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Evaluation of Real-time Property in Embedded Linux

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whoami

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- Hiraku Toyooka
  - Software engineer at Hitachi

- Working on operating systems
  - Linux (mainly) for industrial control systems
    - Server, Embedded
    - Tracing
    - Real-time virtualization (partitioning)

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Agenda

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- What is a real-time system?
- Real-time features in Linux
- Tuning points for evaluation
- Performance measurement

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What is a real-time system?

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What is a real-time system?

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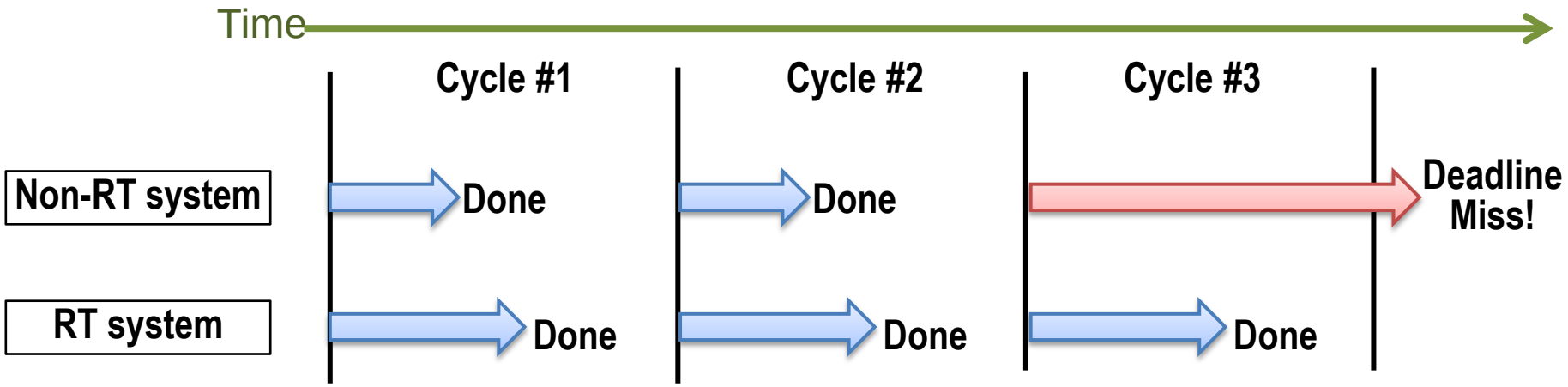
- Real-time system must always handle events within deadlines
  - Real-time doesn't mean fast
  - Worst case performance is important
  - Deterministic behavior is required



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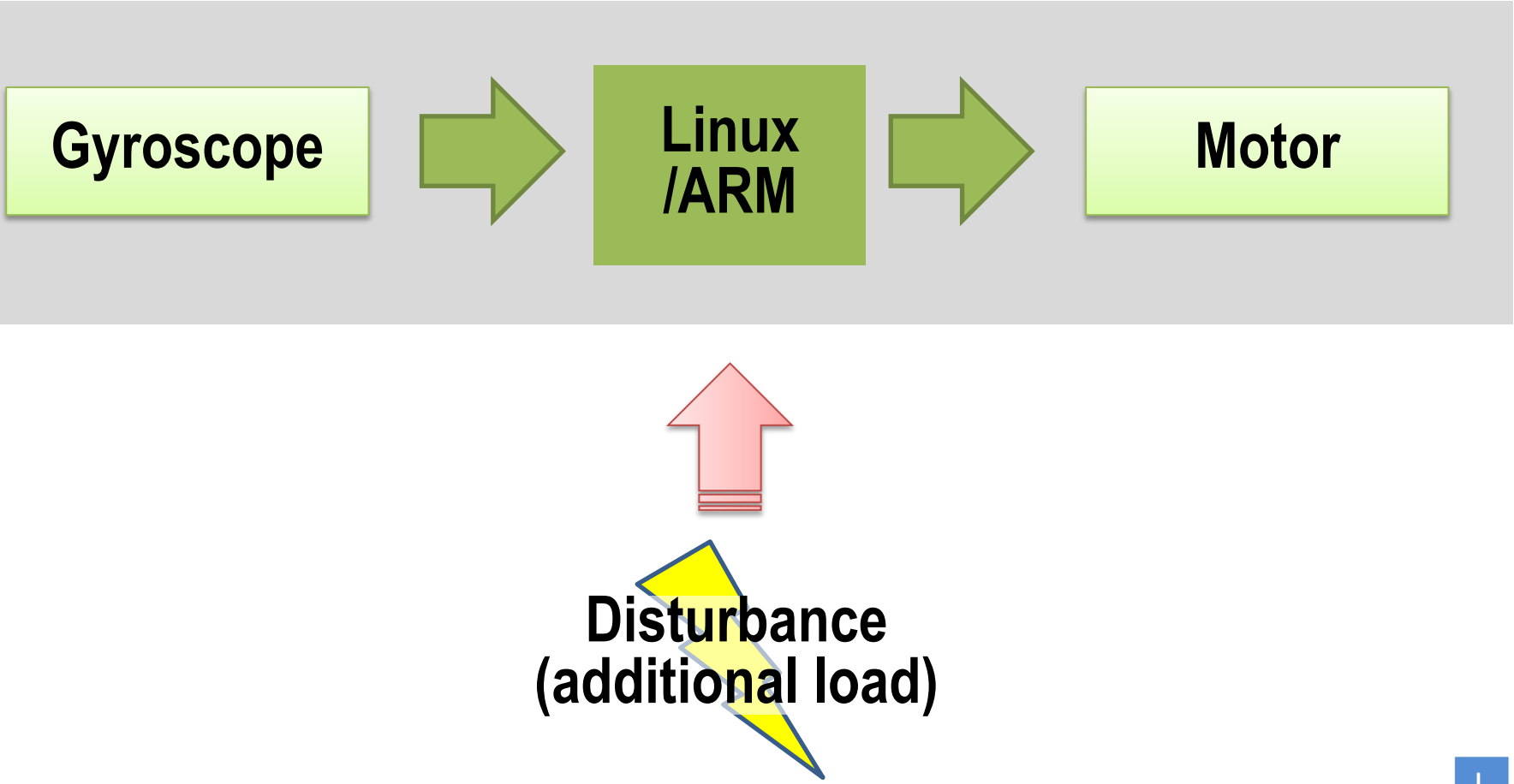
- Robot control (inverted pendulum)



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Real-time features in Linux

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Linux and real-time

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- Linux is originally designed to be a general purpose OS (GPOS)
  - High functionality
  - Average or peak performance is usually important for GPOS
  - Latency varies widely

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Linux and real-time

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- Current mainline Linux has a variety of real-time features
  - Certain level of deterministic behavior by appropriate configurations and tuning

- PREEMPT_RT patchset reduce maximum latency much more
  - Many real-time features in mainline are derived from PREEMPT_RT

(Some) Real-time features

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- Mainline
  - Fixed-priority scheduling
  - Kernel preemption
  - High resolution timer (hrtimer)
  - IRQ thread
  - Others
- Out of tree
  - PREEMPT_RT patchset

Fixed-priority scheduling

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- Linux has three types of schedulers
  - Completely Fair Scheduler (CFS)
    - Policy: SCHED_OTHER(Default), _BATCH, _IDLE
    - Task has dynamic-priority based on time slice (non-deterministic)
  - Real-time scheduler
    - Policy: SCHED_FIFO, _RR
    - Task has fixed-priority (deterministic)
  - Deadline scheduler
    - Policy: SCHED_DEADLINE
    - Merged in 3.14

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Fixed-priority scheduling (cont.)

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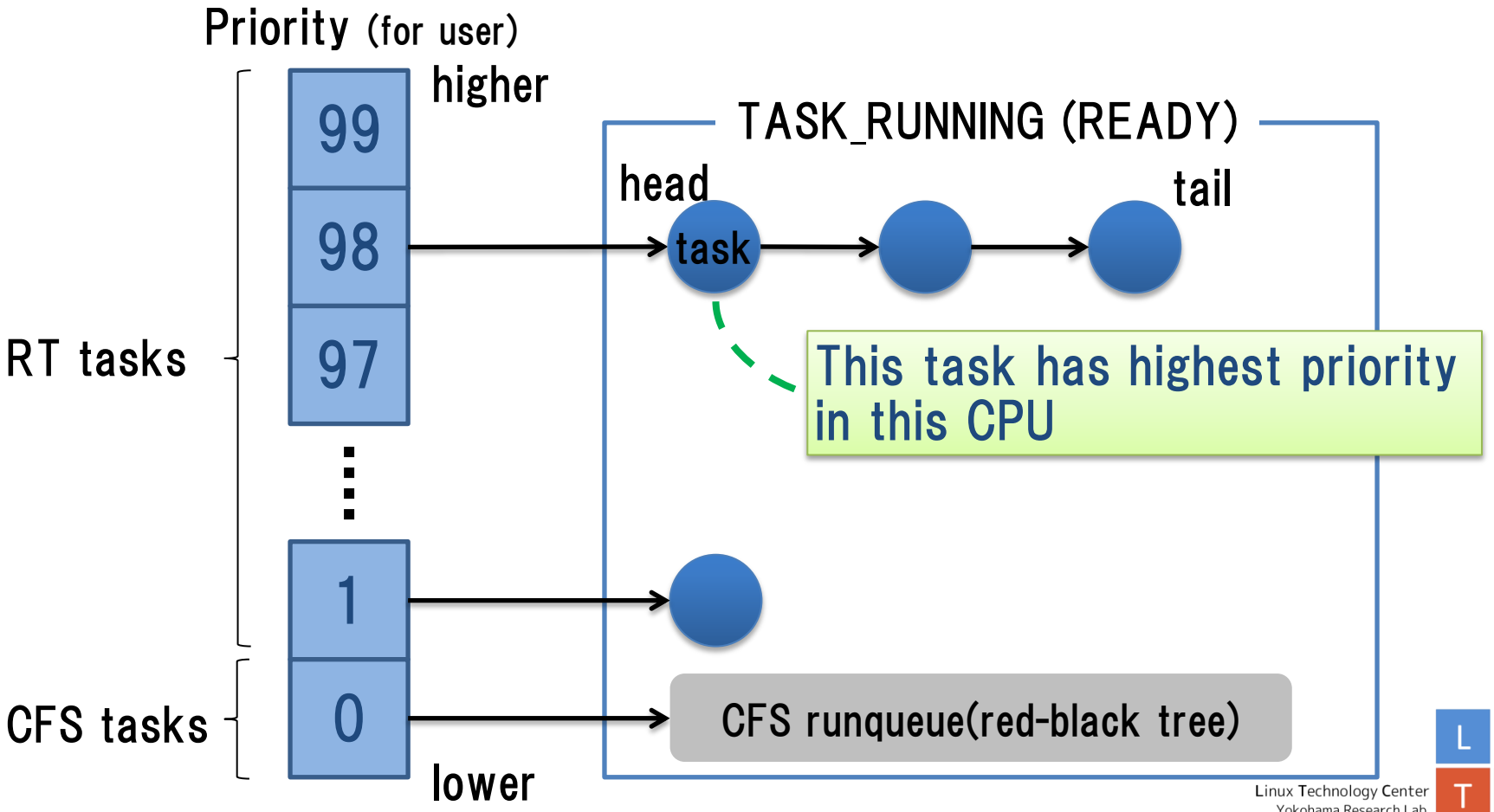
- There are per-cpu runqueues in Linux
  - RT tasks are always dispatched prior to CFS tasks



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Kernel preemption

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- Without preemption support: when higher priority tasks wake up, they are delayed until current task exits from a syscall or yields explicitly

- CONFIG_PREEMPT
  - Enables forcible context-switch even in kernel mode
  - Though spin-locks disable preemption
  - Improves response latency of high priority tasks

High resolution timer（hrtimer）

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- Some real-time systems start processing triggered by periodic timer events
  - But timer_list subsystem has only tick(jiffies) resolution
    - Tick intervals of 1~10ms are too long
    - Tick-independent software timer is necessary
- CONFIG_HIGH _RES_TIMERS
  - Enables software timer mechanism which supports nanosecond resolution
  - Userspace programs using nanosleep, itimers or posix-timers can benefit from this feature

IRQ thread

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- Move a part of the interrupt handler code to a kernel thread
  - reduce interrupt-disabled section
  - prioritize interrupt handlers

- CONFIG_IRQ_FORCED_THREADING
  - Force threading of all interrupt handlers
    - except handlers marked IRQF_NO_THREAD
  - Enabled by boot parameter “threadirqs”

IRQ thread (cont.)

```
# ps |grep irq
    3 root       0:00 [ksoftirqd/0]
   64 root       0:00 [irq/12-edma]
   65 root       0:00 [irq/14-edma_err]
  203 root       0:00 [irq/70-omap_i2c]
  921 root       0:00 [irq/30-omap_i2c]
  956 root       0:00 [irq/18-musb-hdr]
  959 root       0:00 [irq/19-musb-hdr]
  967 root       0:00 [irq/75-rtc0]
  968 root       0:00 [irq/76-rtc0]
  977 root       0:00 [irq/64-mmc0]
  978 root       0:00 [irq/166-mmc0]
  988 root       0:00 [irq/77-wkup_m3]
  989 root       0:00 [irq/78-wkup_m3_]
  990 root       0:00 [irq/120-smartre]
  991 root       0:00 [irq/121-smartre]
 1006 root       0:00 [irq/72-OMAP UAR]
```

Others

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- PI (Priority Inheritance) mutex
- Preemptive RCU
- RT group scheduling
- RT throttling
- Full tickless (no_hz)
- etc…

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PREEMPT_RT patchset

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- provides more deterministic behavior
  - https://www.kernel.org/pub/linux/kernel/projects/rt/
  - It consists of lots of patches lowering maximum latency
    - There are 318 patches in 3.14.2-rt3

- CONFIG_PREEMPT_RT_FULL
  - allows “full preemption”
    - nearly all of the kernel can be preempted
    - replaces spin-locks with mutexes (Sleeping spin-lock)
    - many other improvements

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Tuning points for evaluation

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Tuning points for evaluation

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- Clocksource resolution
- Task priority
- Task switching cost
- Page faults
- Multi-core
- Lock debugging

Clocksource resolution

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- Getting and updating clock time depend on clocksource
  - gettimeofday(2), clock_gettime(2)
- This means that time measurement is affected by clocksource resolution
  - Confirmation is necessary before measurement

```
# dmesg | grep clock
[0.000000] OMAP clocksource: GPTIMER1 at 24000000 Hz
[0.000000] sched_clock: 32 bits at 24MHz, resolution 41ns,
wraps every 178956ms
```

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Task priority

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- We need to use RT policy and priorities for deterministic scheduling
  - sched_setscheduler(2) can change those scheduling attributes of specified tasks
  - In pthread library, new thread's scheduling attributes can be set by pthread_attr_setschedparam(3)
    - Do not forget to call pthread_attr_setinheritsched(3) with PTHREAD_EXPLICIT_SCHED

Task switching

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- Process switching cost is significantly larger than thread switching
  - Process switching needs to flush TLB
  - If your real-time application is composed of lots of processes, process switching measurement is necessary

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Page faults

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- Memory allocation to userspace is usually only virtual address space allocation
  - Initial memory access causes page fault, and this produces more latency
  - Page-out to swap area also causes page faults

- To prevent page faults, mlockall(2) is used
  - All memory-mapped pages remain on physical memory after mlockall(2)

Multi-core

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- In multi-core SoC, tasks can move from local core to remote cores
  - This migration causes additional latency
  - Tasks can be fixed to a specific core by cpuset cgroup

- Influence of unrelated interrupt handling
  - It’s effective to fix real-time tasks to cores which doesn’t handle unrelated IRQs
    - after setting IRQ affinity.

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Lock debugging features

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- Lock debugging features add much more latency
  - Disabling them is effective

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Performance measurement

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Measured items［1/2］

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- Interrupt response time
  - Time period between expiry of a hardware timer and scheduling of a userspace task
  - measured by cyclictest (in rt-tests)
  - cyclictest -a 0 -p 99 -m -n -l 100000 -q --histogram=500
    - -a: set CPU affinity to CPU0
    - -p 99: set priority to 99
    - -m: use mlockall
    - -n: use clock_nanosleep to measure time
    - -l 100000: number of trials
    - -q: don’t print anything while testing
    - --histogram=50: print histogram 0-49us after the test

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Measured items [2/2]

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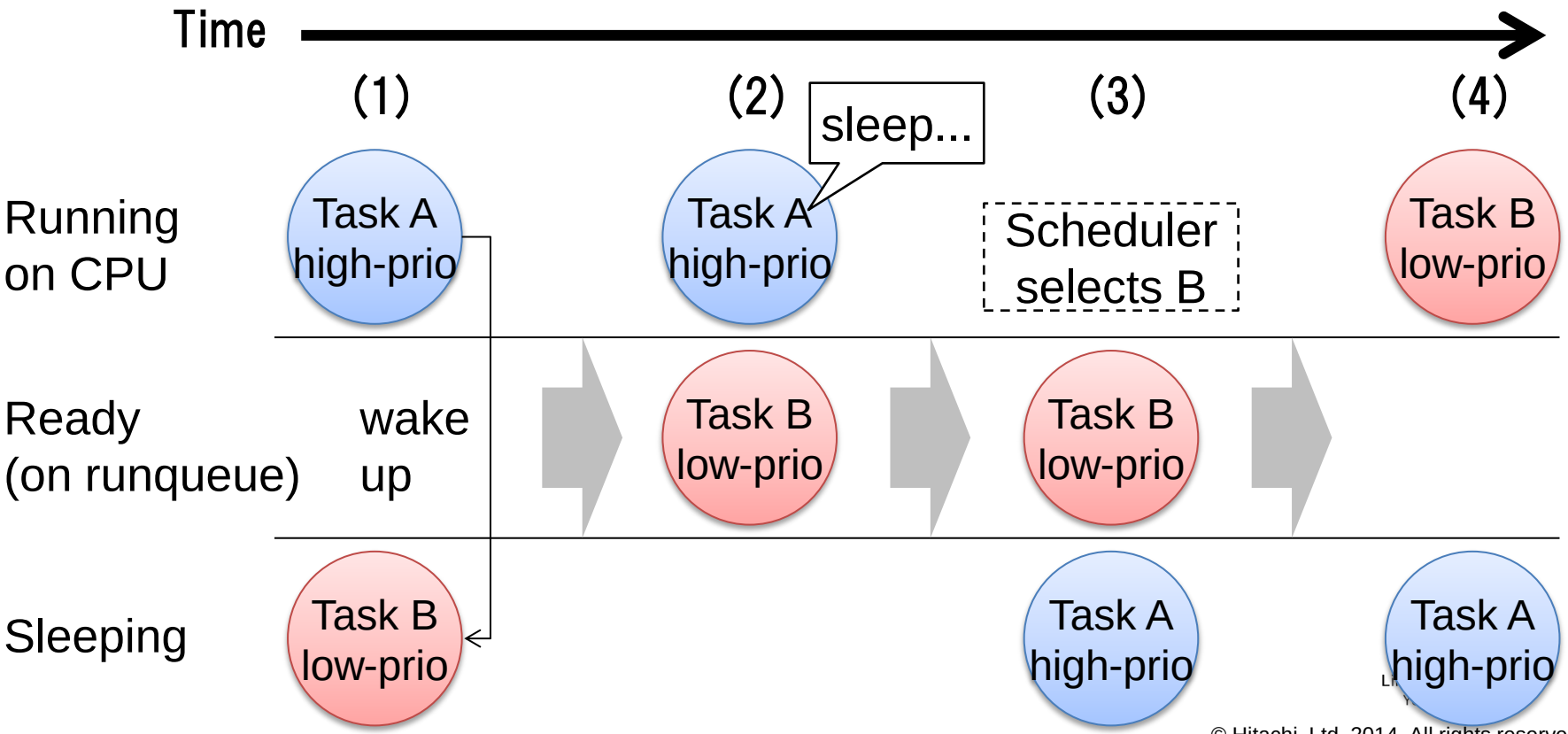
- Task switching time
  - measured by own program (though ptsematest exists…)
    - Cause thread switching by POSIX semaphore 100k times



Evaluation environment

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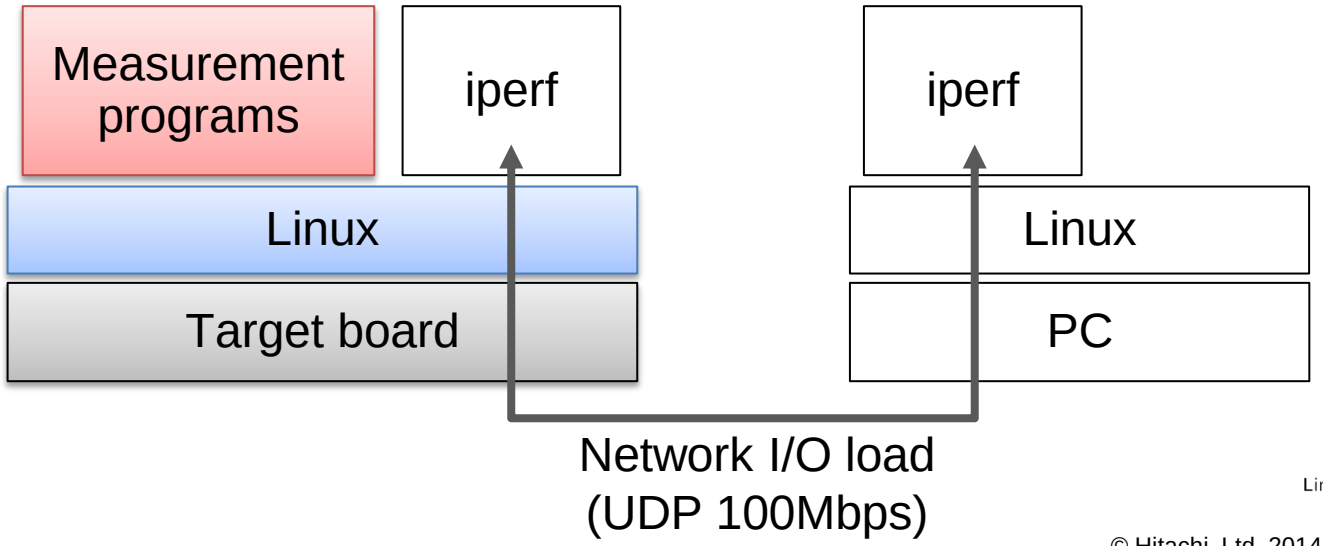
Board	BeagleBone Black	Altima Helio board
SoC	TI Sitara AM3359	Altera Cyclone V
CPU	ARM Cortex-A8 (1GHz)	ARM Cortex-A9 (800MHz x2)
L1 cache (inst. / data)	32KB / 32KB	32KB / 32KB
L2 cache	256KB	512KB
Main memory	512MB	1GB
Linux version	3.14.0	3.14.0 [1]
PREEMPT_RT version	3.14.0-rt1	3.14.0-rt1

[1] http://rocketboards.org/gitweb/?p=linux-socfpga.git



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Comparison

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- Three types of kernels
  - “No preempt”
  - “Preempt”
  - “Preempt RT”

Settings	“No Preempt”	“Preempt”	“Preempt RT”
Kernel version	3.14.0	3.14.0	3.14.0-rt1
Preemption	No	**Yes**	**Yes**
Forced IRQ threading	No	**Yes**	**Yes**
Full preemption (RT patch)	No	No	**Yes**

Interrupt response time (BeagleBoneBlack)

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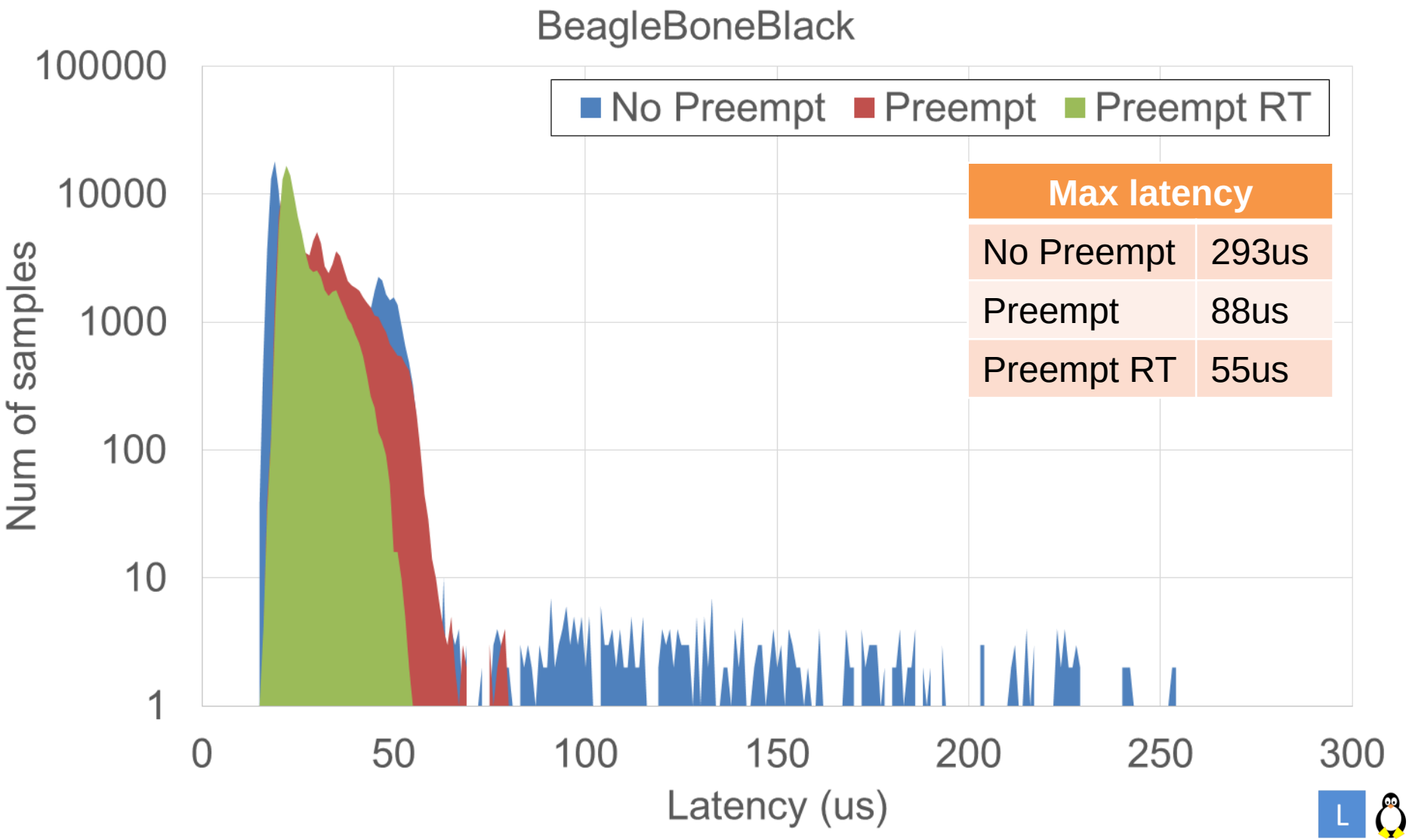

Max latency	
No Preempt	293us
Preempt	88us
Preempt RT	55us

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Interrupt response time (Helio)

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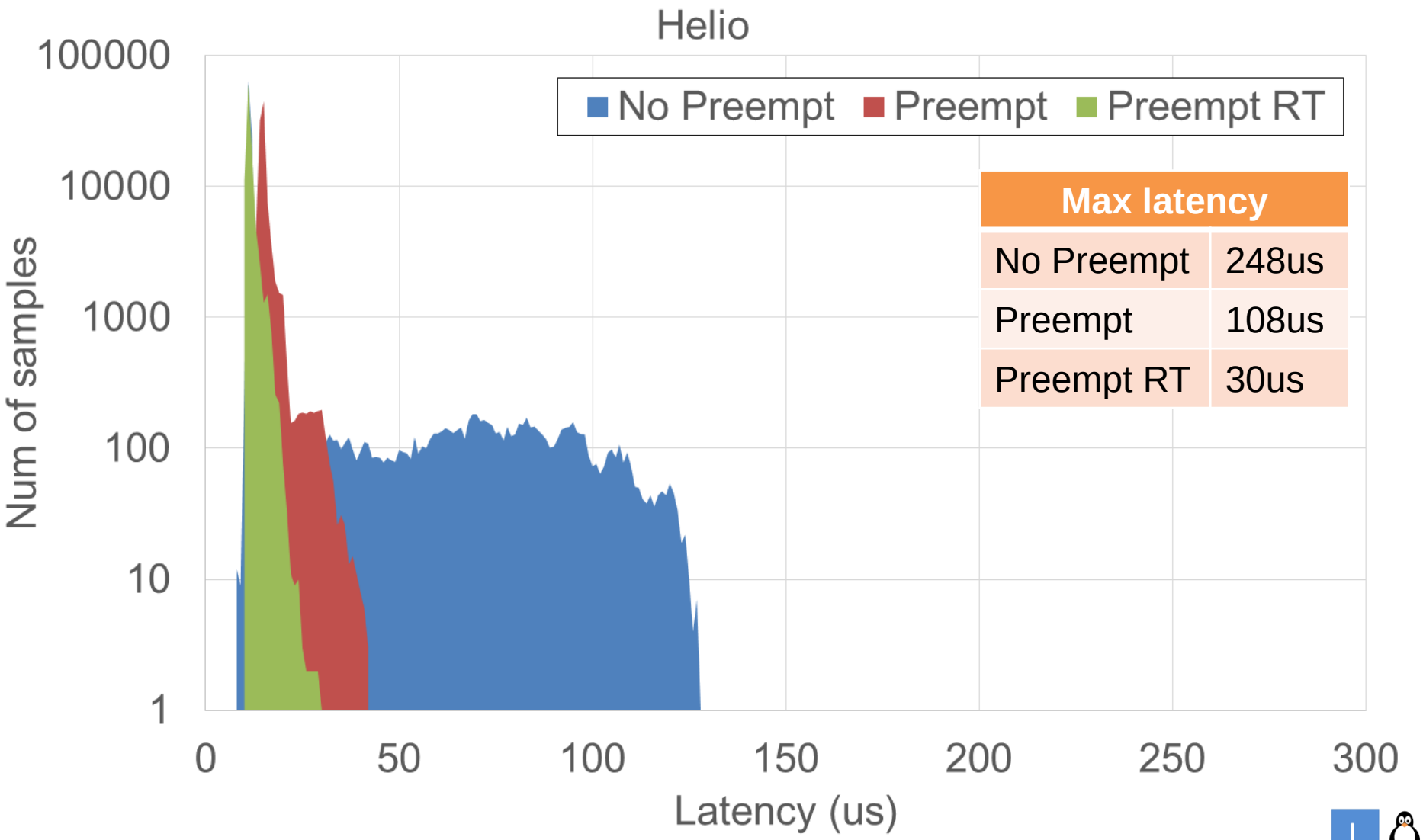

Max latency	
No Preempt	248us
Preempt	108us
Preempt RT	30us

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Task switching time (BeagleBoneBlack)

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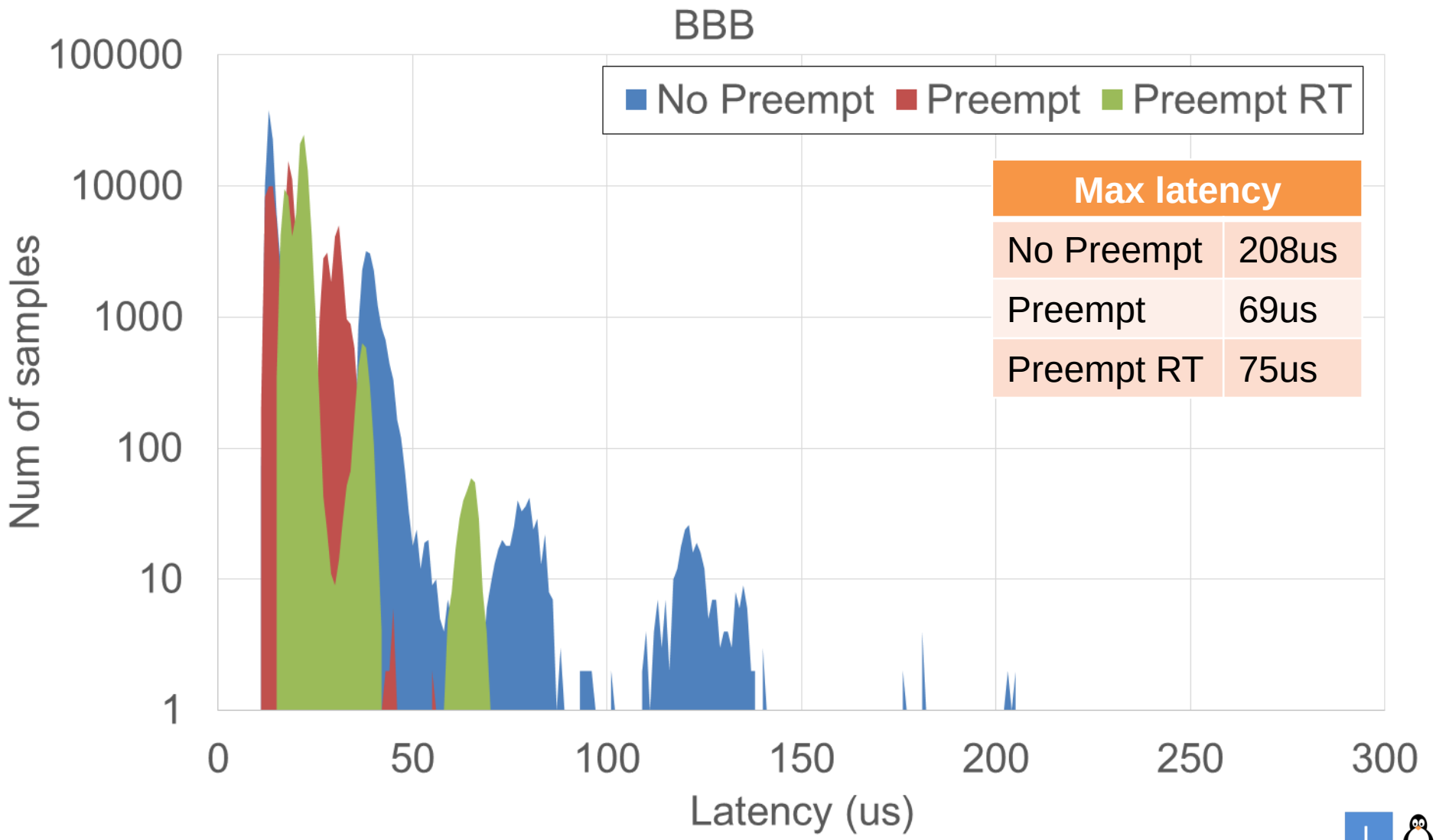

Max latency	
No Preempt	208us
Preempt	69us
Preempt RT	75us

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Task switching time (Helio)

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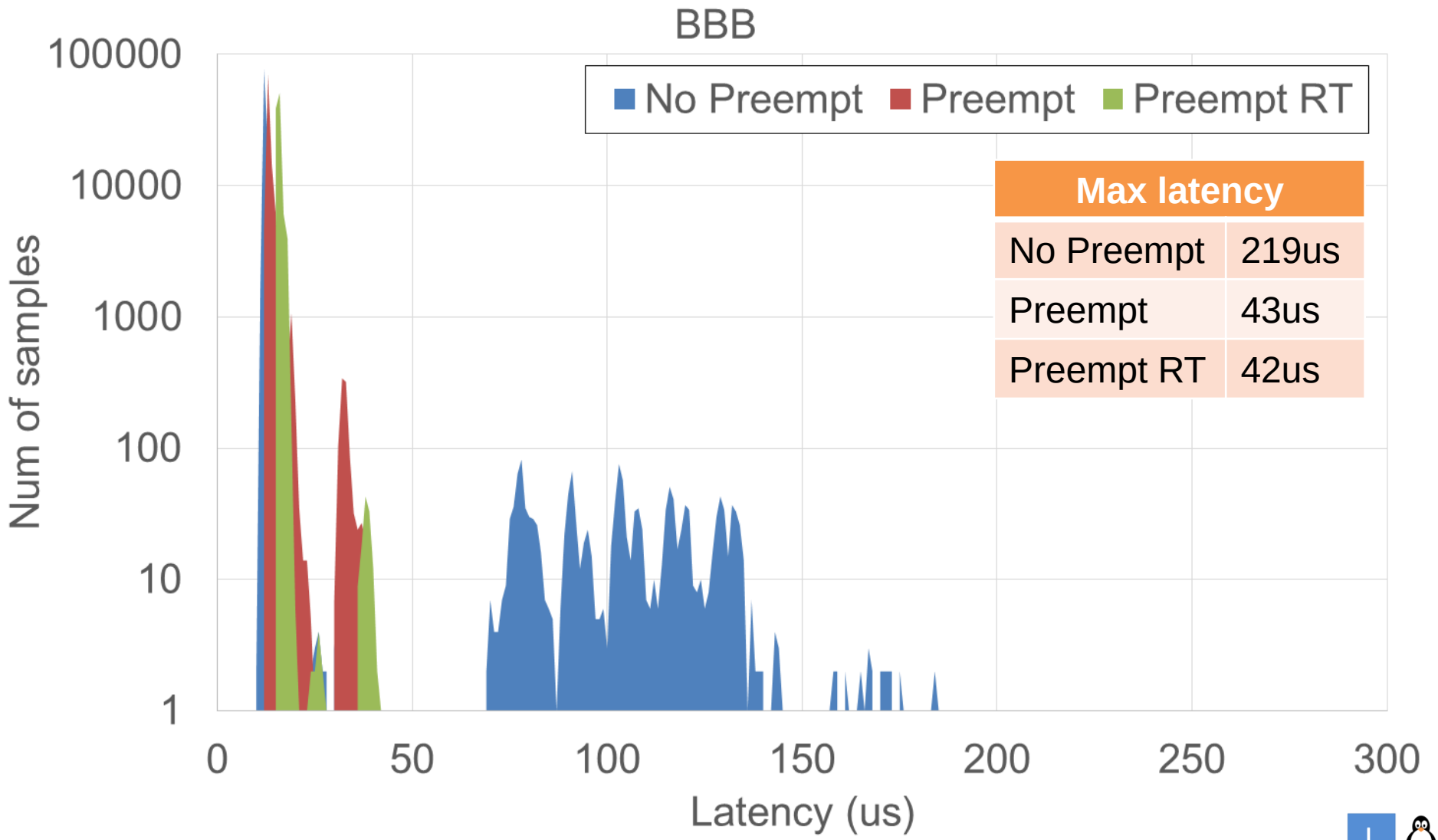

Max latency	
No Preempt	219us
Preempt	43us
Preempt RT	42us

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Conclusion

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- Current mainline Linux has lots of real-time features
- PREEMPT_RT patchset provides more deterministic behavior
- We can reduce maximum latency by using these features with appropriate configuration and tuning

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