K22 - Operating Systems: Design Principles and Internals

Fall 2025 @dit

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Lecture 07

References: Similar OS courses @Columbia, @Stanford, @UC San Diego, @Brown, @di (previous years); and textbooks: Operating Systems: Three Easy Pieces, Operating Systems: Principles and Practice, Operating System Concepts, Linux Kernel Development, Understanding the Linux Kernel

Overview

- We'll start from hardware and follow a question-oriented approach
  - ~~Intro [Q: What is an OS?]~~
  - ~~Events [Q: When does the OS run?]~~
  - ~~Runtime [Q: How does a program look like in memory?]~~
  - ~~Processes [Q: What is a process?]~~
  - ~~IPC [Q: How do processes communicate?]~~
  - Threads [Q: What is a thread?]
  - Synchronization [Q: What goes wrong w/o synchronization?]
  - Time Management [Q: What is scheduling?]
  - Memory Management [Q: What is virtual memory?]
  - Files [Q: What is a file descriptor?]
  - Storage Management [Q: How do we allocate disk space to files?]

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* Basic (H/W & S/W)
* Abstractions
* Primitives
* Mechanisms

Overview

- Threads
  - Q1: What is a thread?
  - Q2: Threads vs. processes?
  - Q3: How does the OS implement threads?
  - Q4: From uniprogramming to multiprogramming?
  - Q5: "How to" concurrency?

The thread abstraction

- What is a thread? "A single flow of control within a process." (Strict POSIX definition, 3/190.)

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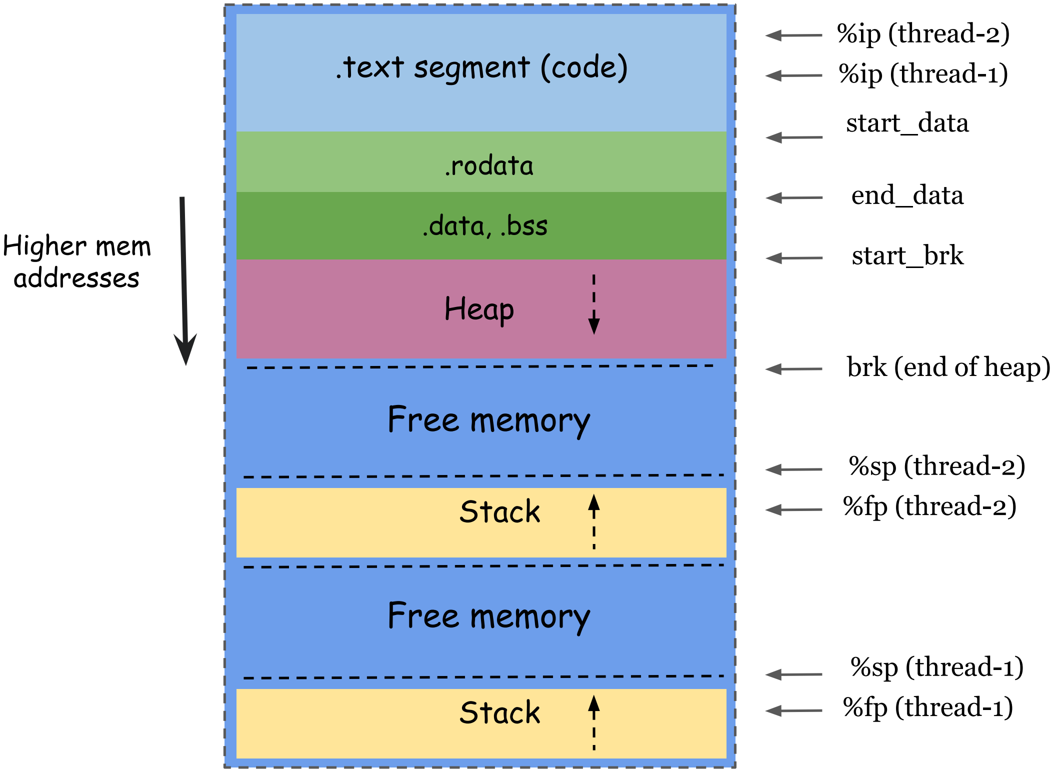
› **All threads of a process share**

- The code, data, and heap segments
- Shared system resources allocated to their process

Multithreaded process VAS



Multithreaded process VAS

```c
#define NUM_THREADS 3

void print_stack_pointer(int thread_id) {
   uint64_t sp;
   asm volatile ("mov %0, sp" : "=r" (sp));
   printf("[tid: %d]; sp: 0x%lx, &sp: %p\n",
           thread_id, sp, &sp);
}

void* foo(void* arg) {
   int thread_id = *(int*) arg;
   print_stack_pointer(thread_id);
   return NULL;
}

void main() {

   int thread_ids[NUM_THREADS];
   pthread_t threads[NUM_THREADS];

   for (int i = 0; i < NUM_THREADS; i++) {
      thread_ids[i] = i + 1;
      pthread_create(&threads[i], NULL, foo,
                     &thread_ids[i]);
   }

  for (int = 0; i < NUM_THREADS; i++) {
      pthread_join(threads[i], NULL);
   }
}
```

```
--- before threads creation ----
aaaab0510000-aaaab0512000 r-xp …      thread_vmas
aaaab0521000-aaaab0522000 r--p …      thread_vmas
aaaab0522000-aaaab0523000 rw-p …      thread_vmas
aaaad9392000-aaaad93b3000 rw-p …      [heap]
ffff8d080000-ffff8d208000 r-xp …      /usr/lib/libc.so.6
…
ffff8d27e000-ffff8d27f000 r-xp …      [vdso]
ffff8d27f000-ffff8d281000 r--p …      /usr/lib/ld-linux-aarch64.so.1
ffff8d281000-ffff8d283000 rw-p …      /usr/lib/ld-linux-aarch64.so.1
ffffd83b9000-ffffd83da000 rw-p …      [stack]

[tid: 0]; sp: 0xffffd83b91a0, &sp: 0xffffd83b91b0

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aaaad9392000-aaaad93b3000 rw-p …   [heap]
ffff8c060000-ffff8c070000 ---p ……
ffff8c070000-ffff8c870000 rw-p …
ffff8c870000-ffff8c880000 ---p …
ffff8c880000-ffff8d080000 rw-p …
ffff8d080000-ffff8d208000 r-xp …      /usr/lib/libc.so.6
…
ffff8d27e000-ffff8d27f000 r-xp …      [vdso]
ffff8d27f000-ffff8d281000 r--p …      /usr/lib/ld-linux-aarch64.so.1
ffff8d281000-ffff8d283000 rw-p …      /usr/lib/ld-linux-aarch64.so.1
ffffd83b9000-ffffd83da000 rw-p …      [stack]

[tid: 2]; sp: 0xffff8c86e810, &sp: 0xffff8c86e830
[tid: 1]; sp: 0xffff8d07e810, &sp: 0xffff8d07e830
```

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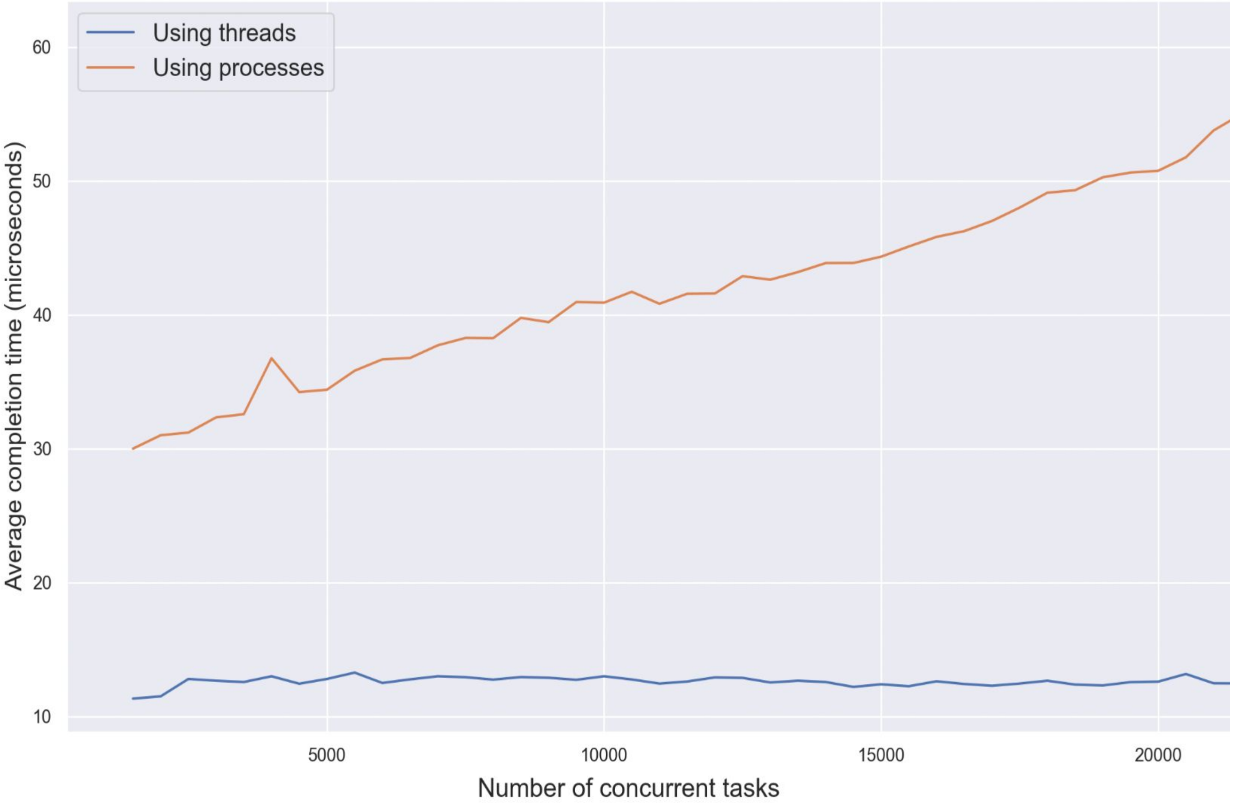
- New powers ⇒ New responsibilities...

Threads vs. Processes




```c
void process_task(int num){
  is_prime(num);
  _exit(0);
}

int main(int argc, char **argv) {
  ...
  for (int i = 0; i < num_tasks; i++)
     numbers[i] = rand() % 10000000;
  ...
  for (int i = 0; i < num_tasks; i++) {
     pid_t pid = fork();
     if (pid == 0)
         process_task(numbers[i]);
  }

  for (int i = 0; i < num_tasks; i++)
     wait(NULL);
}
```

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```
do {
  Get a process 𝒫 from ready queue
  Change to the new address space
    Execute 𝒫 until time 𝒬 expires
      Put 𝒫 back in ready queue
} while(1)
```

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```
do {
    Get a process P from ready queue
    Change to the new address space
    Execute P until time Q expires
    Put P back in ready queue
} while(1)
```

⇒

```
do {
    Get a thread T from ready queue
    Change address space, if needed
    Execute T until time Q expires
    Put T back in ready queue
} while(1)
```

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- There are various thread implementation models. At one end of the spectrum is the "library-thread model". In such a model, the threads of a process are not visible to the operating system kernel, and the threads are not kernel scheduled entities. The process is the only kernel scheduled entity. The process is scheduled onto the processor by the kernel according to the scheduling attributes of the process. The threads are scheduled onto the single kernel scheduled entity (the process) by the run-time library according to the scheduling attributes of the threads. A problem with this model is that it constrains concurrency. Since there is only one kernel scheduled entity (namely, the process), only one thread per process can execute at a time. If the thread that is executing blocks on I/O, then the whole process blocks.

-

- At the other end of the spectrum is the "kernel-thread model". In this model, all threads are visible to the operating system kernel. Thus, all threads are kernel scheduled entities, and all threads can concurrently execute. The threads are scheduled onto processors by the kernel according to the scheduling attributes of the threads. The drawback to this model is that the creation and management of the threads entails operating system calls, as opposed to subroutine calls, which makes kernel threads heavier weight than library threads.

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> User-level threads (Solaris "green" threads, java threads)

- Multiple threads are mapped to one schedulable kernel context
- No real concurrency: One thread blocks ⇒ All process' threads block
- The process is the only kernel scheduled entity
- Only one syscall per time ⇒ One kernel stack per process
- Faster to create (syscalls: ~70 cycles >> procedure calls: ~5 cycles)

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› kernel-level threads (e.g., glibc pthreads in Linux)
  - Slower to create and interact with (glibc uses clone3 syscall)
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Watch out: Kernel-level thread ≠ Kernel-space thread (kthread)

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Read the scheduler activations paper for more on a hybrid approach

Historical Evolution: From uniprogramming to multitasking

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  - Simple idea: The OS is just a library of device drivers for primitive hardware resources
  - OK idea for the 70's mainframes
    - Resource underutilization: one job blocks, everyone waits
    - > Leads to bad throughput: job completion per unit of time

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> Violates one of the three OS desirable properties [Q: Which?]

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    - The OS takes control ⇒ Inspects execution statistics
    - Decides where to allocate the processor next

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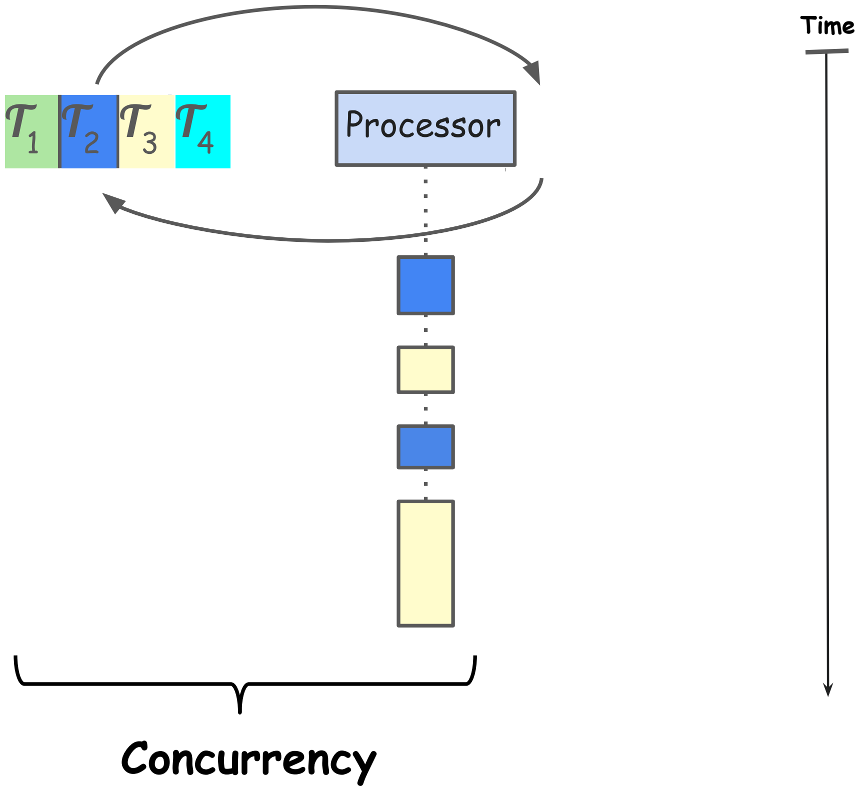
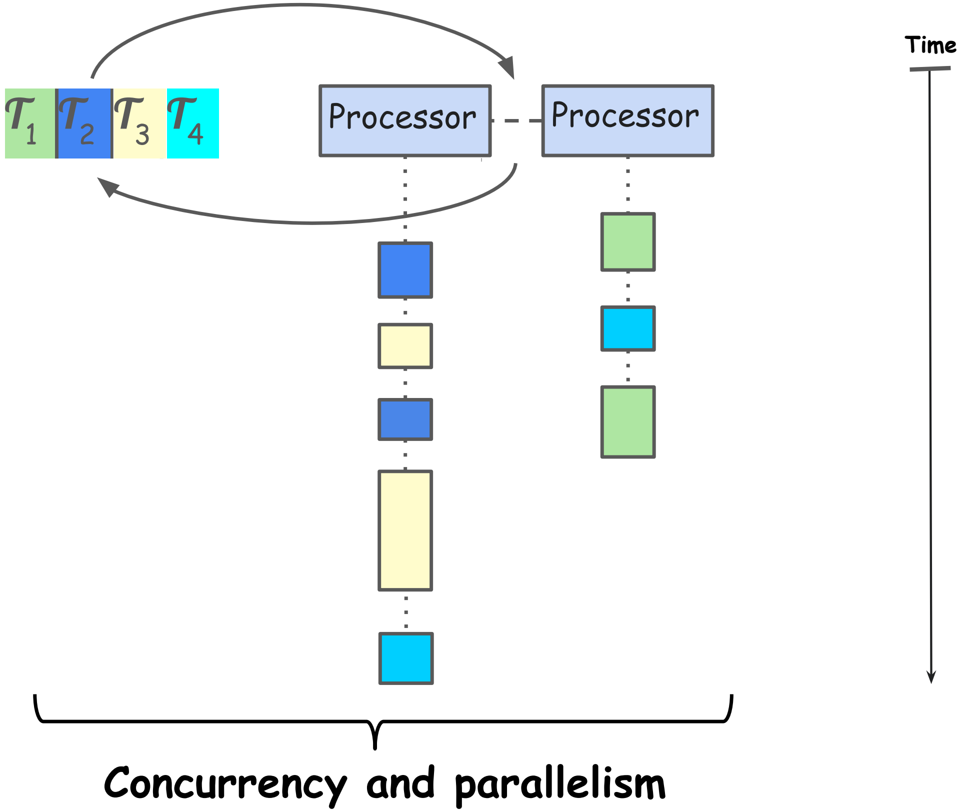
> Improves system responsiveness ⇒ Immediate feedback to users

Multitasking on one processor



Multitasking on Symmetric Multiprocessor (SMP)



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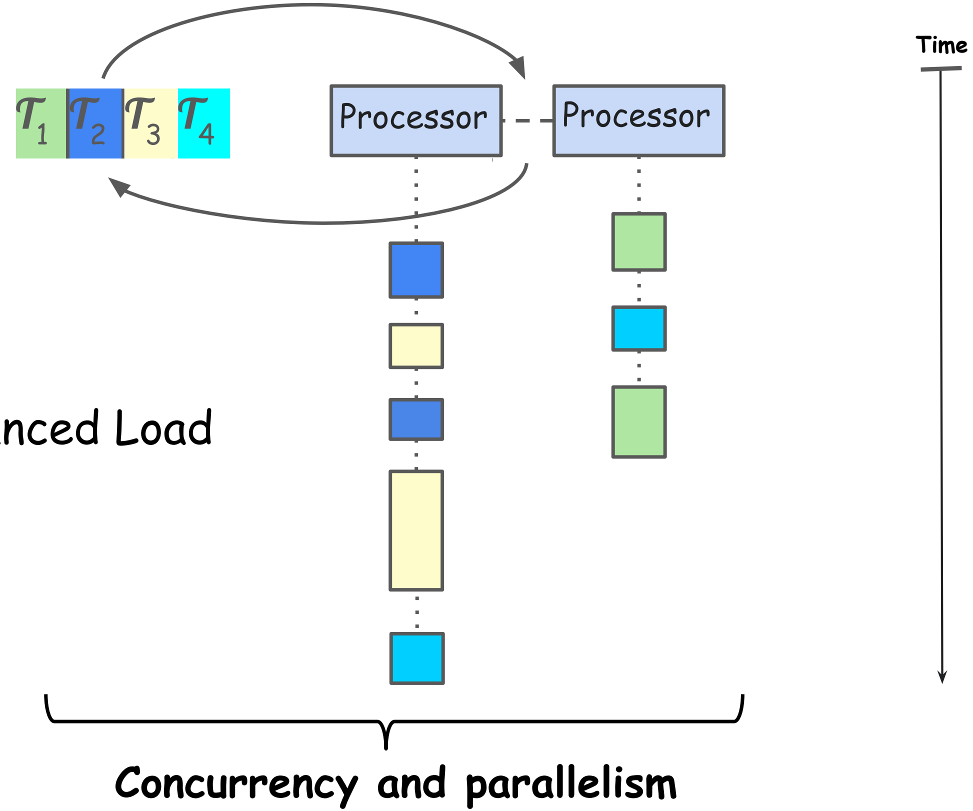
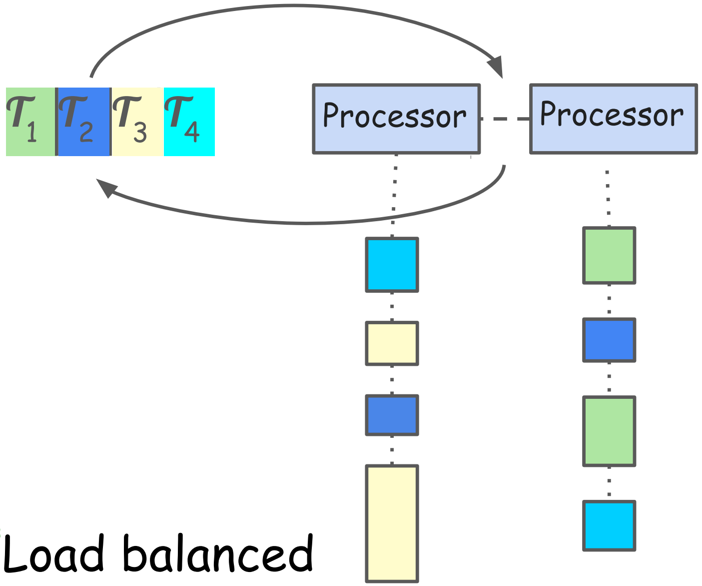


✗ Unbalanced Load

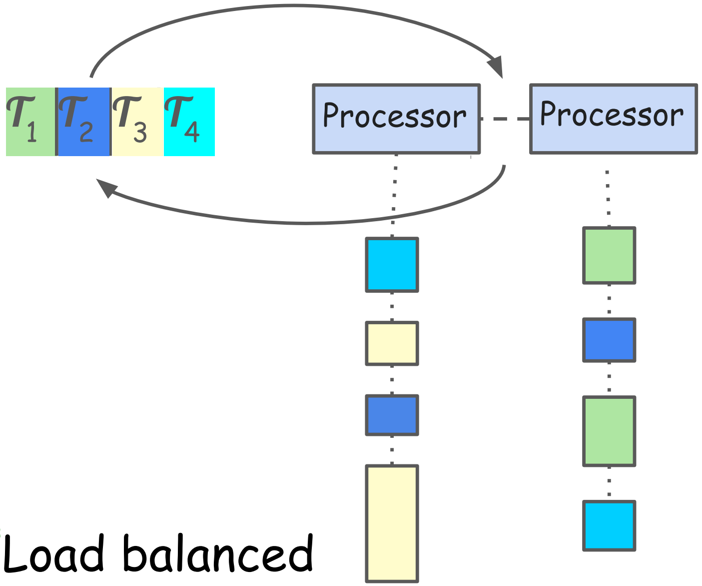
Multitasking on SMP and load balancing



✔Load balanced

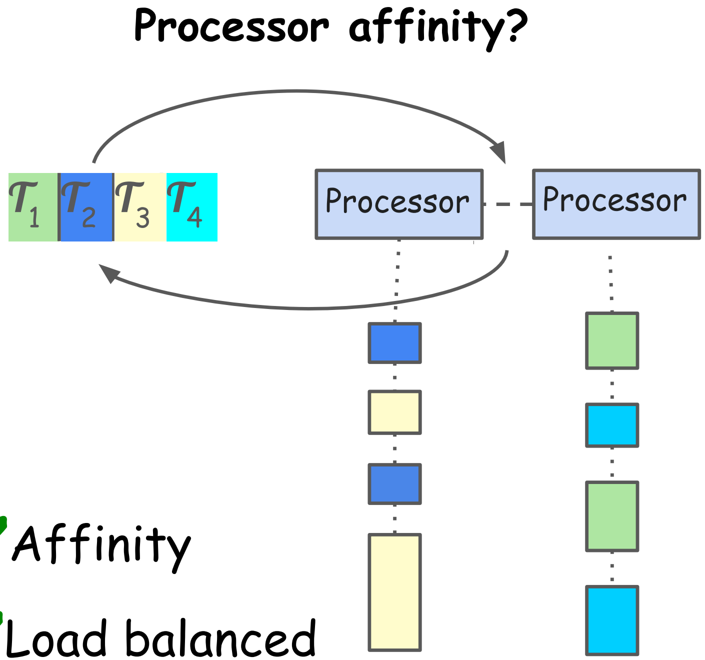
Multitasking on SMP and load balancing

Processor affinity?



✔Load balanced

Multitasking on SMP and load balancing w/ affinity



✔Affinity

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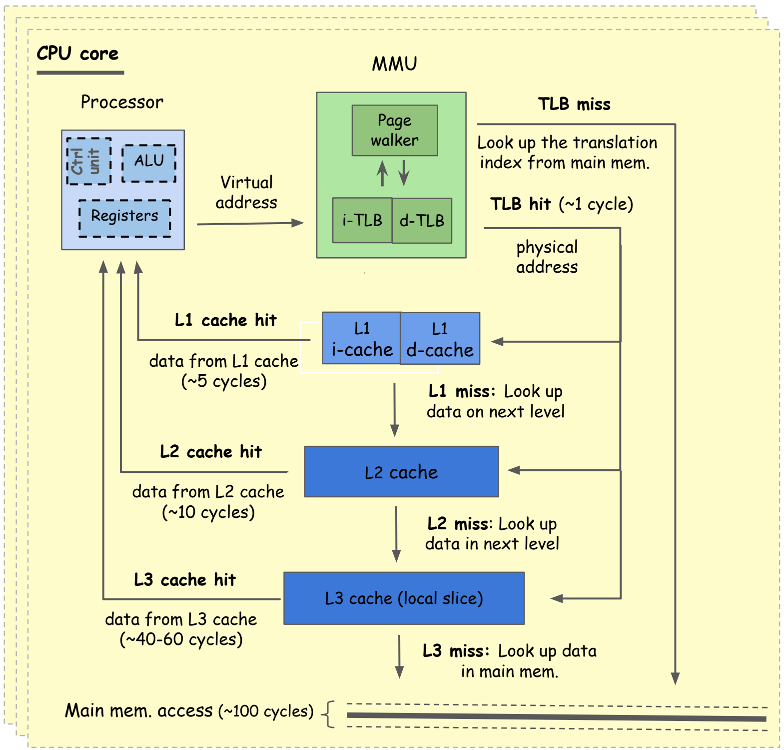

Concurrency

- Concurrency: Multiple tasks (i.e., execution contexts: processes or threads) run seemingly simultaneously on shared hardware resources
- Time-sharing, preemptive scheduling: Tasks run for at most a time quantum, and either yield the processor (voluntarily ctx switch) or get preempted by the OS (involuntarily ctx switch)
- Small quantum (10-100 ms) + SMP ⇒ Tasks execute multiple times per sec and appear responsive to their users (akin to running simultaneously)

Concurrency

> Concurrency is **the** desirable execution paradigm ♡

- Responsiveness: No task stays blocked for perceptibly long
- Throughput: No single task can monopolize the processor ⇒ Allowing, overall, more tasks to execute (and potentially complete) in a unit of time
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- Programmer's responsibilities:
  - Divide and conquer: Split code in small routines of independent tasks
  - Avoid shared state ⇒ Avoid coordination / locks