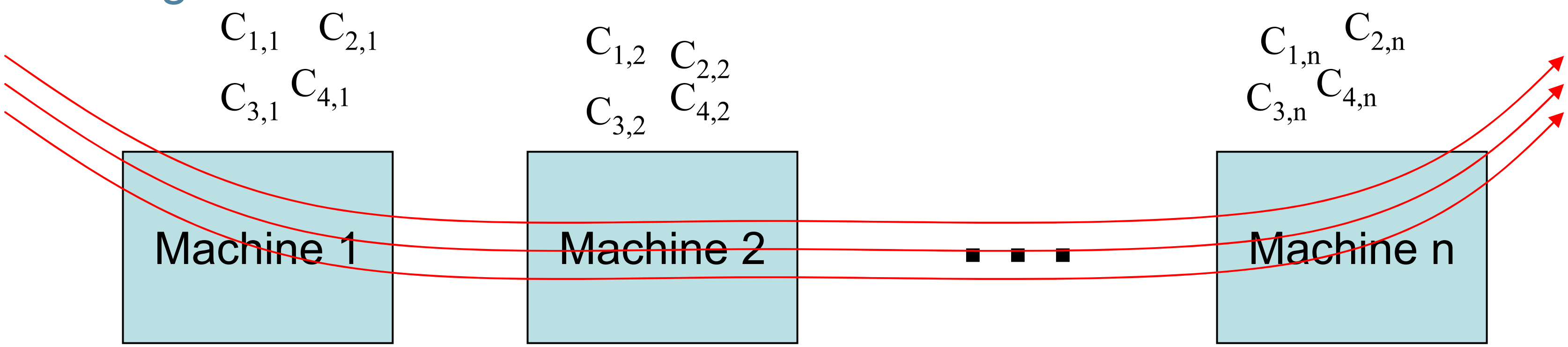
- Results applicable to both periodic and aperiodic tasks
- Results applicable under any priority-based scheduling policy where prioritization is consistent across stages

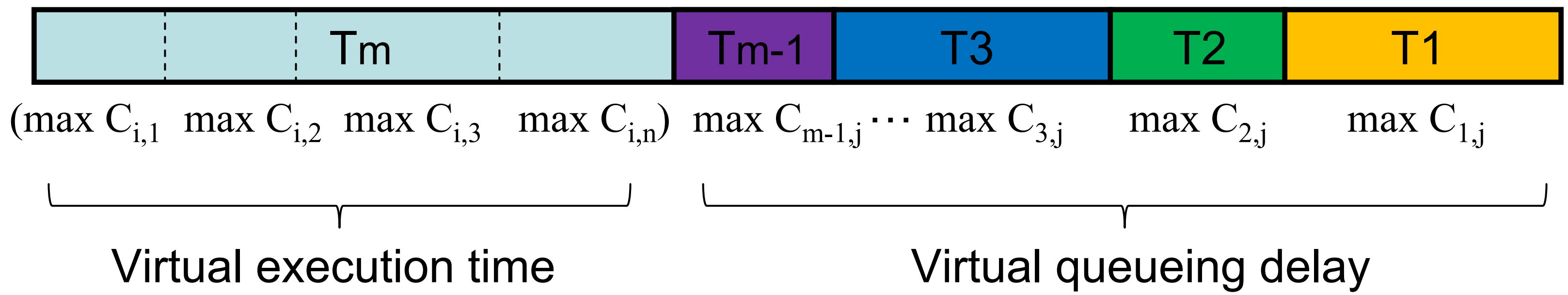


$$\text{Delay} \leq \sum_{\text{allstages}} \max_{\text{jobs}} C_{i,j} + \sum_{\text{jobs}} \max_{\text{allstages}} C_{i,j}$$

General Observation

- For each shared segment of the path that a higher priority task shares with a lower priority one in a distributed system, the former delays the latter by at most its max computation time over the segment.

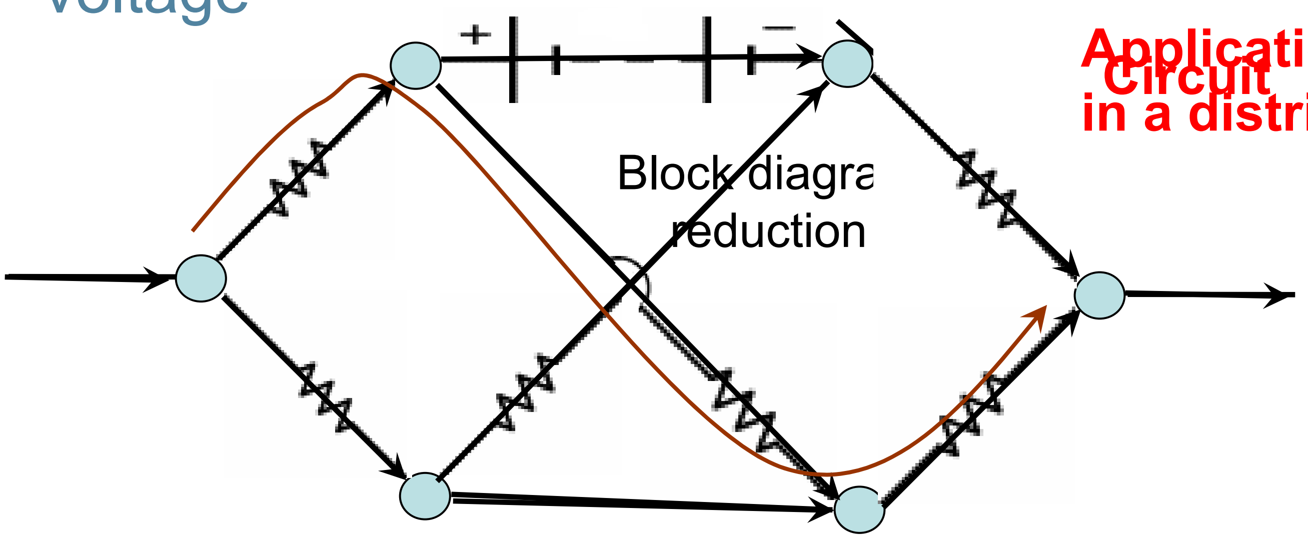




$$\text{Delay} \leq \sum_{\text{allstages}} \max_{\text{jobs}} C_{i,j} + \sum_{\text{jobs}} \max_{\text{allstages}} C_{i,j}$$

A Reduction-based Approach to Distributed System Analysis?

- Control theory
- Circuit theory – Kirchoff's laws - analyze current and voltage



Application flow graph in a distributed system

Circuit

- Reduce schedulability problem on distributed system to problem on uniprocessor?

A Recent Result: Delay Composition Algebra

- A compositional algebraic framework to analyze timing issues in distributed systems
  - Operands represent workload on composed sub-systems
  - Set of operators to systematically transform distributed real-time task systems to uniprocessor task-systems
  - Traditional uniprocessor analysis can be applied to infer schedulability of distributed tasks
- Less pessimistic than traditional analysis with increasing system scale

Delay Composition Algebra

Two operators that apply to node workloads while simplifying the resource graph

- W = **PIPE** (W1, W2)
- W = **SPLIT** (W1)

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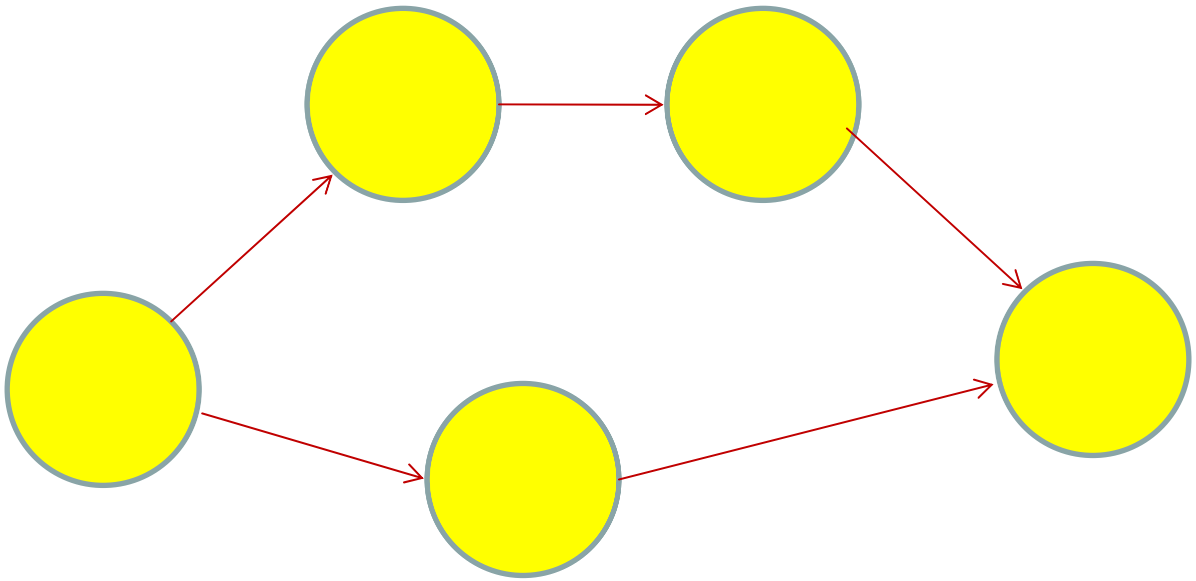

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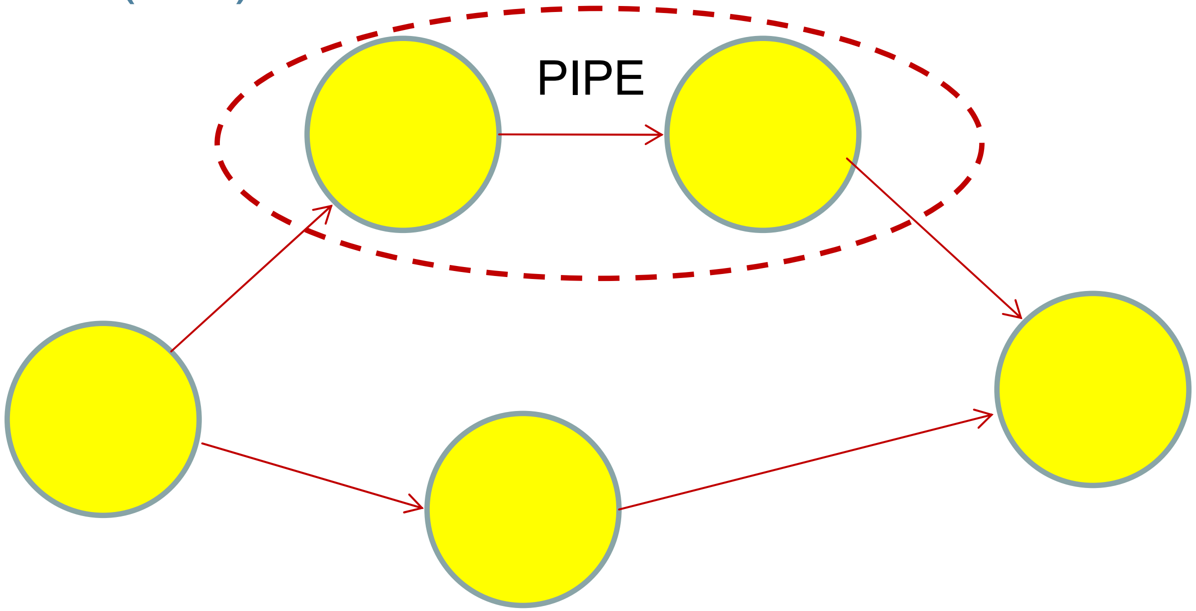

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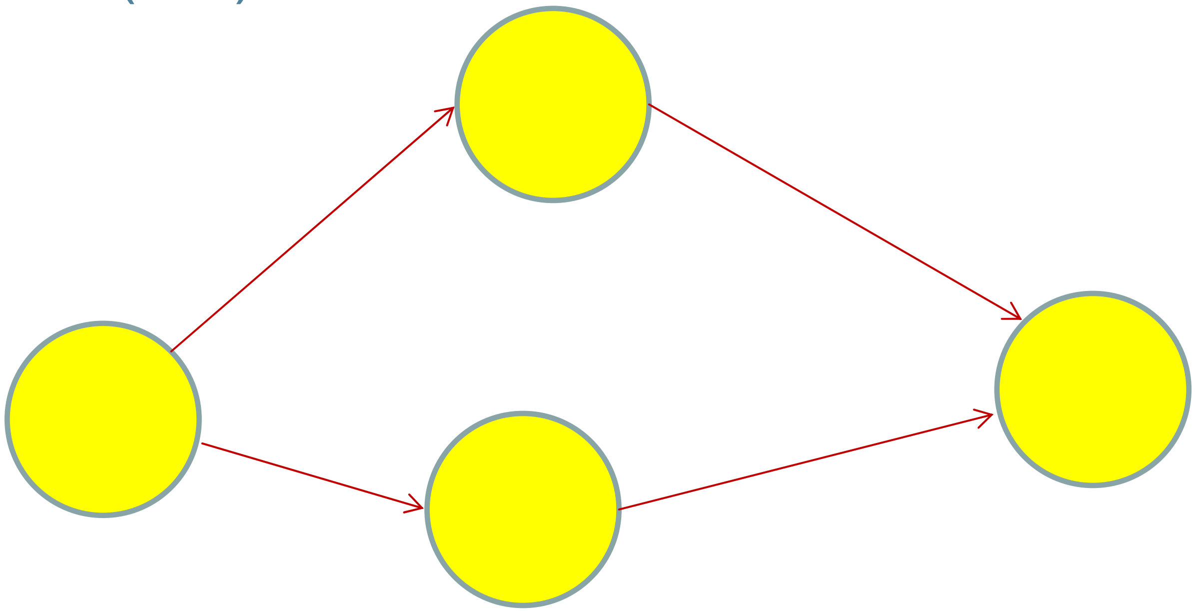

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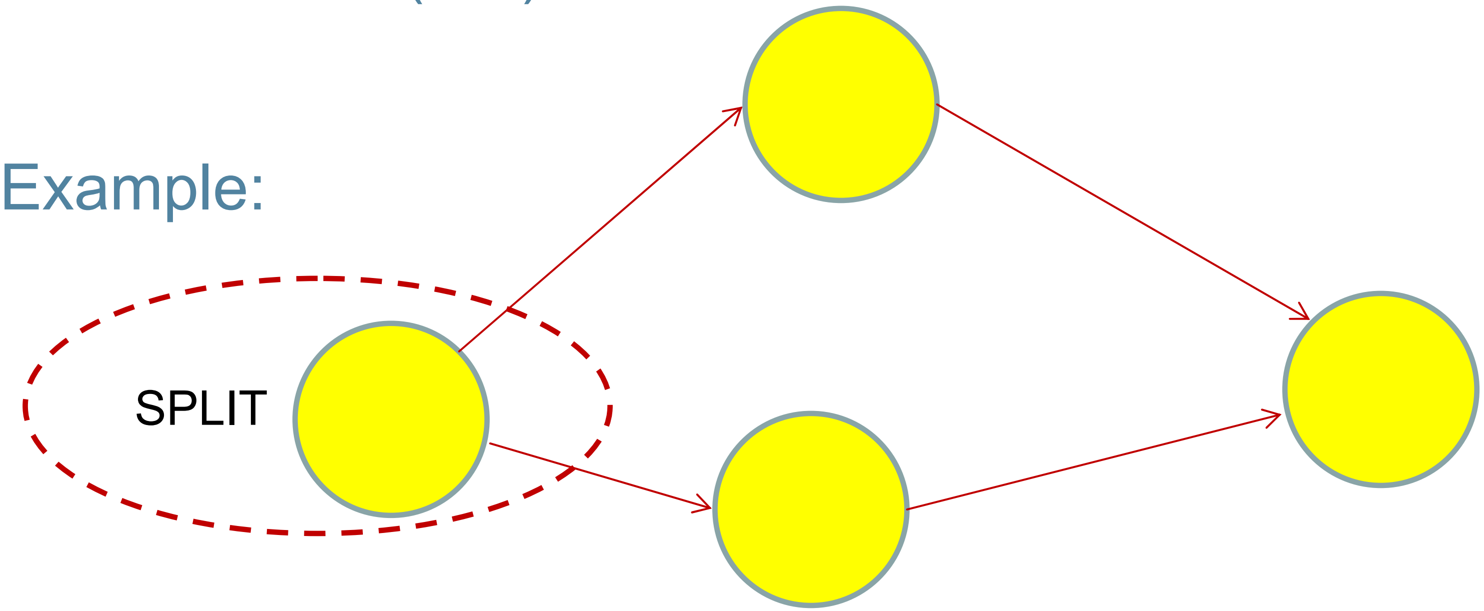

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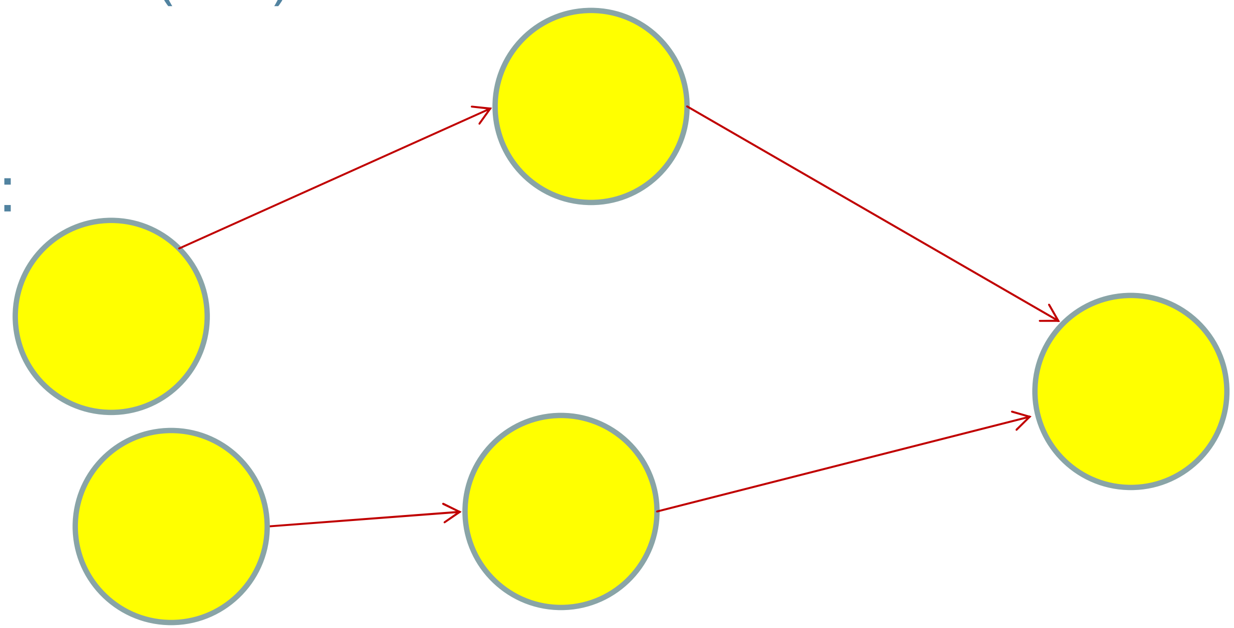

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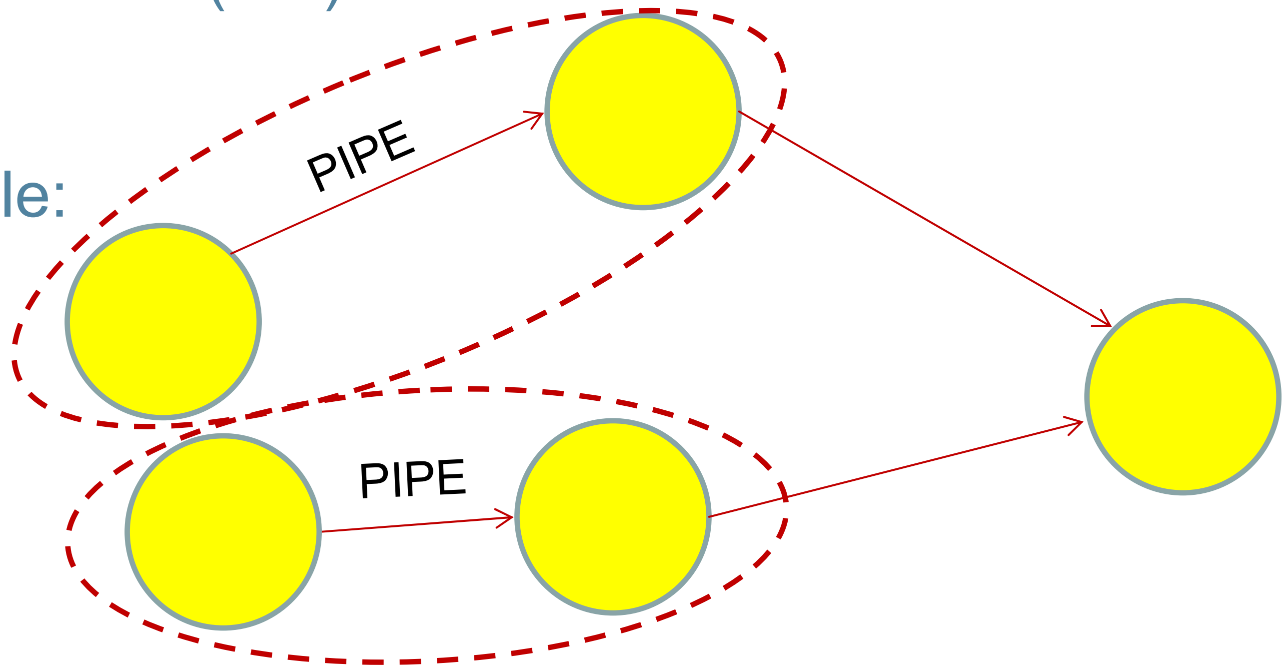

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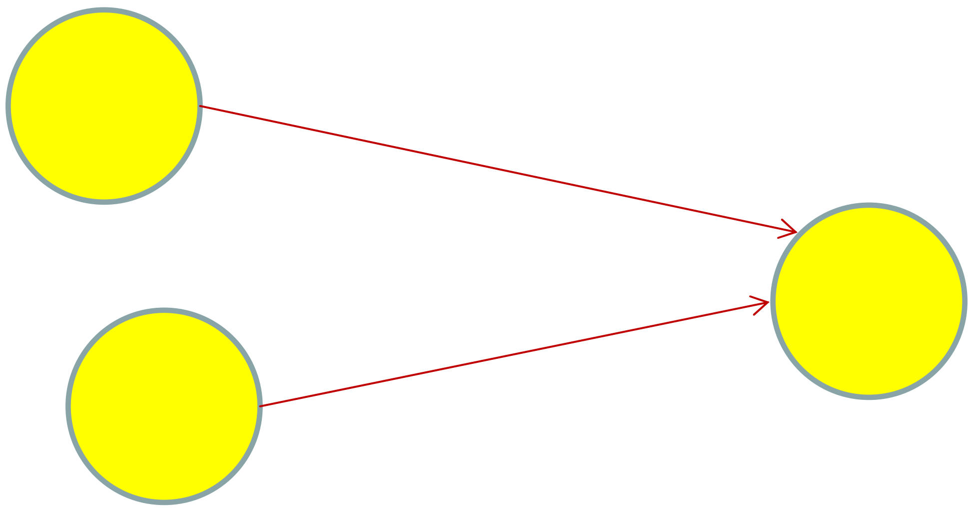

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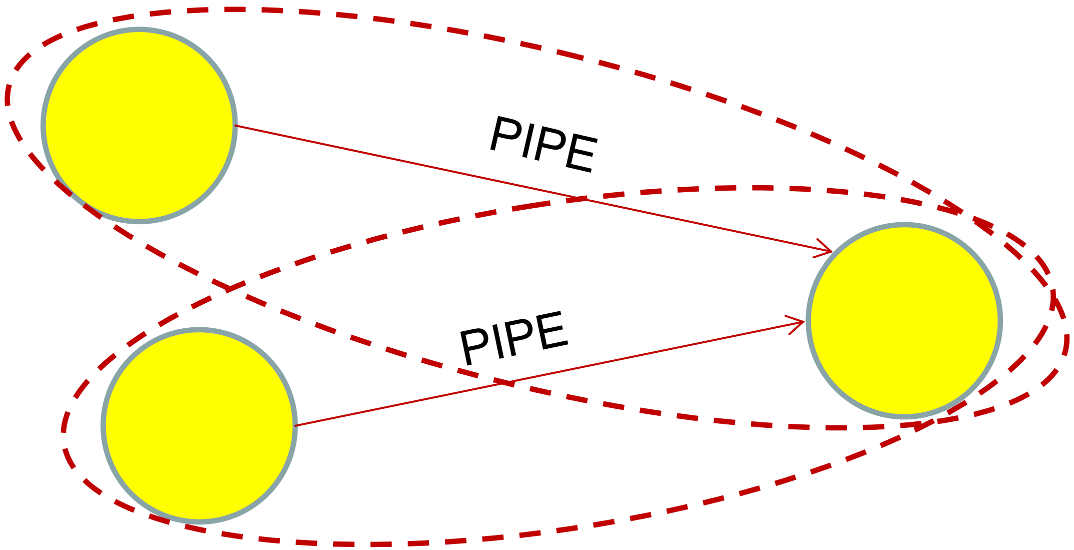

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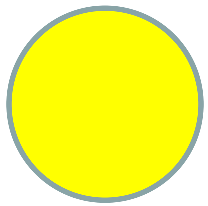


The Workload Matrix

- Each cell i,j holds the delay that job i imposes on job j in the subsystem that the matrix represents.
- Example: System consisting of four jobs *(J_1-J_4)* of which only J_1, J_2, and J_4 execute on the stage

$$\left(\begin{array}{c|cccc} & J_1 & J_2 & J_3 & J_4 \\ \hline J_1 & (C_{1,j},0) & (C_{1,j},0) & (0,0) & (C_{1,j},0) \\ J_2 & (0,0) & (C_{2,j},0) & (0,0) & (C_{2,j},0) \\ J_3 & (0,0) & (0,0) & (0,0) & (0,0) \\ J_4 & (0,0) & (0,0) & (0,0) & (C_{4,j},0) \\ & \multicolumn{4}{c}{\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots} \\ & C_{1,j} & max(C_{1,j},C_{2,j}) & 0 & \begin{array}{c} max(C_{1,j}, \\ C_{2,j},C_{4,j}) \end{array} \end{array}\right)$$

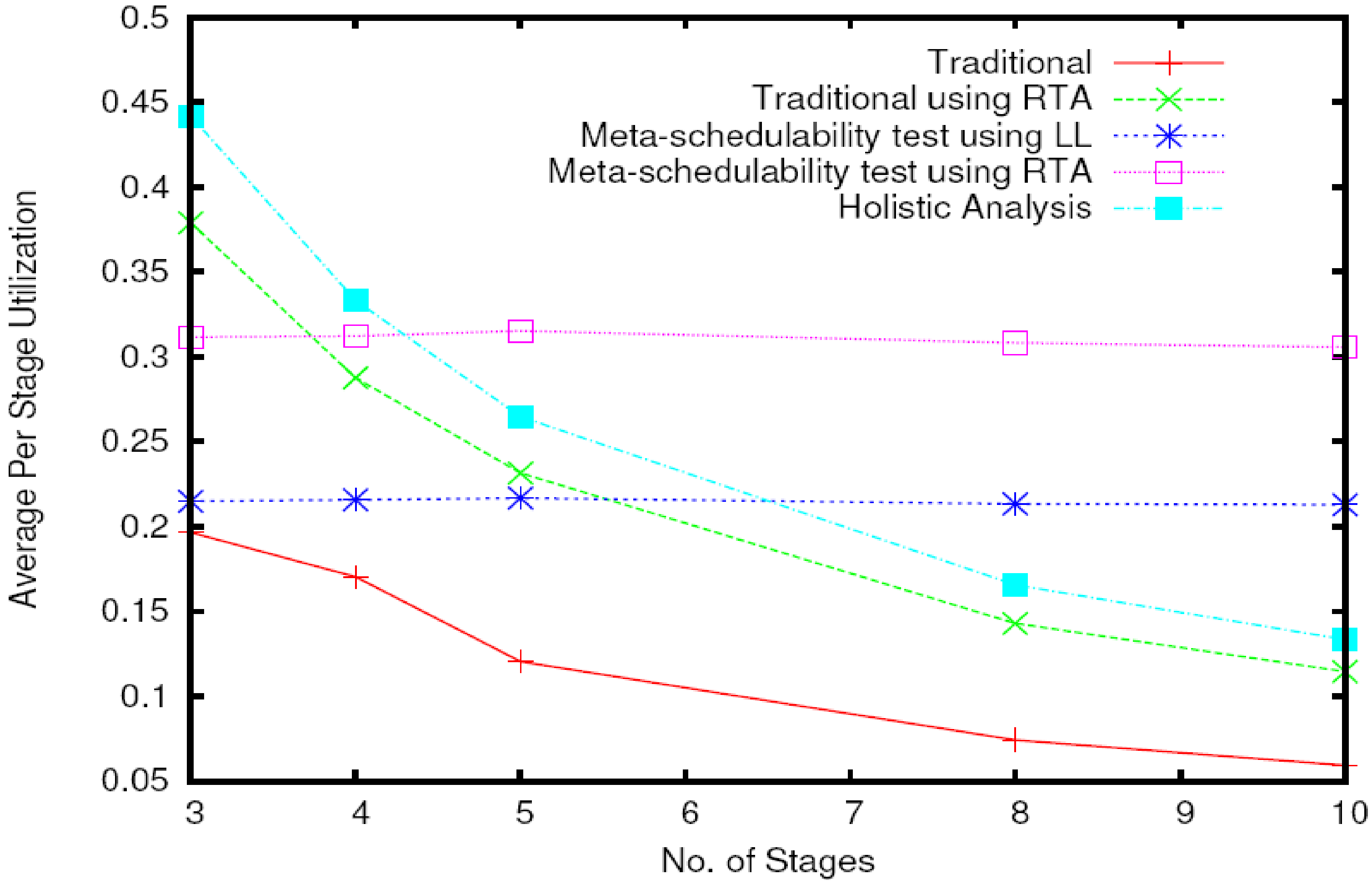
The Operators

$$\left(\begin{array}{c|cc} & J_1 & J_2 \\ \hline J_1 & (q^A_{1,1}, r^A_{1,1}) & (q^A_{1,2}, r^A_{1,2}) \\ J_2 & (0,0) & (q^A_{2,2}, r^A_{2,2}) \\ & \cdots\cdots & \cdots\cdots \\ & s^A_1 & s^A_2 \end{array}\right) PIPE \left(\begin{array}{c|cc} & J_1 & J_2 \\ \hline J_1 & (q^B_{1,1}, r^B_{1,1}) & (q^B_{1,2}, r^B_{1,2}) \\ J_2 & (0,0) & (q^B_{2,2}, r^B_{2,2}) \\ & \cdots\cdots & \cdots\cdots \\ & s^B_1 & s^B_2 \end{array}\right)$$

$$= \left(\begin{array}{c|cc} & J_1 & J_2 \\ \hline J_1 & \begin{array}{c}(max(q^A_{1,1}, q^B_{1,1}),\\ max(r^A_{1,1}, r^B_{1,1}))\end{array} & \begin{array}{c}(max(q^A_{1,2}, q^B_{1,2}),\\ max(r^A_{1,2}, r^B_{1,2}))\end{array} \\ J_2 & (0,0) & \begin{array}{c}(max(q^A_{2,2}, q^B_{2,2}),\\ max(r^A_{2,2}, r^B_{2,2}))\end{array} \\ & \cdots\cdots & \cdots\cdots \\ & s^A_1 + s^B_1 & s^A_2 + s^B_2 \end{array}\right)$$

$$SPLIT \left(\begin{array}{c|cc} & J_1 & J_2 \\ \hline J_1 & (q^A_{1,1}, r^A_{1,1}) & (q^A_{1,2}, r^A_{1,2}) \\ J_2 & (0,0) & (q^A_{2,2}, r^A_{2,2}) \\ & \cdots\cdots & \cdots\cdots \\ & s^A_1 & s^A_2 \end{array}\right) \equiv \left(\begin{array}{c|cc} & J_1 & J_2 \\ \hline J_1 & (q^A_{1,1}, r^A_{1,1}) & (0,0) \\ J_2 & (0,0) & (0,0) \\ & \cdots\cdots & \cdots\cdots \\ & s^A_1 & 0 \end{array}\right), \left(\begin{array}{c|cc} & J_1 & J_2 \\ \hline J_1 & (0,0) & (0, q^A_{1,2} + r^A_{1,2}) \\ J_2 & (0,0) & (q^A_{2,2}, r^A_{2,2}) \\ & \cdots\cdots & \cdots\cdots \\ & 0 & s^A_2 \end{array}\right)$$

Schedulability Analysis Results

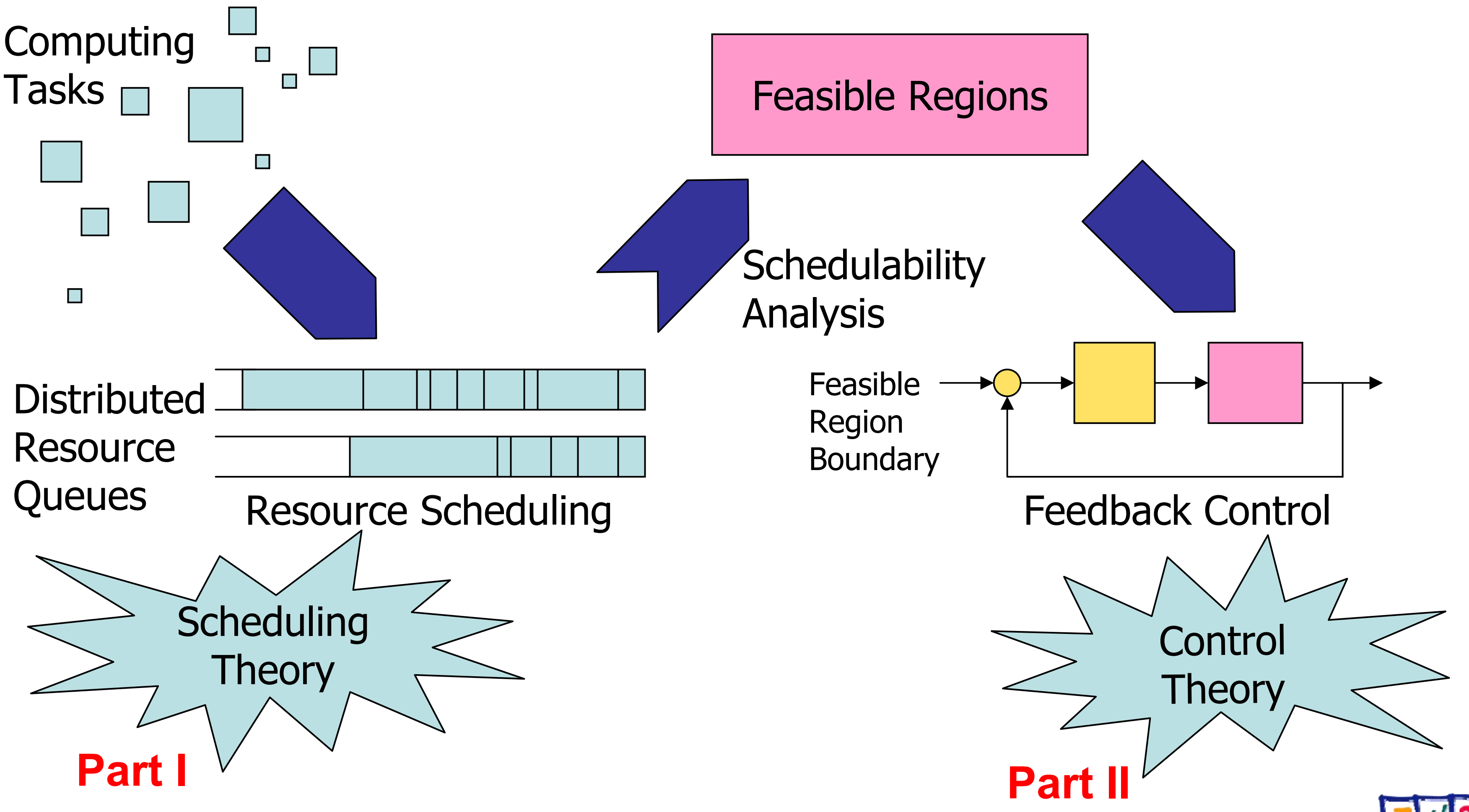


Impact of Delay Composition Algebra

- A simple approach to transform arbitrary task graphs into equivalent uniprocessor workloads amenable to existing analysis techniques
- Transforms schedulability conditions of a distributed task set into a utilization bound (queue state) amenable to control
- Opportunities for future research:
  - Needs extension to resource blocking (mutual exclusion constraints), spatially partitioned resources (as opposed to prioritized), transactions (multiple resource acquired in an all-or-nothing fashion), …
  - Advantages: simplicity, scalability.

Distributed Software Performance Control

Requirements on meeting deadlines → utilization (queue state) → performance control



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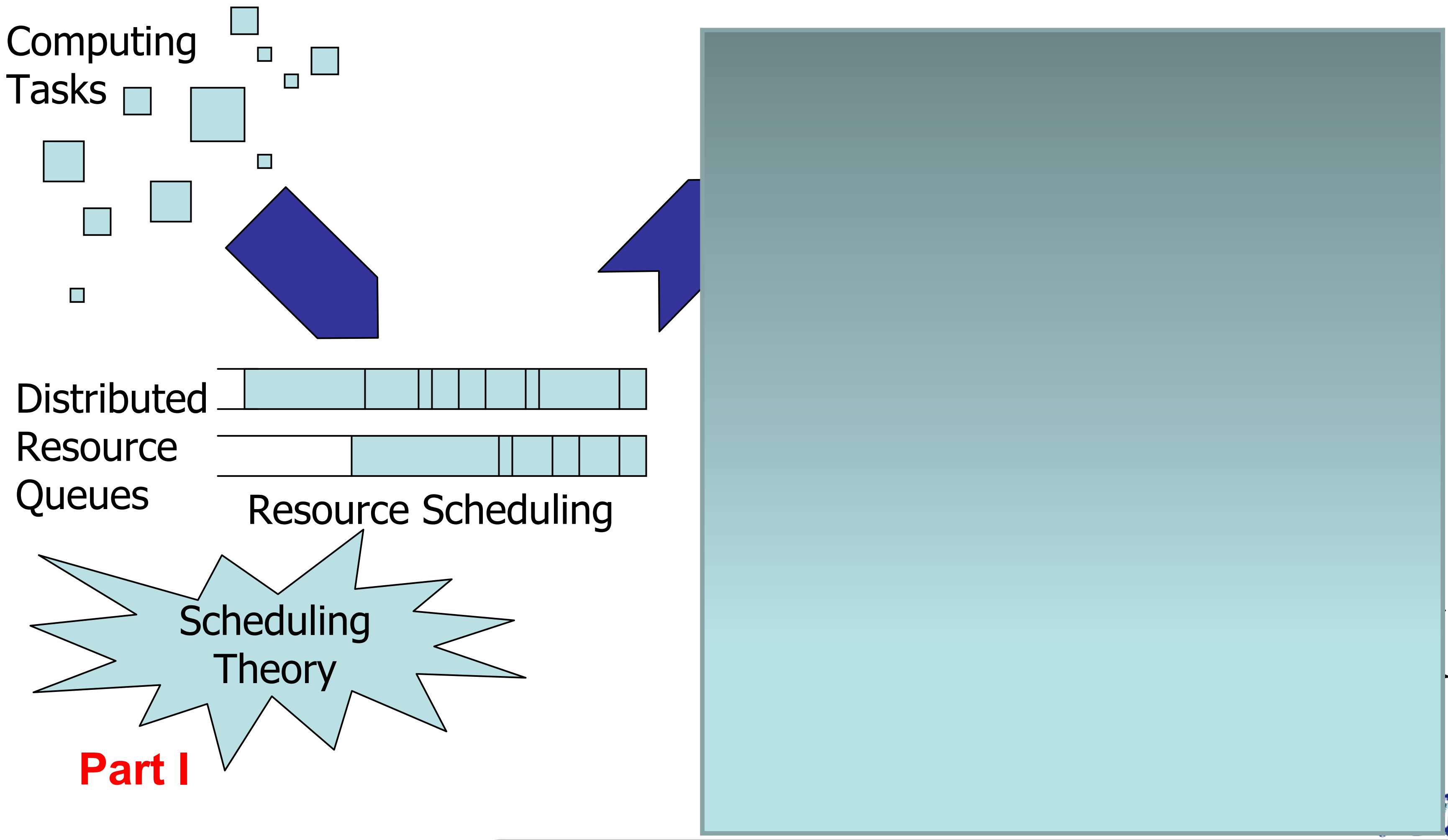
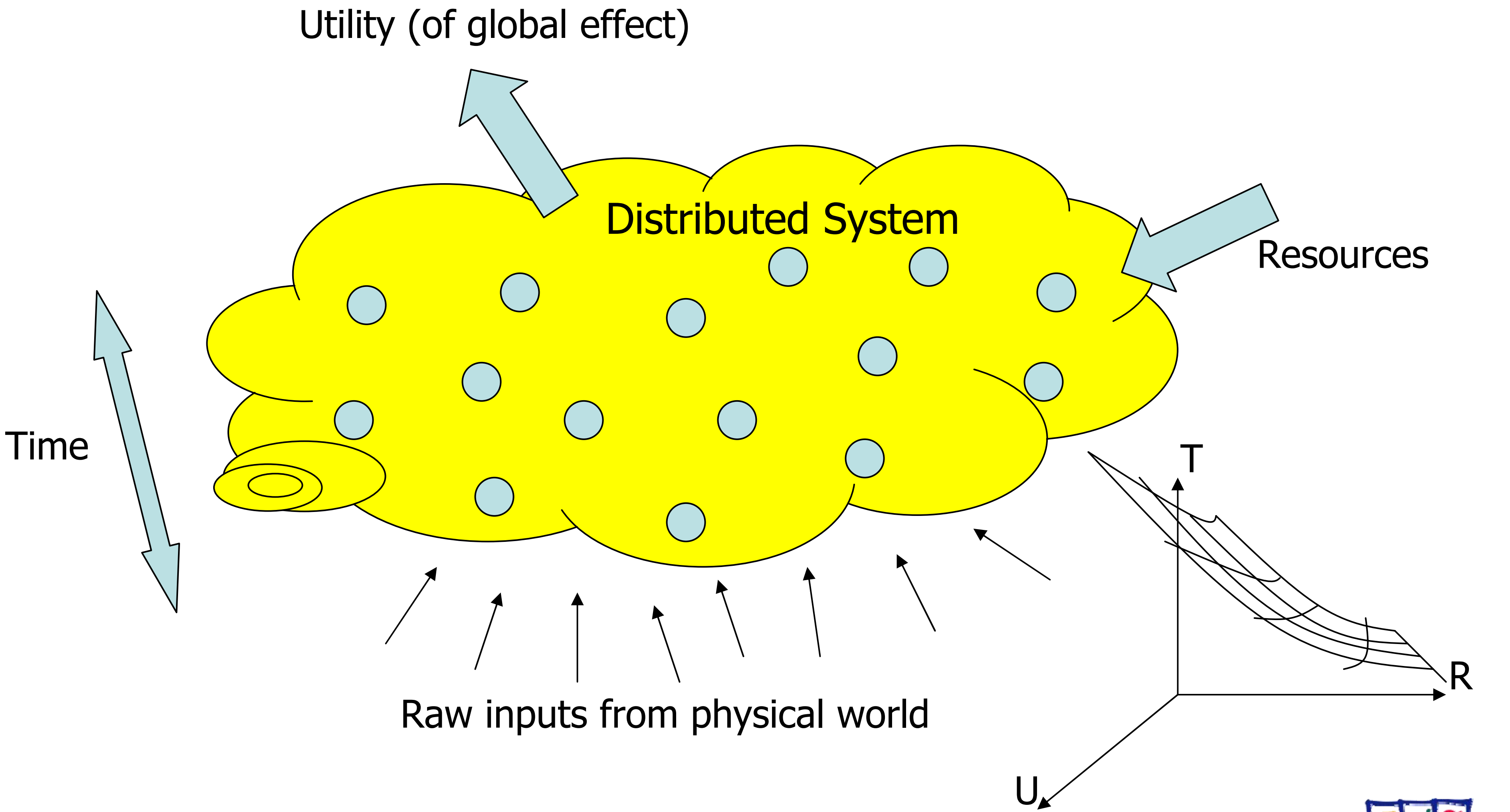


Control of Performance Tradeoffs in Distributed Systems



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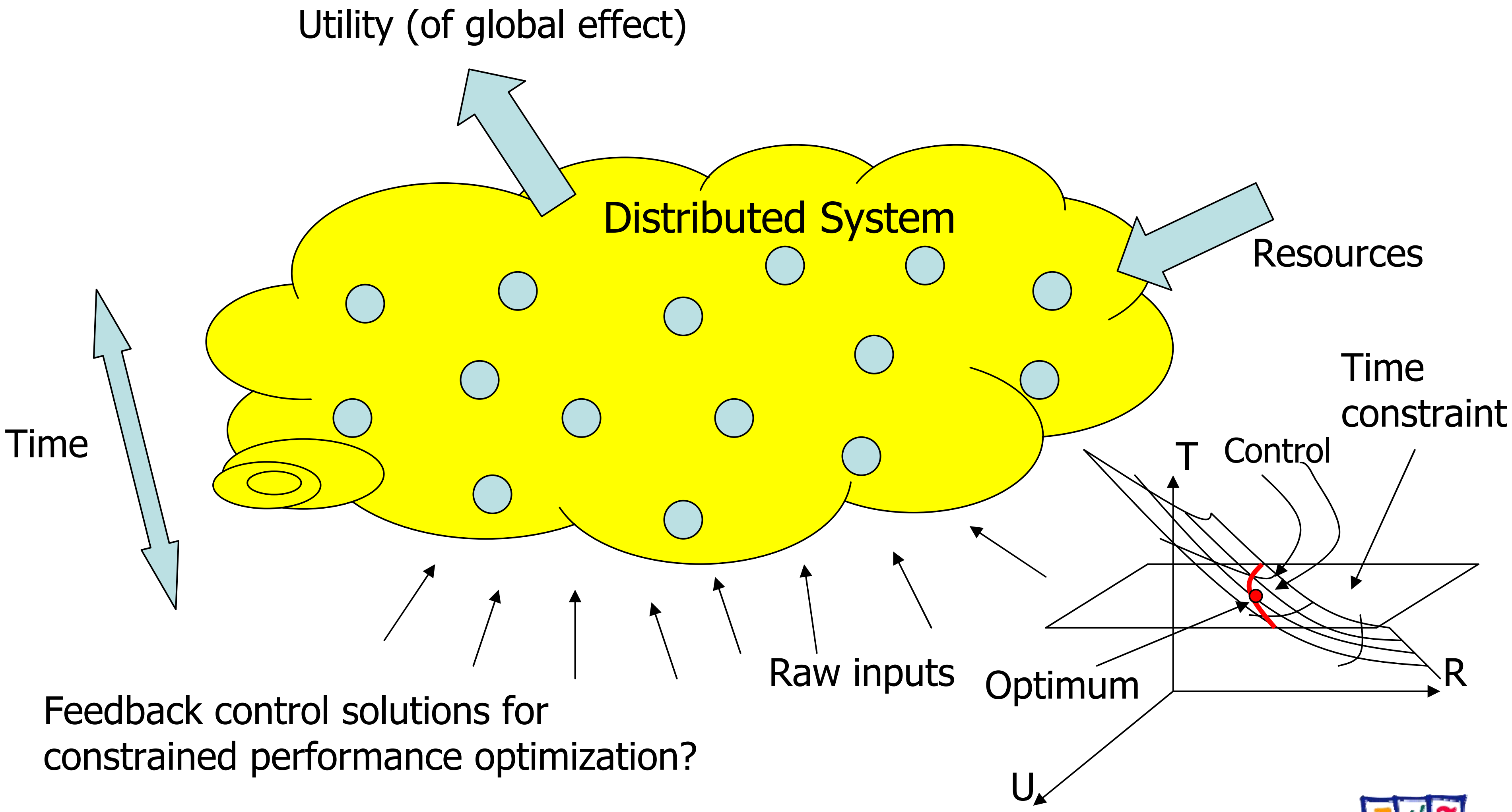

Feedback control solutions for constrained performance optimization?

A Methodology for Applying Feedback Control to Software

- Mapping: Performance management problem → Feedback problem
  - Determine the controlled performance metric (*output*) and its desired value (*set point*)
  - Determine the available actuators (*input*)
  - Map the performance control problem into a set of control loops
- Modeling:
  - Model the input-output relation as a difference equation:

    $Output_k = \Sigma_i\, a_i\, Output_{k-i} + \Sigma_i\, b_i\, Input_{k-i}$
- Controller design:
  - Use control theory to find function *f*, such that:

    Input = f(set point – output) makes *output → set point*

Control Examples in Distributed Systems

- Case 1: Centralized control, centralized actuation
- Case 2: Centralized control, distributed actuation
- Case 3: Distributed (localized) control and actuation

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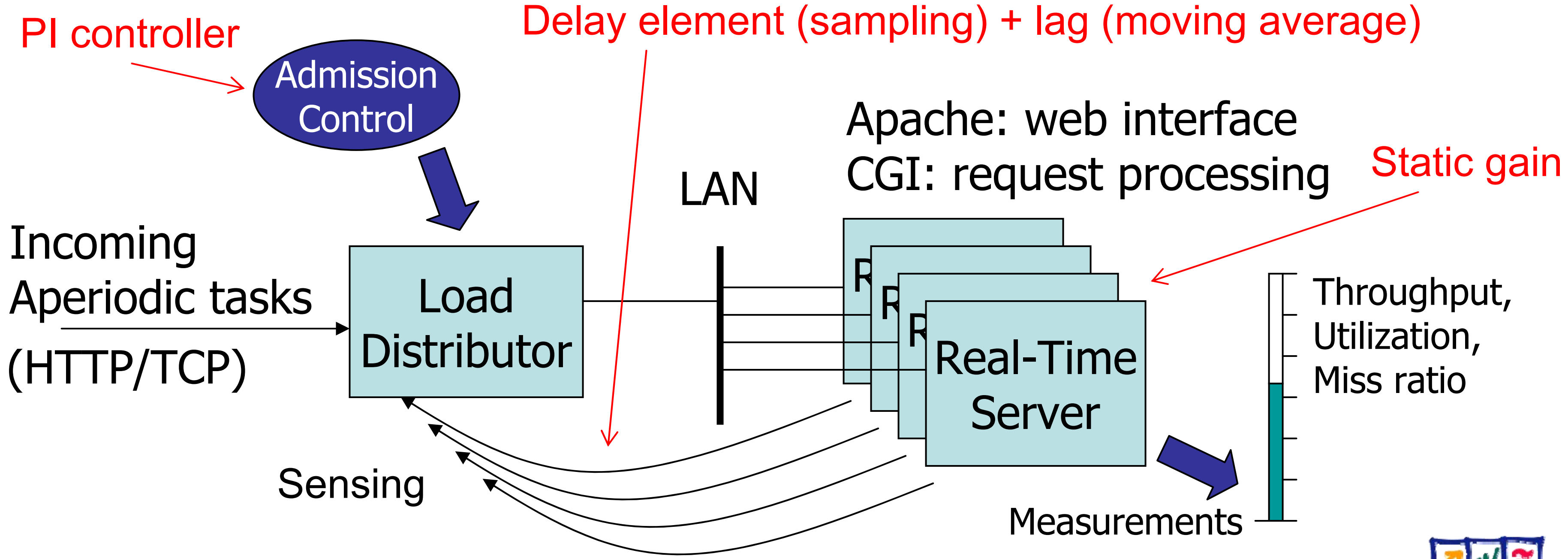
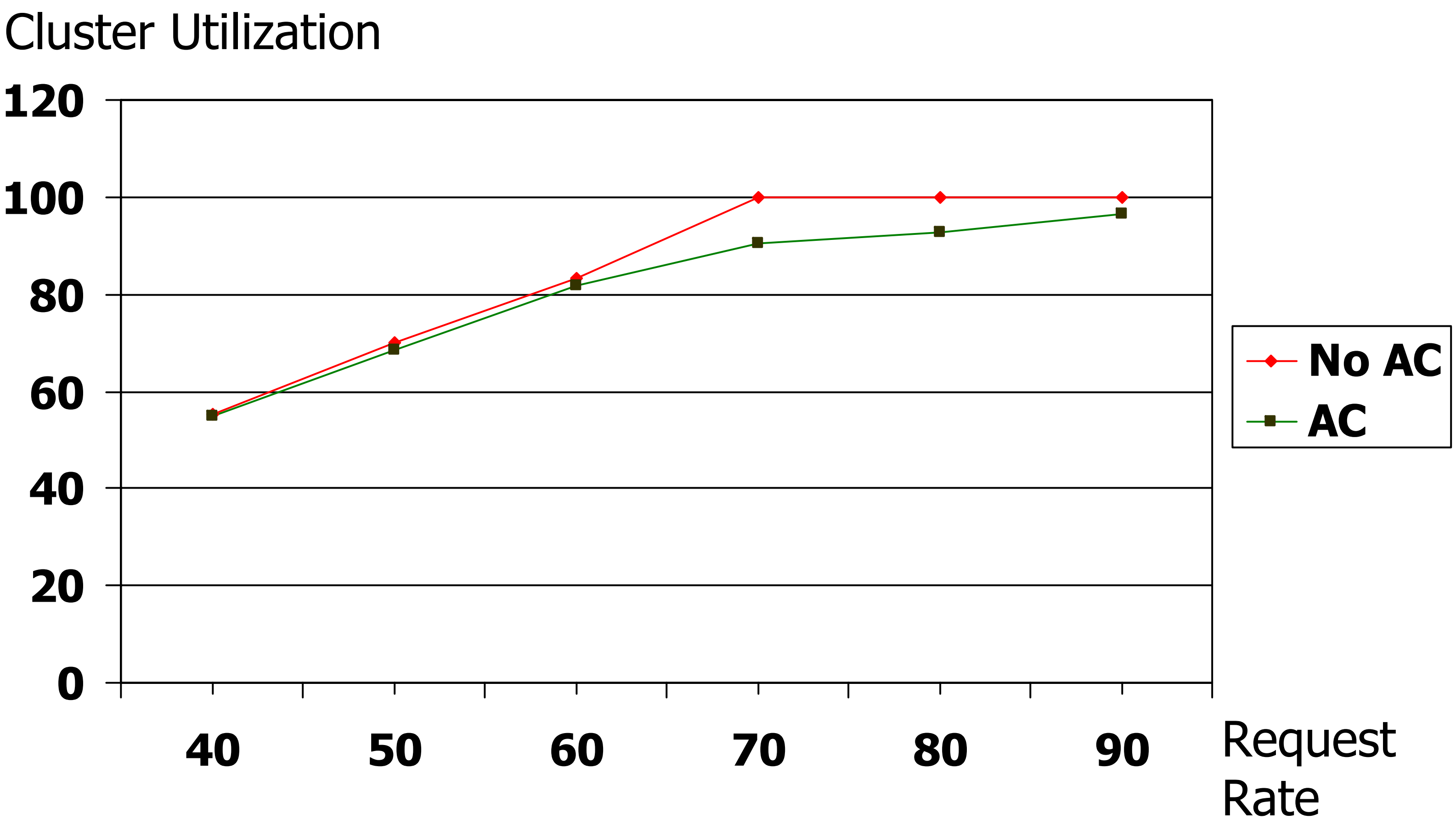
Experimental Testbed and Evaluation

- A real-time computing cluster is developed under Linux
- 4 worker Linux PCs connected by 100Mbps LAN to a front-end load distributor



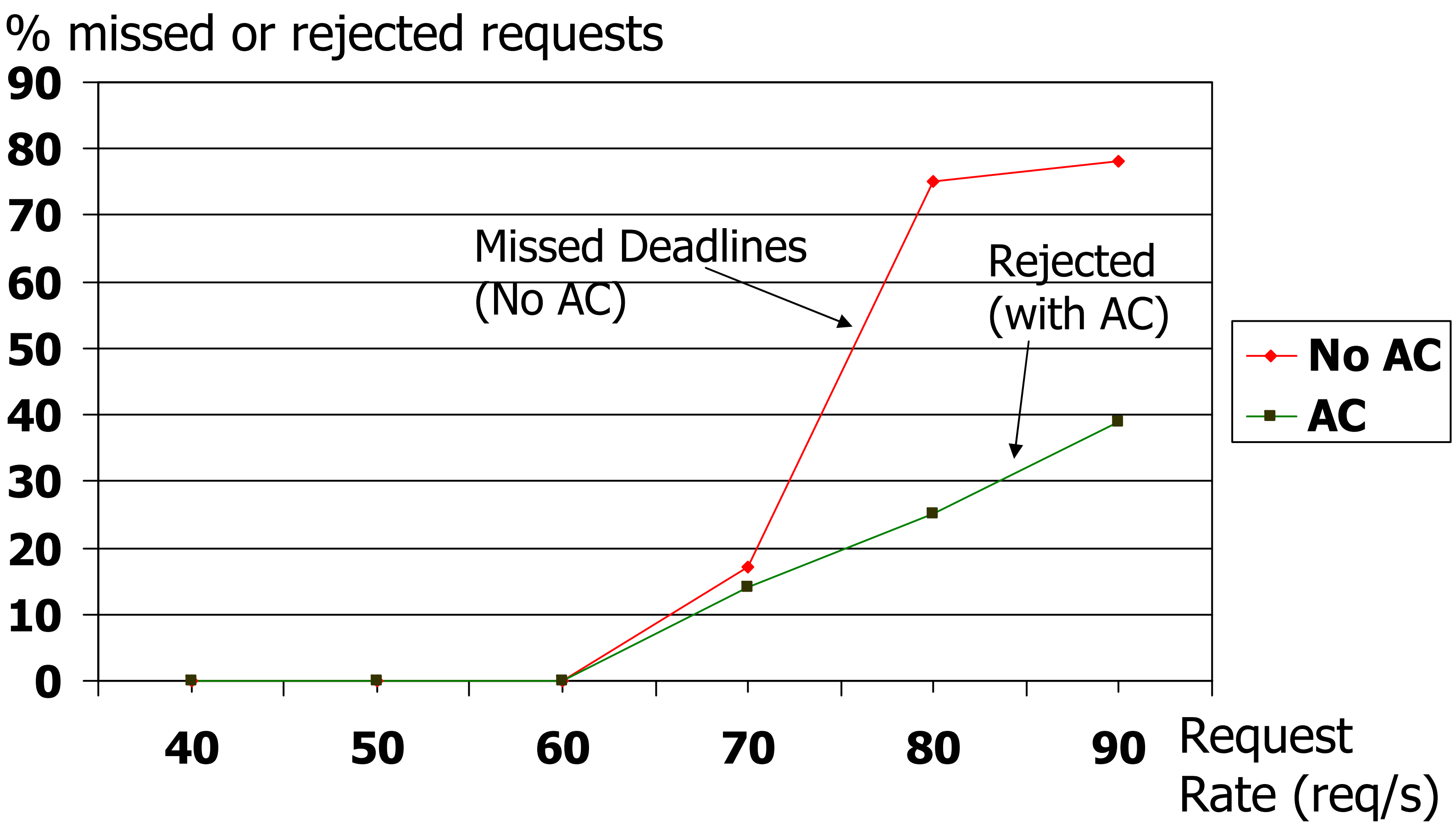
Server Utilization

Utilization-based admission control does not underutilize server



Miss Ratio Profile

Utilization-based admission control improves task success ratio



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Energy Management in Server Farms

Energy expended on:

- Computing (powering up racks of machines)
  - Sensors: Machine utilization, Delay, Throughput, …
  - Actuators: DVS, turning machines On/Off
- Cooling
  - Sensors: Temperature, air flow, …
  - Actuators: Air-conditioning units, fans, …
- Energy bill is 40-50% of total profit

Problem Formulation

Step 1: Formulate objective and constraints

$$\min_{x_1,\ldots,x_n} \quad \overbrace{f(x_1,\ldots,x_n)}^{\text{Control knobs}}$$
$$\text{subject to} \quad g_j(x_1,\ldots,x_n) \leq 0, \quad j = 1,\ldots,m$$

Step 2: Determine optimality conditions (KKT)

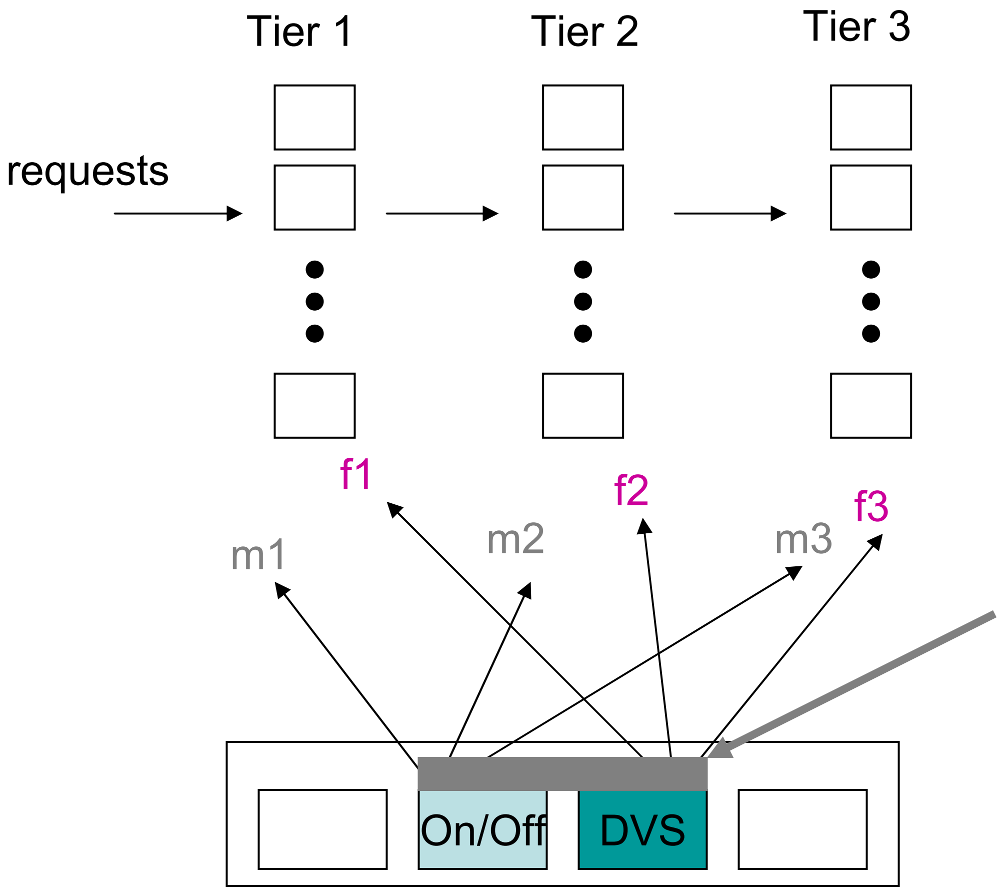
$$\Gamma_{x_i} \leftarrow \boxed{\frac{\partial f(x_1,\ldots,x_n)}{\partial x_i} + \sum_{j=1}^{m} \nu_j \frac{\partial g_j(x_1,\ldots,x_n)}{\partial x_i} = 0}$$

Step 3: Set up control loops

$$\Gamma_{x_1} = \Gamma_{x_2} = \Gamma_{x_2} = \Gamma_{average}$$

Set point

A Server Farm Case study



Composed distributed middleware

Find knob settings, (m1, m2, m3, f1, f2, f3) such that energy consumption is reduced

Formulation

Formulate constrained optimization

$$P_i(f_i) = A_i \cdot f_i^p + B_i$$

Power estimation of a machine at tier i

$$U_i = \frac{\lambda}{\mu} = \frac{\lambda_i/m_i}{f_i} = \frac{\lambda_i}{m_i f_i}$$

Queuing equation using number of machines and arrival rate

$$P_i(U_i, m_i) = A_i \cdot \left(\frac{\lambda_i}{U_i m_i}\right)^p + B_i = \frac{A_i \lambda_i^p}{U_i^p m_i^p} + B_i$$

Power estimation function of a machine at tier i

$$\min_{U_i \geq 0,\ m_i \geq 0} P_{tot}(U_i, m_i) = \sum_{i=1}^{3} m_i \left(\frac{A_i \lambda_1^3}{U_i^3 m_i^3} + B_i\right)$$

$$\text{subject to} \quad \sum_{i=1}^{3} \frac{m_i}{\lambda_i} \cdot \frac{U_i}{1-U_i} \leq K, \qquad \sum_{i=1}^{3} m_i \leq M$$

Find best composition of

(m_1, m_2, m_3, U_1, U_2, U_3),

hence (m_1, m_2, m_3, f_1, f_2, f_3)

Optimality Conditions

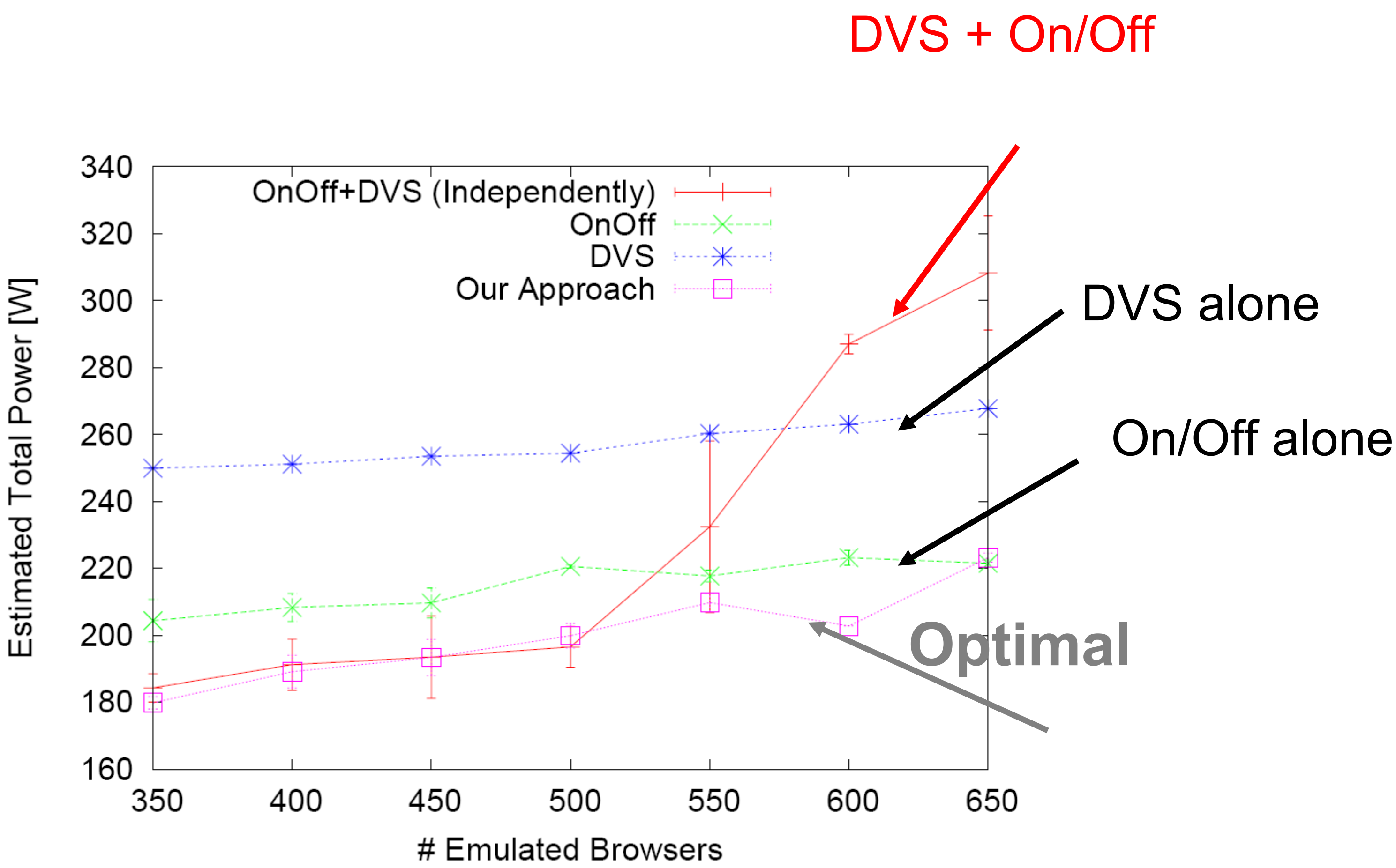
- Derive necessary condition for optimality
  - Karush-Kuhn-Tucker (KKT) condition

$$\frac{\lambda_1^4(1-U_1)^2}{m_1^3U_1^4} = \frac{\lambda_2^4(1-U_2)^2}{m_2^3U_2^4} = \frac{\lambda_3^4(1-U_3)^2}{m_3^3U_3^4}$$

$$\Gamma(m_1, U_1) = \Gamma(m_2, U_2) = \Gamma(m_3, U_3)$$

- $Error_i = \Gamma_{avg} - \Gamma(m_i, U_i)$, where Γ_{avg} is average of $\Gamma(m_i, U_i)$

Evaluation


DVS + On/Off
OnOff+DVS (Independently)
OnOff
DVS
Our Approach
DVS alone
On/Off alone
Optimal
Estimated Total Power [W]
340
320
300
280
260
240
220
200
180
160
350
400
450
500
550
600
650
Emulated Browsers

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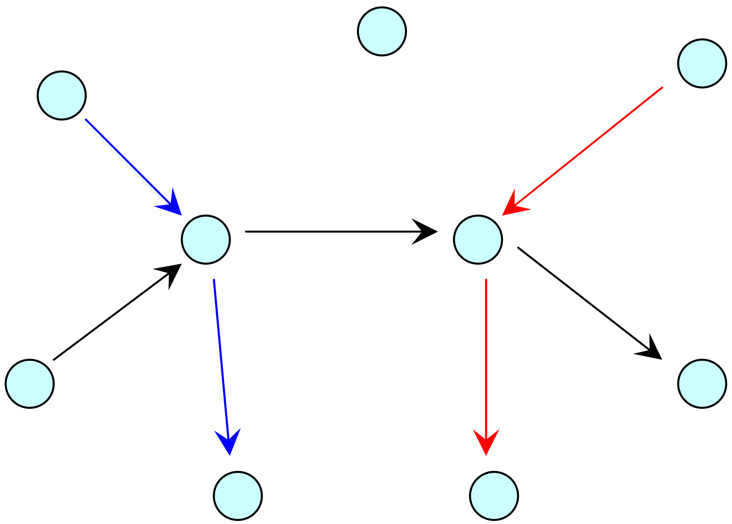
Example: Flow Rate Control in a Wireless Network subject to Delay Constraints



Problem: Allocate rates to elastic flows in a wireless network so as to maximize network utility, while meeting end-to-end delay requirements

Problem Formulation

Step 1: Formulate objective and constraints

$$\min_{x_1,\ldots,x_n} \quad f(\overbrace{x_1,\ldots,x_n}^{\text{Control knobs}})$$

$$\text{subject to} \quad g_j(x_1,\ldots,x_n) \le 0, \quad j = 1,\ldots,m$$

Step 2: Decentralize the constraints: $\sum_{i=1,\ldots,n} Term_i \le 0$

$$\xrightarrow{becomes} Sum_i = Term_i + Sum_{i-1},\ Sum_n \le 0$$

Step 3: Determine optimality conditions (KKT)

$$\Gamma x_i \longleftarrow \boxed{\frac{\partial f(x_1,\ldots,x_n)}{\partial x_i} + \sum_{j=1}^{m} \nu_j \frac{\partial g_j(x_1,\ldots,x_n)}{\partial x_i} = 0}$$

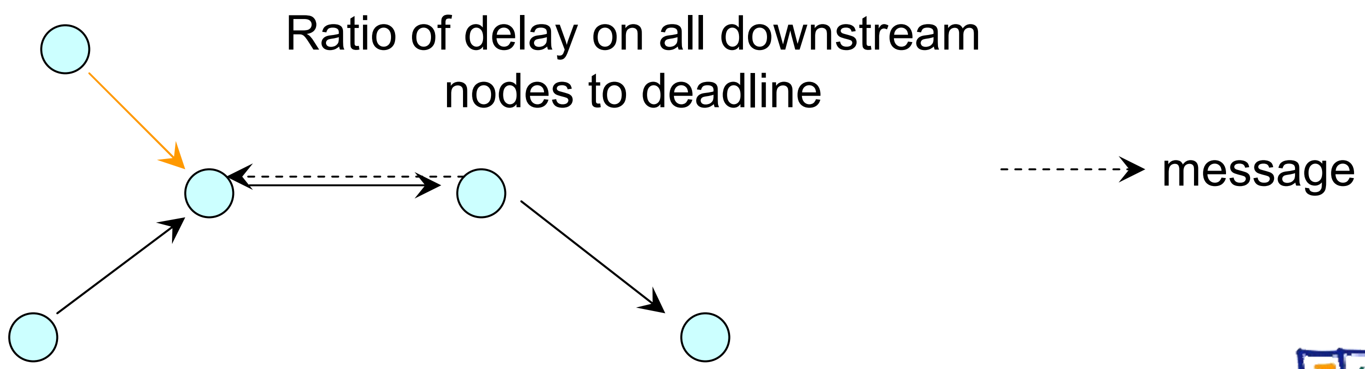
Step 4: Set up control loops

$$x_i(k) = x_i(k-1) + C_i h(\upsilon_i,\ldots,\upsilon_m)$$

$$\upsilon_j(k) = \upsilon_j(k-1) + G_j \psi(x_1,\ldots,x_n)$$

Decentralizing the Delay Constraint

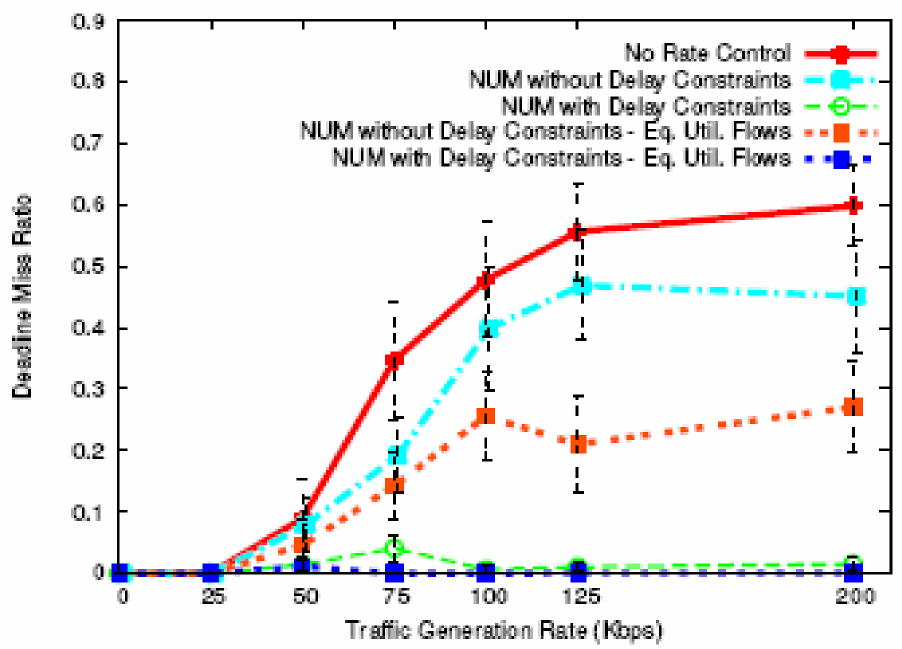
- For each flow *s* and hop *i*, define additional variables to hold the value of the left hand side of the constraint for hops *i* and up to the destination
- Each node only requires value from immediate downstream node
- Source constraint compares end-to-end delay to deadline



Simulation Setup

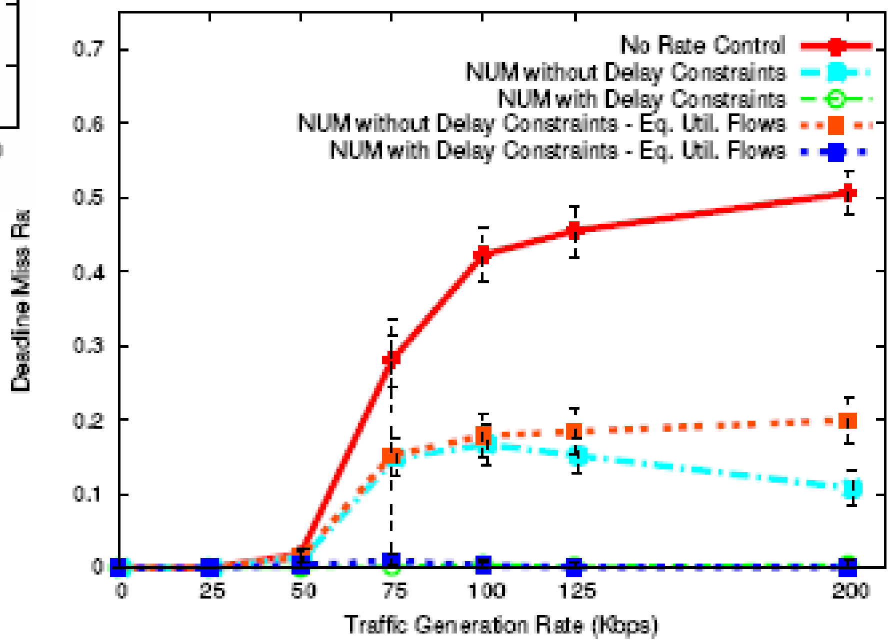
- Implemented on ns2
- 50 nodes placed uniformly at random
- 802.11 with prioritized scheduling; DSDV routing
- 5 elastic flows, 3 priorities with no. of flows in each in the ratio 1:2:4 (for high:medium:low) – end-to-end deadlines 2, 4, 7s
- Algorithms:
  - No rate control
  - NUM w/o delay constraints performs only rate control based on capacity constraints
  - NUM with delay constraints performs rate control based on capacity as well as delay constraints
- Utility function
  - Importance proportional to urgency
  - Importance same for all flows regardless of urgency ('Eq. Util. Flows')

Simulation Results



High Priority Flows

Low Priority Flows



Conclusions

- Emerging distributed systems will feature increased scale, interaction with a physical environment, uncertainty, and autonomy
- We need analytic tools for predicting and controlling the temporal behavior of such systems
- Theoretical foundations are needed to bridge the gap between software and feedback control abstractions
- A theory is developed for translating schedulability constraints in a class of distributed systems into constraints on utilization (or virtual queue) metrics
- These constraints can be decentralized leading to localized algorithms that collectively converge to global optima
- The feedback control problem derives from an optimization problem: The distributed system as an iterative optimizer

A Summary of Challenges

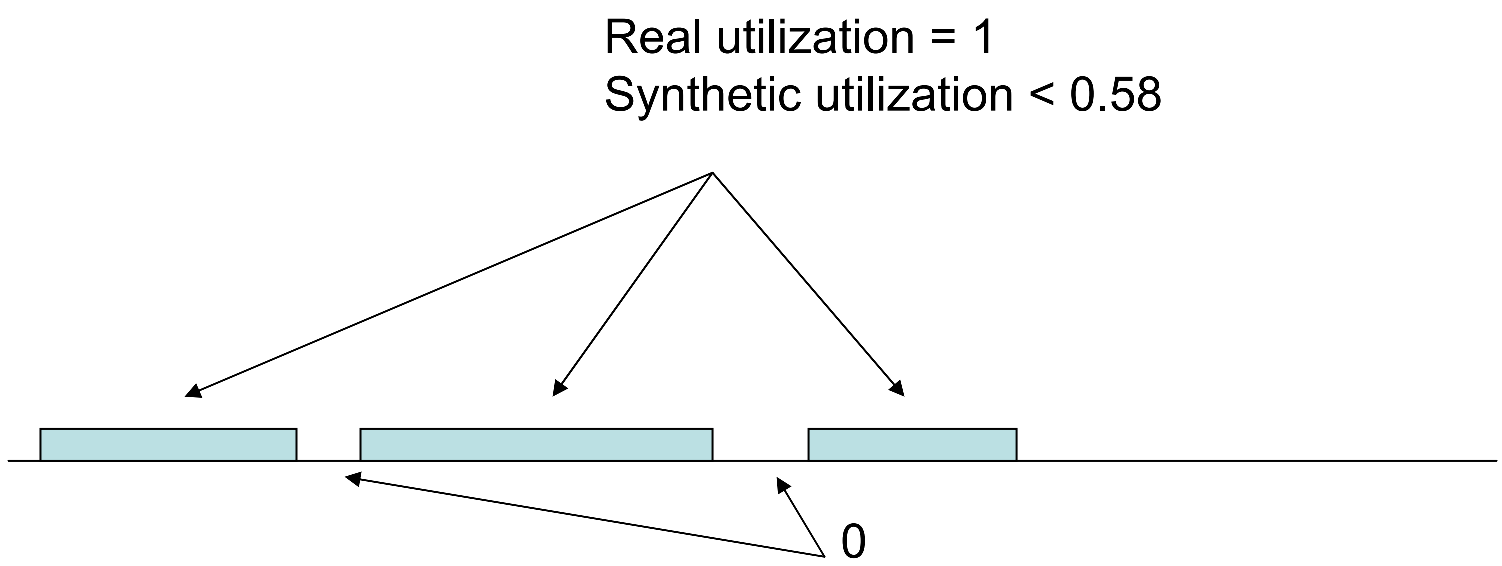
- What are other general categories of fine-grained constraints that can be converted to aggregate state variables amenable to control?
- How to translate desired global properties into localized protocol interactions?
- How to model nonlinearities specific to software?
- How to incorporate complex information extraction algorithms (e.g., data mining) in control loops?
- How to achieve convergence in poorly structured evolving systems? (e.g., mobile ad hoc networks, changing connectivity, non-uniform resource density, etc.)

Backup: Instantaneous versus Real Utilization

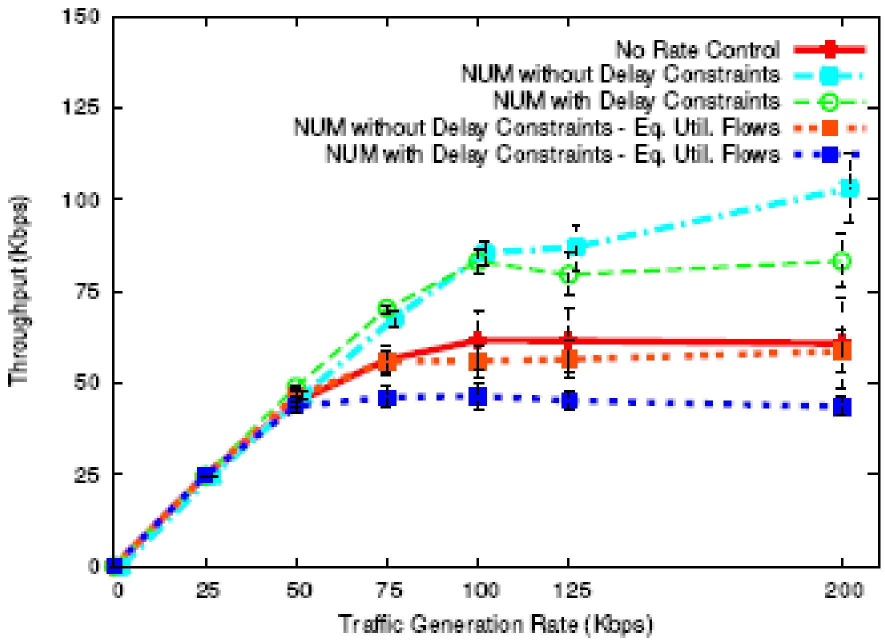
- An important property is that:

  avg. instantaneous utilization < avg. real utilization.

  → Hence, server is not underutilizaed!
- Proof:



Simulation Results (2/3)



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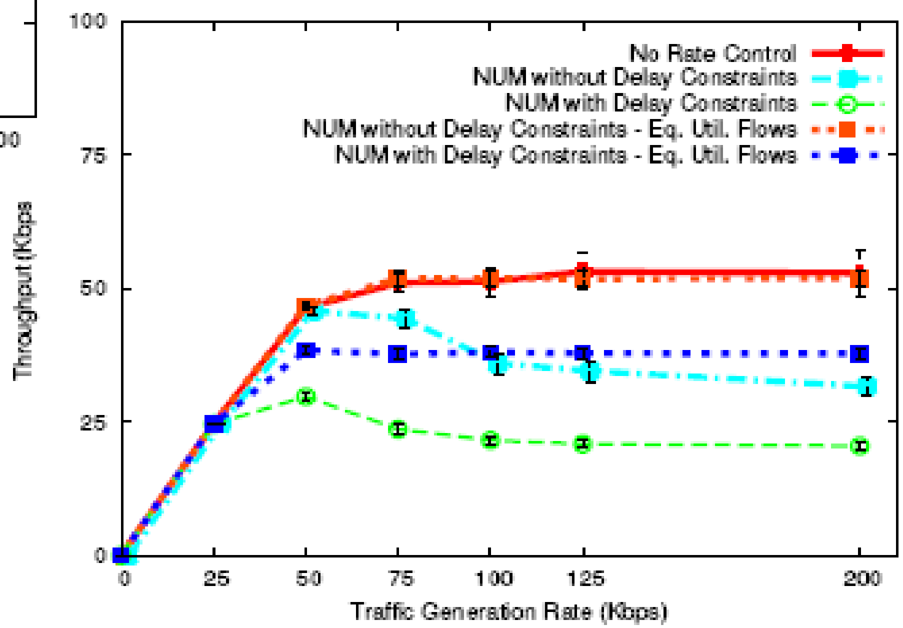
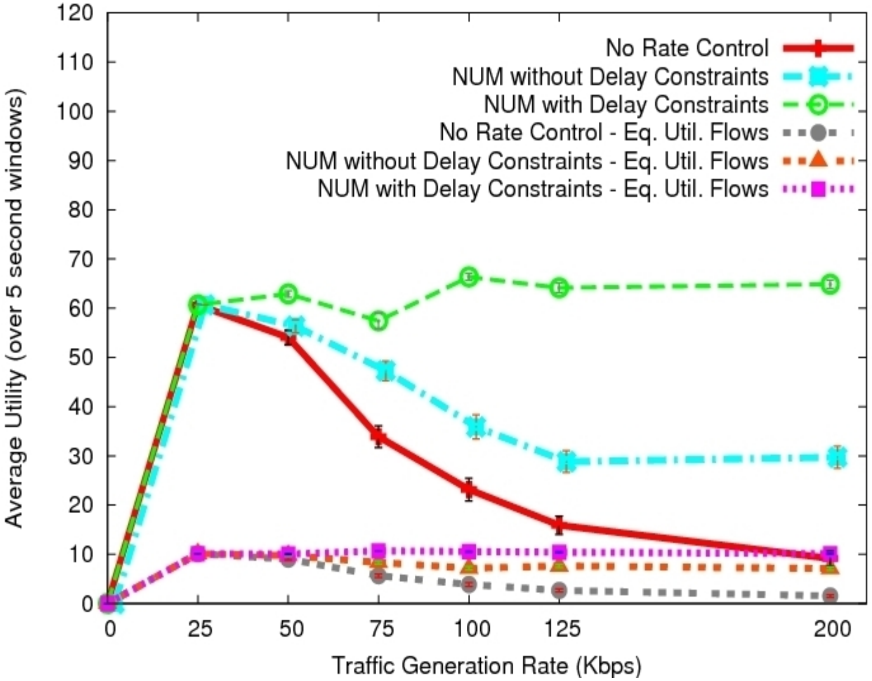


Simulation Results (3/3)



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