Tiptoe: A Compositional Real-Time Operating System

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tiptoe.cs.uni-salzburg.at

- Silviu Craciunas* (Programming Model)
- Hannes Payer* (Memory Management)
- Harald Röck (VM, Scheduling)
- Ana Sokolova* (Theoretical Foundation)
- Horst Stadler (I/O Subsystem)

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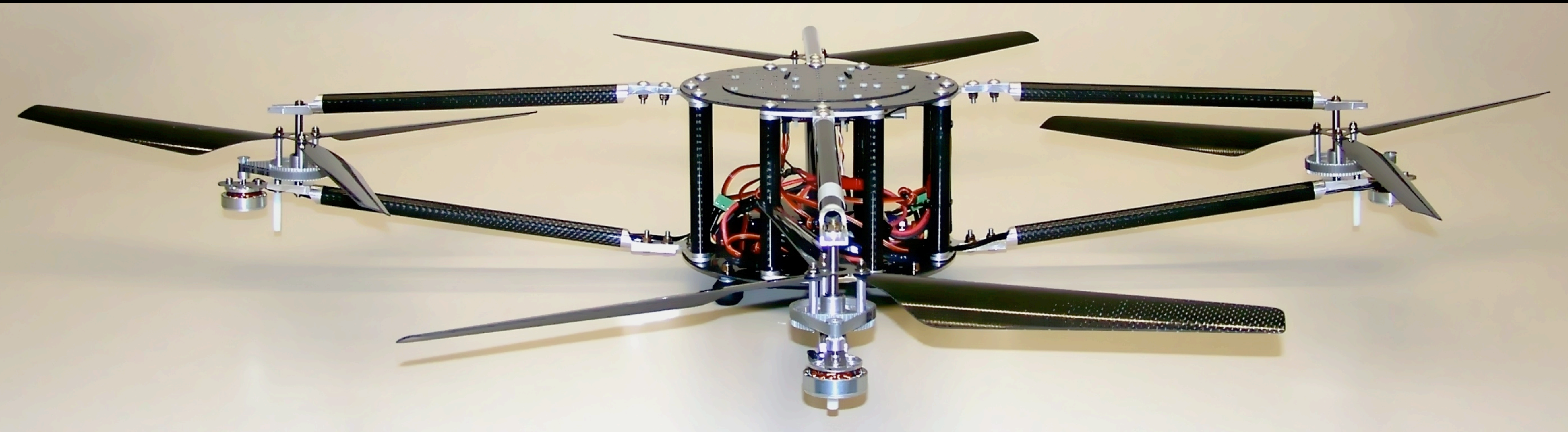

The JAviator

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Quad-Rotor Helicopter

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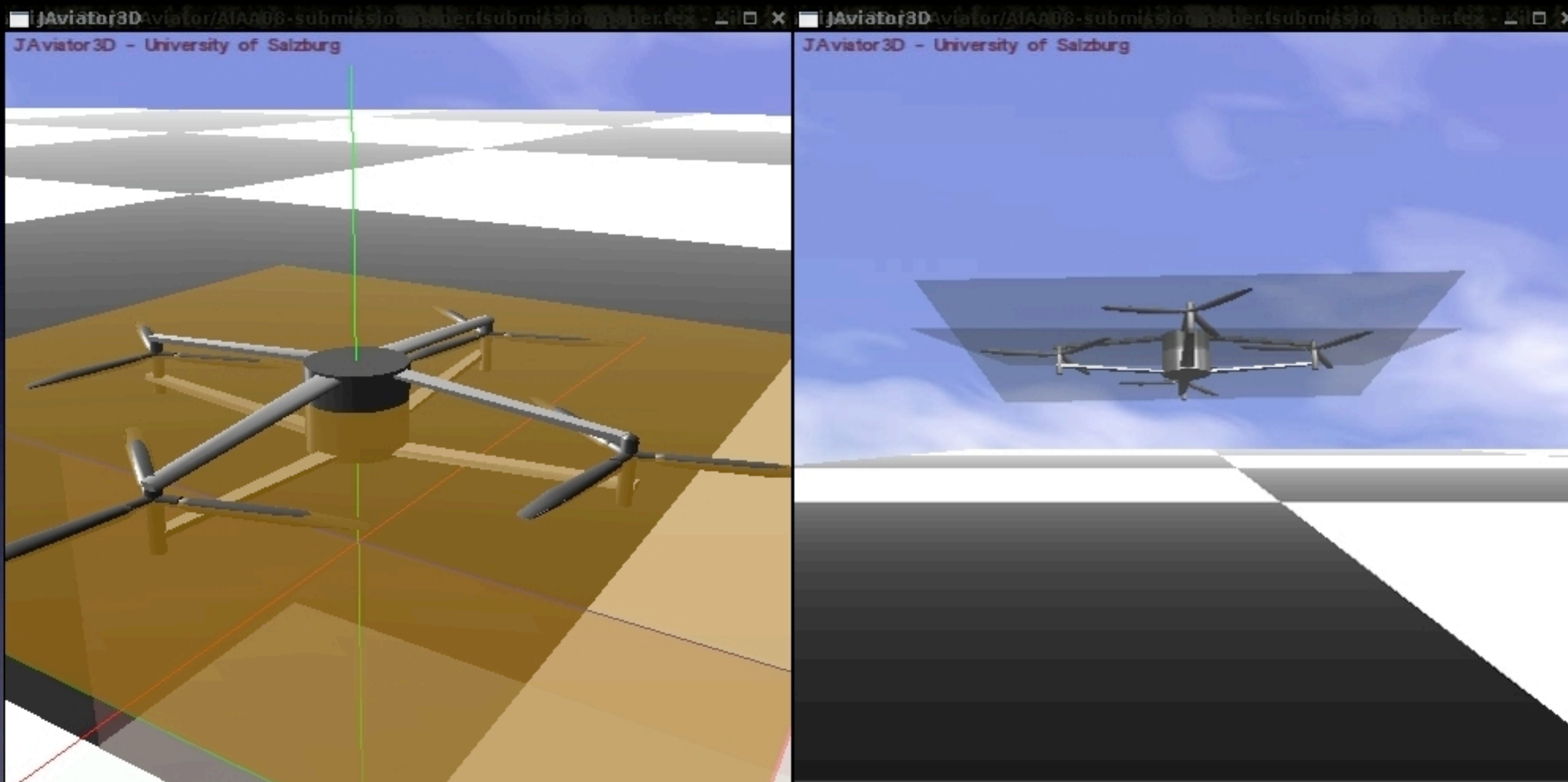

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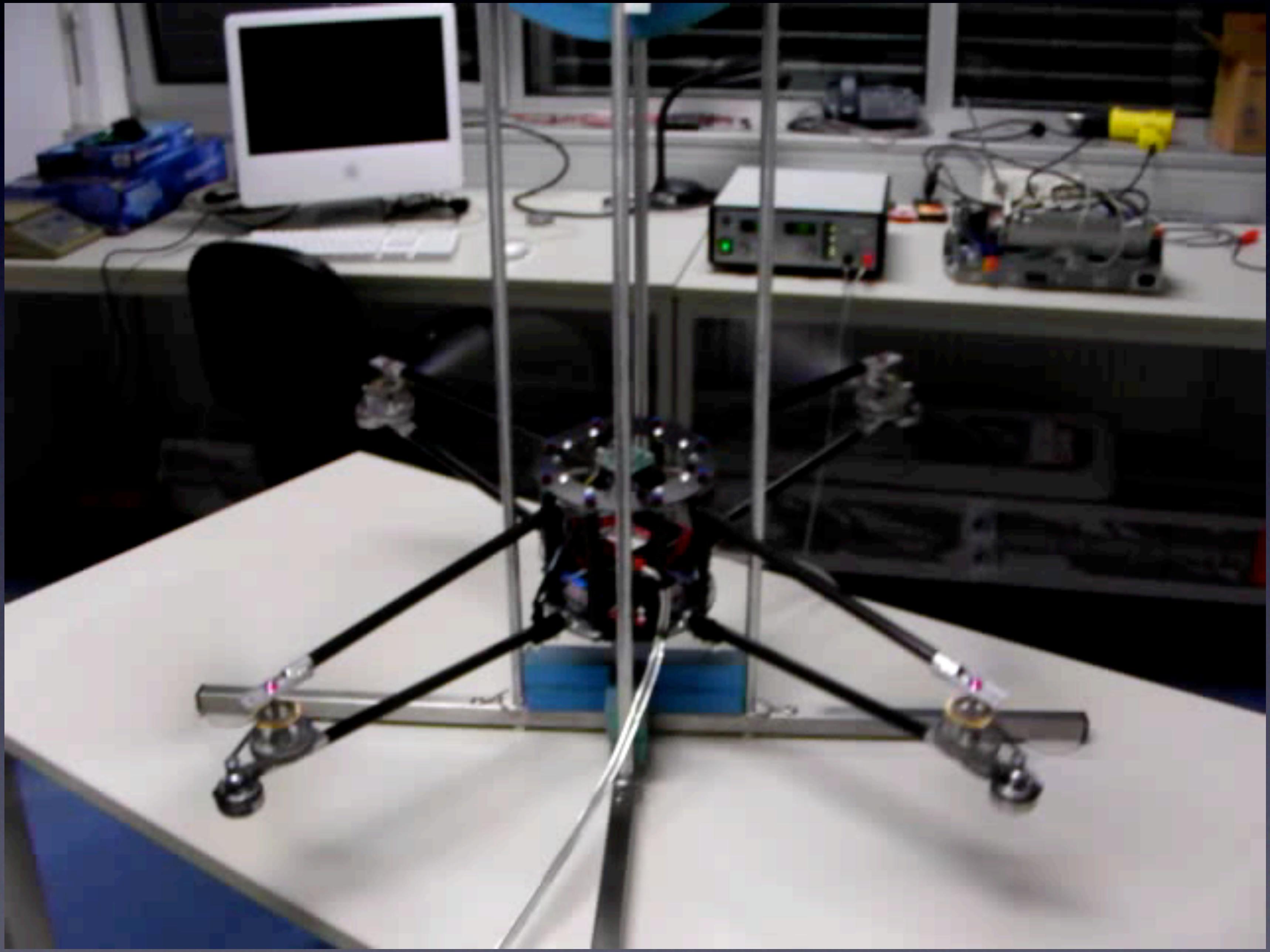
Flight Control



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Free Flight

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“Theorem”

- (Compositionality) The time and space a software process needs to execute is determined by the process, not the system and not other software processes.
- (Predictability) The system can tell how much time and space is available without looking at any existing software processes.

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“Corollary”

- (Memory) The time a software process takes to allocate and free a memory object is determined by the size of the object.
- (I/O) The time a software process takes to read input data and write output data is determined by the size of the data.

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Outline

1. Programming Model
2. Concurrency Management
3. Memory Management
4. I/O Management

State of the Art

- Traditional real-time process model:
  - A set of periodic tasks with deadlines
- Synchronous reactive programs
- Logical execution time (LET) model
  - A set of periodic tasks with deterministic input and output times

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Compositionality

- System of tasks with deadlines:
  - Existing tasks still meet deadlines even when adding/removing tasks
- System of LET tasks:
  - Existing tasks maintain input and output times even when adding/removing tasks

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Tiptoe Process Model

- Tiptoe processes invoke process actions
- Process actions are system calls and procedure calls but also just code, which may have optional workload parameters
- Workload parameters determine the amount of work involved in executing process actions

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Example

- Consider a process that reads a video stream from a network connection, compresses it, and stores it on disk, all in real time
- The process periodically adapts the frame rate, allocates memory, receives frames, compresses them, writes the result to disk, and finally deallocates memory to prepare for the next iteration

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Pseudo Code

```
loop {
  int number_of_frames = determine_rate();

  allocate_memory(number_of_frames);
  read_from_network(number_of_frames);

  compress_data(number_of_frames);

  write_to_disk(number_of_frames);
  deallocate_memory(number_of_frames);
} until (done);
```

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Tiptoe Programming Model

- Process actions are characterized by their execution time and response time in terms of their workload parameters
- The execution time is the time it takes to execute an action in the absence of concurrent activities
- The response time is the time it takes to execute an action in the presence of concurrent activities

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Compositionality

- System of Tiptoe processes:
  - The individual actions of running Tiptoe processes maintain their response times even when adding/removing processes

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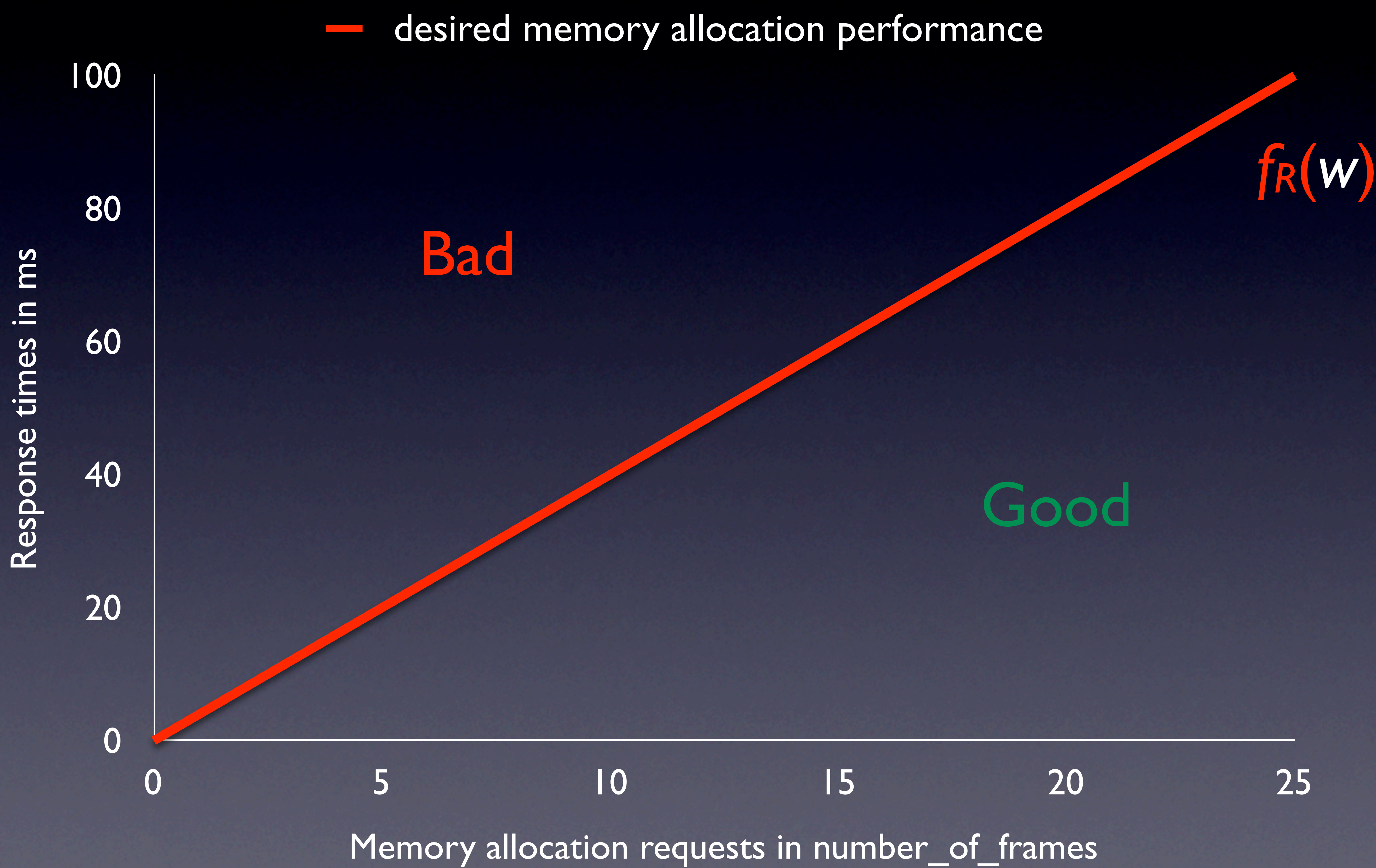
Response-Time Function



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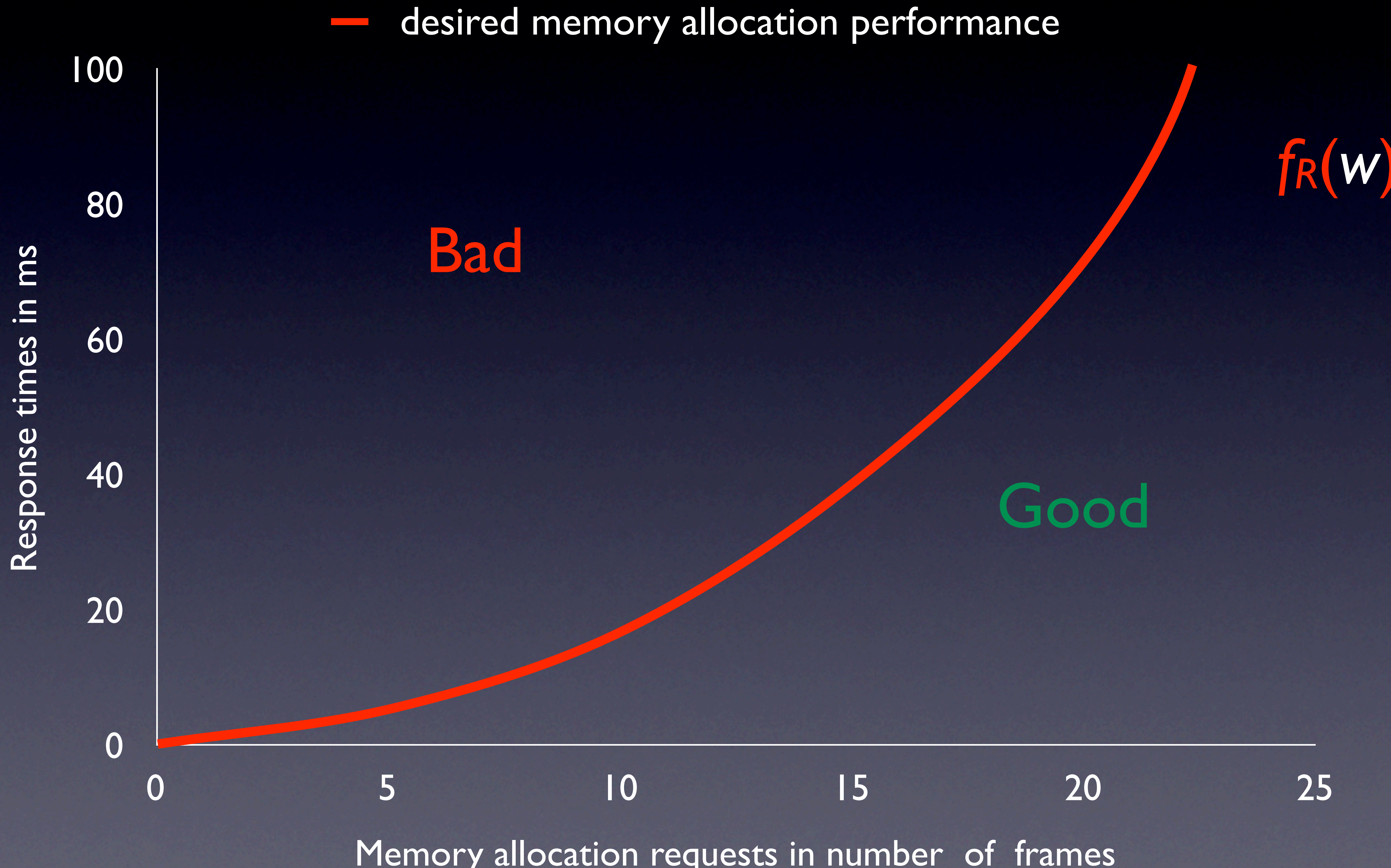
Compositional Response!



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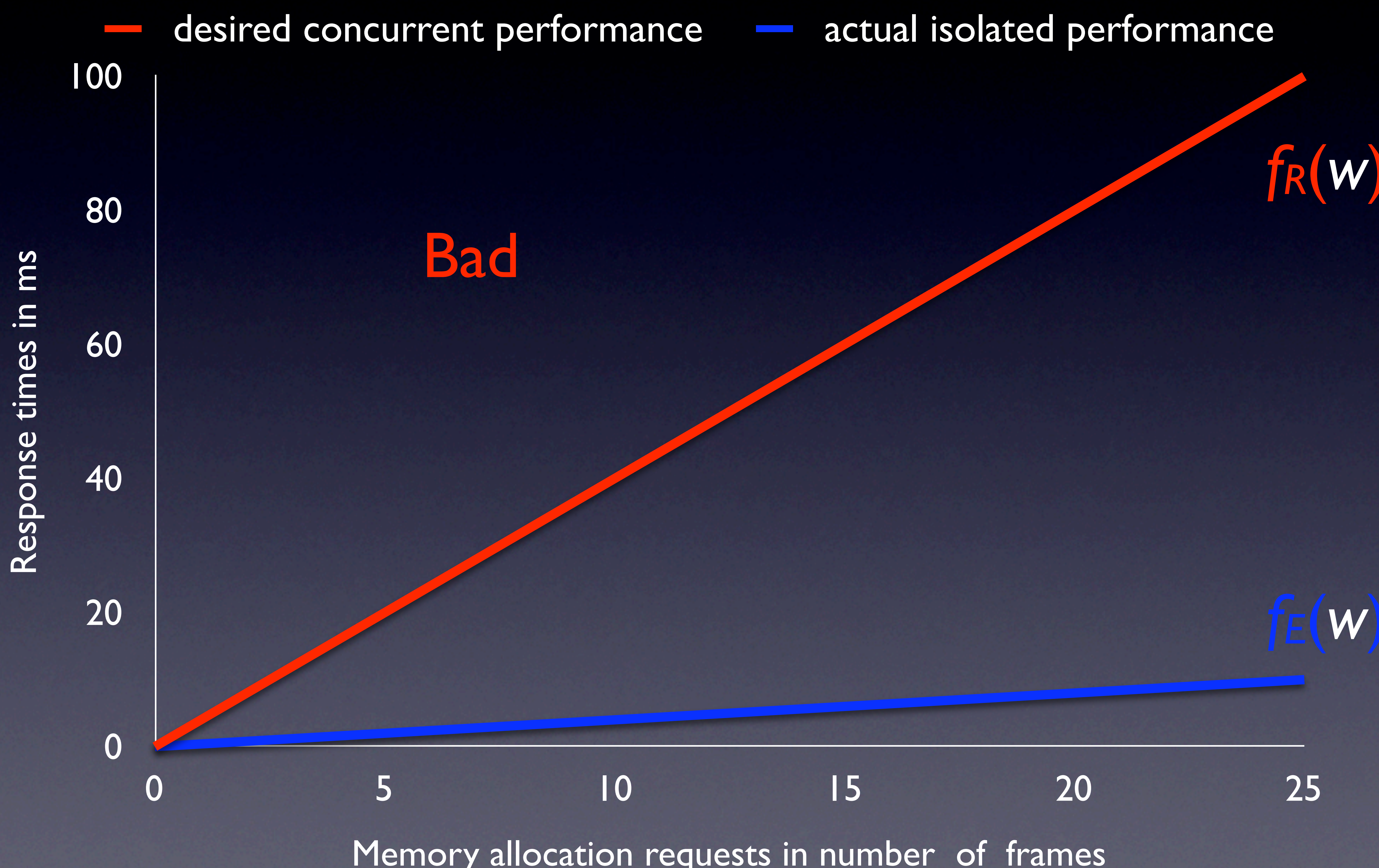
Execution-Time Function



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Utilization Function:

$$f_U(w) = \frac{f_E(w)}{f_R(w)}$$

With

$f_R(w) = 4 * w$ (in ms)
$f_E(w) = 0.4 * w$ (in ms)

we have that

$f_U(w) = 10\%$ (for $w>0$)

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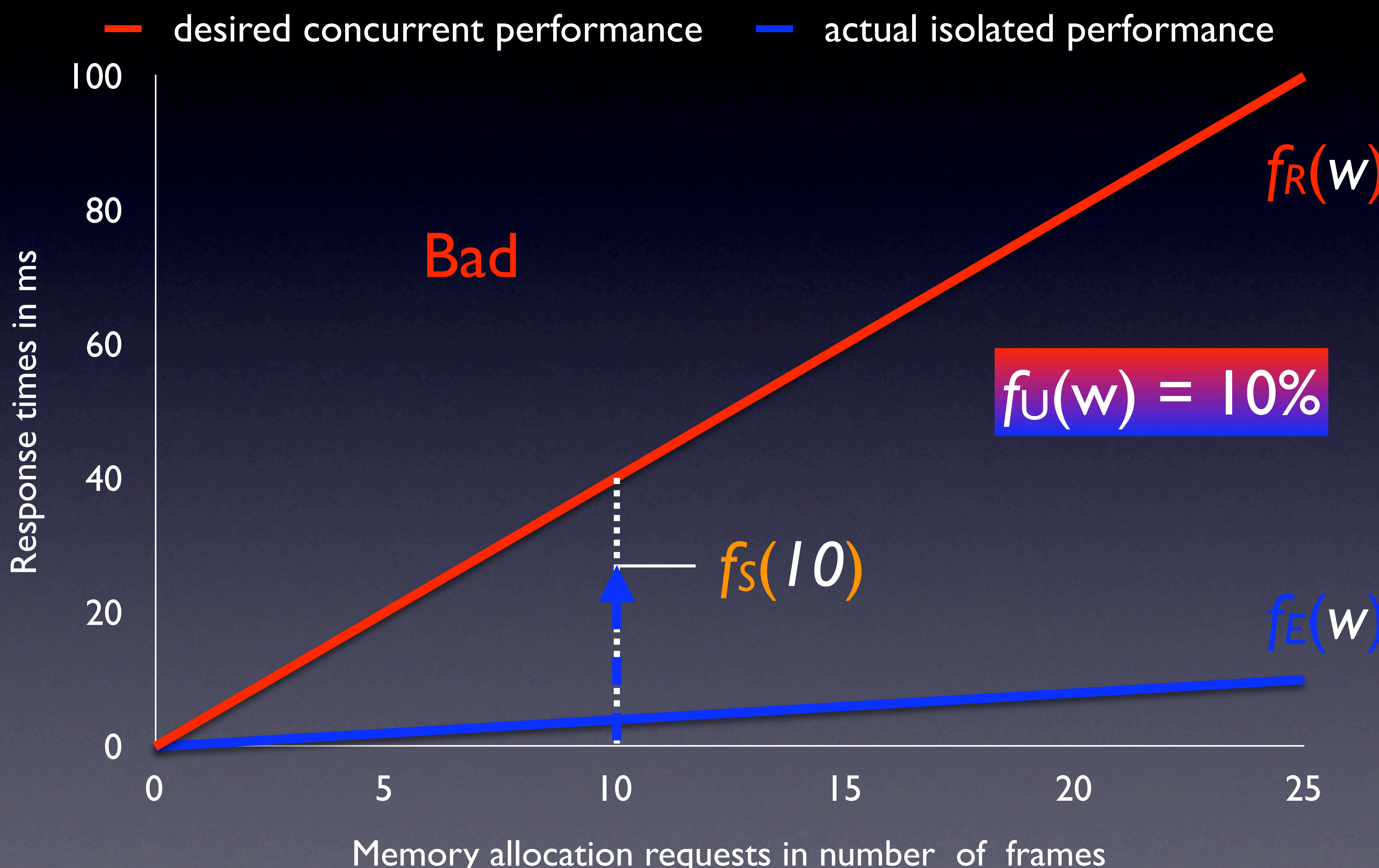
Scheduled Response Time



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Scheduling and Admission

- Process scheduling:
  - How do we efficiently schedule processes on the level of individual process actions?
- Process admission:
  - How do we efficiently test schedulability of newly arriving processes

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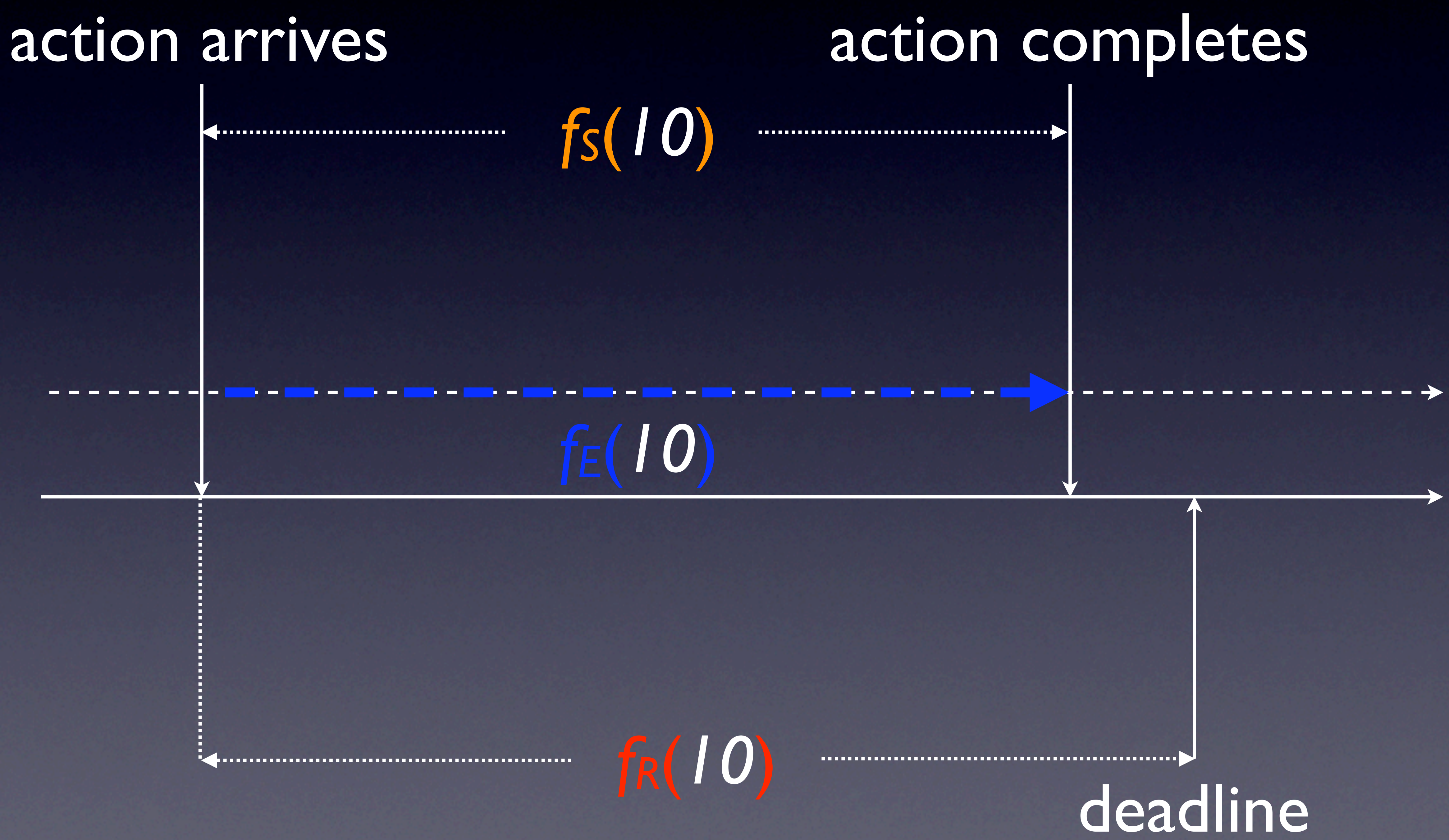
Just use EDF, or not?



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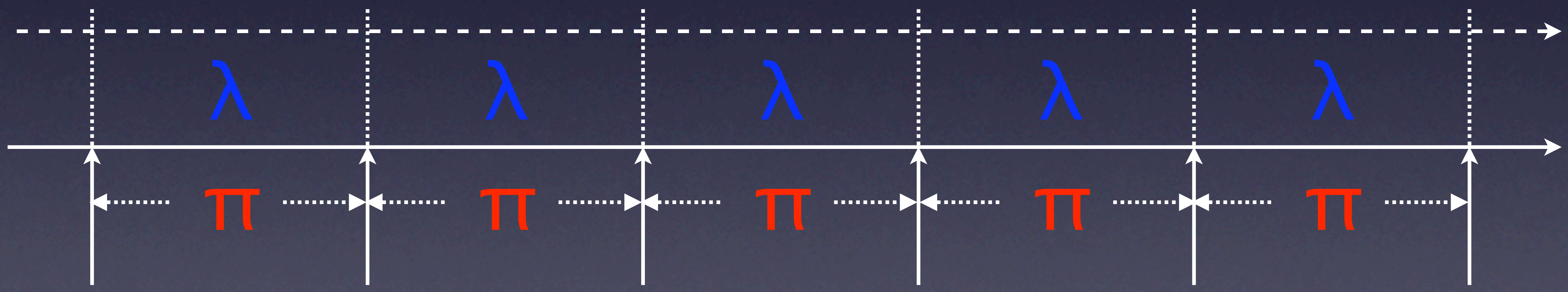
Virtual Periodic Resource

limit: λ

period: π

utilization: λ / π



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Tiptoe Process Model

- Each Tiptoe process declares a finite set of virtual periodic resources
- Each process action of a Tiptoe process uses exactly one virtual periodic resource declared by the process

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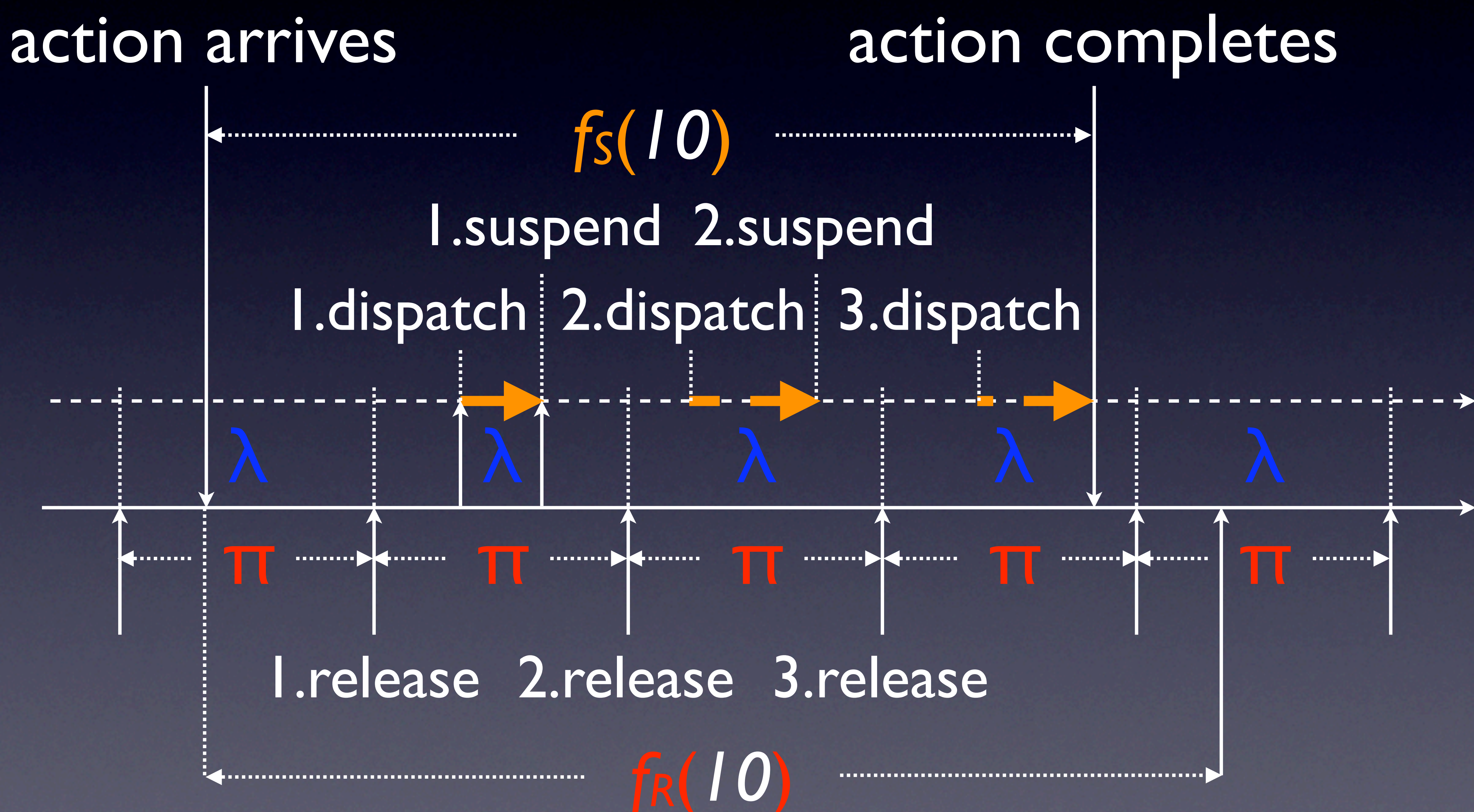
Release, Dispatch, Suspend



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Scheduling Strategies

- release action upon arrival at the beginning of next period (release strategy)
- dispatch released actions in EDF order using periods as deadlines (dispatch strategy)
- suspend running actions until beginning of next period when limit is exhausted (limit strategy)

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$$\forall w \in E_D.\ f_S(w) \leq f_R(w)\ ?$$

$$\forall w \in E_D.$$

$$f_E(w) + (\pi - \lambda) * (\lceil f_E(w) / \lambda \rceil - 1)$$

$$\leq f_S(w) \leq$$

$$(\pi - 1) + \pi * (\lceil f_E(w) / \lambda \rceil - 1) + \pi$$

if

$$\sum_P \max_R(\lambda_{PR} / \pi_{PR}) \leq 1$$

Tiptoe Compositionality

$$\forall fs, fs'. \forall w \in E_D.$$

$$0 \leq | fs(w) - fs'(w) | \leq 2\pi - 2$$

if

$$\sum_P \max_R(\lambda_{PR}/\pi_{PR}) \leq 1$$

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Logical Response Time

worst case (any): $2\pi - 2$
best case (LRT): $\pi - 1$

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With $\lambda / \pi = c_U$, we know that

$\forall w \in U_D.\ f_S(w) \leq f_R(w) + \pi$

if

π divides $f_R(w)$ evenly

and

$\sum_P \max_R(\lambda_{PR}/\pi_{PR}) \leq 1$

$$\forall w \in U_D.\ f_S(w) \leq f_R(w) + \pi$$

Utilization Function:

$$f_U(w) = \frac{f_E(w) - d_E}{f_R(w) - d_R}$$

(if $f_R(w) > d_R$)

For example, with

$f_R(w) = 4 * w + 4$ (in ms)

$f_E(w) = 0.4 * w + 0.2$ (in ms)

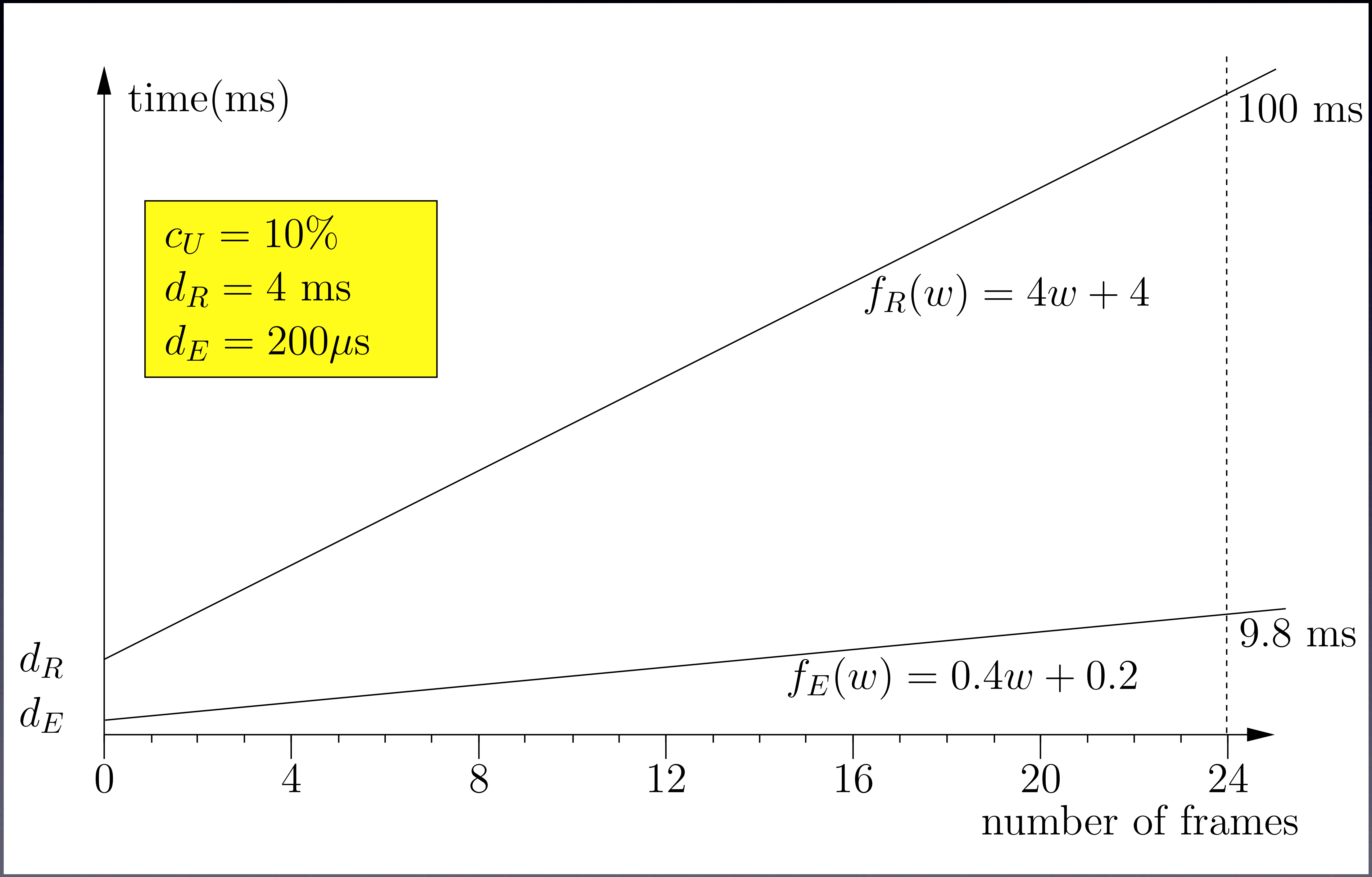
we have again

$f_U(w) = 10\%$ (for $w>0$)

$f_R(1) = 8$ms but only 125fps

$f_R(24) = 100$ms yet 240fps

Intrinisic Delay



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With λ / π = c_U, we know that

$\forall w \in U_D.\ f_S(w) \leq f_R(w)$

if

$0 < \pi \leq d_R - d_E / c_U$, and

π divides d_R and $f_R(w) - d_R$ evenly,

and $\sum_P \max_R(\lambda_{PR}/\pi_{PR}) \leq 1$

Scheduling Algorithm

- maintains a queue of ready processes ordered by deadline and a queue of blocked processes ordered by release times
- ordered-insert processes into queues
- select-first processes in queues
- release processes by moving and sorting them from one queue to another queue

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Time and Space

	list	array	matrix
ordered-insert	$O(n)$	$\Theta(\log(t))$	$\Theta(\log(t))$
select-first	$\Theta(1)$	$O(\log(t))$	$O(\log(t))$
release	$O(n^2)$	$O(\log(t) + n \cdot \log(t))$	$\Theta(t)$

	list	array	matrix
time	$O(n^2)$	$O(\log(t) + n \cdot \log(t))$	$\Theta(t)$
space	$\Theta(n)$	$\Theta(t + n)$	$\Theta(t^2 + n)$

n: number of processes t: number of time instants

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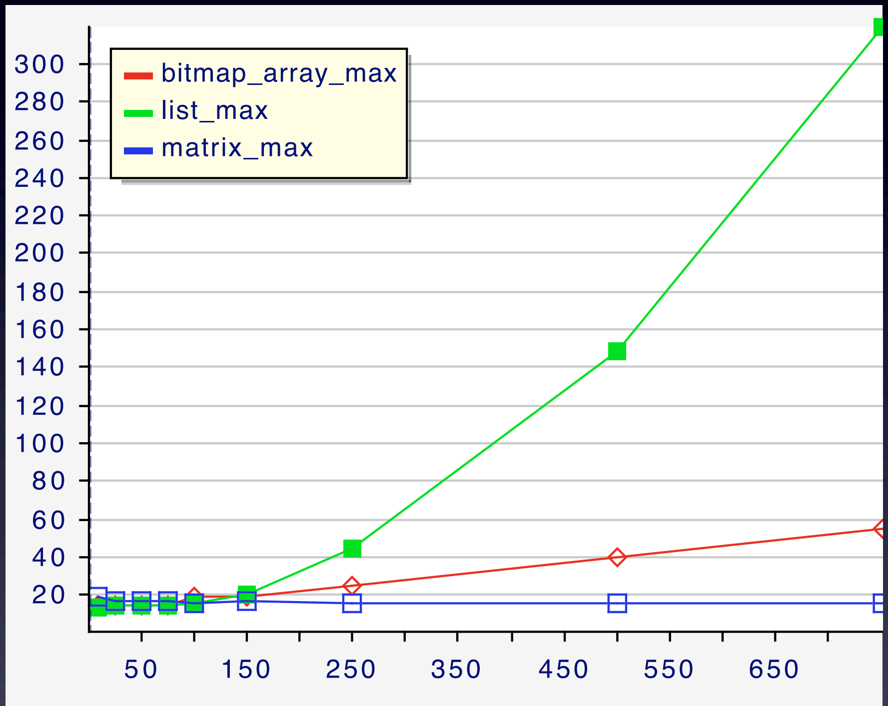
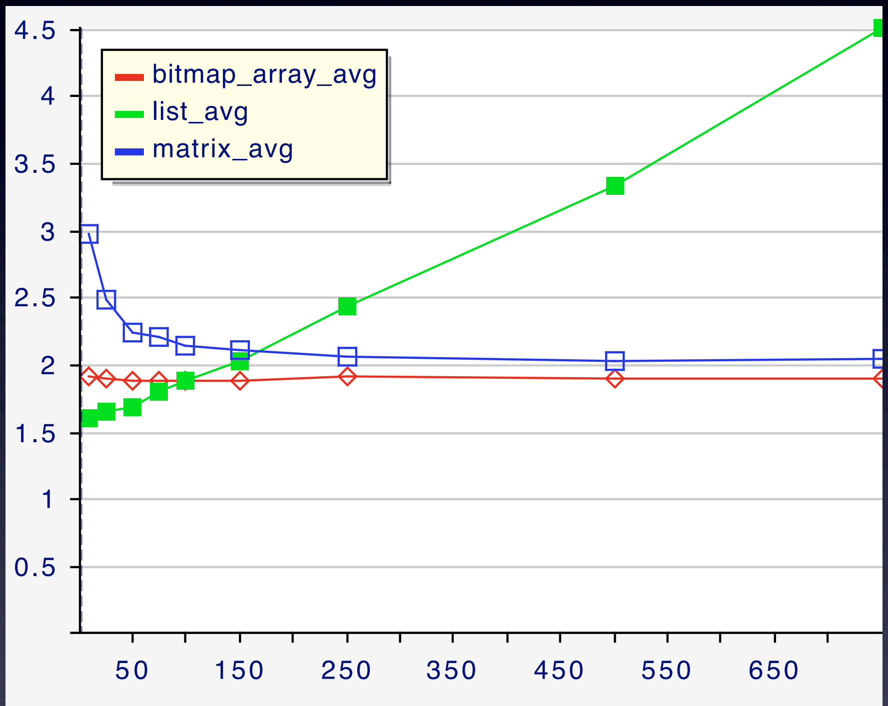
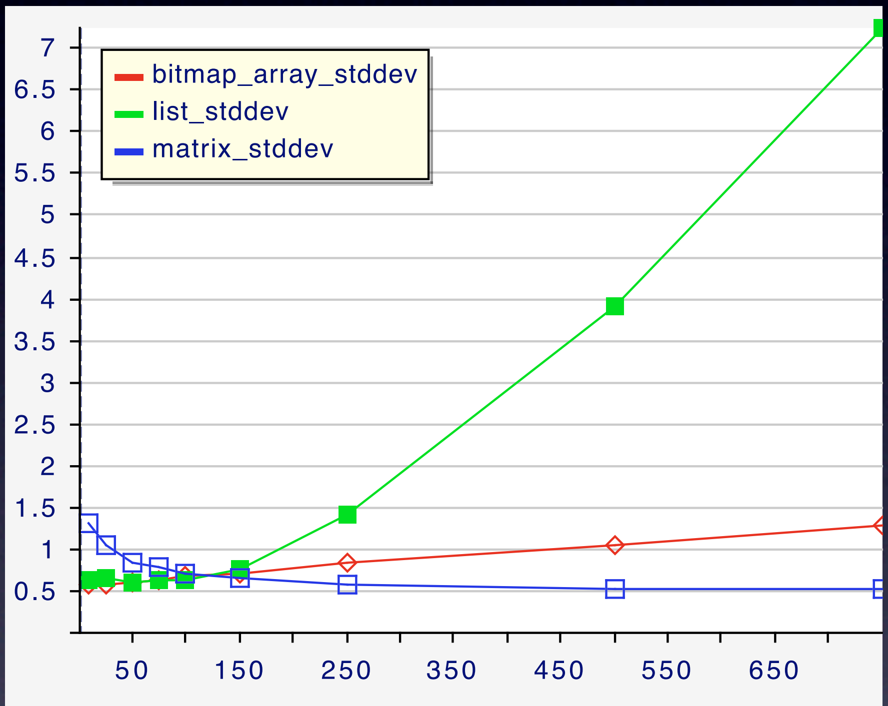
Scheduler Overhead



Max



Average



Jitter

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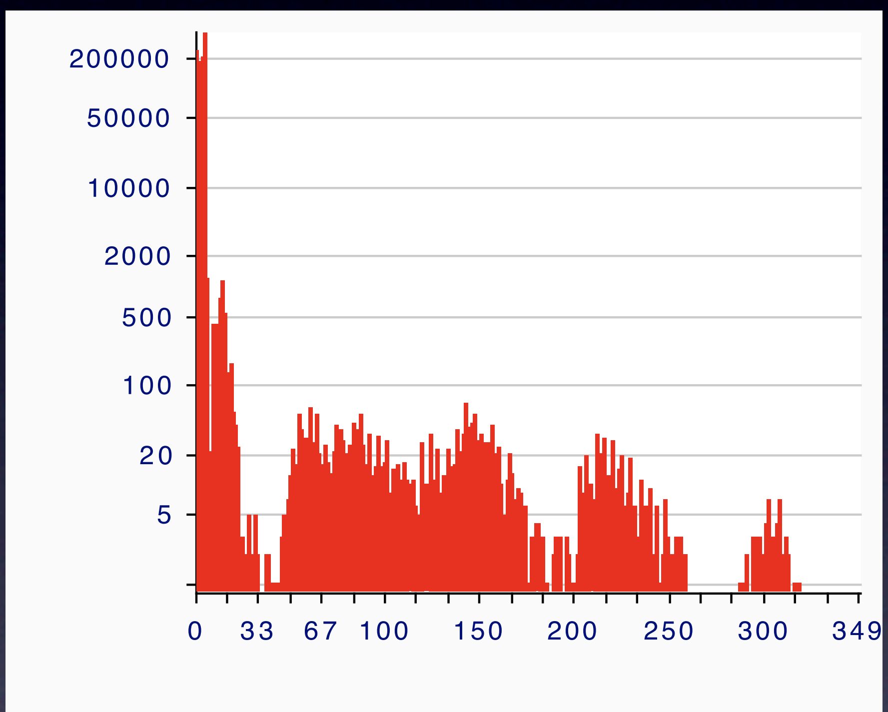
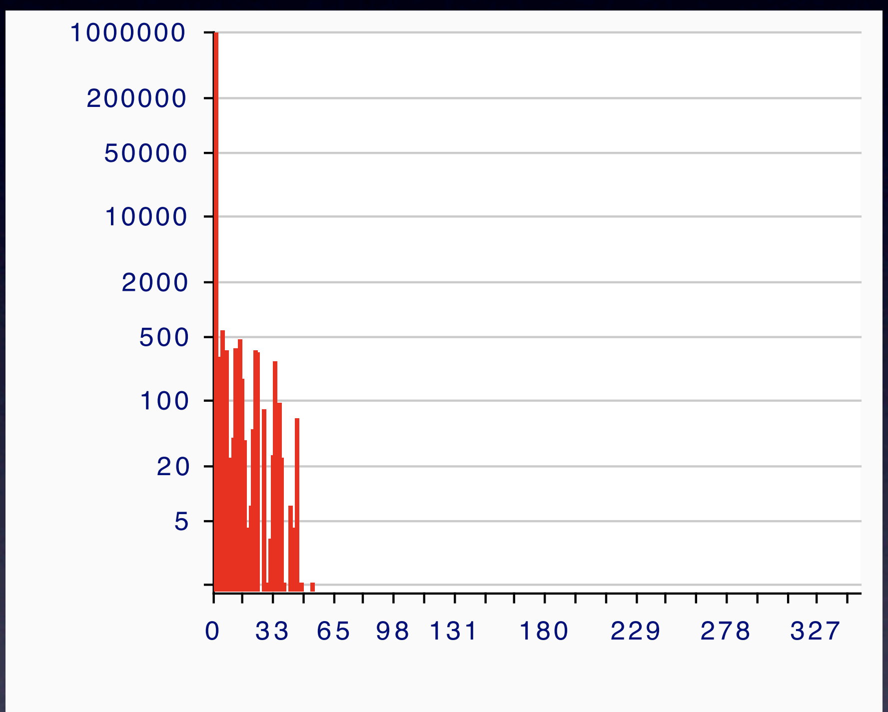
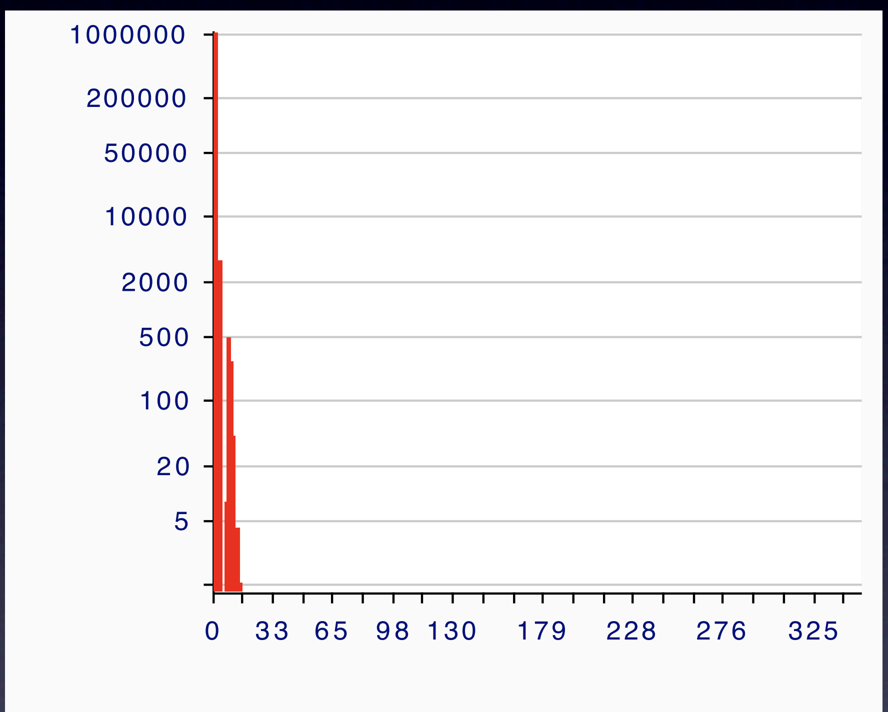
Execution Time Histograms



List



Array



Matrix

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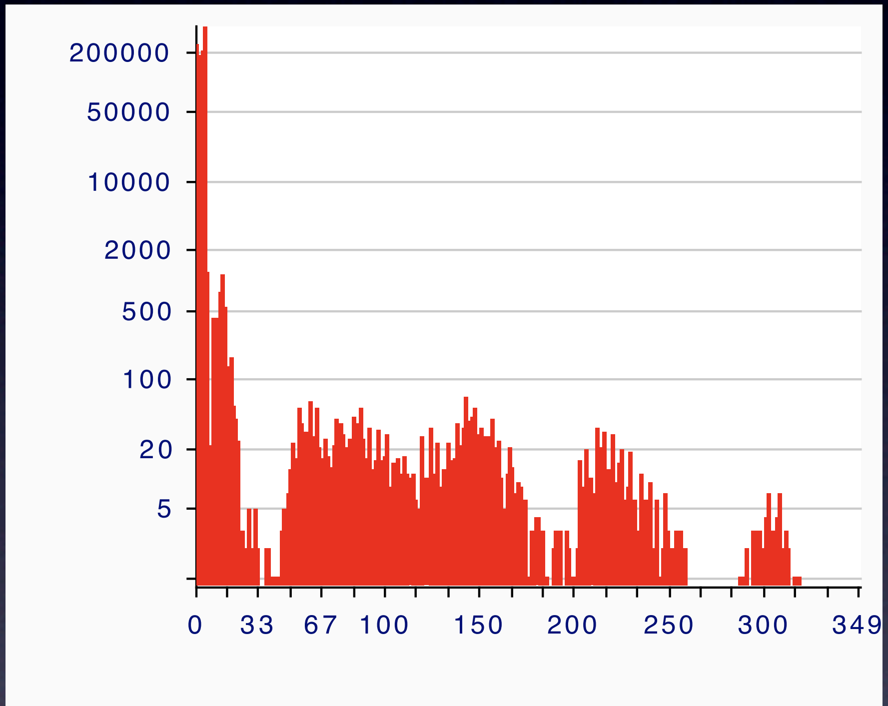
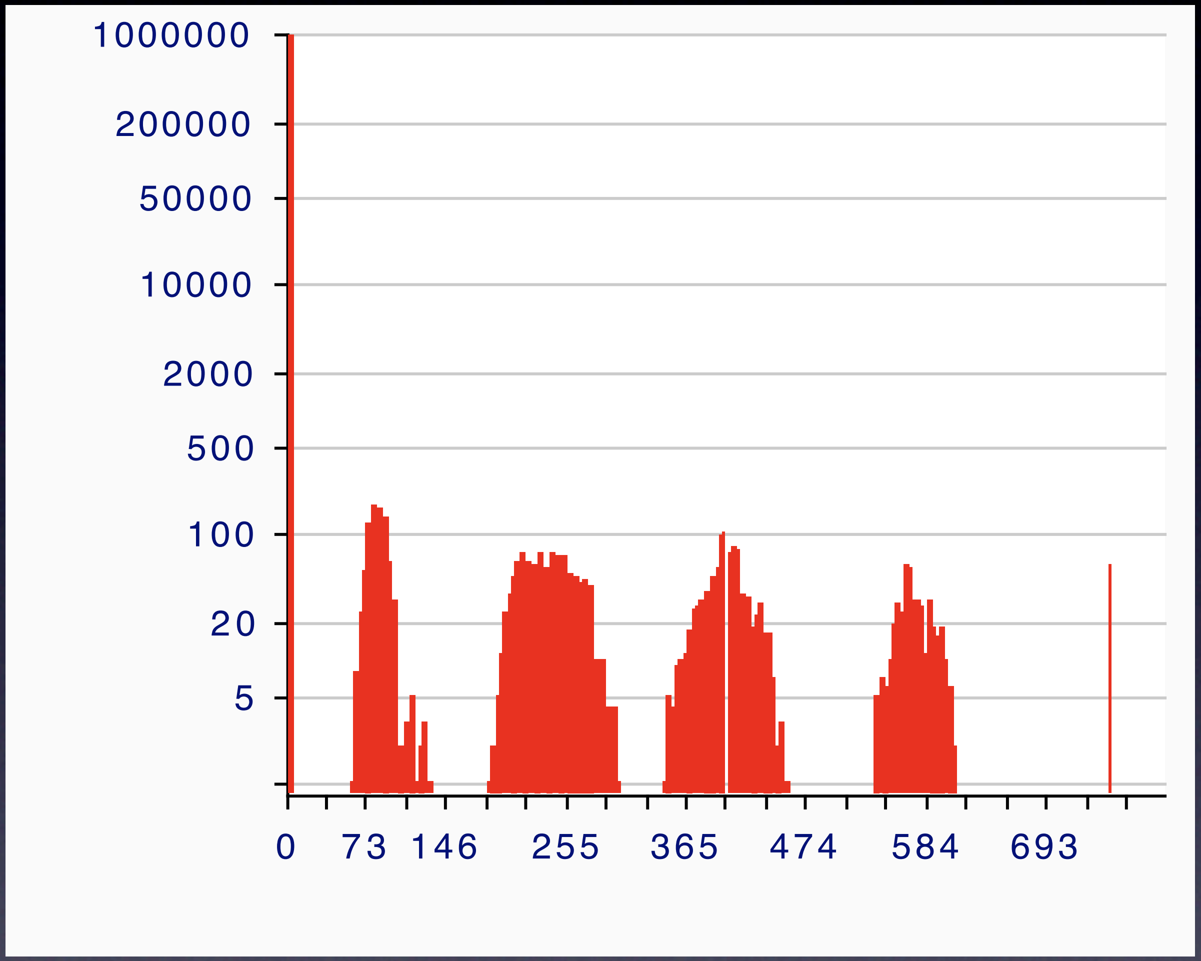
Process Release Dominates



List



Releases per Instant

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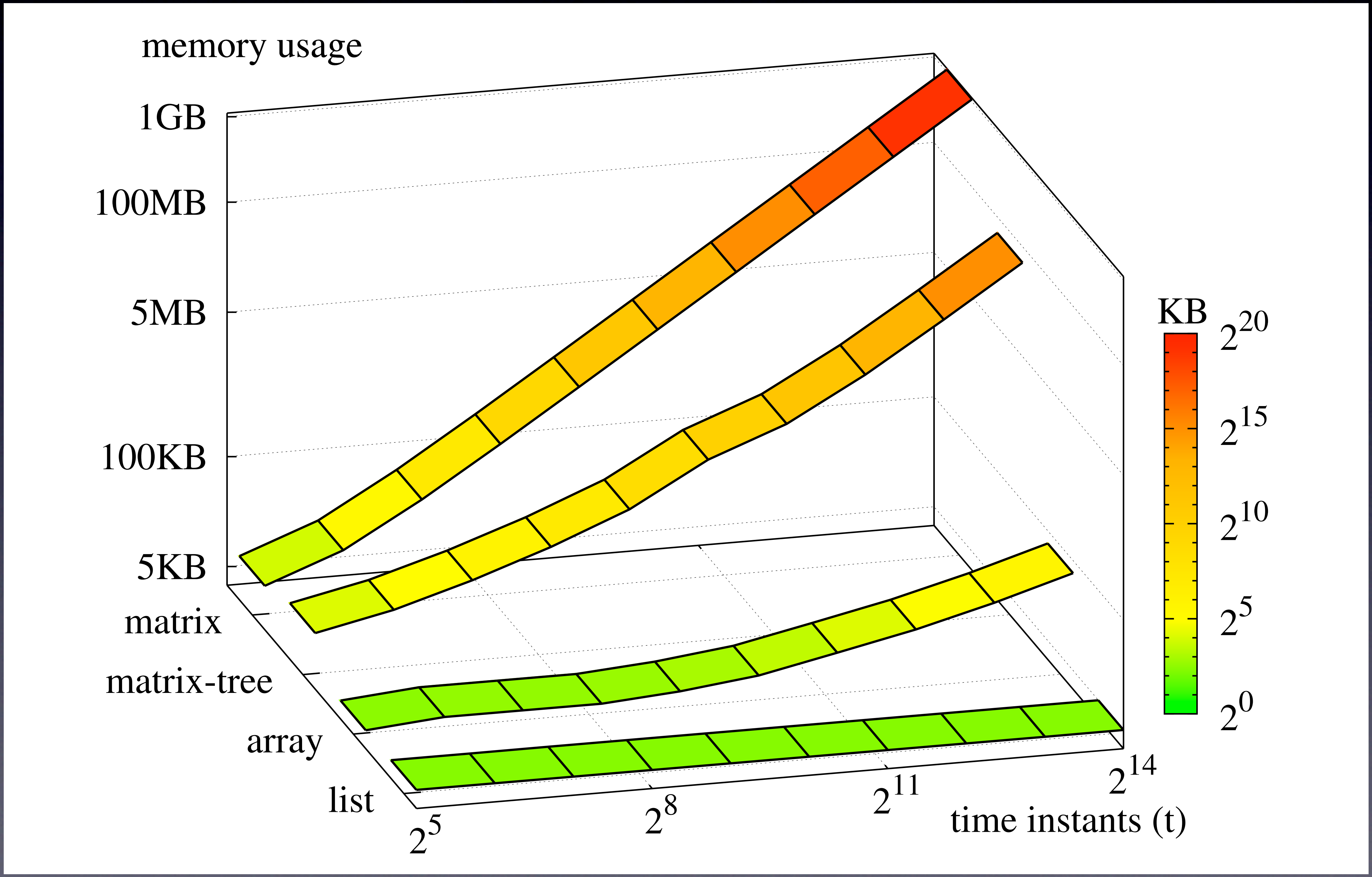
Memory Overhead



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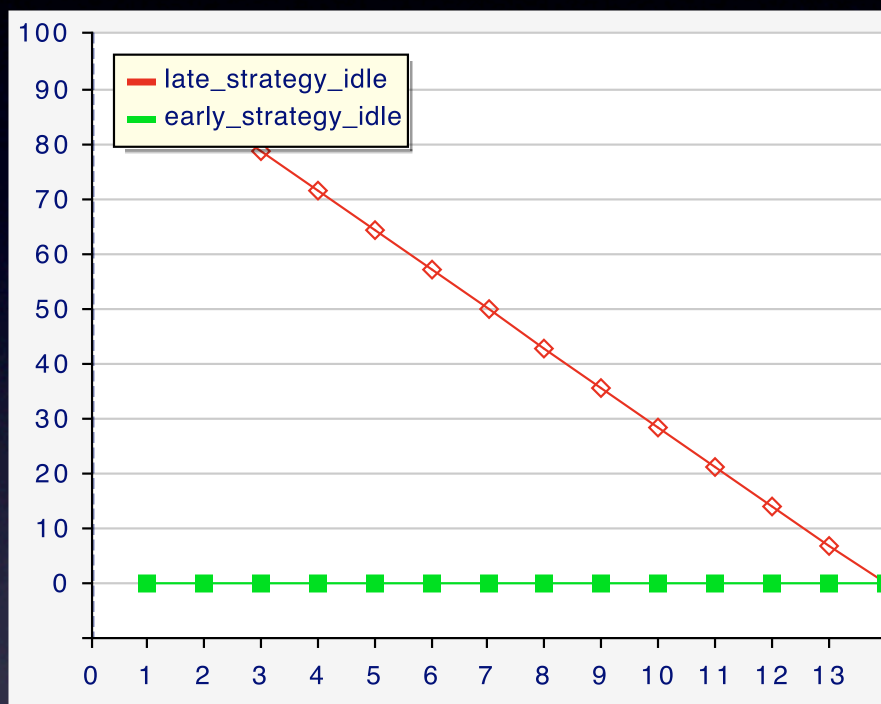
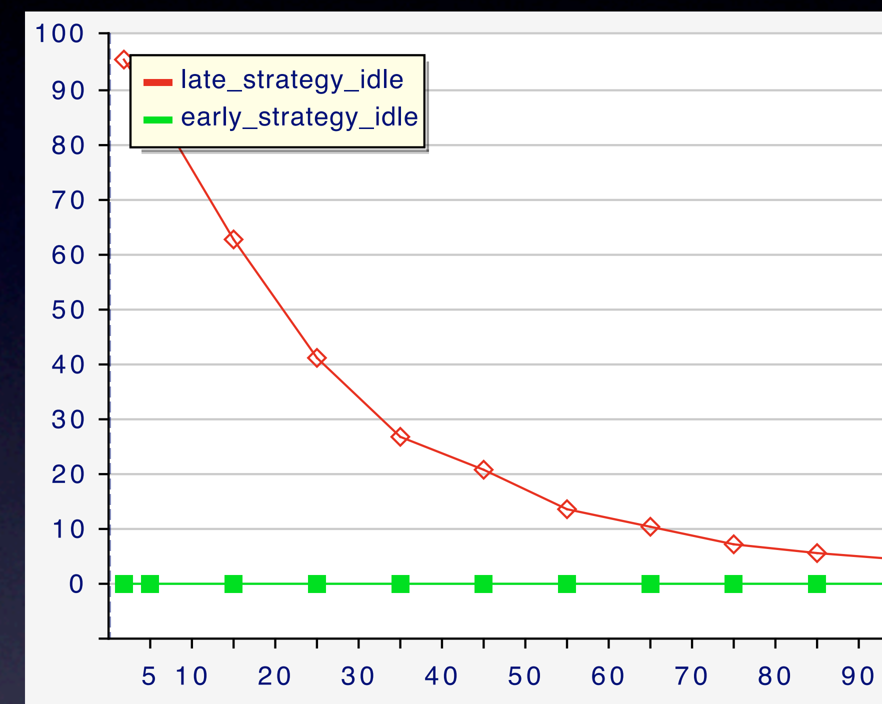
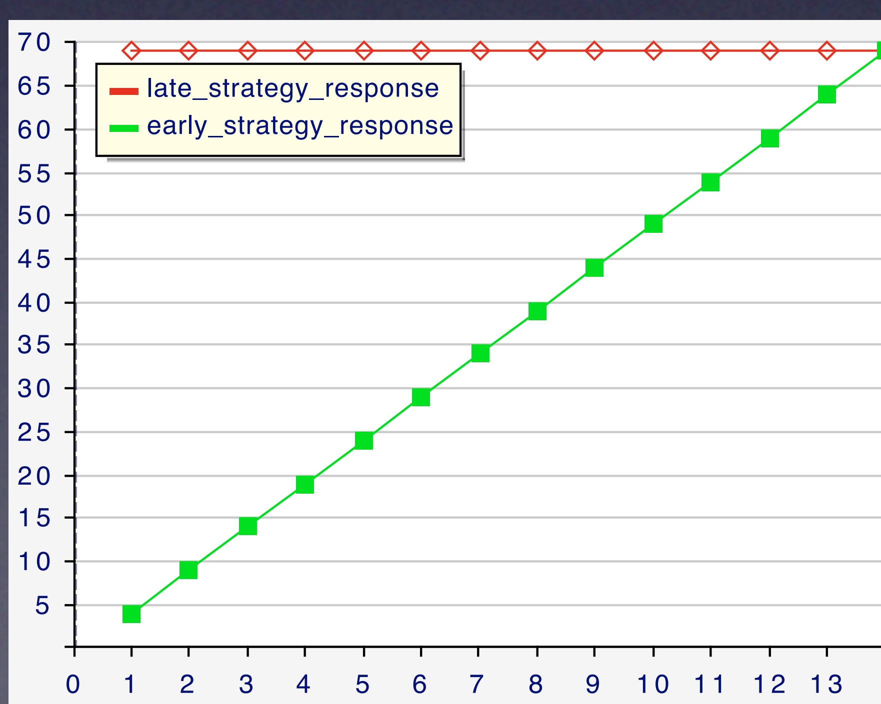
Release Strategies



Idle Time





Response Time

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Current/Future Work

- Concurrent memory management
- I/O subsystem
- Java bytecode VM

Thank you