[544] Control Groups (cgroups)

Tyler Caraza-Harter

Outline

Performance Isolation

Mechanism Examples

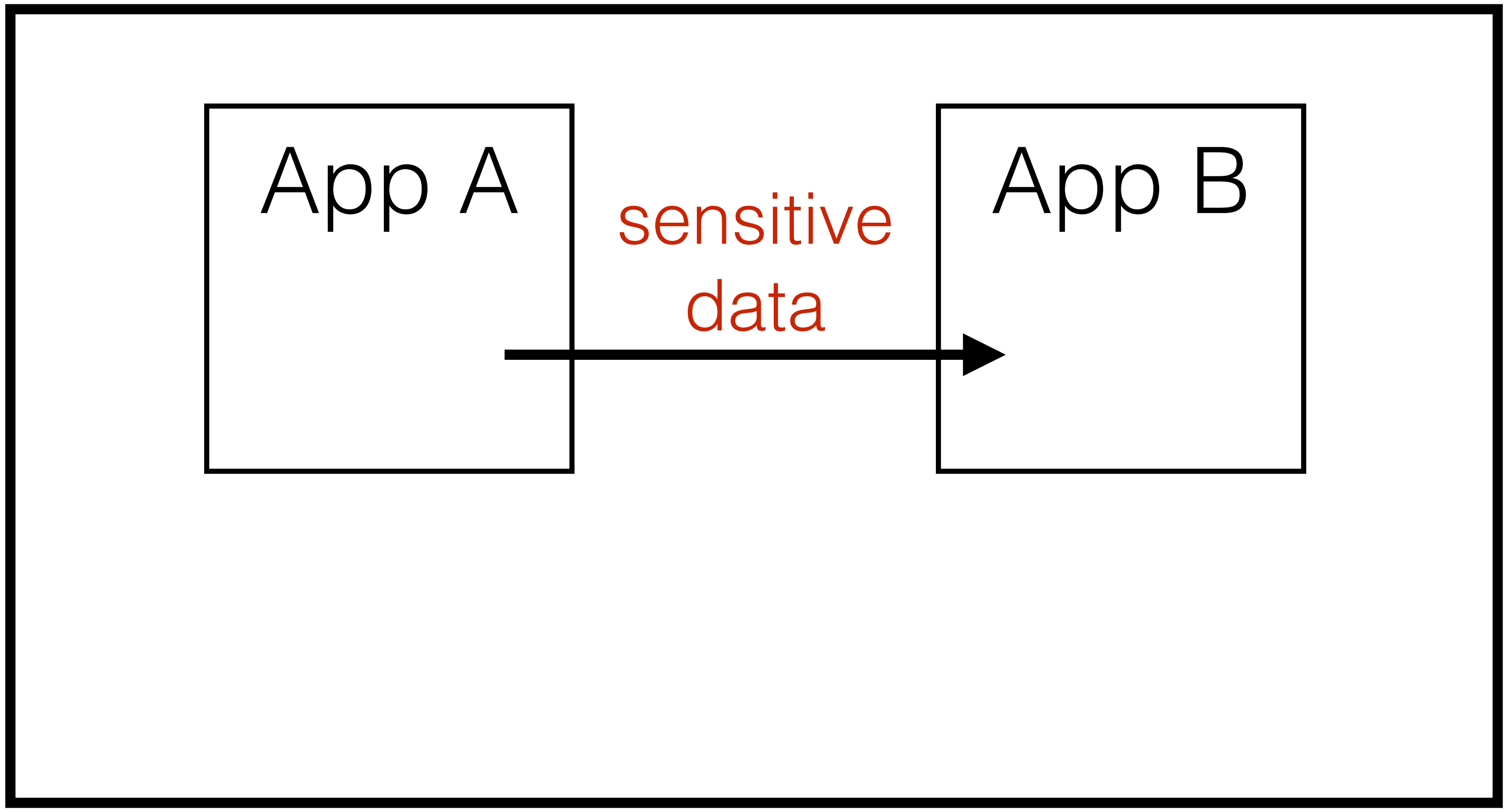
Interface: cgroup overview

Controllers

- freezer/cpu/cpuset
- memory
- io (disk)
- pids
- what about network?

Usage in OpenLambda

Isolating Data



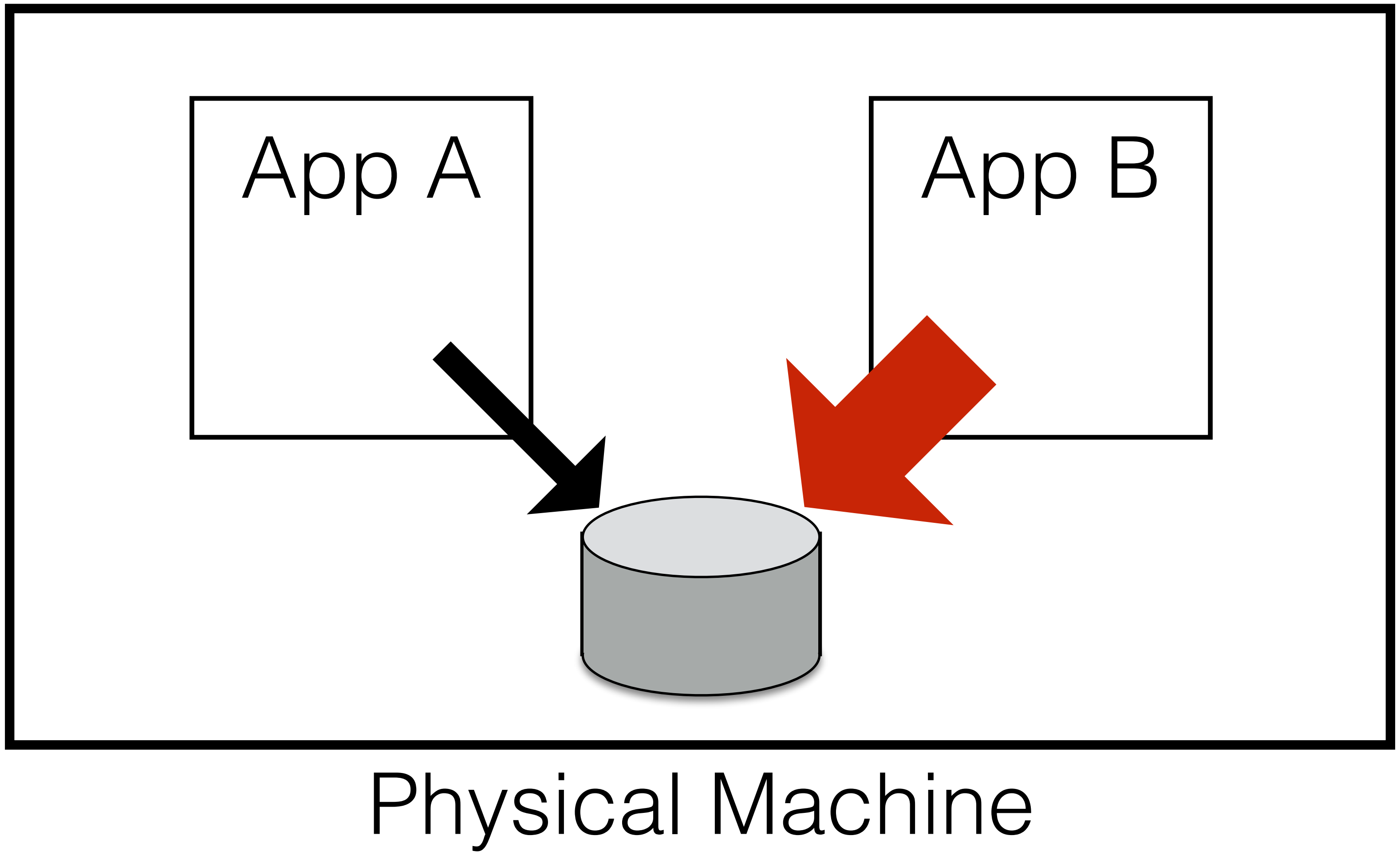
Physical Machine

don’t want: leaks

Linux

- older features: virtual memory, ACLs, etc
- newer features: namespaces (separate session)

Isolating Performance



don’t want: unfairness

This session focuses on **performance** isolation

Perf Isolation: Interface vs. Mechanism

Linux has many **mechanisms** for isolating performace. Examples:

- OOM (out of memory) killer -- randomly kill a process when low on memory (relative to total RAM, or a set limit)
- CPU scheduler, such as CFS (completely fair scheduler)
- Block I/O scheduler, such as BFQ (budget fair queueing)

There are multiple **interfaces** for interacting with these mechanisms:

- nice, ionice
- cgroups v1 (used by OpenLambda when SOCK was published)
- cgroups v2 (used by OpenLambda now)

Observation: cgroups can only be as good as the underlying schedulers/mechanisms.

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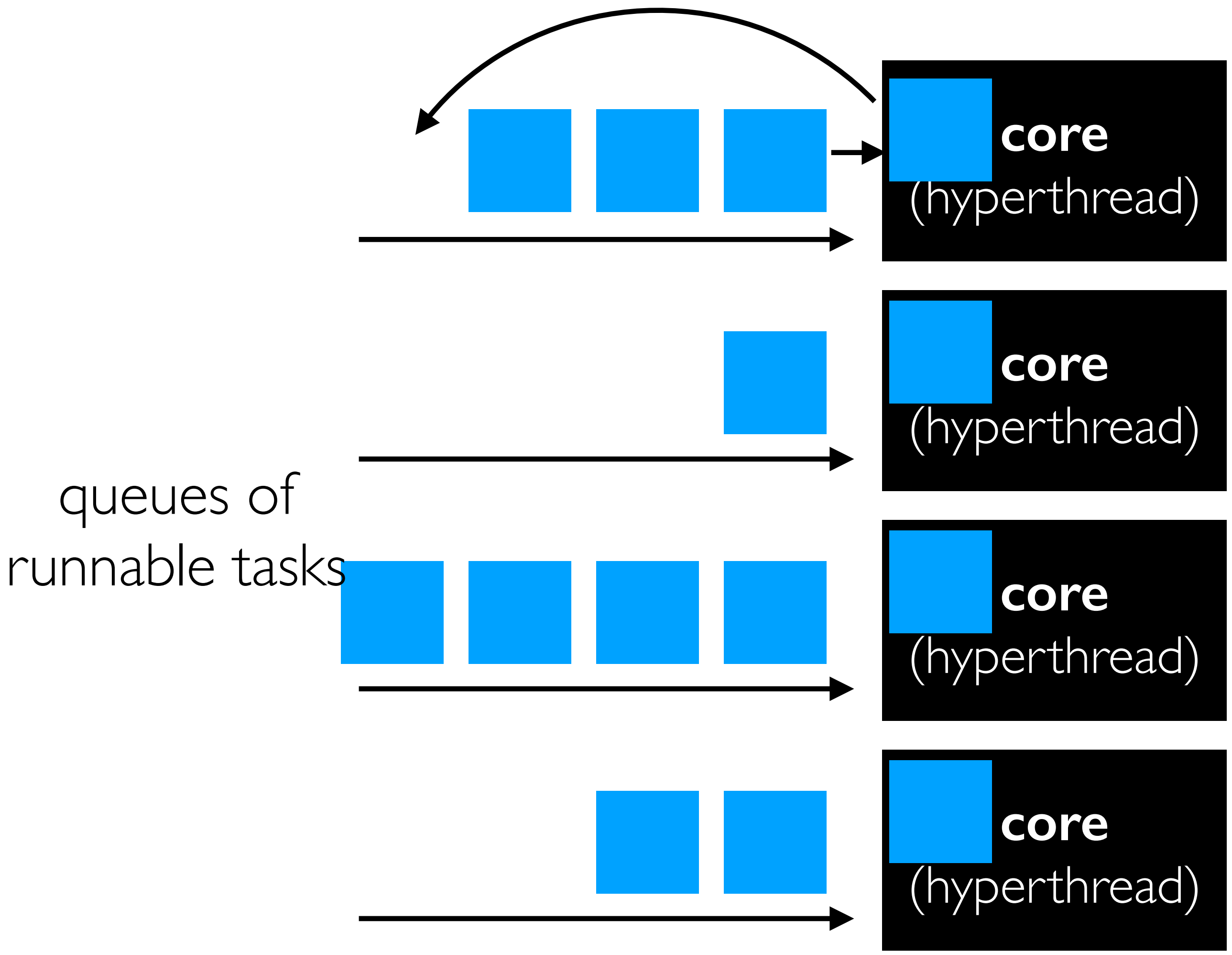
CFS (Completely Fair Scheduler) - Default

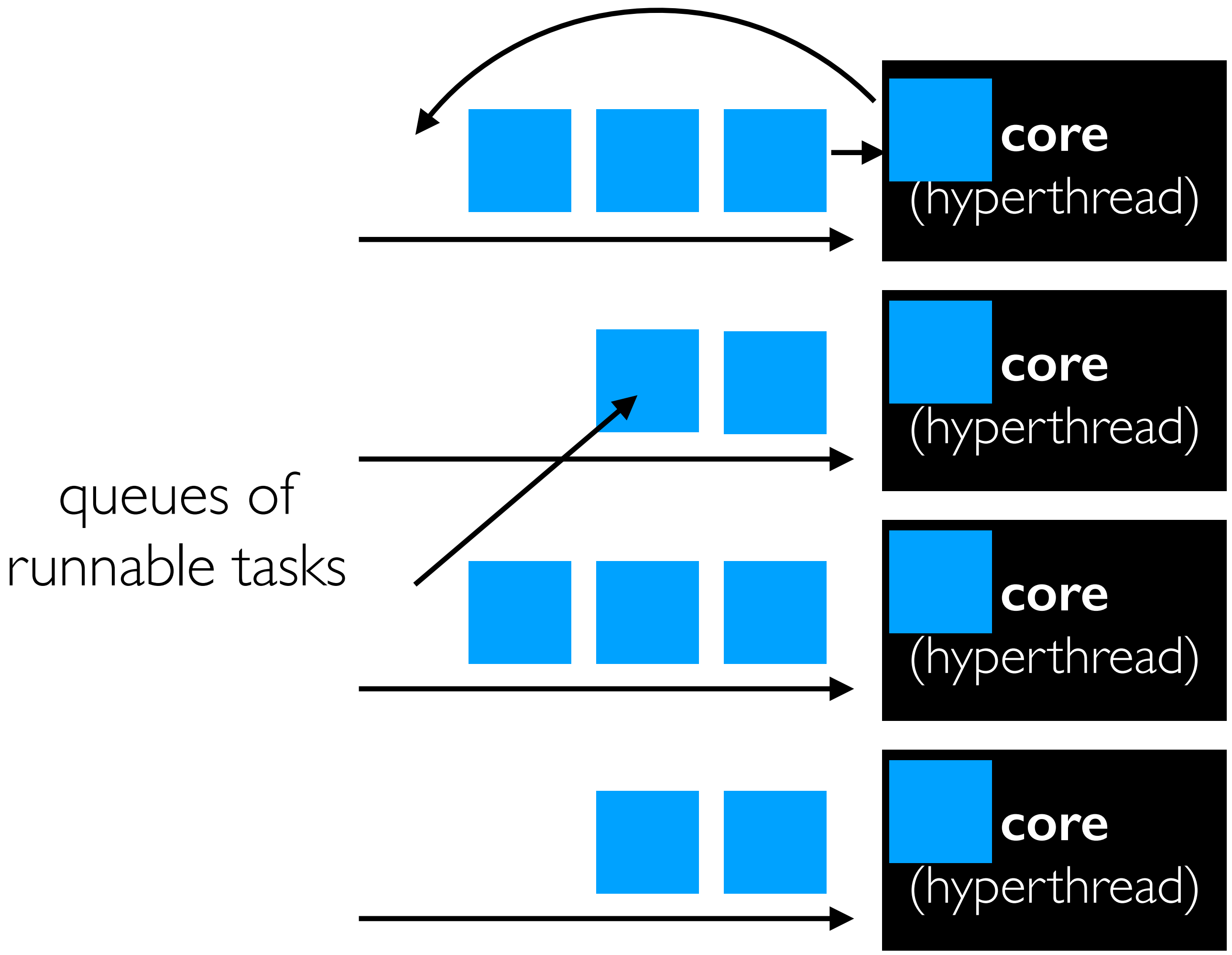


Operation

- each core/hyperthread has its own queue
  (want to spend more time where CPU cache is warm)
- cycle through processes: higher priority = more time running

```
time nice -n 10 python3 -c 'sum(range(int(1e9)))'
```

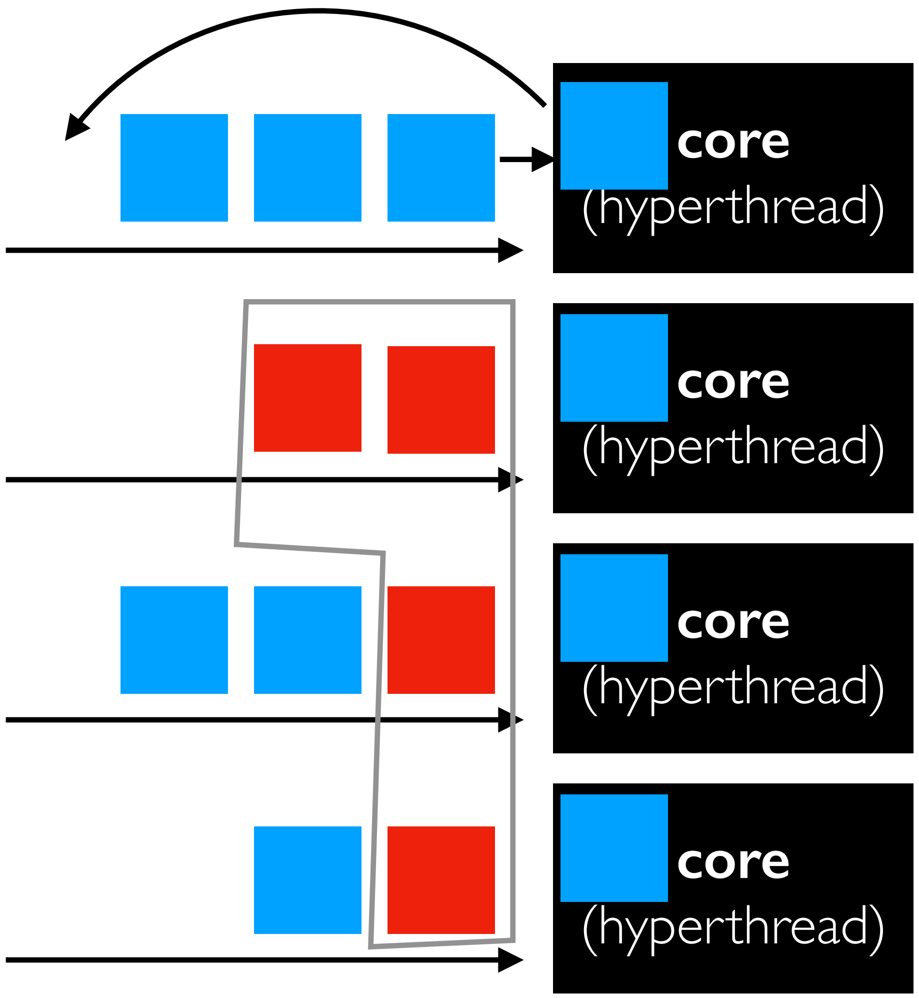
CFS (Completely Fair Scheduler) - Default



Operation

- each core/hyperthread has its own queue
  (want to spend more time where CPU cache is warm)
- cycle through processes: higher priority = more time running
- occasionally rebalance

CFS (Completely Fair Scheduler) - Default



queues of
runnable tasks

Operation

- each core/hyperthread has its own queue
  (want to spend more time where CPU cache is warm)
- cycle through processes: higher priority = more time running
- occasionally rebalance
- task groups's let multiple threads in a process (or in a multi-process app) share accounting

Disk I/O: Block Scheduler

partitions

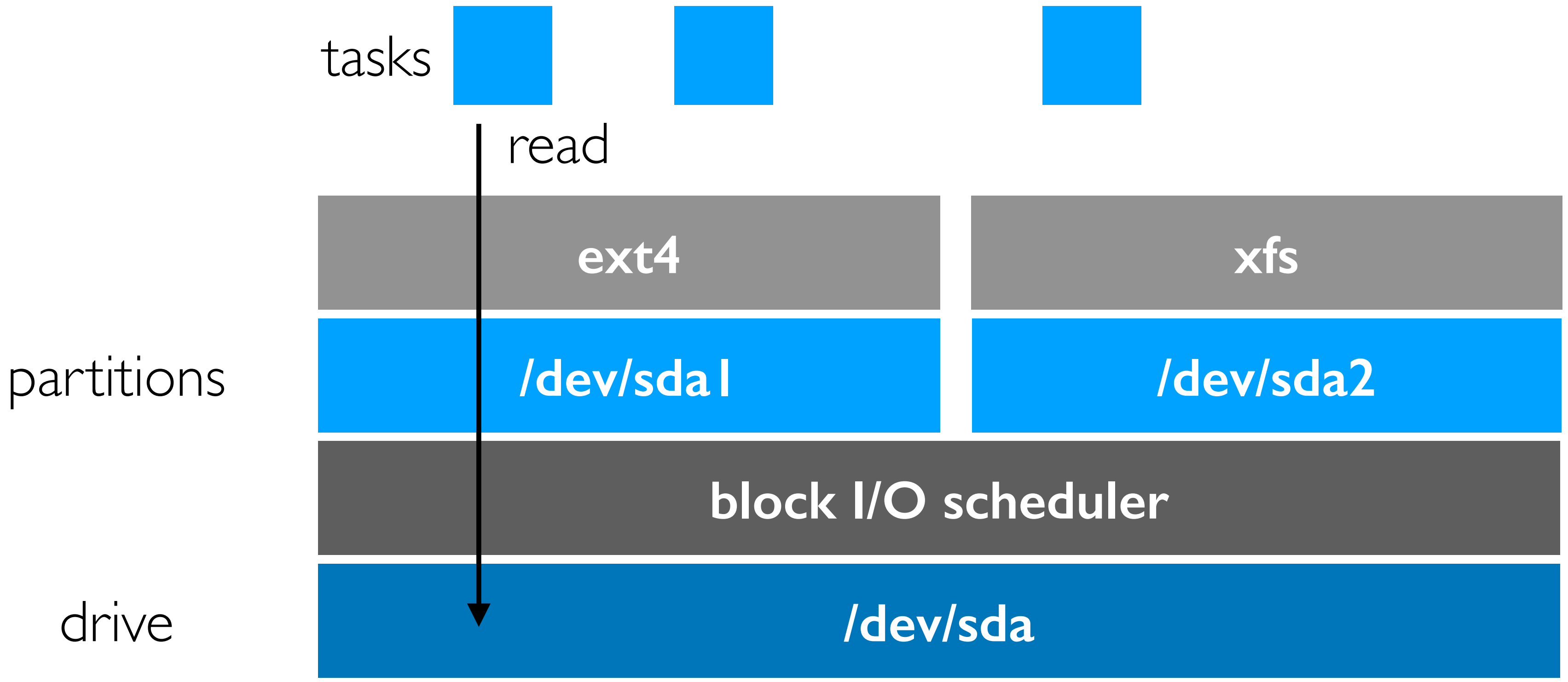
/dev/sda1

/dev/sda2

drive

/dev/sda

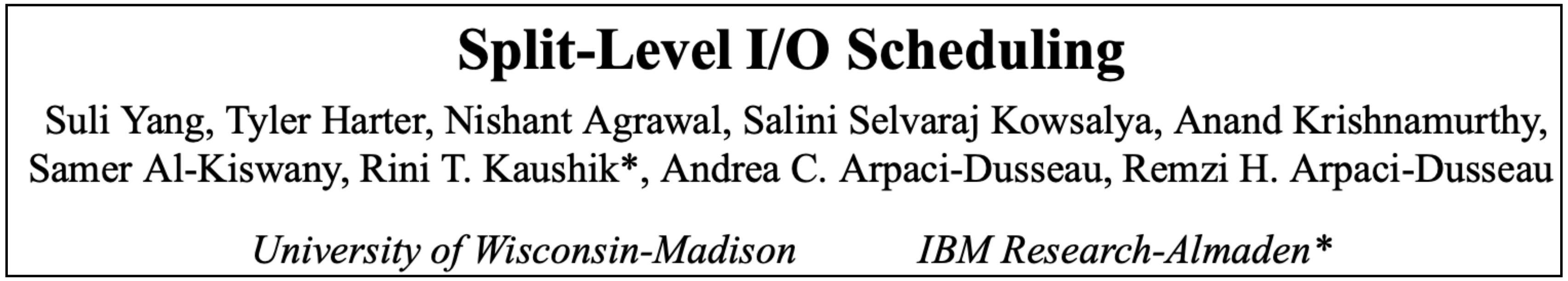
Disk I/O: Block Scheduler



```
$ cat /sys/block/sda/queue/scheduler
[mq-deadline] none
$ echo none > /sys/block/sda/queue/scheduler
```

ionice works like nice, but for block I/O schedulers that support priorities

Block I/O Scheduling Limitations



Split-Level I/O Scheduling

Suli Yang, Tyler Harter, Nishant Agrawal, Salini Selvaraj Kowsalya, Anand Krishnamurthy,
Samer Al-Kiswany, Rini T. Kaushik*, Andrea C. Arpaci-Dusseau, Remzi H. Arpaci-Dusseau

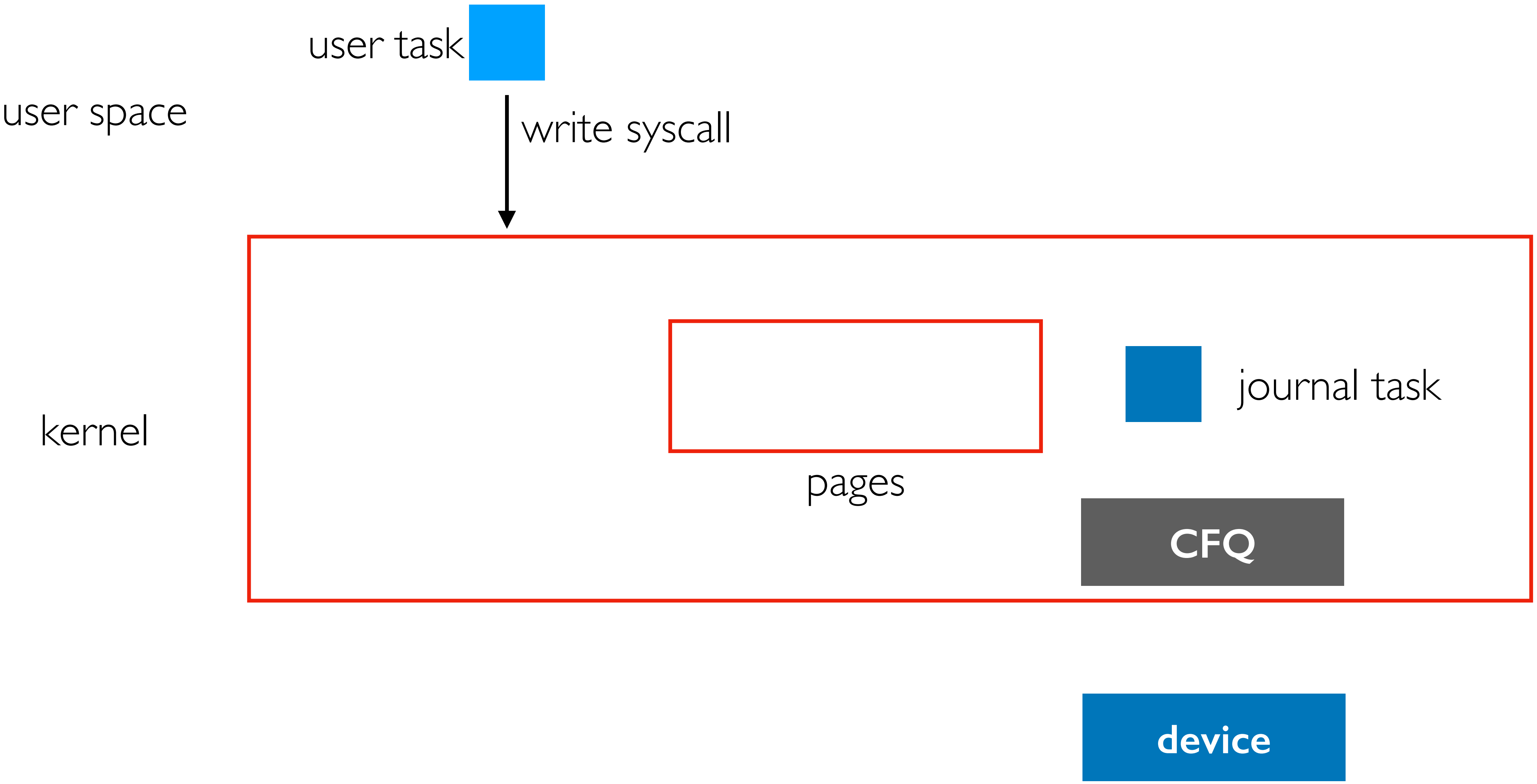
University of Wisconsin-Madison *IBM Research-Almaden**

https://research.cs.wisc.edu/wind/Publications/split-sosp15.pdf

Issue: block schedulers associate I/O with tasks, but due to the page cache and journaling, blame is often misdirected.

Remember: cgroups can only be as good as the underlying schedulers/mechanisms.

Block I/O Scheduling Limitations



user space

user task

write syscall

kernel

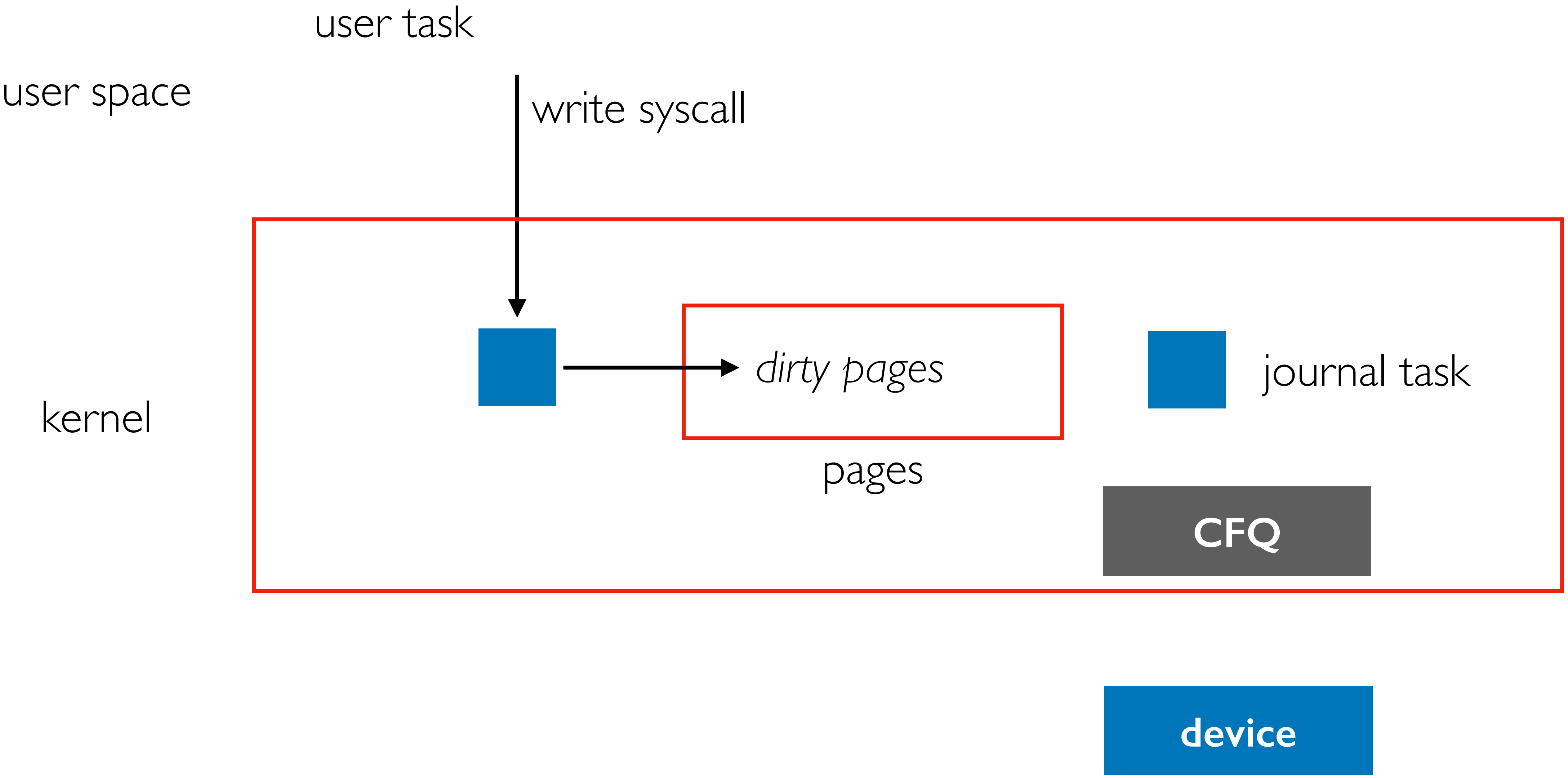
pages

journal task

CFQ

device

Block I/O Scheduling Limitations



user task

user space

write syscall

kernel

dirty pages

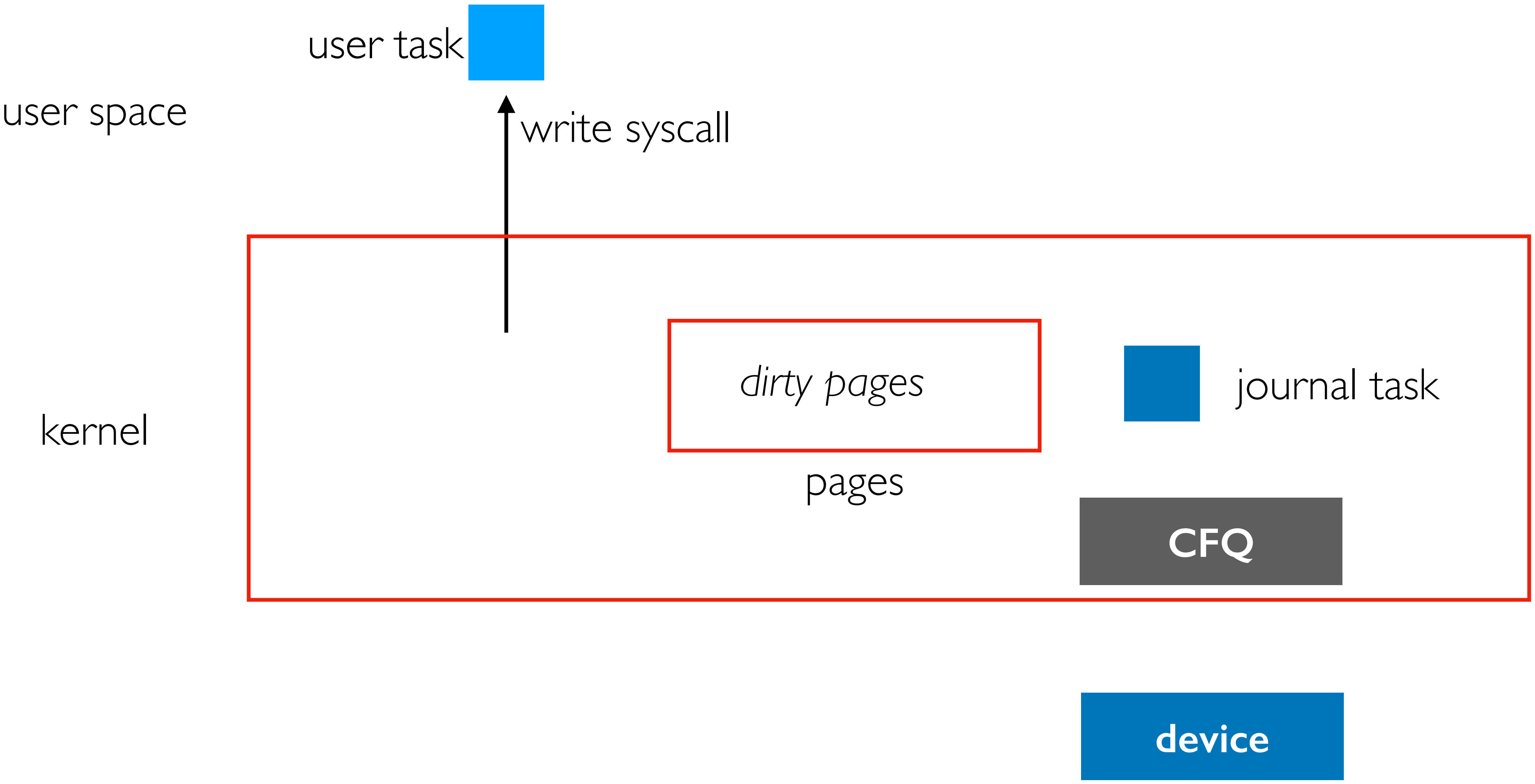
pages

journal task

CFQ

device

Block I/O Scheduling Limitations



user task

user space

write syscall

kernel

dirty pages

pages

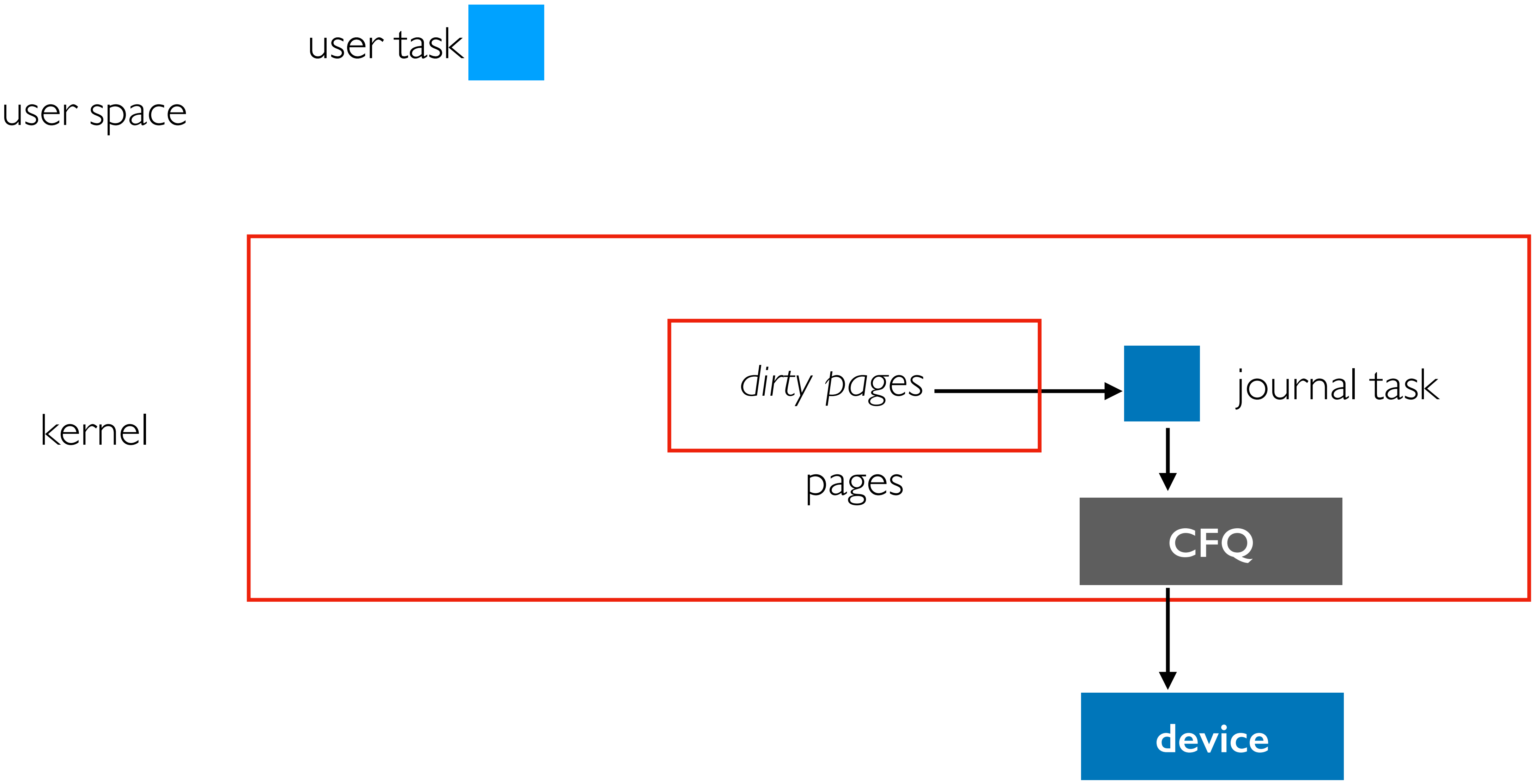
journal task

CFQ

device

problem 1: user task has already created work that must be done but hasn't been accounted for

Block I/O Scheduling Limitations



problem 2: from scheduler's perspective, all writes
can be blamed on one task (journal task)

Problem 1: Too Much Work Created before Accounting

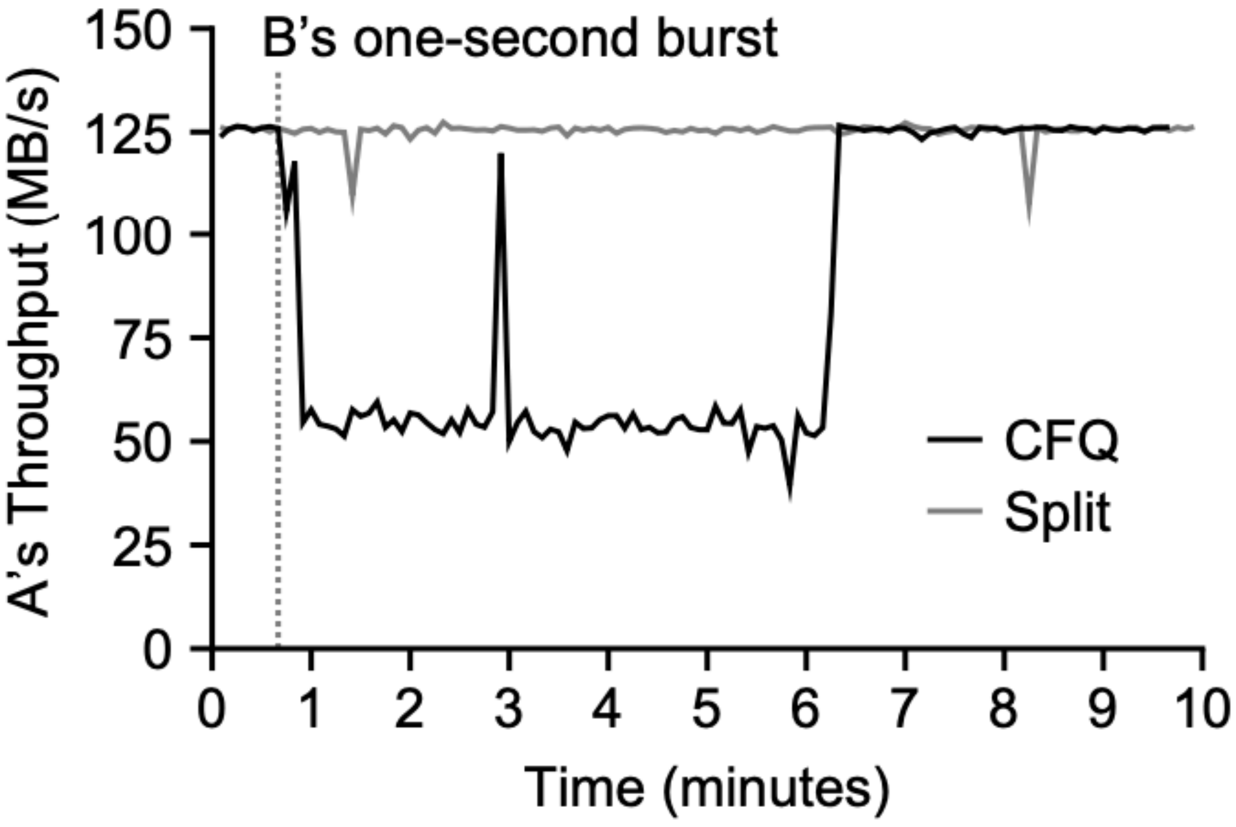


Figure 1: **Write Burst.** *B's one-second random-write burst severely degrades A's performance for over five minutes. Putting B in CFQ's idle class provides no help.*

Split-Level I/O Scheduling

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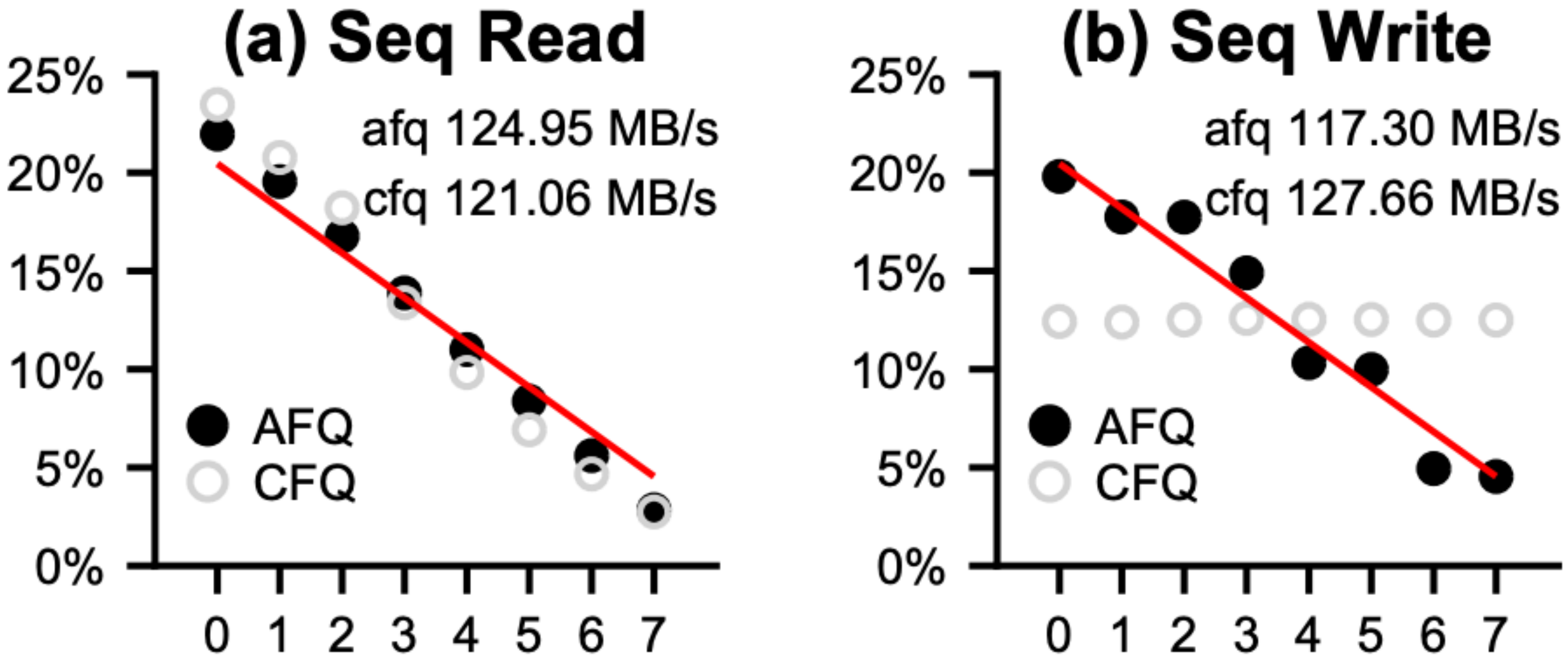
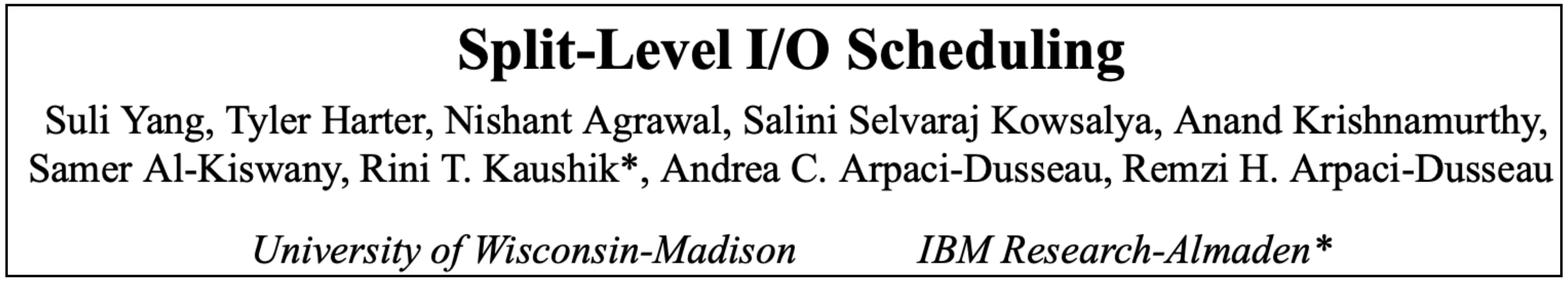
University of Wisconsin-Madison *IBM Research-Almaden**

Problem 2: Write Priority is Meaningless





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Usage in OpenLambda

cgroups

Control Groups

Controllers (per resource type) enable limiting/sharing consumption

- **compute:** `cpu`, `cpuset`, `freezer`
- **memory:** `memory`, `hugetlb`, `rdma`
- `io` (disk only)
- `pids`
- `perf_event`

Groups of proceses (sometimes threads)

- groups are hierarchical
- different combinations of controllers/settings can be applied to groups
- implemented as a pseudo file system (for example, you mount the cgroup2 file system, and create cgroups with `mkdir`)

cgroups v1 vs. v2

- v1 is more flexible (probably too flexible)
- v2 just makes more "sense"
- both can be used simultaneously (but you probably shouldn't)

cgroups

Control Groups

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- compute: `cpu`, `cpuset`, `freezer`
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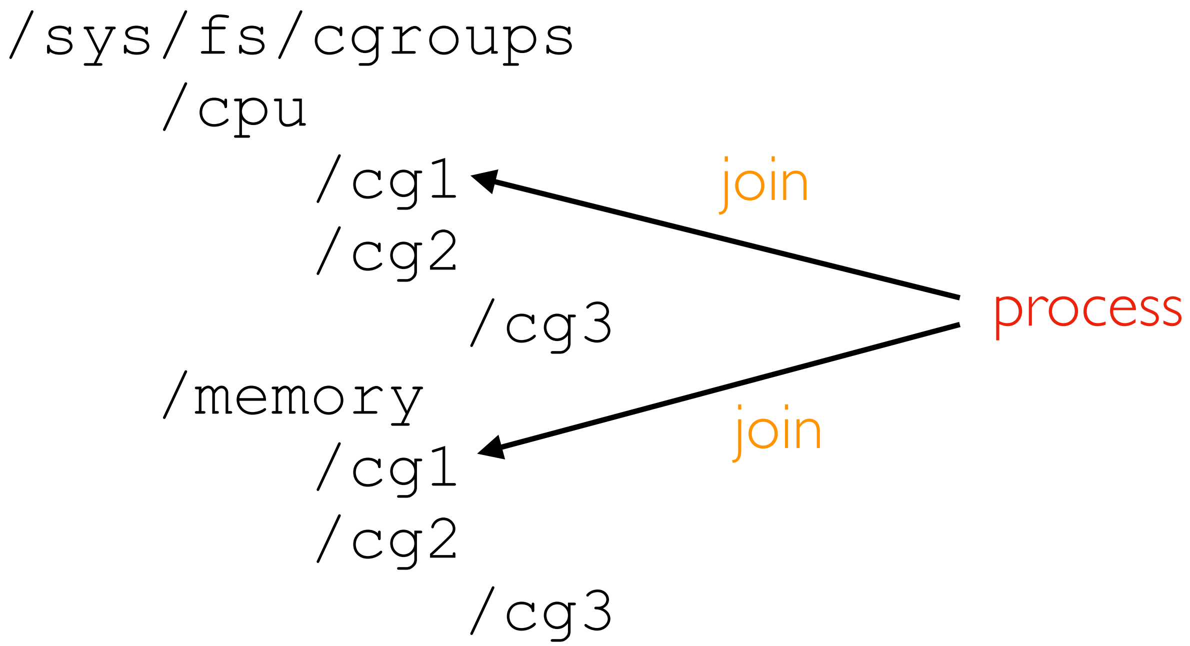
cgroups VERSION 1 hierarchy

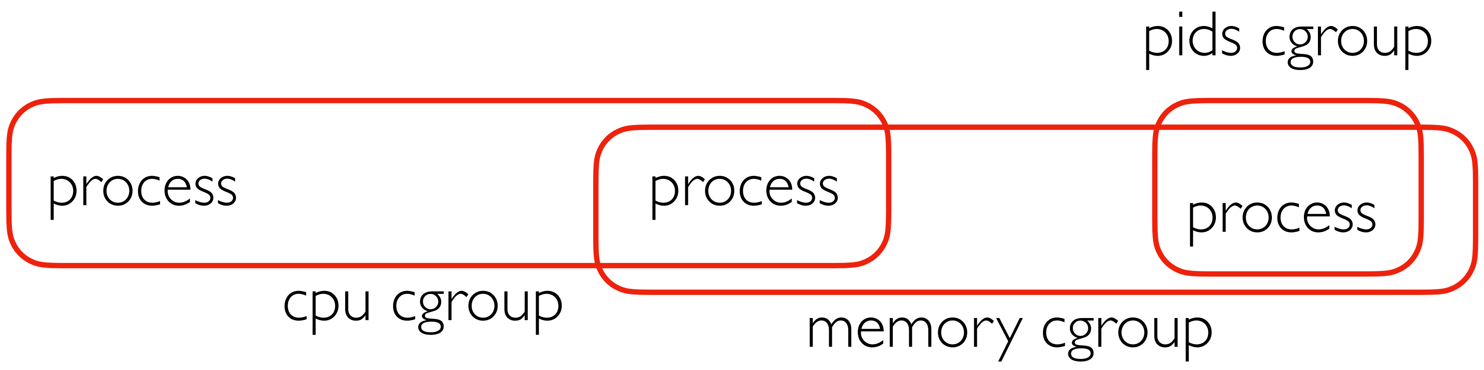
example hierarchy with two controllers (cpu and memory) and three groups (cg1, cg2, and cg3)



```
/sys/fs/cgroups
    /cpu
        /cg1
        /cg2
            /cg3
    /memory
        /cg1
        /cg2
            /cg3
```

With v1, you had to join many different cgroups, for each type.

cgroups VERSION 1 hierarchy



pids cgroup

process

process

process

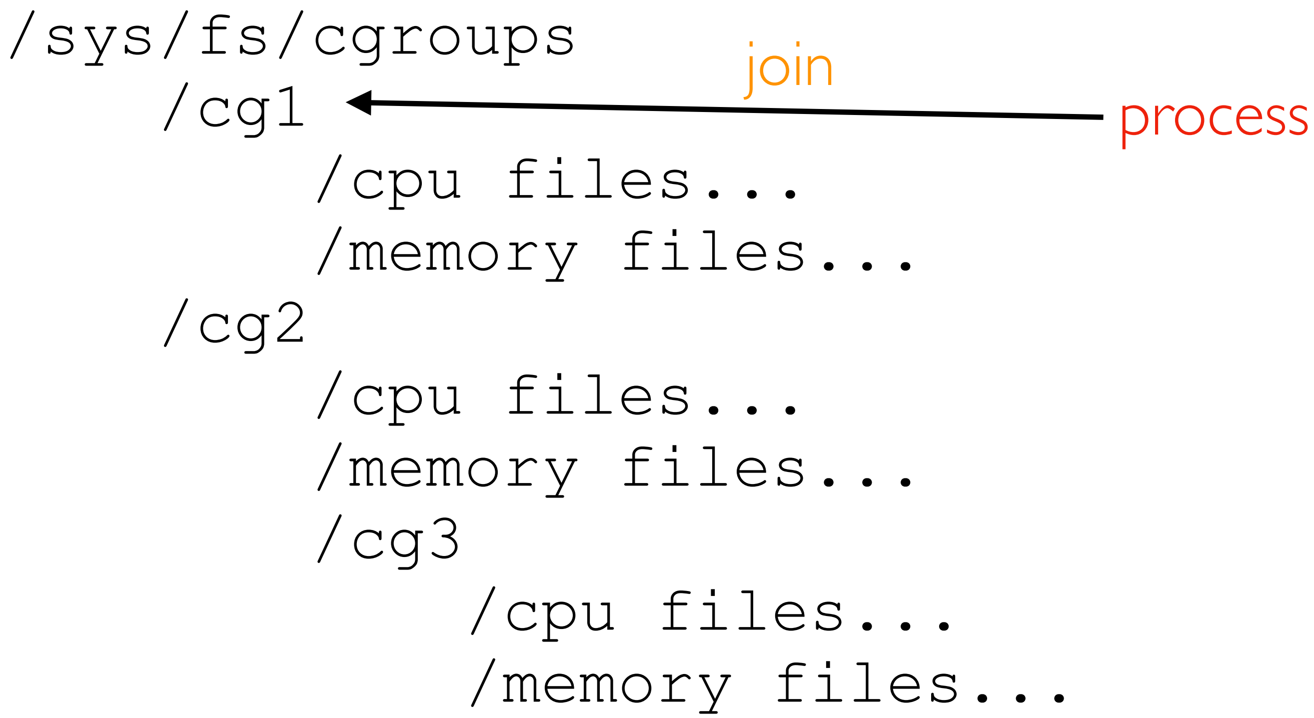
cpu cgroup

memory cgroup

cgroups v1 allowed a lot of flexibility
with almost no imaginable use case

cgroups VERSION 2 hierarchy

example hierarchy with two controllers (cpu and memory)
and two groups (cg1 and cg2)



```
/sys/fs/cgroups
    /cg1
        /cpu files...
        /memory files...
    /cg2
        /cpu files...
        /memory files...
        /cg3
            /cpu files...
            /memory files...
```

join

process

Other Simplications

Mount Points

- **v1:** instances of the cgroup FS could be mounted in different places, with different controllers applied
- **v2:** all mount points are just identicialy views into the same hierarchy

Nodes having processes

- **v1:** any node in the tree can have processes
- **v2:** only the root and leaves can have processes (some exceptions)

Threads

- **v1:** threads OR processes can be in a group
- **v2:** only processes can be in a group (this evolved some...)

Threads

Memory cgroups don't make sense for threads: heap space is not assigned to specific threads, and the kernel isn't involved on every malloc, so it couldn't apply different memory limits to different threads anyway.

crgoups V2 dropped support for threaded cgroups.

BUT! CPU cgroups are useful for threads in some case (threads doing background work should perhaps get less share).

Conclusion: V2 added back limited support by implementing different kinds of controller.

- **domain:** for processes (the default)
- **threaded:** for resources like CPU

Controller Types: Domain vs. Threaded

example hierarchy with two controllers (cpu and memory)
and two groups (cg1 and cg2)

```
/sys/fs/cgroups
    /myapp [domain]
        /cg1 [domain threaded]
            /memory files...
            /foreground [threaded]
                /cpu files...
            /background [threaded]
                /cpu files...
```

process is at this level,
with a memory limit

Controller Types: Domain vs. Threaded

example hierarchy with two controllers (cpu and memory)
and two groups (cg1 and cg2)

```
/sys/fs/cgroups
    /myapp [domain]
        /cg1 [domain threaded]
            /memory files...
            /foreground [threaded]
                /cpu files...
            /background [threaded]
                /cpu files...
```

threads of the cg1 will
be in one of these

Joining a cgroup

approach 1: after creation

each cgroup has a `cgroup.procs` and `cgroup.threads` entry. Write a PID or thread ID to one of these to join it.

approach 2: during creation

these days `fork()` is just a wrapper around a clone call (`clone`, `clone2`, or `clone3`).

Recently (Linux 5.7, released 2020), clone3 added CLONE_INTO_CGROUP flag.

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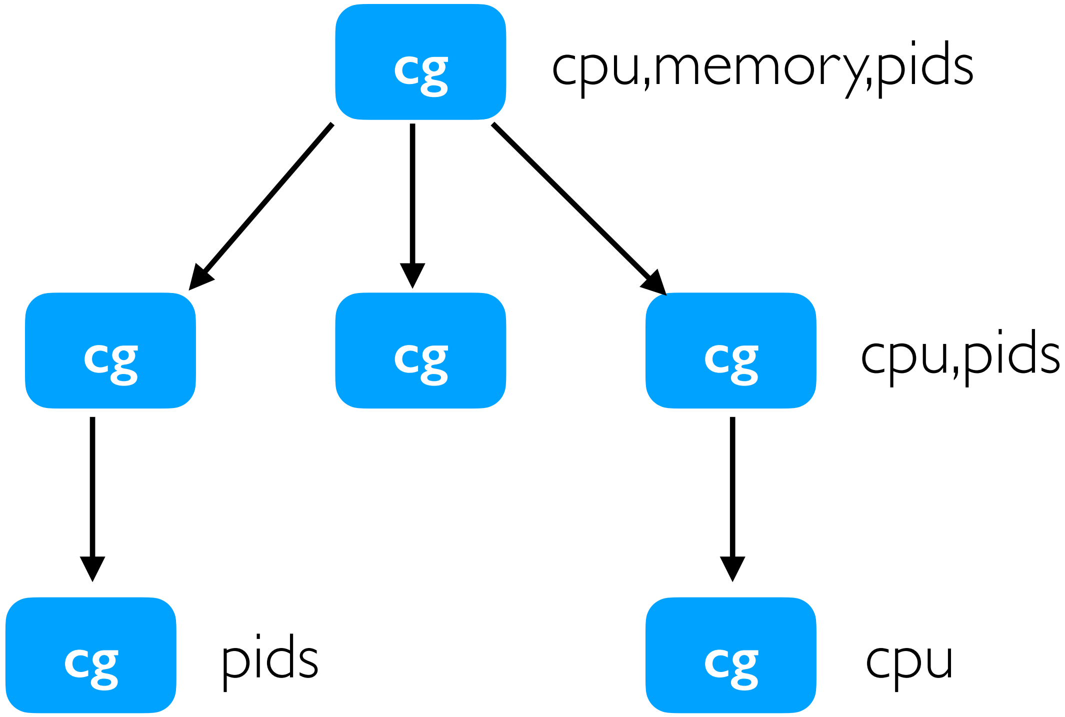
Usage in OpenLambda

Controllers



- a cgroup will have a subset of controllers enabled
- control of some of these can be passed to children
- implication: as you go deeper, the set of controllers can only get smaller

```
/sys/fs/cgroups
    /cg1
        /cgroup.controllers
        /cgroup.subtree_control
        /cg2
            /cgroup.controllers
            /cgroup.subtree_control
```

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Usage in OpenLambda

Controlling Compute Resources

Should a cgroup run? Where should it run? How much time should it run?

These are controlled by freezer, cpuset, cpu and respectively.

Freeze

```
/sys/fs/cgroups
    /cg1
        /cgroup.freeze
        /cgroup.events
    /cg2
        /cgroup.freeze
        /cgroup.events
```

write 1 to freeze (make non-schedulable), 0 to unfreeze

note: this is not a regular controller, so you don't need to enable it.

Freezing/unfreezing is asyncronous. Use `poll()` or `inotify` on `cgroup.events` to observe when the action is complete. Note: OpenLambda should do this, but it doesn't yet.

Typical use in serverless: unfreeze when it's time to service an event. Bill for non-frozen time. Freeze after request (so user can't get free compute with a background thread).

Anecdote: Early Version of Google Cloud Functions

Peeking Behind the Curtains
of Serverless Platforms

Liang Wang, *UW-Madison;* Mengyuan Li and Yinqian Zhang, *The Ohio State University;*
Thomas Ristenpart, *Cornell Tech;* Michael Swift, *UW-Madison*

https://www.usenix.org/conference/atc18/presentation/wang-liang

https://www.usenix.org/system/files/conference/atc18/atc18-wang-liang.pdf

"Background processes. We found in Google one could execute an external script in the background that continued to run even after the function invocation concluded. The script we ran posted a 10 M file every 10 seconds to a server under our control, and the longest time it stayed alive was 21 hours. We could not find any logs of the network activity performed by the background process and were not charged for its resource consumption."

Perhaps the freezer wasn't being used correctly?

cpuset

```
echo "2,3" > cpuset.cpus
```

this group of processes will
only run on these cores

- guarantees will not run on other cores
- they are not guaranteed these cores -- other things might get scheduled here
- good: get warmer CPU cache
- bad: other cores might be idle, but we can't use them even if we're doing lots of compute

cpu

- cpu is more flexible: specify share or limit of resource, without constraining WHERE it is achieved
- lots of configs:

`cpu.idle`
`cpu.max`
`cpu.stat`
`cpu.uclamp.max`
`cpu.max.burst`
`cpu.uclamp.min`
`cpu.pressure`
`cpu.weight.nice`
`cpu.weight`

> "When distributing CPU time to the children, all of their `cpu.weight` values are summed up and then each active child gets CPU in proportion to their weight relative to the total. This means that if all `cpu.weight` files have the same value, all children will get equal shares of the CPU time. The actual `cpu.weight` values only matter if they're different; if they're all the same, the value is arbitrary."

https://utcc.utoronto.ca/~cks/space/blog/linux/CgroupV2FairShareScheduling

- for sole tenant, you probably want to never waste cores when something is runnable
- when customers are billed per compute, you probably don't want to give away extra cores for free just to be nice

cpu

- cpu is more flexible: specify share or limit of resource, without constraining WHERE it is achieved
- lots of configs:

```
cpu.idle      cpu.stat         cpu.max.burst     cpu.pressure
cpu.max       cpu.uclamp.max   cpu.uclamp.min    cpu.weight.nice
                                                 cpu.weight
```

`runtime walltime` (both in microseconds)

```
echo "50000 100000" > cpu.max
```

out of each 100ms period, only give 50ms of compute

```
echo "5000 10000" > cpu.max
```

same ratio, but over 10ms period. Shorter: more interactive, but less efficient (context switches)

```
echo "200000 100000" > cpu.max
```

runtime > walltime, meaning can use >1 core (in this case, 2 cores).

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Usage in OpenLambda

memory

```
memory.events.local  memory.low
memory.min       memory.oom.group     memory.stat
memory.swap.events     memory.high             memory.numa_stat
memory.pressure    memory.swap.current  memory.swap.highMechanism
memory.max     memory.swap.max     memory.current    memory.events
```

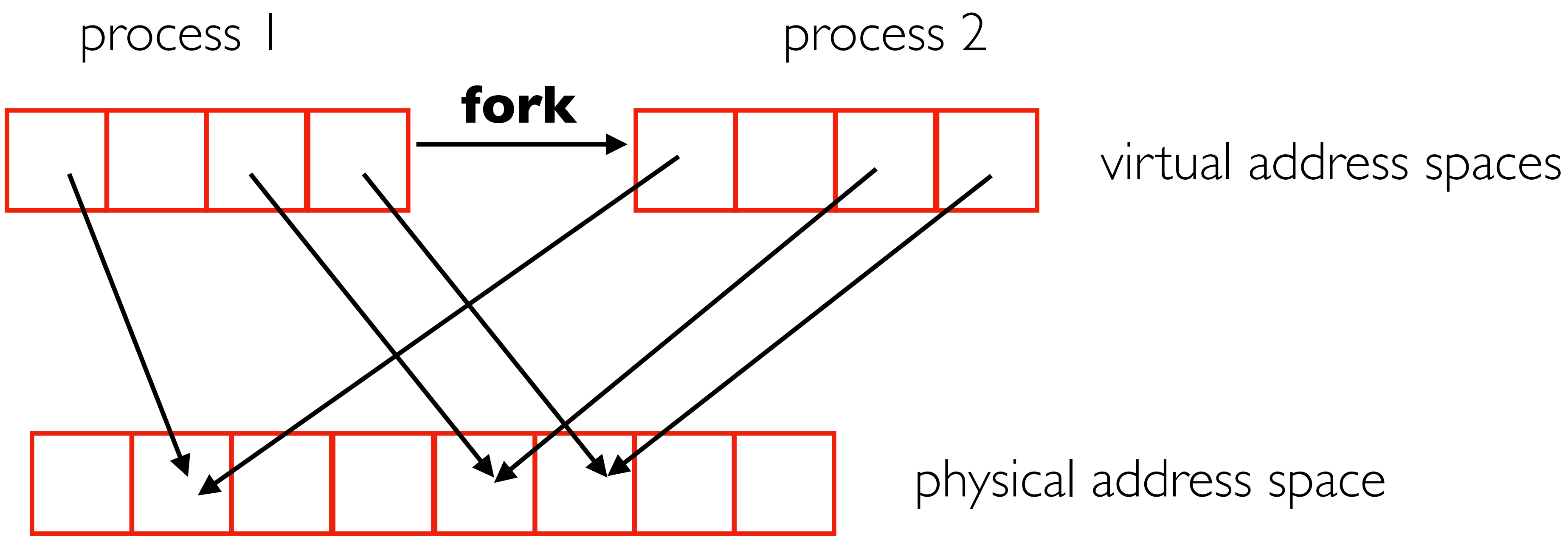
hard limit on RAM usage.
Exceed it and the OOM
killer gets you. (bytes)

bytes of space that can be
used in a swapfile.

current memory usage
(in bytes).

can be read to determine
whether the OOM killer
terminated a process. Very
useful for generating a useful
error message for the user.

Who to charge?

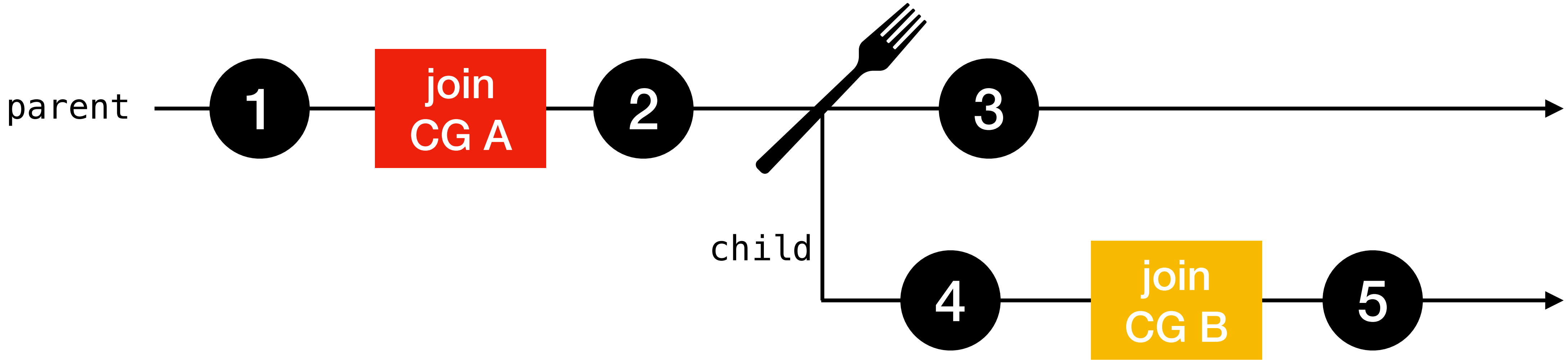


We're using 12 KB (3 pages) of physical memory total. How should we do accounting across the two processes?

- 6 KB each? If process 2 stops, does the memory accounting for process 1 pop, leading to a kill?
- 12 KB for process 1, since it allocated it first? Why should process 2 have a free ride?

No good answers here, and even if we know what we want, cgroups provide limited control.

Accounting (cgroup V1 experiment)

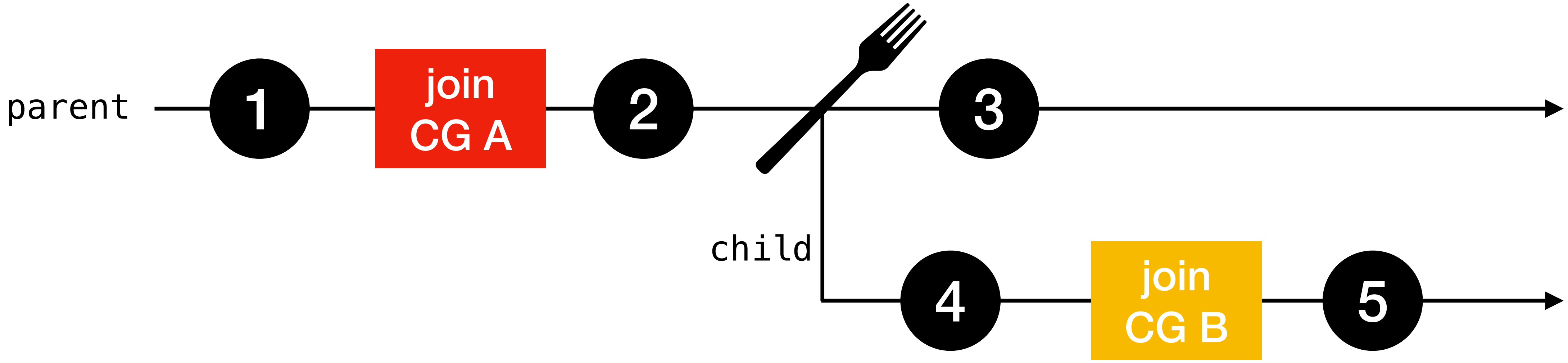


Each circle above is a memory allocation.
What should be blamed on A? On B?

cgroups V1 has a "memory.move_charge_at_immigrate" setting to provide some control.
cgroups V2 is simpler and lacks this!

```
shell> bash
bash> mkdir /sys/fs/cgroup/memory/my-cg
bash> echo $$ > /sys/fs/cgroup/memory/my-cg/tasks # own PID
bash> echo 4M > /sys/fs/cgroup/memory/my-cg/memory.limit_in_bytes
```

Accounting (cgroup V1 experiment)



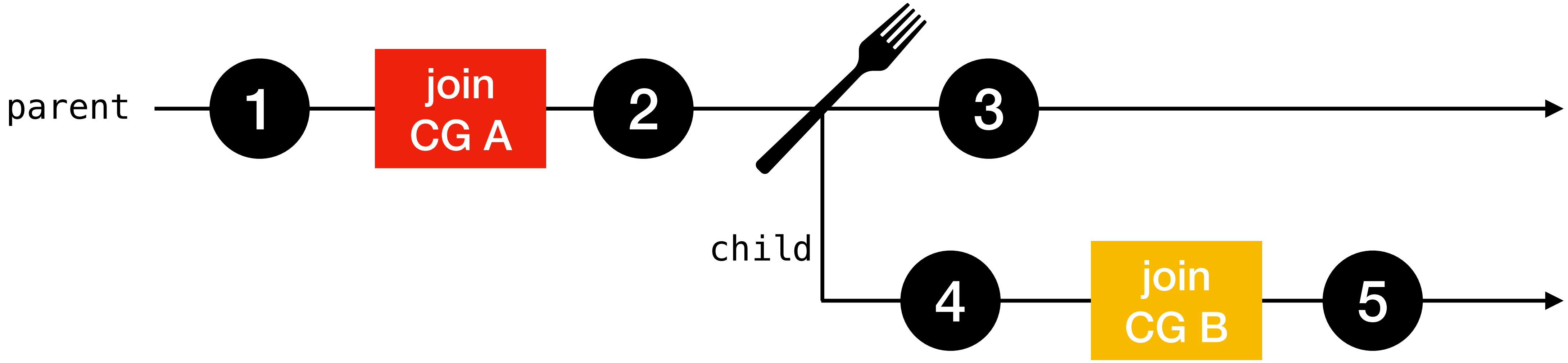
Allocation Point

Move Charge on Immigrate

	1	2	3	4	5
neither	-	A	A	A	B
A	A	A	A	A	B
B	-	B	A	B	B
both	B	B [96%]	A	B [84%]	B

```
bash> echo 1 > /sys/fs/cgroup/memory/my-cg/memory.move_charge_at_immigrate
```

Accounting (cgroup V1 experiment)



Allocation Point

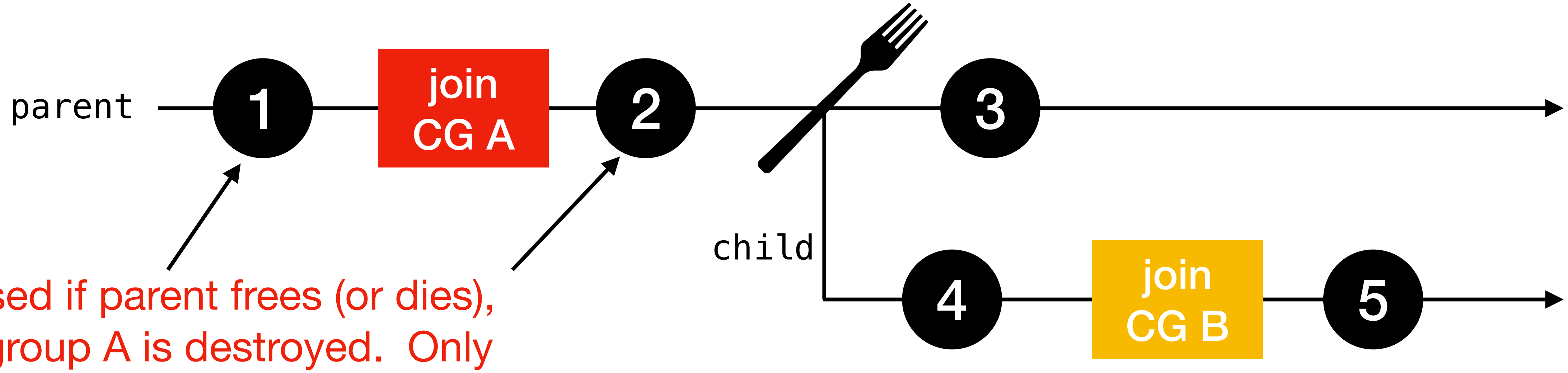
Move Charge on Immigrate

	1	2	3	4	5
neither	-	A	A	A	B
A	A	A	A	A	B
B	-	B	A	B	B
both	B	B [96%]	A	B [84%]	B

"leak" ~300KB
per fork

Implication: ONLY use **`move_charge_on_immigrate`** for parentless sandboxes.
Avoid accruing memory charges between fork and joining child CG.

Accounting (cgroup V1 experiment)



not released if parent frees (or dies), even if cgroup A is destroyed. Only released if child exits/frees too.

Allocation Point

Move Charge on Immigrate

	1	2	3	4	5
neither	-	A	A	A	B
A	A	A	A	A	B
B	-	B	A	B	B
both	B	B [96%]	A	B [84%]	B

Implication: never assume memory can me reclaimed from a dead sandbox until its children exit too.

Outline

Performance Isolation

Mechanism Examples

Interface: cgroup overview

Controllers

- freezer/cpu/cpuset
- memory
- io (disk)
- pids
- what about network?

Usage in OpenLambda

io

The io controller is for disk only.

io.max is like cpu.max, in that it sets a hard cap regardless of what other processes are doing. There is more granularity to differentiate reads/writes, etc.

io.weight is like cpu.weight.

Both these settings can indicate which device the configs apply to.

Remember the limitations of I/O scheduling mentioned earlier! It's hard to be fair across tasks if you don't know which task originated a write.

Note: I'm not aware of a cgroup controller for limited disk space used. Better to look into quota settings for particular local FS in use?

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Usage in OpenLambda

pids

pids.max limits the number of processes in a cgroup. Prevent fork bombs from getting out of control.

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Usage in OpenLambda

Network I/O

V1

- net_cls cgroup could specify a classid, used by firewall and traffic shaping config.
- net_prio cgroup could specify priority per network interface

V2

- network related controllers were removed

Extended Berkeley Packed Filters (eBPF): https://en.wikipedia.org/wiki/EBPF

- provide way to run safe code in the kernel to make decisions about blocking/prioritizing packets
- eBPF filters can be written that observe cgroup names and make decisions accordingly

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SOCK cgroup Usage

SOCK (Serverless Optimized Container) is main the sandbox engine in OpenLambda and uses cgroups.

SOCK paper (2018): we just created and joined all the cgroups (to get meaningful perf measurements) but didn't actually set any limits.

We have been using more settings over time. It's on ongoing process, but it's far from complete:

- disk/network I/O: we don't do anything
- pids controller: one configurable limit on proc count for all lambdas
- cpu controller: specify cpu.max for all (no cpuset)
- **memory** is where we have done the most work

Admission + Eviction

Version 1 (SOCK paper)

- Evict **idle** sandboxes if cgroup_usage_sum > soft_limit
- Only admit new sandboxes if cgroup_usage_sum < hard_limit

Problems:

1. what if every sandbox is active?
2. containers growing their mem footprint aren't subject to admission

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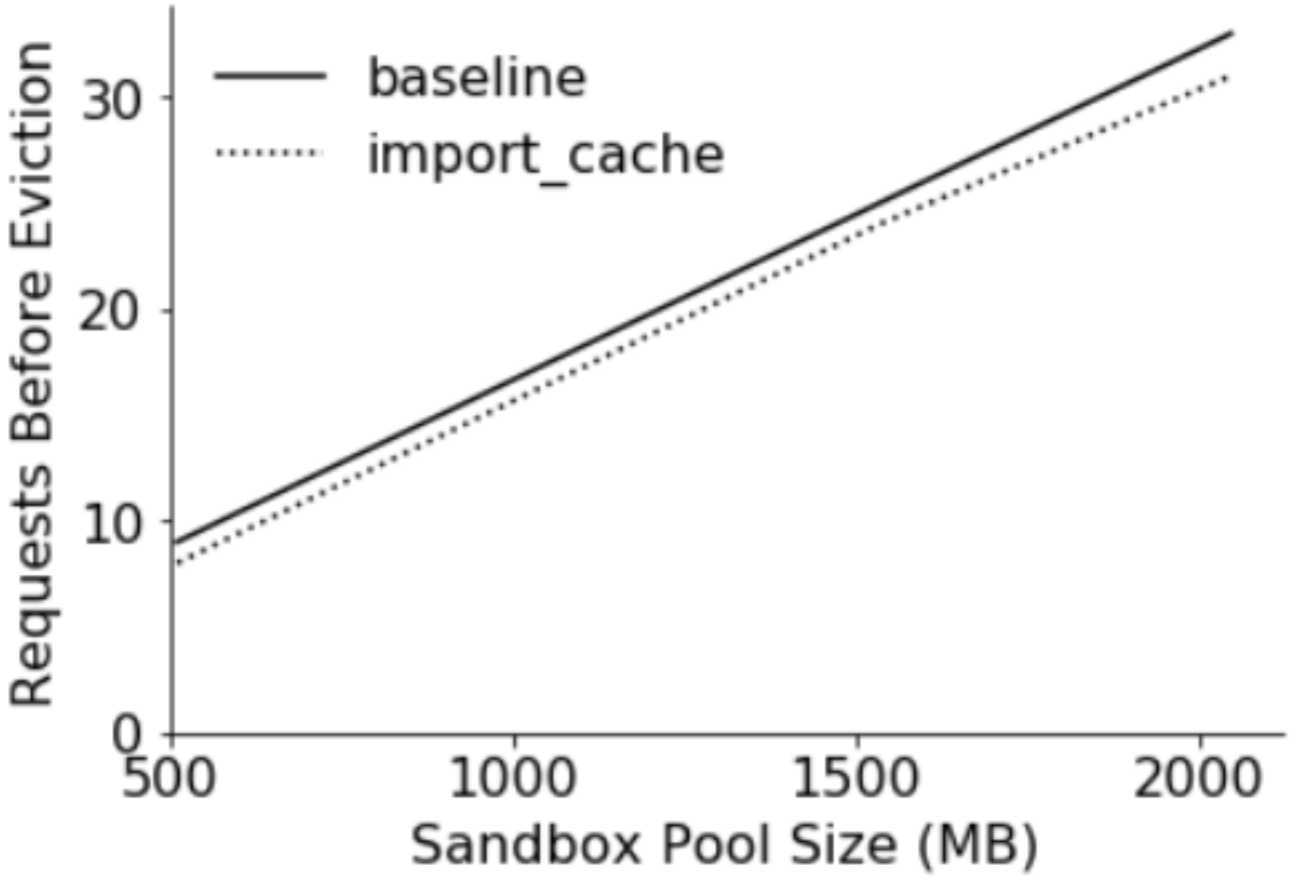
Version 2

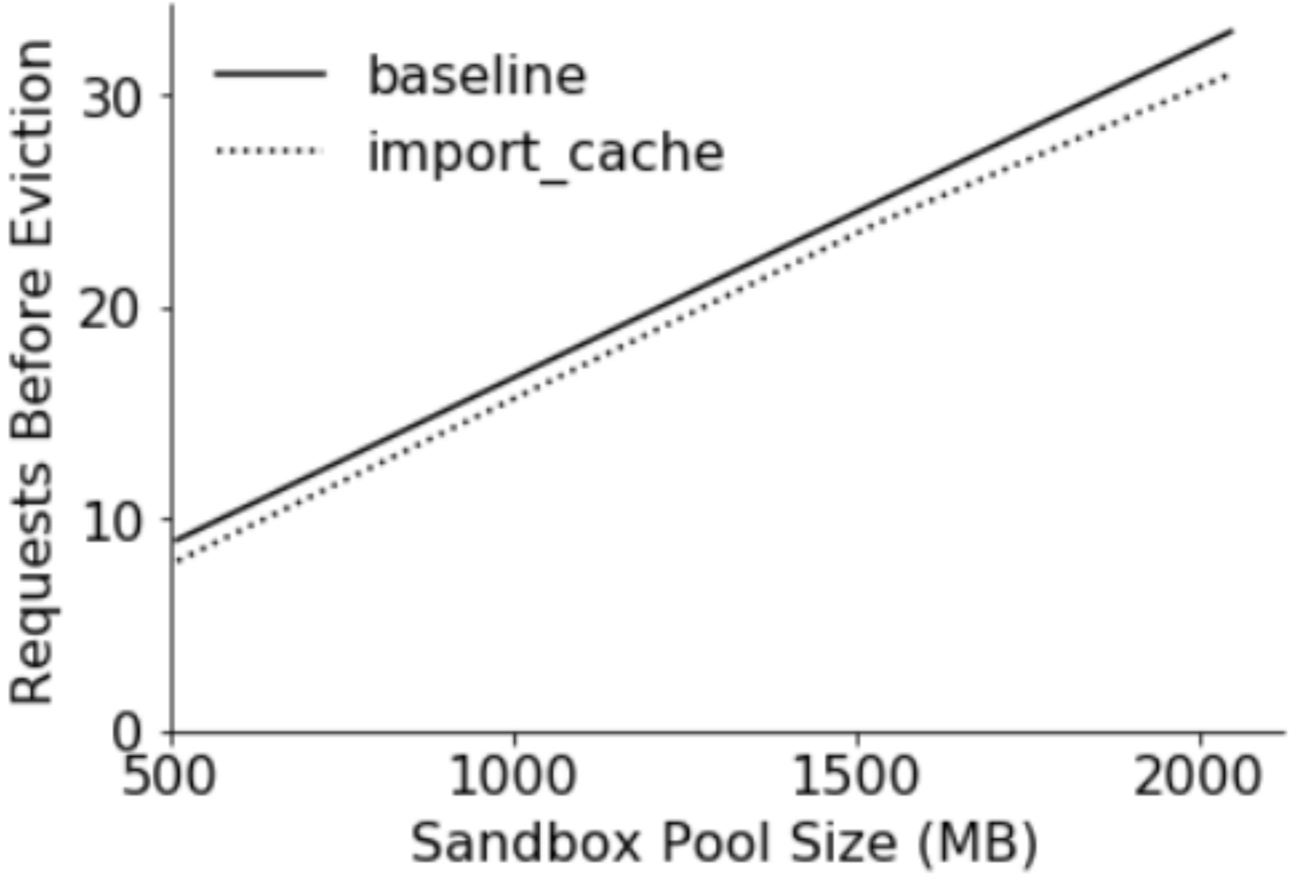
- Eviction policy: evict idle sandboxes that haven't been unfrozen for the longest time (basically LRU, where usage is unfreezing)
- Only admit new sandboxes if cgroup_**limit**_sum < hard_limit

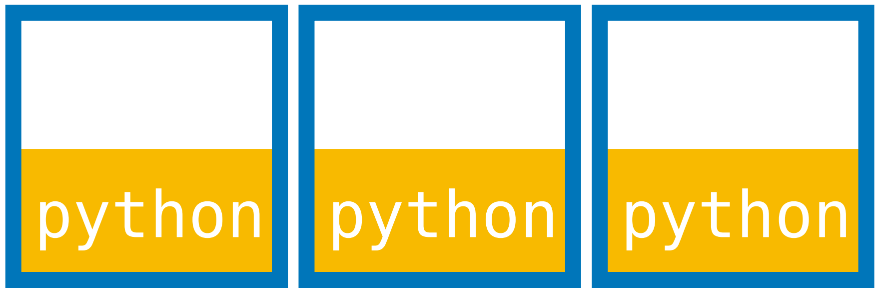
no-op lambdas, call each once



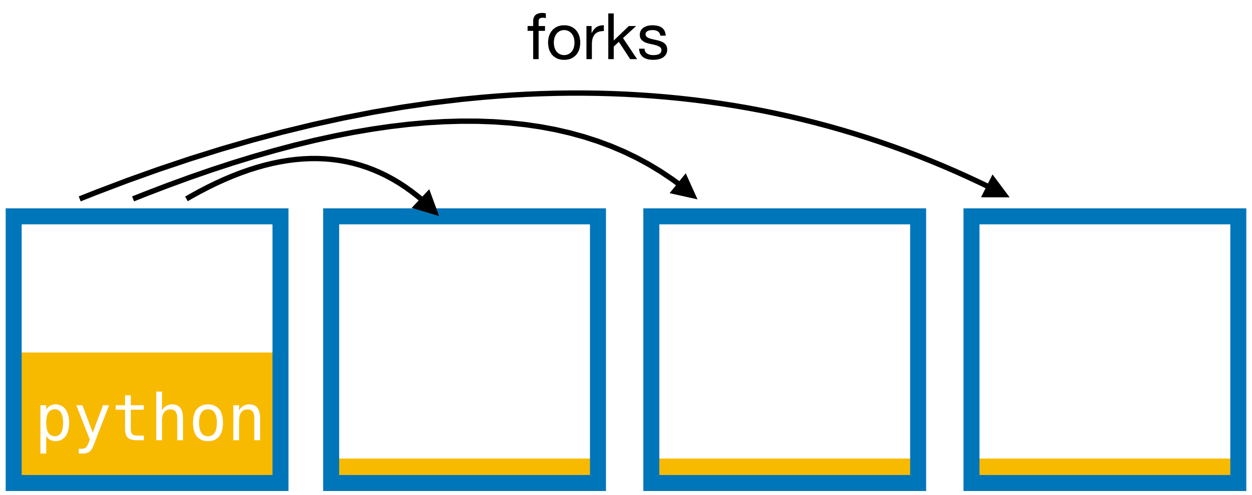
Both lines are the new (v2) admission+eviction policy, with and without the Zygote import cache enabled

Problem: import cache reduces memory usage; that doesn't matter if we admit based on limits (not usage)





vs.



more usage, lower cumulative cap

less usage, higher cumulative cap

[without Zygote]

[with Zygote]

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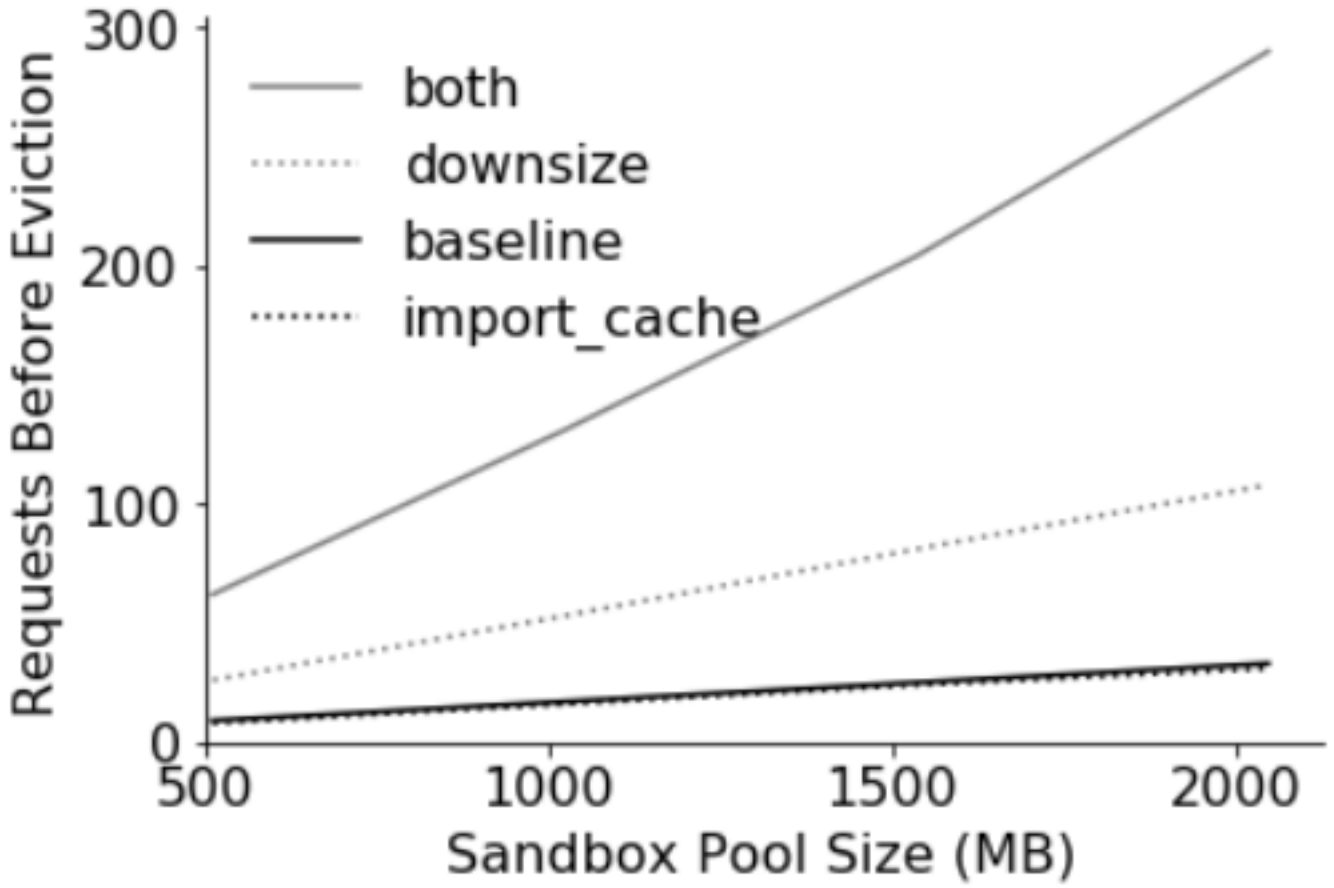
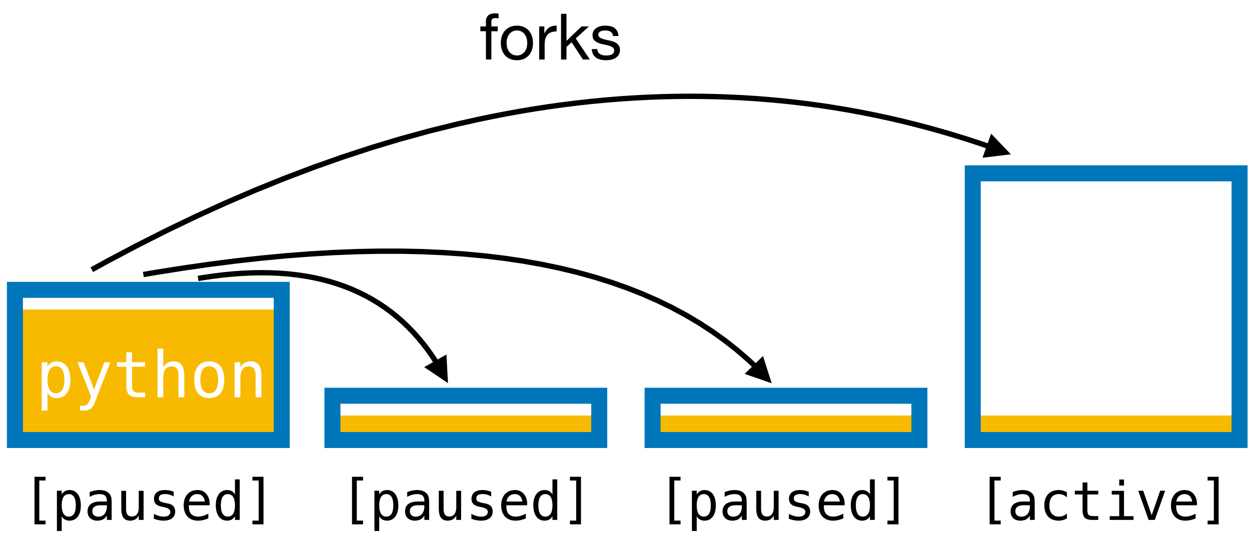
Version 2

- Eviction policy described later...
- Only admit new sandboxes if cgroup_limit_sum < hard_limit

Version 3

- Drop cgroup mem limit to actual usage when Sandbox is paused
- Otherwise same as V2


Requests Before Eviction
300
200
100
0
500
1000
1500
2000
Sandbox Pool Size (MB)
both
downsize
baseline
import_cache


forks
python
[paused]
[paused]
[paused]
[active]

Configs for cgroups

Relevant subset of worker's config.json file:

```
{
  "mem_pool_mb": 7449,
  "limits": {
    "procs": 10,
    "mem_mb": 50,
    "cpu_percent": 100,
    "max_runtime_default": 30,
    "swappiness": 0,
    "installer_mem_mb": 500
  },
  "features": {
    "reuse_cgroups": false,
  },
  "trace": {
    "cgroups": false,
    "memory": false,
    "evictor": false,
  },
}
```

sum of all cgroup memory limits will never exceed this (default depends on total system RAM available)

fork bomb will fail after 10 processes

memory per regular lambda (more than you think because the Python runtime gets accounted to a zygote)

installing packages with pip can use a lot of memory (because it often needs a compiler for C/Fortran dependencies

this should probably always be off (will probably remove it)

cgroups Going Forward in OpenLambda

See current code here: https://github.com/open-lambda/open-lambda/tree/main/src/worker/sandbox/cgroups

SOCK cgroups are probably due for a re-write

- configurable settings on a per-lambda/invocation basis
- use `cgroup.events` with `poll()` to wait for freeze and depopulate events
- use `CLONE_INTO_CGROUP` with `clone3()` so we don't need to move cgroups after creation (the lack of this leads to an ugly loop where we keep checking if new processes have been launched before the move so we don't leave any new ones behind)
- remove cgroup reuse (this subsystem is already brittle enough as is)
- set aside cgroups when rmdir fails (instead of panic'ing)
- use io limits; do something reasonable with swap
- add users with file quotes to accomplish space limits