10. Multiprocessor Scheduling (Advanced)

Operating System: Three Easy Pieces

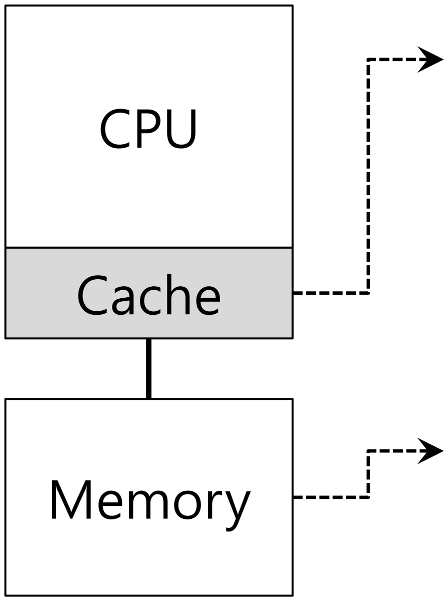
Multiprocessor Scheduling

- The rise of the multicore processor is the source of multiprocessor-scheduling proliferation.
  - **Multicore**: Multiple CPU cores are packed onto a single chip.

- Adding more CPUs does not make that single application run faster.
  → You'll have to rewrite application to run in parallel, using **threads**.

How to schedule jobs on Multiple CPUs?

Single CPU with cache



Cache

- Small, fast memories
- Hold copies of popular data that is found in the main memory.
- Utilize *temporal* and *spatial* locality

Main Memory

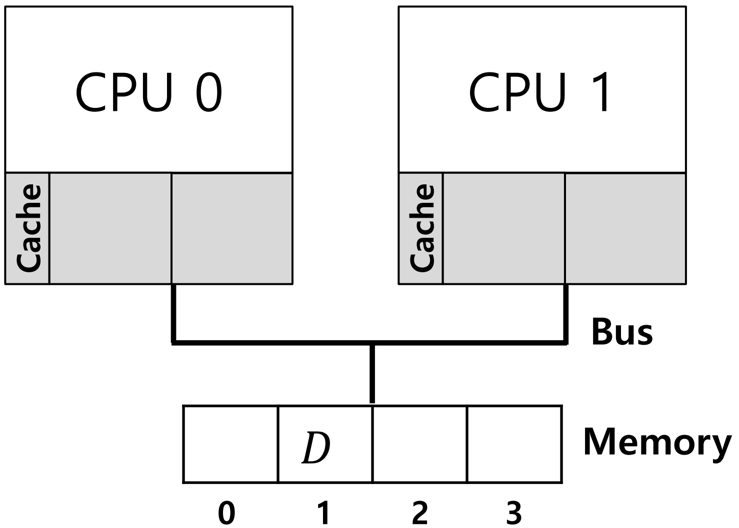
- Holds all of the data
- Access to main memory is slower than cache.

By keeping data in cache, the system can make slow memory appear to be a fast one

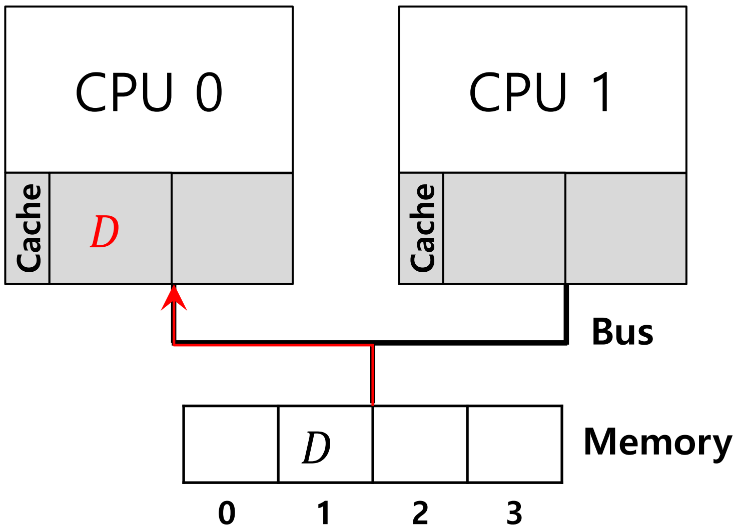
Cache coherence

- Coherence of shared resource data stored in multiple caches.

0. Two CPUs with caches sharing memory

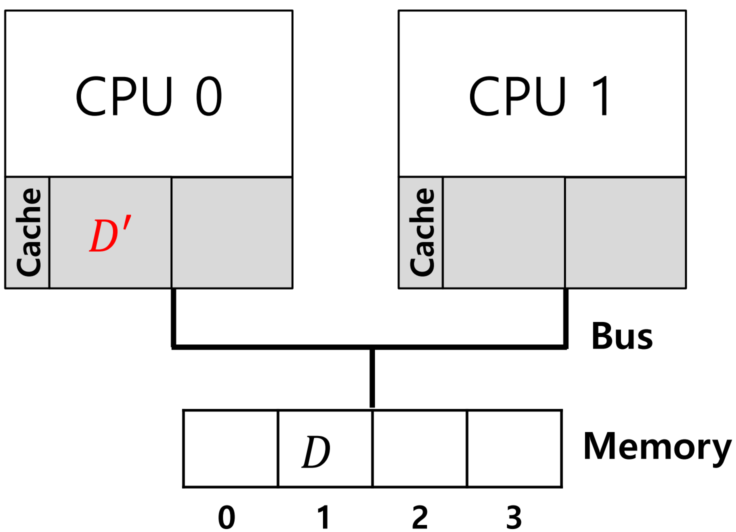


1. CPU0 reads a data at address 1.

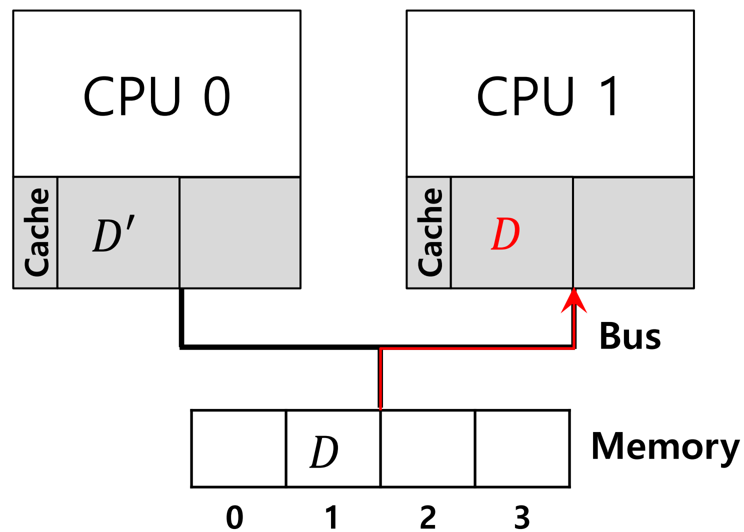


Cache coherence (Cont.)

2. D is updated and CPU1 is scheduled.



3. CPU1 re-reads the value at address A



CPU1 gets the old value D instead of the correct value D'.

Cache coherence solution

- Bus snooping
  - Each cache pays attention to memory updates by **observing the bus**.
  - When a CPU sees an update for a data item it holds in its cache, it will notice the change and either <u>invalidate</u> its copy or <u>update</u> it.

Don't forget synchronization

- When accessing shared data across CPUs, mutual exclusion primitives should likely be used to guarantee correctness.

```
typedef struct __Node_t {
        int value;
        struct __Node_t *next;
} Node_t;

int List_Pop() {
        Node_t *tmp = head;           // remember old head ...
        int value = head->value;      // ... and its value
        head = head->next;            // advance head to next pointer
        free(tmp);                    // free old head
        return value;                 // return value at head
}
```

Simple List Delete Code

Don’t forget synchronization (Cont.)

- Solution

```
pthread_mtuex_t m;
typedef struct __Node_t {
        int value;
        struct __Node_t *next;
} Node_t;

int List_Pop() {
        lock(&m)
        Node_t *tmp = head;           // remember old head ...
        int value = head->value;      // ... and its value
        head = head->next;            // advance head to next pointer
        free(tmp);                    // free old head
        unlock(&m)
        return value;                 // return value at head
}
```

Simple List Delete Code with lock

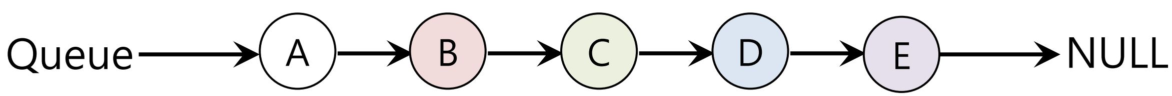
Cache Affinity

- Keep a process on the same CPU if possible
  - A process builds up a fair bit of state in the cache of a CPU.
  - The next time the process run, it will run faster if some of its state is *already present* in the cache on that CPU.

A multiprocessor scheduler should consider cache affinity when making its scheduling decision.

Single queue Multiprocessor Scheduling (SQMS)

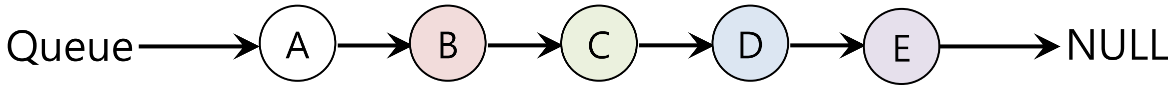
- Put all jobs that need to be scheduled into a single queue.
  - Each CPU simply picks the next job from the globally shared queue.
  - Cons:
    - Some form of **locking** must be used → Lack of scalability
    - Cache affinity
    - Example:



    - Possible job scheduler across CPUs:

CPU0	A	E	D	C	B	… (repeat) …
CPU1	B	A	E	D	C	… (repeat) …
CPU2	C	B	A	E	D	… (repeat) …
CPU3	D	C	B	A	E	… (repeat) …

Scheduling Example with Cache affinity



CPU0	A	E	A	A	A	... (repeat) ...
CPU1	B	B	E	B	B	... (repeat) ...
CPU2	C	C	C	E	C	... (repeat) ...
CPU3	D	D	D	D	E	... (repeat) ...

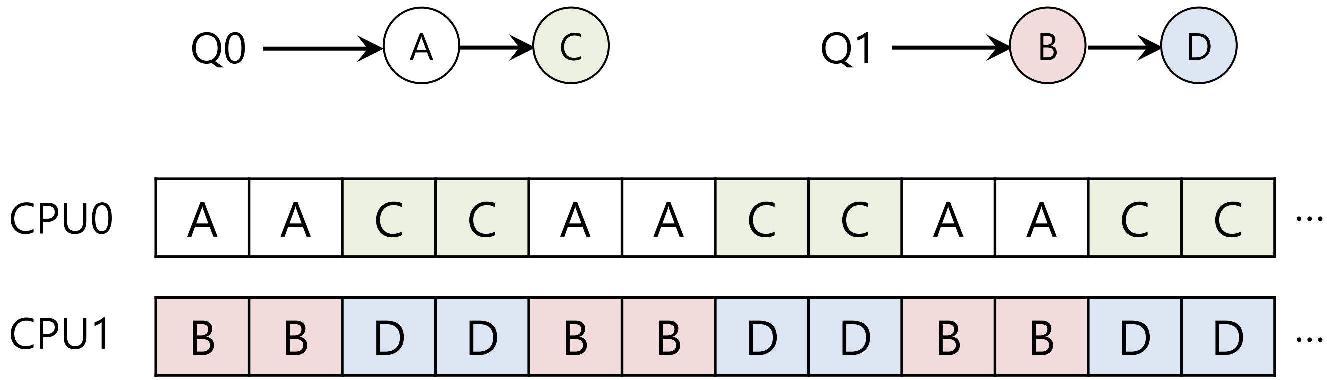
- Preserving affinity for most
  - Jobs A through D are not moved across processors.
  - Only job e Migrating from CPU to CPU.
- Implementing such a scheme can be **complex**.

Multi-queue Multiprocessor Scheduling (MQMS)

- MQMS consists of multiple scheduling queues.
  - Each queue will follow a particular scheduling discipline.
  - When a job enters the system, it is placed on **exactly one** scheduling queue.
  - Avoid the problems of information sharing and synchronization.

MQMS Example

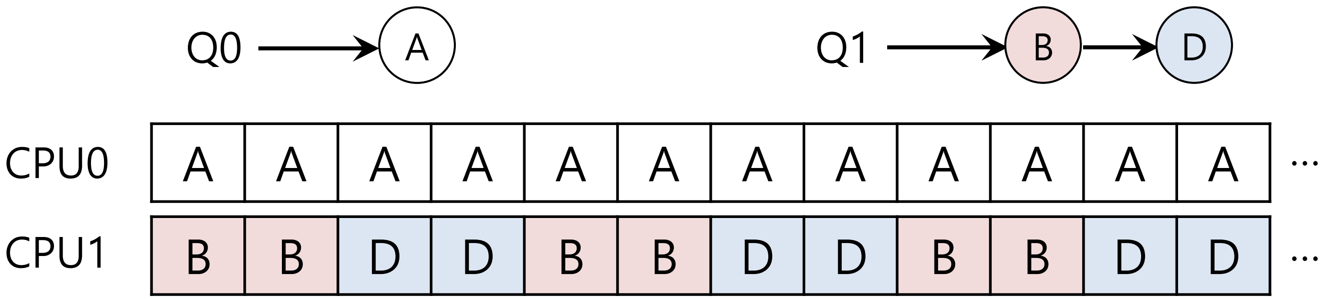
- With **round robin**, the system might produce a schedule that looks like this:



MQMS provides more scalability and cache affinity.

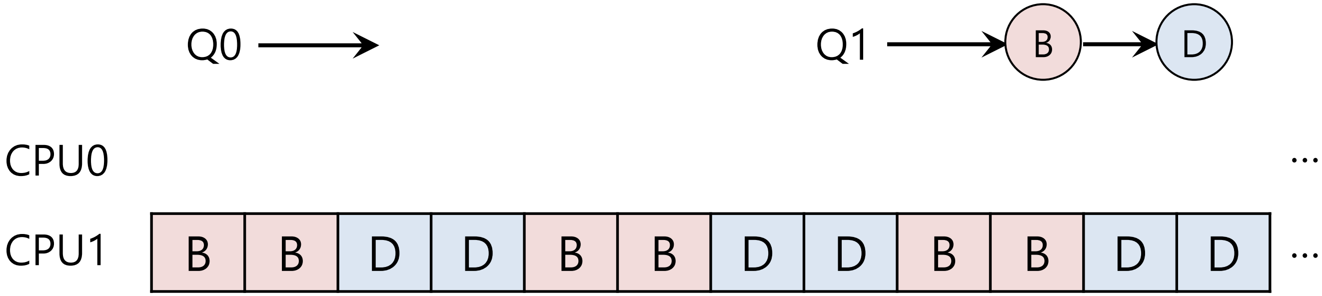
Load Imbalance issue of MQMS

- After job C in Q0 finishes:



A gets twice as much CPU as B and D.

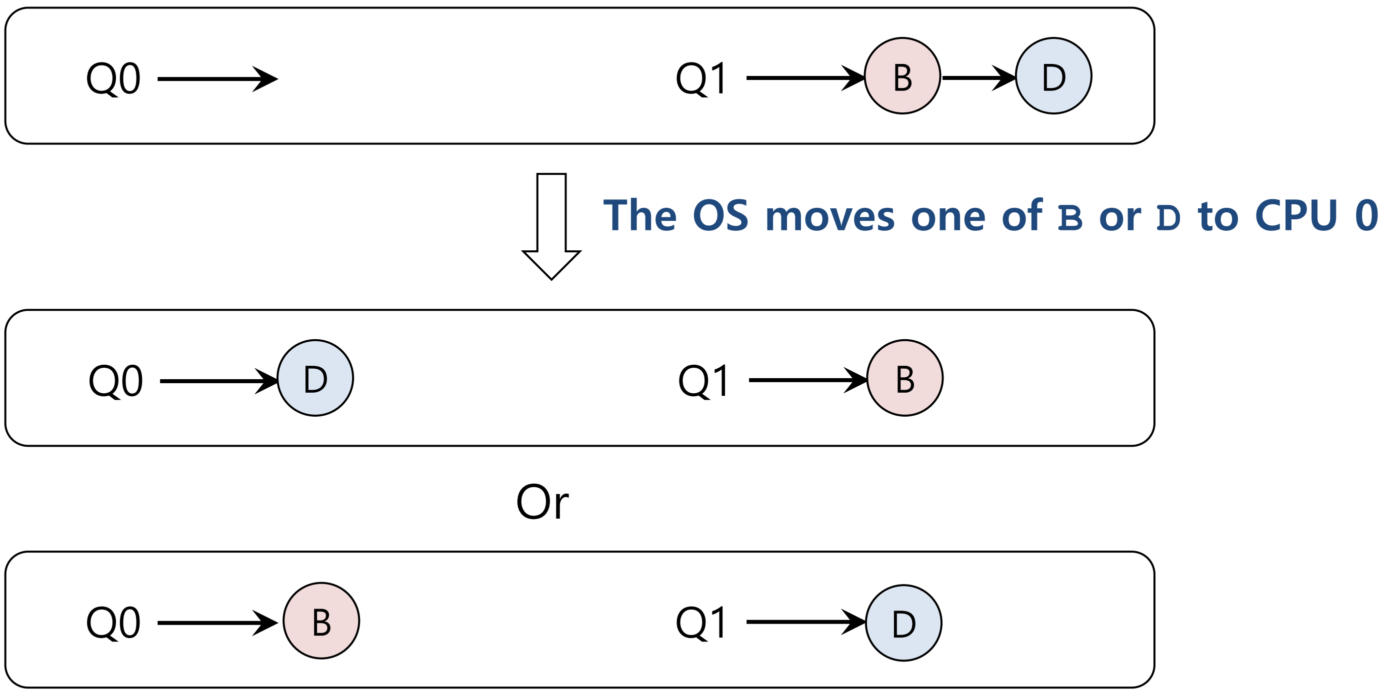
- After job A in Q0 finishes:



CPU0 will be left idle!

How to deal with load imbalance?

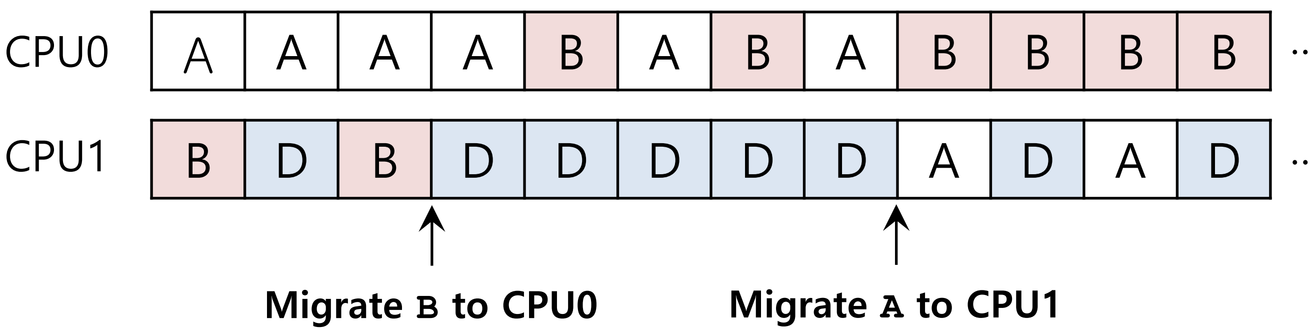
- The answer is to move jobs (**Migration**).
  - Example:



How to deal with load imbalance? (Cont.)

- A more tricky case:

- A possible migration pattern:
  - Keep switching jobs



Work Stealing

- Move jobs between queues
  - Implementation:
    - A source queue that is <u>low on jobs</u> is picked.
    - The source queue occasionally peeks at another target queue.
    - If the target queue is <u>fuller than</u> the source queue, the source will "**steal**" one or more jobs from the target queue.
  - Cons:
    - *High overhead* and trouble *scaling*

Linux Multiprocessor Schedulers

- O(1)
  - A Priority-based scheduler
  - Use Multiple queues (similar to MLFQ)
  - Change a process's priority over time
  - Schedule those with highest priority
  - Interactivity is a particular focus

- Completely Fair Scheduler (CFS) (current mainline)
  - Deterministic proportional-share approach
  - Based on Staircase Deadline (fairness is the focus)
  - Red-black tree for scalability

Linux Multiprocessor Schedulers (Cont.)

- BF Scheduler (BFS) (Not in the mainline)
  - A single queue approach
  - Proportional-share
  - Based on Earliest Eligible Virtual Deadline First (EEVDF)
  - Focus on interactive (not scale well with cores). Superseded by MuQSS to fix that

- The battle of schedulers : Kolivas (SD) vs Molnar (CFS)

"And you have to realize that there are not very many things that have a ged as well as the scheduler. Which is just another proof that scheduling is easy."

Linus Torvalds, 2001 [43]

Scheduling is not easy!, E.g:

"The Linux Scheduler: a Decade of Wasted Cores "
http://www.ece.ubc.ca/~sasha/papers/eurosys16-final29.pdf

Aside: Current hardware is hard to handle by the scheduler

- SMT, Frequency scaling,…
- Complex caches (Non-uniform cache architectures)
- Multi-socket is hard
- Multi-die is even harder
- Big-little (P/E), etc…

Aside: real systems are really nasty

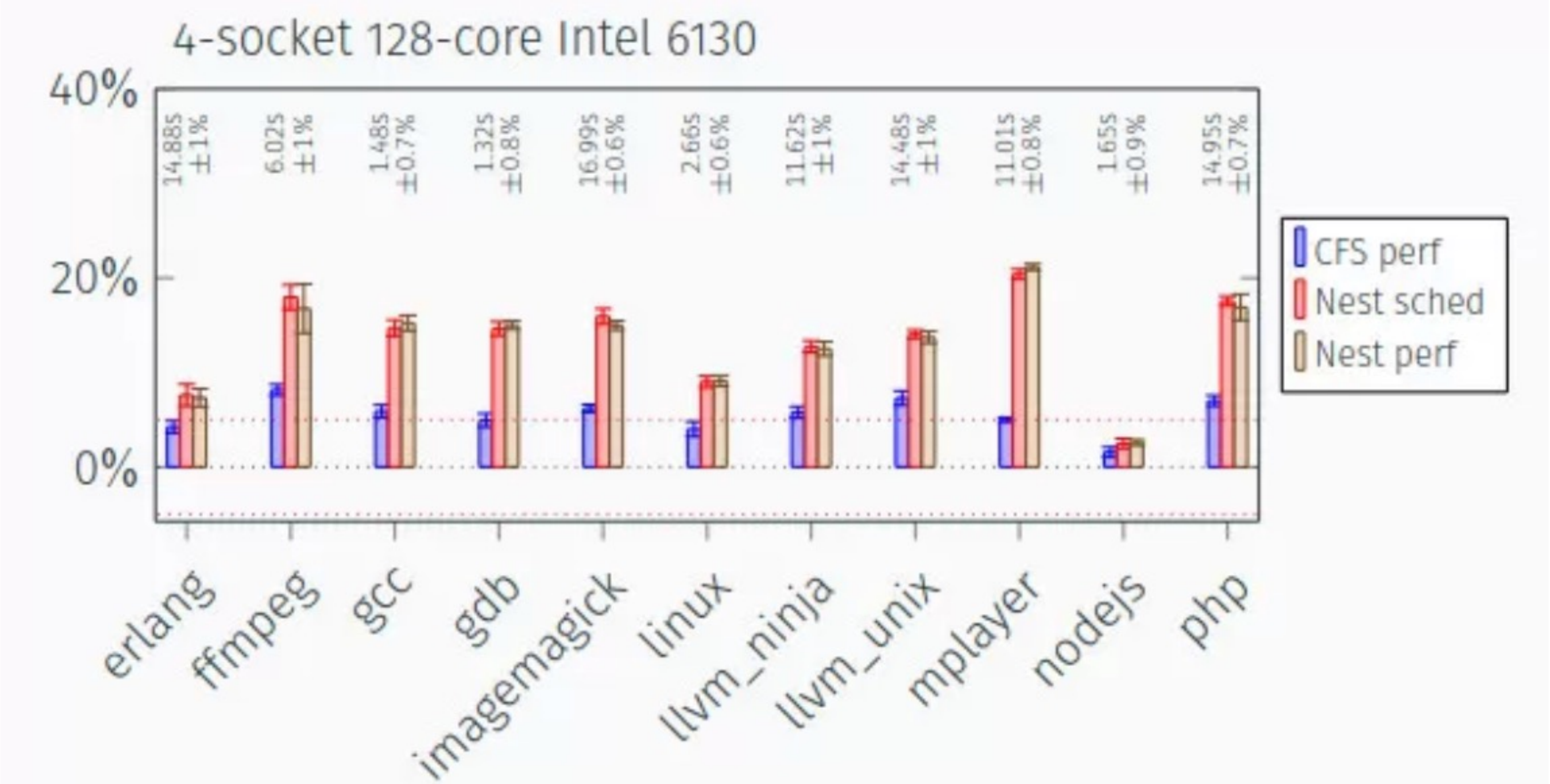
Ryzen 9 3950X Core-to-Core Latency

C -> C (ns)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	X	6.7	31.3	31.3	30.9	30.9	31.3	31.4	83.5	83.2	86.9	87.7	83.7	83.8	84.0	84.0	84.3	84.4	83.1	83.1	86.4	86.3	85.6	85.5	82.6	82.5	83.1	83.1	88.8	88.9	85.7	85.6
1	6.7	X	31.0	31.0	30.7	30.8	31.2	31.2	82.7	82.8	86.0	86.1	83.9	83.8	83.9	83.9	84.3	84.0	83.1	83.0	86.3	86.3	85.4	85.5	82.5	82.5	83.1	83.1	88.8	88.8	85.7	85.6
2	31.3	31.0	X	6.8	30.9	31.0	31.8	31.8	85.5	85.4	88.9	89.0	85.8	85.8	86.0	85.9	82.1	82.1	82.3	82.3	85.5	85.5	83.4	83.5	81.7	81.7	82.3	82.3	86.0	86.0	83.5	83.6
3	31.3	31.0	6.8	X	30.9	30.9	31.8	31.8	85.4	84.8	88.7	88.4	85.7	85.7	86.0	86.0	82.1	82.1	82.3	82.3	85.5	85.5	83.5	83.5	81.8	81.8	82.3	82.3	86.0	85.9	83.5	83.4
4	30.9	30.7	30.9	30.9	X	6.9	30.5	30.6	82.2	82.1	84.9	85.2	82.4	82.5	82.5	82.5	82.1	82.0	83.4	83.6	86.5	86.5	83.4	83.4	82.8	82.8	83.4	83.4	85.7	86.2	83.4	83.5
5	30.9	30.8	31.0	30.9	6.9	X	30.5	30.6	82.1	82.1	85.0	84.8	82.5	82.5	82.5	82.6	82.1	82.0	83.4	83.4	86.5	86.5	83.5	83.4	82.7	82.8	83.4	83.3	85.8	86.2	83.5	83.5
6	31.3	31.2	31.8	31.8	30.5	30.5	X	6.9	83.0	83.1	85.6	85.7	82.5	82.5	82.6	82.6	85.5	85.8	86.1	86.3	89.3	89.3	87.2	87.2	85.5	85.5	86.2	86.3	89.6	89.4	87.2	87.2
7	31.4	31.2	31.8	31.8	30.6	30.6	6.9	X	83.0	83.2	85.6	85.6	82.5	82.6	82.6	82.6	85.7	85.7	86.1	86.2	89.3	89.3	87.2	87.2	85.5	85.4	86.2	86.2	88.8	89.5	87.2	87.2
8	83.5	82.7	85.5	85.4	82.2	82.1	83.0	83.0	X	6.9	31.7	31.6	30.9	30.9	31.2	31.2	83.9	84.1	83.1	83.1	86.3	86.3	85.3	85.4	82.5	82.5	83.1	83.2	88.9	88.9	85.6	85.7
9	83.2	82.8	85.4	84.8	82.1	82.1	83.1	83.2	6.9	X	31.7	31.6	30.9	30.9	31.2	31.2	84.3	84.0	83.1	83.1	86.3	86.3	85.7	85.4	82.5	82.5	83.1	83.1	88.9	88.9	85.6	85.6
10	86.9	86.0	88.9	88.7	84.9	85.0	85.6	85.6	31.7	31.7	X	6.9	31.1	31.2	31.9	31.8	82.1	82.0	82.5	82.4	85.5	85.5	83.4	83.4	81.8	81.8	82.3	82.3	86.0	86.0	83.5	83.5
11	87.7	86.1	89.0	88.4	85.2	84.8	85.7	85.6	31.6	31.6	6.9	X	31.2	31.2	31.9	31.9	82.1	82.1	82.3	82.3	85.5	85.5	83.6	83.5	81.8	81.8	82.3	82.3	86.0	86.0	83.5	83.5
12	83.7	83.9	85.8	85.7	82.4	82.5	82.5	82.5	30.9	30.9	31.1	31.2	X	6.9	30.6	30.6	82.0	82.1	82.2	83.3	86.4	86.6	83.3	83.4	82.8	82.8	83.4	83.4	86.2	86.2	83.5	83.5
13	83.8	83.8	85.8	85.7	82.5	82.5	82.5	82.6	30.9	30.9	31.2	31.2	6.9	X	30.6	30.6	82.0	82.0	83.4	83.7	86.5	86.5	83.5	83.4	82.7	82.7	83.4	83.4	86.1	86.1	83.5	83.5
14	84.0	83.9	86.0	86.0	82.5	82.5	82.6	82.6	31.2	31.2	31.9	31.9	30.6	30.6	X	6.9	85.8	85.7	86.0	86.2	89.3	89.3	87.2	87.2	85.5	85.5	86.2	86.2	88.7	89.5	87.2	87.2
15	84.0	83.9	85.9	86.0	82.5	82.6	82.6	82.6	31.2	31.2	31.8	31.9	30.6	30.6	6.9	X	85.7	85.7	86.1	86.2	89.3	89.3	87.2	87.2	85.5	85.5	86.2	86.2	88.5	89.5	87.2	87.2
16	84.3	84.3	82.1	82.1	82.1	82.1	85.5	85.7	83.9	84.3	82.1	82.1	82.0	82.0	85.8	85.7	X	7.2	33.1	33.1	32.1	32.1	32.6	32.5	84.9	84.9	85.1	85.1	88.6	88.6	86.1	86.2
17	84.4	84.0	82.1	82.1	82.0	82.0	85.8	85.7	84.1	84.0	82.0	82.1	82.1	82.0	85.7	85.7	7.2	X	33.1	33.1	32.1	32.1	32.5	32.5	84.9	84.8	85.1	85.1	88.6	88.6	86.1	86.2
18	83.1	83.1	82.3	82.3	83.4	83.4	86.1	86.1	83.1	83.1	82.5	82.3	82.2	83.4	86.0	86.1	33.1	33.1	X	7.1	32.3	32.4	33.0	33.0	85.0	85.0	85.4	85.4	88.8	89.0	86.5	86.6
19	83.1	83.0	82.3	82.3	83.6	83.4	86.3	86.2	83.1	83.1	82.4	82.3	83.3	83.7	86.2	86.2	33.1	33.1	7.1	X	32.4	32.4	33.0	33.1	85.0	85.1	85.4	85.4	89.0	88.9	86.5	86.5
20	86.4	86.3	85.5	85.5	86.5	86.5	89.3	89.3	86.3	86.3	85.5	85.5	86.4	86.5	89.3	89.3	32.1	32.1	32.3	32.4	X	7.1	31.9	31.9	88.3	88.3	88.6	88.6	92.2	92.3	90.0	90.1
21	86.3	86.3	85.5	85.5	86.5	86.5	89.3	89.3	86.3	86.3	85.5	85.5	86.6	86.5	89.3	89.3	32.1	32.1	32.4	32.4	7.1	X	31.9	32.0	88.3	88.3	88.6	88.6	92.5	92.4	90.0	90.1
22	85.6	85.4	83.4	83.5	83.4	83.5	87.2	87.2	85.3	85.7	83.4	83.6	83.3	83.5	87.2	87.2	32.6	32.5	33.0	33.0	31.9	31.9	X	7.2	86.2	86.1	86.4	86.4	90.0	90.1	87.5	87.5
23	85.5	85.5	83.5	83.5	83.4	83.4	87.2	87.2	85.4	85.4	83.4	83.5	83.4	83.4	87.2	87.2	32.5	32.5	33.0	33.1	31.9	32.0	7.2	X	86.2	86.2	86.5	86.4	90.0	90.1	87.6	87.6
24	82.6	82.5	81.7	81.8	82.8	82.7	85.5	85.5	82.5	82.5	81.8	81.8	82.8	82.7	85.5	85.5	84.9	84.9	85.0	85.0	88.3	88.3	86.2	86.2	X	7.1	32.9	32.9	32.1	32.1	32.6	32.6
25	82.5	82.5	81.7	81.8	82.8	82.8	85.5	85.4	82.5	82.5	81.8	81.8	82.8	82.7	85.5	85.5	84.9	84.8	85.0	85.1	88.3	88.3	86.1	86.2	7.1	X	32.9	32.9	32.1	32.1	32.6	32.6
26	83.1	83.1	82.3	82.3	83.4	83.4	86.2	86.2	83.1	83.1	82.3	82.3	83.4	83.4	86.2	86.2	85.1	85.1	85.4	85.4	88.6	88.6	86.4	86.5	32.9	32.9	X	7.1	32.5	32.5	33.1	33.1
27	83.1	83.1	82.3	82.3	83.4	83.3	86.3	86.2	83.2	83.1	82.3	82.3	83.4	83.4	86.2	86.2	85.1	85.1	85.4	85.4	88.6	88.6	86.4	86.4	32.9	32.9	7.1	X	32.6	32.5	33.1	33.1
28	88.8	88.8	86.0	86.0	85.7	85.8	89.6	88.8	88.9	88.9	86.0	86.0	86.2	86.1	88.7	88.5	88.6	88.6	88.8	89.0	92.2	92.5	90.0	90.0	32.1	32.1	32.5	32.6	X	7.2	31.9	32.0
29	88.9	88.8	86.0	85.9	86.2	86.2	89.4	89.5	88.9	88.9	86.0	86.0	86.2	86.1	89.5	89.5	88.6	88.6	89.0	88.9	92.3	92.4	90.1	90.1	32.1	32.1	32.5	32.5	7.2	X	31.9	32.0
30	85.7	85.7	83.5	83.5	83.4	83.5	87.2	87.2	85.6	85.6	83.5	83.5	83.5	83.5	87.2	87.2	86.1	86.1	86.5	86.5	90.0	90.0	87.5	87.6	32.6	32.6	33.1	33.1	31.9	31.9	X	7.2
31	85.6	85.6	83.6	83.4	83.5	83.5	87.2	87.2	85.7	85.6	83.5	83.5	83.5	83.5	87.2	87.2	86.2	86.2	86.6	86.5	90.1	90.1	87.5	87.6	32.6	32.6	33.1	33.1	32.0	32.0	7.2	X

```
vpuente@compute-gpu-0:~$ sudo numactl --hardware
available: 8 nodes (0-7)
node 0 cpus: 0 1 2 3 32 33 34 35
node 0 size: 32097 MB
node 0 free: 30877 MB
node 1 cpus: 4 5 6 7 36 37 38 39
node 1 size: 16125 MB
node 1 free: 15219 MB
node 2 cpus: 8 9 10 11 40 41 42 43
node 2 size: 16125 MB
node 2 free: 14937 MB
node 3 cpus: 12 13 14 15 44 45 46 47
node 3 size: 8061 MB
node 3 free: 6498 MB
node 4 cpus: 16 17 18 19 48 49 50 51
node 4 size: 32253 MB
node 4 free: 31868 MB
node 5 cpus: 20 21 22 23 52 53 54 55
node 5 size: 16125 MB
node 5 free: 10104 MB
node 6 cpus: 24 25 26 27 56 57 58 59
node 6 size: 16104 MB
node 6 free: 8043 MB
node 7 cpus: 28 29 30 31 60 61 62 63
node 7 size: 8060 MB
node 7 free: 7271 MB
node distances:
node   0   1   2   3   4   5   6   7
  0:  10  16  16  16  32  32  32  32
  1:  16  10  16  16  32  32  32  32
  2:  16  16  10  16  32  32  32  32
  3:  16  16  16  10  32  32  32  32
  4:  32  32  32  32  10  16  16  16
  5:  32  32  32  32  16  10  16  16
  6:  32  32  32  32  16  16  10  16
  7:  32  32  32  32  16  16  16  10
```

Aaside: Nest Scheduler

- https://www.phoronix.com/news/Nest-Linux-Scheduling-Warm-Core
- Idea: Form a primary and secondary nest to choose the core to run
  - Locality, prefer warm-cores (higher frequency)



Aside: Other Solutions

- Strawman solution:
  - `taskset –p <range-processors> your_task`

- Hardware assistance?
  - V.gr., Intel Thread Director (Alder Lake + windows 11, Linux 5.18)
  - https://www.anandtech.com/show/16881/a-deep-dive-into-intels-alder-lake-microarchitectures/2

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