IN2140:
Introduction to Operating Systems and Data Communication

Operating Systems:

Processes & CPU Scheduling

Pål Halvorsen

Overview

- Processes
  - primitives for creation and termination
  - states
  - context switches
  - (processes vs. threads)

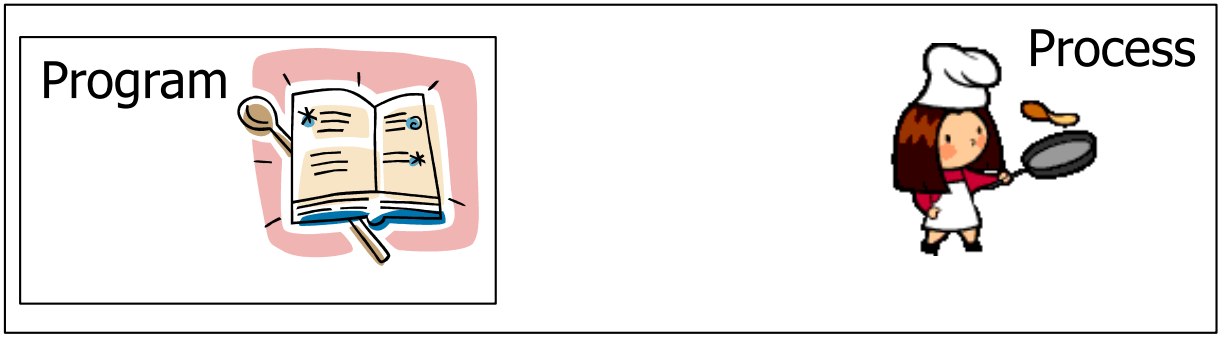
- CPU scheduling
  - classification
  - timeslices
  - algorithms

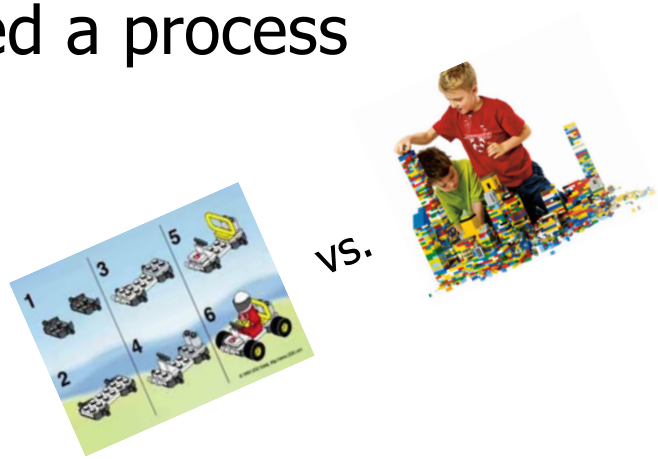
Processes

Processes

- What is a process?

The "execution" of a program is often called a process





- Process table entry (process control block, PCB):

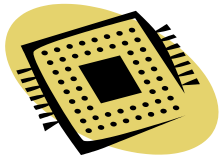
Process management	**Memory management**	**File management**
Registers	Pointer to text segment	Root directory
Program counter	Pointer to data segment	Working directory
Program status word	Pointer to stack segment	File descriptors
Stack pointer		User ID
Process state		Group ID
Priority		
Scheduling parameters		
Process ID		
Parent process		
Process group		
Signals		
Time when process started		
CPU time used		
Children's CPU time		
Time of next alarm		

Process Creation

- A process can create another process using the `pid_t fork(void)` system call (see `man 2 fork`) :
  - makes a **duplicate** of the calling process including a copy of the virtual address space, open file descriptors, etc…
    (only PIDs are different – locks and signals are not inherited)
  - both processes continue in parallel
  - returns
    - … if parent: **child process' PID** when successful, -1 otherwise
    - … if child: **0** (if successful - if not, there will not be a child)

- Other possibilities include
  - `int clone(…)` – shares memory, descriptors, signals (see `man 2 clone`)
  - `pid_t vfork(void)` – suspends parent in `clone()` (see `man 2 vfork`)

Process Creation – `fork()`



Prosess 1


right after `fork`


time)


Prosess 2

Process control block (process descriptor)

- PID
- address space (text, data, stack)
- state

make_sa
make_bi
fork
make_bi
buy_char

righ

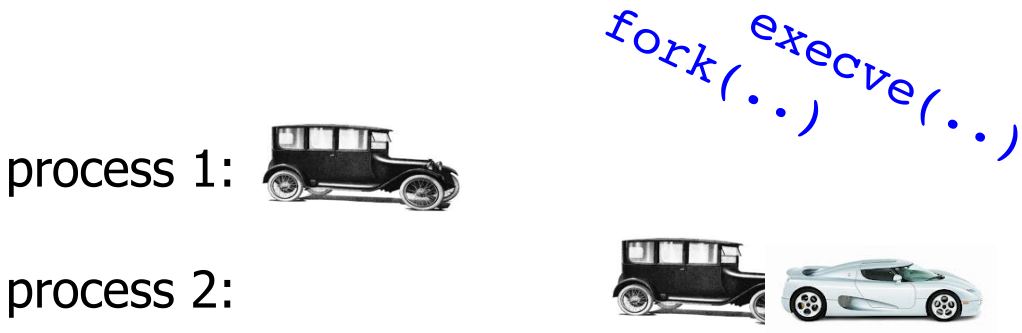
```
if ((pid = fork()) == -1) {printf("Failure\n"); exit(1);}

if (pid != 0) {
        /* Parent: pid != 0 */
        … do something …
} else {
        /* Child: pid == 0 */
        … do something else …
}
```

How is it possible to get different results?
(the processes do run the same program!!)

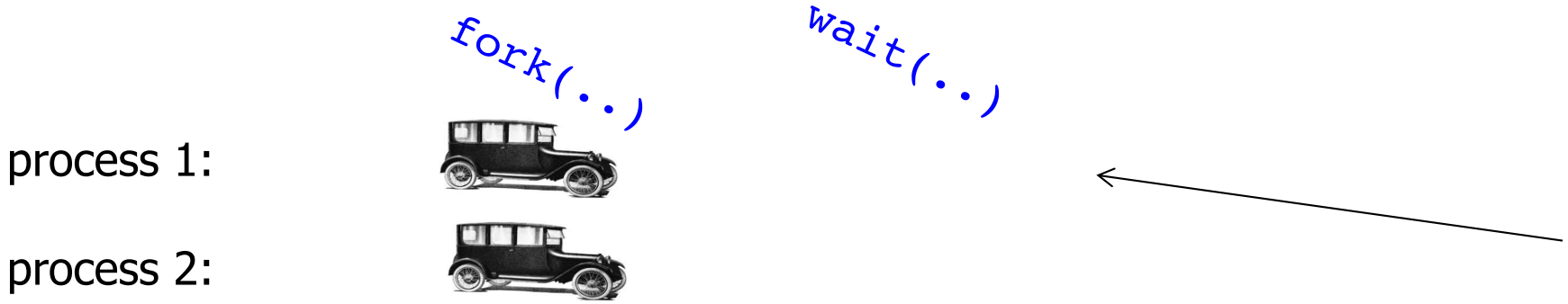
Program Execution

- To make a process execute a program, one might use the
  `int execve(char *filename, char *params[], char *envp[])`
  system call (see `man 2 execve`):
  - executes the program pointed to by `filename` (binary or script) using the parameters given in `params` and in the environment given by `envp`
  - returns
    - no return value on success, actually no process to return to
    - -1 is returned on failure (and `errno` set)
- Many other versions (frontends to **`execve`**) exist, e.g.,
  `execl`, `execlp`, `execle`, `execv` and `execvp` (see `man 3 exec`)



Process Waiting

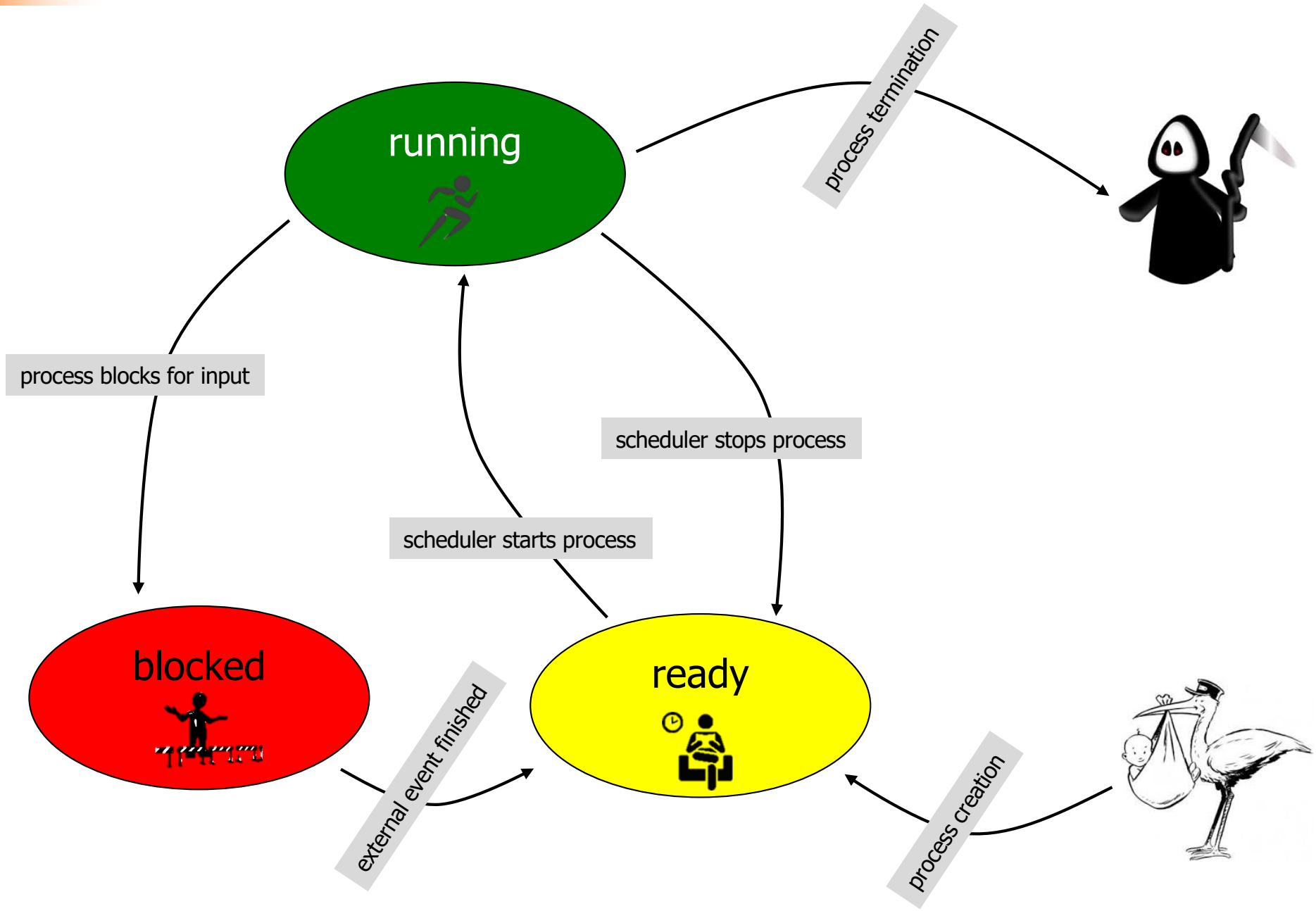
- To make a process wait for another process, one can use the `pid_t wait(int *status)` system call (see `man 2 wait`):
  - waits until *any* of the child processes terminates (if there are running child processes)
  - returns
    - -1 if no child processes exist
    - PID of the terminated child process and puts the status of the process in `status`
  - see also
    - `waitpid` – adds parameter pid which can be any, group or a particular pid
    - `wait3, wait4` – also returns resource usage



Process Termination

- A process can terminate in several different ways:
  - no more instructions to execute in the program – unknown status value
  - a function in a program finishes with a `return` – parameter to return the status value
  - the system call `void exit(int status)` – terminates a process and returns the status value (see `man 3 exit`)
  - the system call `int kill(pid_t pid, int sig)` – sends a signal to a process to terminate it (see `man 2 kill, man 7 signal`)
- Usually, a status value of 0 indicates success, other values indicate errors

Process States



Context Switches

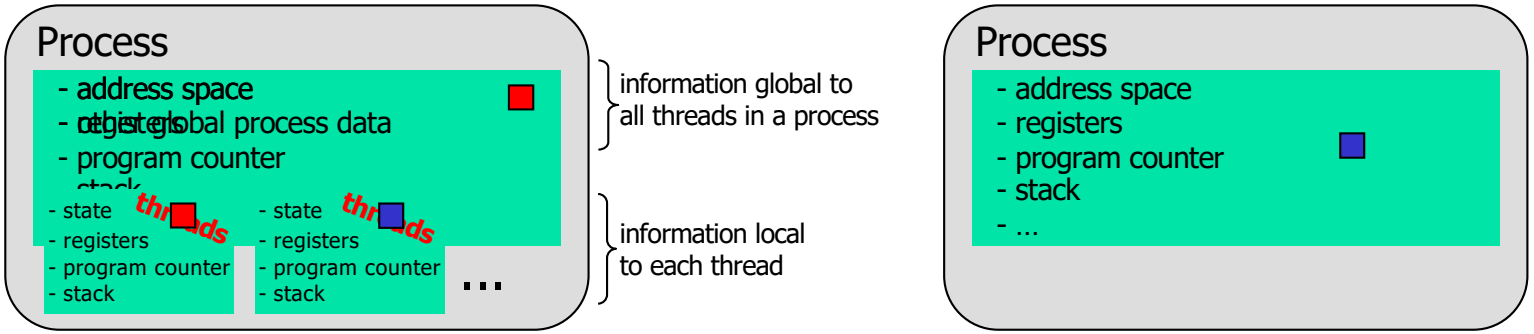
- Context switch: the process of switching one running process to another
  1. stop running *process 1*
  2. store the state (like registers, instruction pointer) of *process 1* (usually on stack or PCB)
  3. restore state of *process 2*
  4. resume operation on program counter for *process 2*

  - essential feature of multi-tasking systems
  - computationally intensive, important to optimize the use of context switches
  - some hardware support, but usually only for general purpose registers

- Possible causes:
  - scheduler switches processes (and contexts) due to algorithm and time slices
  - interrupts
  - required transition between user-mode and kernel-mode

Processes vs. Threads

- Processes: resource grouping and execution
- Threads (light-weight processes)
  - enable more efficient cooperation among execution units
  - share many of the process resources (most notably address space)
  - have their own state, stack, processor registers and program counter



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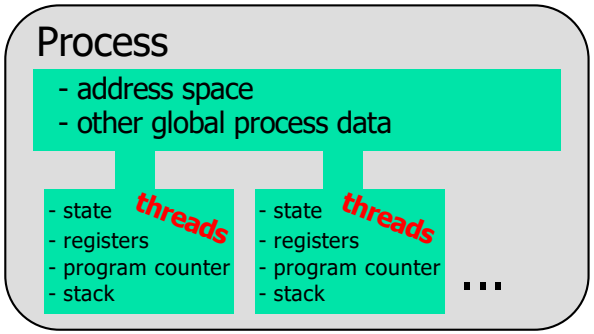


Example: time using `futex` to suspend and resume processes (incl. systemcall overhead):

Intel 5150:	~1900ns/process switch,	~1700ns/thread switch
Intel E5440:	~1300ns/process switch,	~1100ns/thread switch
Intel E5520:	~1400ns/process switch,	~1300ns/thread switch
Intel X5550:	~1300ns/process switch,	~1100ns/thread switch
Intel L5630:	~1600ns/process switch,	~1400ns/thread switch
Intel E5-2620:	~1600ns/process switch,	~1300ns/thread switch

http://blog.tsunanet.net/2010/11/how-long-does-it-take-to-make-context.html

  - no memory address switch
  - thread switching is much cheaper
  - parallel execution of concurrent tasks within a process

- No standard, several implementations (e.g., Win32 threads, Pthreads, C-threads) (see `man 3 pthreads`)

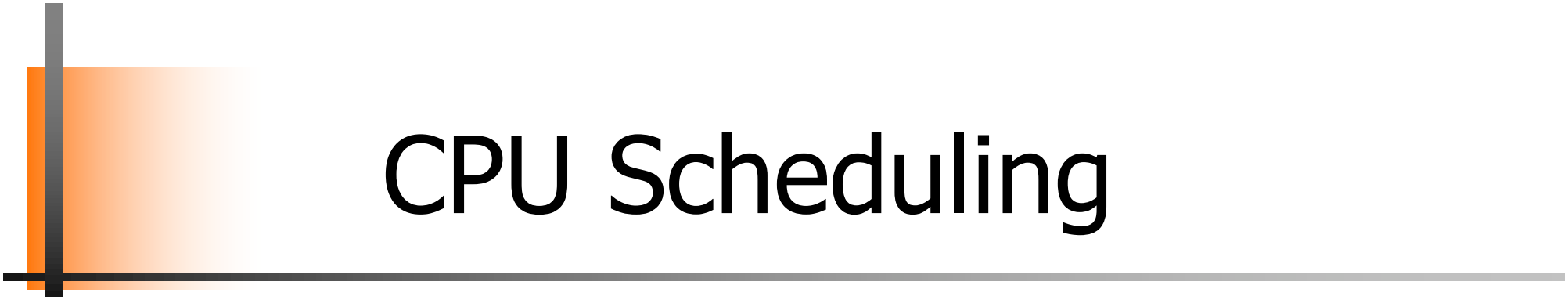
Example – multiple processes

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <sys/wait.h>
#include <unistd.h>

int main(void){
   pid_t pid, n;
   int status = 0;

   if ((pid = fork()) == -1) {printf("Failure\n"); exit(1);}

   if (pid != 0) {  /* Parent */
      printf("parent PID=%d, child PID = %d\n",
                              (int) getpid(), (int) pid);

      printf("parent going to sleep (wait)...\n");

      n = wait(&status);

      printf("returned child PID=%d, status=0x%x\n",
                              (int)n, status);
      return 0;
   } else {          /* Child */
      printf("child PID=%d\n", (int)getpid());
      printf("executing /store/bin/whoami\n");
      execve("/store/bin/whoami", NULL, NULL);
      exit(0);       /* Will usually not be executed */
   }
}
```

[vizzini] > ./testfork
parent PID=2295, child PID=2296
parent going to sleep (wait)...
child PID=2296
executing /store/bin/whoami
paalh
returned child PID=2296, status=0x0

[vizzini] > ./testfork
child PID=2444
executing /store/bin/whoami
parent PID=2443, child PID=2444
parent going to sleep (wait)...
paalh
returned child PID=2444, status=0x0

Two concurrent processes running, **scheduled** differently



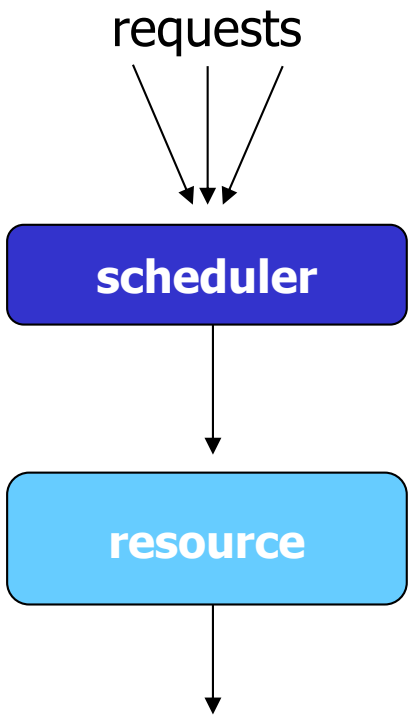
CPU Scheduling

Scheduling

- A task is a schedulable entity/something that can run
  (a process/thread executing a job, e.g.,
  a packet through the communication system or
  a disk request through the file system)

- In a multi-tasking system, several
  tasks may wish to use a resource
  simultaneously

- A scheduler decides which task
  that may use the resource,
  i.e., determines order
  by which requests are serviced,
  using a scheduling algorithm



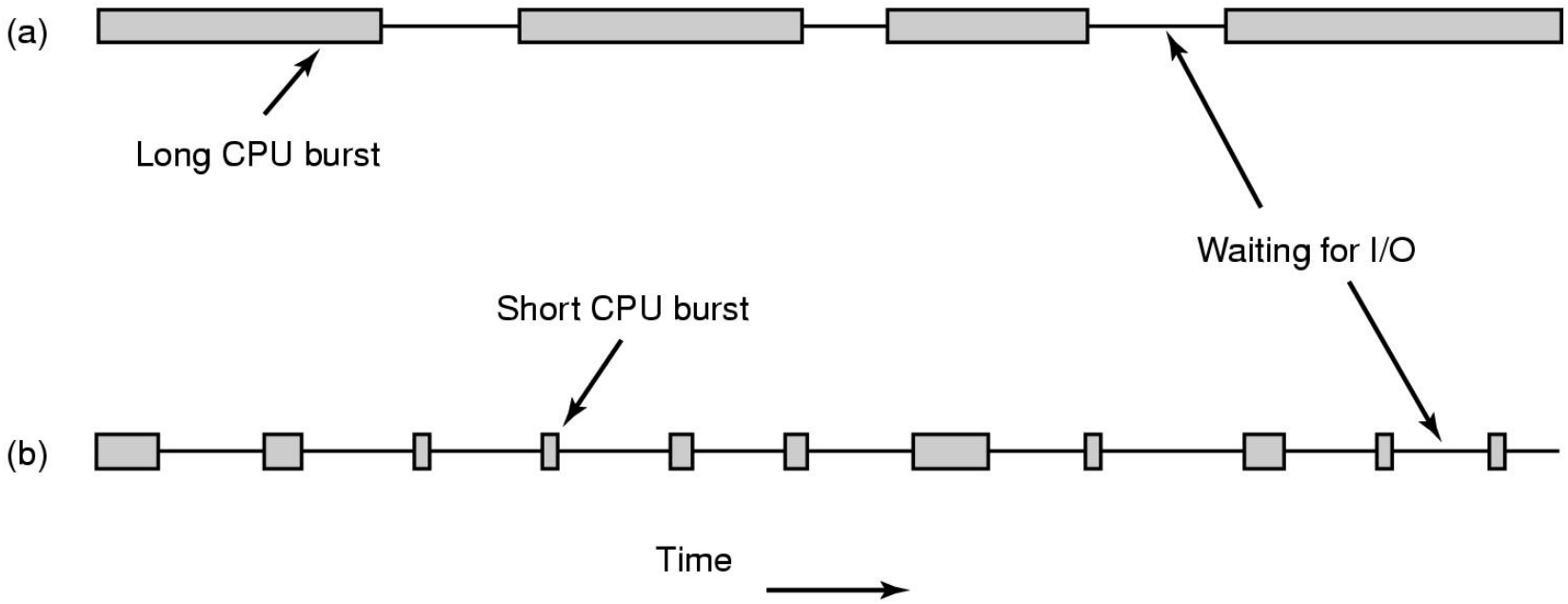
- Finally, the dispatcher "moves" the selected process to the CPU

Why Spend Time on Scheduling?

- Scheduling is complex and takes time – RT vs NRT example (support priorities or not…)

Why Spend Time on Scheduling?

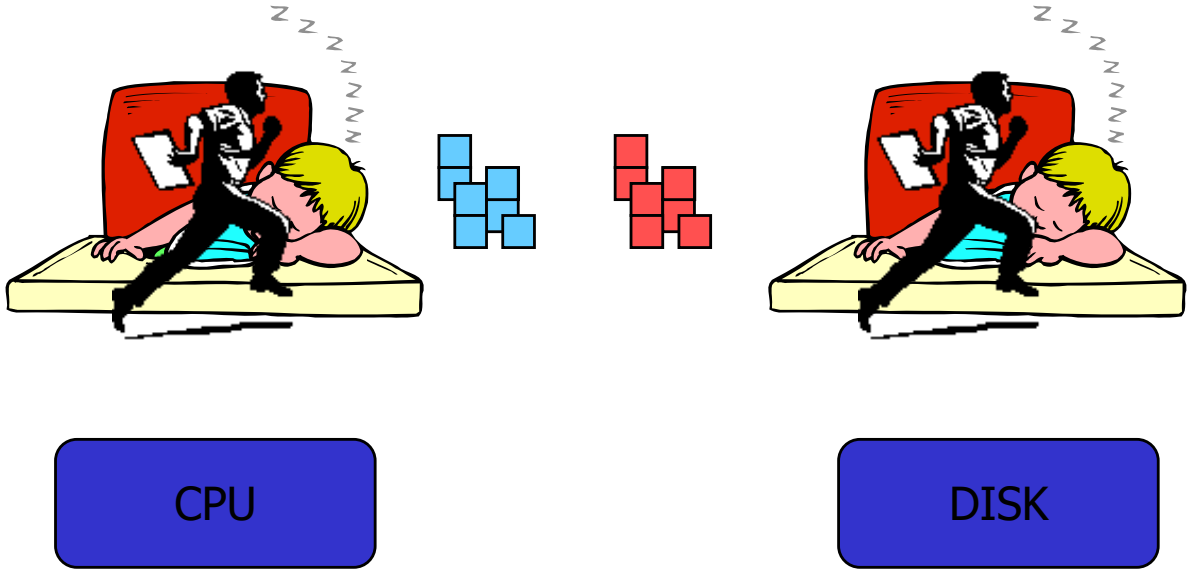
- Optimize the system to the given goals
  - e.g., CPU utilization, throughput, response time, fairness, …
- Example: CPU-bound vs. I/O-bound Processes:



  - Bursts of CPU usage alternate with periods of I/O wait

Why Spend Time on Scheduling?

- Example: CPU-bound vs. I/O-bound processes (cont.) – observations:
  - schedule all CPU-bound processes first, then I/O-bound



  - schedule all I/O-bound processes first, then CPU-bound?
  - possible solution:
    mix of CPU-bound and I/O-bound: overlap slow I/O devices with fast CPU

Many Algorithms Exist

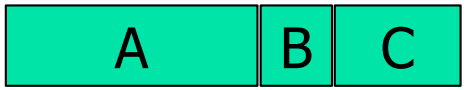
- First In First Out (FIFO)
- Round-Robin (RR)
- Shortest Job First
- Shortest Time to Completion First
- Shortest Remaining Time to Completion First (a.k.a. Shortest Remaining Time First)
- Lottery
- Fair Queuing
- …

FIFO and Shortest Job First (SFJ)

- FIFO: First in, First Out
- SFJ: Select first tasks with *shortest processing requirement (completion time)*

- Example: Arrival order:processing requirement - A:8, B:2, C:4

  - FIFO:

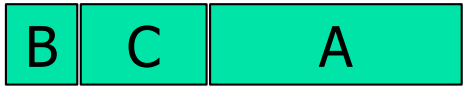


    - Average wait time: 6
    - Average finishing time: 10,67

    - simple
    - fair?
    - long waiting and finishing times

	Requirement	Wait	Finish
A	8	0	8
B	2	8	10
C	4	10	14

  - SJF:



    - Average wait time: 2,67
    - Average finish time: 7,33

    - simple
    - better average times compared to FIFO
    - hard to determine processing requirement
    - potentially huge finishing times and starvation (new shorter jobs arrive)

	Requirement	Wait	Finish
A	8	6	14
B	2	0	2
C	4	2	6

FIFO and Round Robin

FIFO:

- Run
  - to completion (old days)
  - until blocked, yield or exit
- Advantages
  - simple
- Disadvantage
  - long waiting times

Round-Robin (RR):

- FIFO queue
- Each process runs a given time
  - each process gets 1/n of the CPU in max t time units per round
  - the preempted process is put back in the queue

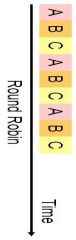
FIFO and Round Robin

- Example: 10 jobs and each takes 100 seconds, assuming no overhead (!?)

- FIFO – the process runs until finished

  - start: job1: 0s, job2: 100s, ... , job10: 900s → **average** 450s
  - finished: job1: 100s, job2: 200s, ... , job10: 1000s → **average** 550s
  - some get long waiting time, but some are lucky

- RR – time slice of 1s



  - start: job1: 0s, job2: 1s, ... , job10: 9s → **average** 4.5s
  - finished: job1: 991s, job2: 992s, ... , job10: 1000s → **average** 995.5s
  - fair, but no one is lucky

- Comparisons
  - FIFO better for long CPU-intensive jobs (there **is** overhead in switching!!)
  - but RR much better for interactivity!

- **But, how to choose the right time slice??**

Case: Time Slice Size

- Resource utilization example
  - **A** and **B** run forever, and each uses "100%" CPU
  - **C** loops forever (1 ms CPU and 10 ms disk)
  - (assume no switching overhead)

- Long or short time slices?
  - 100% of CPU utilization regardless of size
  - Time slice 100 ms: nearly 5% of disk utilization with RR
    [per round: A:100 + B:100 + C:1 → 201 ms CPU vs. 10 ms disk]
  - Time slice 1 ms: nearly 91% of disk utilization with RR
    [per round: 5x (A:1 + B:1) + C:1 → 11 ms CPU vs. 10 ms disk]

- What do we learn from this example?
  - The right time slice (in this case shorter) can improve overall utilization, but note - context switches do cost!
  - CPU bound: benefits from having longer time slices (>100 ms)
  - I/O bound: benefits from having shorter time slices (≤10 ms)

Scheduling: goals

- A variety of (contradicting) factors to consider
  - treat similar tasks in a similar way
  - no process should wait forever
  - short response times ($\text{time}_{\text{response given}} - \text{time}_{\text{request submitted}}$)
  - maximize throughput
  - maximum resource utilization (100%, but 40-90% normal)
  - minimize overhead
  - predictable access
  - …

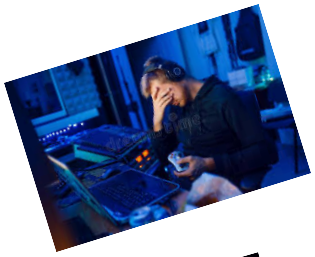
- Several ways to achieve these goals, …
  …but hard (impossible?) to achieve all …
  …but which criteria is most important, most reasonable?

Scheduling: goals

- "Most reasonable" criteria depend on who you are

vs.

  - Kernel
    - Resource management
      - processor utilization, throughput, fairness
  - User
    - Interactivity
      - response time
        (*Example:* when playing a game, we will not accept waiting 10s each time we use the joystick)



    - Predictability
      - identical performance every time
        (*Example:* when using the editor, we will not accept waiting 5s one time and 5ms another time to get echo)

- "Most reasonable" criteria depend on environment
  - Server vs. end-system
  - Stationary vs. mobile
  - ...

vs.

Scheduling: goals

- "Most reasonable" criteria depend on target system
  - Most/All types of systems
    - fairness – giving each process a fair share
    - balance – keeping all parts of the system busy
  - Batch systems
    - turnaround time – minimize time between submission and termination
    - throughput – maximize number of jobs per hour
    - (CPU utilization – keep CPU busy all the time)

  - Interactive systems
    - response time – respond to requests quickly
    - proportionality – meet users' expectations

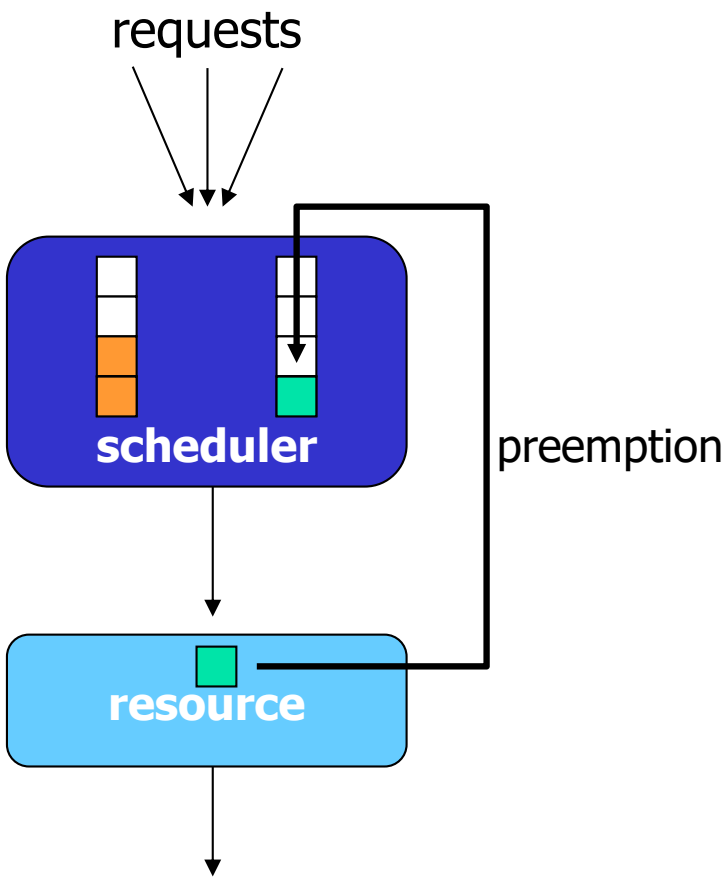
  - Real-time systems
    - meet deadlines – avoid loosing data
    - predictability – avoid quality degradation in multimedia systems

Scheduling classification

- Scheduling algorithm classification:
  - dynamic
    - makes scheduling decisions at run-time
    - flexible to adapt
    - considers only the actual task requests and execution time parameters
    - large run-time overhead finding a schedule
  - static
    - makes scheduling decisions off-line (also called pre-run-time)
    - generates a dispatching table for the run-time dispatcher at compile time
    - needs complete knowledge of the task before compiling
    - small run-time overhead
  - preemptive
    - running tasks may be interrupted (preempted) by higher priority processes
    - preempted process continues later at the same state
    - overhead of contexts switching
  - non-preemptive
    - running tasks will be allowed to finish its time-slot (higher priority processes must wait)
    - reasonable for short tasks like sending a packet (used by disk and network cards)
    - less frequent switches

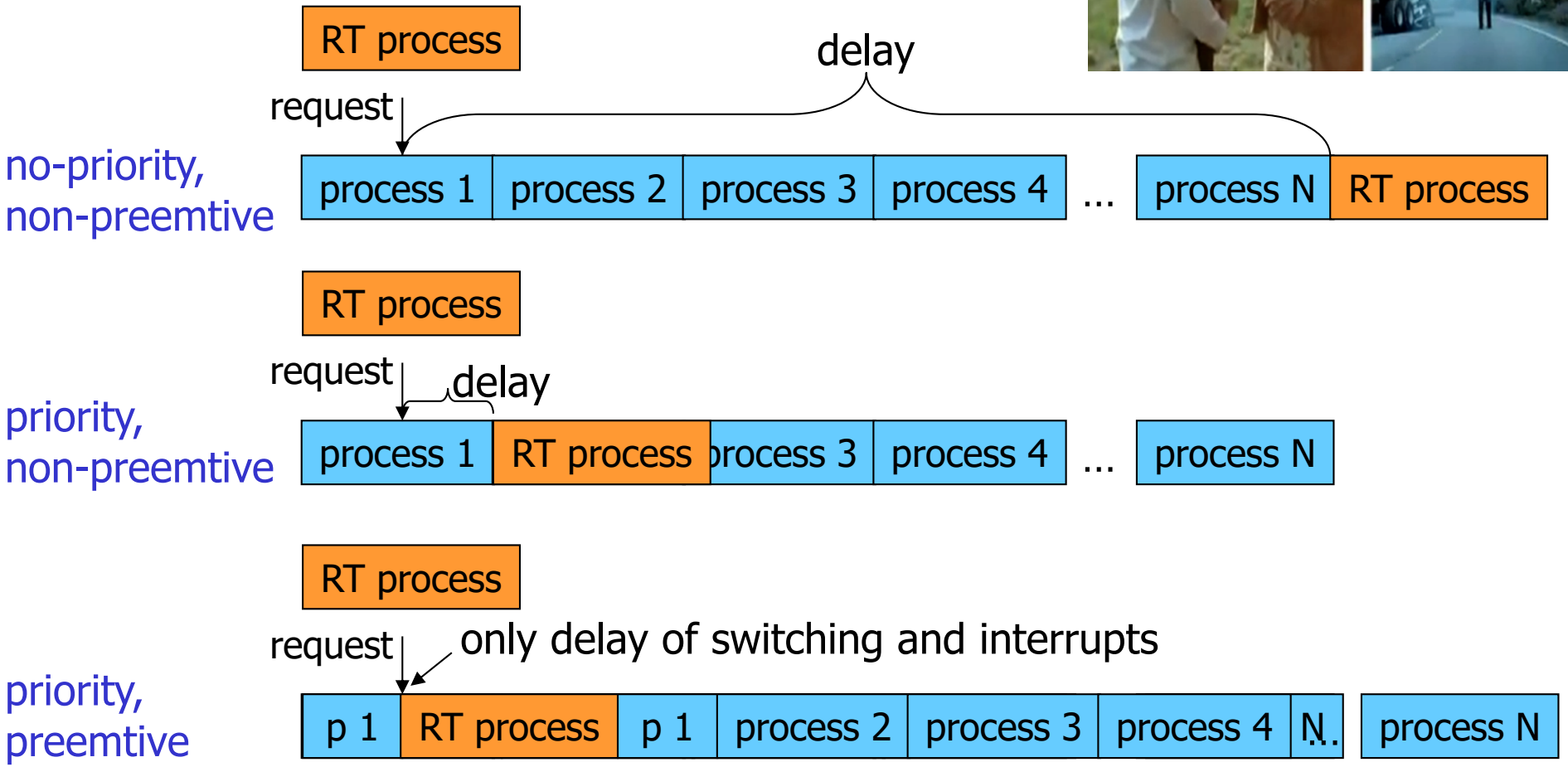
Preemption

- Tasks waits for processing
- Scheduler assigns priorities
- Task with highest priority will be scheduled first
- Preempt current execution if
  - a higher priority (more urgent) task arrives
  - timeslice is consumed
  - …
- Real-time and best effort priorities
  - real-time processes have higher priority
    (if such processes exist, they will run)
- To kinds of preemption:
  - preemption points
    - predictable overhead
    - simplified scheduler accounting
  - immediate preemption
    - needed for hard real-time systems
    - needs special timers and fast interrupt and context switch handling



Priority & Preemption

- RT vs NRT example:



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- *Round-Robin (RR)*
- *Shortest Job First*
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- Lottery
- Fair Queuing
- …

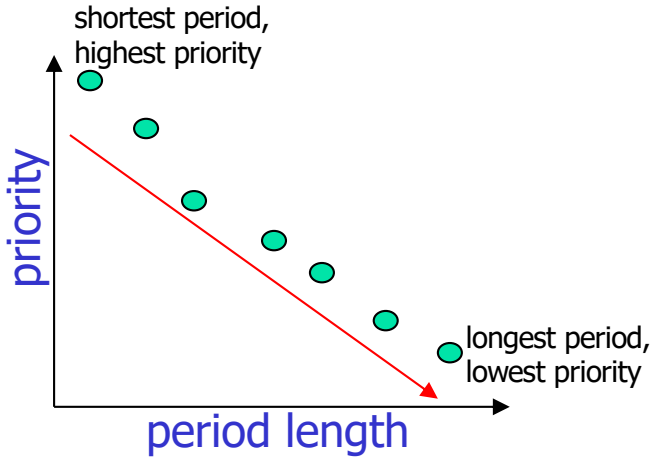
- Earliest Deadline First (EDF)
- Rate Monotonic (RM)
- …

Rate Monotonic (RM) Scheduling

- Classic algorithm for hard real-time systems with one CPU
- Pre-emptive scheduling based on *static task priorities*
- Optimal:
  no other algorithms with *static* task priorities can schedule tasks that cannot be scheduled by RM
- Assumptions:
  - requests for all tasks with deadlines are periodic
  - the deadline of a task is equal to the end on its period (starting of next)
  - independent tasks (no precedence)
  - run-time for each task is known and constant
  - context switches can be ignored
  - *any non-periodic task has no deadline*

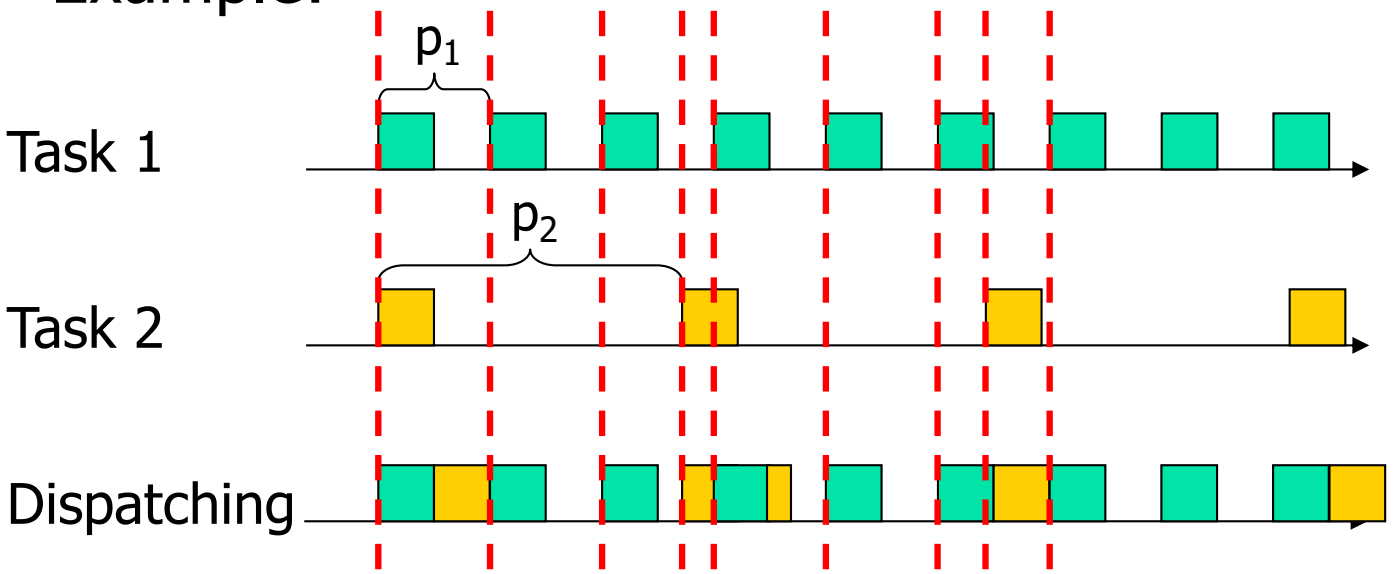
Rate Monotonic (RM) Scheduling

- Process priority based on task periods
  - task with shortest period gets highest *static* priority
  - task with longest period gets lowest *static* priority
  - dispatcher always selects task requests with highest priority



- Example:

P_i = period for task i



$P_1 < P_2$
→ $Task_1$ highest priority

Earliest Deadline First (EDF)

- Preemptive scheduling based on dynamic task priorities
- Task with *closest deadline has highest priority (dynamic)*
  → stream priorities vary with time
- Dispatcher selects the highest priority task
- Optimal:
  if any task schedule without deadline violations exits, EDF will find it
- Assumptions:
  - requests for all tasks with deadlines are periodic
  - the deadline of a task is equal to the end on its period (starting of next)
  - independent tasks (no precedence)
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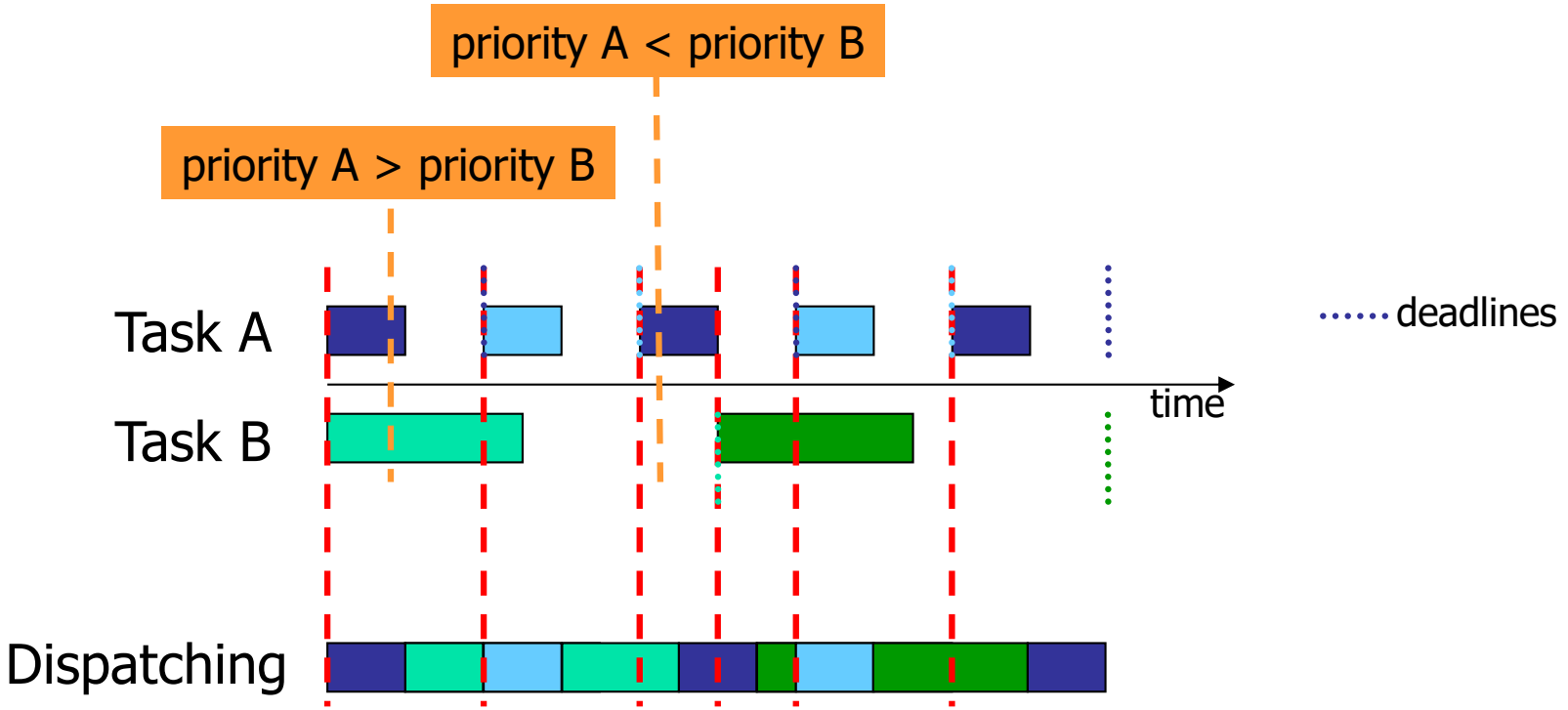
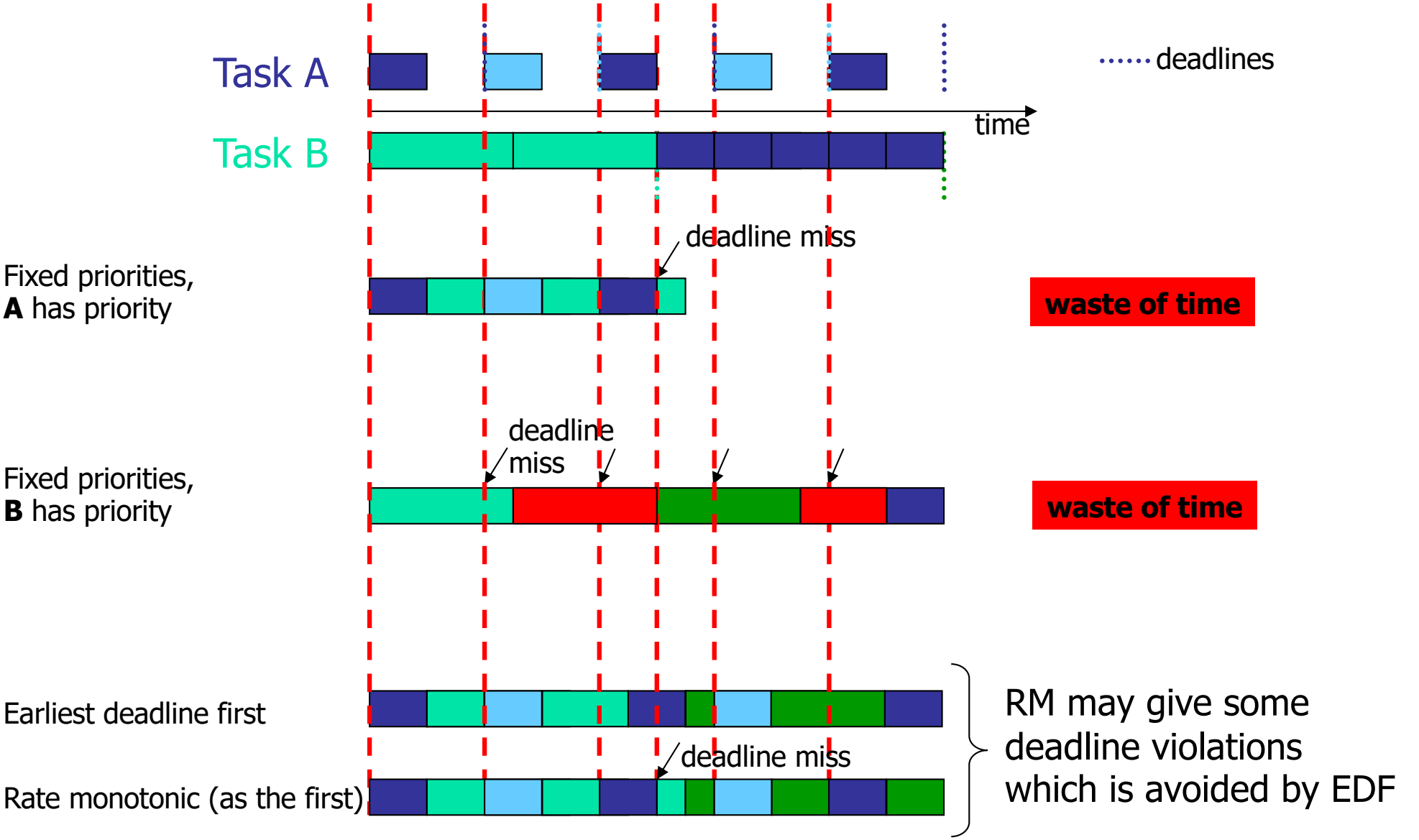
Earliest Deadline First (EDF)

- Example:



EDF Versus Fixed priorities (RM)

- It might be impossible to prevent deadline misses in a strict, fixed priority system:

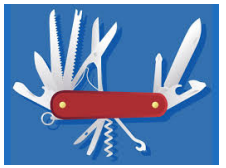


Many Algorithms Exist

- *First In First Out (FIFO)*
- *Round-Robin (RR)*
- Shortest Job First
- Shortest Time to Completion First
- Shortest Remaining Time to Completion First (a.k.a. Shortest Remaining Time First)
- Lottery
- Fair Queuing
- …

- *Earliest Deadline First (EDF)*
- *Rate Monotonic (RM)*
- …

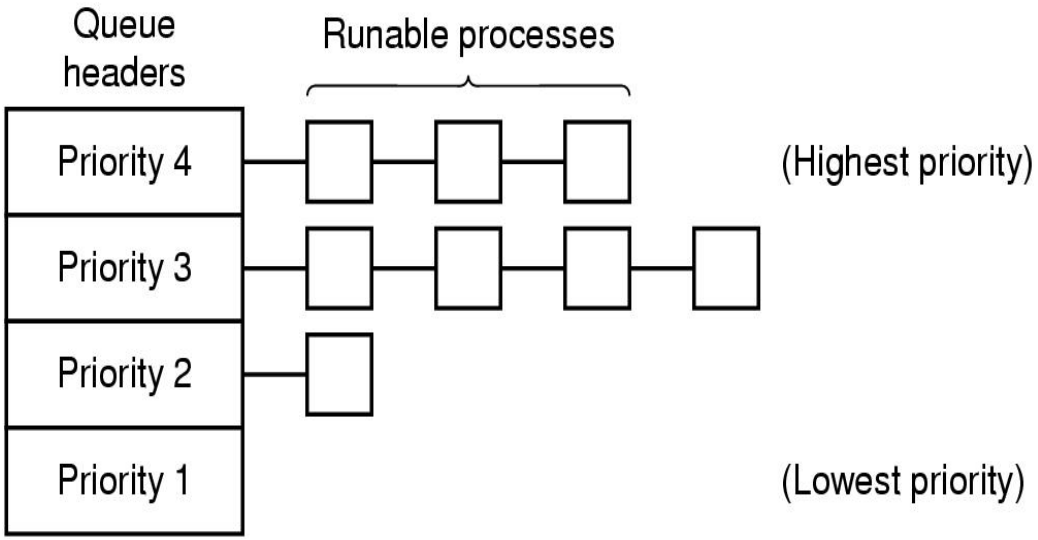
- Today, the same machine performs various tasks
  → most systems use some kind of *priority scheduling*



Priority Scheduling

- Assign each process a priority
- Run the process with highest priority in the ready queue first

- Multiple queues, often RR in each



- Advantage
  - (Fairness)
  - Different priorities according to importance

- Disadvantage
  - Starvation: so maybe use dynamic priorities?

Scheduling in Windows 2000, XP, …

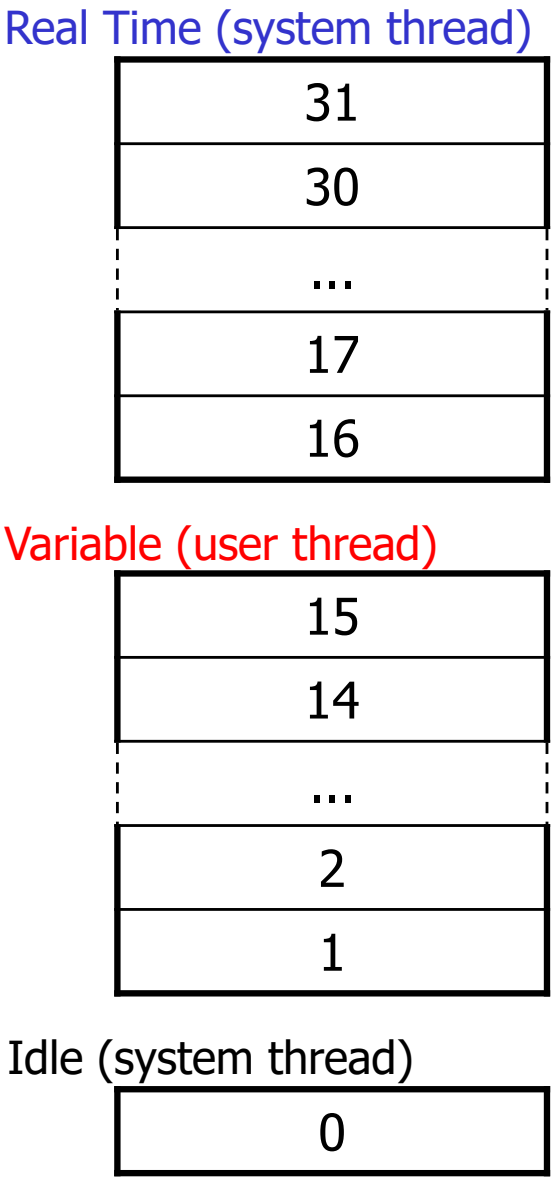
- Preemptive kernel
- Schedules threads individually

- Time slices given in quantums
  - 3 quantums = 1 clock interval (length of interval may vary)
  - defaults:
    - Win2000 server: 36 quantums
    - Win2000 workstation: 6 quantums (professional)
  - may manually be increased between threads (1x, 2x, 4x, 6x)
  - foreground quantum boost (add 0x, 1x, 2x):
    an active window can get longer time slices (assumed need for fast response)

Scheduling in Windows 2000, XP, …

- 32 priority levels:
  Round Robin (RR) within each level

- Interactive and throughput-oriented
  - "Real time" – 16 system levels
    - fixed priority
    - may run forever
  - Variable – 15 user levels
    - priority may change:
      thread priority = process priority ± 2
    - **decrease**: much CPU usage
    - **increase**: user interactions, I/O completions
  - Idle/zero-page thread – 1 system level
    - runs whenever there are no other processes to run
    - clears memory pages for memory manager



Scheduling in Windows 8/10 (...server 2008, 7)

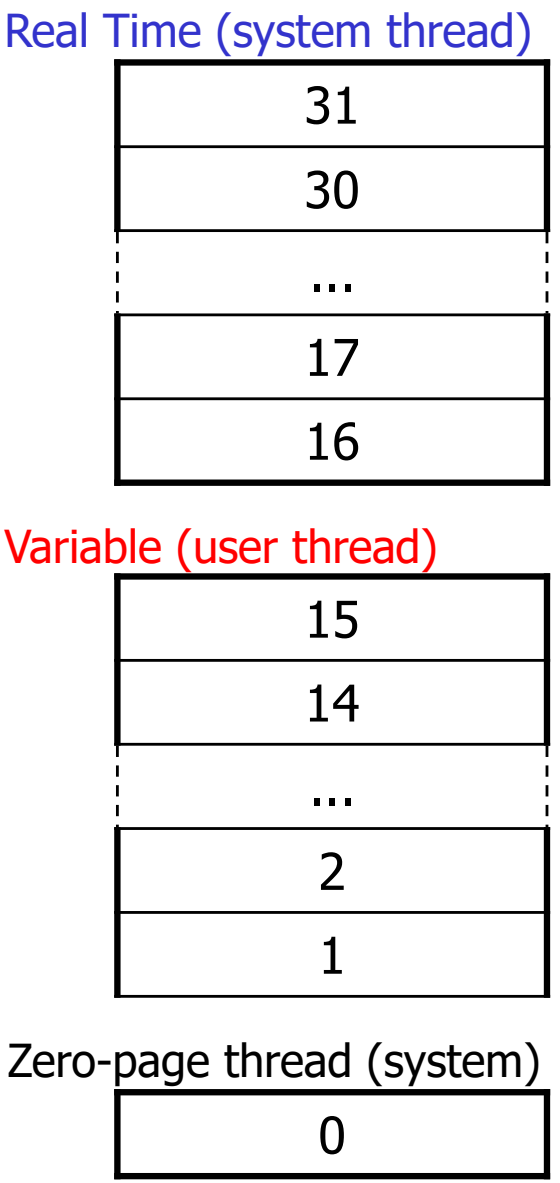
http://msdn.microsoft.com/en-us/library/windows/desktop/ms681917(v=vs.85).aspx

- Still 32 priority levels, 6 process classes - RR within each:
  - REALTIME_PRIORITY_CLASS
  - HIGH_PRIORITY_CLASS
  - ABOVE_NORMAL_PRIORITY_CLASS
  - ***NORMAL_PRIORITY_CLASS*** (default)
  - BELOW_NORMAL_PRIORITY_CLASS
  - IDLE_PRIORITY_CLASS

  ➥ each class has 7 thread priority levels with different base priorities
  (IDLE, LOWEST, BELOW NORMAL, NORMAL, ABOVE NORMAL, HIGHEST, TIME_CRITICAL)

  ➥ thread base priority depends on priority class and priority level

THREAD PRIORITY LEVEL: / PROCESS PRIORITY CLASS:	IDLE	LOWEST	BELOW NORMAL	NORMAL	ABOVE NORMAL	HIGHEST	TIME_CRITICAL
REALTIME_PRIORITY	16	22	23	24	25	26	31
HIGH_PRIORITY	1	11	12	13	14	15	15
ABOVE_NORMAL_PRIORITY	1	8	9	10	11	12	15
NORMAL_PRIORITY	1	6	7	8	9	10	15
BELOW_NORMAL_PRIORITY	1	4	5	6	7	8	15
IDLE_PRIORITY	1	2	3	4	5	6	15



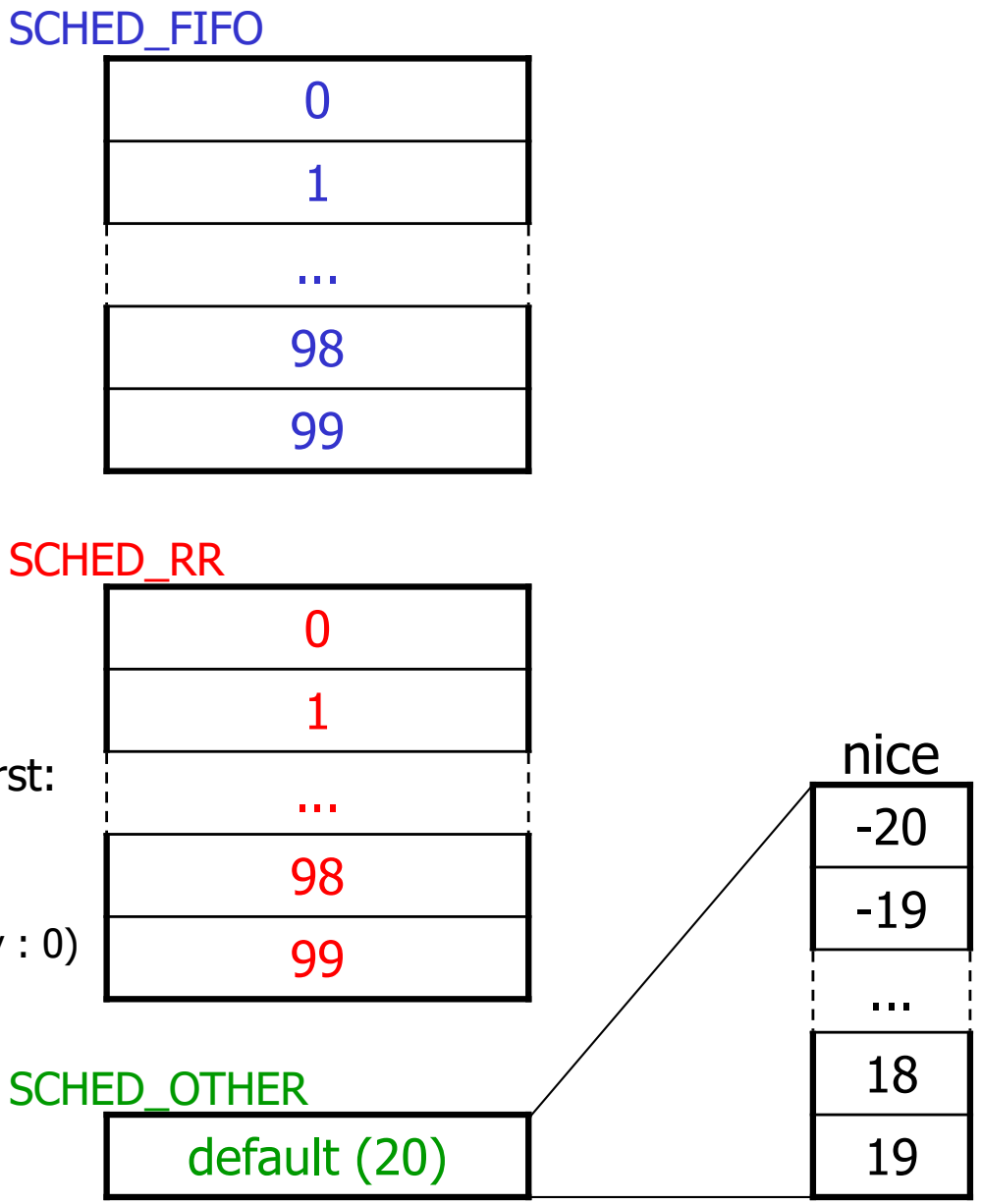
Scheduling in Linux

- Preemptive kernel
- Threads and processes used to be equal, but Linux uses (from 2.6) thread scheduling

- SCHED_FIFO
  - may run forever, no timeslices
  - may use it's own scheduling algorithm
- SCHED_RR
  - each priority in RR
  - timeslices of 10 ms (quantums)
- SCHED_OTHER
  - ordinary user processes
  - uses "nice"-values: 1≤ priority≤40
  - timeslices of 10 ms (quantums)

- Threads with highest *goodness* are selected first:
  - realtime (FIFO and RR):
    goodness = 1000 + priority
  - timesharing (OTHER):
    goodness = (quantum > 0 ? quantum + priority : 0)

- *Quantums* are reset when no *ready* process has quantums left (end of *epoch*):
  quantum = (quantum/2) + priority

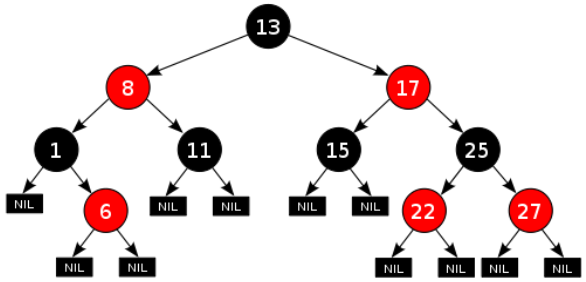


https://www.linuxjournal.com/node/10267

Scheduling in Linux

The current kernels (v.2.6.23+) use the ***Completely Fair Scheduler*** *(CFS)*

- addresses unfairness in desktop and server workloads – all given a fair amount
- uses extensible hierarchical scheduling classes
  - SCHED_RR and SCHED_FIFO (SCHED_RT) - remain more or less as before - use priorities 1 - 99
  - SCHED_IDLE – very low priority jobs (weaker than "nice -19")
  - SCHED_DEADLINE – deadline tasks (highest user-controllable priorities, earliest-deadline-first sorted)
  - **SCHED_NORMAL** (OTHER) – the default desktop scheduler
  - **SCHED_BATCH** – similar to SCHED_OTHER, but assumes CPU intensive workloads (slightly disfavored)
- uses ns granularity, does not rely on jiffies or HZ details
- no run-queues, a *red-black tree* -based timeline of future tasks based on *virtual runtime*



- does not directly use priorities, but instead uses them as a decay factor for the time a task is permitted to execute
- group scheduling – fair between users

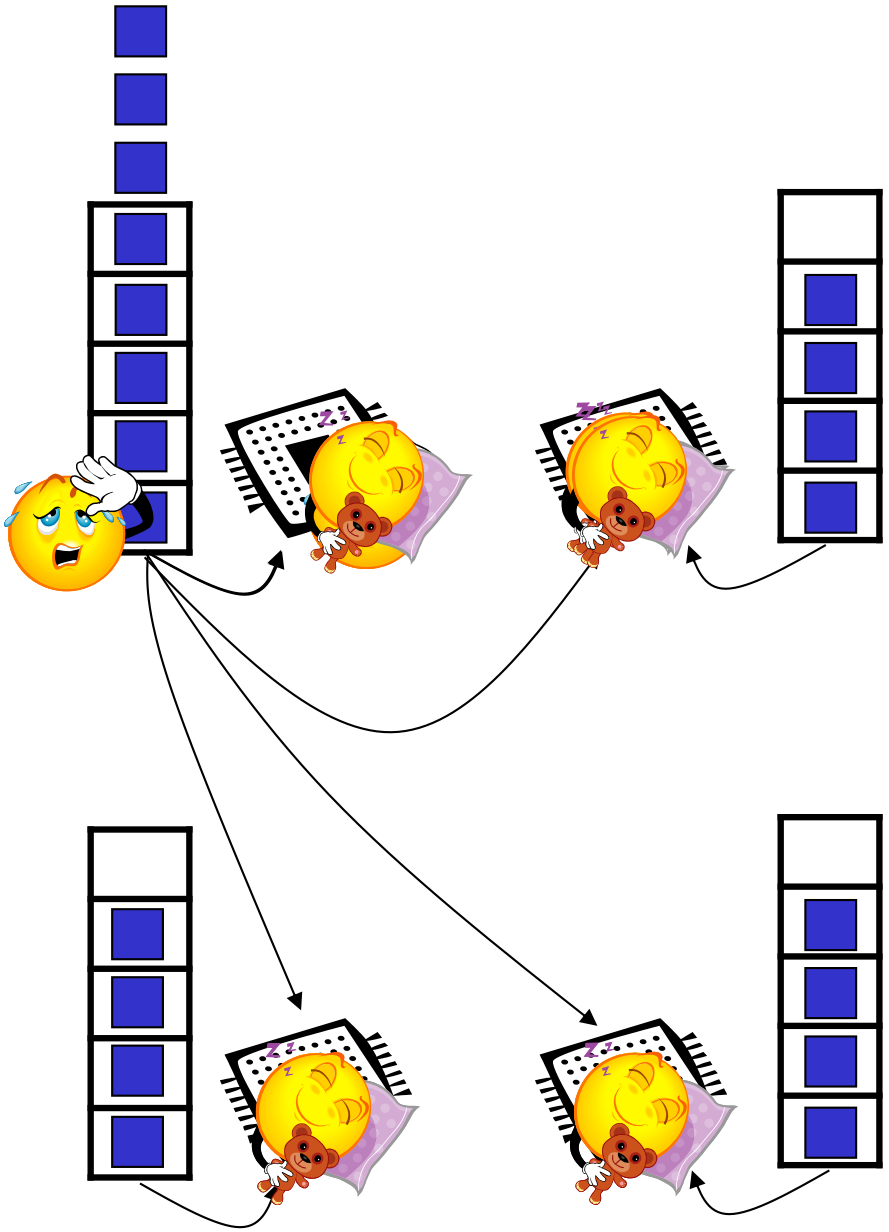
When to Invoke the Scheduler?

- Process creation 
- Process termination 
- Process blocks 
- Interrupts occur 
- Clock interrupts in the case of preemptive systems 

Some complicating factors …

Multicore

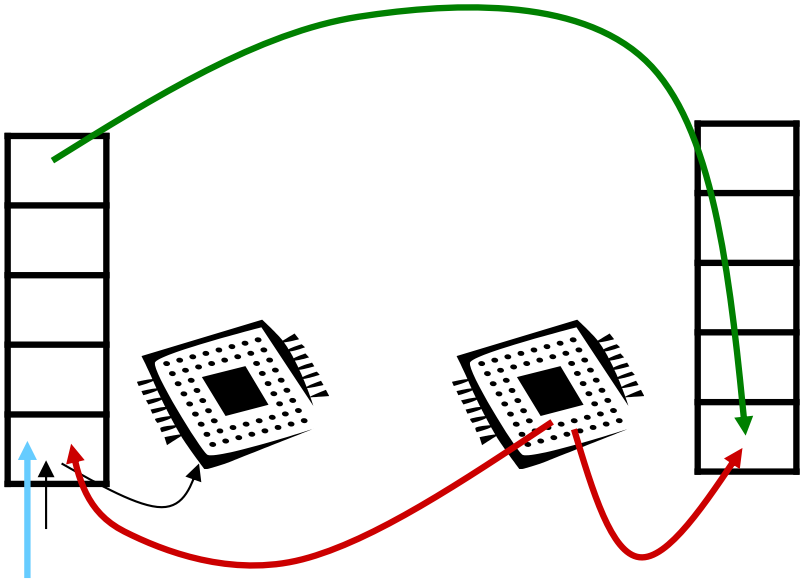
- So far, one single core…
  - … multiple cores/CPUs
    - 1 single queue
      - potential bottleneck?
        - locking/contention on the single queue
    - Multiple queues
      - potential bottleneck?
        - load balancing
    - Load balancing
      - Linux checks every 200 ms
      - But where to place a new process?
      - And where to wake up a blocked process?

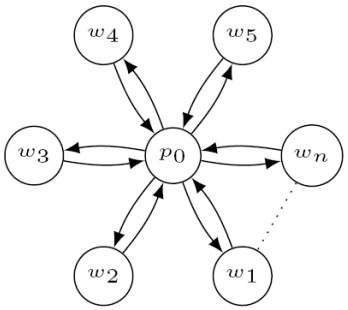


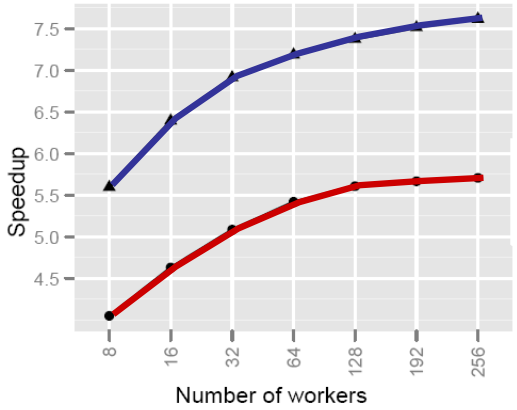
Multicore: Effect of placement (on Work Stealing)

- Scheduling mechanism in the Intel Tread Building Block (TBB) framework
- LIFO queues (insert and remove from beginning of queues)
- One master thread (CPU)
  - new processes are placed here
  - awaken processes are placed here
- If own queue is empty, STEAL:
  - select random CPU_x
  - if CPU_x queue not empty
    - steal from the back of the queue
    - place first in own queue
- Importance of process placement?
  - change CPU of where wake up a process
  - Small experiment: scatter-gather workload (100 µs work per thread, 12500 iterations, 8 over 1 CPU speedup)

⇨ 300.000 more steal attempts per second

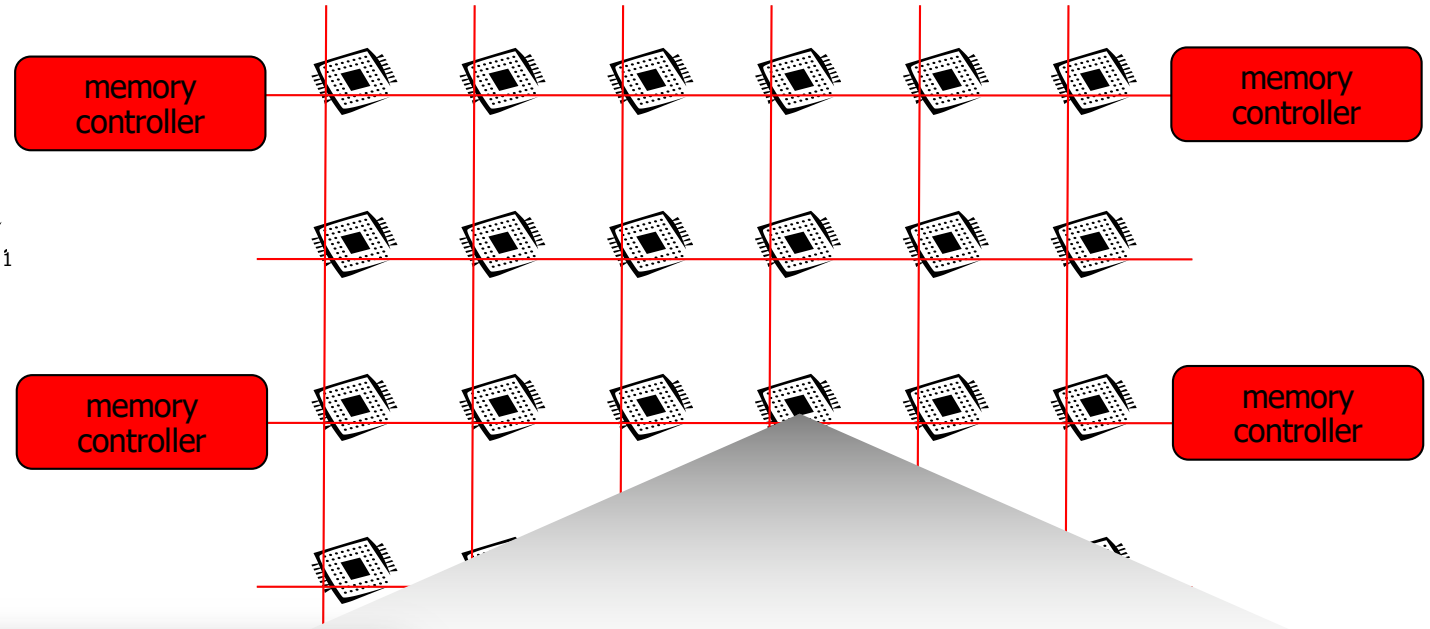


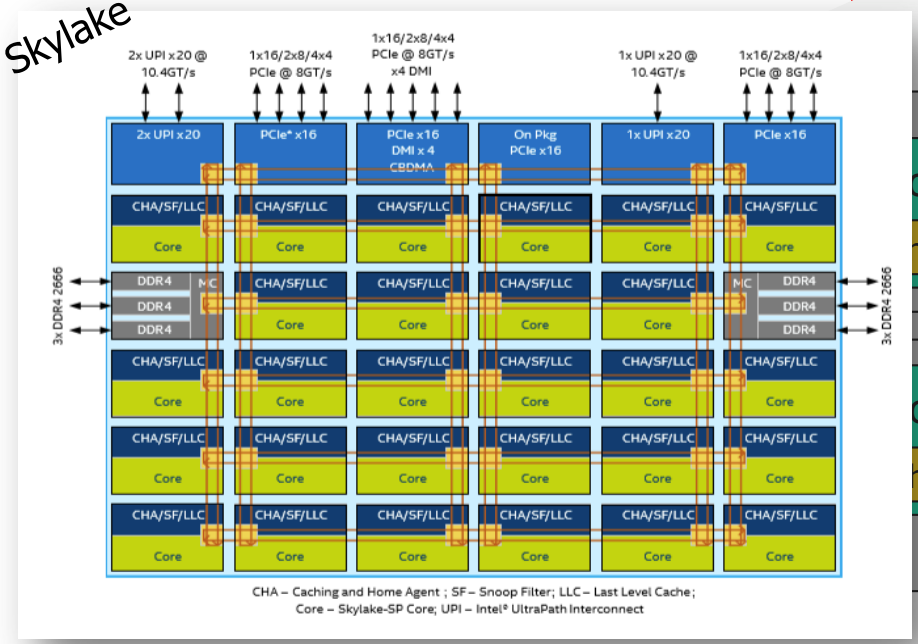


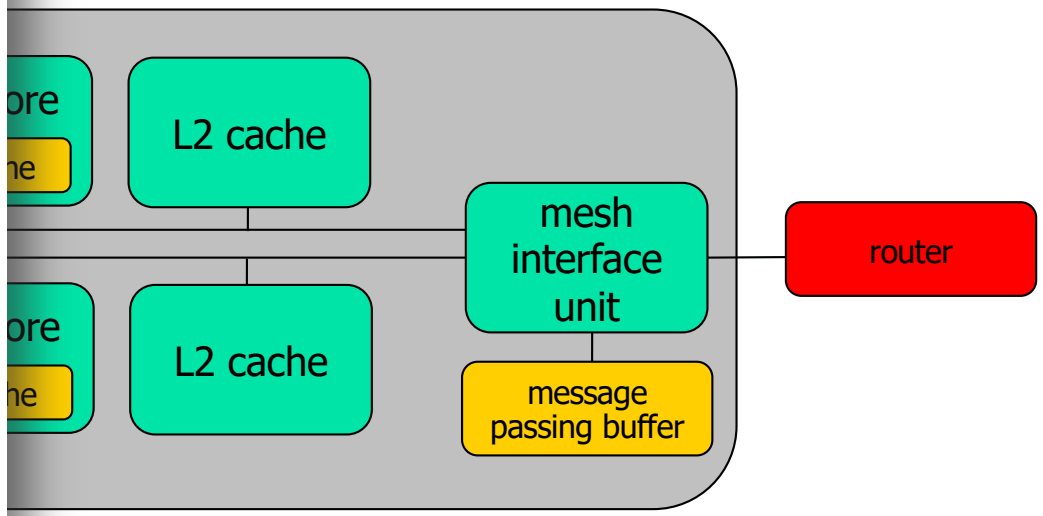


Future Chips: Something to think about!?

- Intel's Single-chip Cloud Computer (SCC)

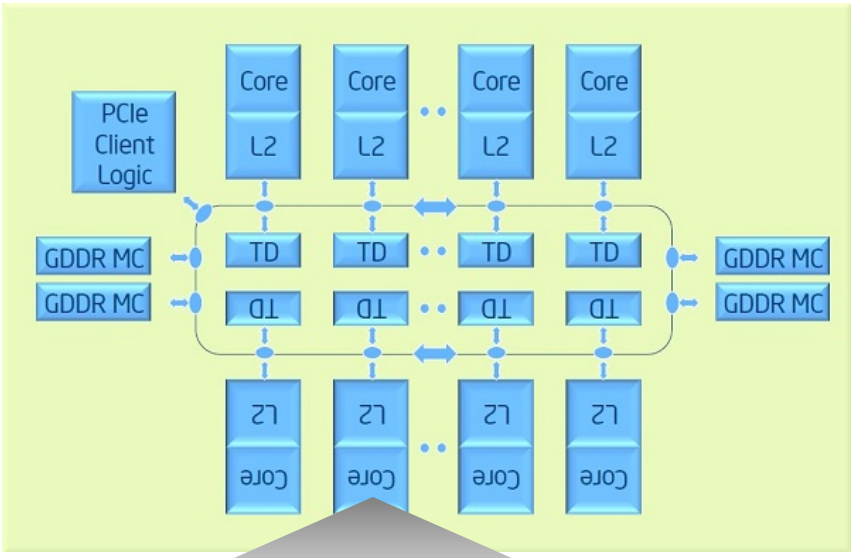






New Chips: Something to think about!?

- Intel's Xeon Phi
  - up to 61 cores
  - 8 memory controllers
  - High Performance On-Die Bidirectional Interconnect
  - …



- nVidia GPUs, e.g., Volta:
  - 5120 CUDA cores
  - 32 GB memory
  - …

- What does such processors mean in terms of scheduling?
  - many cores
  - different capabilities
  - different memory access latencies
  - different connectivity
  - affinity
  - … (more in later courses)

Summary

- Processes are programs under execution
- Scheduling performance criteria and goals are dependent on environment
- The right timeslice can improve overall utilization
- There exists several different algorithms targeted for various systems
- Traditional OSes like Windows, UniX, Linux, MacOS ... usually use a priority-based algorithm