Robust Real-Time Multiprocessor Interrupt Handling Motivated by GPUs

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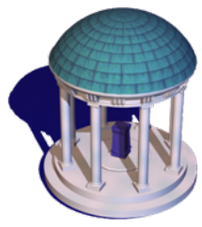

The University *of* North Carolina *at* Chapel Hill

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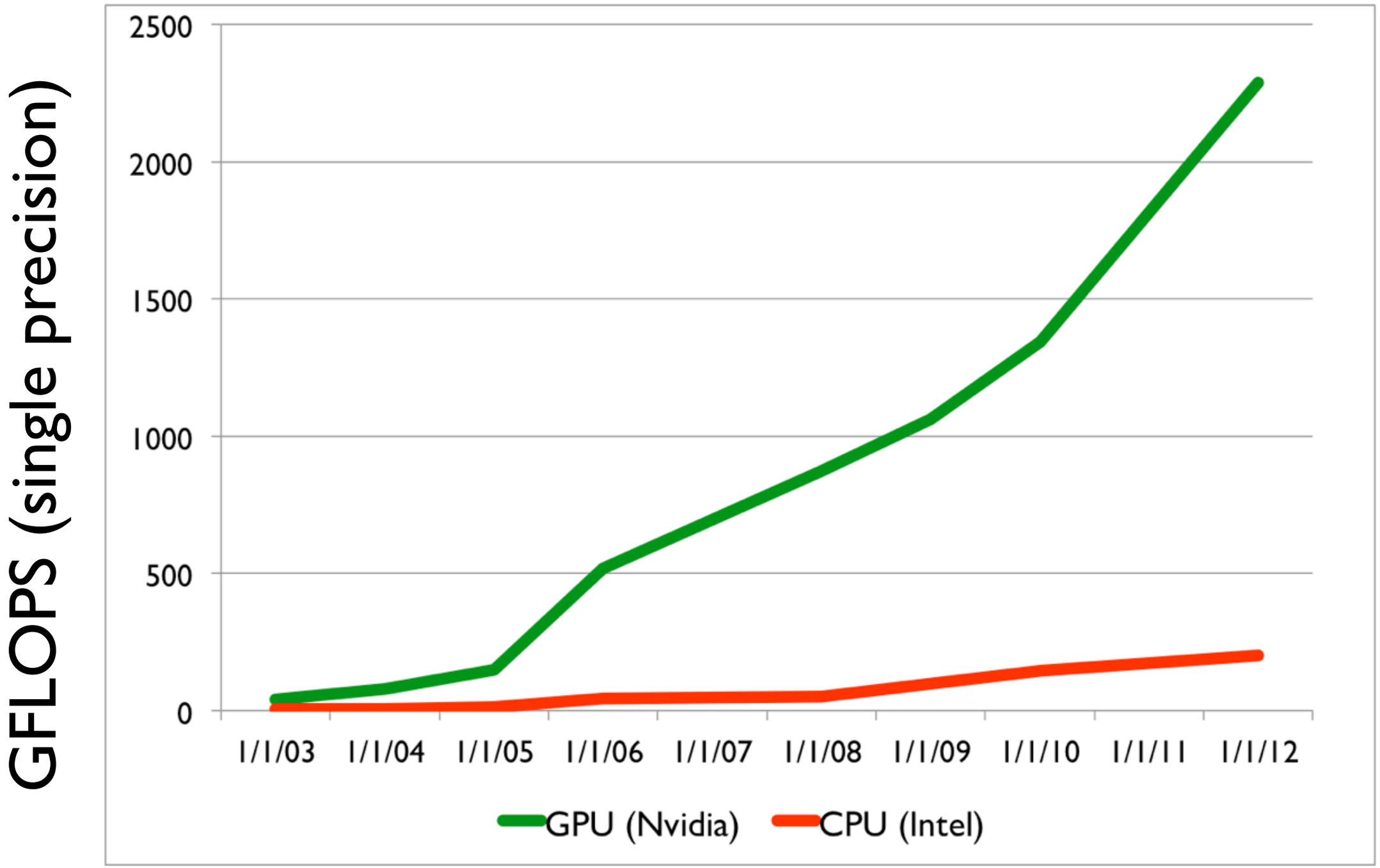
- **Why use GPUs in real-time systems?**

Primary Motivation: Performance



Domains for GPUs

- GPUs excel at data parallel problems
  - Digital signal processing
  - Matrix-like computations
  - Sorting and searching

Future Automotive Applications

- Vehicle and pedestrian detection
- Object tracking
- Fusion of video, laser, and radar sensor data
- **Clear real-time implications!**

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  - Linux-based operating system

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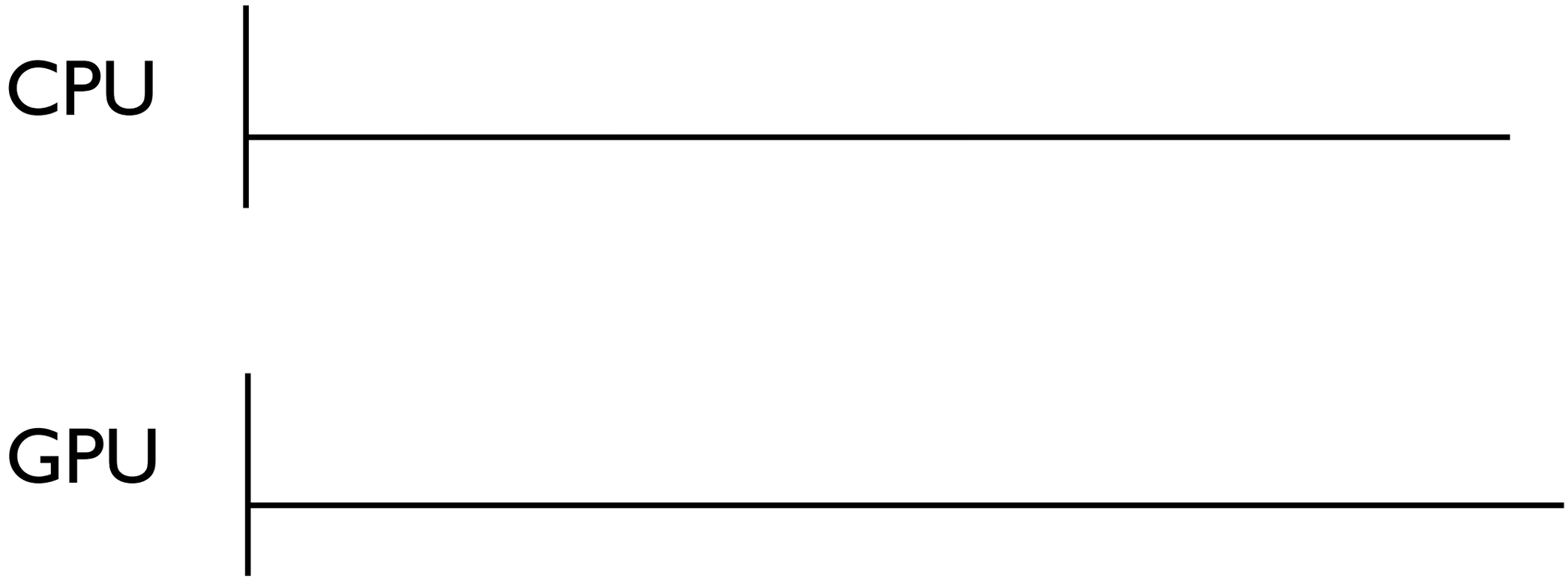
3. Interrupt-driven communication

Synchronous GPU Usage Pattern



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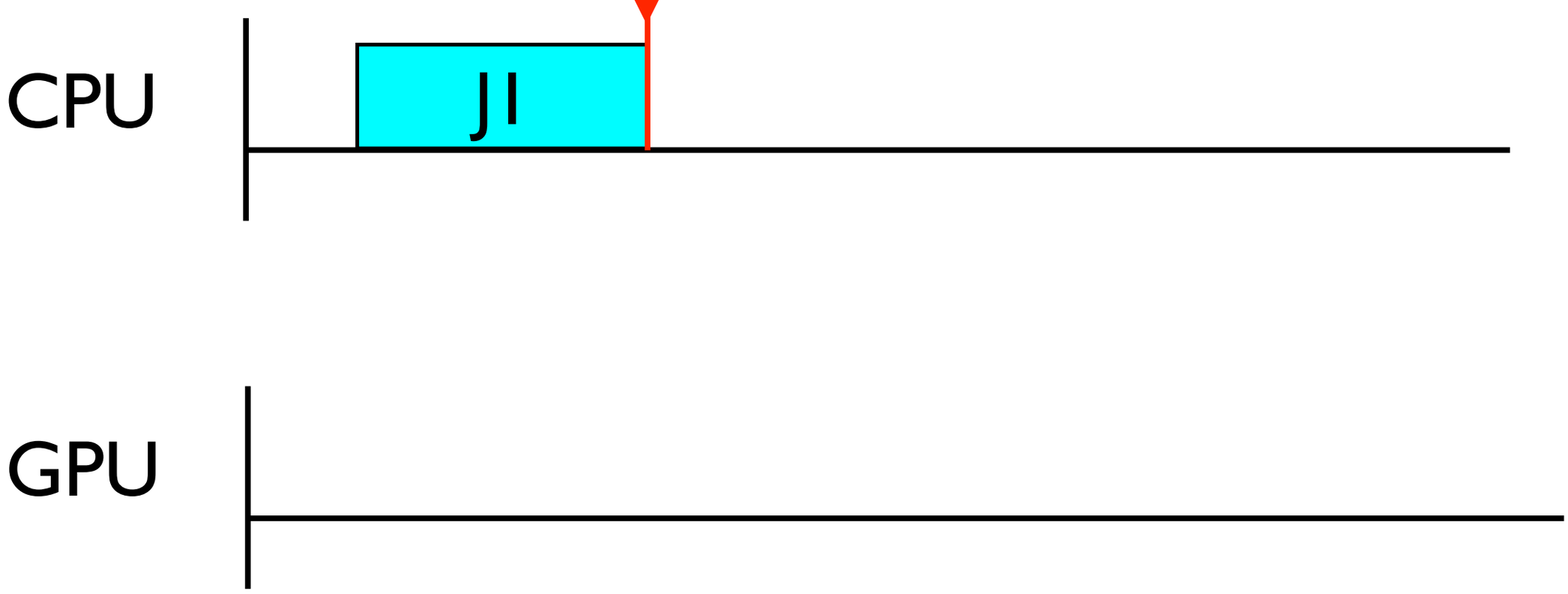

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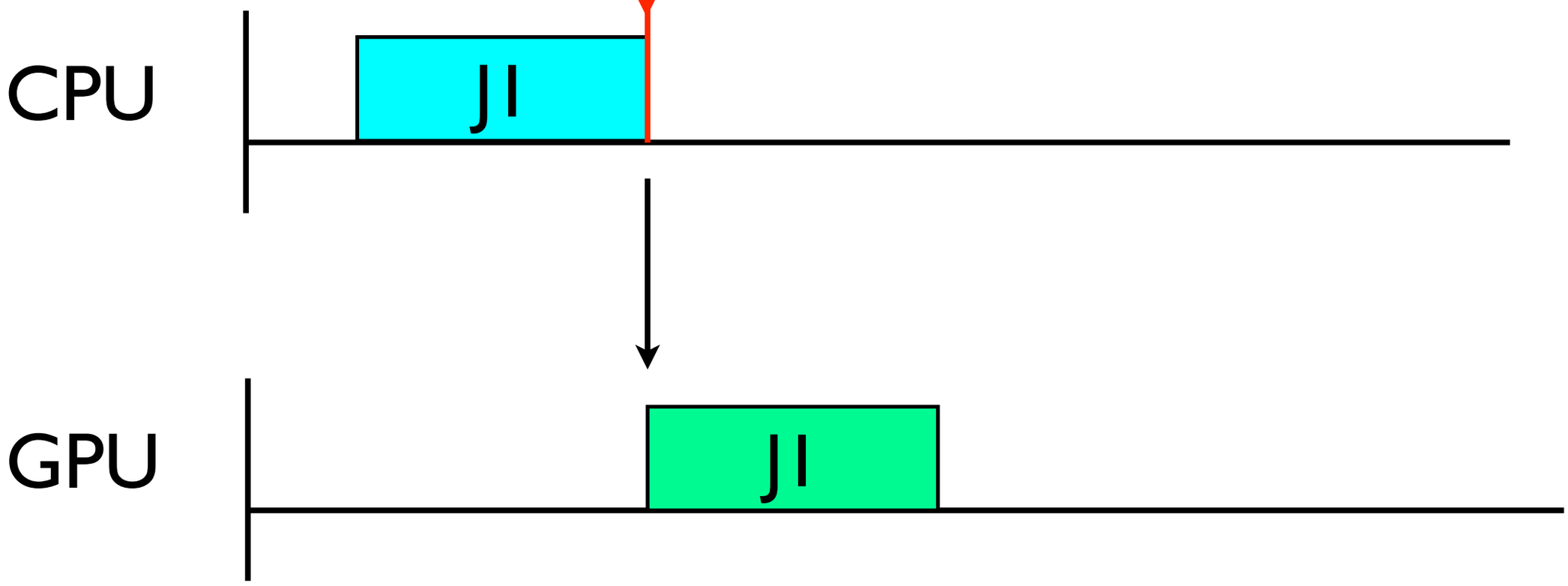

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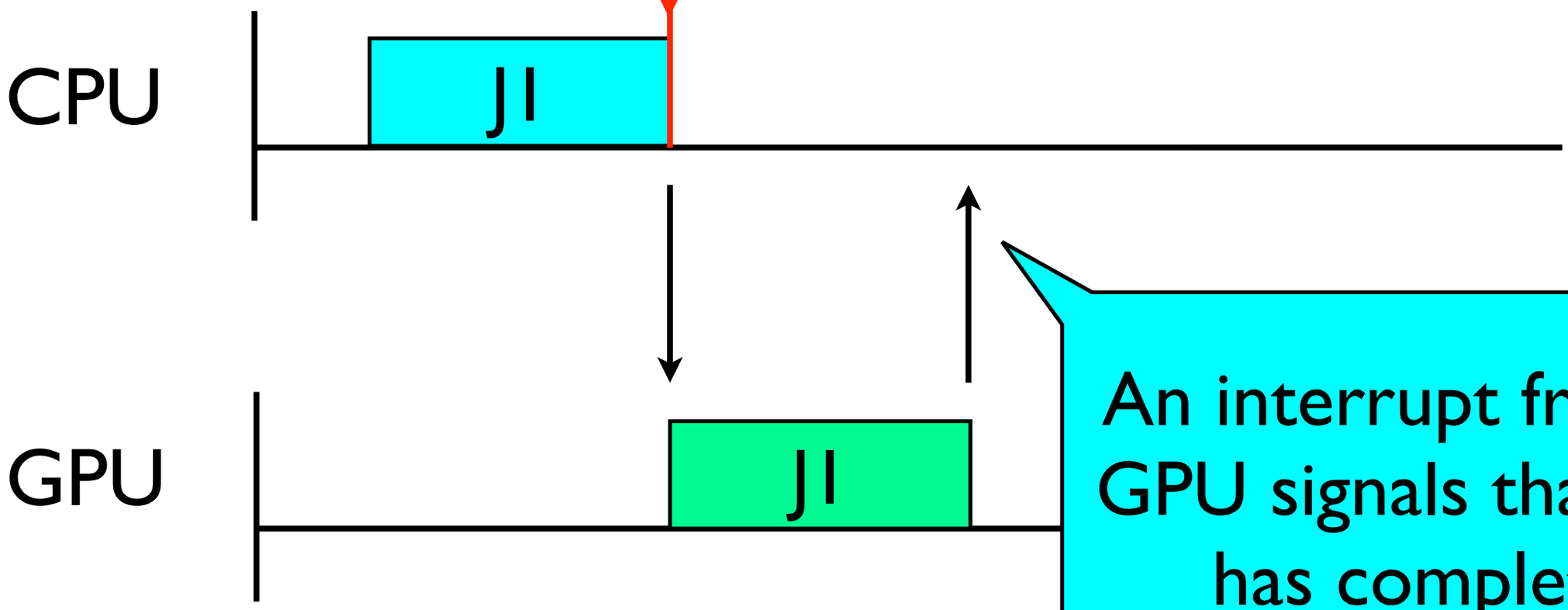

An interrupt from the GPU signals that work has completed. (Handler not depicted.)

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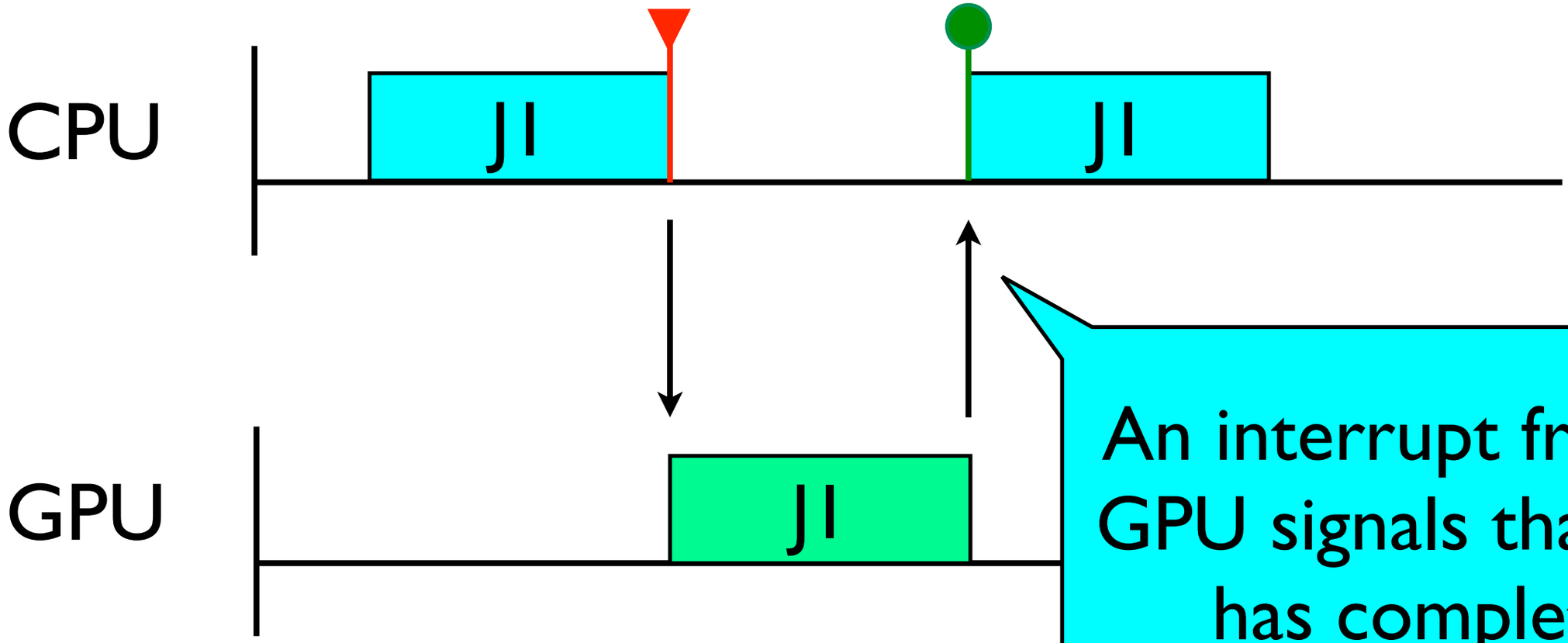

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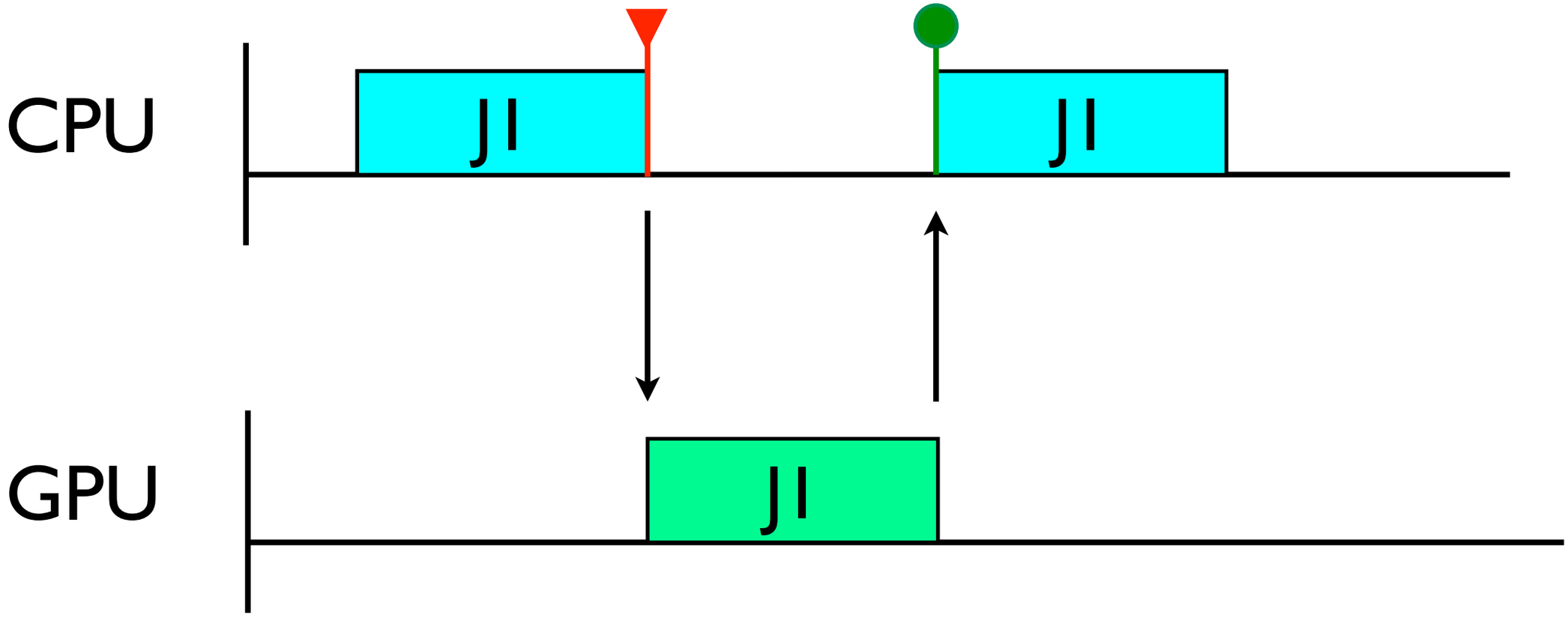
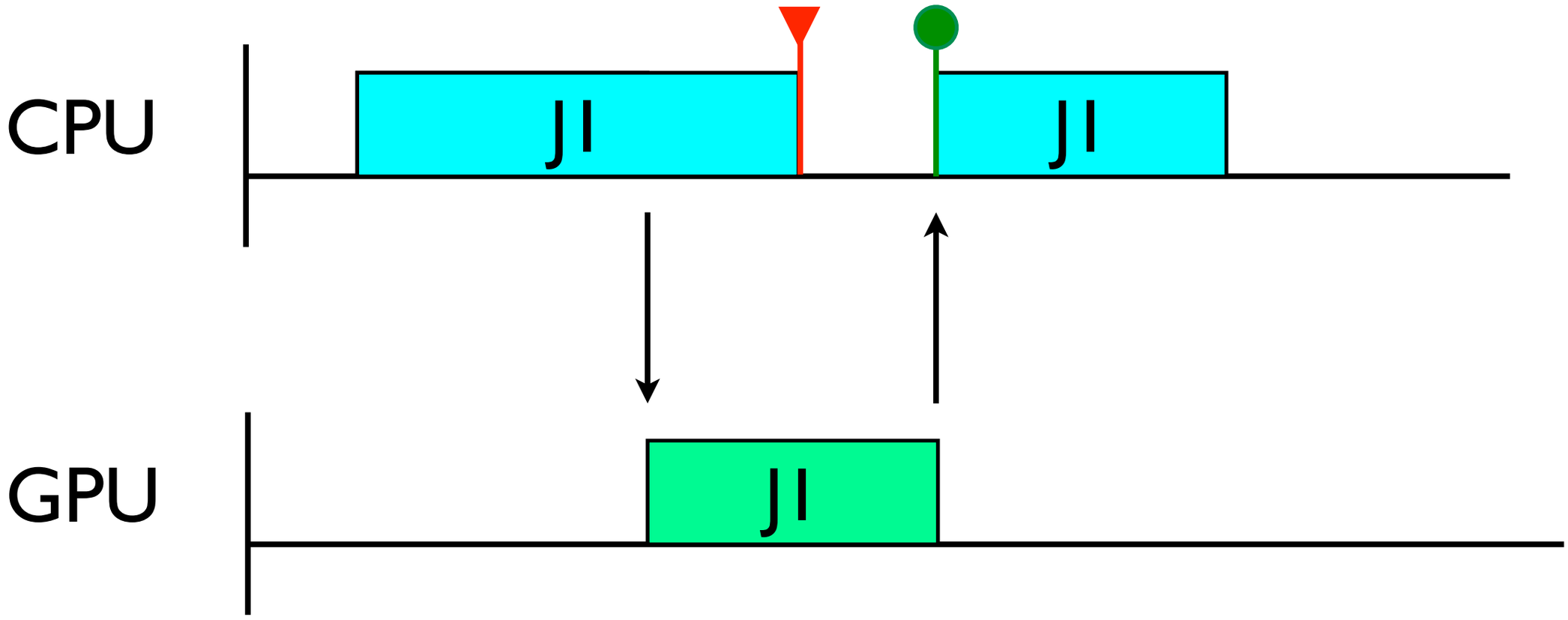


Asynchronous GPU Usage Pattern

J1 may continue executing before blocking...



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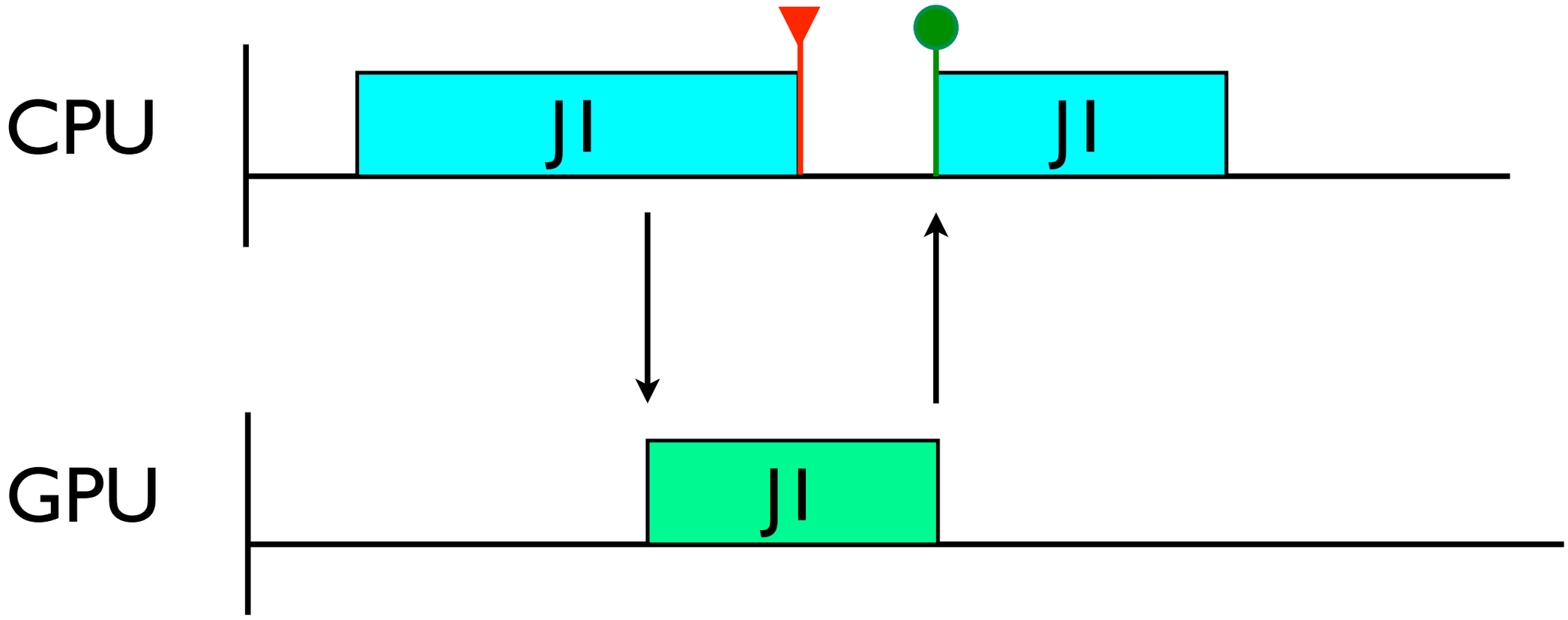

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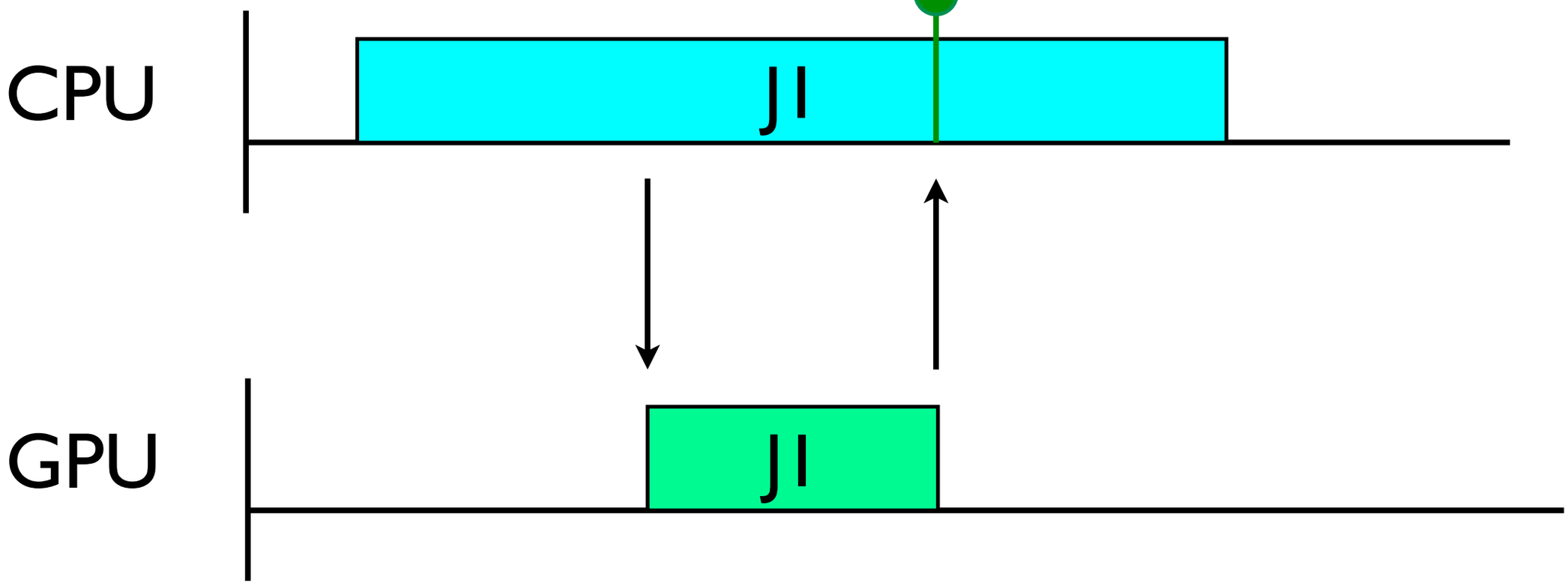
...or may never block if GPU finishes before J1 needs results.



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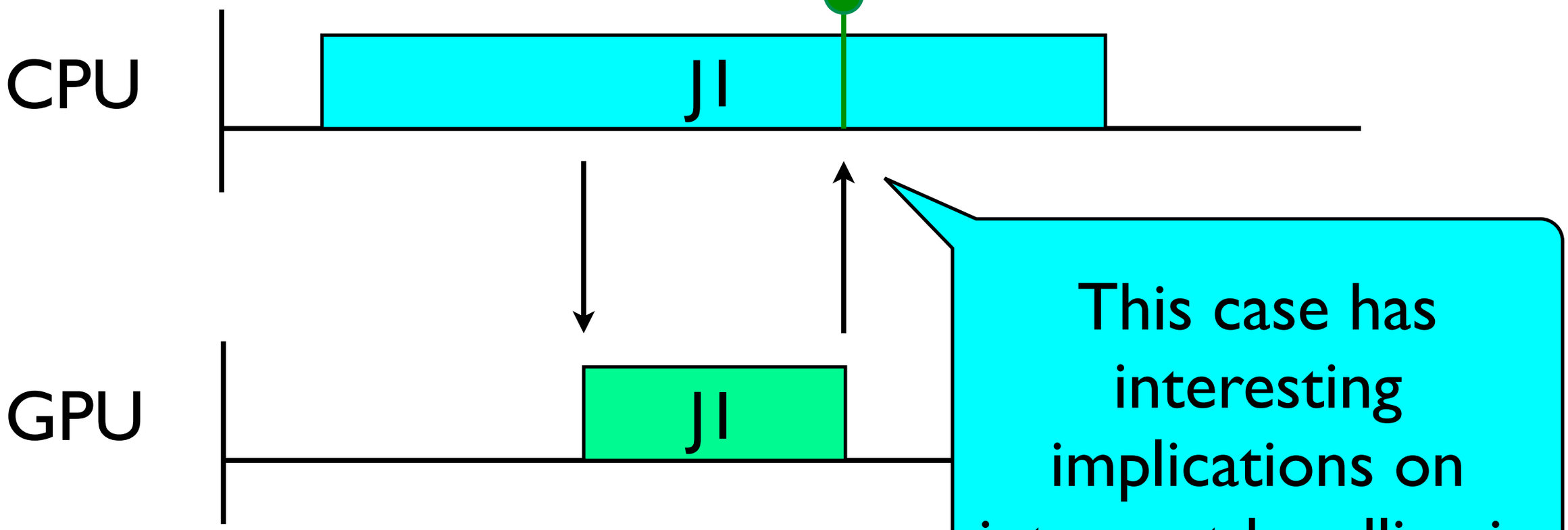

This case has interesting implications on interrupt handling in global schedulers.

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  - **Bottom Half**: performs computations

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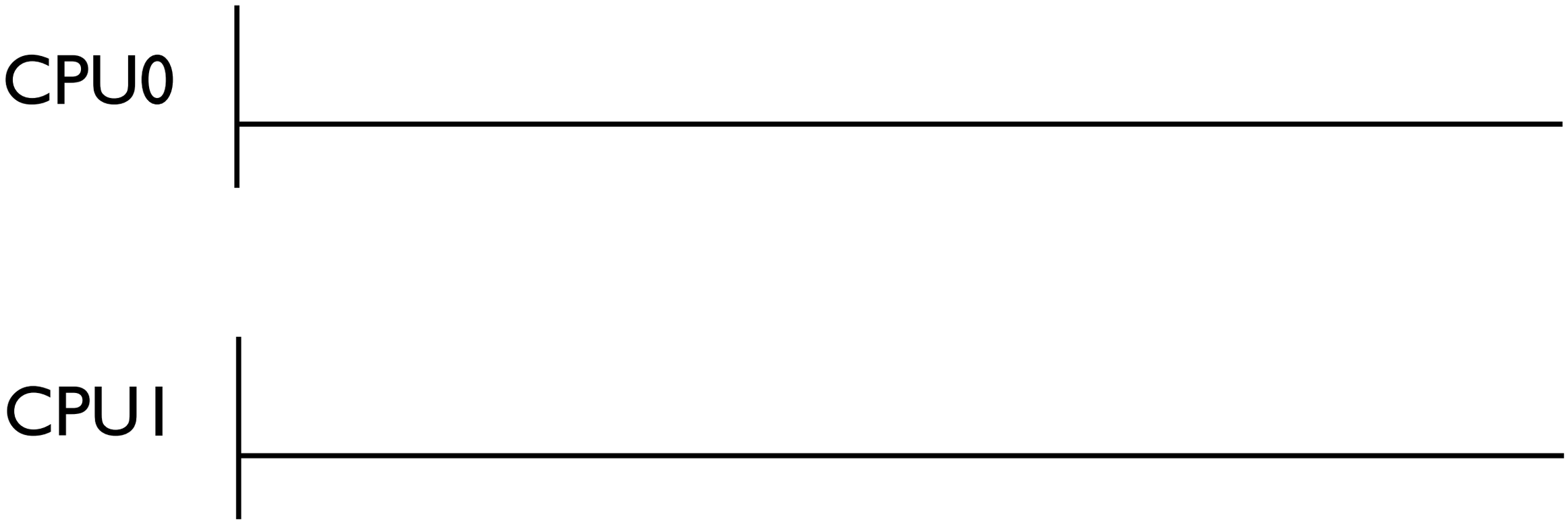

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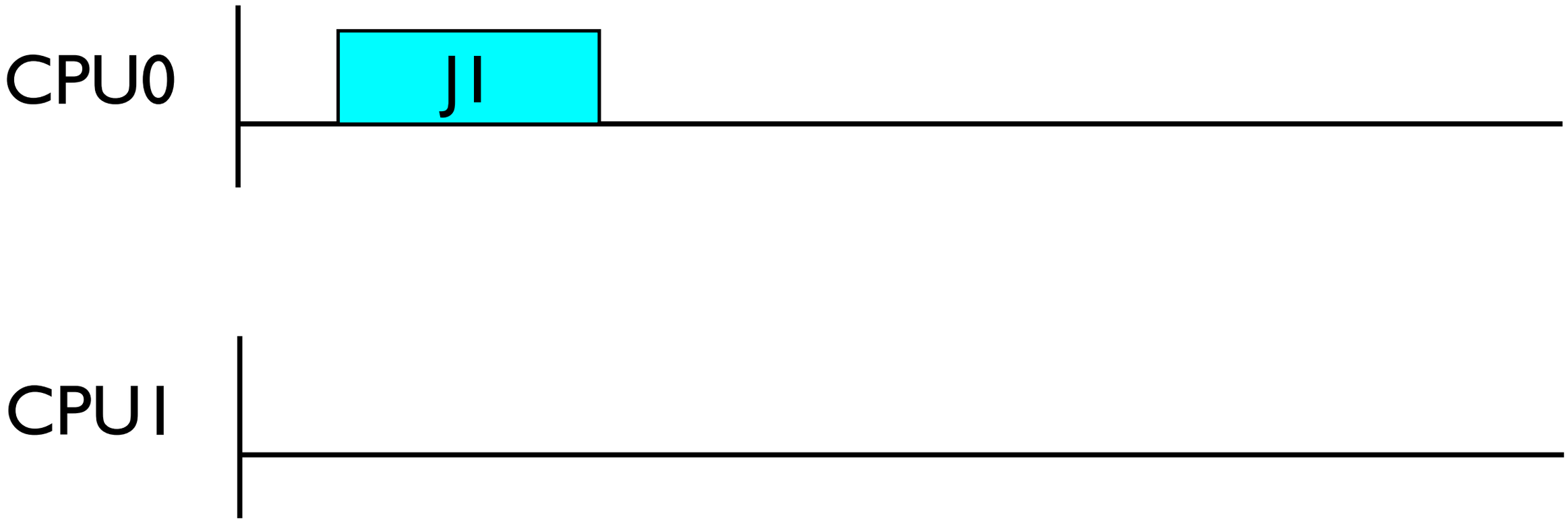

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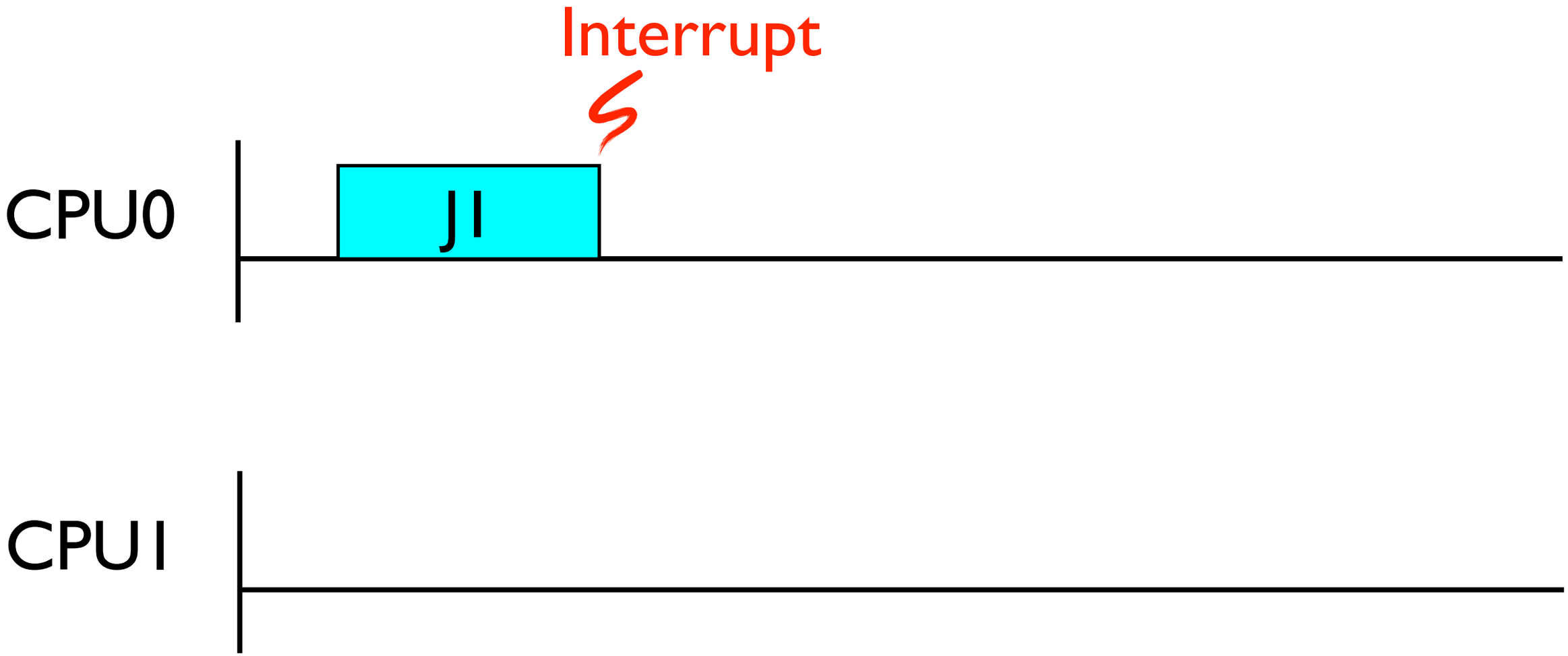

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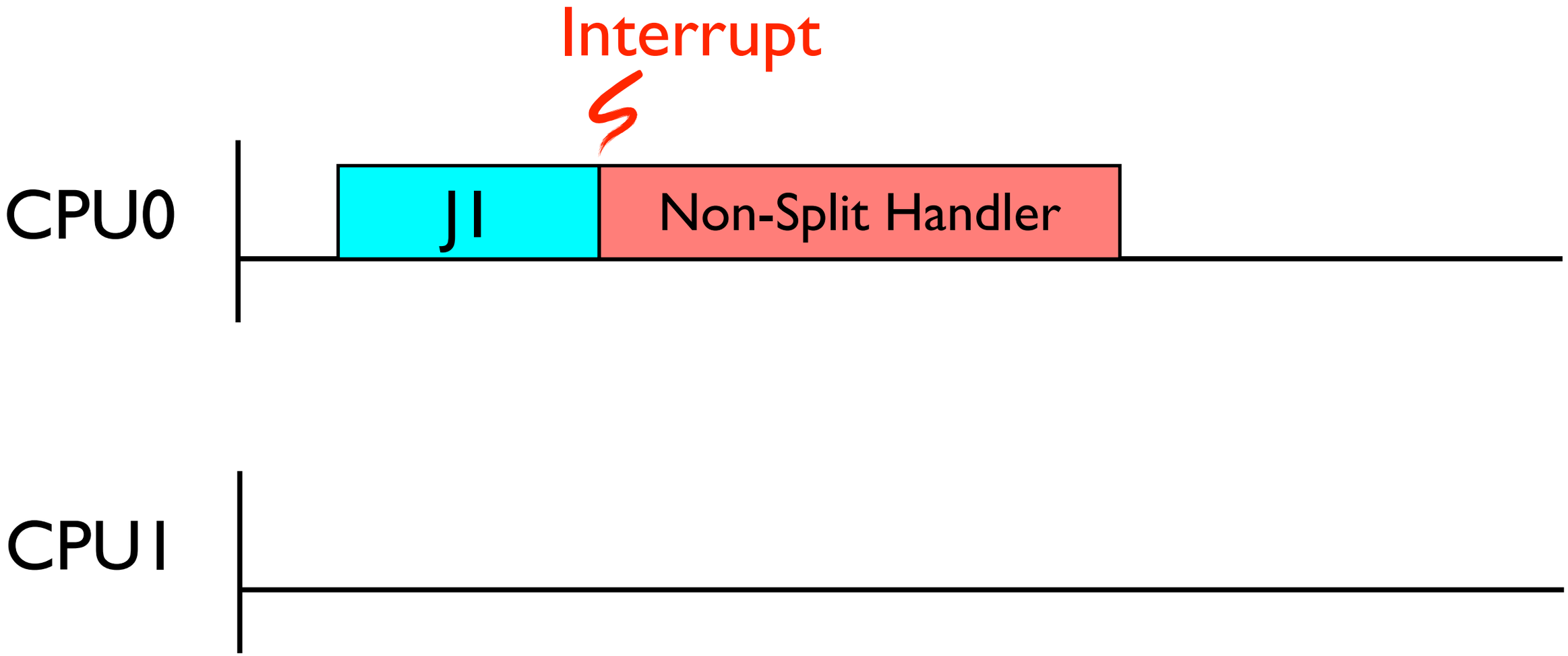

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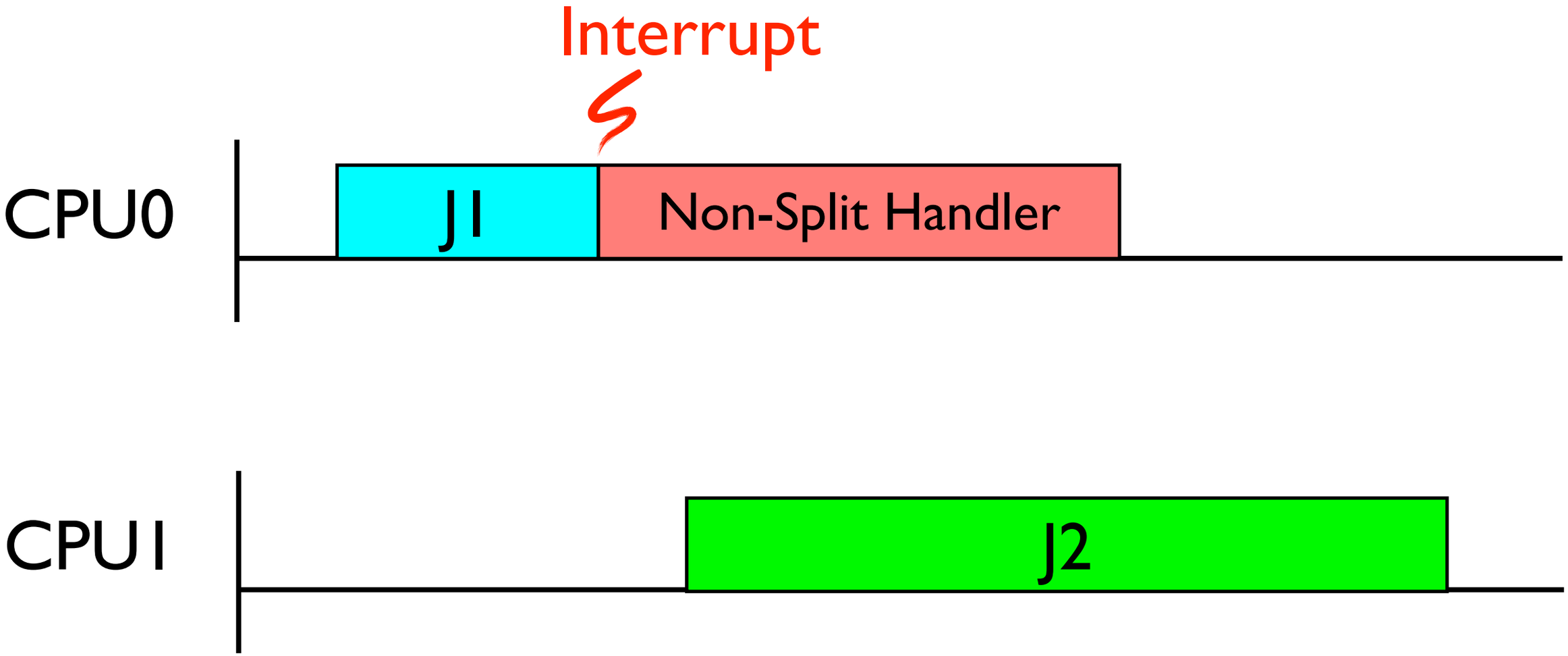

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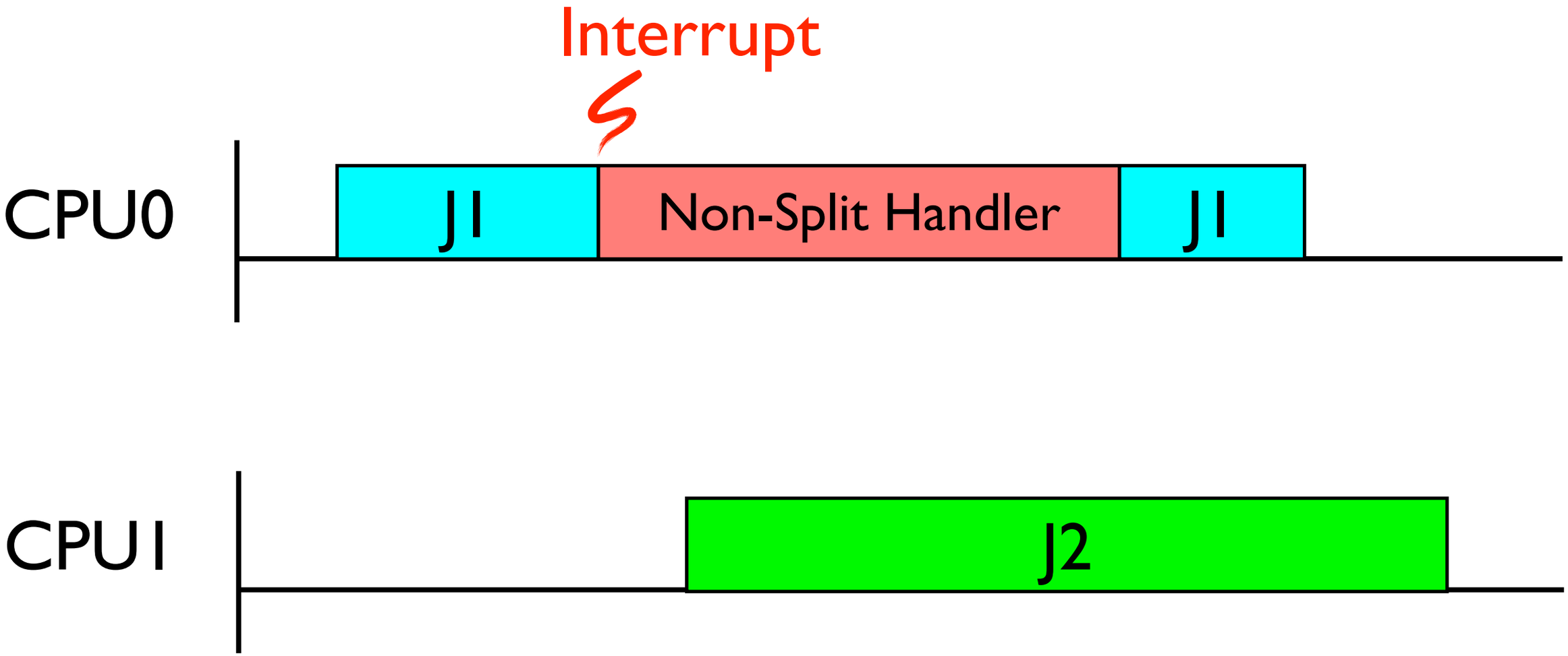

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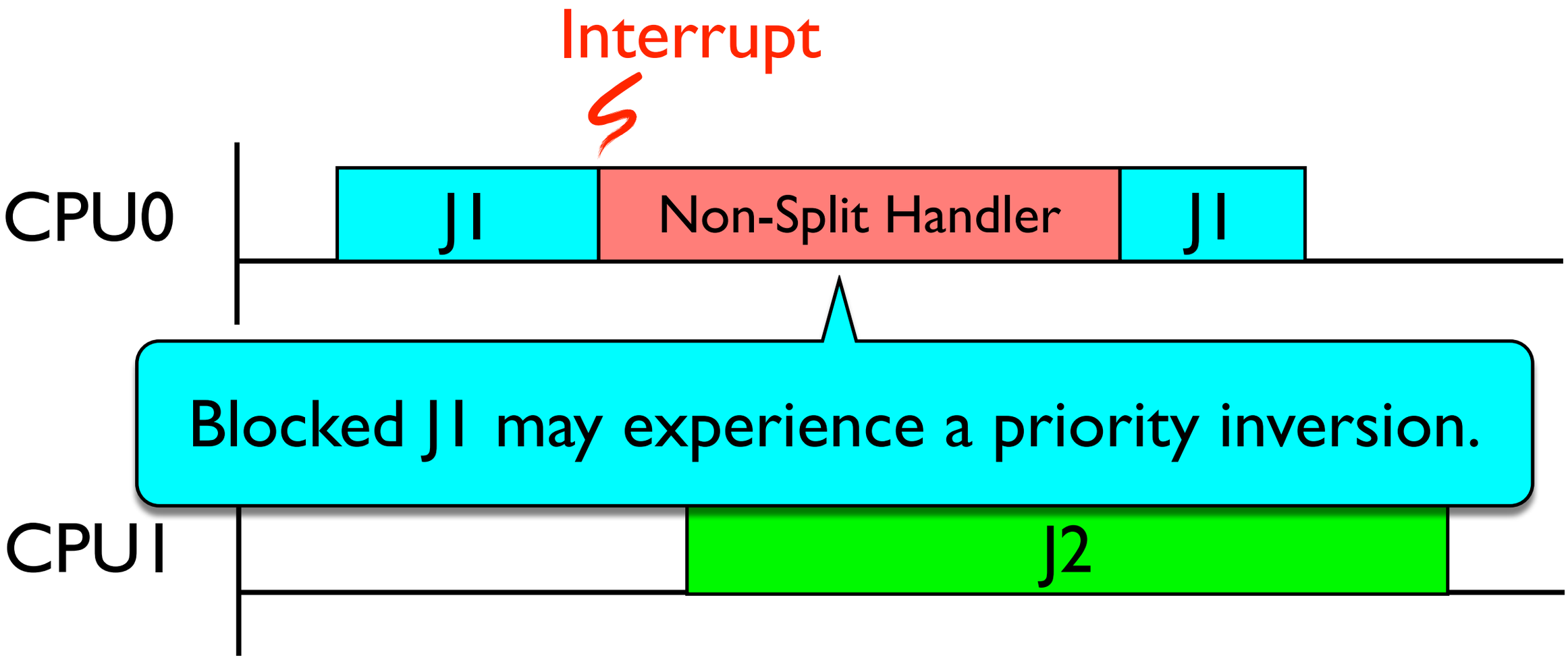

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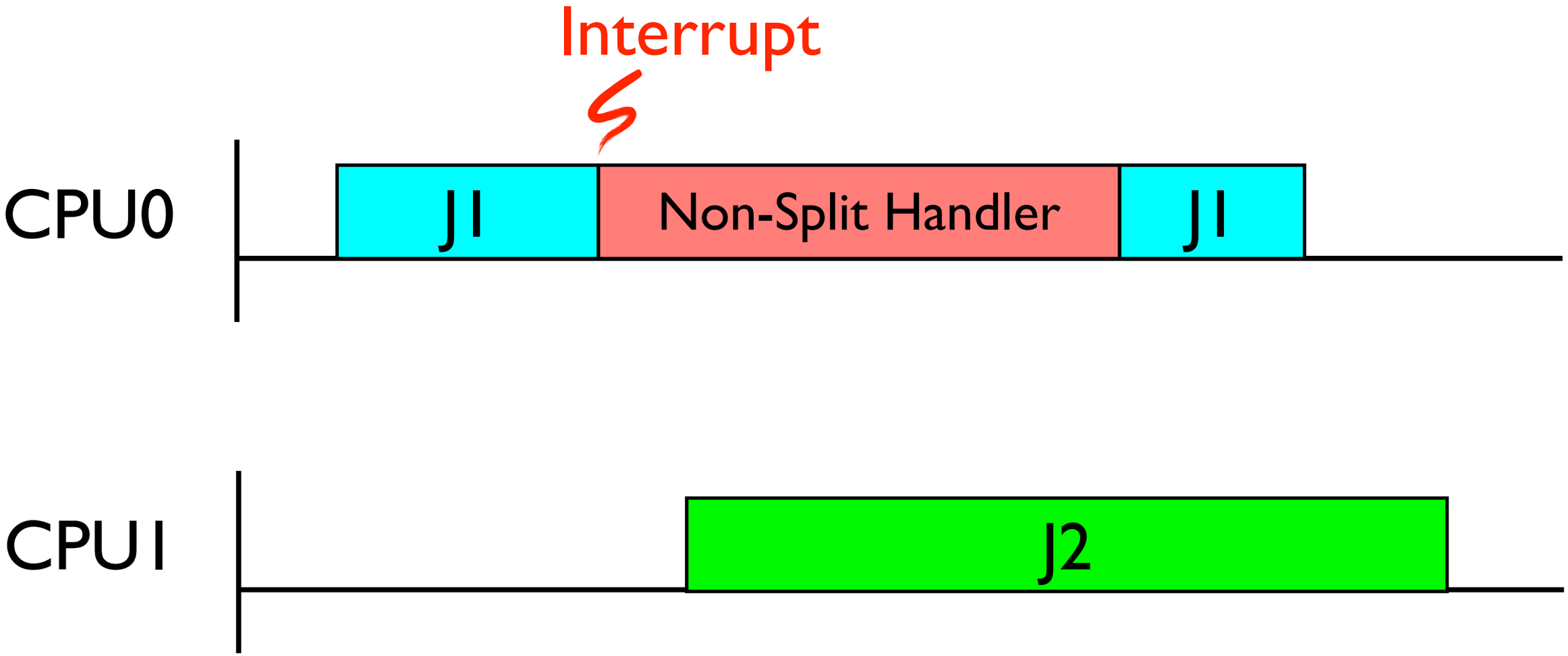

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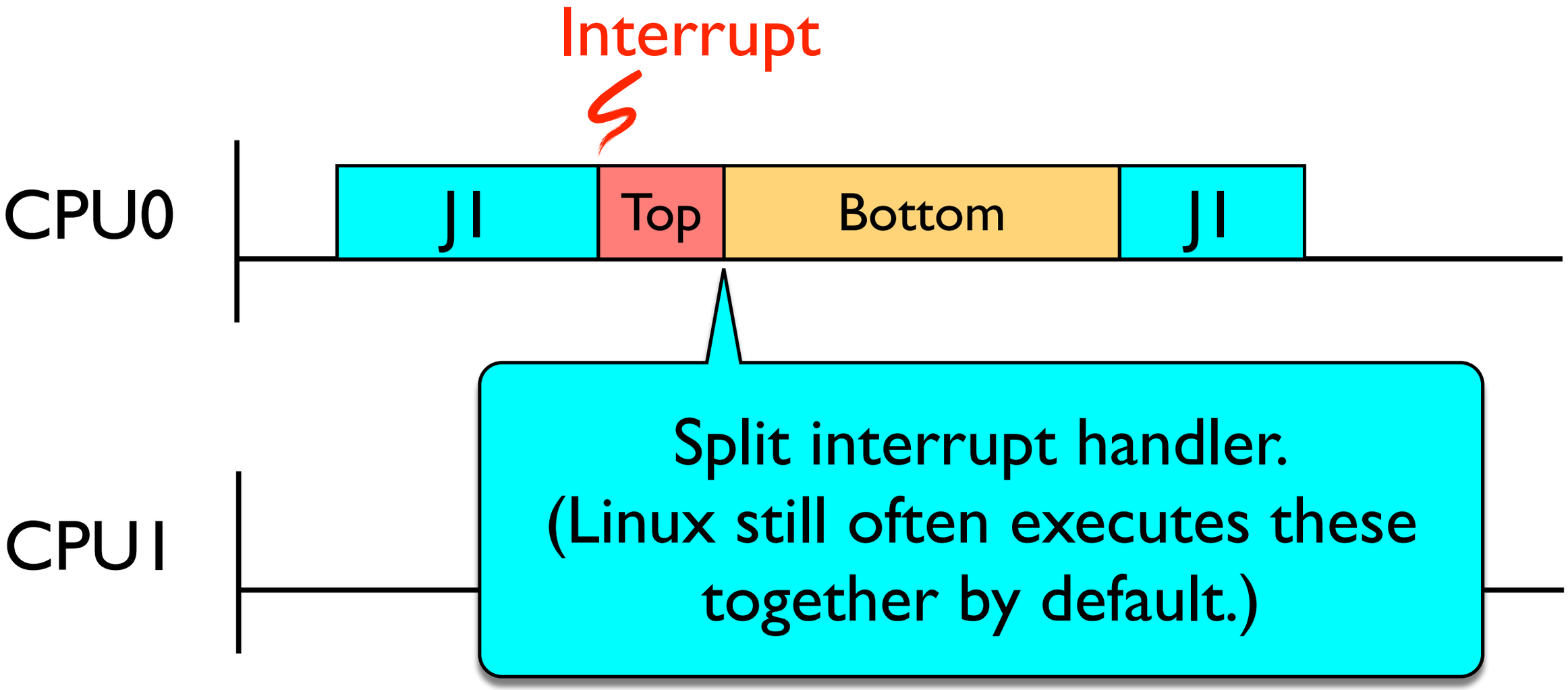

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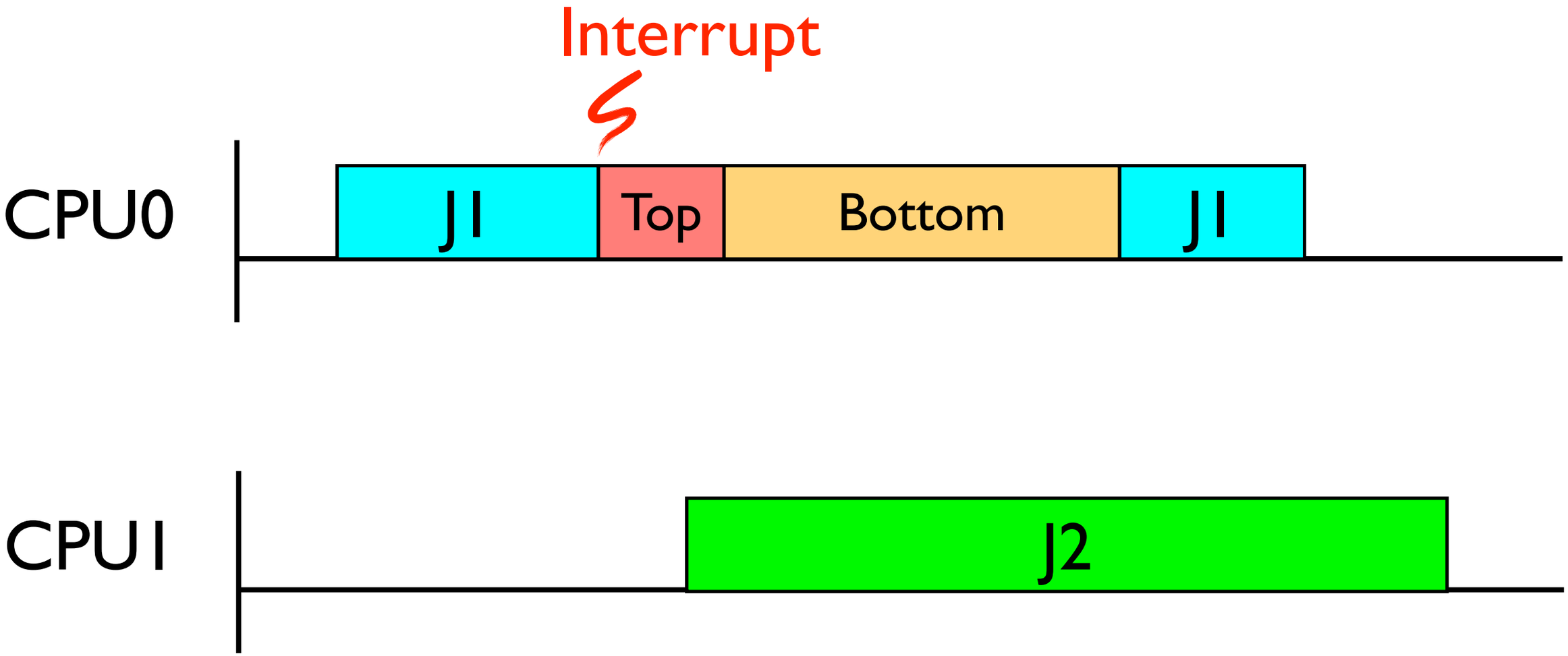

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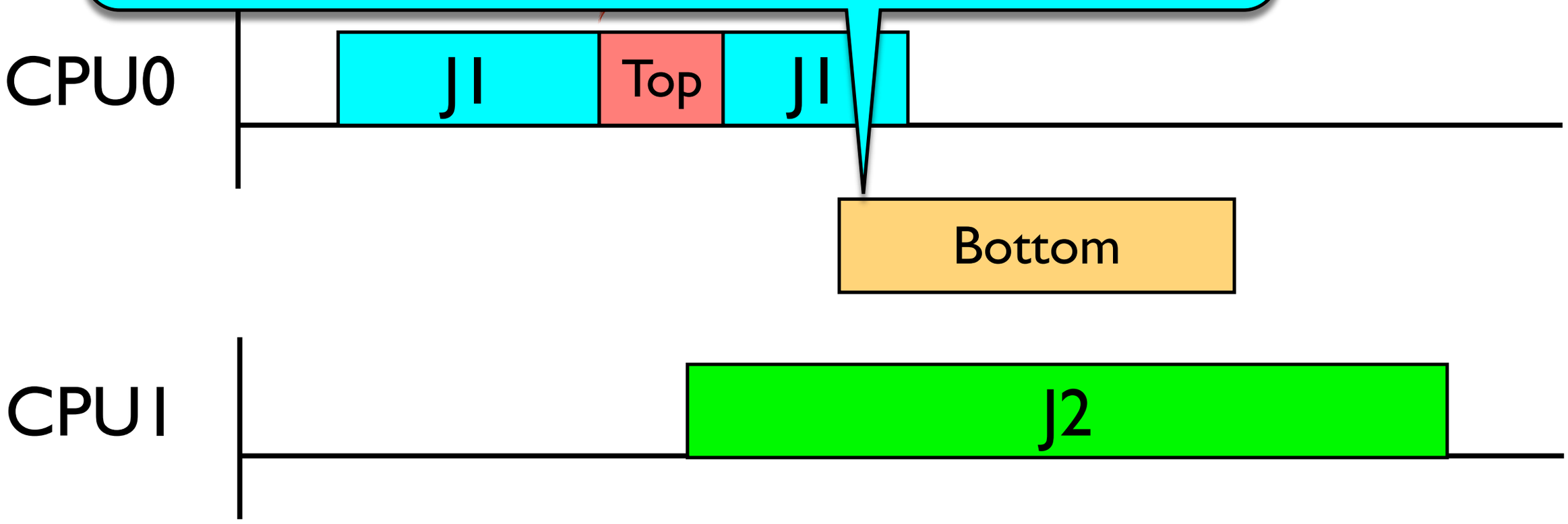

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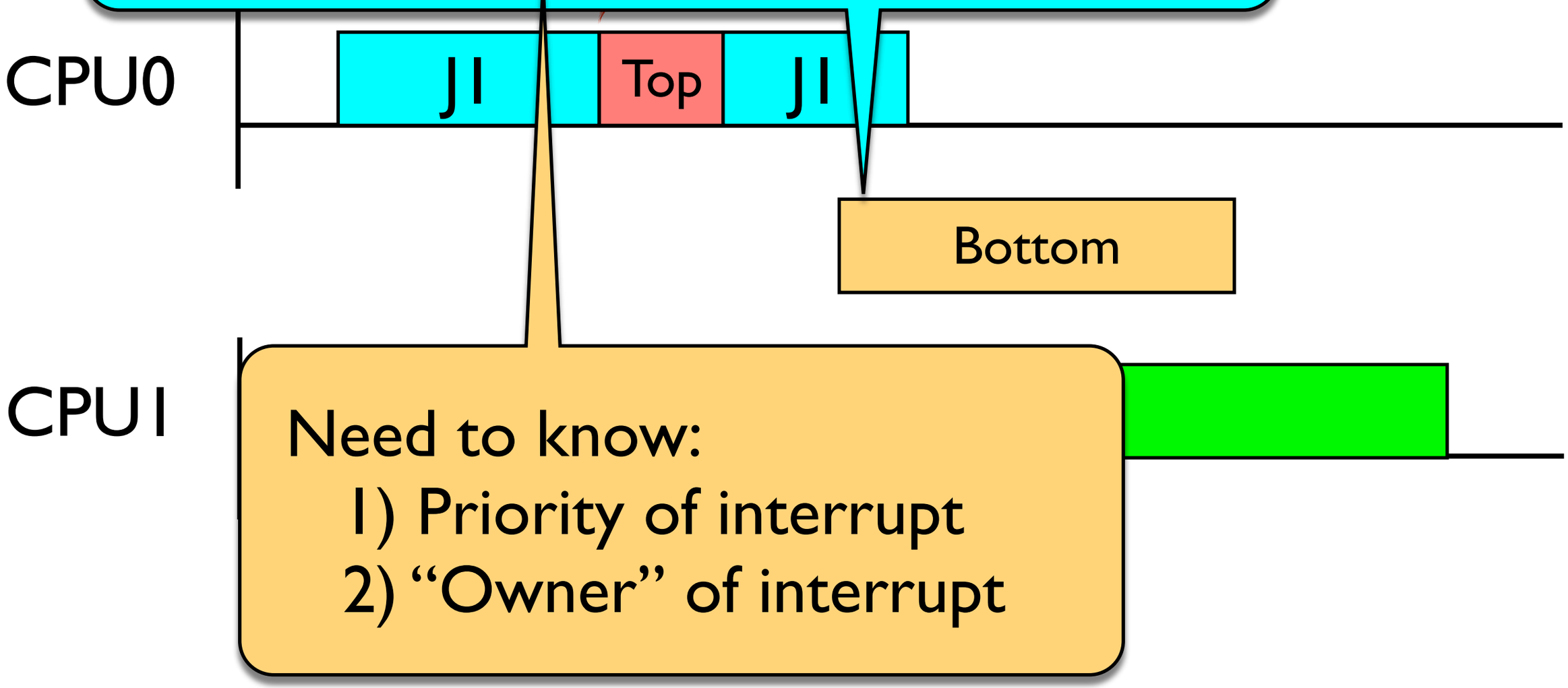

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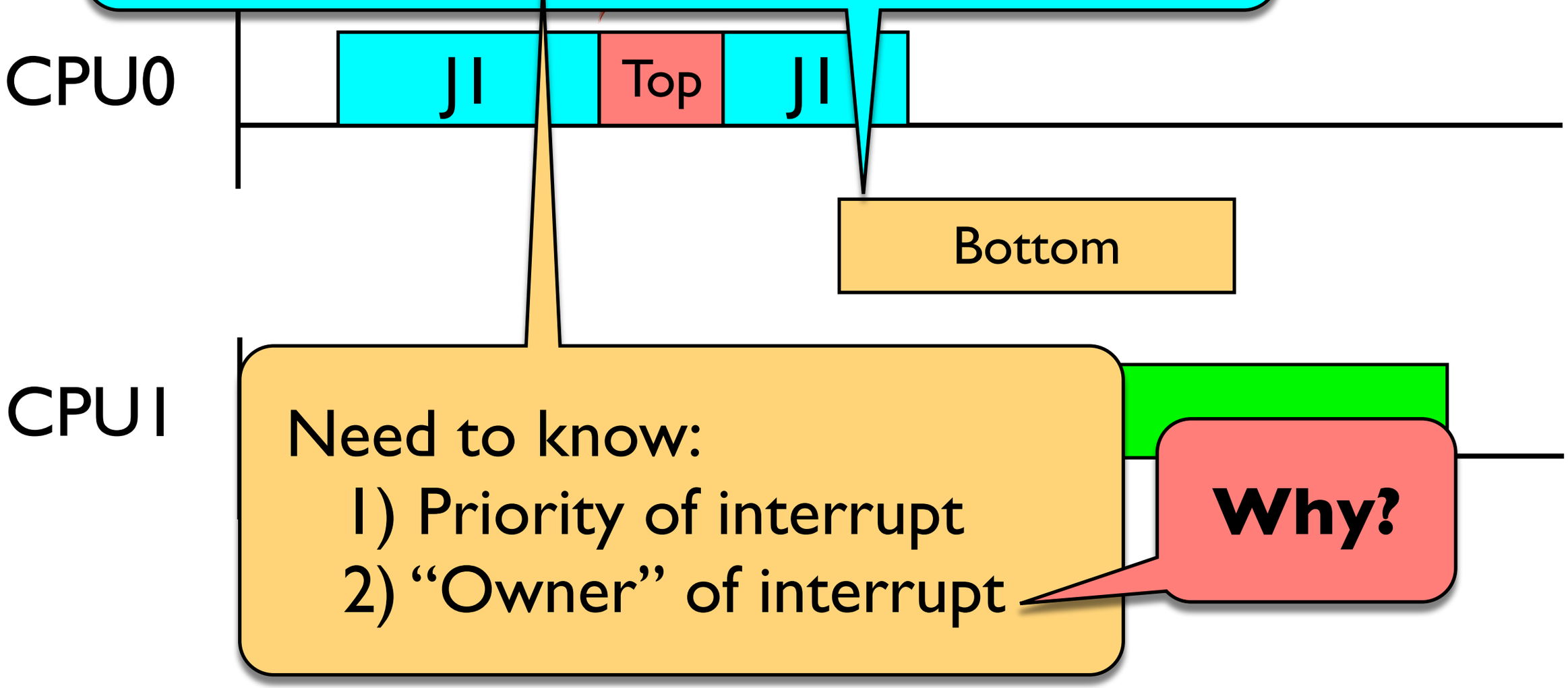

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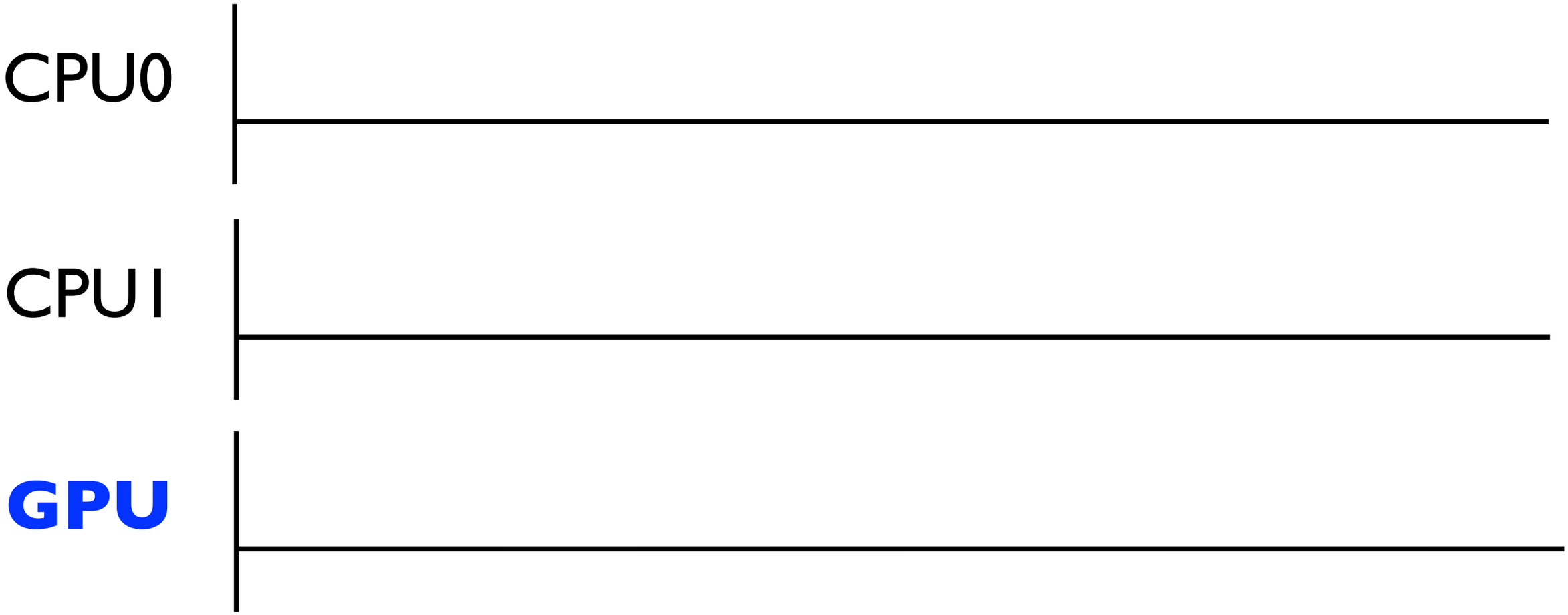

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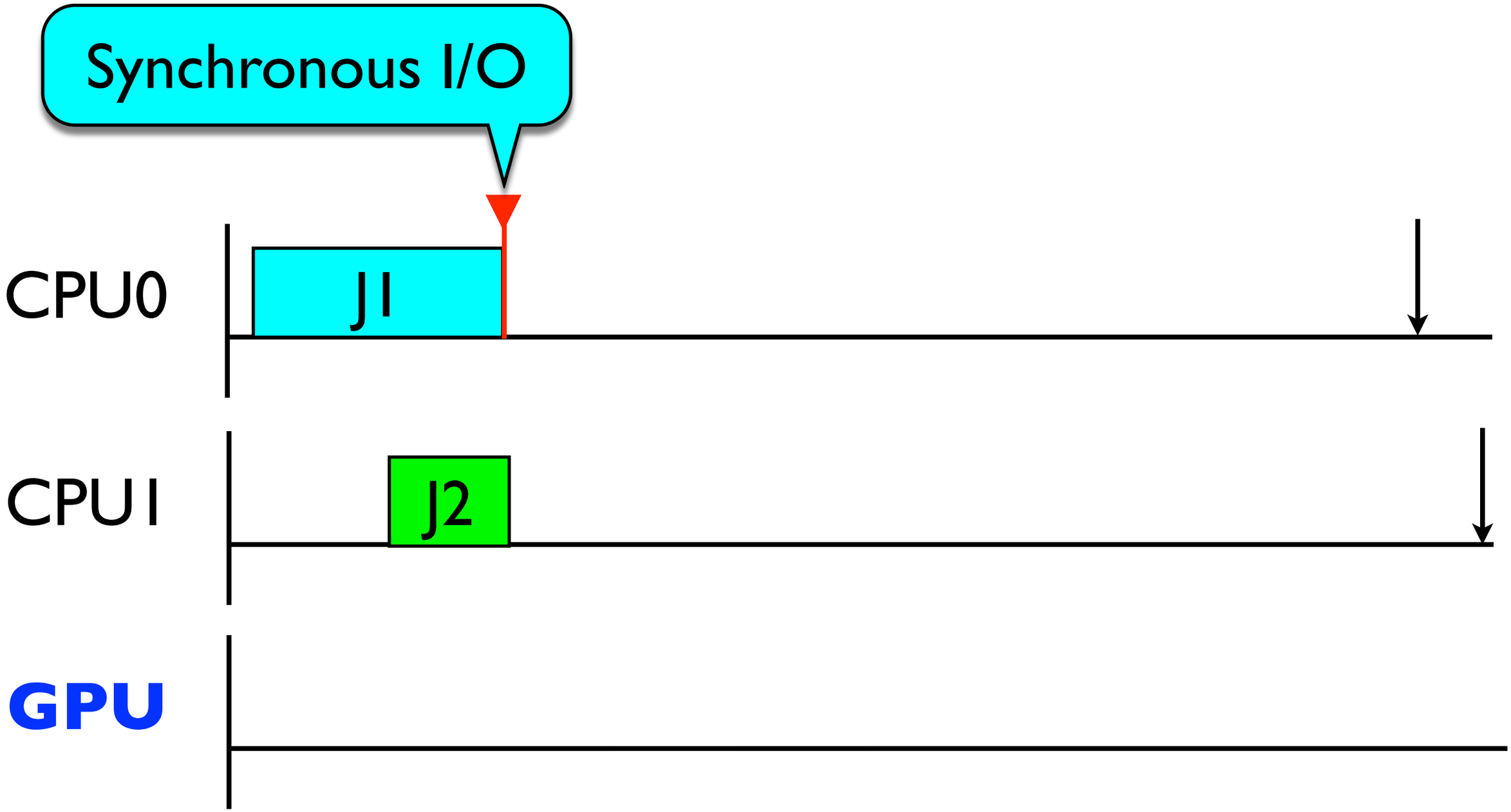

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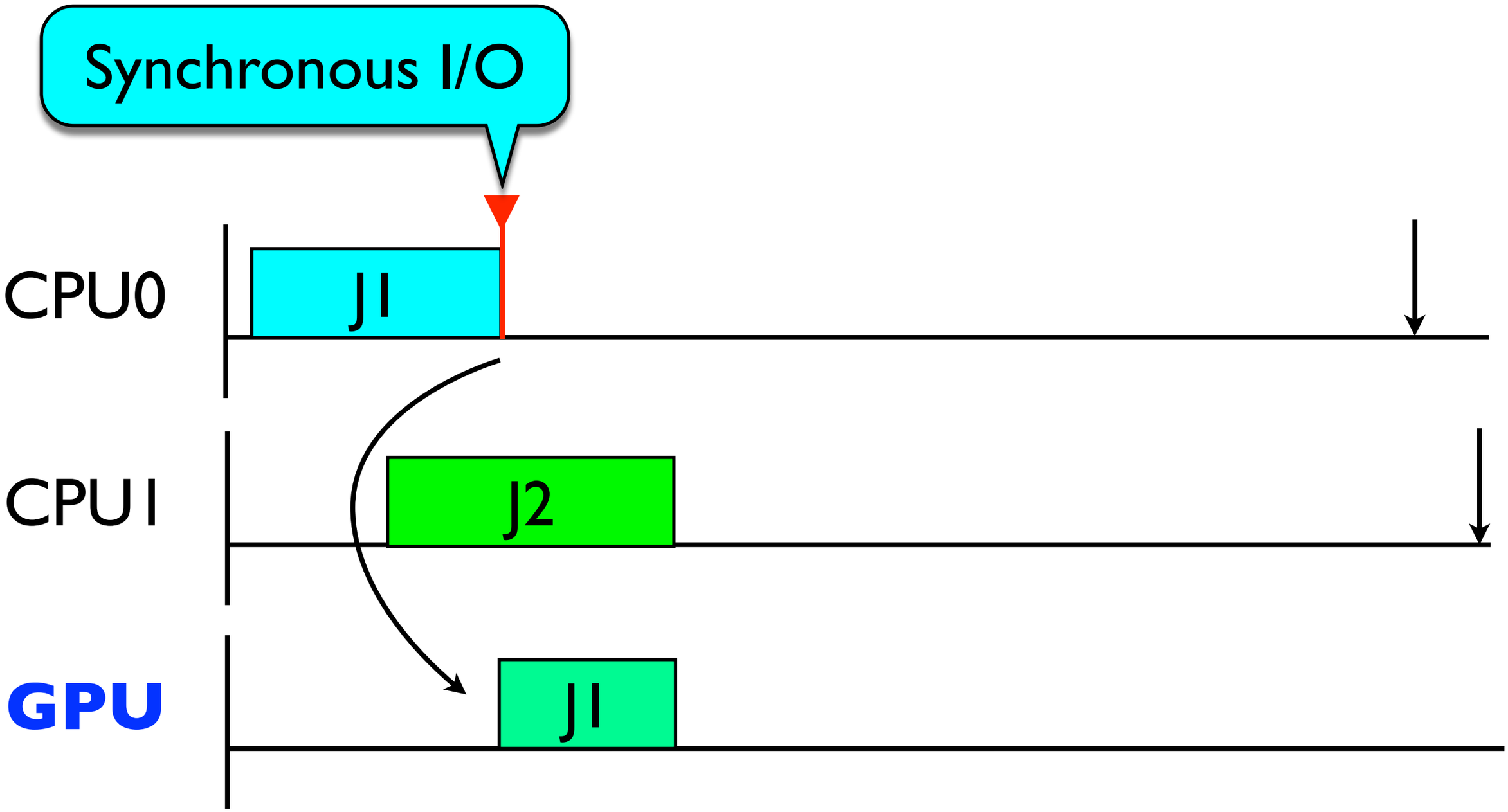

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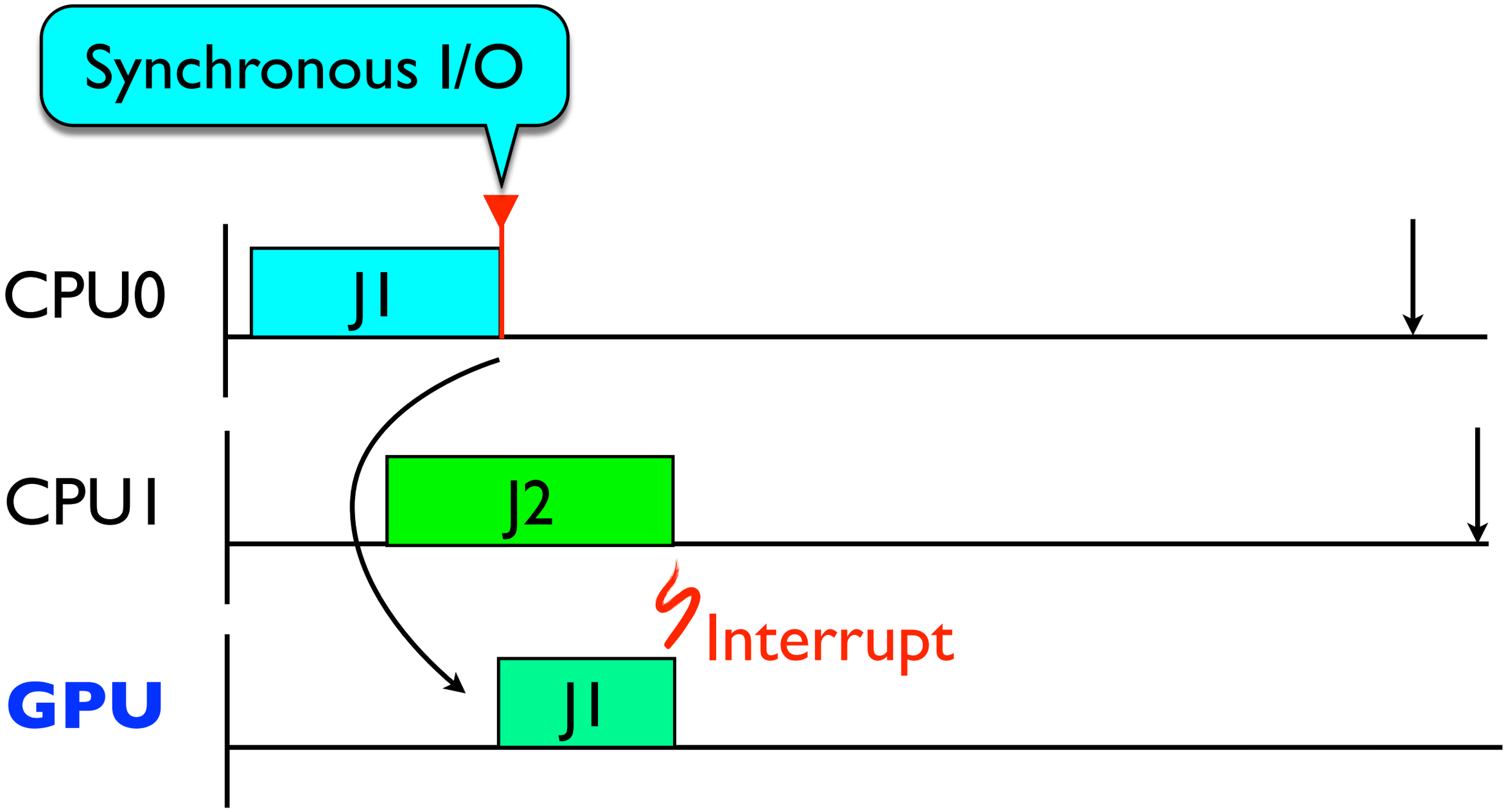

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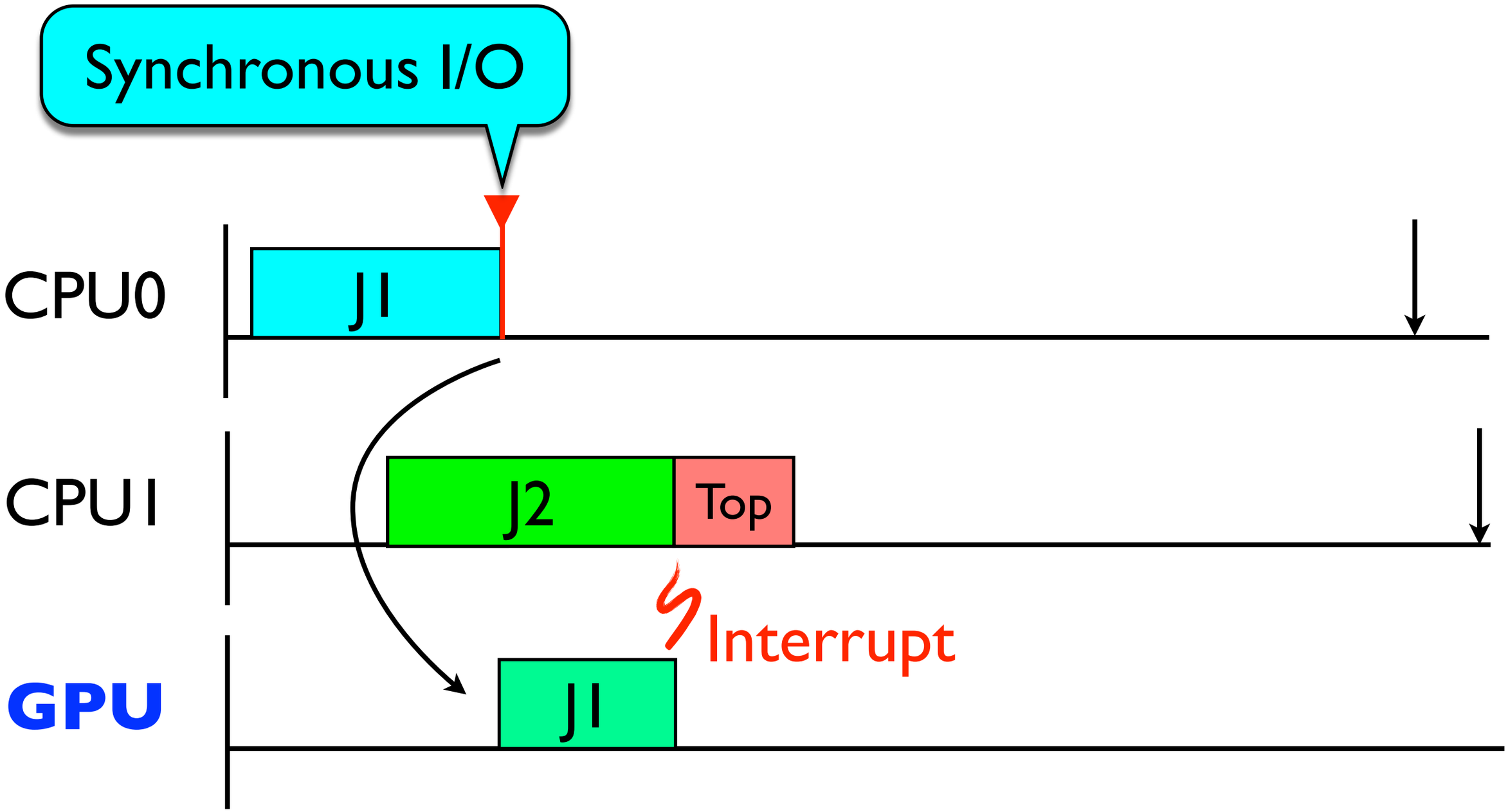

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Schedule bottom half.
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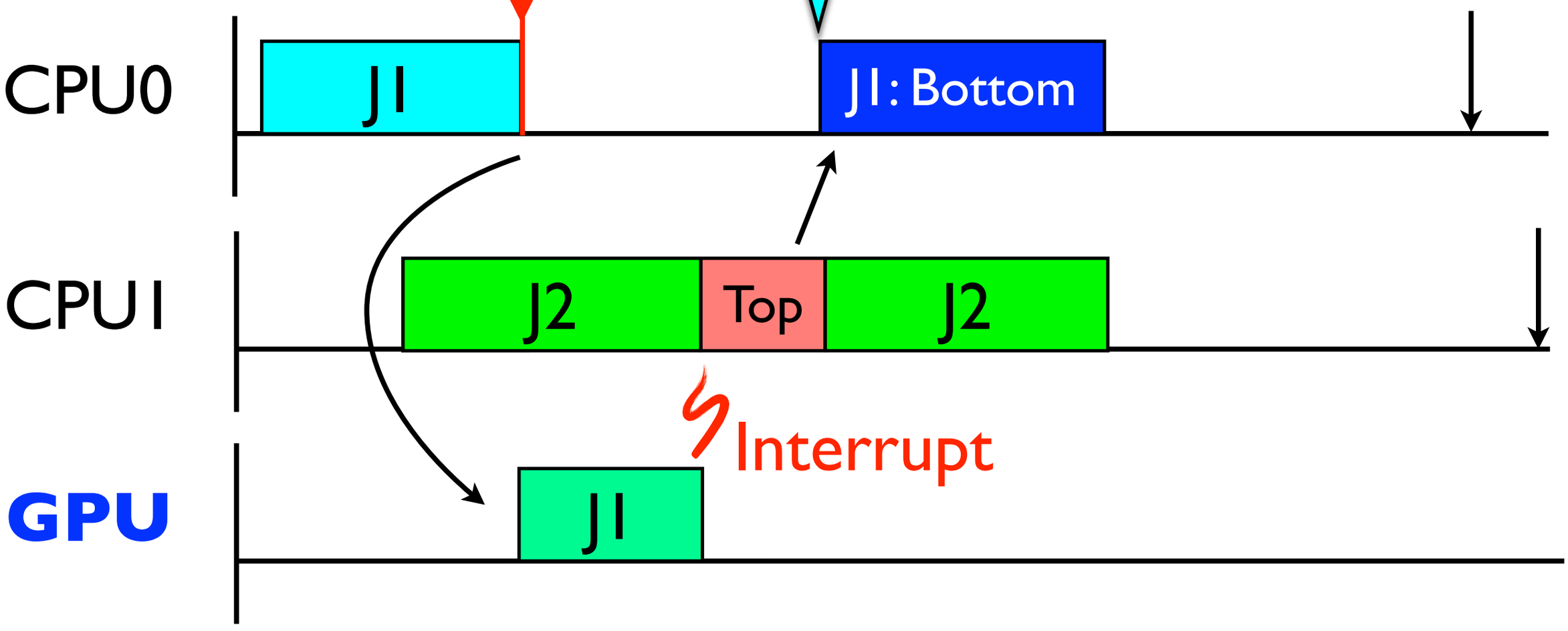

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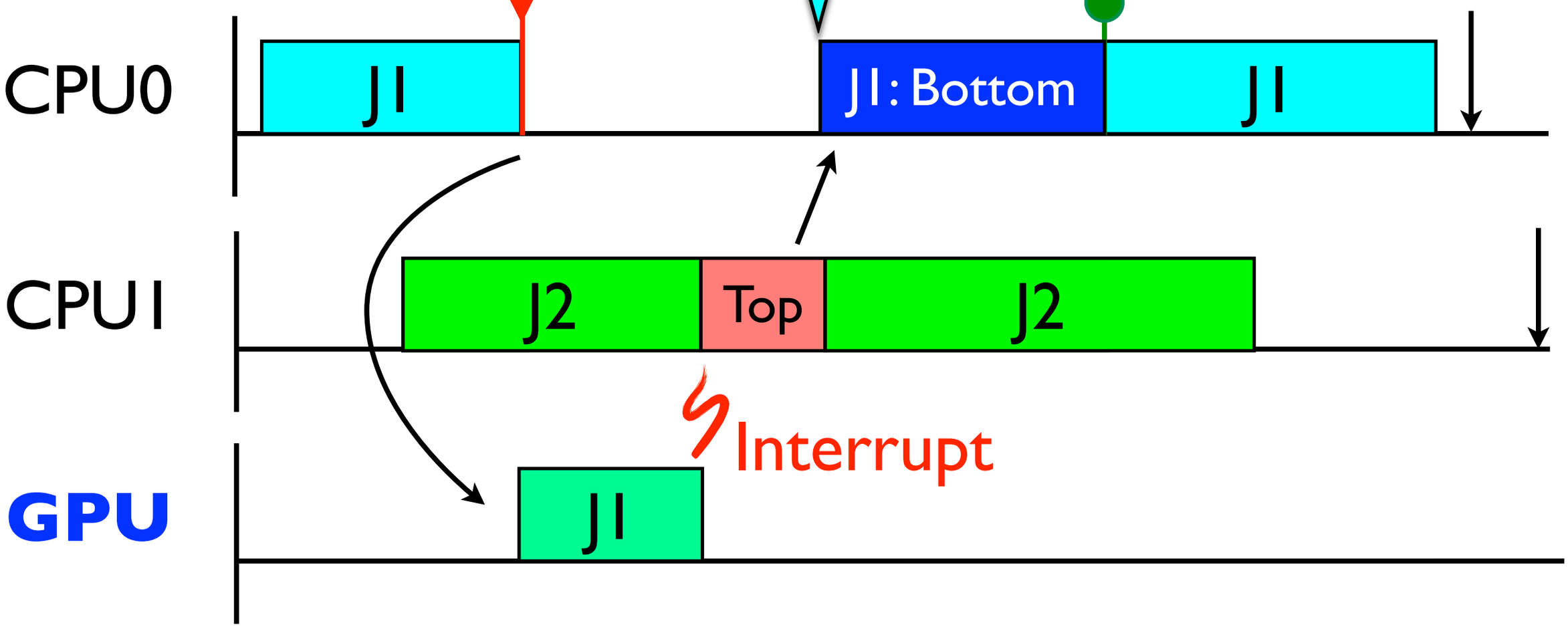

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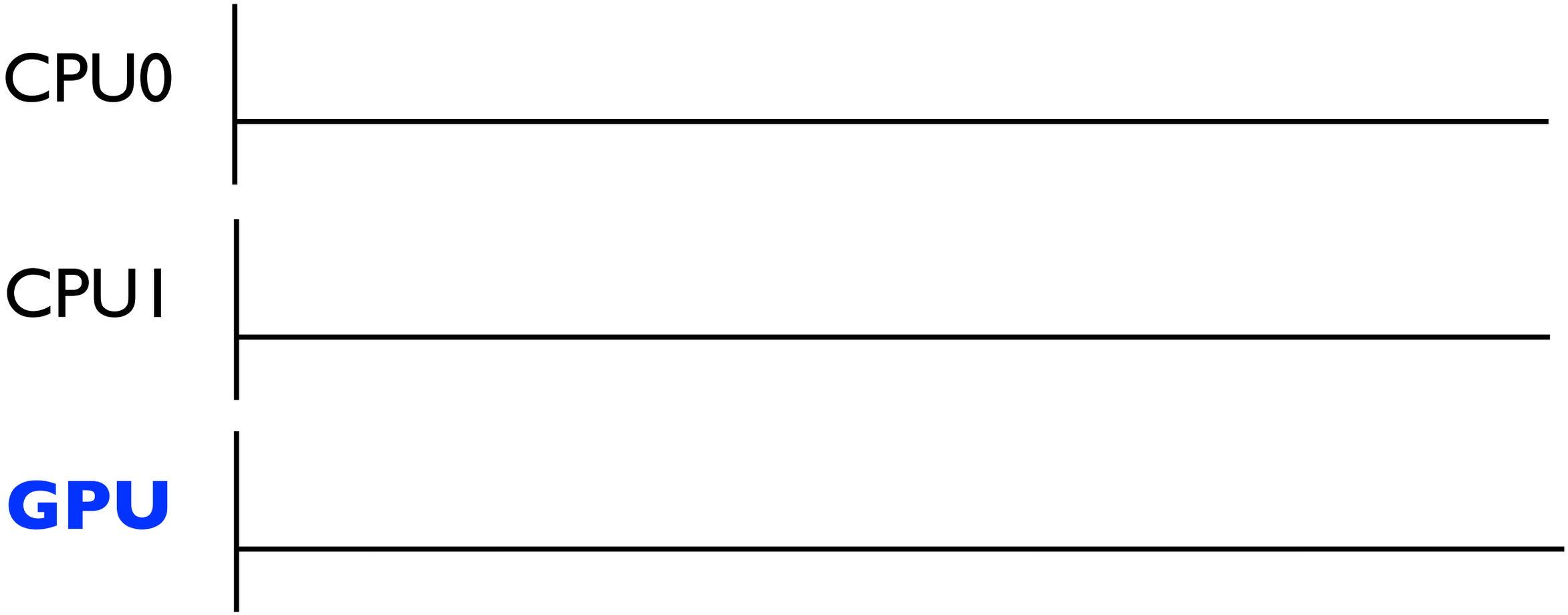

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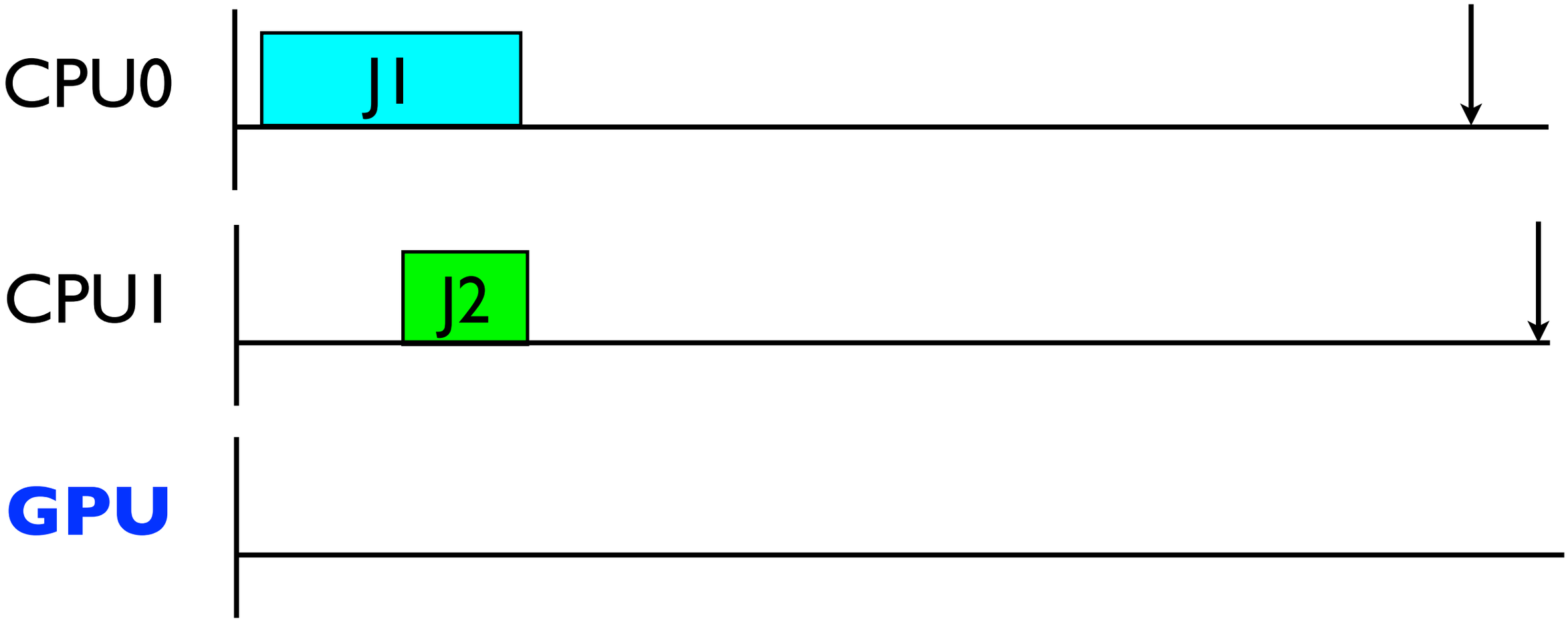

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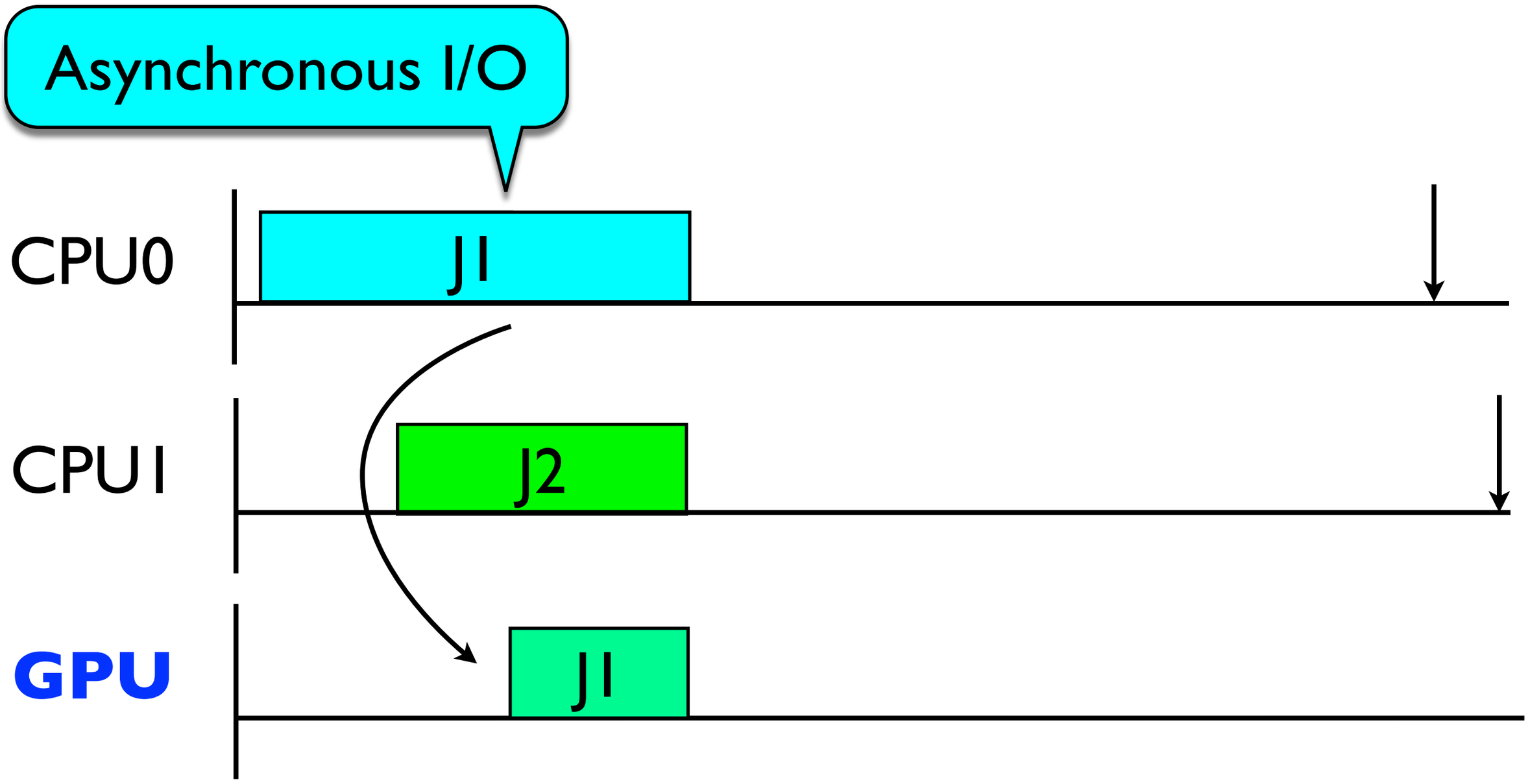

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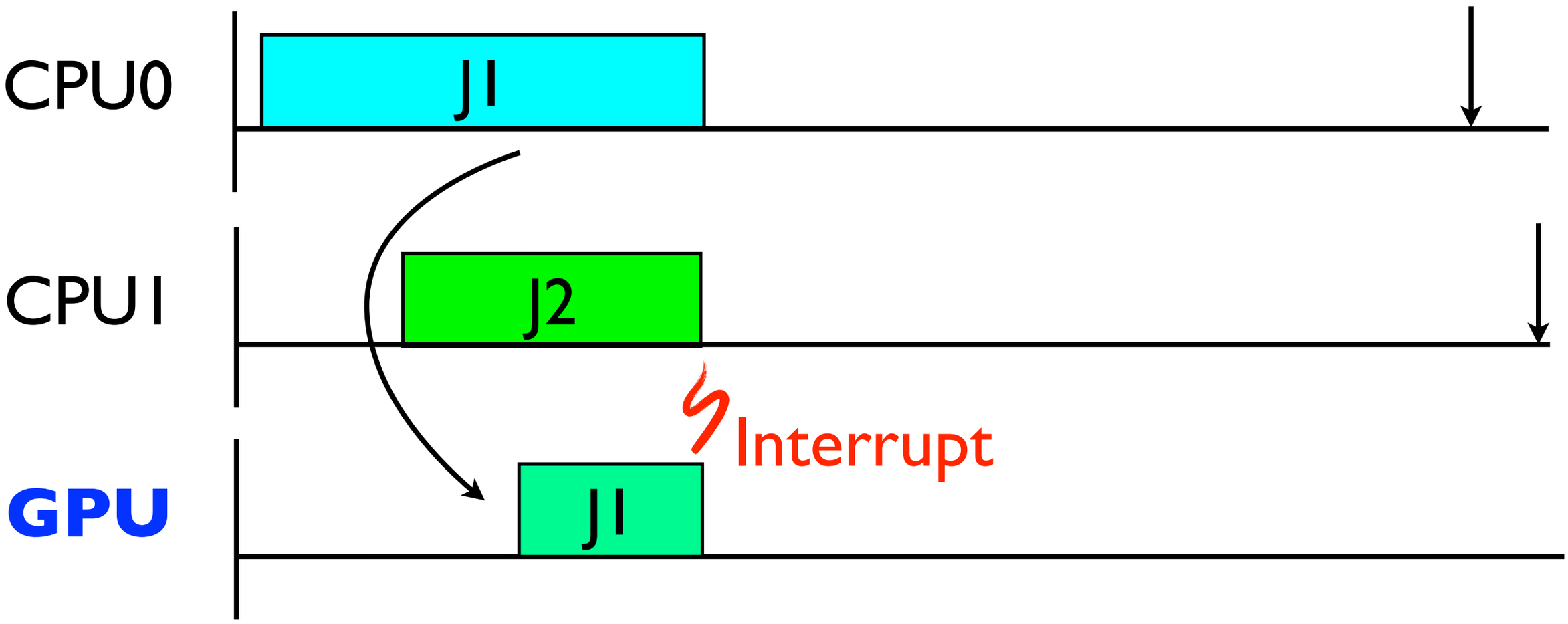

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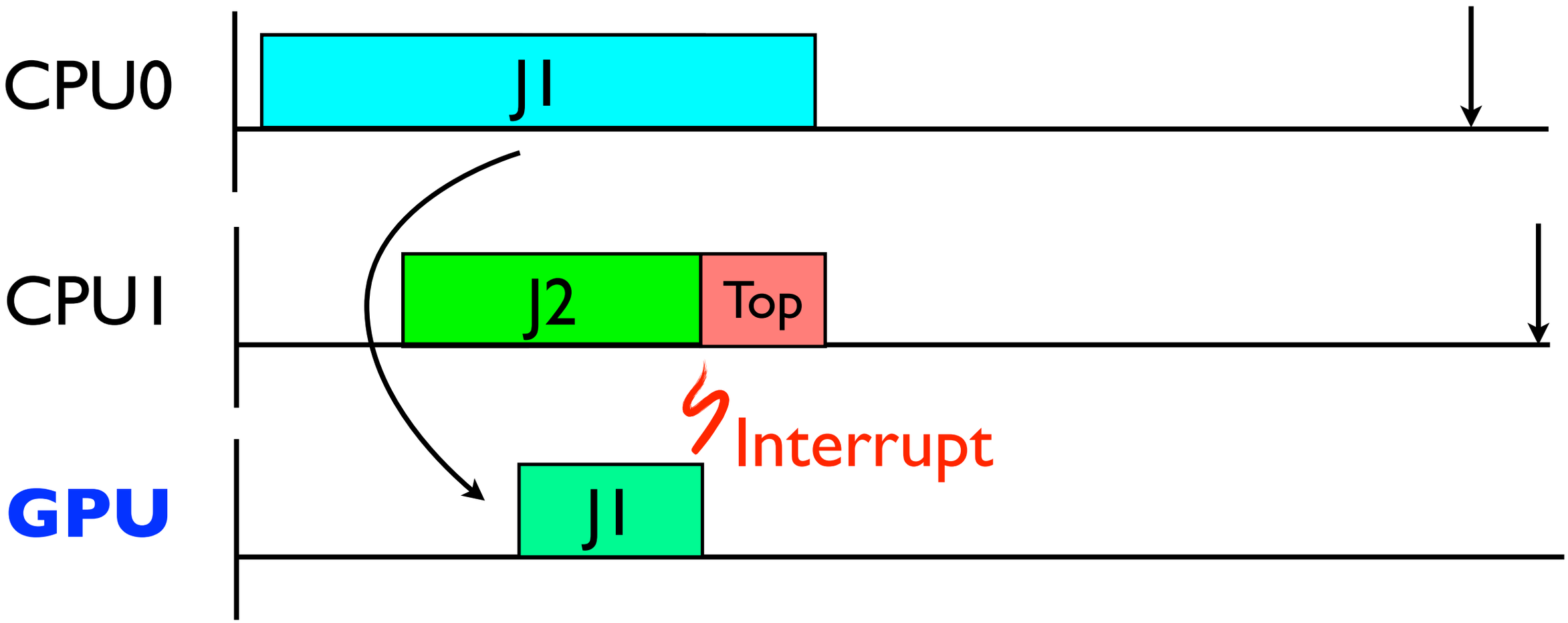

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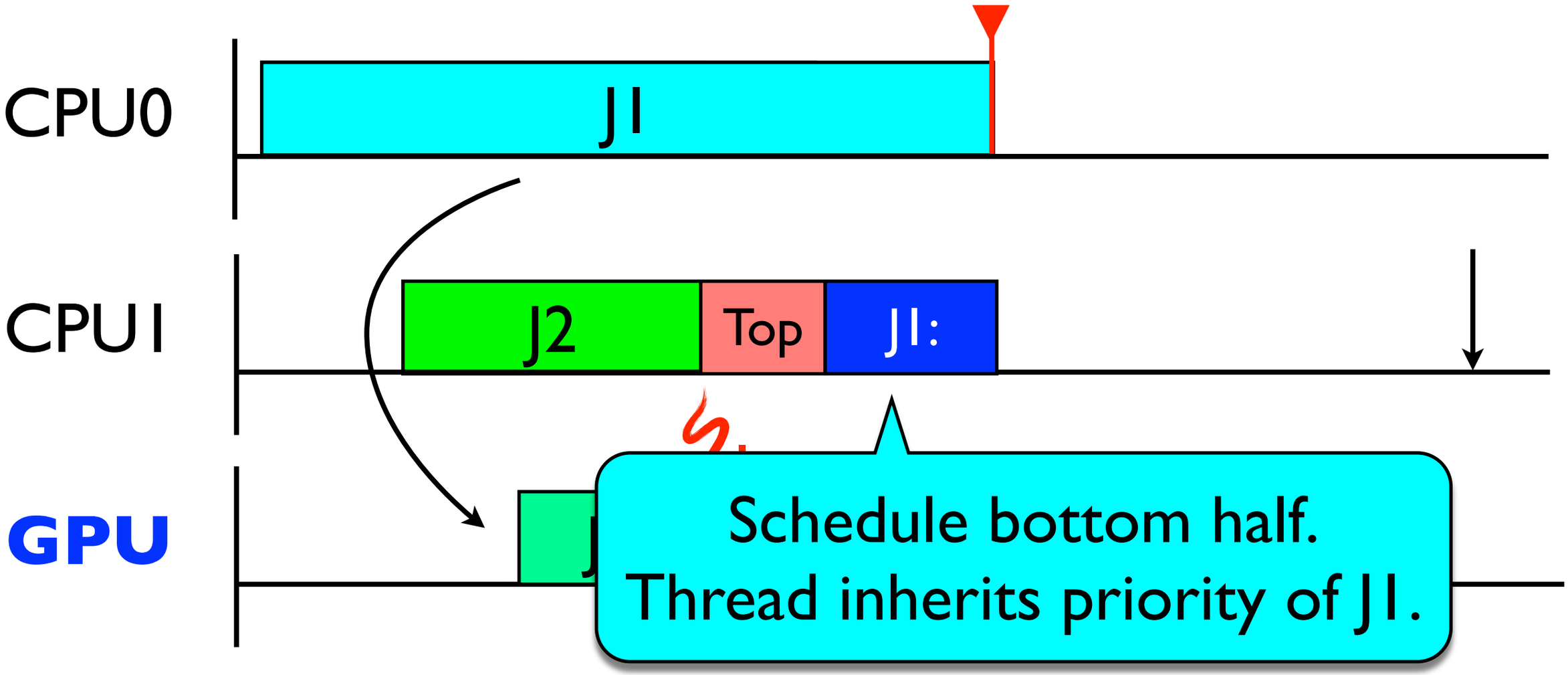

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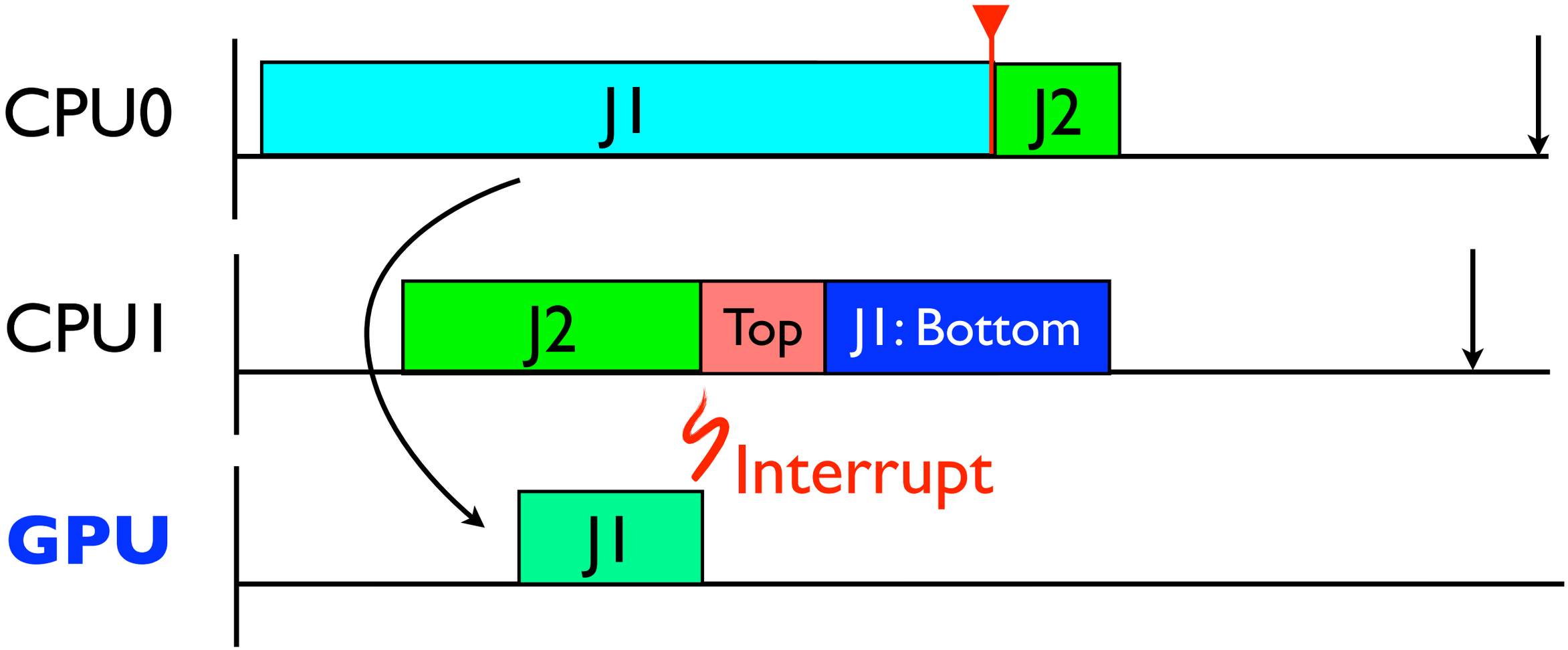

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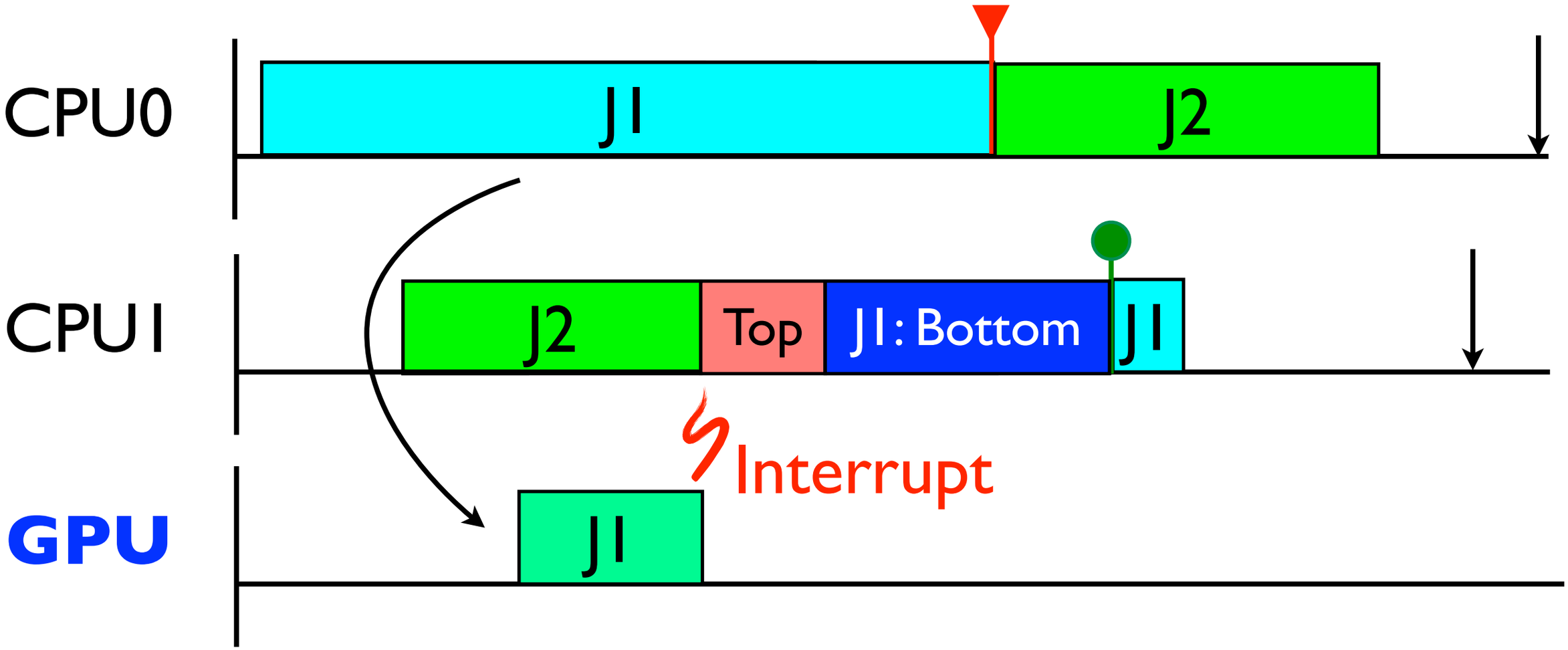

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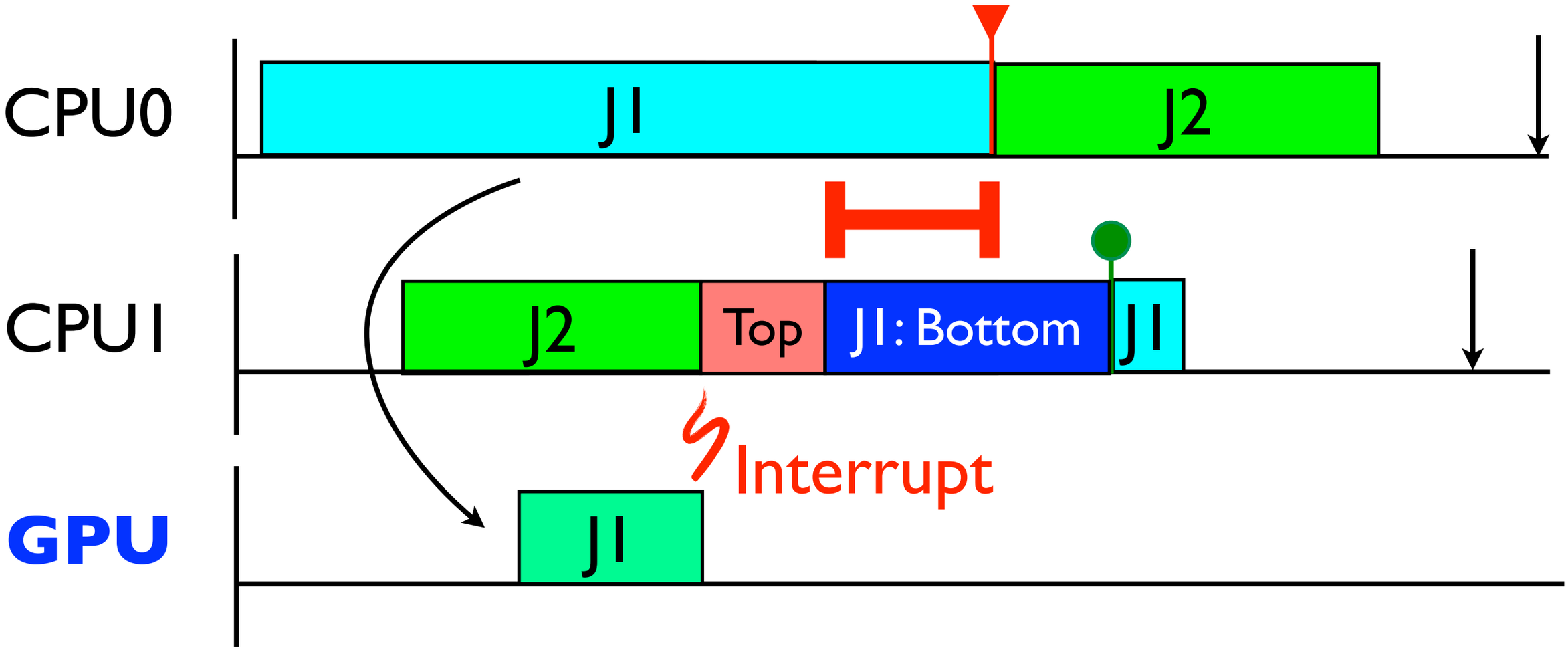
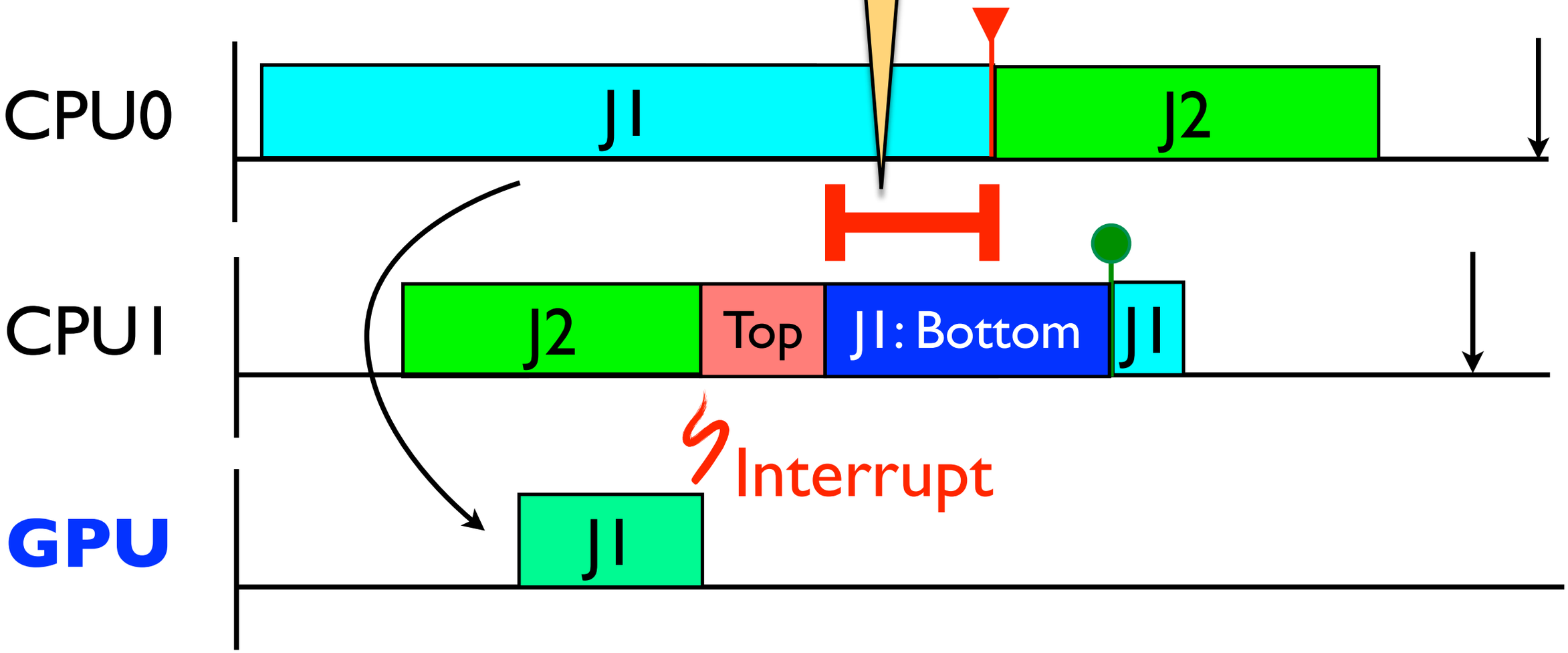
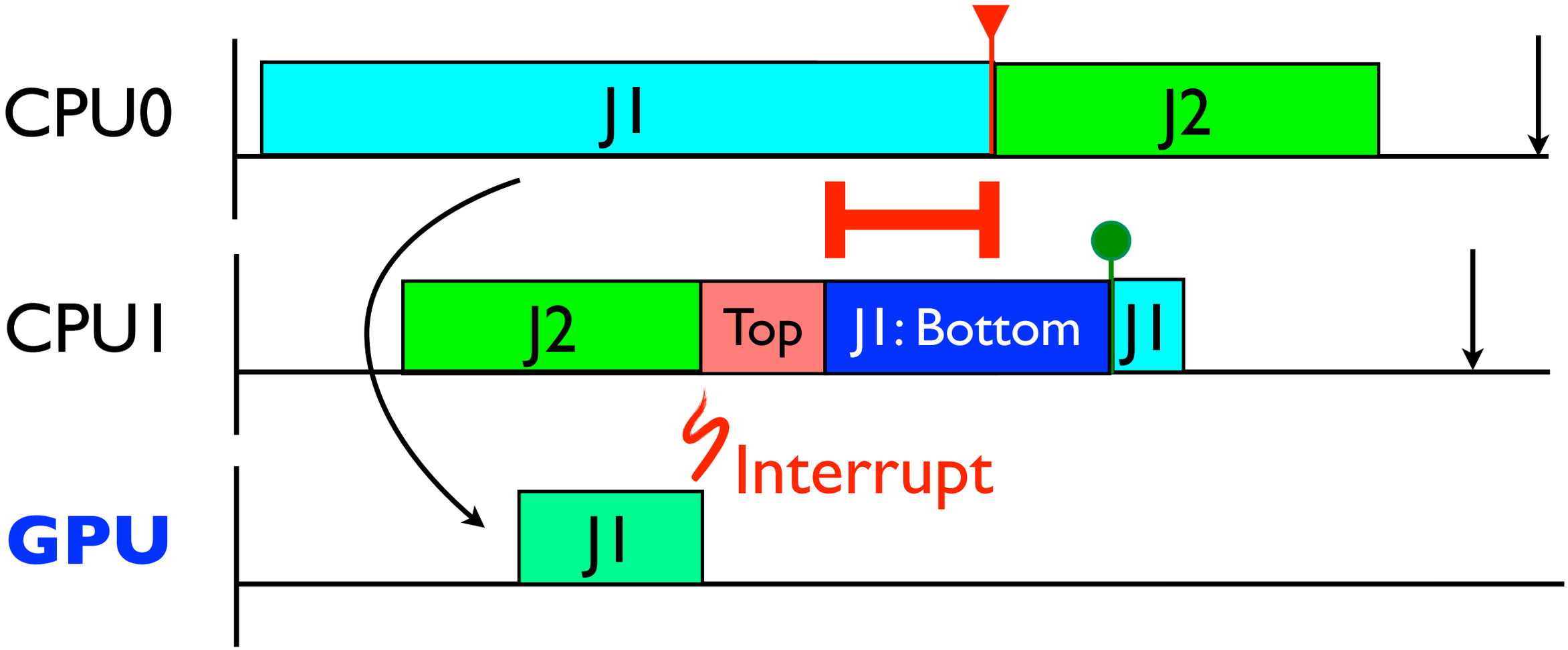


Two threads with same identity!
Breaks single threaded sporadic task model!



Interrupt Ownership

This can only occur under global scheduler with asynchronous I/O.



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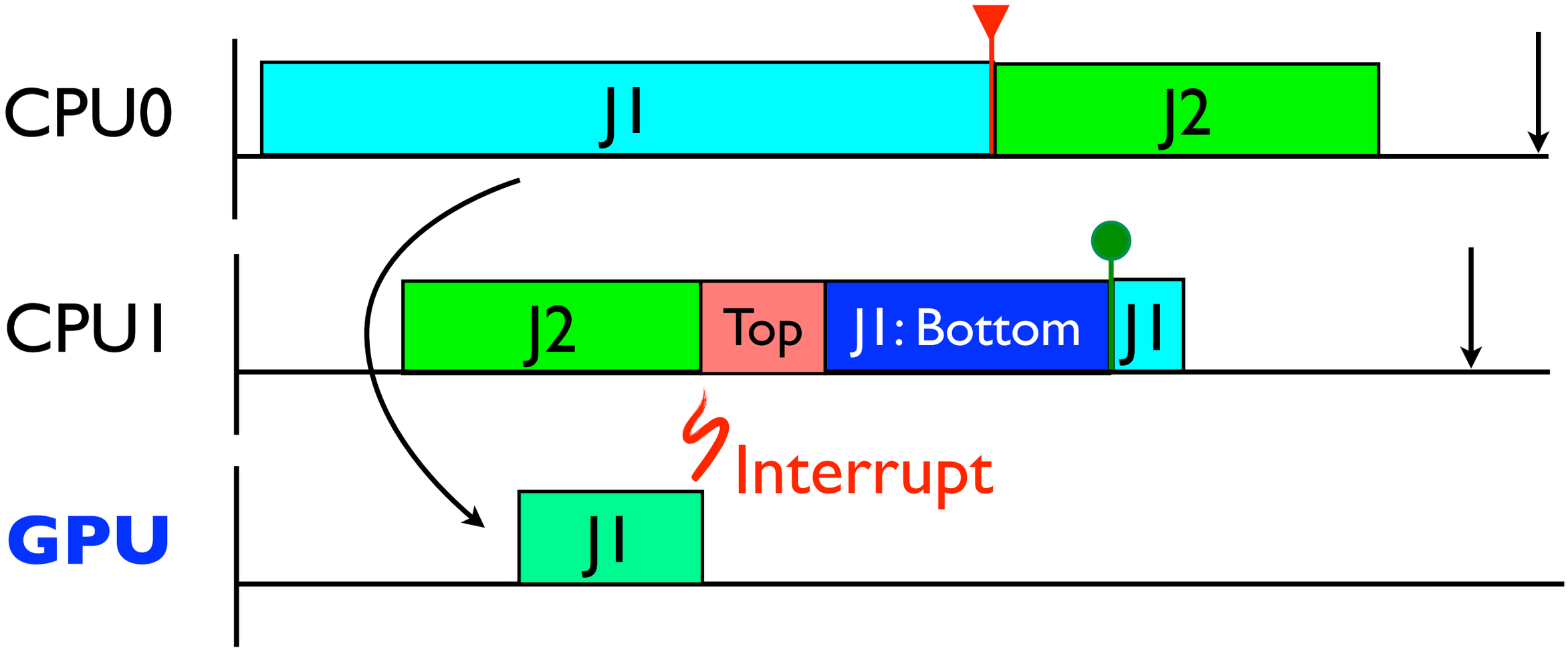
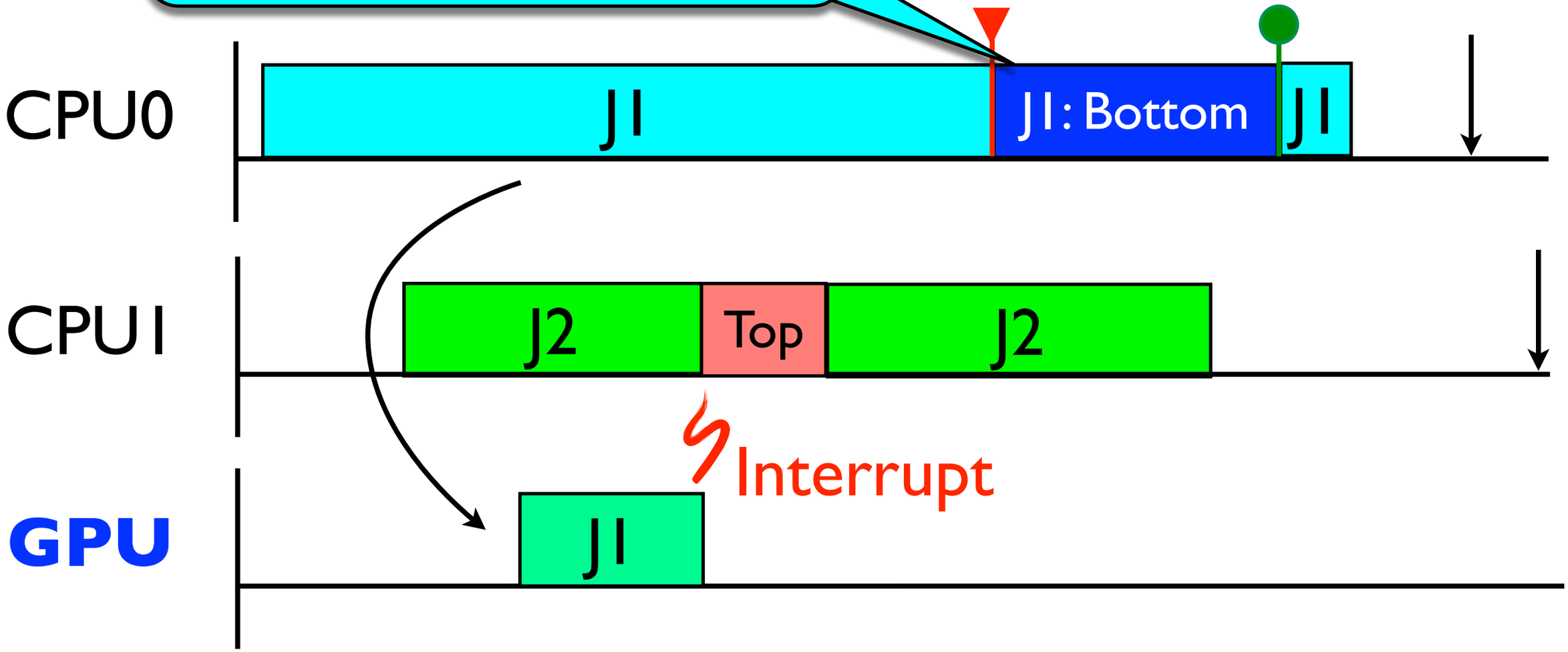


Interrupt Ownership

Defer bottom half until J1 suspends, preventing co-scheduling.



Interrupt O

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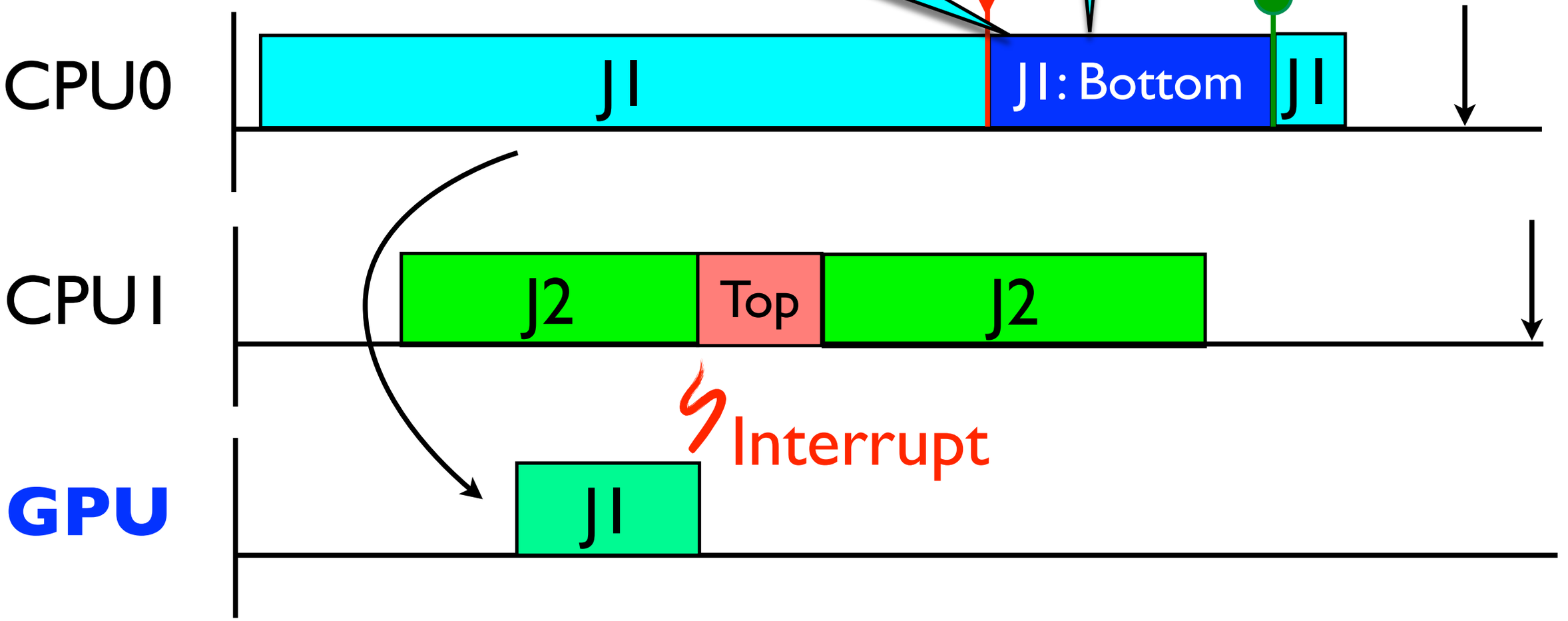
Account for bottom half execution time as being of J1.



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- Real-Time GPU Interrupts:
  1. Thread bottom halves of GPU interrupts, inheriting priority of owners
  2. Prevent co-scheduling of bottom halves and owners
- **PROBLEM: GPU driver is closed source.**
  - Which GPU raised the interrupt?
  - What is the priority of the bottom half?

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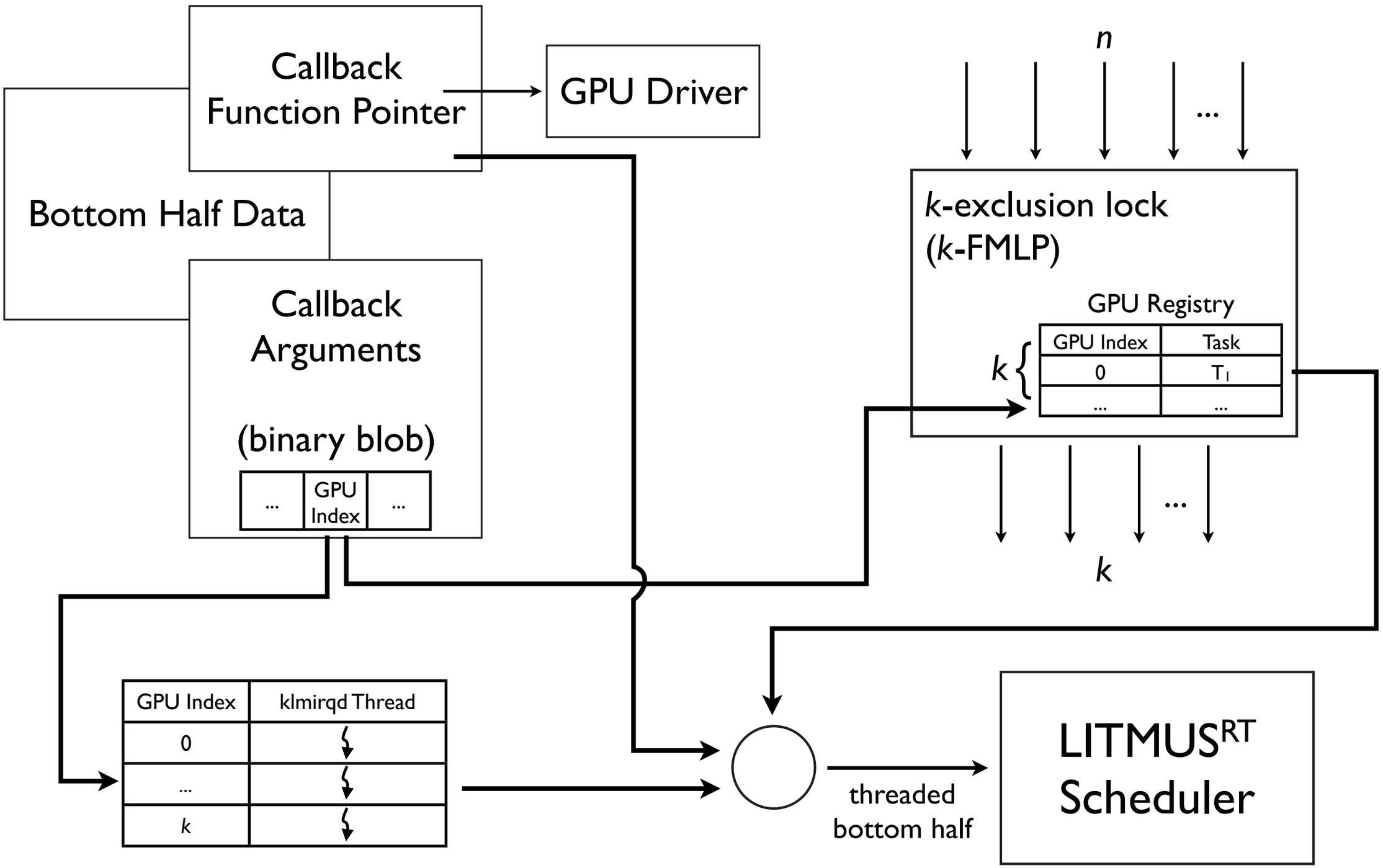
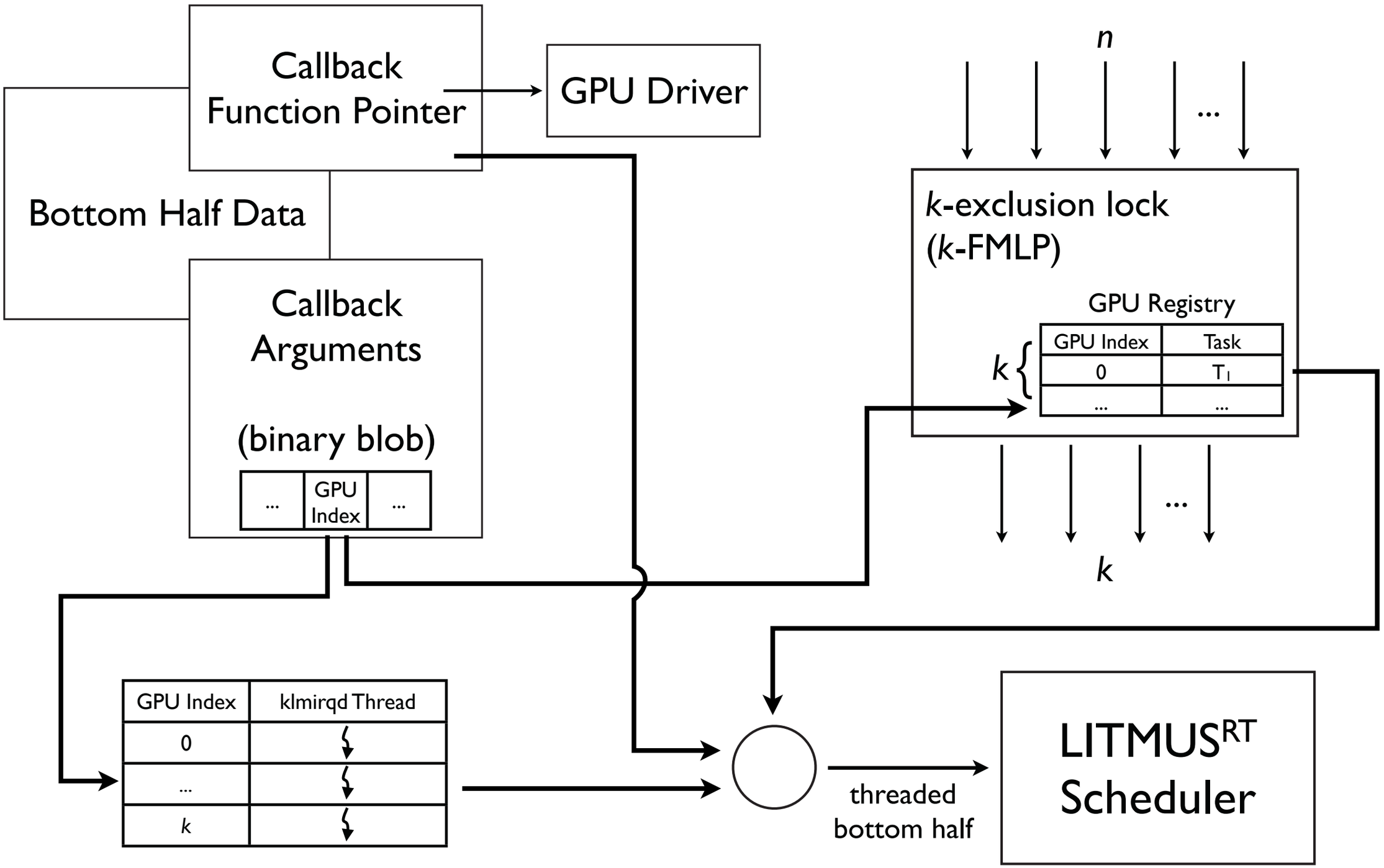
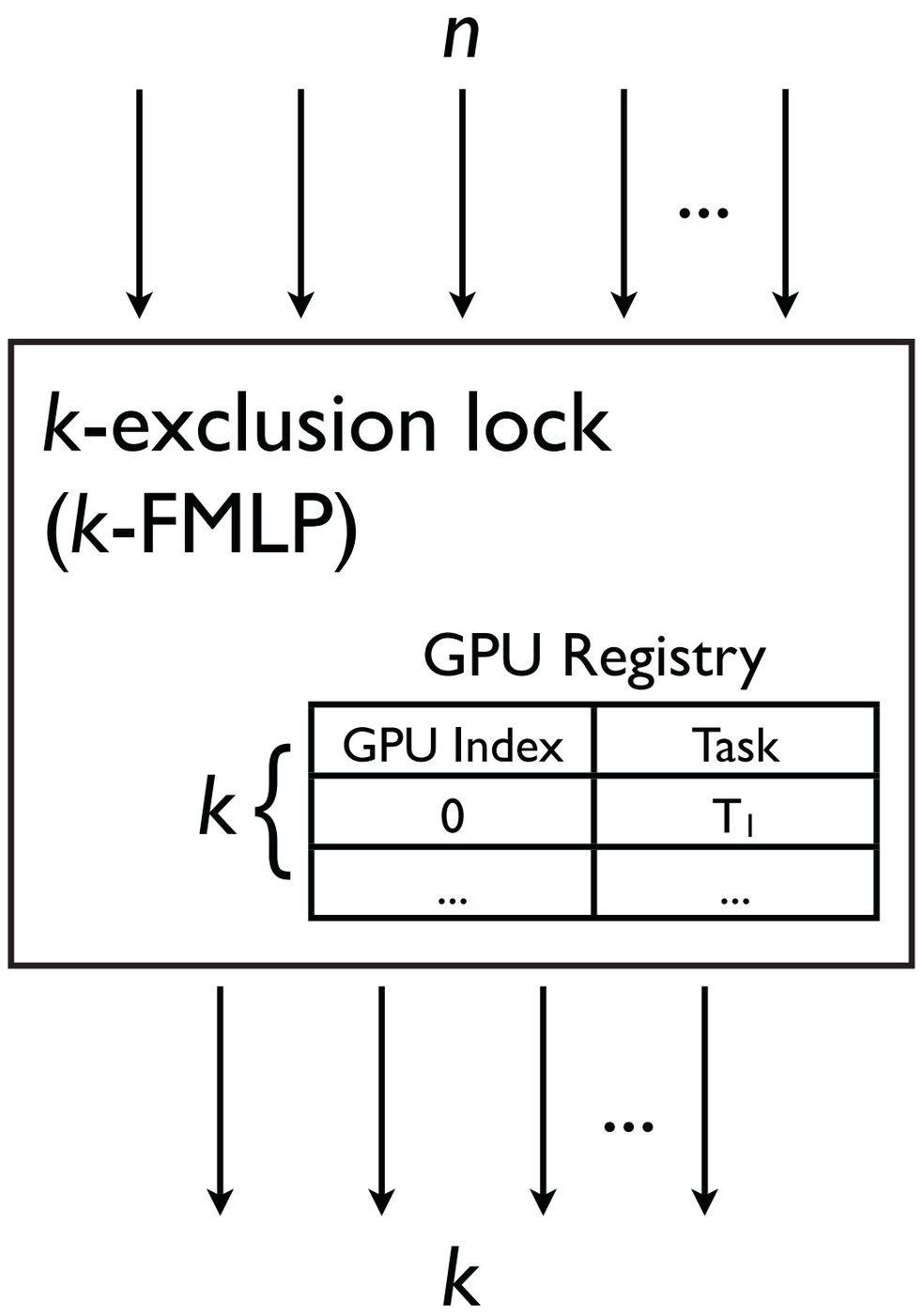


GPU Allocation



GPU Allocation



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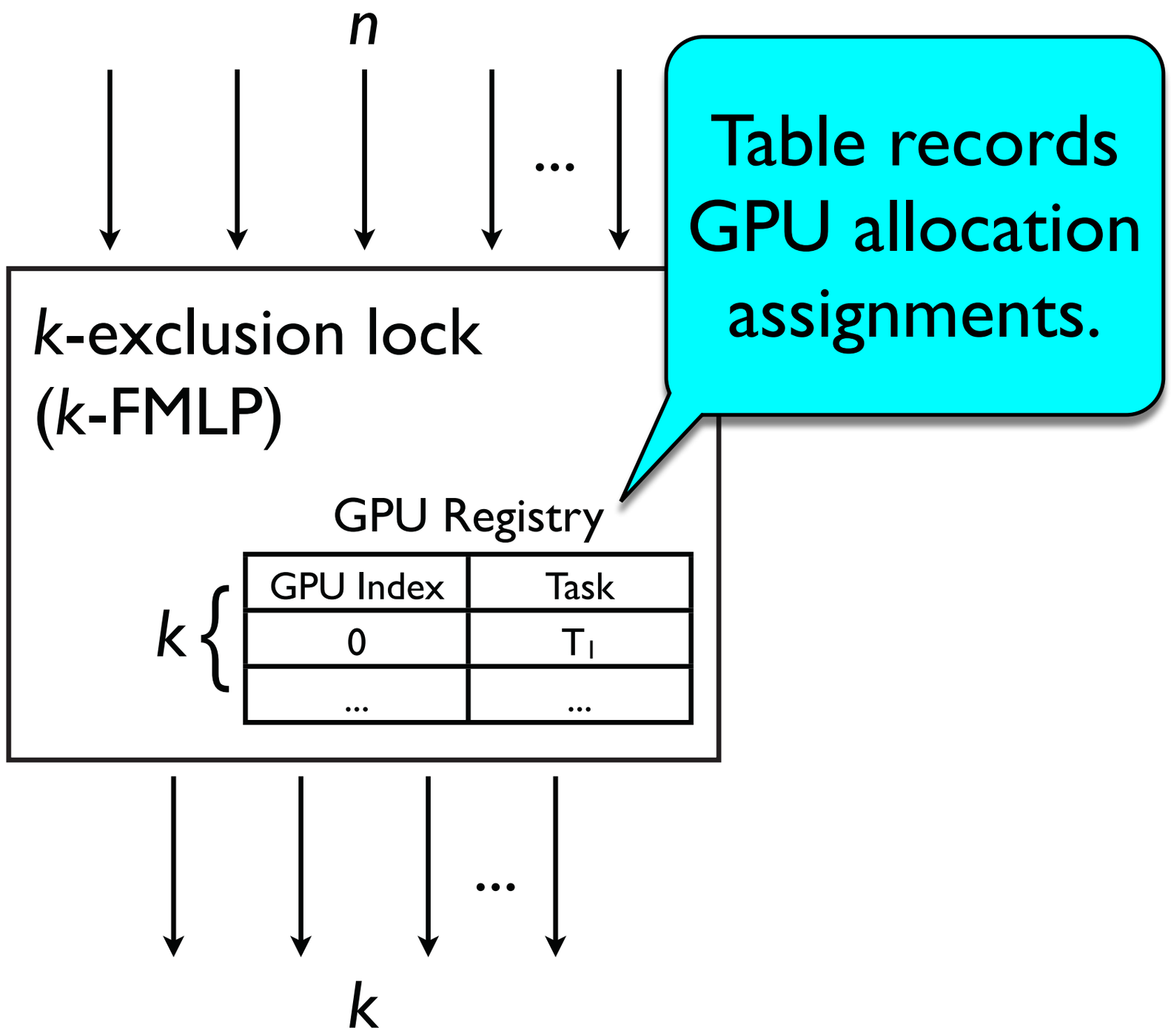
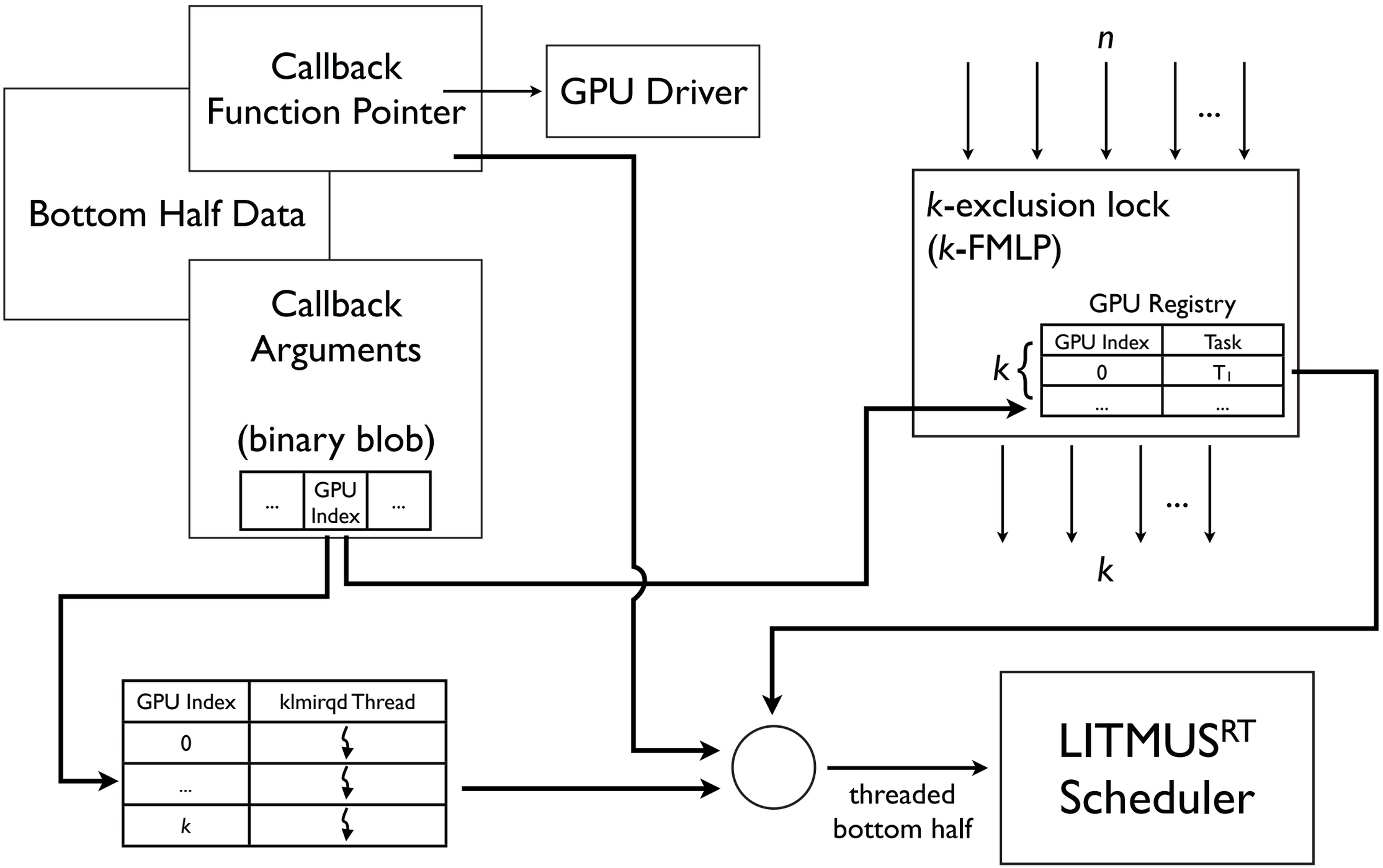
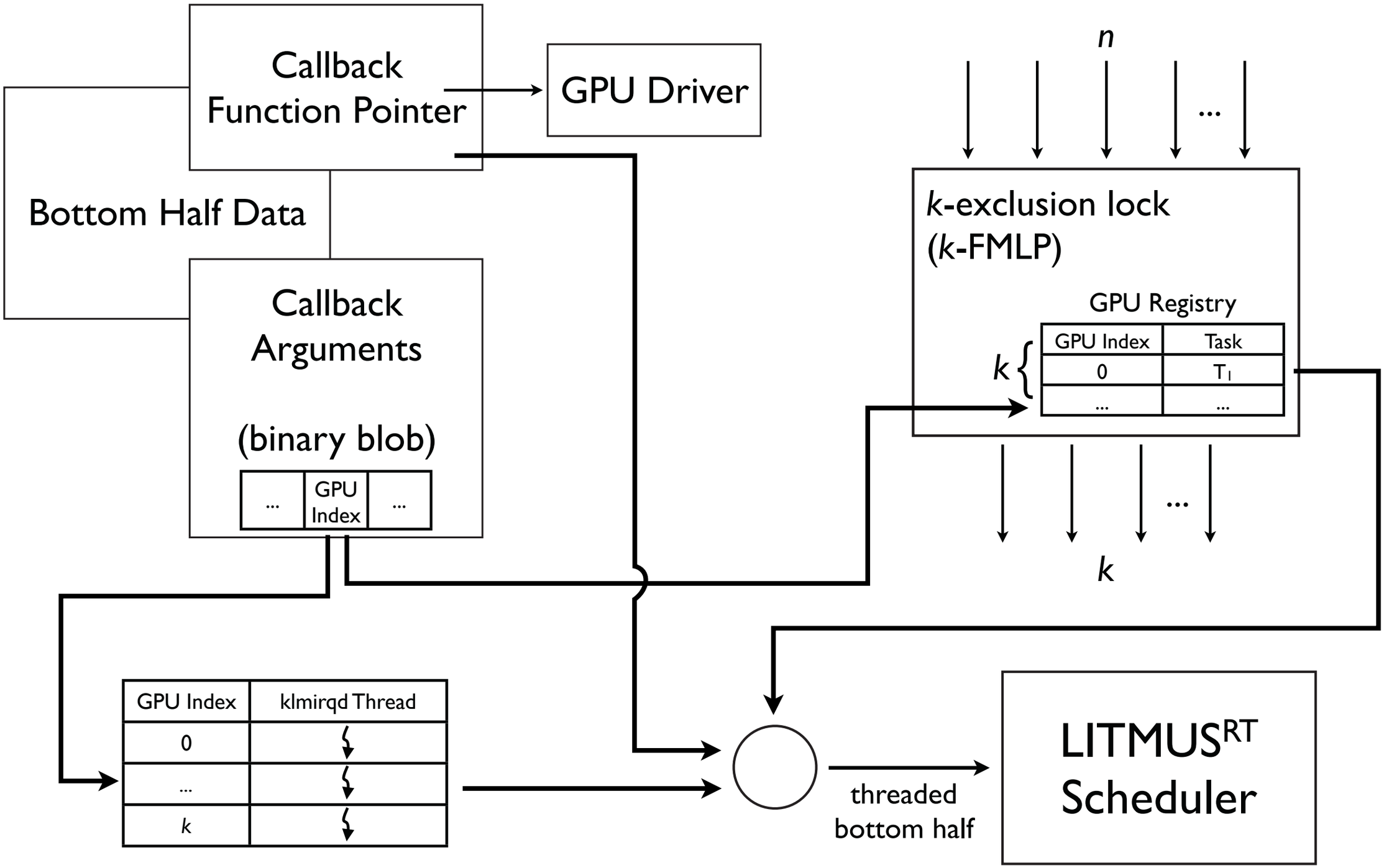


GPU Allocation



klmirqd GPU Threads



klmirqd GPU Threads

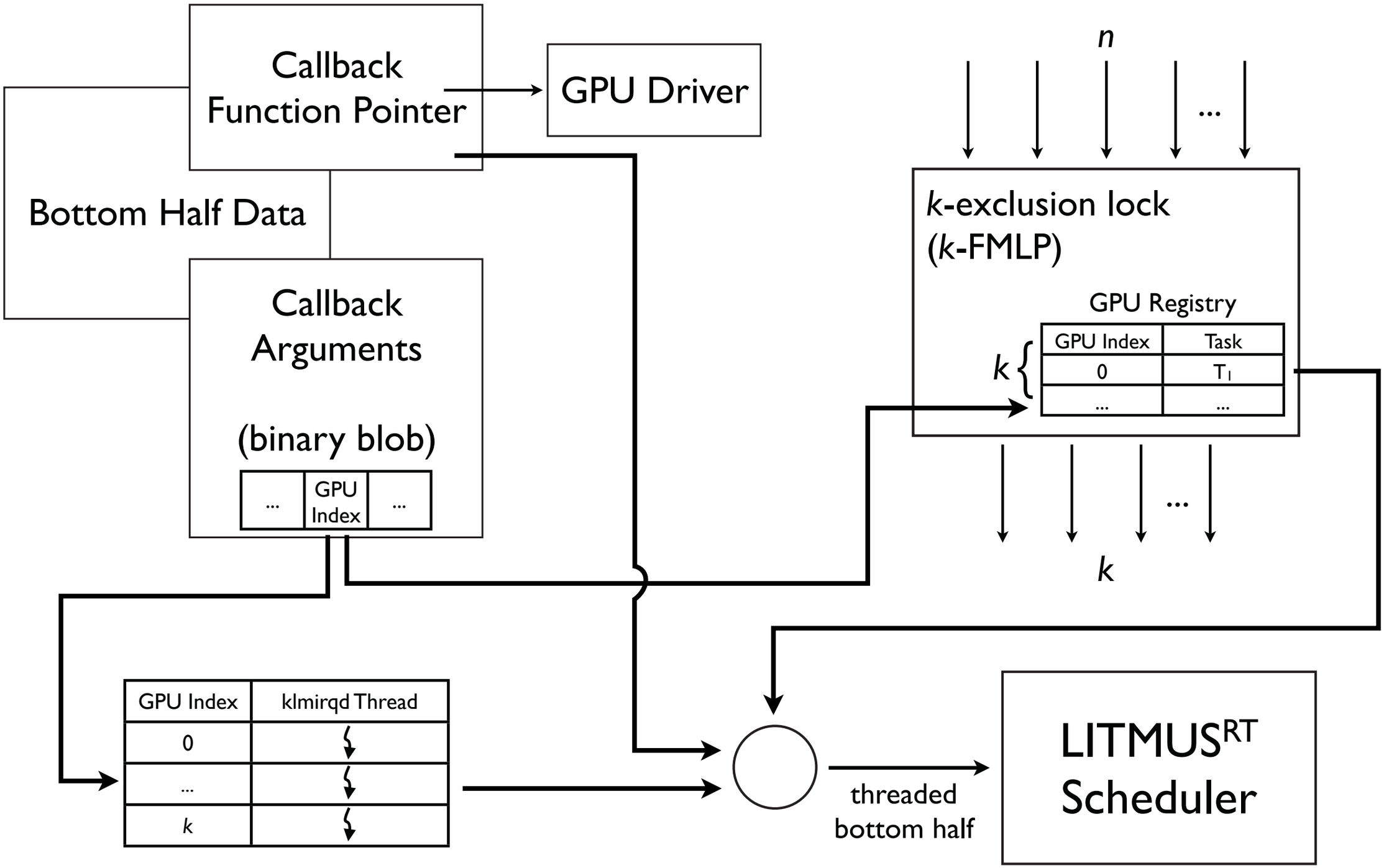
GPU Index	klmirqd Thread
0	
...	
k	

klmirqd GPU Th

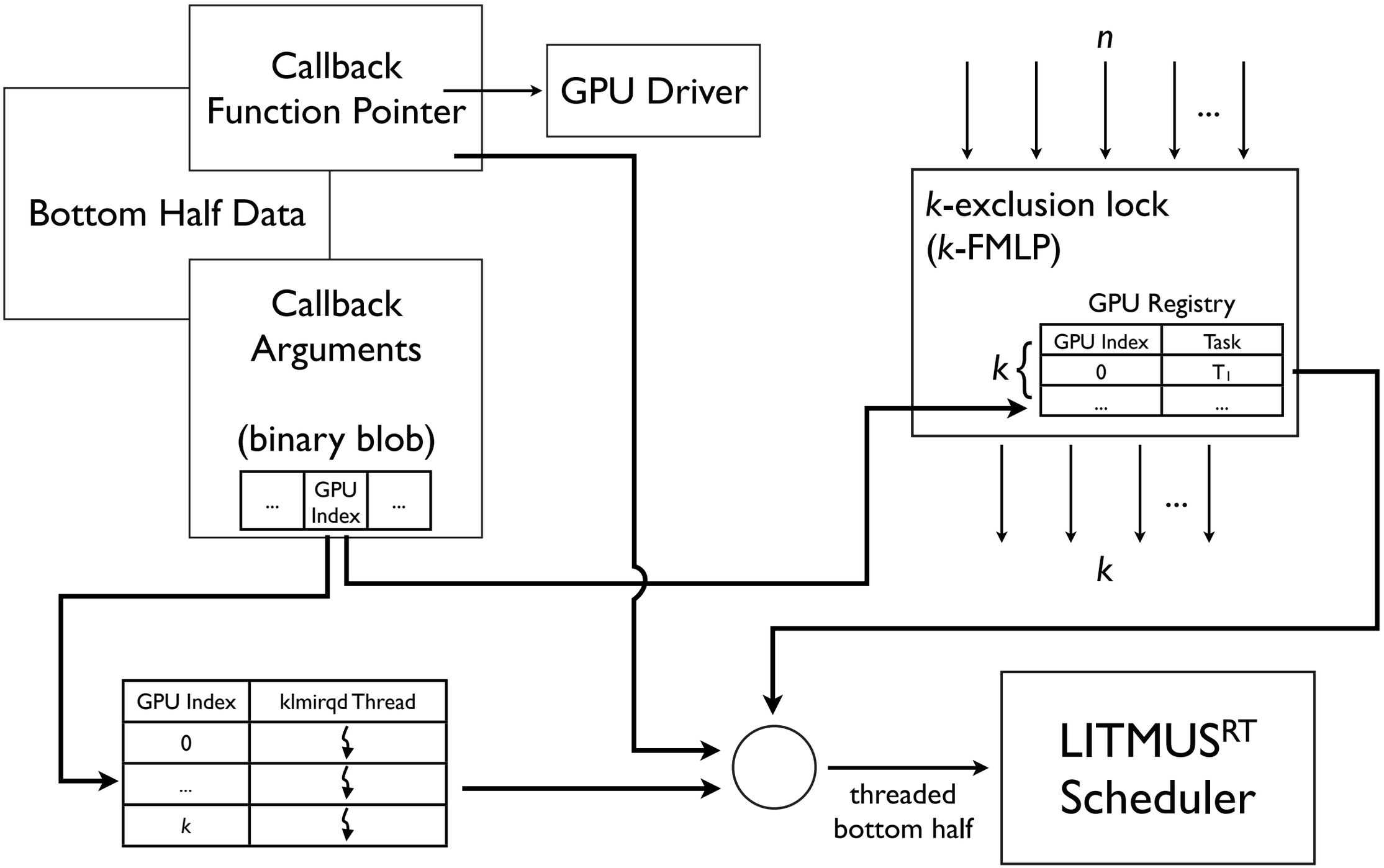
One klmirqd thread per GPU.

GPU Index	klmirqd Thread
0	
...	
k	

klmirqd GPU Threads

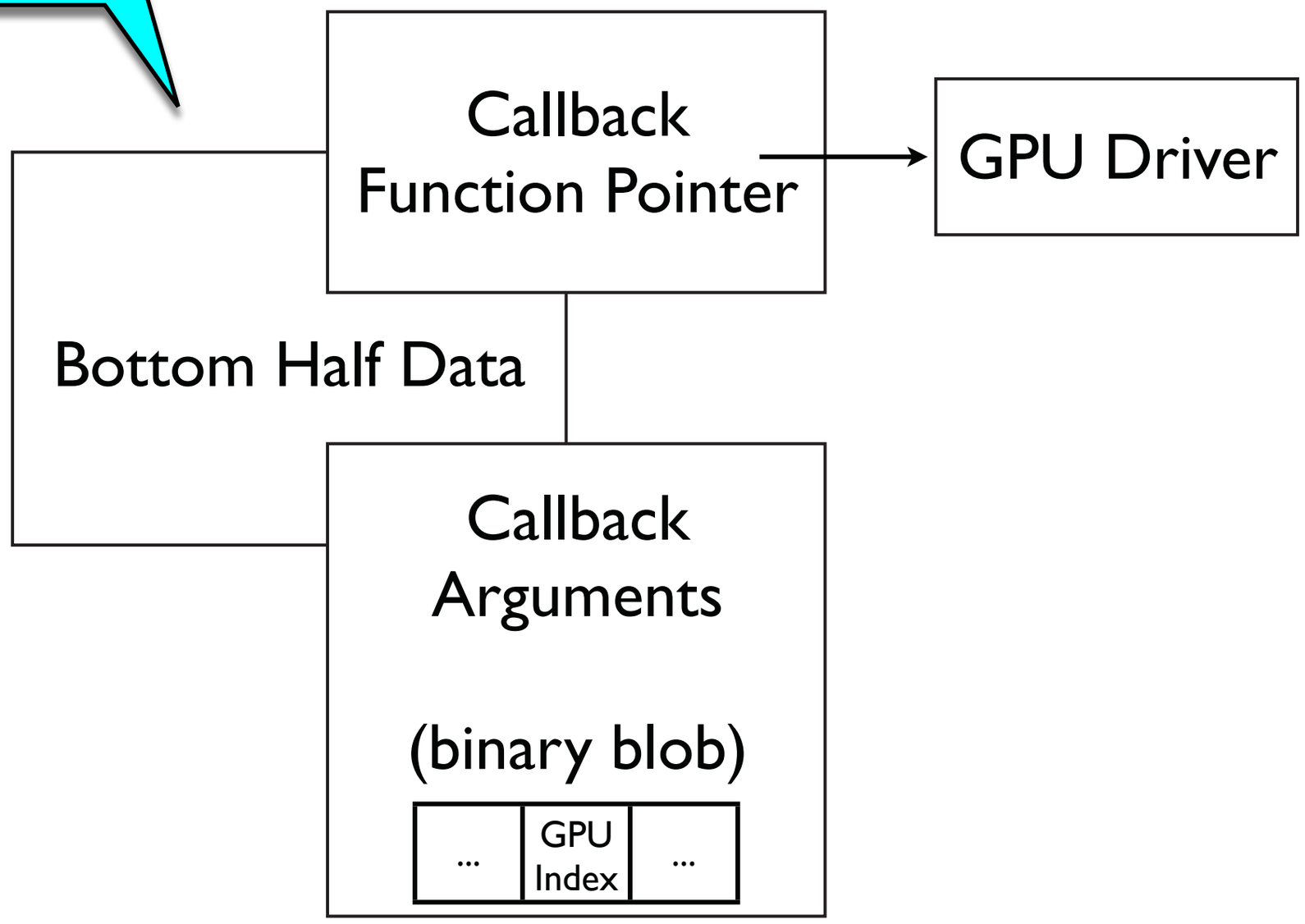


Interrupt Interception

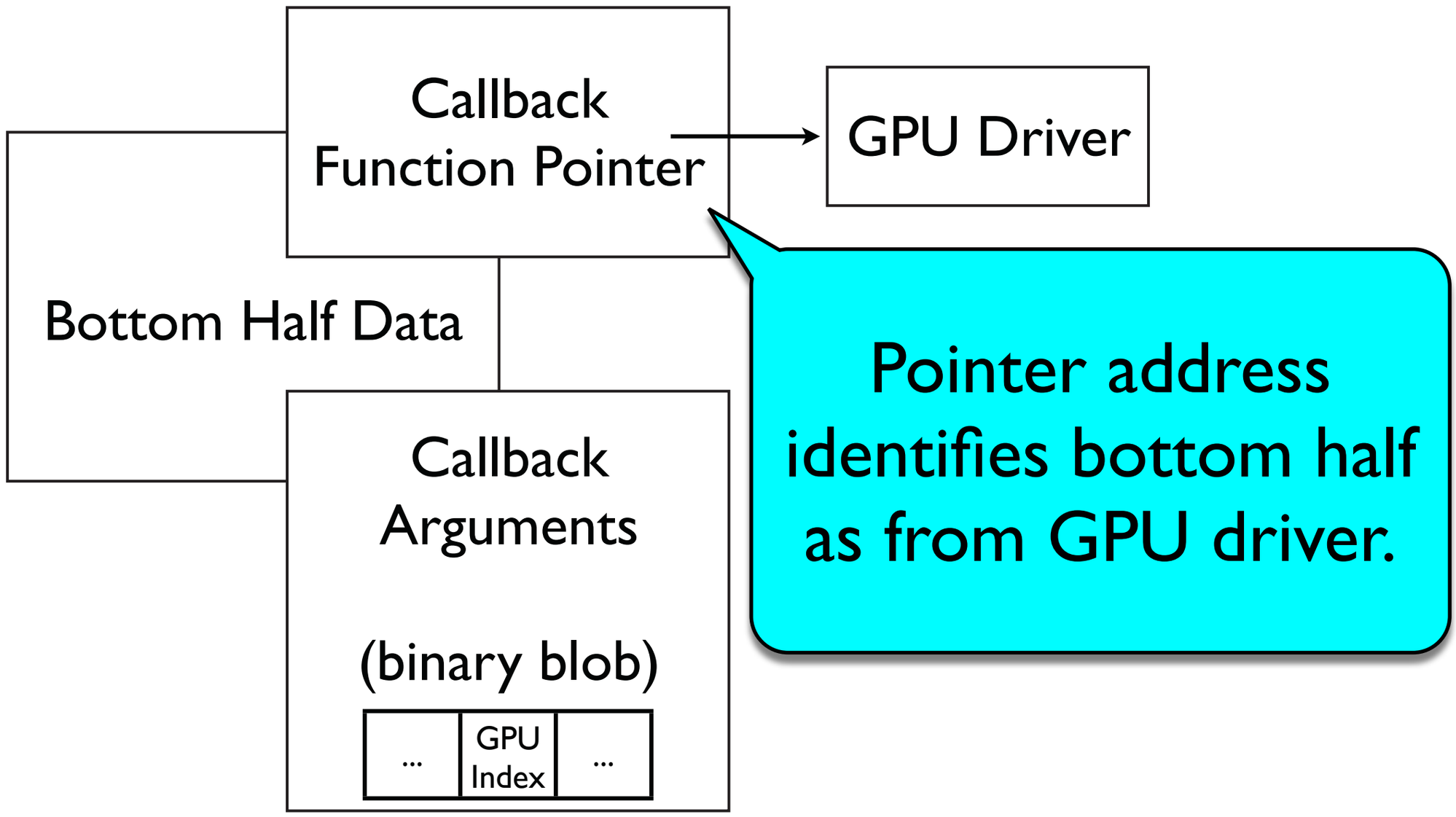


terrupt Interception

Spawned by top half.



Interrupt Interception



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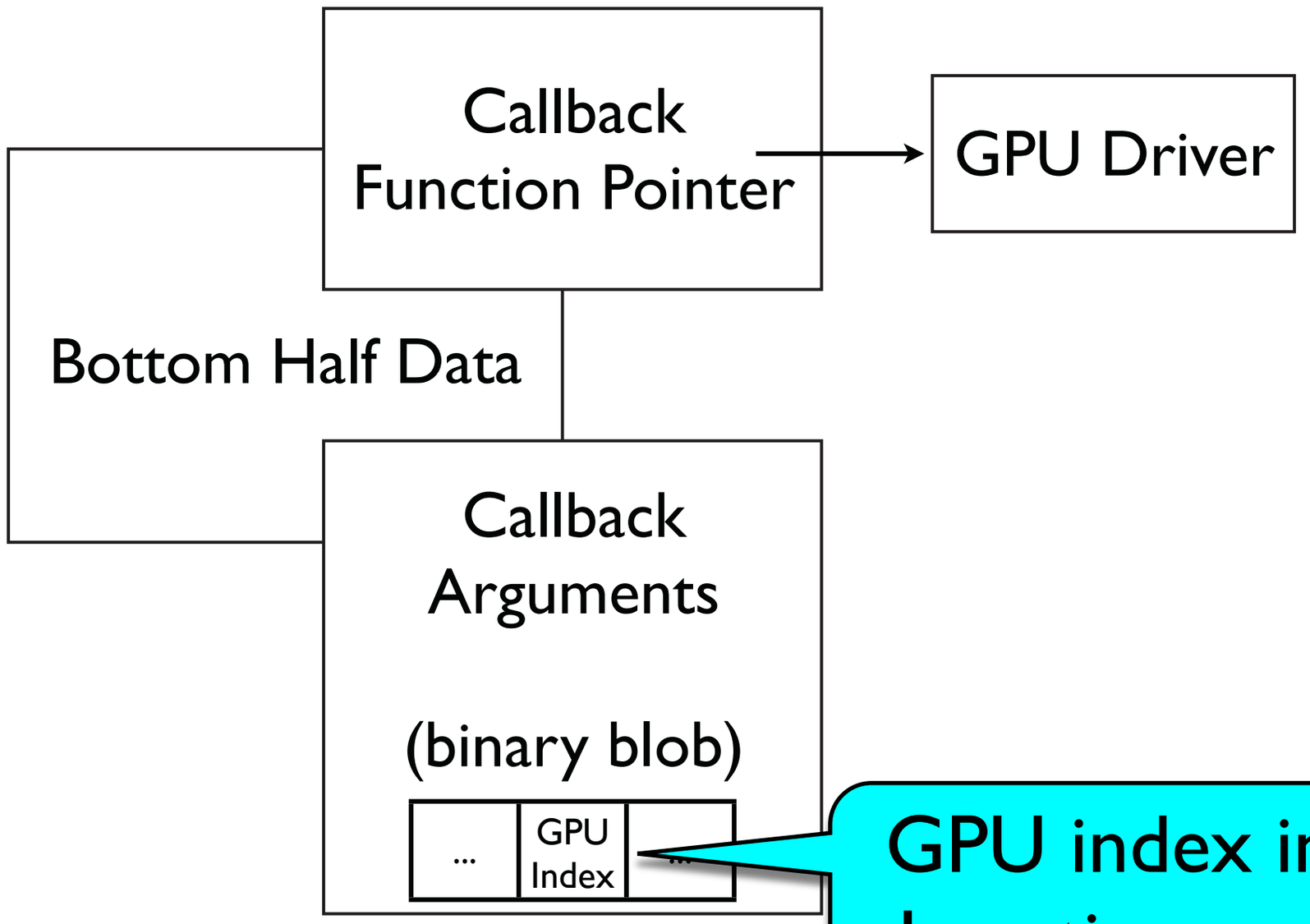

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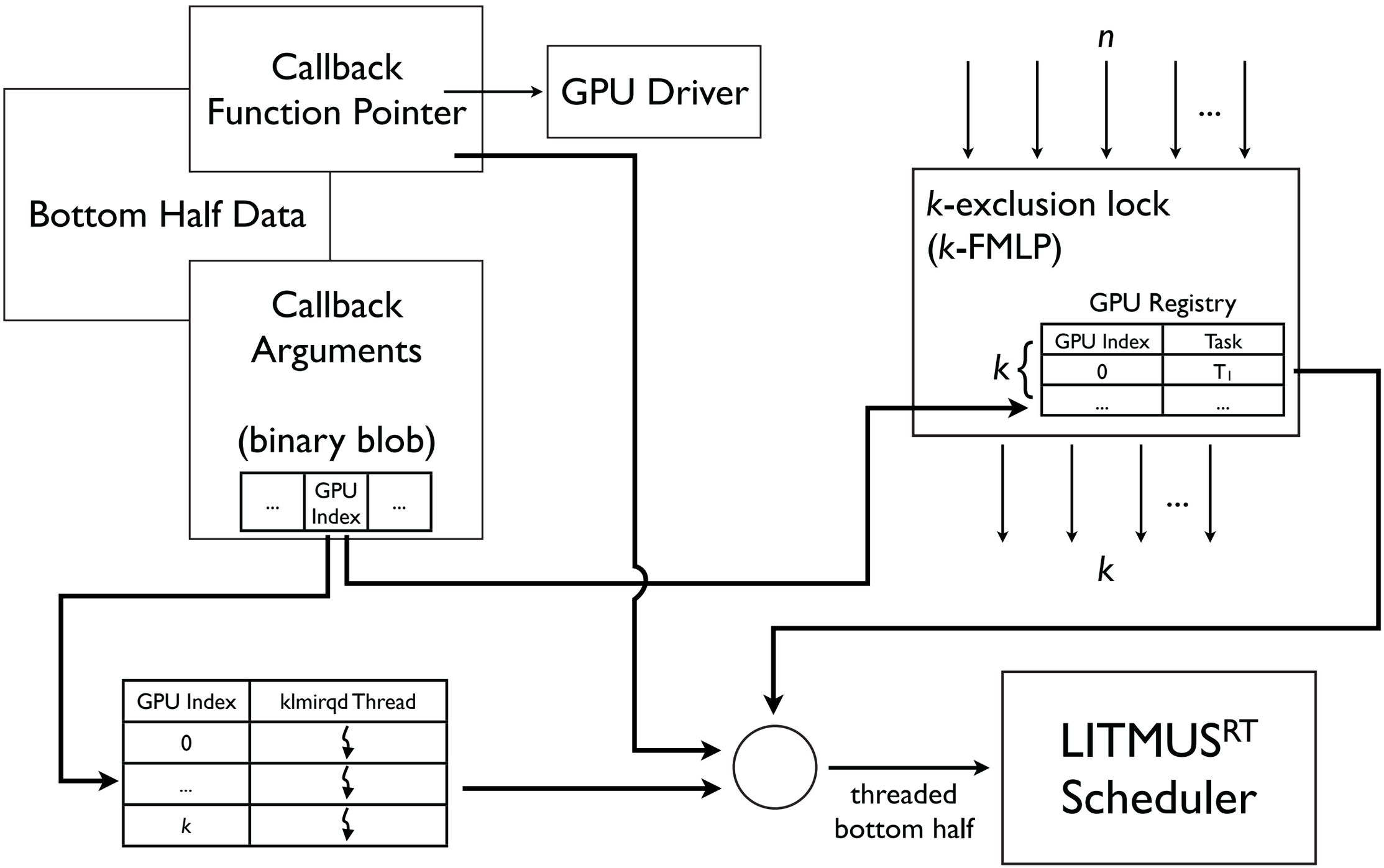
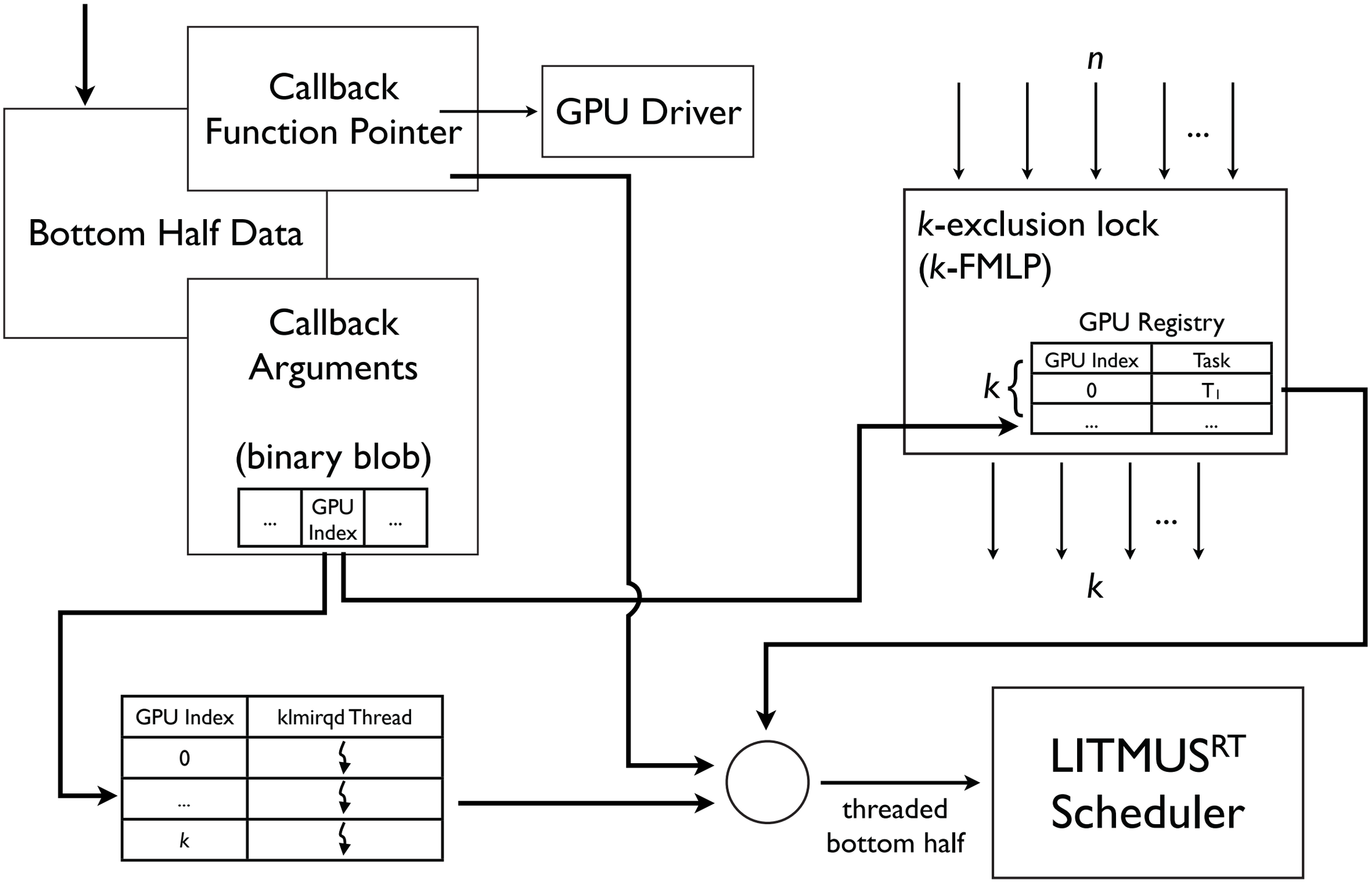


GPU Interrupt Handling



rrupt Handling

GPU bottom half arrives.

Callback
Function Pointer

GPU Driver

Bottom Half Data

Callback
Arguments

(binary blob)

...	GPU Index	...

n

k-exclusion lock
(*k*-FMLP)

GPU Registry

GPU Index	Task
0	T_1
...	...

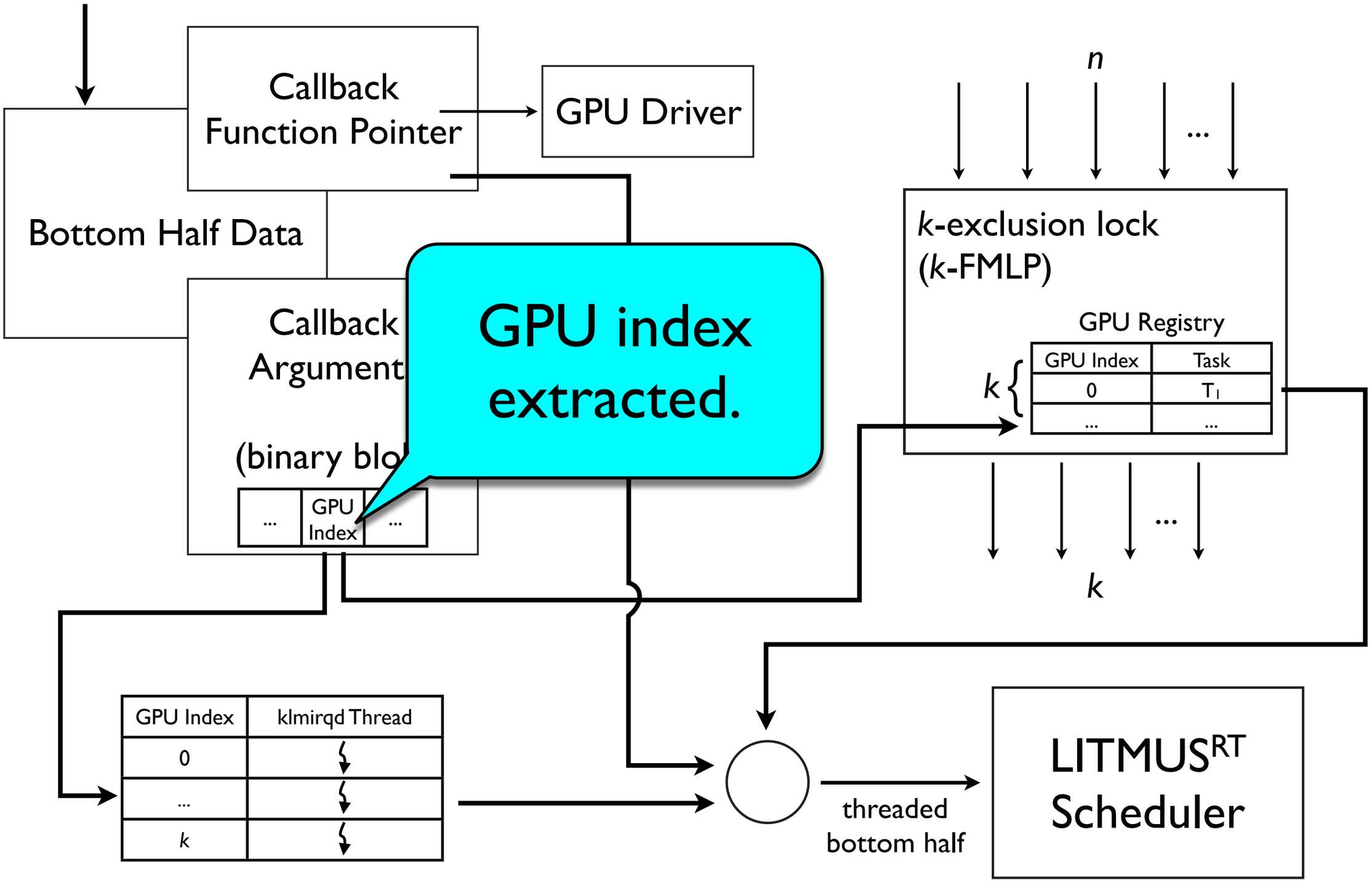
k

GPU Index	klmirqd Thread
0	
...	
k	

threaded
bottom half

LITMUS^{RT}
Scheduler

GPU Interrupt Handling



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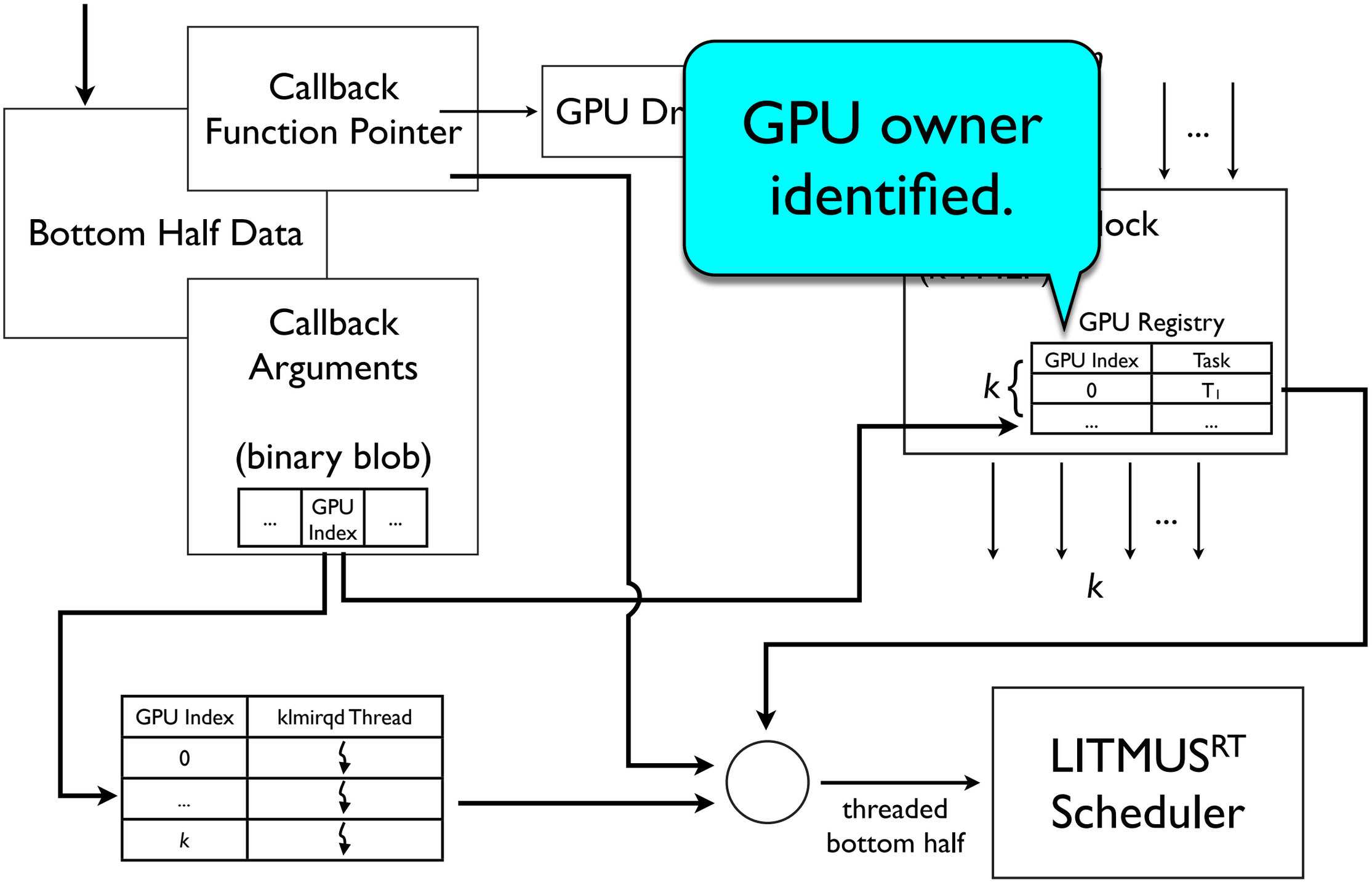

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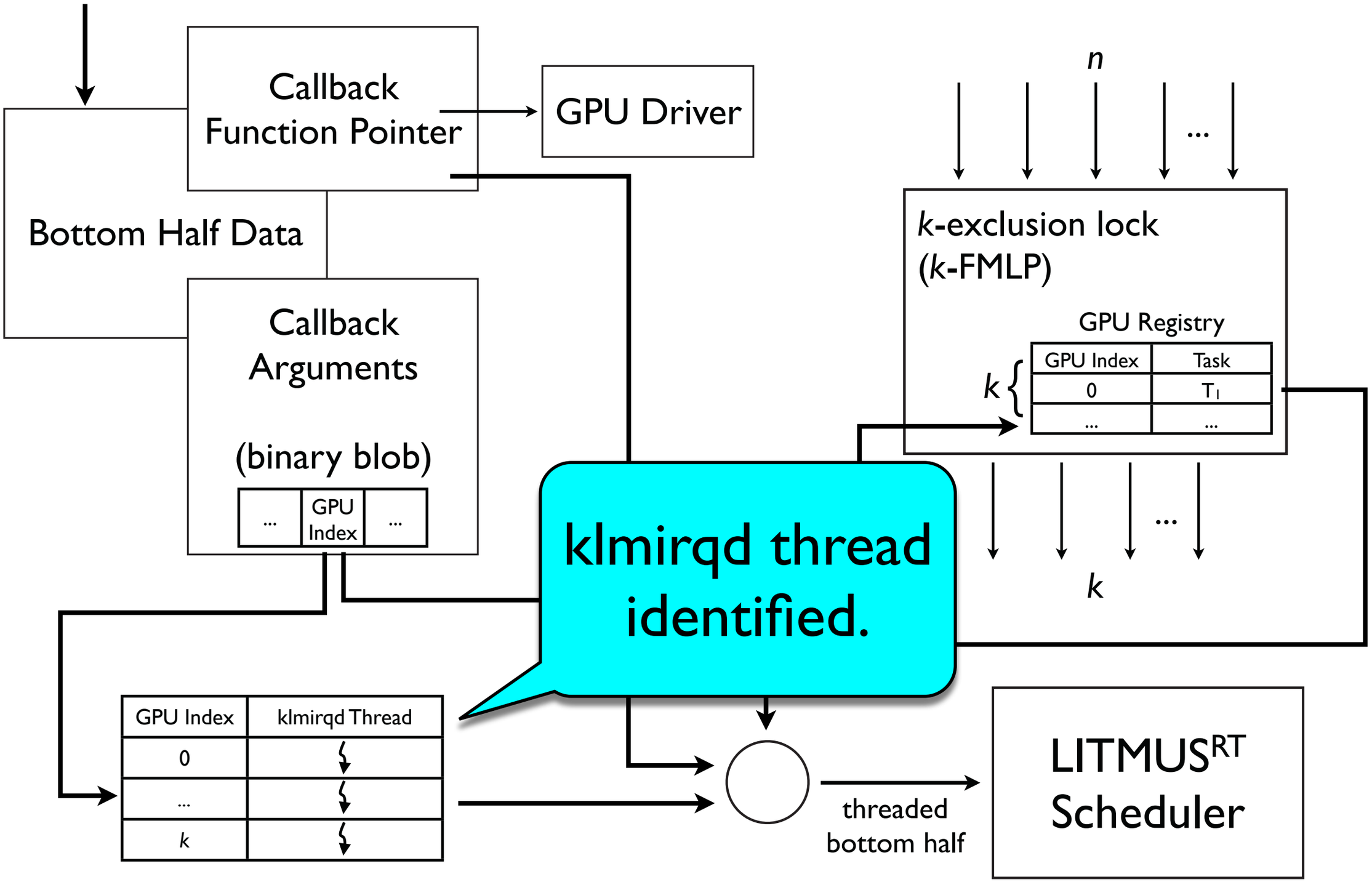

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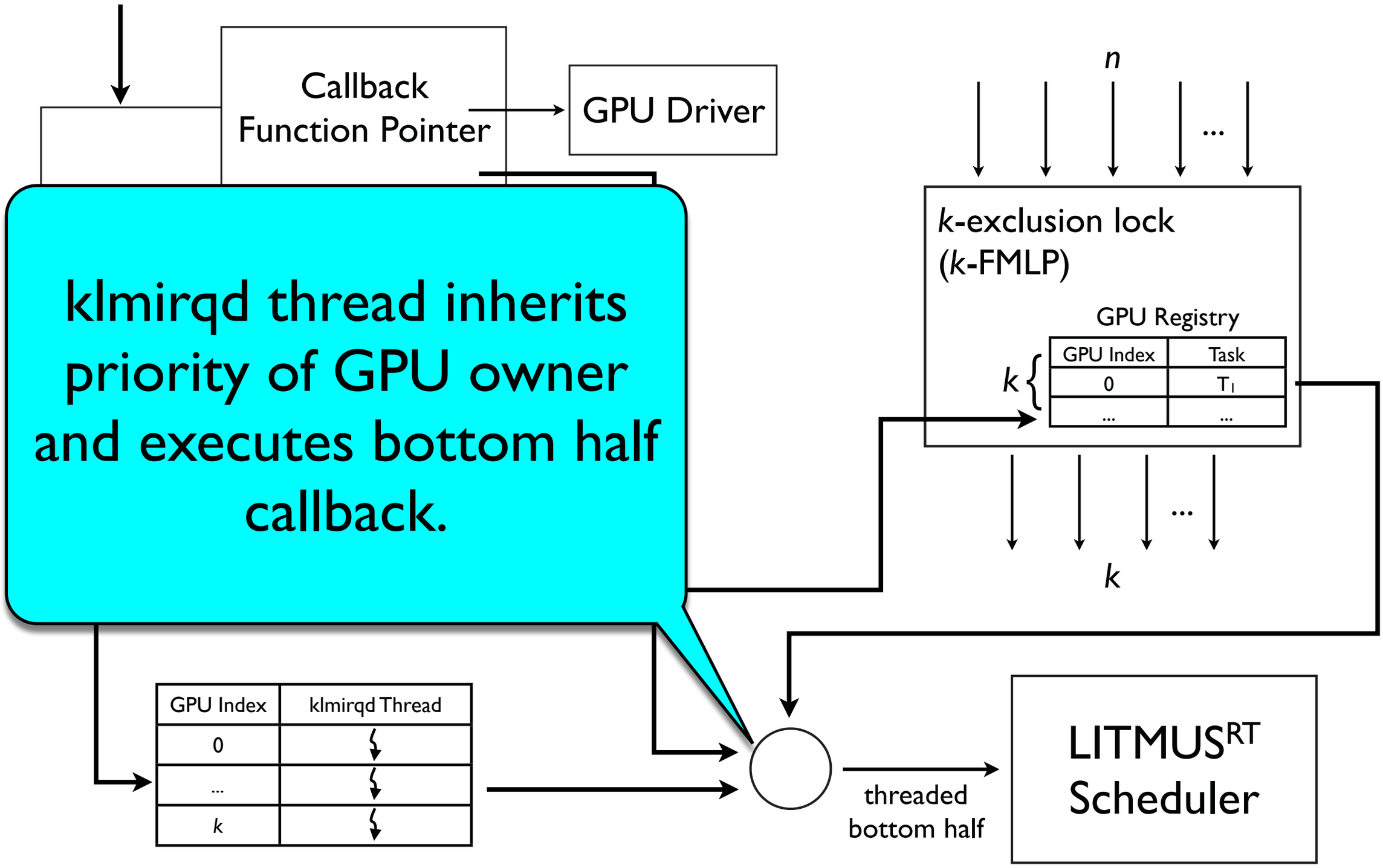

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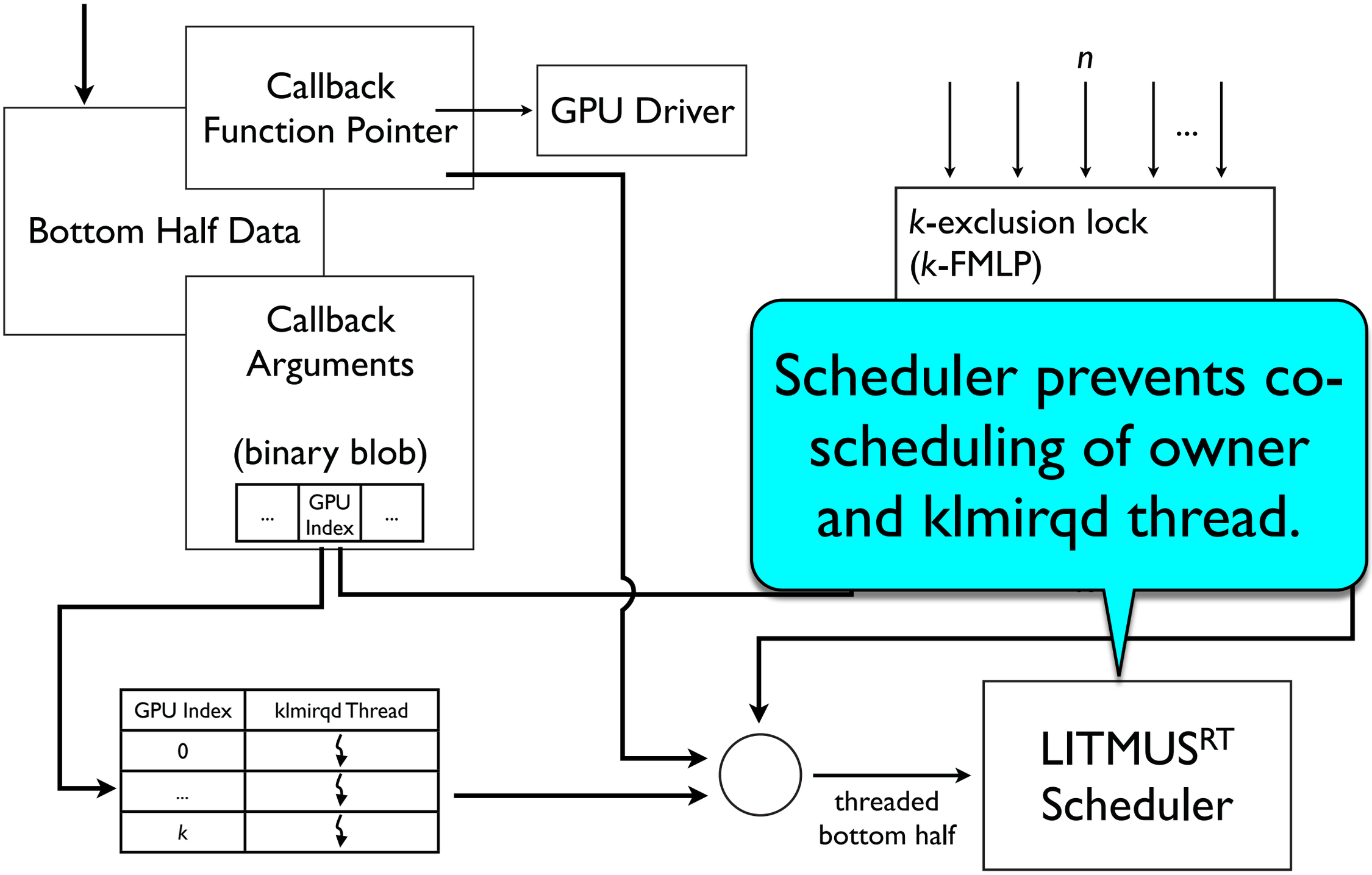

Evaluation

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- Test platform:

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- Test platform:
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  - Two six-core Xeon X5060 processors at 2.67GHz
  - Eight NVIDIA GTX-470 GPUs
  - Scheduled in clusters along NUMA boundaries
    - One X5060 and four GPUs per cluster

Effect on Priority Inversions

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- Inversions measured in LITMUS^{RT} for:

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  - klmirqd

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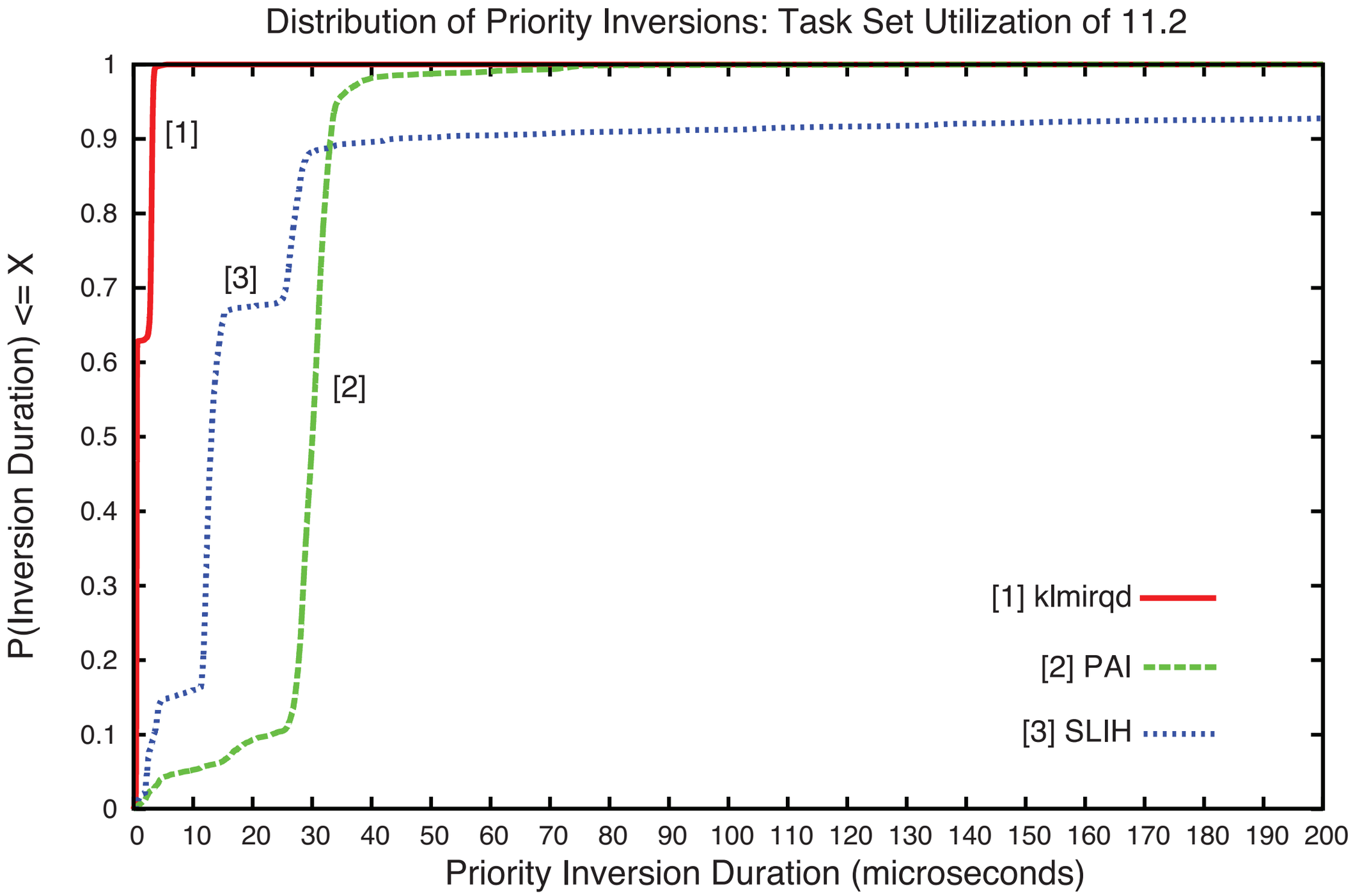
Effect on Priority Inversions



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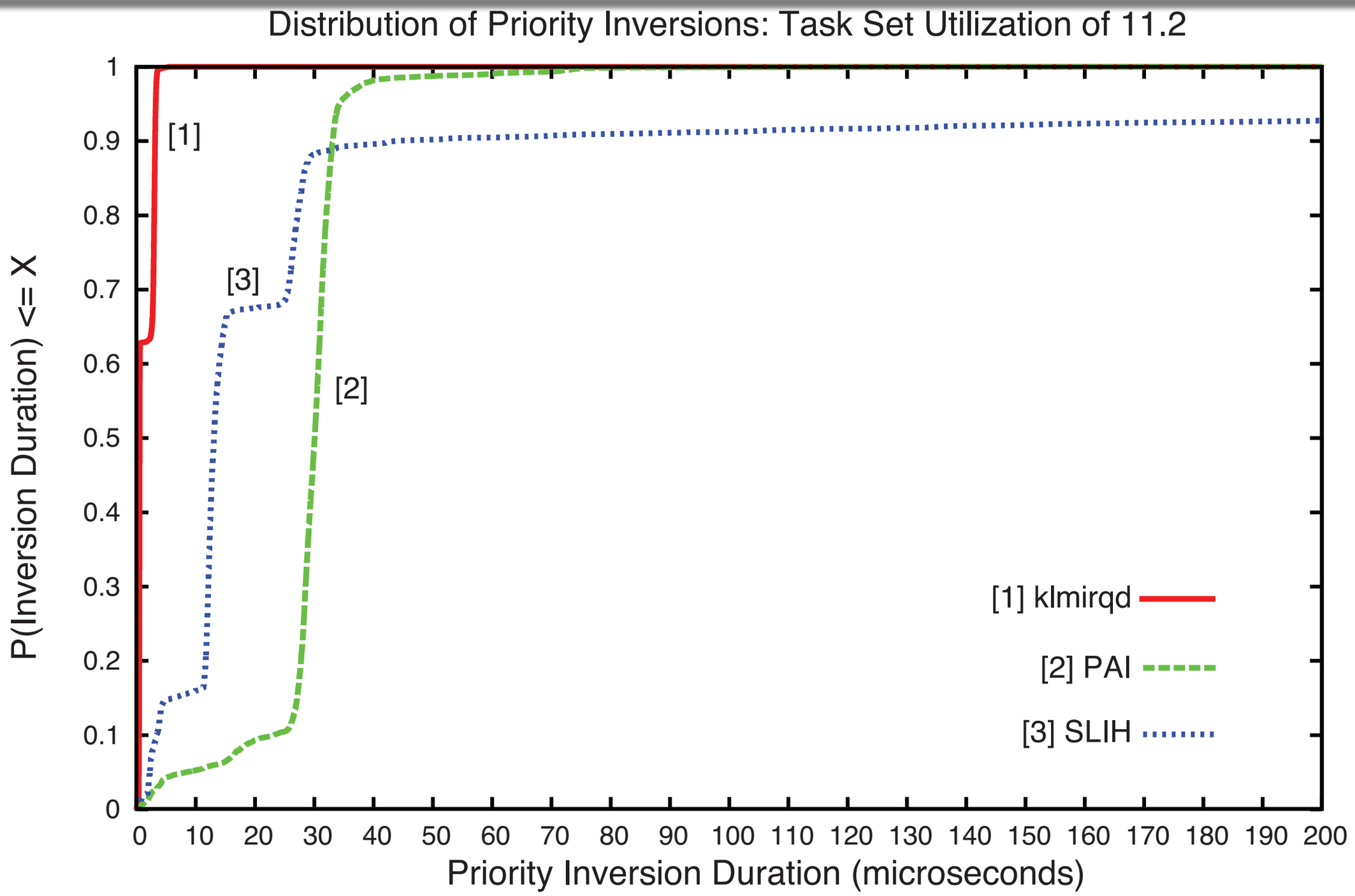
Priority inversion durations decreased.



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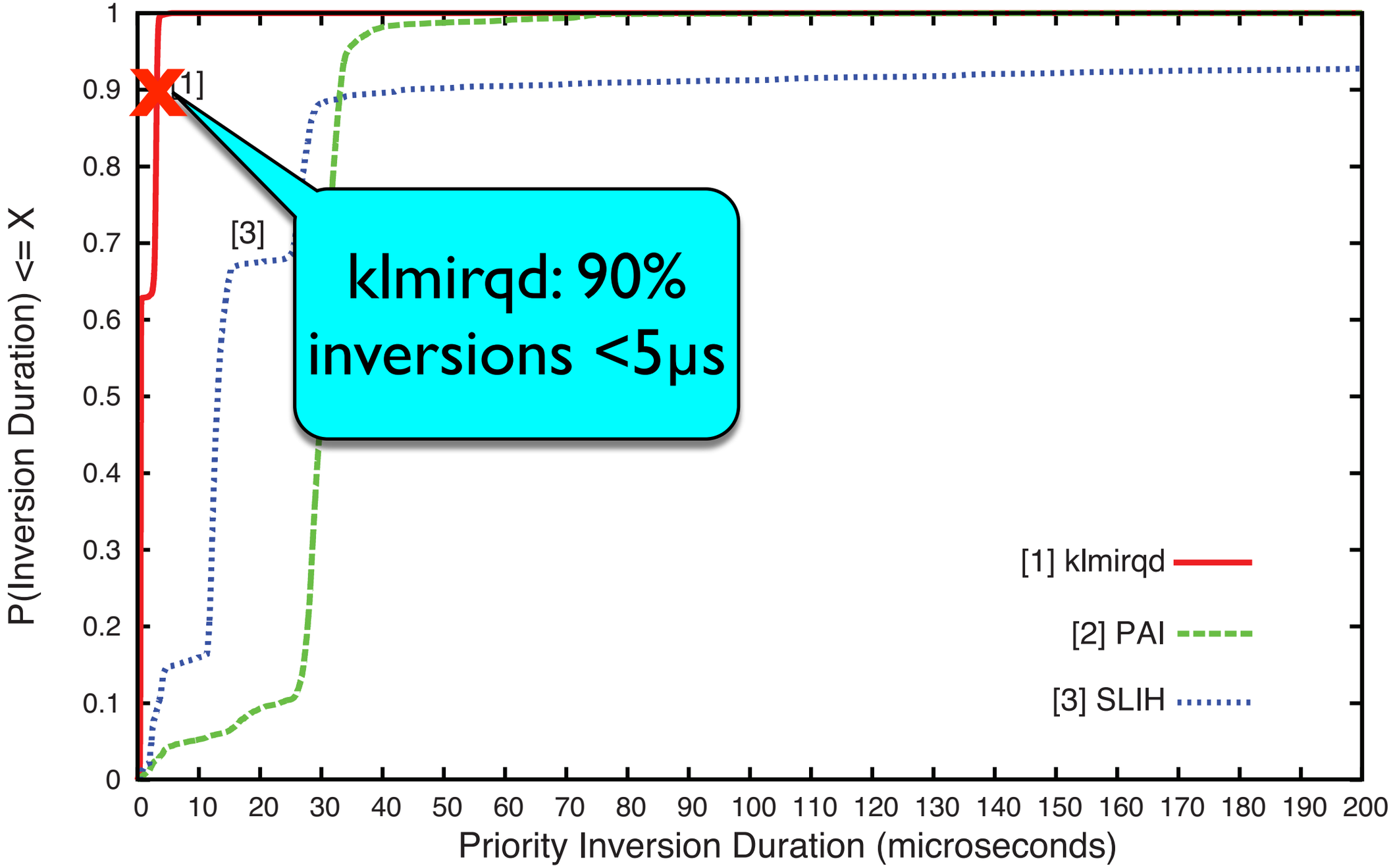

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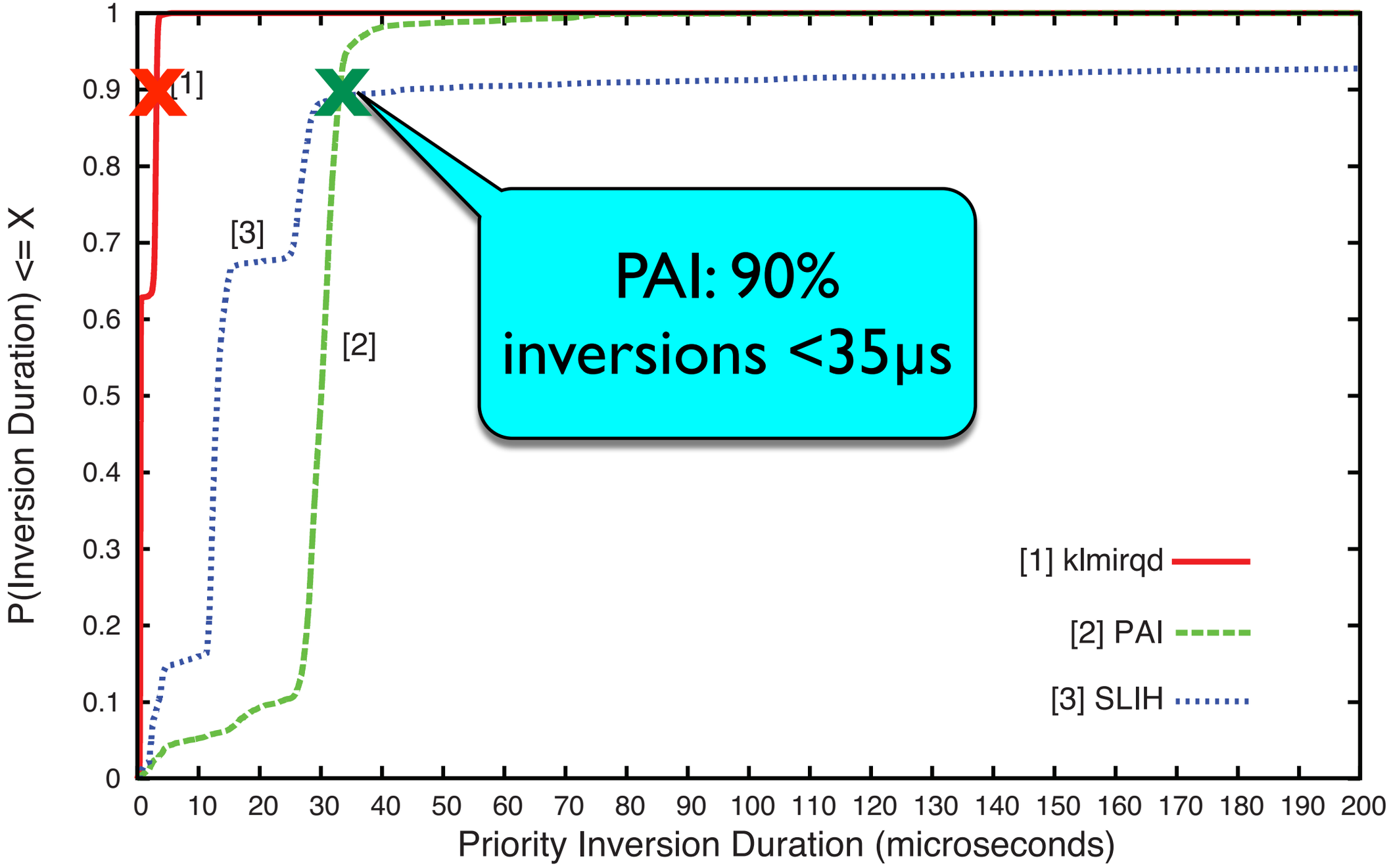

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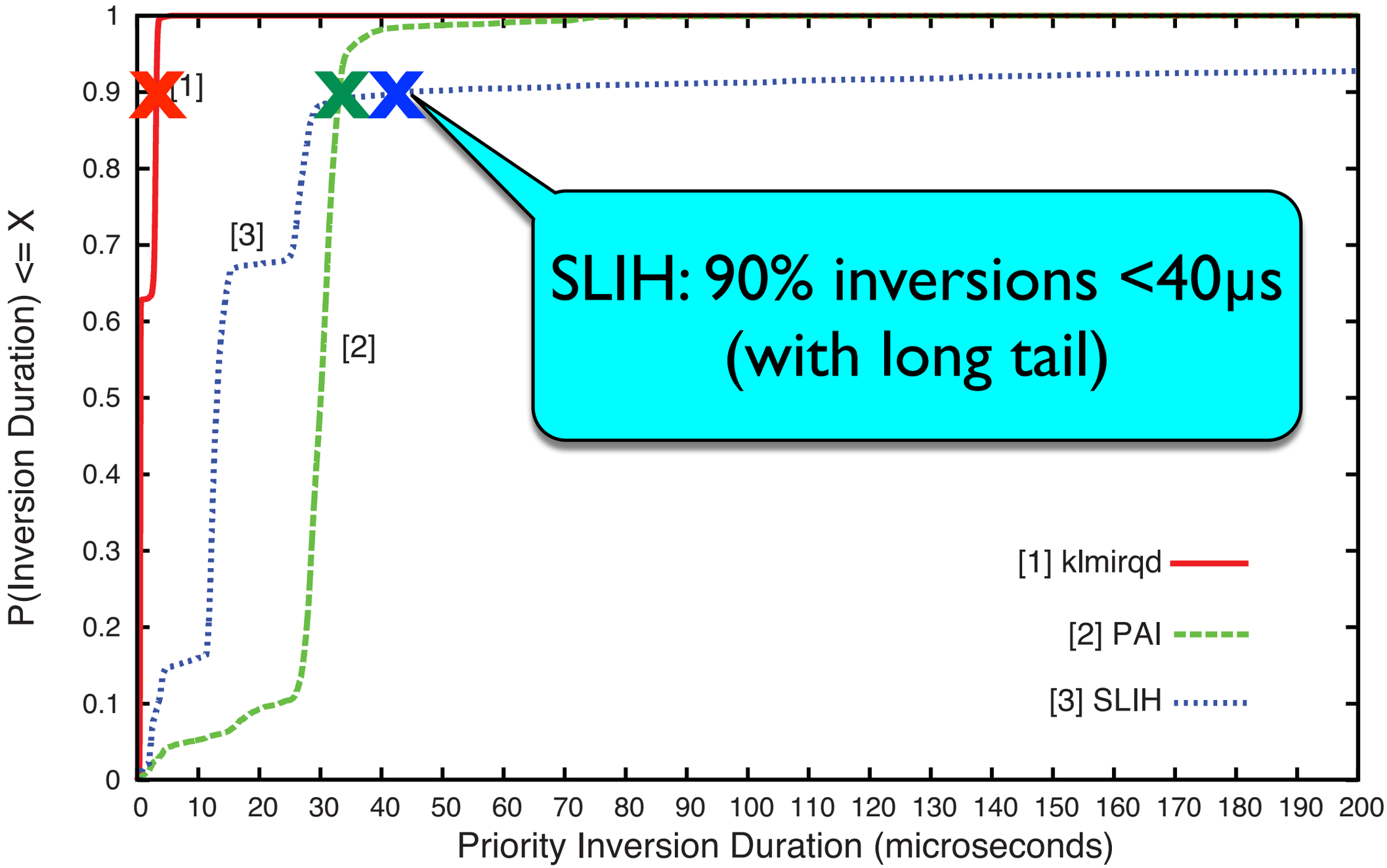

SLIH: 90% inversions <40µs (with long tail)

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Overhead-Aware Schedulability Experiments

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- Gathered overhead measurements for many system tasks (such as scheduling)
- Incorporated overheads into soft real-time schedulability experiments
  - Task sets a mix of GPU-using and CPU-only
- Different accounting techniques are required for each interrupt handling method

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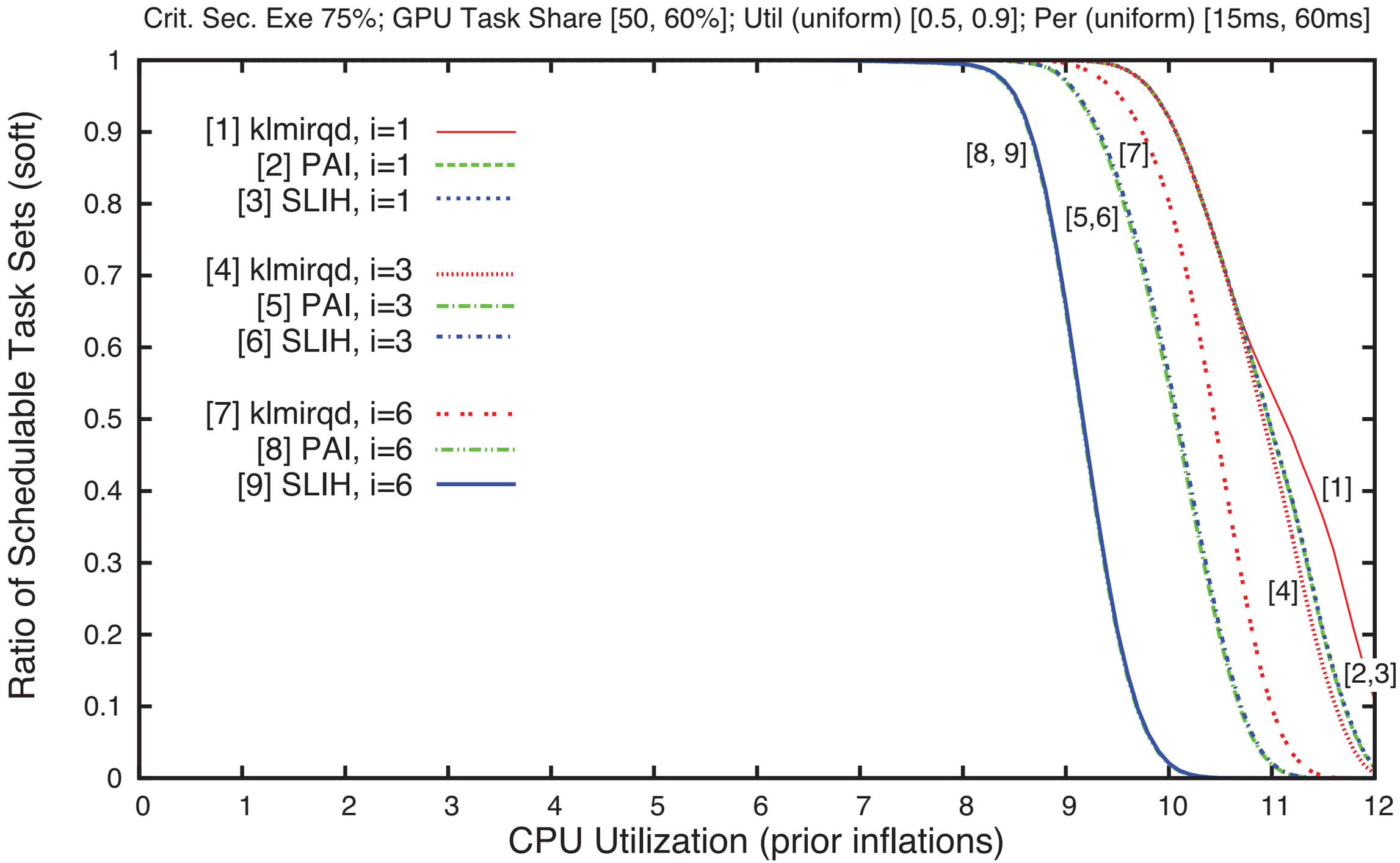
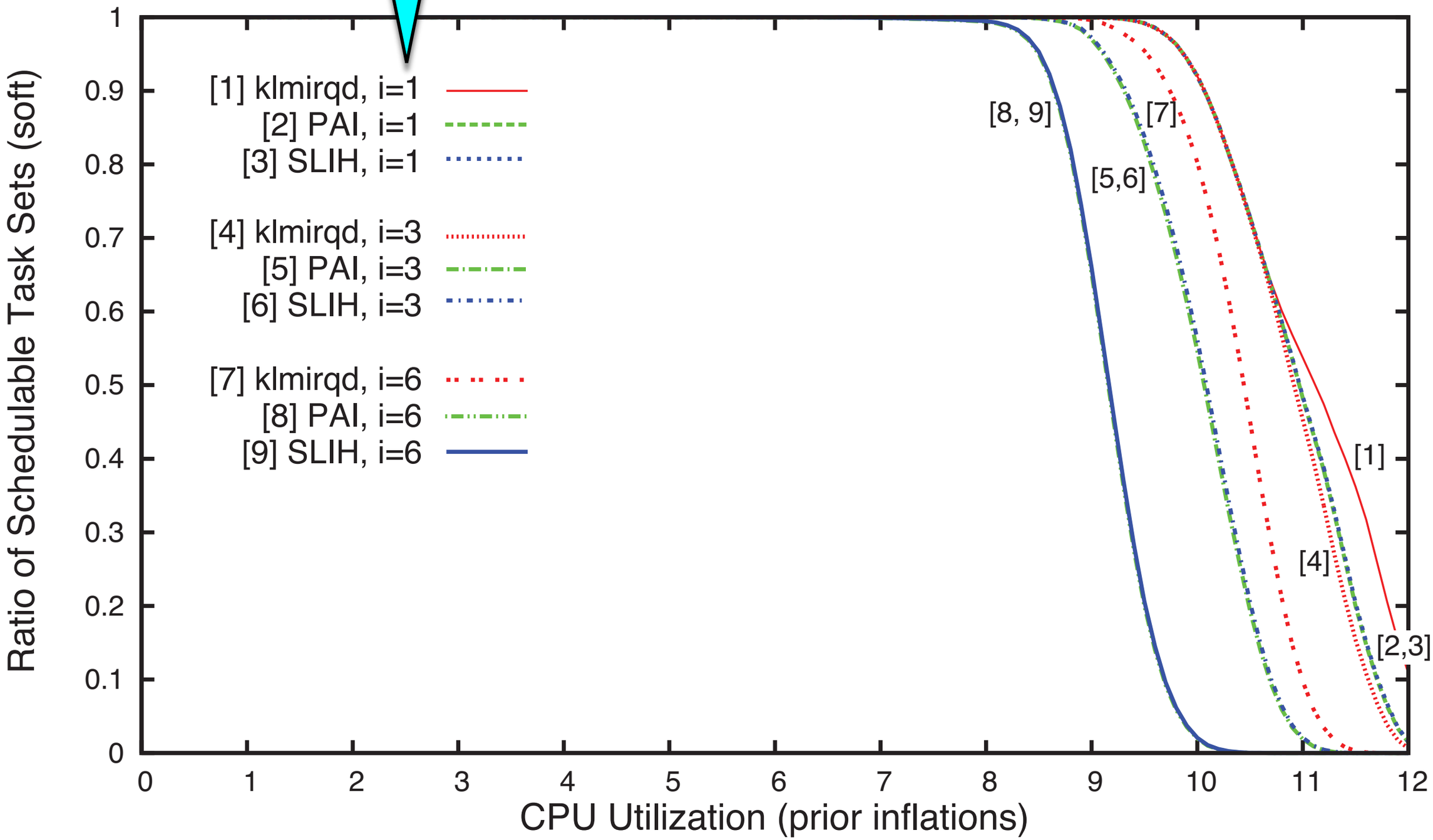
Overhead-Aware Schedulability Experiments



i is number of interrupts generated per job

vare Schedulability eriments

60%]; Util (uniform) [0.5, 0.9]; Per (uniform) [15ms, 60ms]



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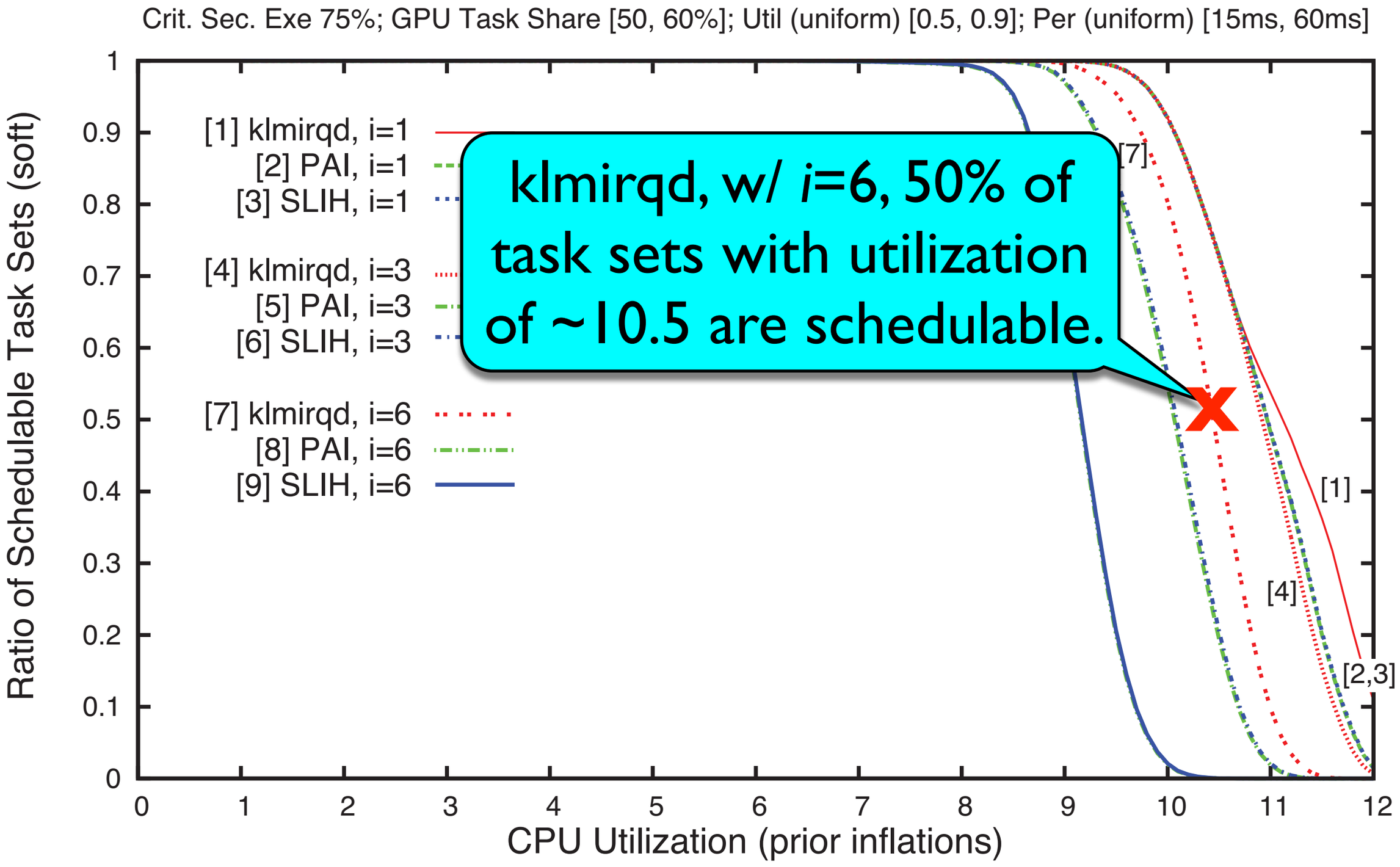

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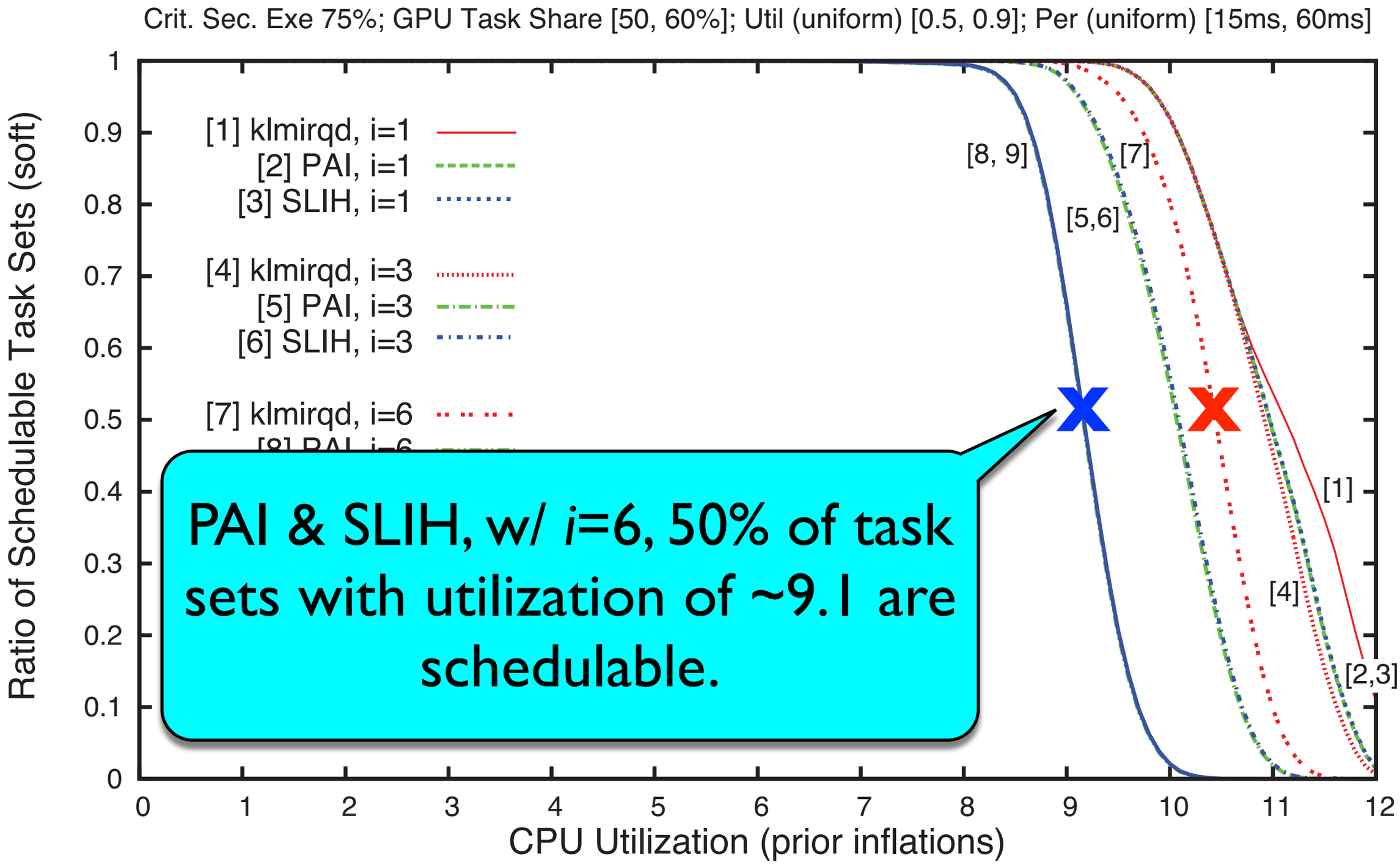

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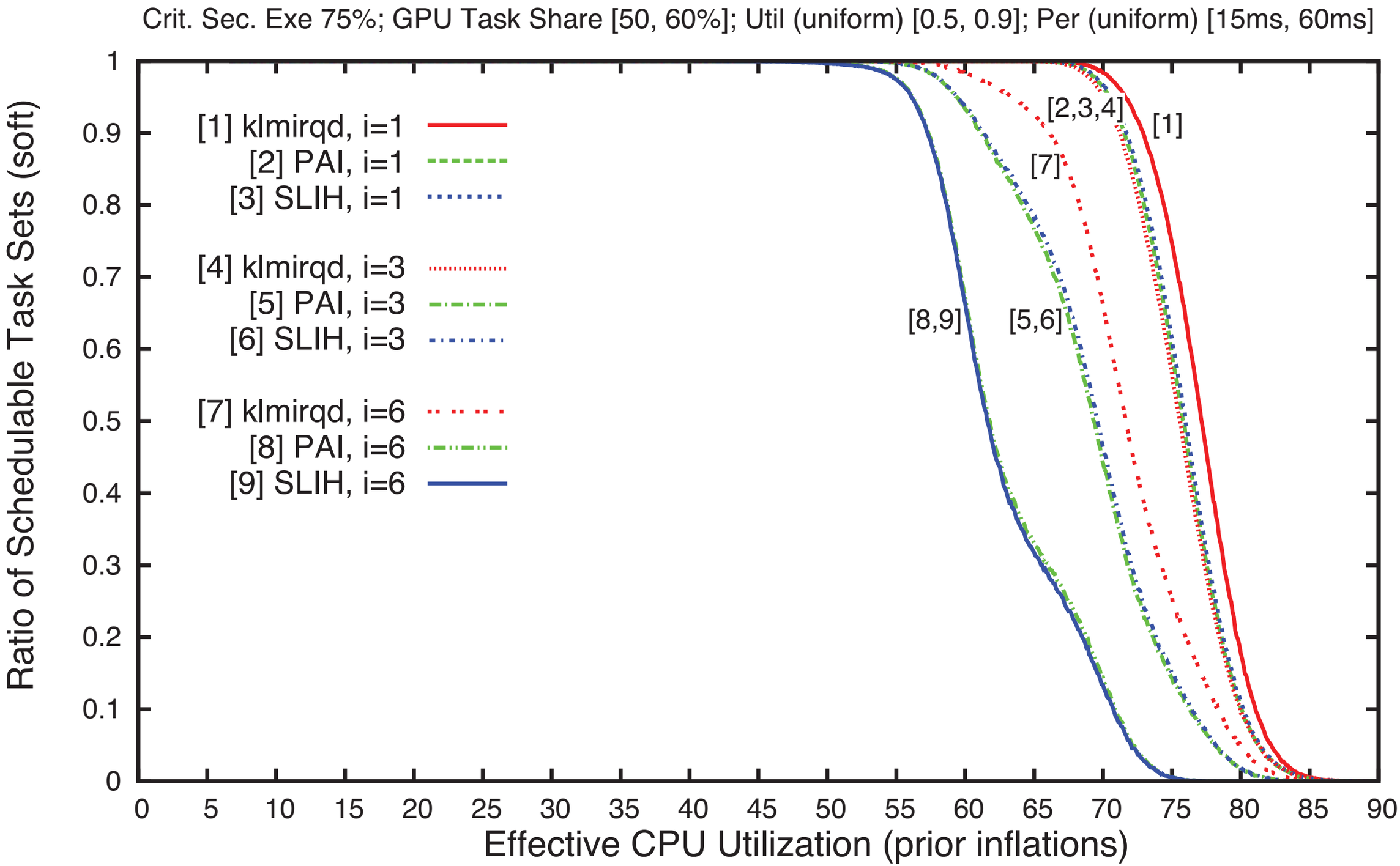

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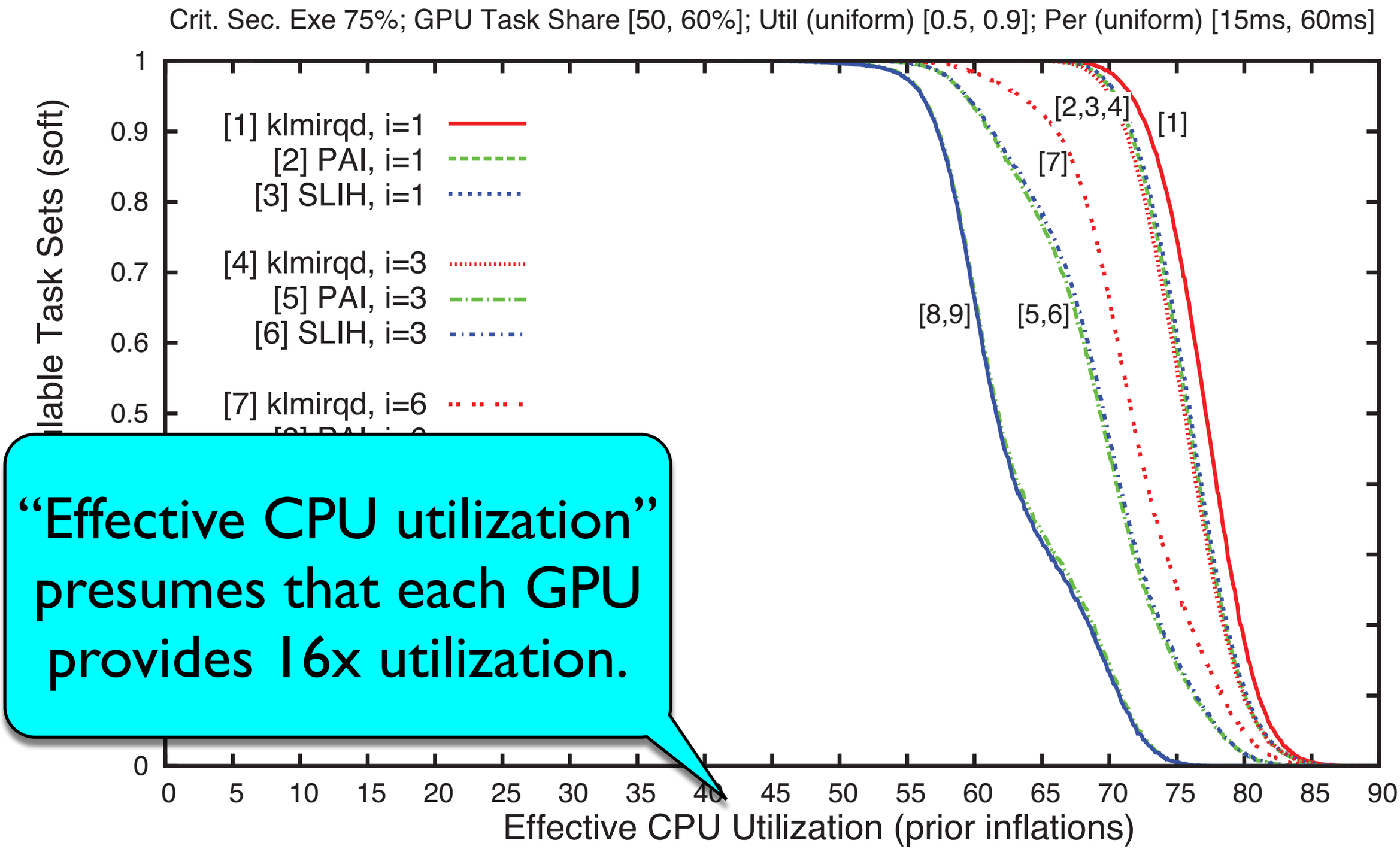

"Effective CPU utilization" presumes that each GPU provides 16x utilization.

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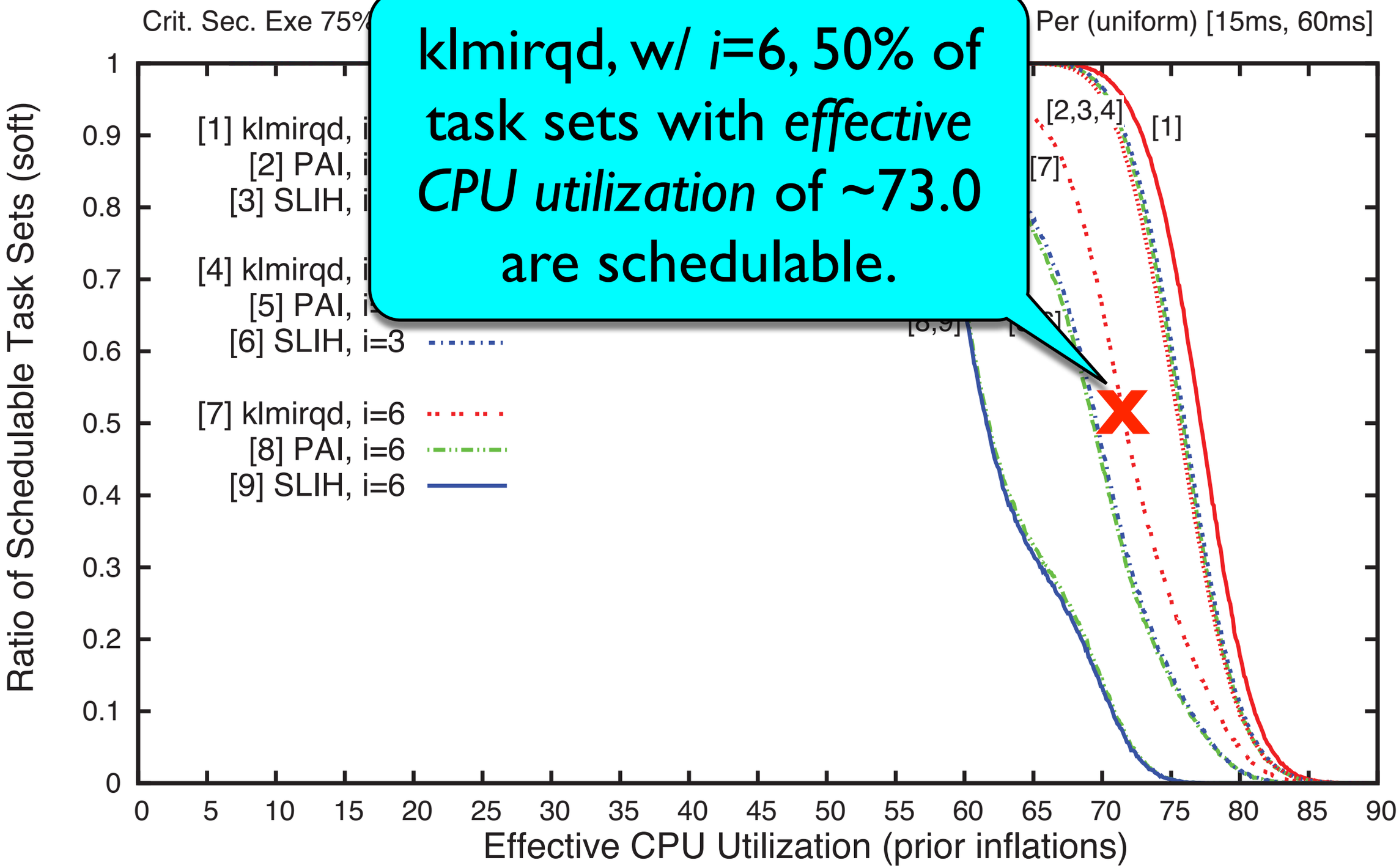
Overhead-Aware Schedulability Experiments



klmirqd, w/ *i*=6, 50% of task sets with *effective CPU utilization* of ~73.0 are schedulable.

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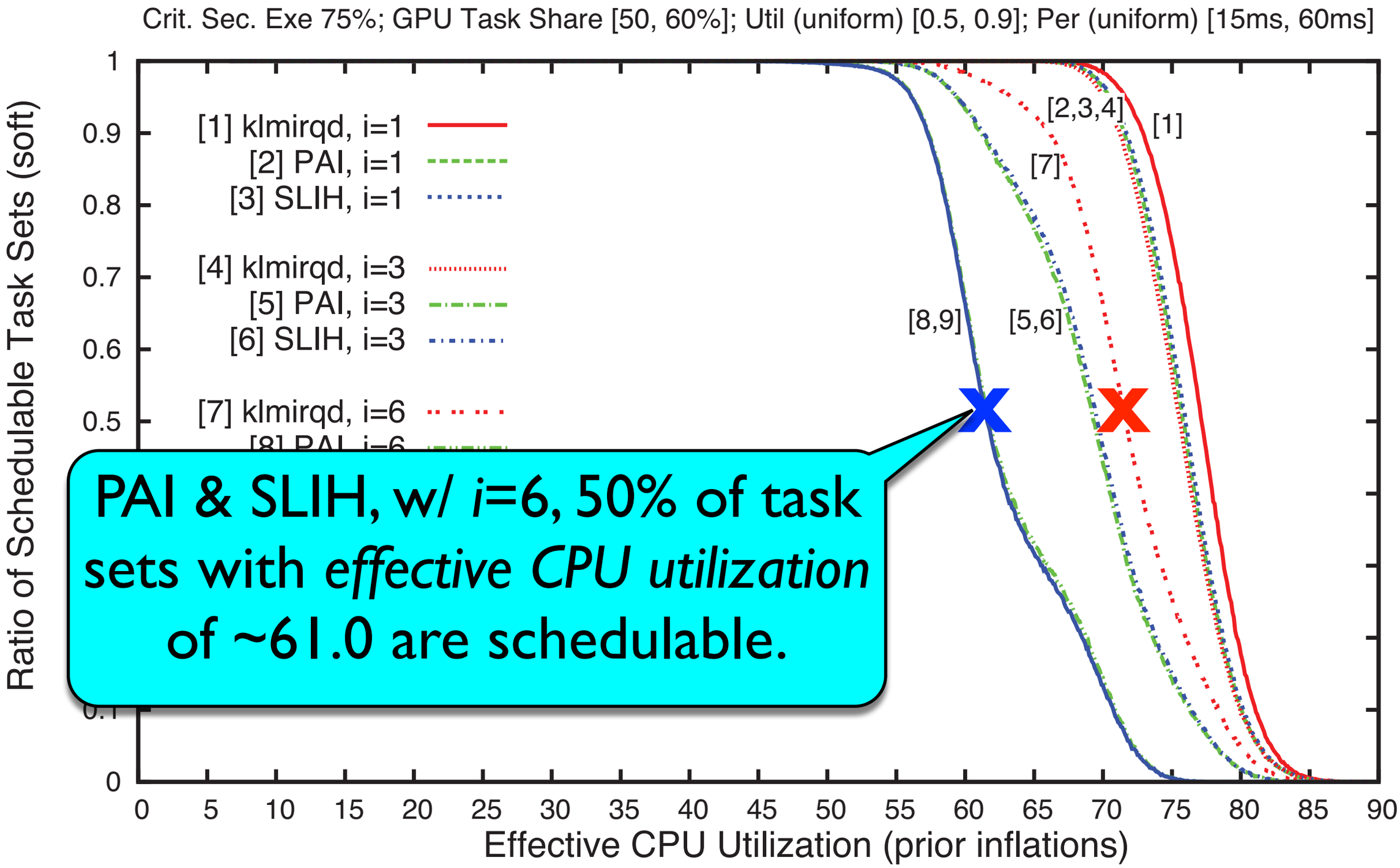
Overhead-Aware Schedulability Experiments



Conclusion

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Conclusion

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- Integrated closed source GPU driver through interrupt interception and decoding
- Evaluations indicate klmirqd significantly reduces priority inversions while avoiding schedulability analysis pitfalls
- Source available at www.litmus-rt.org

Thank you!

Questions?

Backup Slides

Measured Overheads

Overhead	Average Time (µs)
Scheduling	0.63
Context Switch	0.36
IPI	0.60
Job Release	0.67
Top Half	**16.44**
Bottom Half	**29.90**
klmirqd Release	1.39
PAI Release	0.13
PAI Scheduling	0.56

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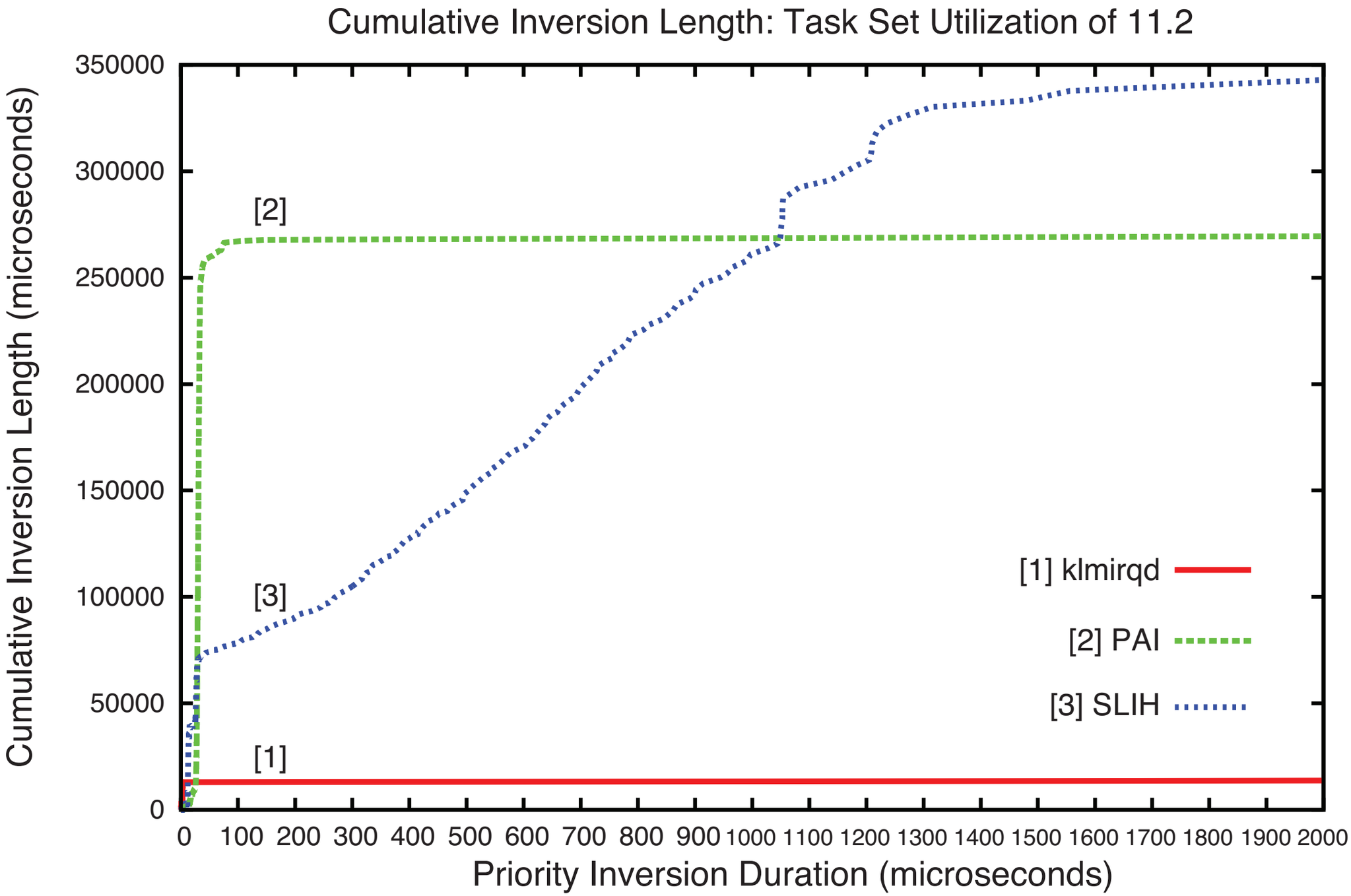
Effect on Priority Inversions



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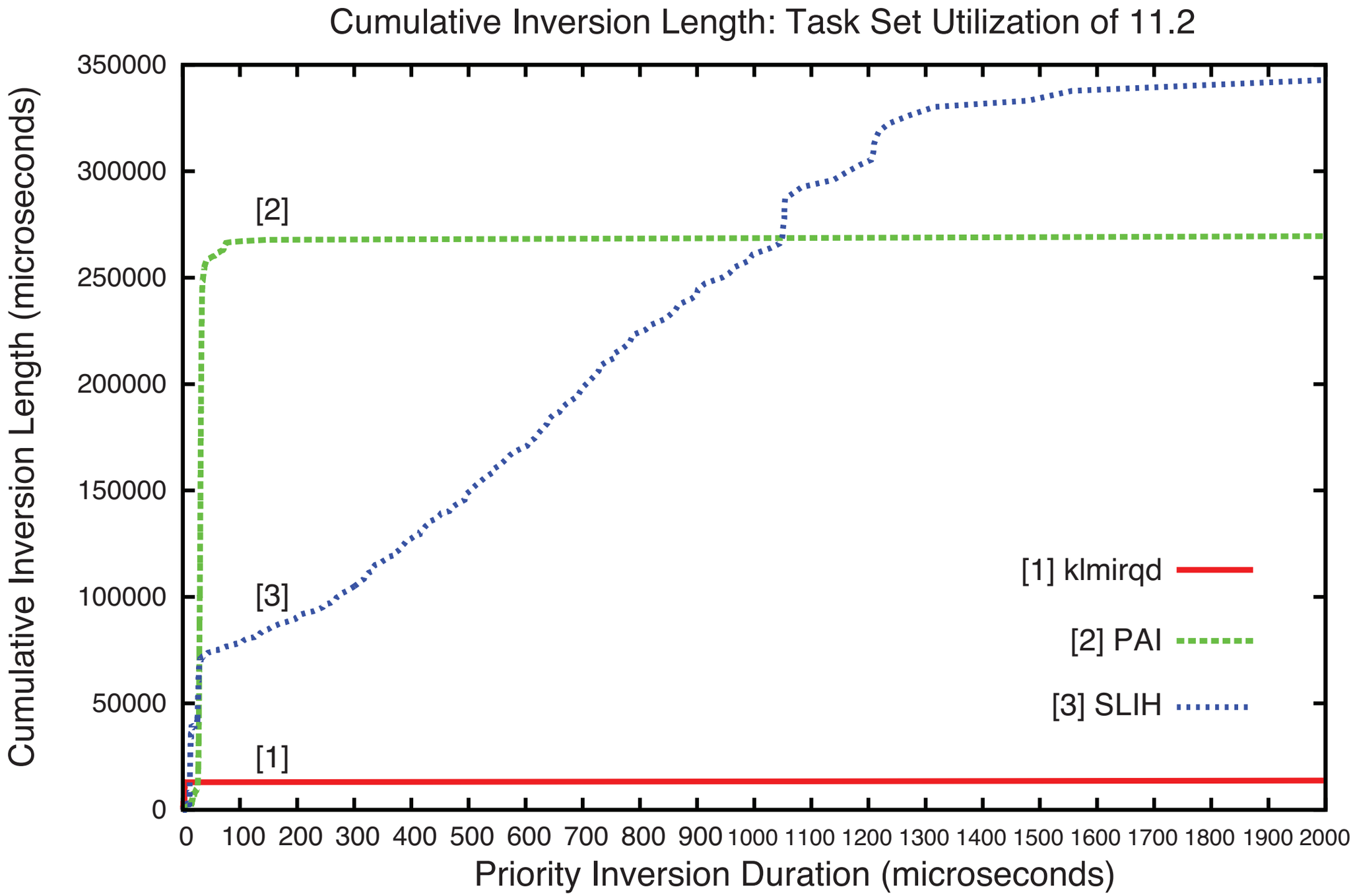
Total inversion time reduced.



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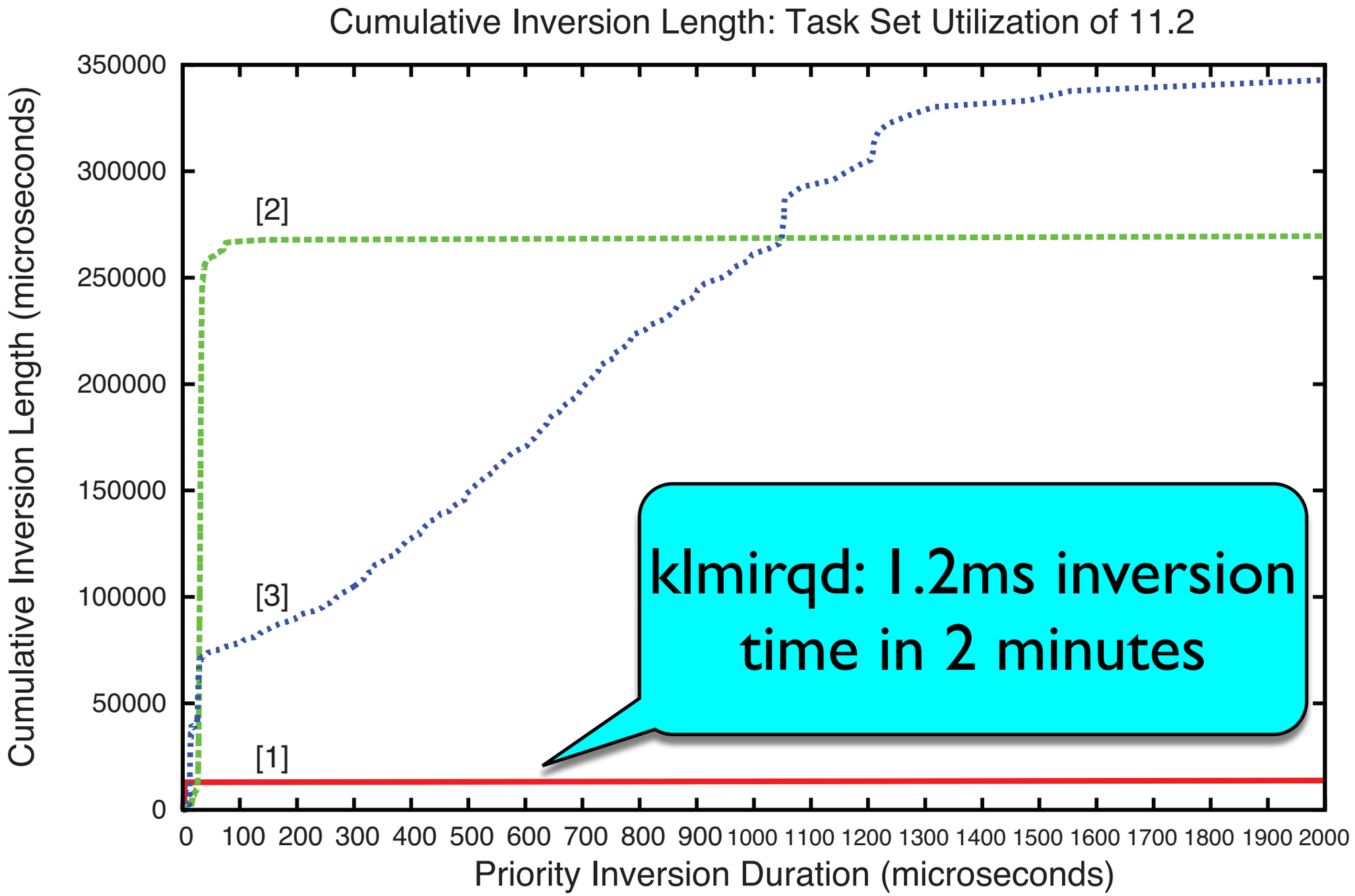

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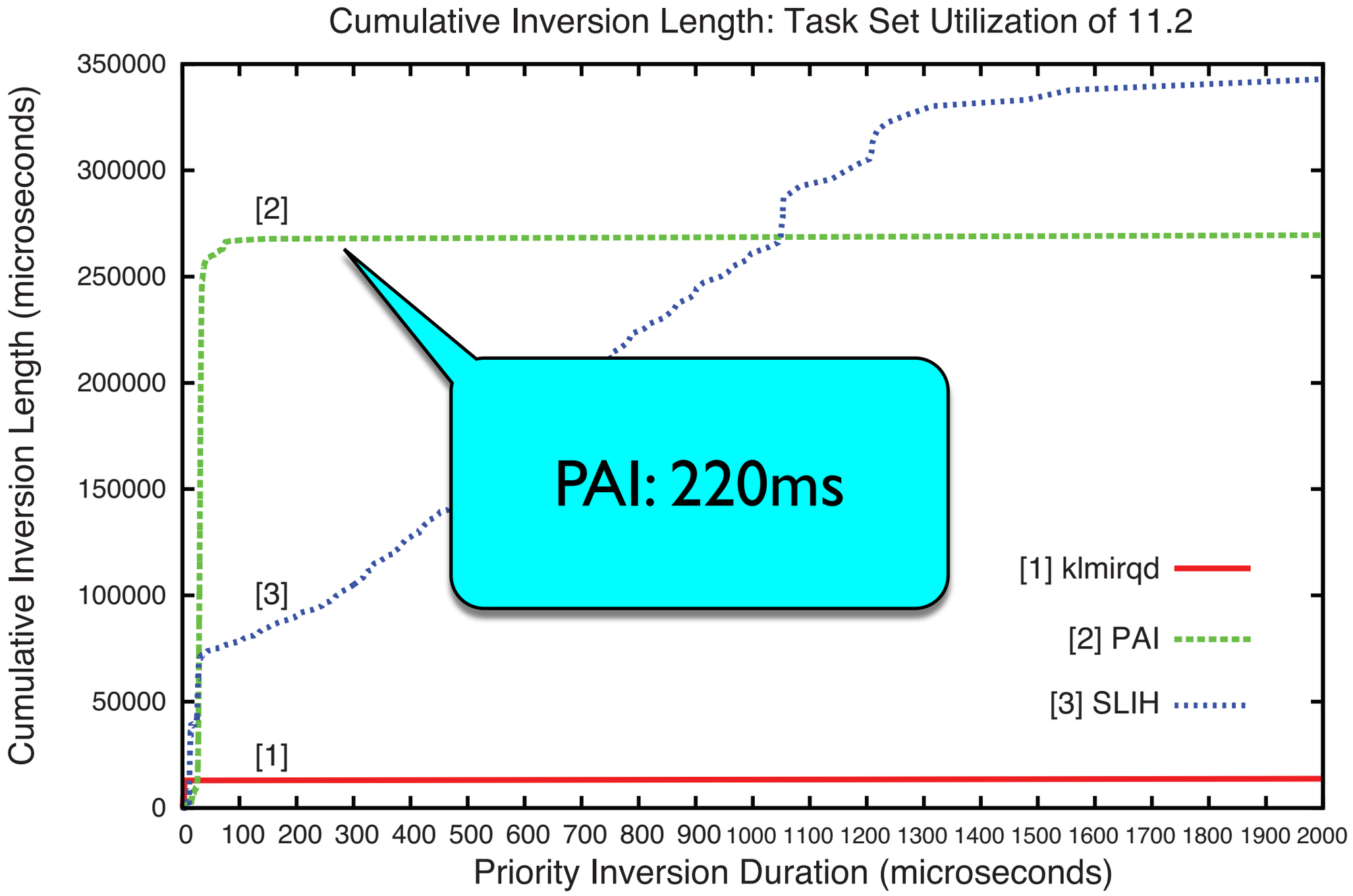

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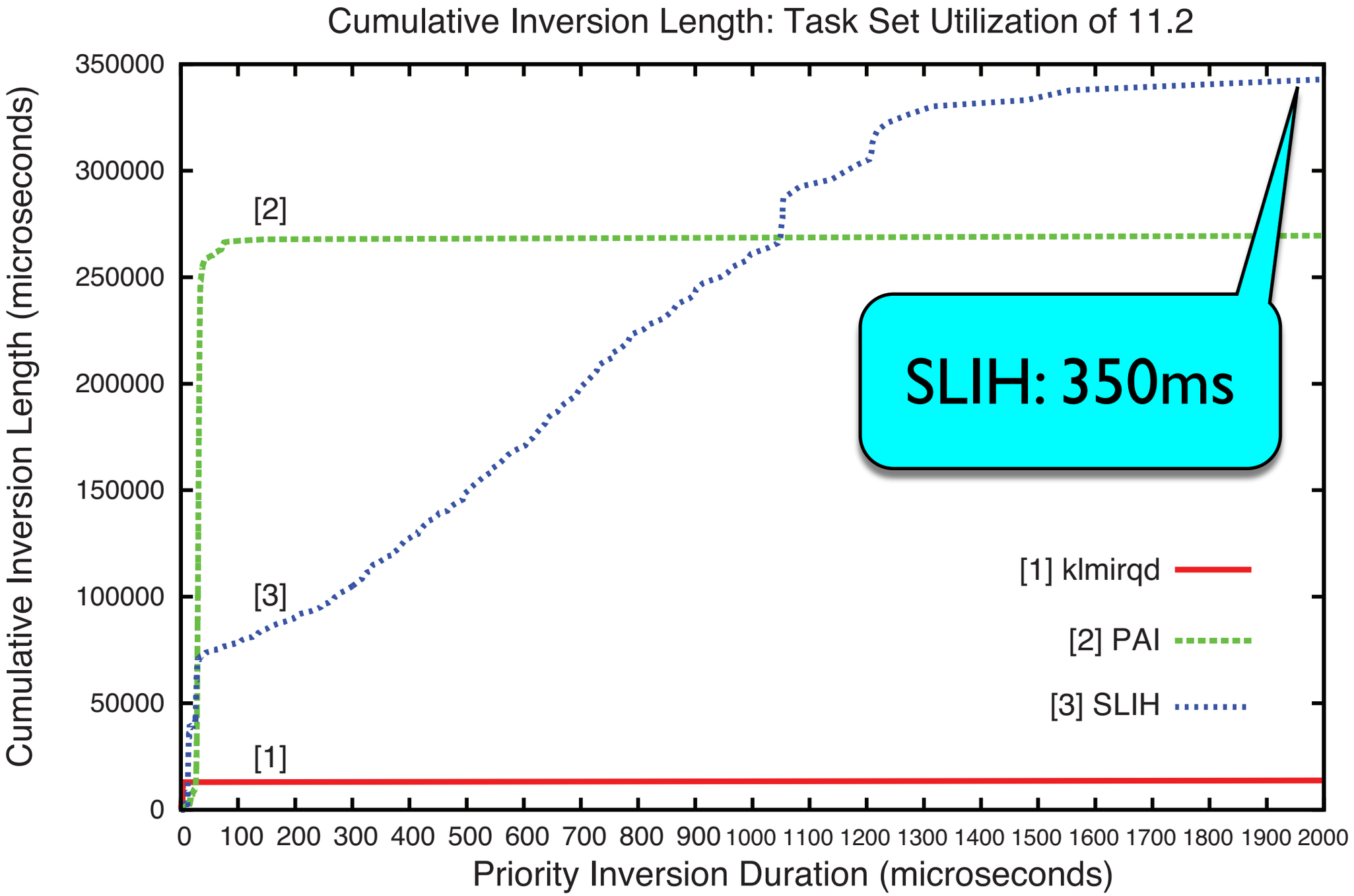
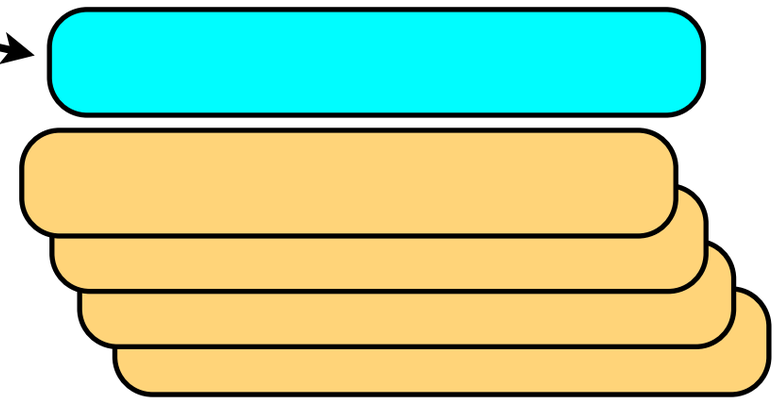


System-Level Evaluation

- Compared klmirqd against SLIH, PAI, and PREEMPT_RT (real-time Linux patch)
- PREEMPT_RT interrupt handler threads have *fixed* priority
- Scheduled using Clustered Rate Monotonic
  - Needed to make fair comparisons to PREEMPT_RT

Pathological Task Set

One GPU-using,
period = 19.9ms



20 CPU-only,
period = 20ms

Four GPU-using,
period = 20.1ms

One "sandwich"
on each cluster.

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System-Level Evaluation

Scheduler:	C-RM						C-EDF	
Operating System:	PREEMPT_RT		Unmod. Linux	LITMUS^{RT}				
Interrupt Handling Method:	Low Prio. Interrupts (a)	High Prio. Interrupts (b)	SLIH (c)	SLIH (d)	klmirqd (e)	PAI (f)	klmirqd (g)	PAI (h)
Avg. % Miss Per Task								
CPU-Only Tasks	12.5%	12.5%	1.6%	10.0%	10.0%	9.9%	0%	0%
GPU-Using Tasks	10.1%	8.5%	6.8%	0%	0%	0%	0%	0%
Avg. Resp. Time as % Period								
CPU-Only Tasks	22474.5%	24061.0%	8992.1%	55.8%	55.8%	55.6%	55.4%	55.4%
GPU-Using Tasks	23066.1%	34263.5%	61131.7%	46.7%	49.6%	46.2%	46.2%	46.2%

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GPU starvation

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System-Level Evaluation

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CPU response time increase