CS4410

Operating Systems

Lecture 2: Four fundamental OS concepts

Rachit Agarwal

Context for today's lecture

- One of the harder lectures
  - A lot of new "terminology"
  - Little connection on what you have seen in the past: applications
  - You may feel lost
  - It is okay ….

- We will discuss some of the building blocks of an OS
  - We will cover them in much more detail in upcoming lectures
  - **Today: understand "why" we need these building blocks**
  - And what are the **conceptual challenges in designing them**

Goal of Today's Lecture

- Wrap up discussion from the last lecture
  - Now I know we finish at 4 PM :-)
  - My teaching style, and caveats
- **Four fundamental OS concepts**
- **Some announcements**

Last lecture: 8 basic questions

1. **What is an "operating system", and what does it do?**
2. Why study operating systems?
3. **What is CS4410 about?**
4. What is the course workload, grading policies, etc.?
5. How will this course be organized?
6. **Who am I?**
7. **How do I teach?**
8. Is CS4410 the right class for you?

Recall: What is an operating system, and what does it do?

A **software layer** designed with three goals:

- Enable applications to **conveniently access hardware**
- **Manage** all hardware resources
- **Implement common services** for applications

Recall: What does an OS do?

- Enables **convenient "abstractions"** for applications to access hardware
  - **CPU:** threads
  - **Memory:** virtual memory
  - **Storage devices:** files
  - **Network:** sockets
  - **Server:** collection of resources needed by an application (processes, VM,..)
- **Manages** hardware resources
  - Resource **allocation, sharing and isolation**
- Implements **common services** for applications
  - Security, protection and authentication
  - Reliability
  - Communication
  - Input/output operations
  - Program execution
  - ….

Recall: What is this course about?

Architectural principles, design goals and performance objectives in OS

- **<u>How to think</u> about abstractions offered by OSes?**
  - What abstractions should an OS offer, and why?
  - What should be the semantics (correctness conditions)?

- **<u>How to think</u> about performing resource management in OSes?**
  - What should applications know about other applications?
  - How to share resources? How to ensure isolation?
  - Why statistical multiplexing?

- **<u>How to think</u> about the common services in OSes?**
  - What constitutes a "common service"?
  - How to achieve commonality?

#6: Who am I?

Instructor — Rachit Agarwal

- **Assistant Professor, starting Fall 2016**
- **Previously**: UC Berkeley, UIUC
- **Office:** 411c, Gates Hall
- **Proud of: my students**
  - PhD students (Saksham, Qizhe, **Midhul, Abhishek, Shubham**)
  - Postdocs (Jaehyun, Mina)
  - Undergrad researchers (Grace Jia, Melissa Genaldi)
  - Graduated 5 students so far
    - 4x undergrads
      - 3x now PhD students at MIT (Alana, Akshay, Yannan)
      - 1x now PhD student at UC Berkeley (Lloyd Brown)
    - 1x MS—now PhD student at CMU

Instructor — Rachit Agarwal

- **Research interests**: **problems that excite me**
    - Publish in top conferences of several areas:
        - **Operating systems (OSDI)**
        - **Networking (NSDI, SIGCOMM)**
        - **Databases (SIGMOD)**
        - **Theory (SODA)**
        - **Information Theory (ISIT)**
    - **Diversity reflects my learning and teaching style!**
    - Competitive advantage: ignorance (and curiosity)!

- **Non-research interests:**
    - Food: Chocolate
    - Activity: Flying planes (still training; rarely get time)
    - Skill: Mixing cocktails
    - Sleep: 2-3 hours (so, expect Ed Discussions answers at random hours)

#8: Is 4410 the right course for you?

Ask yourself…

- **Agree with the contract?**
    - No violation to the agreement

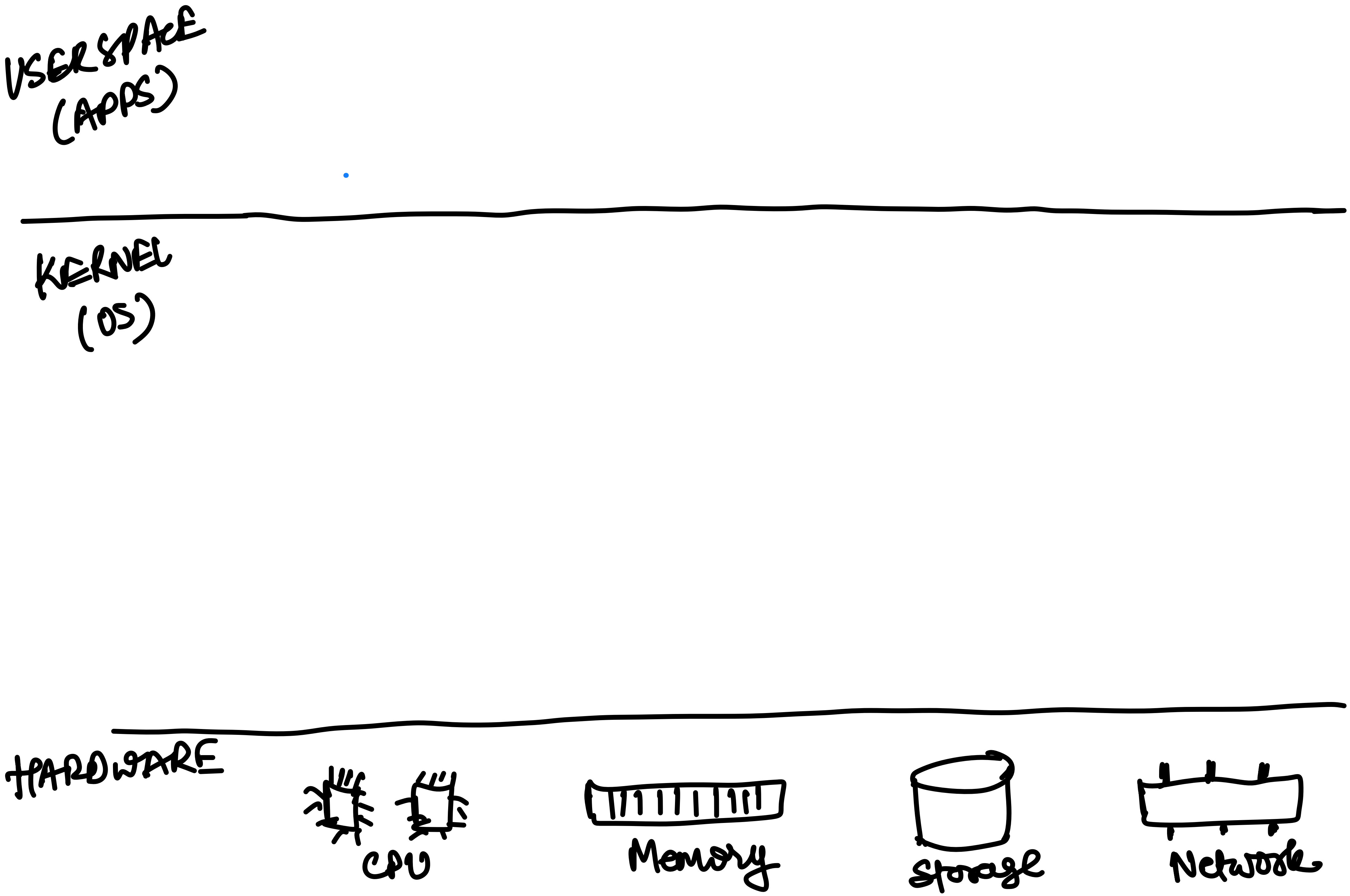
- **Want to understand the “concepts” and the “why” of OS**
    - **4411:** Implementation details
    - **4414:** optimizations and building high-performance application

Questions?

Diving one level deeper

Today: Four Fundamental OS Concepts

- **Thread: Execution Context**
  - A single, sequential execution context
- **Address space** (with **translation**)
  - Program's view of memory is distinct from physical memory
- **Process: an instance of a running program**
  - Address Space + One or more Threads + …
- **Protection/Isolation**
  - Only the “system” can access certain resources
  - Combined with translation, isolates programs from each other


USERSPACE
(APPS)
KERNEL
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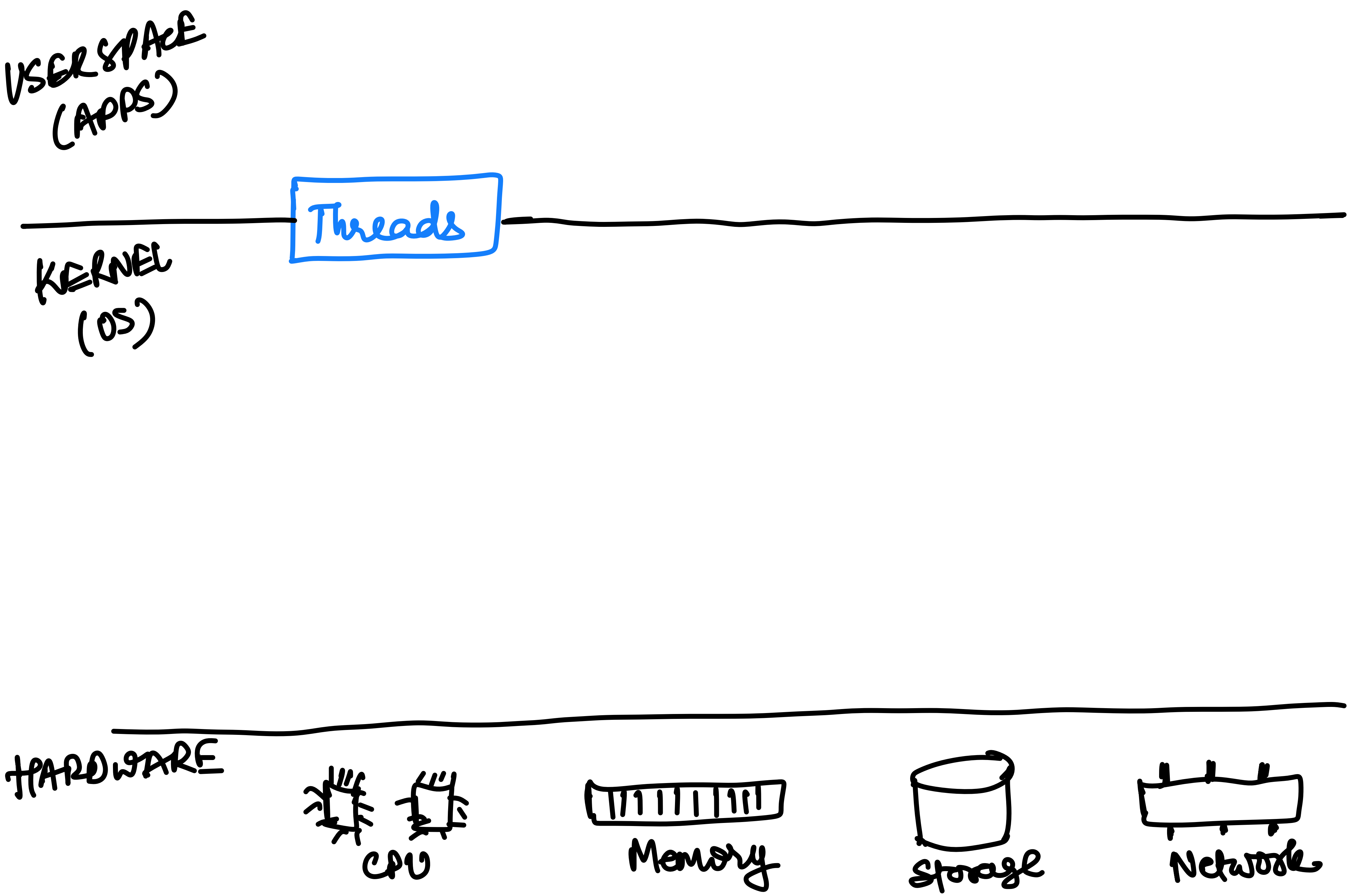
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Thread

- **Definition: A single, sequential *execution context***
  - Executes a series of instructions in order
  - Only one thing happens at a time
- **Executes** on a processor (core) when resident in that processor's registers
- **Each thread has some "state"**
  - *Program counter (PC):* progress of thread's instruction sequence execution
  - *Thread stack:* reserved region of memory
  - *Stack pointer (SP):* location of last item put onto the stack
  - …. (details in next lecture)
- **Where is thread state stored?**
  - Registers of the processor where thread is running (PC, SP, ..)
  - The rest is "in memory" (*Thread Control Block*)
  - What if there is not enough memory?

Thread

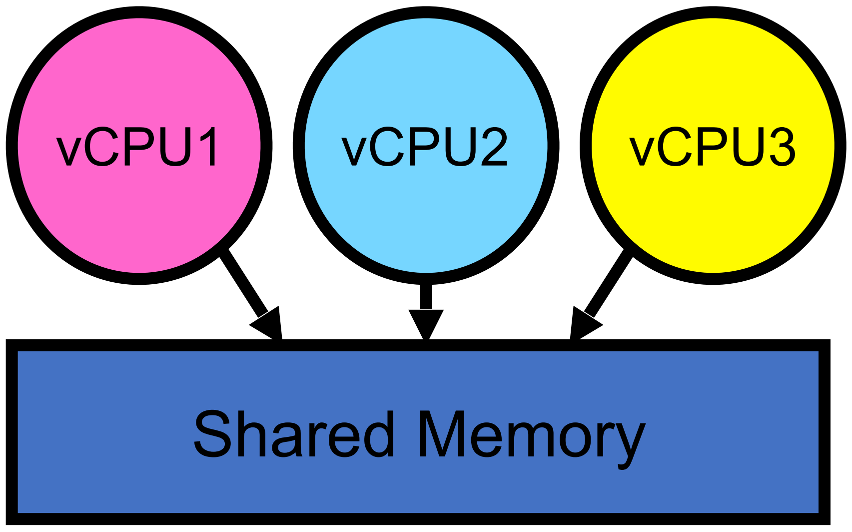
- **What is the difference between a thread and a core?**
  - Thread: “virtual” core
- **Why do we need virtual cores?**
  - In early years: single application, single thread
    - Multiplex over long timescales
    - Problem?
    - Resource underutilization (why? when?)
  - *Statistical multiplexing:* multiple applications, multiple threads
    - When one thread is idle, run another thread
- As an aside, many modern processors support **hyperthreading:**
  - Each physical core behaves as if it is actually two cores
  - Can run two threads simultaneously
  - E.g., execute one thread while the other is waiting on a cache miss

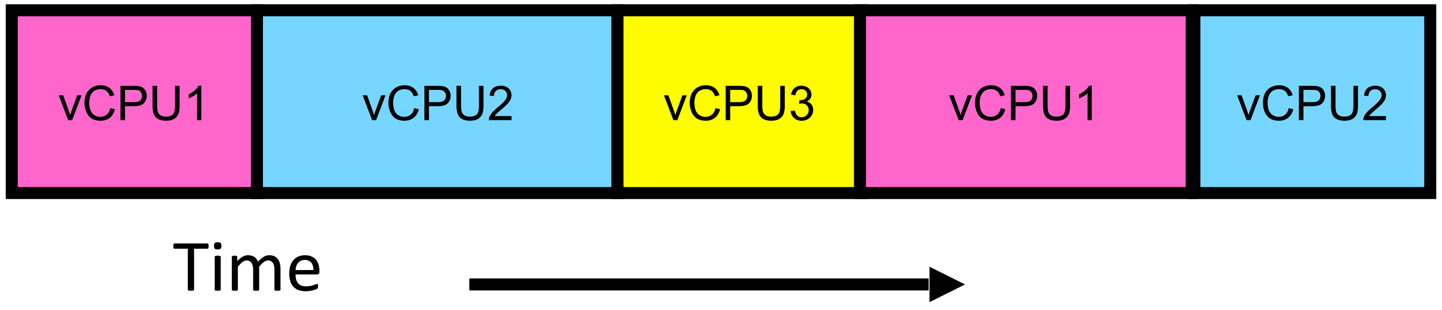
Challenges in designing virtual cores?

- **Scheduling**
    - Sharing physical resources across virtual cores

- **Synchronization**
    - Correctness despite multiple virtual cores

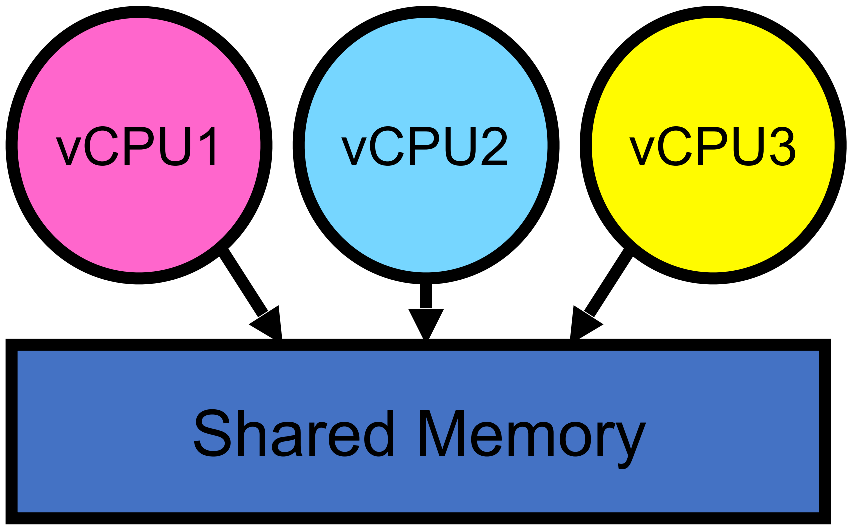
Threads give an illusion of multiple processors

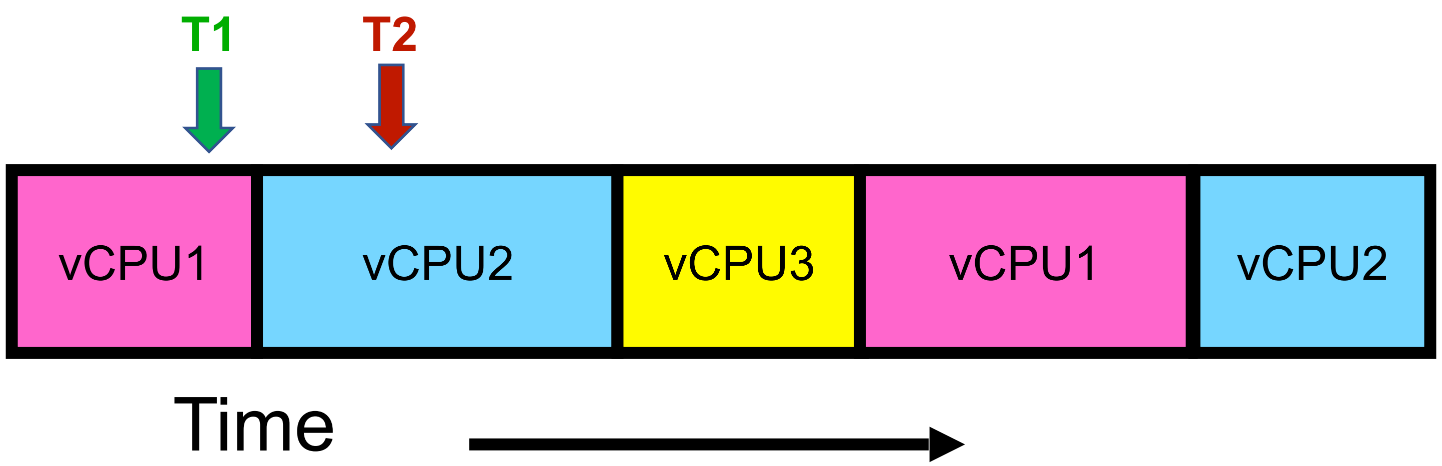




- Each thread has its own state
    - Program counter (PC)
    - Stack pointer (SP)
    - Thread control block (TCB)
        - Everything not in registers

Threads give an illusion of multiple processors





- **At T1:** vCPU1 on real core, vCPU2 in memory
- **At T2:** vCPU2 on real core, vCPU1 in memory
- What does the OS do at the end of T1?
  - Saved PC, SP, … in vCPU1's thread control block (memory)
  - Loaded PC, SP, … from vCPU2's thread control block
    - Jumped to PC

Questions?

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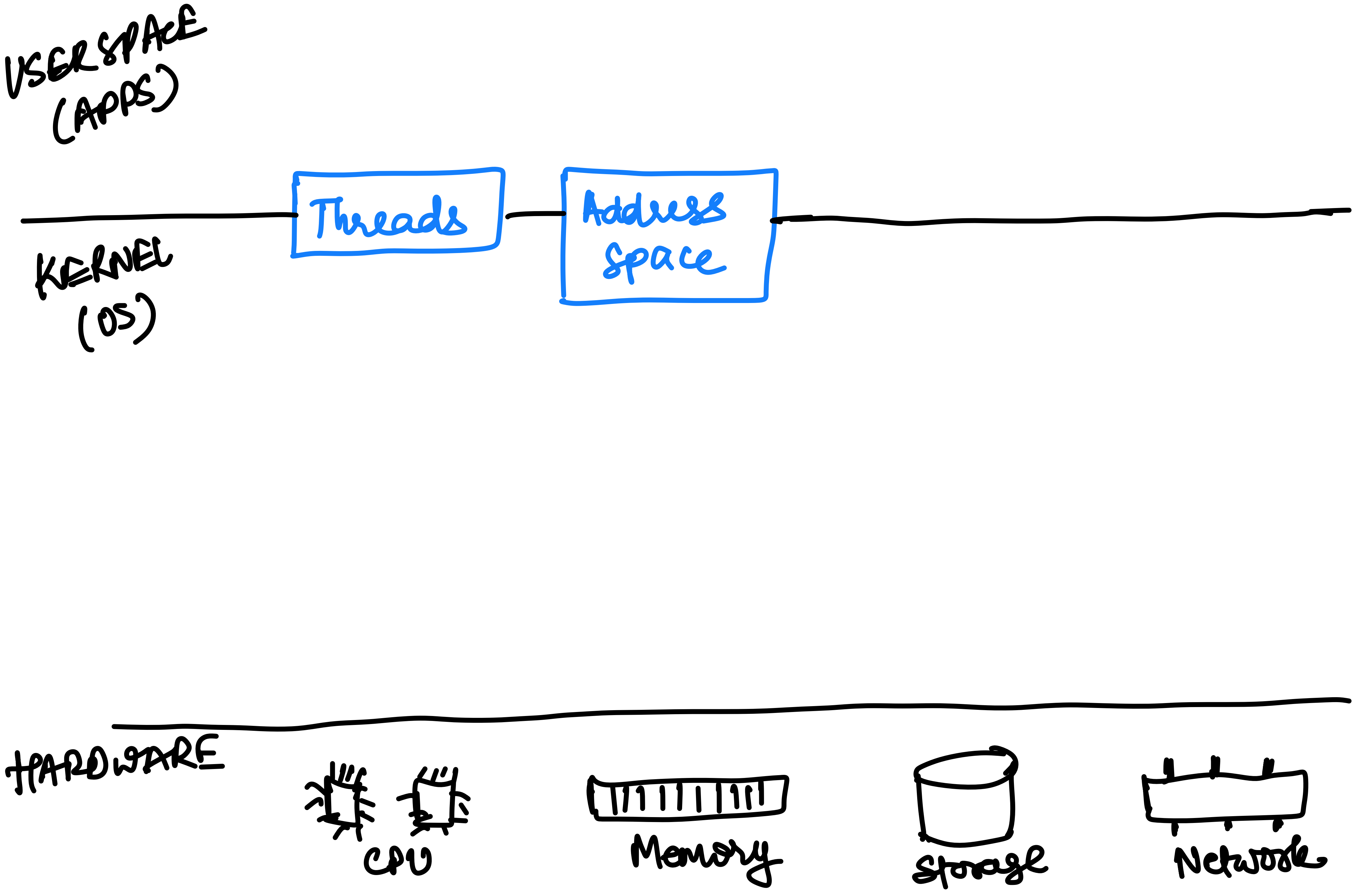
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Key OS Concept: Address Space

- **Physical** address space: where the data *actually* resides
- "**Virtual**" address space: where the program *thinks* the data resides
- Definition: **Set of accessible addresses and the state associated with them**
    - 2^{32} = ~4 Gigabytes on a 32-bit machine
    - 2^{64} = ~18 Exabytes on a 64-bit machine

Virtual address space

- **Why do we need a virtual address space?**
  - In early years: single application over long timescales
  - Now: multiple applications at the same time
    - How do we share memory across applications?
- One possible approach: **static partitioning of the physical address space**
  - Any physical address can be used only by one application
    - Problem?
    - Memory underutilization (why? when?)
- *Statistical multiplexing:* fine-grained sharing of physical address space
  - Give each application an illusion of infinitely large memory

Challenges in designing Virtual address space

- **Granularity**
    - Individual addresses?
    - Memory regions?
    - ….?

- ***Efficient* translation from virtual to physical?**
    - Why *efficient*?

Virtual Address Space at the "page" granularity

- Sharing at the granularity of "pages"
- Treat memory as page size frames and put any page into any frame
- Map each page in virtual address space to any (page-sized) memory frame
  - What if virtual address space is larger than physical memory?
  - Interesting design questions; return later
- Whenever one needs to access a virtual address
  - Find the page (and offset) that contains that virtual address
  - Translate to page's physical address
  - **Done by the hardware: using a look up table (page table)**
- **Where is the "efficient" part?**

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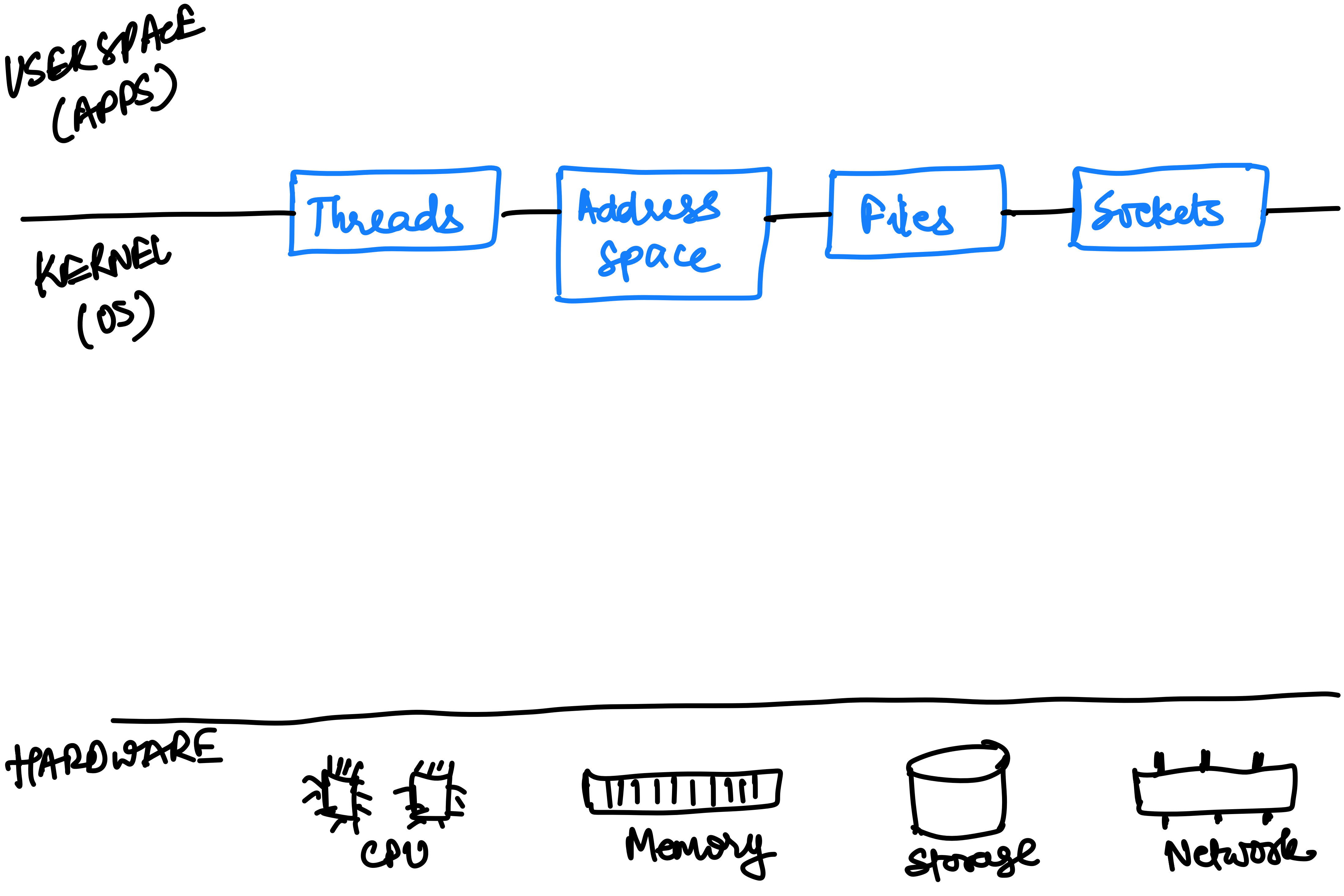
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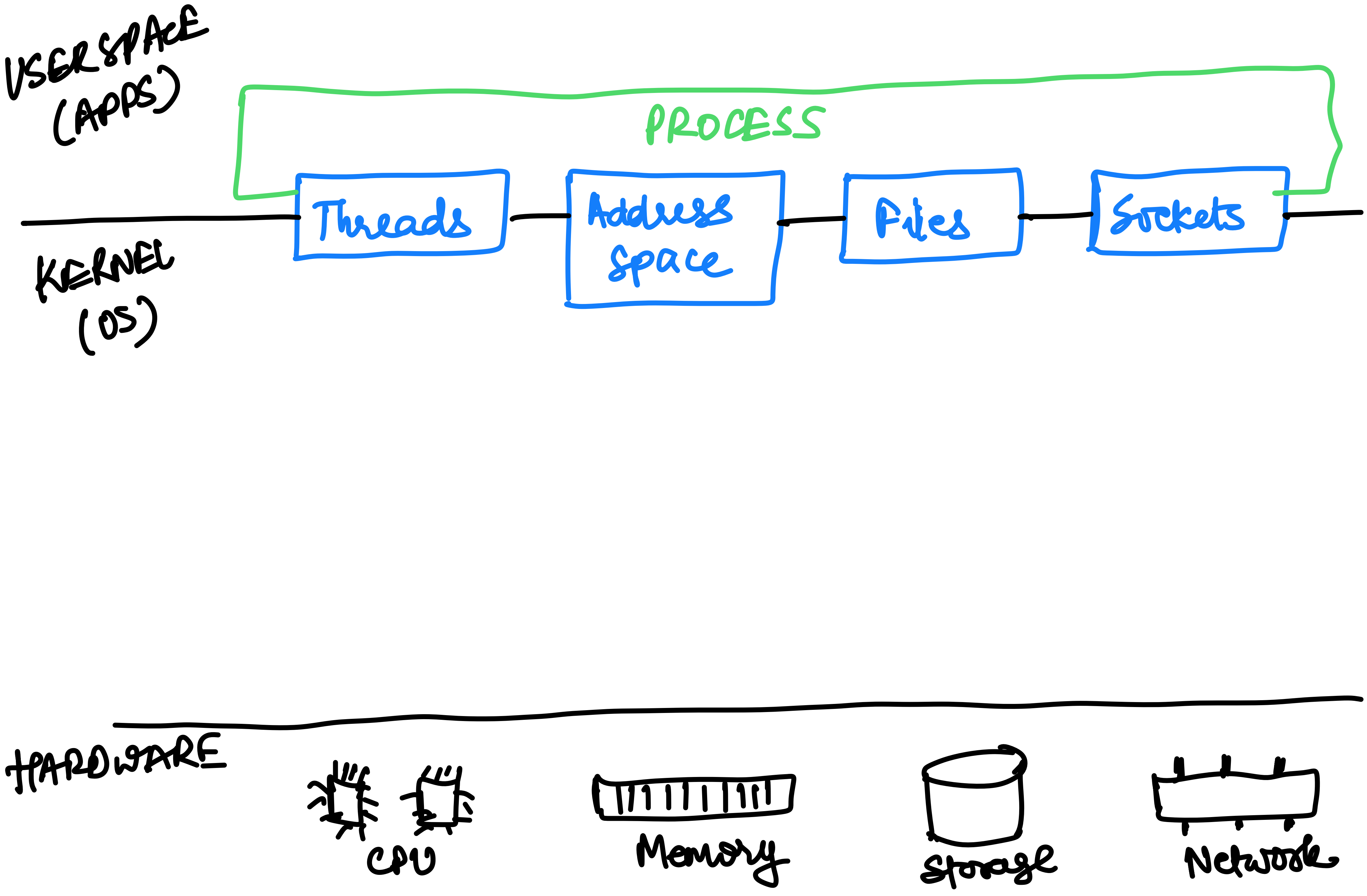
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Process

- **Definition: execution environment with restricted rights**
  - One or more threads
  - Execution state: everything that can affect, or be affected by, a thread
    - Code, data, registers, call stack, files, sockets, etc.
  - Part of the process state is “owned” by individual threads
  - Part is shared among all threads in the process

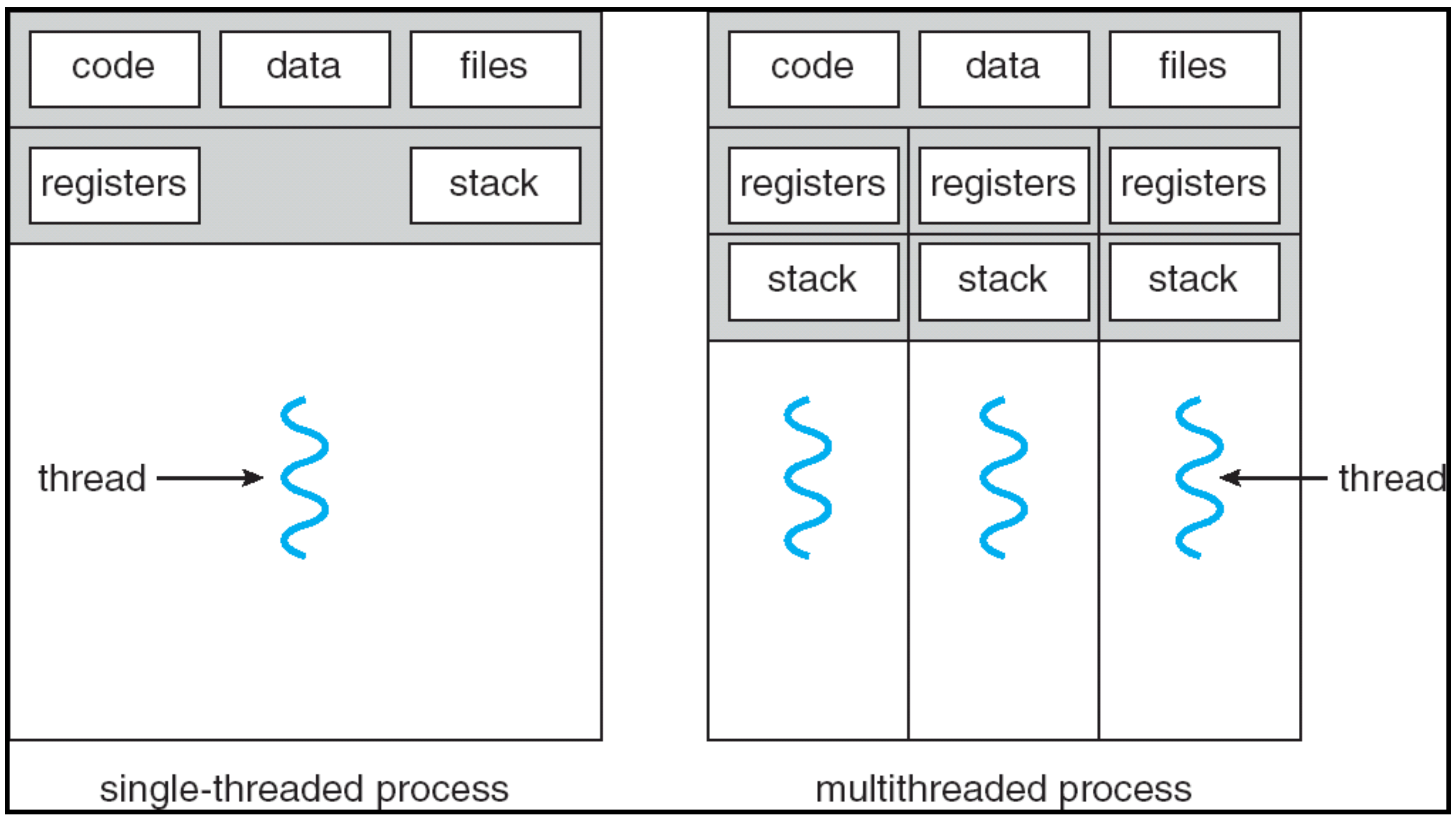
- **Each process has a “state”—Process control block (PCB)**
  - Execution state for each thread
  - Scheduling information
  - Information about memory used by the process
  - Information about files, sockets, etc.
  - ….

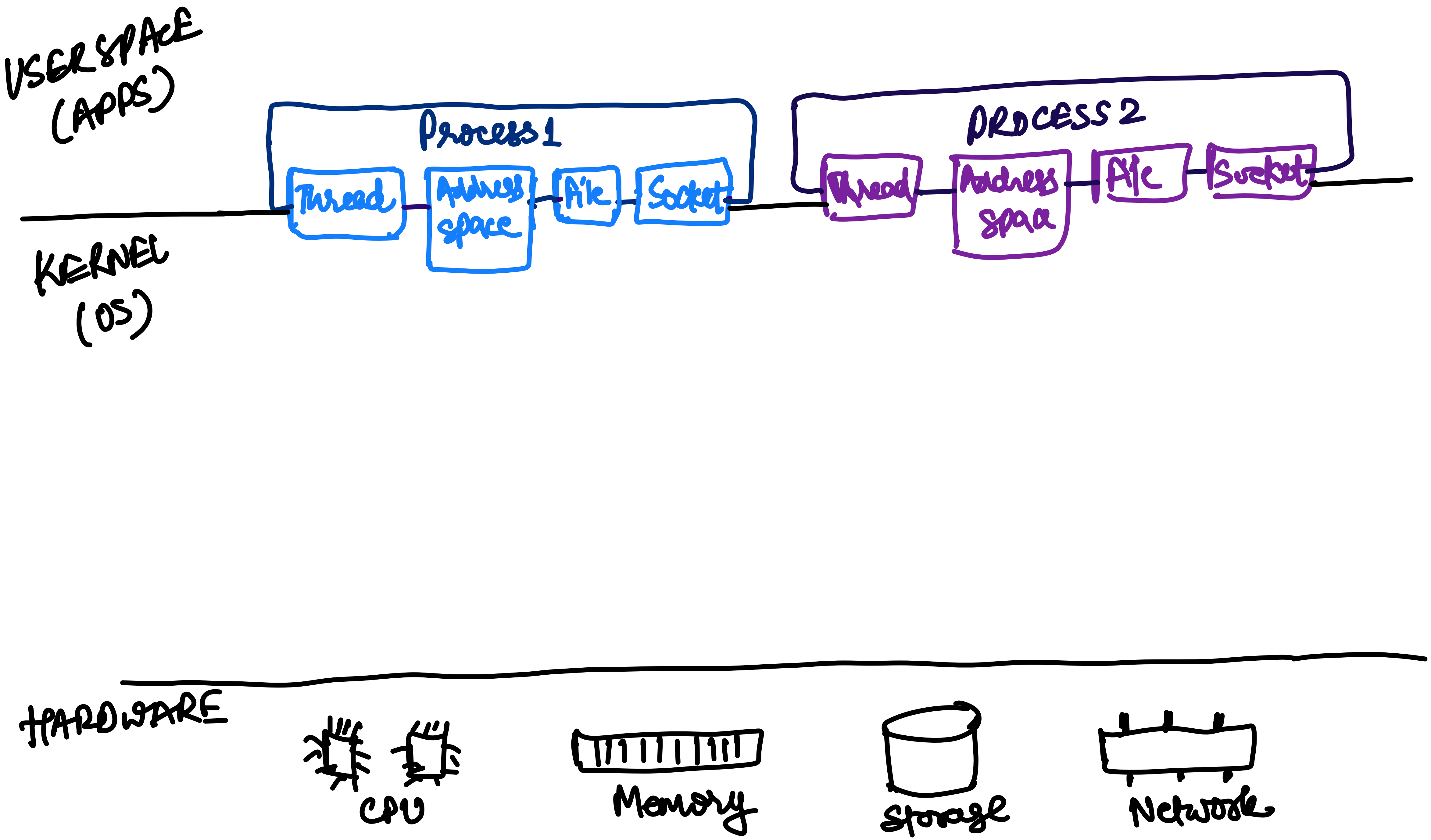
Evolution of OS process model

- **Early operating systems: single tasking**
    - Single process, single thread
    - “switch” applications over long timescales
    - Problem?
- **Late 1970s: multitasking**
    - Multiple processes, single thread per process
    - Share resources across processes
    - Problem?
- **1990s: multitasking, multithreading**
    - Multiple processes, multiple threads
    - Challenges?

Single and Multithreaded Processes

- Why have multiple threads within the same process?
- Threads encapsulate concurrency

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Process 1
Thread
Address space
File
Socket
PROCESS 2
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The core challenge with multiple processes?

- Protection/Isolation/Sharing
    - **Reliability:** buggy processes can only hurt themselves
    - **Security:** a process does not have to trust other processes
    - **Fairness:** a good granularity to enforce fair utilization of resources

Questions?

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- **Mechanisms to enable isolation:**
  - **Virtualization**
    - Virtual cores, virtual address space (in particular)
  - **Dual mode operations**
    - Only the OS can access certain resources