CS 370: OPERATING SYSTEMS
[CPU SCHEDULING]

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Frequently asked questions from the previous class survey

- `wait(mutex)` ensures that `readcount` is only being accessed by one reader at a time?
- Why should each thread have its own turnstile?
- Does the kernel "see" threads?
- When would you use atomic variables vs regular ones?
- What is stored in a timestamp?
- How could priority figure into dining philosophers?

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Topics covered in this lecture

- CPU Scheduling
- Scheduling Criteria
- Scheduling Algorithms
  - First Come First Serve (FCFS)
  - Shortest Job First (SJF)

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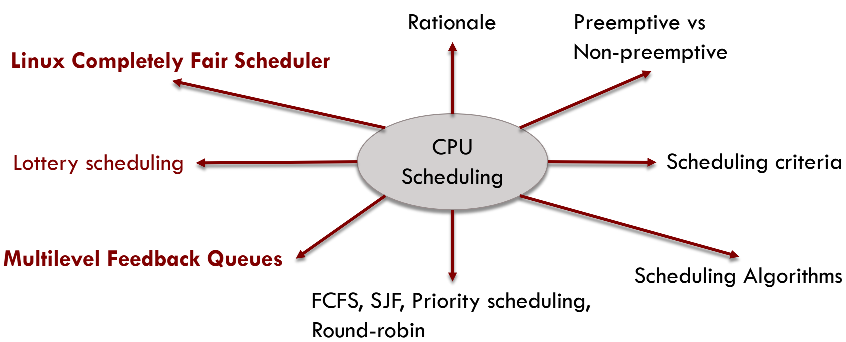
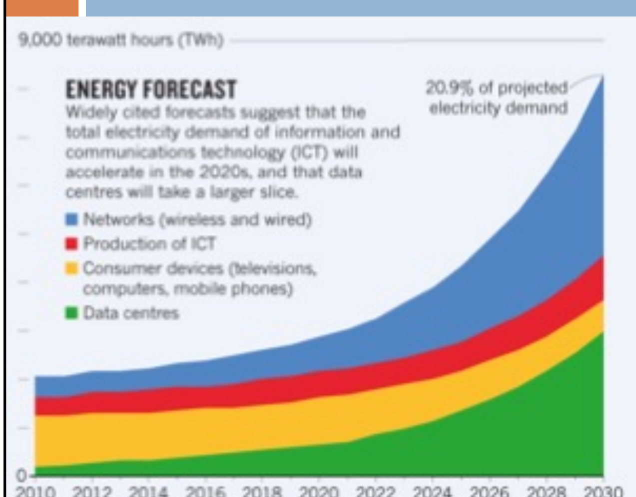
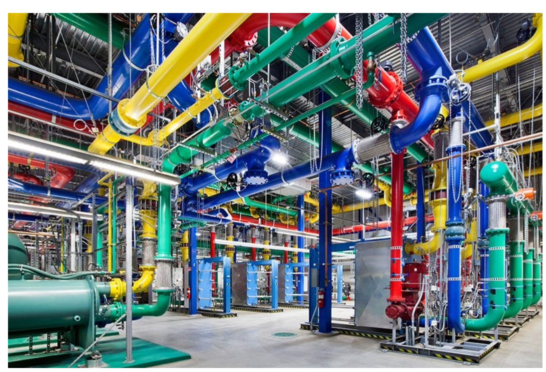
CPU Scheduling: Topics that we will cover



Data Centers





Source: https://www.nature.com/articles/d41586-018-06610-y

Time is money — Benjamin Franklin

CPU SCHEDULING

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When there are multiple things to do, how do you choose which one to do first?

- At any point in time, some tasks are running on the system's processor
  - Others are waiting their turn for a processor
  - Still other tasks are blocked waiting for I/ O to complete, a condition variable to be signaled, or for a lock to be released
- When there are more runnable tasks than processors?
  - The processor **scheduling policy** determines which tasks to run first

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Just do the work in the order in which it arrives?

- After all, that seems to be the only **fair** thing to do
  - Because of this, almost all government services work this way
- When you go to your local DMV to get a driver's license, you take a number and wait your turn
  - Although fair, the DMV often feels slow
- Advertising that your OS uses the same scheduling algorithm as the DMV is probably not going to increase your sales!

Multiprogramming organizes jobs so that the CPU always has one to execute

- A single program (generally) **cannot** keep CPU & I/O devices busy at all times
- A user frequently runs multiple programs
- When a job needs to **wait**, the CPU **switches** to another job
- Utilizes resources effectively
  - CPU, memory, and peripheral devices

Observed Property of Process execution: CPU-I/O burst cycle

Processes **alternate** between CPU-I/O bursts

load store **add store** **read** from file	CPU burst
wait for I/O	I/O burst
store increment **index** **write** to file	CPU burst
wait for I/O	I/O burst
load store **add store** **read** from file	CPU burst
wait for I/O	I/O burst

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Distribution of the duration of CPU bursts

- Large number of short CPU bursts
  - A typical **I/O bound** process
- Small number of long CPU bursts
  - A typical **CPU-bound** process

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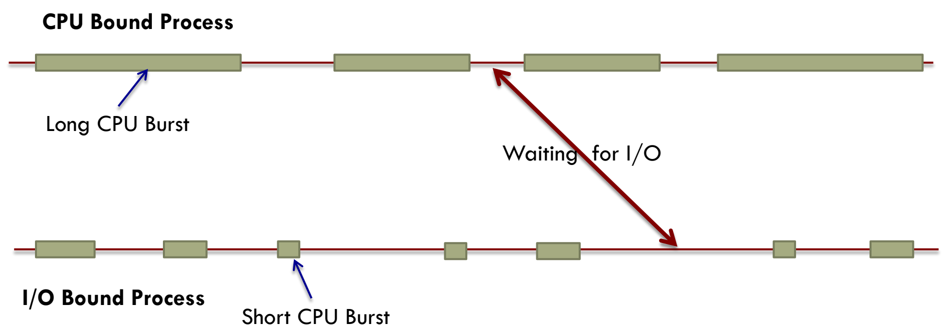
Bursts of CPU usage alternate with periods of waiting for I/O

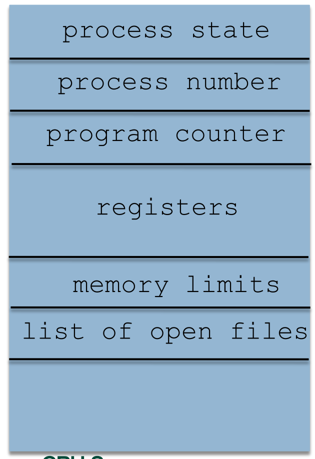


As CPUs get faster …

- Processes tend to get more I/O bound
  - CPUs are improving faster than disks
- Scheduling of I/O bound processes will continue to be important

When CPU is idle, OS selects one of the processes in the ready queue to execute

- Records in the ready queue are **process control blocks** (PCB)



- **Implemented** as:
  - FIFO queue
  - Priority queue
  - Tree
  - Linked list

The Process Control Block (PCB)

- When a process is not running
  - The kernel maintains the hardware execution state of a process within the PCB
    - Program counter, stack pointer, registers, etc.
- When a process is being context-switched away from the CPU
  - The hardware state is transferred into the PCB

The Process Control Block (PCB) is a data structure with several fields

- Includes process ID, execution state, program counter, registers, priority, accounting information, etc.
- In Linux:
  - Kernel stores the list of tasks in a circular, doubly-linked list called the **task list**
  - Each element in the task list is a process descriptor of the type struct `task_struct`, which is defined in `<linux/sched.h>`
  - Relatively large data structure: 1.7 KB on a 32-bit machine with ~100 fields

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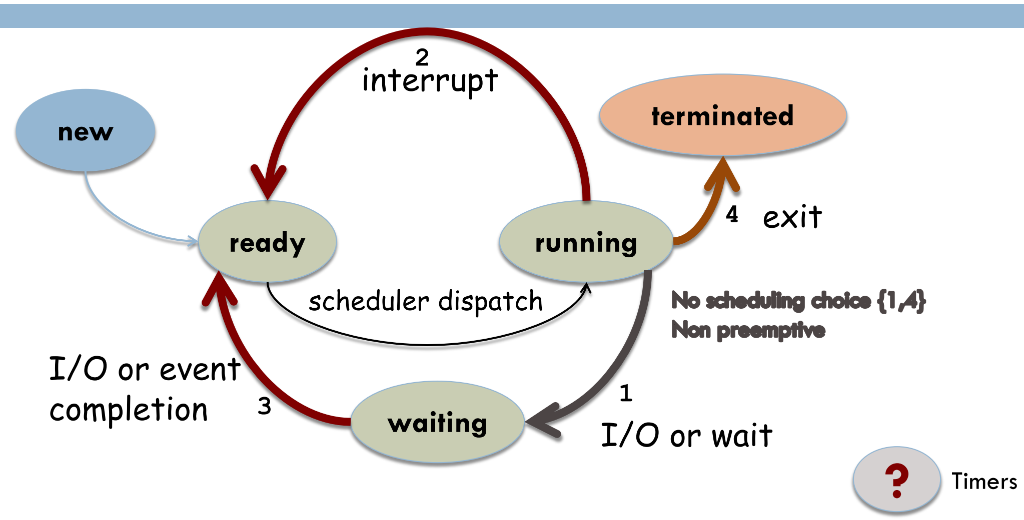
CPU scheduling takes places under the following circumstances



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Nonpreemptive or cooperative sheduling

- Process **keeps** CPU *until it relinquishes* it when:
  1. It terminates
  2. It switches to the waiting state
- Sometimes the *only* method on certain hardware platforms
  - E.g., when they don't have a hardware timer
- Used by initial versions of OS
  - Windows: Windows 3.x
  - Mac OS

Preemptive scheduling

- Pick a process and let it run for a **maximum of some fixed time**
- If it is still running at the end of time interval?
  - **Suspend** it …
  - Pick another process to run

Preemptive scheduling: Requirements

- A **clock interrupt** at the end of the time interval to give control of CPU back to the scheduler
- If no hardware timer is available?
  - Nonpremptive scheduling is the only option

Preemptive scheduling impacts …

- Concurrency management
- Design of the OS
- Interrupt processing

Preemptive scheduling incurs some costs: Manage concurrency

- Access to **shared data**
  - Processes **A** and **B** share data
  - Process **A** is updating *when* it is **preempted** to let Process **B** run
  - Process **B** tries to read data, which is now in an *inconsistent* state

Preemptive scheduling incurs some costs: Affects the design of the OS

- System call processing
  - Kernel may be changing kernel data structure (I/O queue)
- Process preempted in the middle AND
  - Kernel needs to read/modify same structure?
- SOLUTION: **Before** context switch
  - Wait for system call to complete OR
  - I/O blocking to occur

Preemptive scheduling incurs some costs: Interrupt processing

- Interrupts can occur at **any** time
  - Cannot always be ignored by kernel
    - Consequences: Inputs lost or outputs overwritten
- Guard code affected by interrupts from simultaneous use:
  - Disable interrupts during entry
  - Enable interrupts at exit
  - CAVEAT: Should not be done often, and critical section must contain few instructions

The dispatcher is invoked during **every** process switch

- **Gives control** of CPU to process selected by the scheduler
- Operations performed:
  - Switch context
  - Switch to user mode
  - Restart program at the right location
- Dispatch latency
  - Time to stop one process and start another

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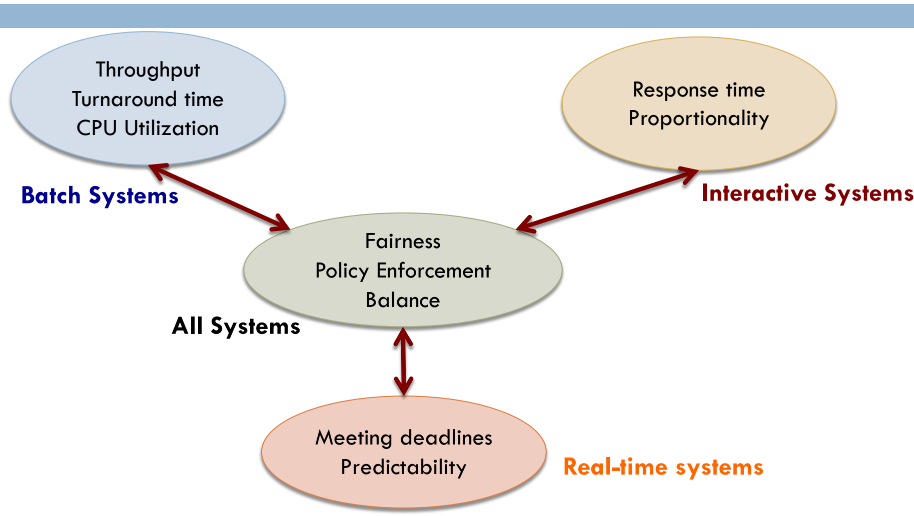
Scheduling Algorithms: Goals



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CPU Utilization

- Difference between elapsed time and idle time
- Average over a period of time
  - Meaningful only within a context

Scheduling Criteria: Choice of scheduling algorithm may favor one over another

- **CPU Utilization**: Keep CPU as busy as possible
  - 40% for lightly loaded system
  - 90% for heavily loaded system
- **Throughput**: Number of completed processes per time unit
  - Long processes: 1/hour
  - Short processes: 10/second

Scheduling Criteria: Choice of scheduling algorithm may favor one over another [1/2]

- Turnaround time
  - $t_{completion} - t_{submission}$
- **Waiting** time
  - Total time spent waiting in the ready queue
- Response time
  - Time to start responding
  - $t_{first\_response} - t_{submission}$
  - Generally *limited* by speed of output device

Scheduling Criteria: Choice of scheduling algorithm may favor one over another [2/2]

- Predictability
  - **Low variance** in response times to repeated requests
- Fairness
  - Equality in the number and timeliness of resources given to each task
- Starvation
  - Lack of progress for one task, due to resources being given to a higher priority task

What are we trying to achieve?

- Objective is to *maximize* the **average** measure
- Sometimes averages are not enough
  - Desirable to optimize minimum & maximum values
    - For good service put a ceiling on maximum response time
  - **Minimize the variance** instead of the average
    - *Predictability* more important
    - *High variability*, but faster on average, not desirable

Scheduling Algorithms

- **Decides** which process in the ready queue is allocated the CPU
- Could be preemptive or nonpreemptive
- Optimize ***measure*** of interest
- We will use **Gantt charts** to illustrate *schedules*
  - Bar chart with start and finish times for processes

It is important to note that

- Scheduling policy is not a panacea
  - Without enough capacity, performance may be poor regardless of what task you run first
- There is **no one right answer**!
  - Scheduling policies pose a *complex set of tradeoffs* between various desirable properties

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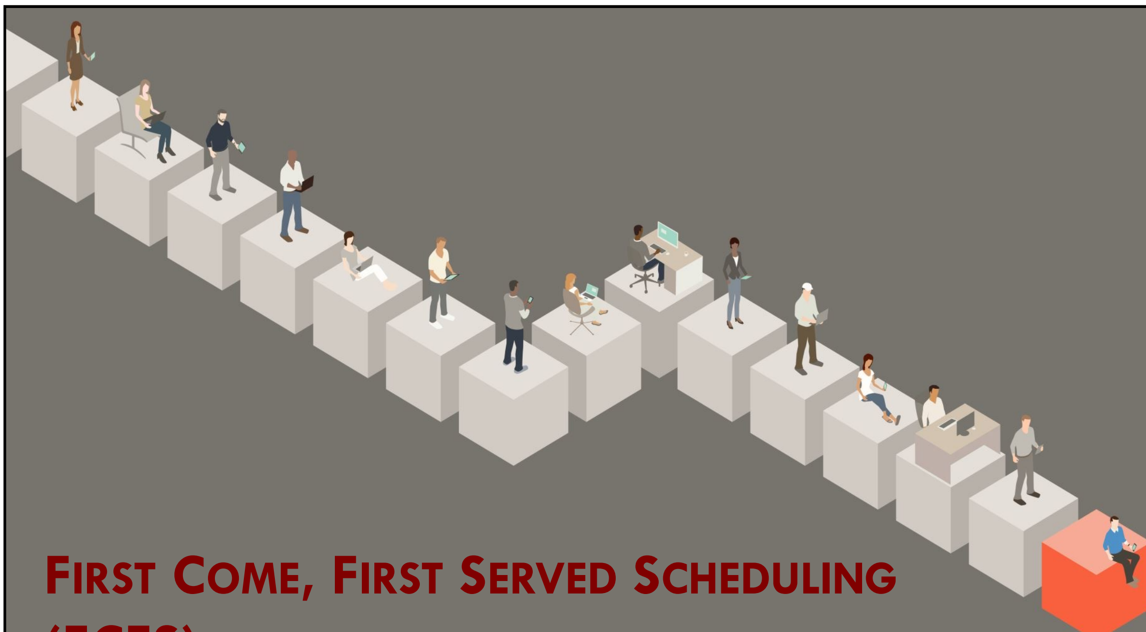

FIRST COME, FIRST SERVED SCHEDULING (FCFS)

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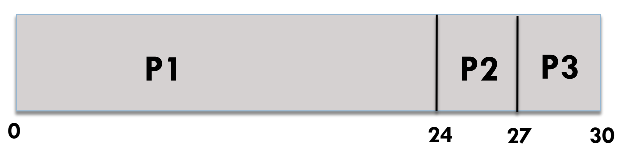
First-Come, First-Served Scheduling (FCFS)

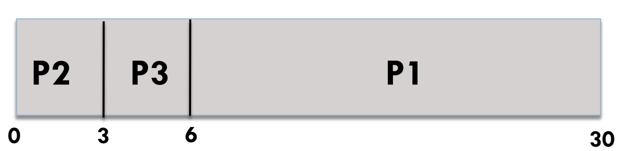
- Process requesting CPU first, gets it first
- Managed with a FIFO queue
  - When process **enters** ready queue?
    - PCB is tacked to the **tail** of the queue
  - When CPU is **free**?
    - It is allocated to process at the **head** of the queue
- Simple to write and understand
- FIFO **minimizes overhead**: Switches between tasks *only when* each one completes

Average waiting times in FCFS depend on the order in which processes arrive

Process	Burst Time
P1	24
P2	3
P3	3



Wait time = (0 + 24 + 27)/3 = 17



Wait time = (6 + 0 + 3)/3 = 3

Disadvantages of the FCFS scheme [1/2]

- Once a process gets the CPU, it keeps it
  - Till it terminates or does I/O
  - Unsuitable for time-sharing systems
- Average waiting time is generally not minimal
  - In fact, FCFS is a poor choice for average response times
  - **Varies substantially** if CPU burst times vary greatly

Disadvantages of the FCFS scheme [2/2]

- Poor performance in certain situations
  - 1 CPU-bound process and many I/O-bound processes
  - **Convoy effect**: Smaller processes wait for the one big process to get off the CPU

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Shortest Job First (SJF) scheduling algorithm

- When CPU is available it is assigned to process with **smallest CPU burst**
- Moving a short process before a long process?
  - Reduction in waiting time for short process
    GREATER THAN
    Increase in waiting time for long process
- Gives us **minimum average waiting time** for a **set** of processes that arrived *simultaneously*
  - Provably Optimal

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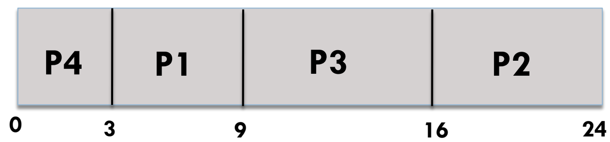
Depiction of SJF in action

Process	Burst Time
P1	6
P2	8
P3	7
P4	3

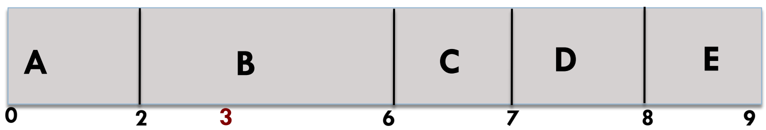


`Wait time = (3 + 16 + 9 + 0)/4 = 7`

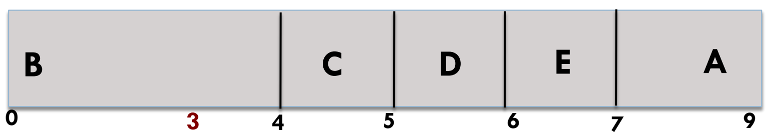
SJF is optimal ONLY when ALL the jobs are available simultaneously

- Consider 5 processes **A**, **B**, **C**, **D** and **E**
  - Run times are: 2, 4, 1, 1, 1
  - Arrival times are: 0,0, 3, 3, 3
- SJF will run jobs: **A**, **B**, **C**, **D** and **E**
  - Average wait time: (0 + 2 + 3 + 4 + 5)/5 = 2.8
  - **But** if you run **B**, **C**, **D**, **E** and **A** ?
    - Average wait time: (7 + 0 + 1 + 2 +3)/5 = 2.6!

Visualizing the different runs of A, B, C, D and E



Average wait time: (0 + 2 + 3 + 4 + 5)/5 = 2.8



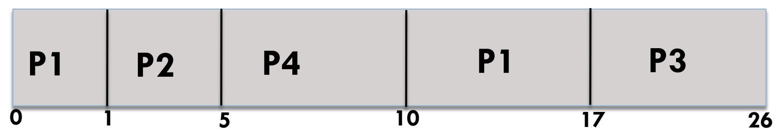
Average wait time: (7 + 0 + 1 + 2 +3)/5 = 2.6

Preemptive SJF

- What counts as "**shortest**" is the remaining time left on the task, not its original length
  - If you are a nanosecond away from finishing an hour-long task, stay on that task
    - Instead of preempting for a minute long task
- Also known, as **shortest-remaining-time-first** (SRTF)

Preemptive SJF

- A new process arrives in the ready queue
  - If it is shorter (i.e., shorter time remaining) than the currently executing process?
    - Preemptive SJF will preempt the current process



Process	Arrival	Burst
P1	0	8
P2	1	4
P3	2	9
P4	3	5

```
Wait time =
[(10-1) + (1-1) + (17-2) + (5-3)]/4
= 26/4 = 6.5
```


Characteristics of Preemptive SJF

- Can suffer from **starvation** and **frequent context switches**
  - If enough short tasks arrive, long tasks may never complete
- Analogy
  - Supermarket manager switching to SJF to reduce waiting times

Does Preemptive SJF has any other downsides?

- Turns out, SJF is **pessimal** for variance in response time
- By doing the shortest tasks as quickly as possible, SJF necessarily does longer tasks *as slowly as possible*
- Fundamental **tradeoff** between reducing average response time and reducing the variance in average response time

Use of SJF in long term schedulers

- Length of the process time limit
  - Used as CPU burst estimate
- Motivate users to accurately estimate time limit
  - Lower value will give faster response times
  - Too low a value?
    - Time limit exceeded error
    - Requires resubmission!

The SJF algorithm and short term schedulers

- **No way to know** the length of the next CPU burst
- So, try to **predict** it
- Processes scheduled *based on predicted* CPU bursts

Prediction of CPU bursts: Make estimates based on past behavior

- t_n : Length of the n^{th} CPU burst
- τ_n : Estimate for the n^{th} CPU burst
- α : Controls weight of recent and past history
- $\tau_{n+1} = \alpha t_n + (1-\alpha)\,\tau_n$
- Burst is predicted as an exponential average of the measured lengths of previous CPU bursts

α controls the relative weight of recent and past history

- $\tau_{n+1} = \alpha t_n + (1-\alpha)\,\tau_n$
- Value of t_n contains our most recent information, while τ_n stores the past history
- $\tau_{n+1} = \alpha t_n + (1-\alpha)\,\alpha t_{n-1} + \ldots + (1-\alpha)^j\,\alpha t_{n-j} + \ldots + (1-\alpha)^{n+1}\,\alpha\tau_0$
- α is less than 1, $(1-\alpha)$ is also less than one
  - **Each successive term has less weight than its predecessor**

The choice of α in our predictive equation

- If α=1/2
  - Recent history and past history are **equally weighted**
- With α = ½; successive estimates of τ

  $t_0/2$ $t_0/4 + t_1/2$ $t_0/8 + t_1/4 + t_2/2$ $t_0/16 + t_1/8 + t_2/4 + t_3/2$

  - By the 3rd estimate, weight of what was observed at t_0 has dropped to 1/8.

An example: Predicting the length of the next CPU burst

CPU burst (t_i)		**6**	**4**	**6**	**4**	**13**	**13**	**13**
"Guess" (τ_i)	10	8	6	6	5	9	11	**12**

The choice of α in our predictive equation

- $\tau_{n+1} = \alpha t_n + (1-\alpha)\,\tau_n$
- If $\alpha=0$, $\tau_{n+1} = \tau_n$
  - Current conditions are transient
- If $\alpha=1$, $\tau_{n+1} = t_n$
  - Only most recent bursts matter
  - History is assumed to be old and irrelevant

The contents of this slide-set are based on the following references

- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 6]
- *Andrew S Tanenbaum. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620.* [Chapter 2]
- *Thomas Anderson and Michael Dahlin. Operating Systems: Principles and Practice, 2nd Edition. Recursive Books. ISBN: 0985673524/978-0985673529. [Chapter 7]*