Scheduling Algorithms

Dispatcher vs. Scheduler

- Dispatcher
  - Low-level mechanism
  - Responsibility: context switch
    - `context_switch()` in Linux kernel

- Scheduler
  - High-level policy
  - Responsibility: deciding which process to run
    - `pick_next_task()` in Linux kernel

Scheduling performance metrics

- Min waiting time: don't have process wait long in ready queue
- Max CPU utilization: keep CPU busy
- Max throughput: complete as many processes as possible per unit time
- Min response time: respond immediately
- Fairness: give each process (or user) same percentage of CPU

First-Come, First-Served (FCFS)

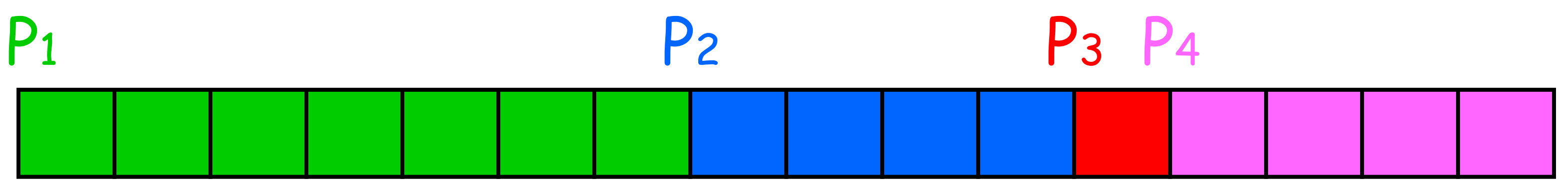
- Simplest CPU scheduling algorithm
  - First job that requests the CPU gets the CPU
  - Nonpreemptive
- Implementation: FIFO queue

Example of FCFS

Process	Arrival Time	Burst Time
P_1	0	7
P_2	0	4
P_3	0	1
P_4	0	4

- Gantt chart

Schedule:

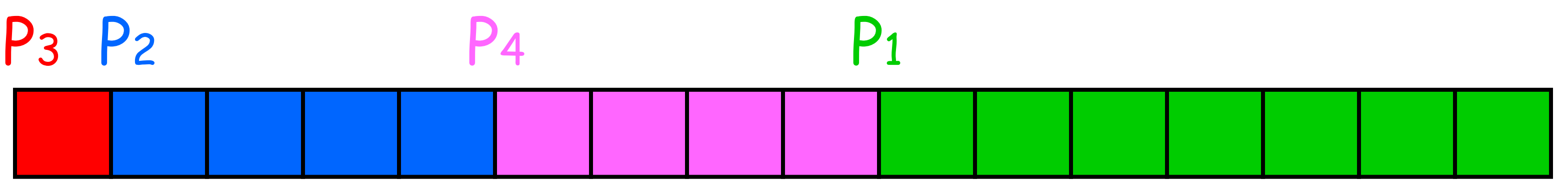


- Average waiting time: (0 + 7 + 11 + 12)/4 = 7.5

Example of FCFS: different arrival order

Process	Arrival Time	Burst Time
P_1	0	7
P_2	0	4
P_3	0	1
P_4	0	4

Arrival order: P_3 P_2 P_4 P_1



- Average waiting time: (9 + 1 + 0 + 5)/4 = 3.75

FCFS advantages and disadvantages

- Advantages
  - Simple
  - Fair
- Disadvantages
  - waiting time depends on arrival order
  - Convoy effect
    - Short process stuck waiting for long process
    - Also called head of the line blocking

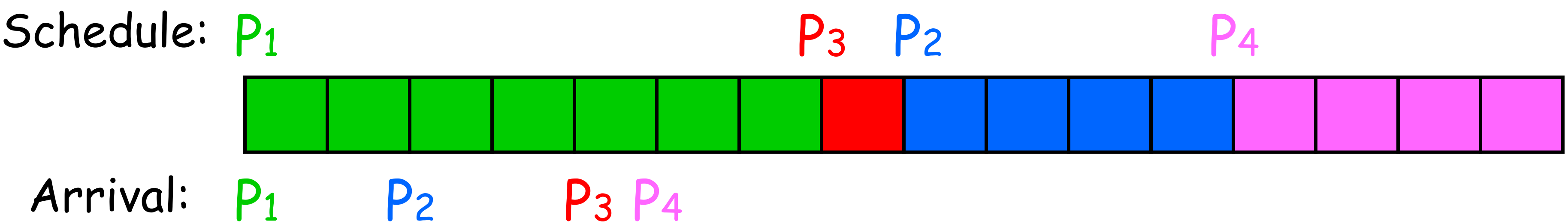
Shortest Job First (SJF)

- Schedule the process with the shortest time
- FCFS if same time

Example of SJF (w/o preemption)

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4

- Gantt chart



- Average waiting time: (0 + 6 + 3 + 7)/4 = 4

Shortest Remaining Time First (SRTF)

- If new process arrives w/ shorter CPU burst than the remaining for current process, schedule new process

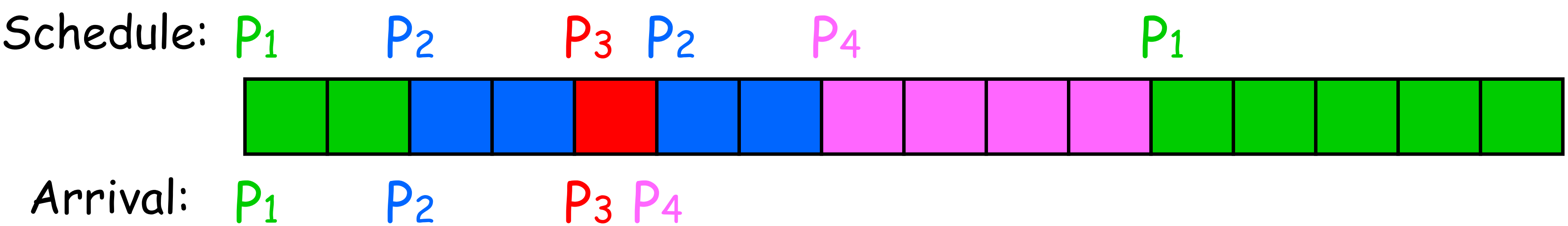
- Also known as:
  - SJF with preemption
  - Shortest Time-to-Completion First (STCF)

- Advantage: reduces average waiting time
  - Provably optimal

Example of SRTF

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4

- Gantt chart



- Average waiting time: $(9 + 1 + 0 + 2)/4 = 3$

SJF Advantages and Disadvantages

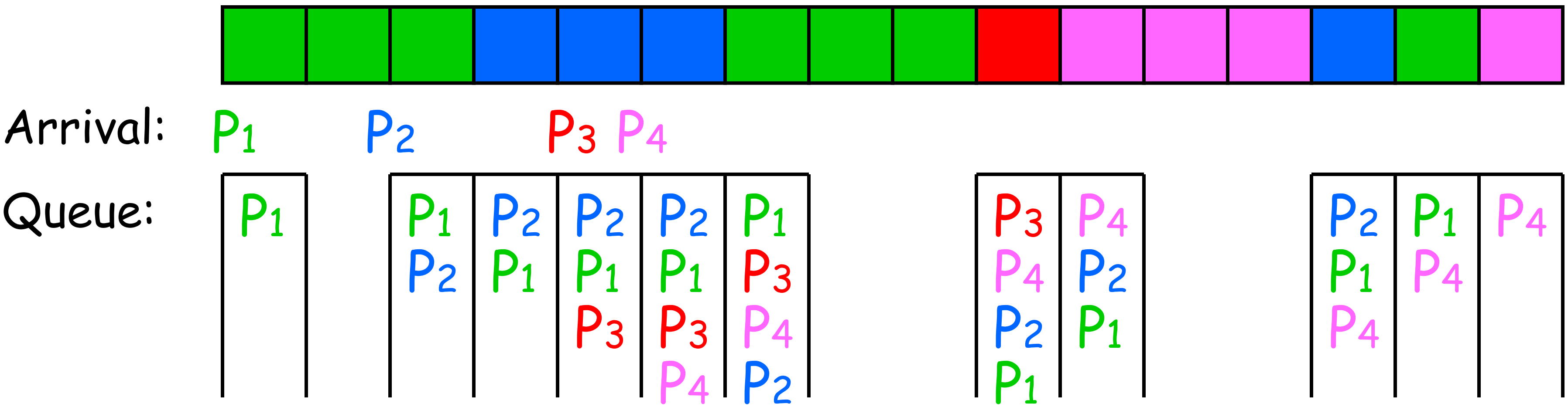
- Advantages
  - Minimizes average wait time.
  - Provably optimal if no preemption allowed
- Disadvantages
  - Not practical: difficult to predict burst time
    - Possible: past predicts future
  - May starve long jobs

Round-Robin (RR)

- Process runs for a predetermined time slice, and then moves to back of queue
- Process gets preempted at the end of time slice
- How long should the time slice be?

Example of RR: time slice = 3

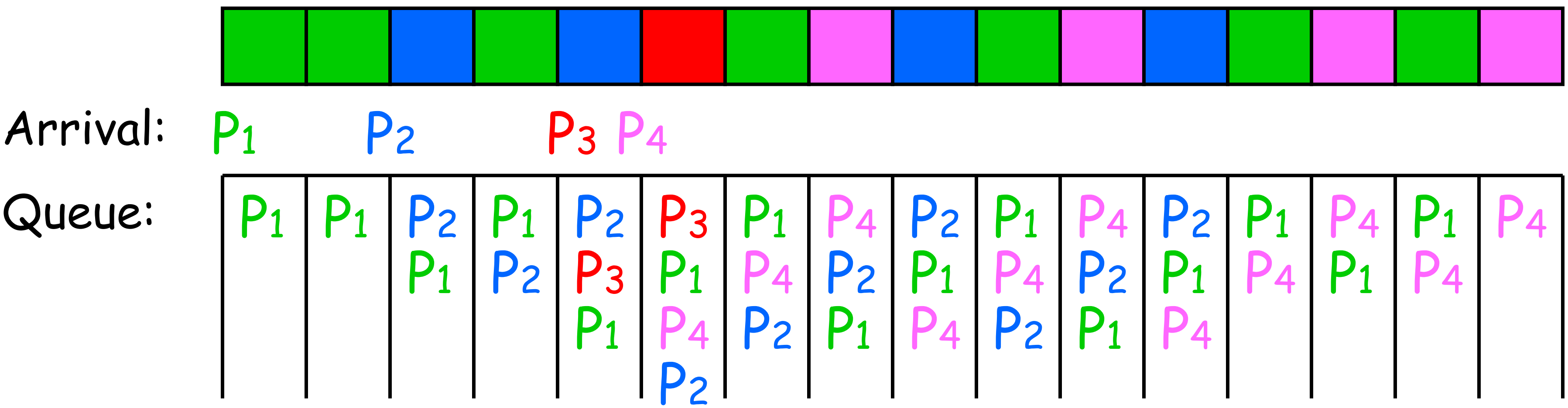
Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4



- Average waiting time: (8 + 8 + 5 + 7)/4 = 7
- Average response time: (0 + 1 + 5 + 5)/4 = 2.75
- # of context switches: 7

Smaller time slice = 1

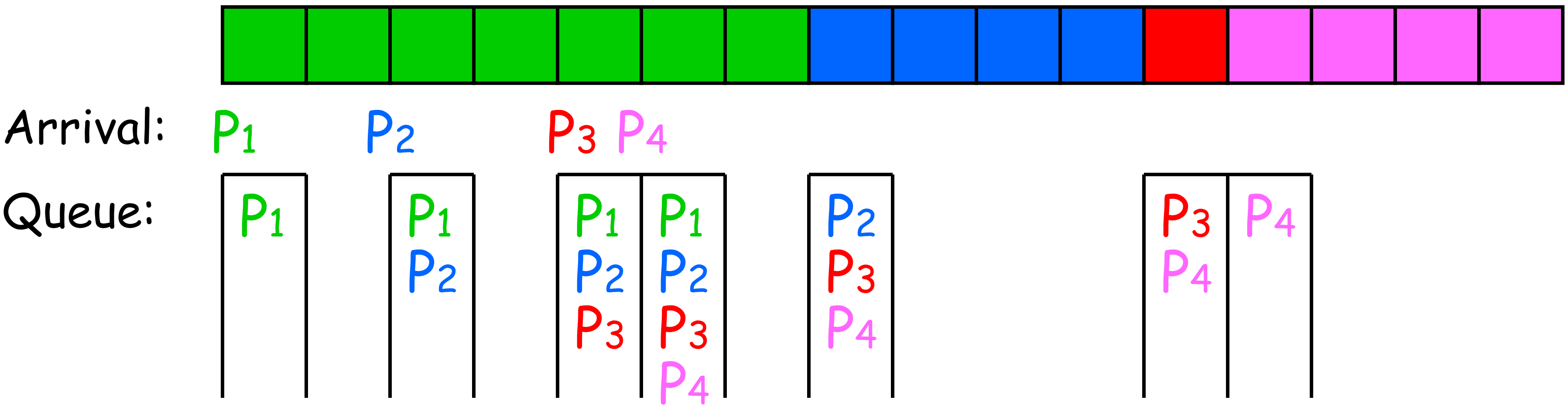
Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4



- Average waiting time: (8 + 6 + 1 + 7)/4 = 5.5
- Average response time: (0 + 0 + 1 + 2)/4 = 0.75
- # of context switches: 14

Larger time slice = 10

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4



- Average waiting time: (0 + 5 + 7 + 7)/4 = 4.75
- Average response time: same
- # of context switches: 3 (minimum)

RR advantages and disadvantages

- Advantages
  - Low response time, good interactivity
  - Fair allocation of CPU across processes
  - Low average waiting time when job lengths vary widely
- Disadvantages
  - Poor average waiting time when jobs have similar lengths
    - Average waiting time is even worse than FCFS!
  - Performance depends on length of time slice
    - Too high ➔ degenerate to FCFS
    - Too low ➔ too many context switches, costly

Priorities

- Priority is associated with each process
  - Run highest priority process that is ready
  - Round-robin among processes of equal priority
- Priority can be statically assigned
  - Some always have higher priority than others
- Priority can be dynamically changed by OS
  - Aging: increase the priority of processes that wait in the ready queue for a long time

```
for (pp = proc; pp < proc+NPROC; pp++) {
        if (pp->prio != MAX)
                pp->prio++;
        if (pp->prio > curproc->prio)
                reschedule();
}
```

Code from

6th Edition UNIX

circa 1976

Priority inversion

- High priority process depends on low priority process (e.g. to release a lock)
  - Another process with in-between priority arrives?

P1 (low): lock(my_lock) (gets my_lock)

P2(high): lock(my_lock)

P3(medium): while (…) {}

P2 waits, P3 runs, P1 waits

P2's effective priority less than P3!

- Solution: priority inheritance
  - Inherit highest priority of waiting process
  - Must be able to chain multiple inheritances
  - Must ensure that priority reverts to original value
- Google for "mars pathfinder priority inversion"

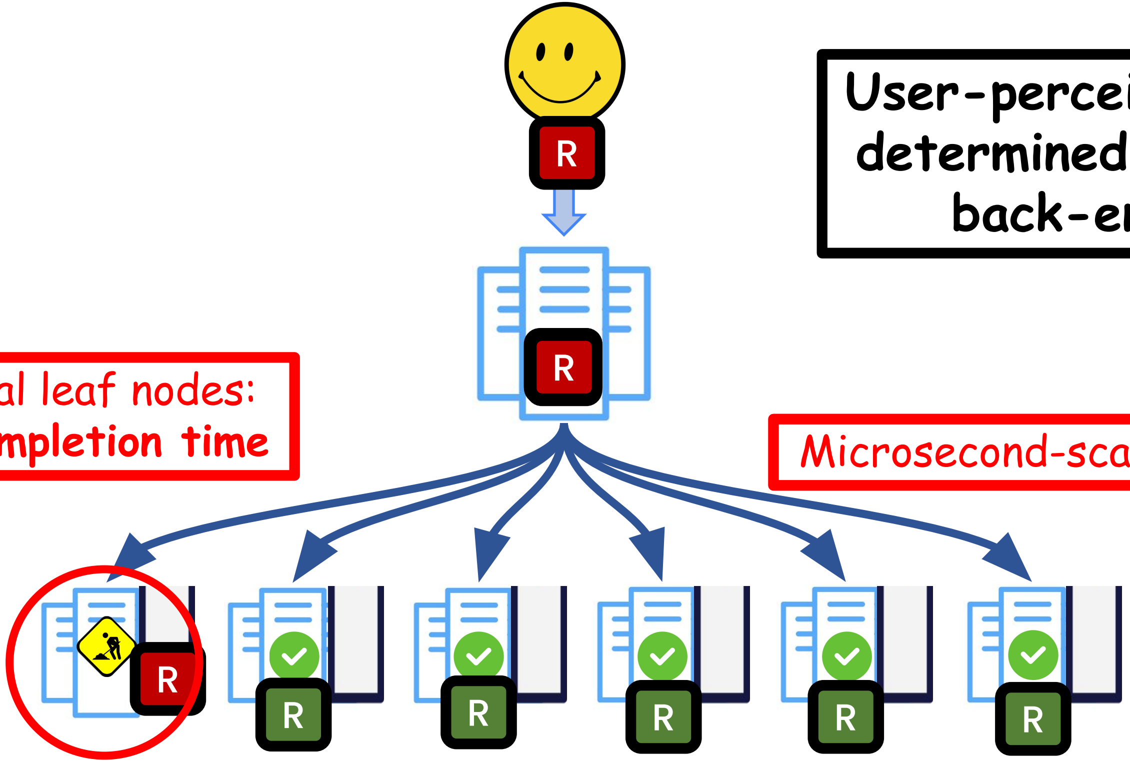
Multi-Level Feedback Queue (MLFQ)

- Processes move between queues
  - Queues have different priority levels
  - Priority of process changes based on observed behavior
- MLFQ scheduler parameters:
  - number of queues
  - scheduling algorithms for each queue
  - when to upgrade a process
  - when to demote a process
  - which queue a process will start in

MLFQ example from OSTEP book

- Rule 1: If Priority(A) > Priority(B), A runs (B doesn't)
- Rule 2: If Priority(A) = Priority(B), A & B run in RR using the time slice of the queue
- Rule 3: When a job enters the system, it starts in the topmost queue (of the highest priority)
- Rule 4: Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down one queue)
- Rule 5: After some time period S, move all the jobs in the system to the topmost queue

Modern Schedulers: Tail Completion Time Matters

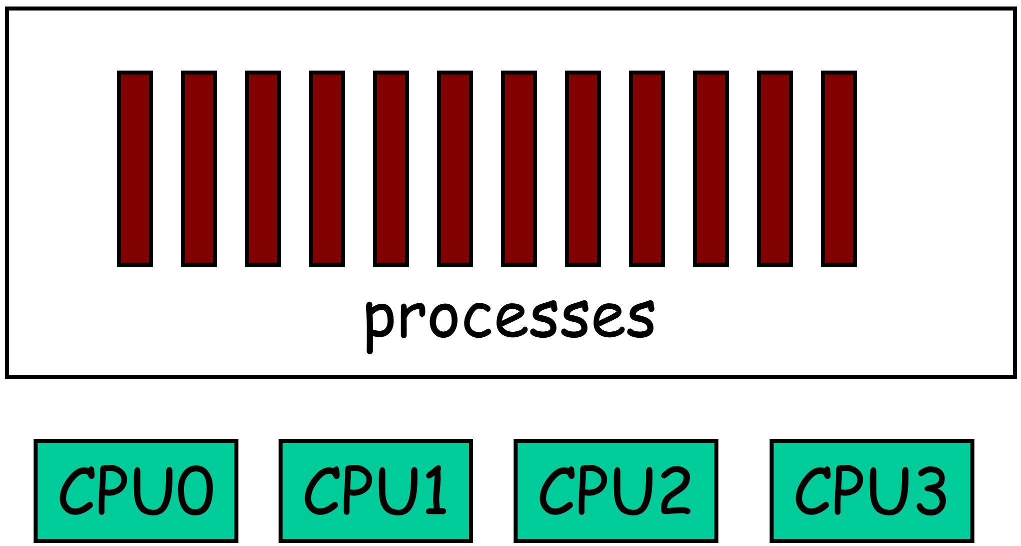


User-perceived latency determined by slowest back-end node

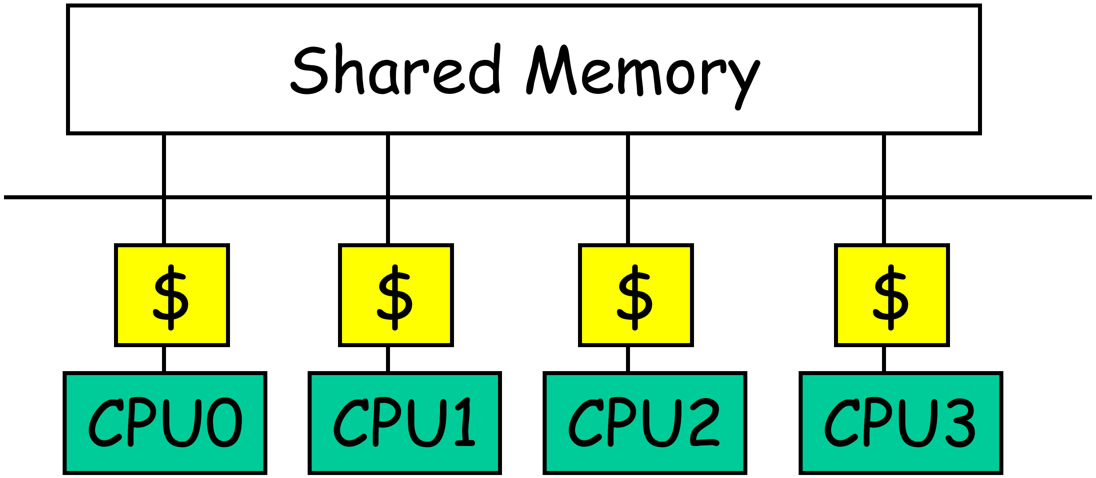
Goal on individual leaf nodes: minimize **tail completion time**

Microsecond-scale Service Times

How to allocate processes to CPUs?



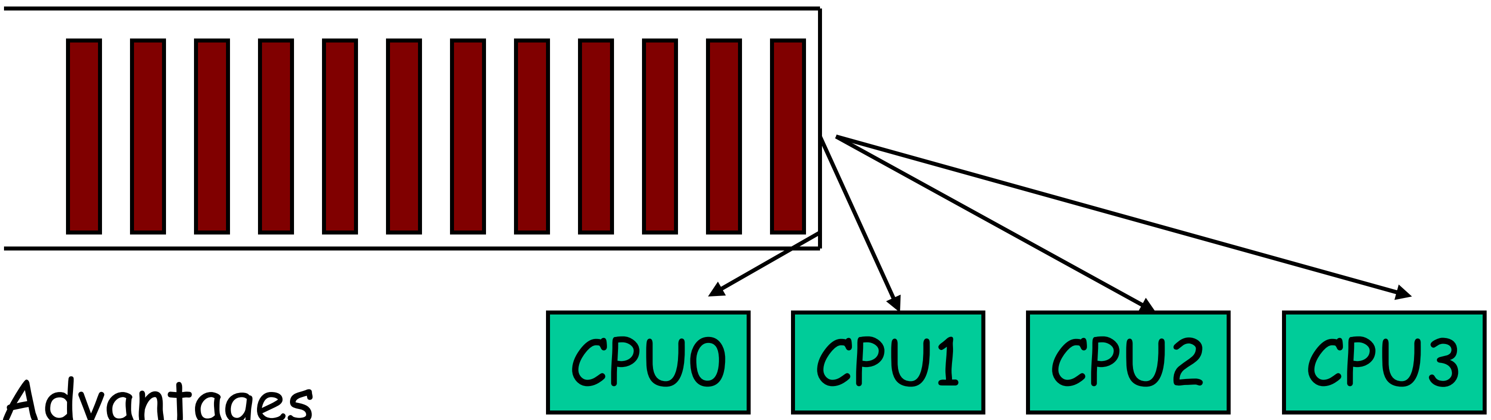
Symmetric multiprocessing (SMP)



- Multiple identical CPUs
- Same access time to main memory
- Private cache

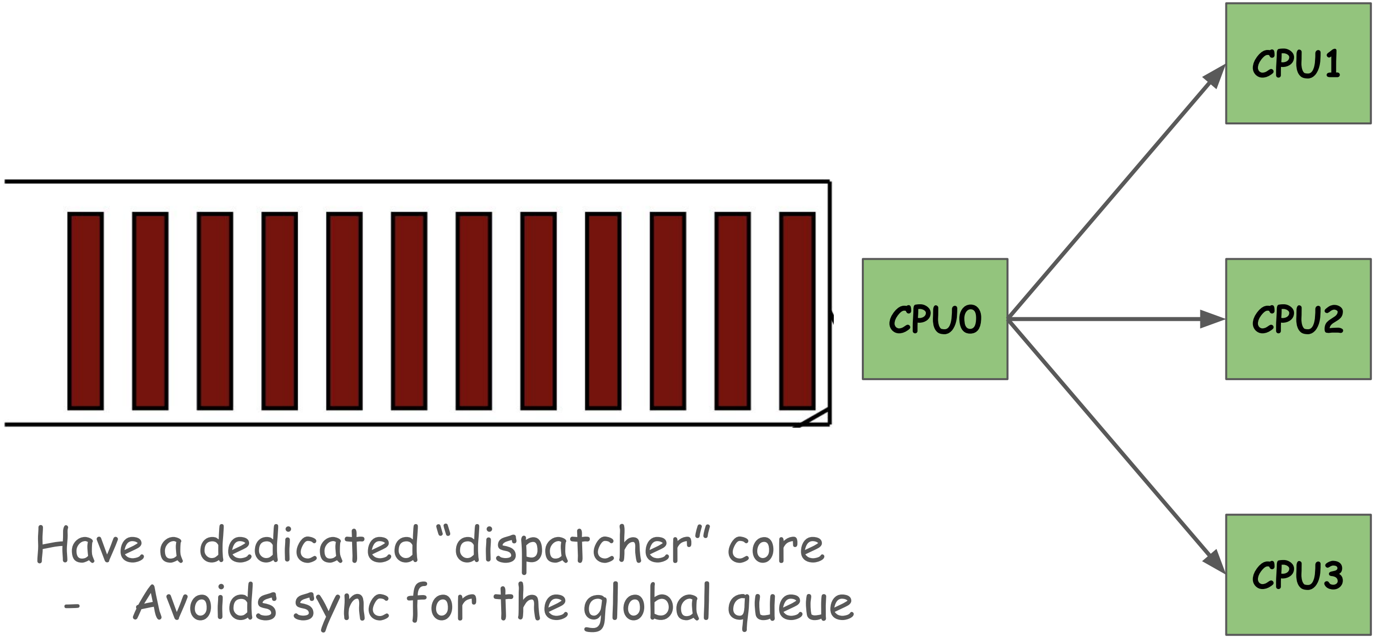
Global queue of processes

- One ready queue shared across all CPUs



- Advantages
  - Good CPU utilization
  - Fair to all processes
- Disadvantages
  - Not scalable (contention for global queue lock)
  - Poor cache locality

How to scale a single queue?



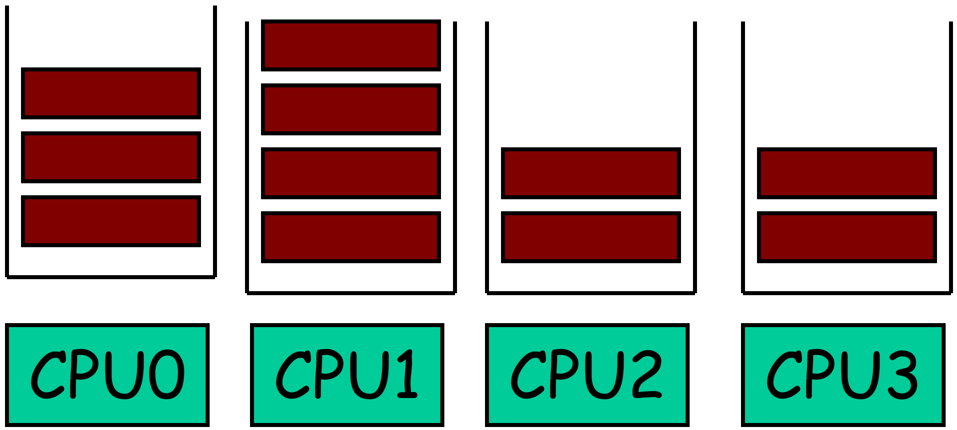
Have a dedicated "dispatcher" core

- Avoids sync for the global queue
- Need to establish communication channels with "worker" cores

e.g., Shinjuku

Per-CPU queue of processes

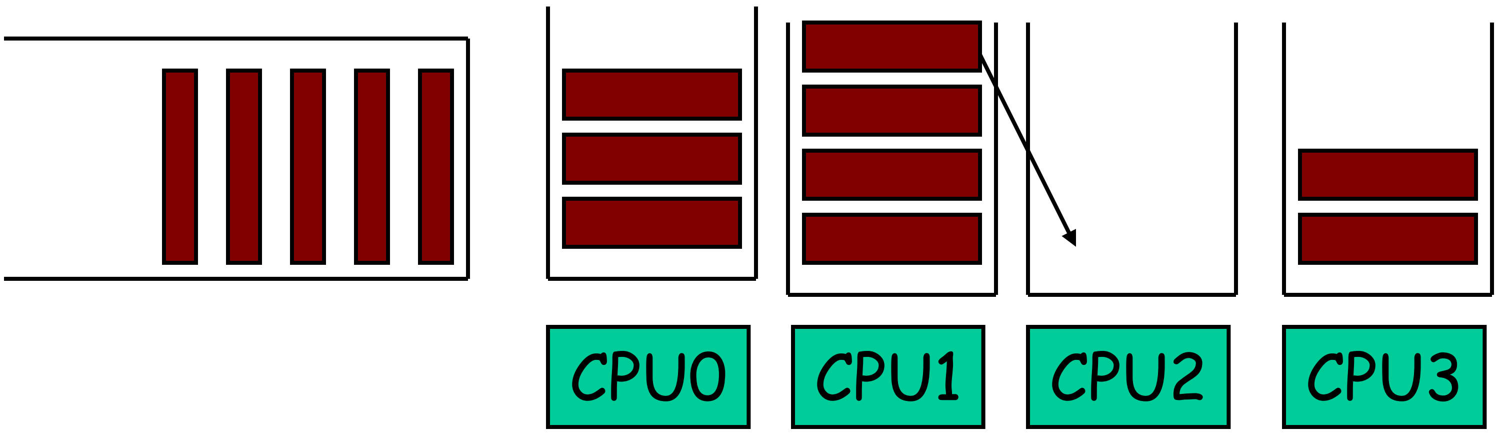
- Static partition of processes to CPUs



- Advantages
  - Easy to implement
  - Scalable (no contention on ready queue)
  - Better cache locality
- Disadvantages
  - Load-imbalance (some CPUs have more processes)
    - Unfair to processes and lower CPU utilization

Modern OSes take hybrid approaches

- Use both global and per-CPU queues
- Migrate processes across per-CPU queues



- Processor Affinity
  - Add process to a CPU's queue if recently run on the CPU
    - Cache state may still present

Heterogeneous CPU topology

- Latest trends in CPUs
  - Apple silicon
  - Intel Alder Lake
- Technically AMP, but closer to SMP
  - Cores have same ISA but different speeds
  - Mix of performance (P) and efficient (E) cores
- Ex: Apple M1 Pro
  - 8 P-cores (3228MHz) & 2 E-cores (2064MHz)
  - L1 cache: 192/128KB on P-core & 128/64KB on E-core
  - L2 cache: two 12M on P-core & one 4M on E-core
- Support being added to recent OS
  - Quality of Service (QoS) classes in macOS
  - Energy Aware Scheduling in Linux