Distributed Systems

Processes and Threads in Distributed Systems

WEEK 3: Processes, Threads, Multithreading, Concurrency, Process Management.

Online Lecture Series - 3

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Course Outline

Topics We Will Cover

- **Threads** — Basics & Distributed Use
- **Virtualization** — Principles, Containers, VMs vs. Containers, Applications
- **Clients** — Interfaces, Virtual Desktops, Transparency Tools
- **Servers** — Design Issues, Object Servers, Apache, Clusters
- **Code Migration** — Why, Models, Heterogeneous Systems
- **Summary & Next Steps**

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Processes in Distributed Systems

Overview: Role of Processes

- **Processes** — Fundamental units in distributed systems
  - Program in execution (from OS perspective)
  - OS focuses on management scheduling
  - Distributed systems add concerns for performance structure
- **Threads** — Enhancing system efficiency
  - Structure clients and servers
  - Improve performance on multicore/multiprocessor systems
  - Sometimes replaced by processes for protection communication

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Introduction to Threads

What is a Process?

- A **process**:- program in execution
- OS creates virtual processors to run programs
- Process context stores:
  - CPU registers (program counter, stack pointer)
  - Memory maps
  - Open files, privileges, and accounting info
- Provides **concurrency transparency** between processes

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Introduction to Threads

Thread vs Process

- A **thread** executes a piece of code independently
- Thread context contains minimal info for CPU sharing
- Threads do not enforce strict concurrency protection
- Implications:
  - Often improves performance (multithreading)
  - Requires careful design to avoid data issues

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Multithreading for Parallelism

Key Points

- Threads can run on separate CPUs/cores
- Shared data stored in main memory
- Transparent performance: works on uniprocessor systems too
- Increasingly important due to cheap multicore systems
- Applications: Servers, client-server apps, smartphones

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Contexts in Multithreading

Understanding Contexts

- **Processor Context** — Minimal info stored in CPU registers
  - Includes program counter, stack pointer, addressing registers
  - Required to resume execution after an interrupt
- **Thread Context** — Adds thread-specific info
  - Contains processor context plus thread state
  - Enables CPU sharing among multiple threads
- **Process Context** — Full context for a process
  - Includes thread context and additional OS info
  - May include Memory Management Unit (MMU) registers
  - Supports isolation between processes

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Why Use Threads

Key Benefits of Threads

- **Avoid needless blocking**
  - In single-threaded processes, I/O operations block the entire process
  - Multithreading allows the OS to switch the CPU to another thread
- **Exploit parallelism**
  - Threads can run simultaneously on multiple cores or processors
  - Improves performance in multicore/multiprocessor systems
- **Avoid costly process switching**
  - Using threads in large applications lowers overhead and boosts responsiveness.

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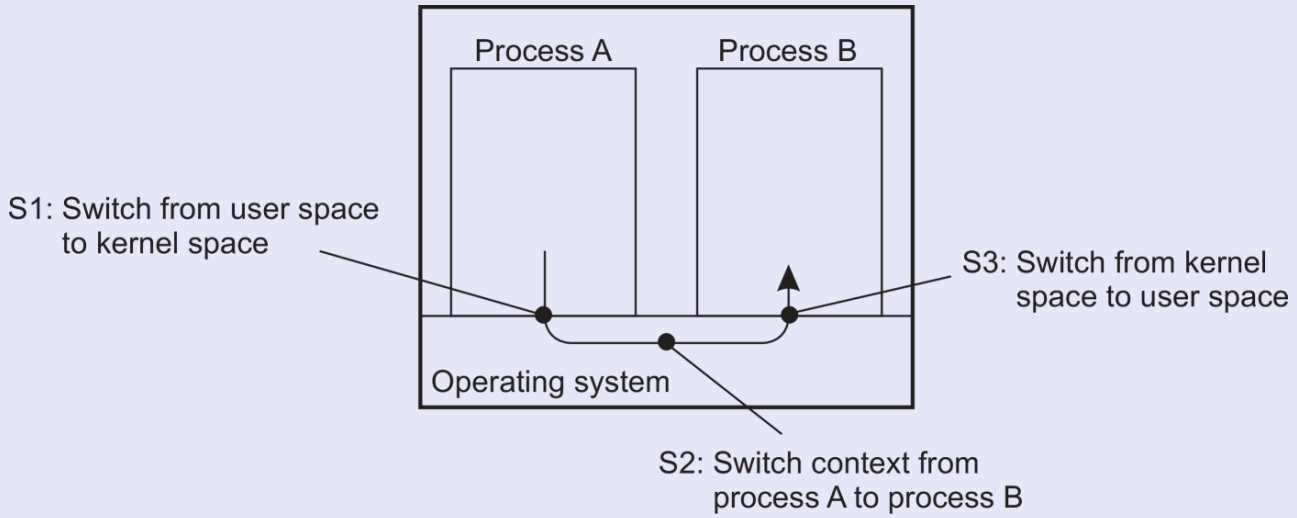
Avoid process switching

Avoid expensive context switching



M. van Steen and A. S. Tanenbaum, *Distributed Systems*, 4th ed., 2024.

Advanced Topic: Cost of Context Switch

Measuring Context Switch Overhead

- Context switches incur performance costs, studied extensively.
- Clock handlers (interrupts) are often used to measure overhead.
- Typical clock intervals: 0.5–20 ms (50–2000 Hz).
- Clock handlers assist in:
  - Timing and CPU usage tracking
  - Alarm signals
  - Preempting tasks for fair CPU sharing

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Advanced Topic: Cost of Context Switch

Direct vs Indirect Overhead

- **Direct overhead**: Time for actual context switch + handler execution
- **Indirect overhead**: Mainly due to cache perturbations
- Intel processors:
  - Context switch: 0.5–1 s
  - Handler execution: 0.5–7 s (implementation dependent)
- Indirect overhead can be much larger (e.g., 80

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Cache Effects of Context Switches

Impact on Performance

- Interrupts can reorganize the cache significantly
- Example: Least Recently Used (LRU) cache block may be evicted
- Accessing evicted blocks reloads them into cache, evicting others
- Even simple interrupts can cause long-lasting cache reorganization
- Overall effect: noticeable performance degradation

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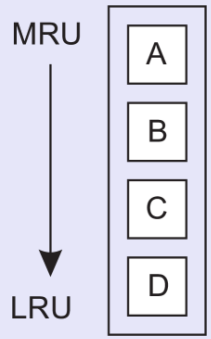
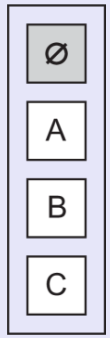
Context Switch and Cache Effects

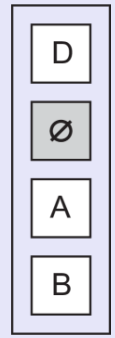
Context Switch



Cache Before Switch



Cache After Switch



M. van Steen and A. S. Tanenbaum, *Distributed Systems*, 4th ed., 2024.

Multiprocessing Example — Highlighted

Python Code

```
1 from multiprocessing import Process
2 from time import gmtime, sleep
3 from random import randint
4 def sleeper(name):
5     t = gmtime()
6     s = randint(1, 20)
7     txt = f"{t.tm_min}:{t.tm_sec} {name} sleeping {s}
8     print(txt)
9     sleep(s)
```

Multiprocessing Example — Part 2

Python Code

```
1       t = gmtime()
2       txt = f"{t.tm_min}:{t.tm_sec} {name} woke up"
3       print(txt)
4
5   if __name__ == "__main__":
6       p = Process(target=sleeper, args=("eve",))
7       q = Process(target=sleeper, args=("bob",))
8       p.start(); q.start()
9       p.join(); q.join()
```

Sample Output

Execution Output

```
40:23 eve is going to sleep for 14 sec
40:23 bob is going to sleep for 4 sec
40:27 bob has woken up
40:37 eve has woken up
```

Multithreading + Multiprocessing Example — Part 1

Python Code — Setup Sleeping Function

```
1 from multiprocessing import Process
2 from threading import Thread
3 from time import sleep
4 from random import randint
5 shared_x = randint(10, 99)
6 def sleeping(name):
7     global shared_x
8     s = randint(1, 20)
```

Multithreading + Multiprocessing Example — Part 2

Python Code — Thread Creation Execution

```
    sleep(s)
    shared_x += 1
def sleeper(name):
    sleeplist = list()
    for i in range(3):
        subsleeper = Thread(target=sleeping, args=(f{nam
        sleeplist.append(subsleeper)
    for s in sleeplist: s.start()
    for s in sleeplist: s.join()
```

Multithreading + Multiprocessing — Sample Output (Part 1)

Execution Output — Part 1

```
eve sees shared x being 71
53:21 eve 0 is going to sleep for 20 seconds
bob sees shared x being 84
53:21 eve 1 is going to sleep for 15 seconds
53:21 eve 2 is going to sleep for 3 seconds
53:21 bob 0 is going to sleep for 8 seconds
53:21 bob 1 is going to sleep for 16 seconds
53:21 bob 2 is going to sleep for 8 seconds
```

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Multithreading + Multiprocessing — Sample Output (Part 2)

Execution Output — Part 2

```
53:24 eve 2 has woken up, seeing shared x being 72
53:29 bob 0 has woken up, seeing shared x being 85
53:29 bob 2 has woken up, seeing shared x being 86
53:36 eve 1 has woken up, seeing shared x being 73
53:37 bob 1 has woken up, seeing shared x being 87
bob sees shared x being 87
53:41 eve 0 has woken up, seeing shared x being 74
eve sees shared x being 74
```

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Thread Implementation Approaches

User-Level vs Kernel-Level Threads

- **User-Level Threads**
  - Cheap to create and destroy (memory allocation only)
  - Fast context switching (CPU registers only)
  - Blocking system calls block the entire process
- **Kernel-Level Threads (One-to-One Model)**
  - Each thread is a schedulable entity
  - Operations handled by kernel system calls
  - Thread context switch can be as expensive as process context switch

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Many-to-Many Threading Model — Concept

Hybrid User-Level Kernel-Level Threads

- **Overview:**
  - Each kernel thread can run multiple user threads
  - User threads managed entirely in user space
  - Scheduler routine selects the next runnable user thread
- **Thread Table:**
  - Shared among kernel threads
  - Mutexes ensure mutually exclusive access

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Many-to-Many Threading Model — Execution

Execution Flow Context Switching

- **Kernel Threads:**
  - Each executes its own scheduler
  - Finds a runnable user thread
  - Context switch for user threads done entirely in user space
- **Handling Blocking System Calls:**
  - Kernel thread switches from user mode to kernel mode
  - Other kernel threads may continue executing
  - Process-level execution is not blocked

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Many-to-Many Threading Model — Advantages

Benefits of Using Many-to-Many Model

- Efficient creation, destruction, and synchronization of threads
- Blocking calls in one user thread do not suspend the entire process
- Application sees only user threads, kernel threads hidden
- Multiprocessing support: kernel threads can run on different CPUs/cores

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Many-to-Many Threading Model — Implementations

Example Implementations

- Go programming language — combines user kernel threads
- Libfibre runtime system — exemplary many-to-many threading
- Arachne — kernel threads hidden, supports core allocation visibility

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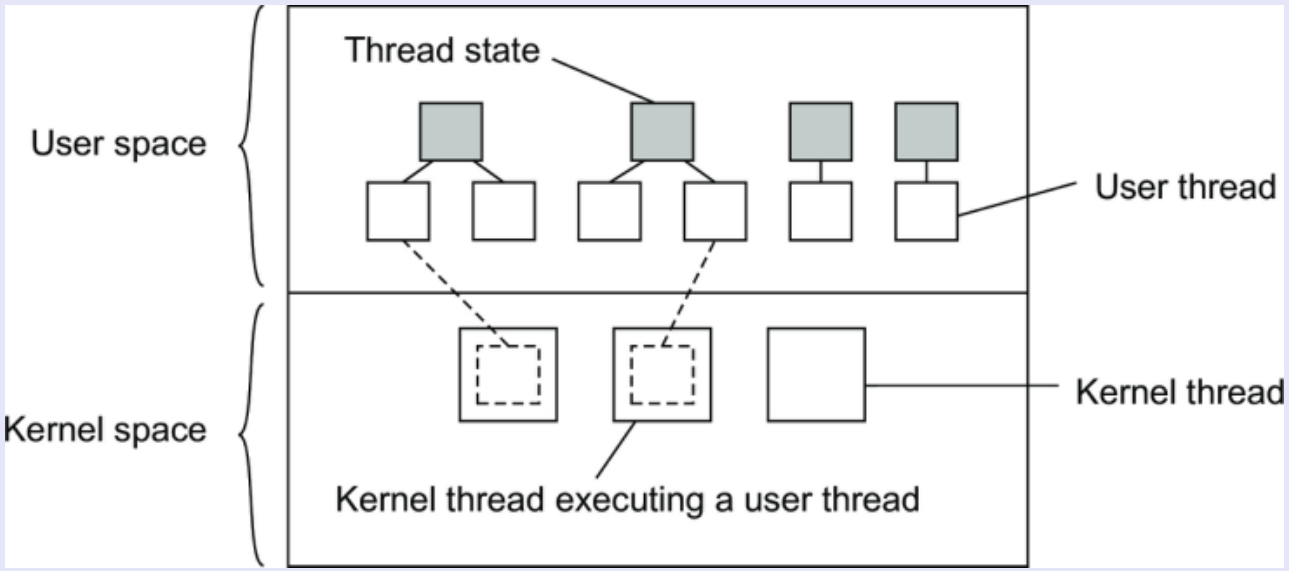
Combining user-level and kernel-level threads

Two-level threading approach



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Multithreaded Clients — Parallel Connections

Parallel Connections Example

- After fetching main HTML file, separate threads fetch remaining components
- Each thread sets up its own connection to the server
- Standard blocking calls can be used without suspending the main process
- Result: user can interact with content while additional data is still being fetched

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Multithreaded Clients — Replicated Servers

Performance Advantages

- Servers can be replicated to handle load or improve speed
- Threads allow simultaneous connections to different replicas
- Entire web document can be displayed faster compared to a non-multithreaded client
- True parallel streams of incoming data are possible only with threads

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Thread-Level Parallelism (TLP)

Mathematical Definition of TLP

- Let c_i denote the fraction of time exactly i threads are executing
- c_0 is the fraction of idle time (no threads running)
- Maximum number of threads that can execute simultaneously: N

$$\text{TLP} = \frac{\sum_{i=1}^{N} i \cdot c_i}{1 - c_0}$$

- TLP measures effective hardware utilization by multithreading
- Example: A TLP of 2.0 implies two cores are effectively utilized

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TLP Example in Web Browsers

Web Browser Performance

- Suppose a browser executes up to $N = 4$ threads:

$$c_0 = 0.2, \quad c_1 = 0.4, \quad c_2 = 0.3, \quad c_3 = 0.1$$

- Compute TLP:

$$\text{TLP} = \frac{1 \cdot 0.4 + 2 \cdot 0.3 + 3 \cdot 0.1}{1 - 0.2} = \frac{1.3}{0.8} \approx 1.625$$

- Interpretation: Effectively 1–2 cores are utilized
- Multithreading organizes tasks but may not fully exploit all cores

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Multithreaded Servers in Distributed Systems

Key Advantages of Multithreaded Servers

- Simplifies server code and improves maintainability
- Exploits parallelism even on uniprocessor systems
- On multicore processors, multithreading enables high performance
- Threads allow handling blocking operations without halting the entire server

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Dispatcher/Worker Model in Multithreaded Servers

Server Operation Steps

- Dispatcher thread continuously reads incoming client requests
- Each request is assigned to an idle worker thread
- Worker threads perform blocking operations (e.g., reading from disk)
- If a worker thread is blocked, another thread is scheduled immediately
- Maximizes CPU utilization and increases the number of requests handled per time unit

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Benefits of Using Threads in Servers

Advantages

- Enables sequential programming with blocking system calls
- Multiple threads can run in parallel, improving throughput
- Threads vs Processes: Processes offer better protection but may reduce performance
- Parallelism through threads is easier to maintain and understand

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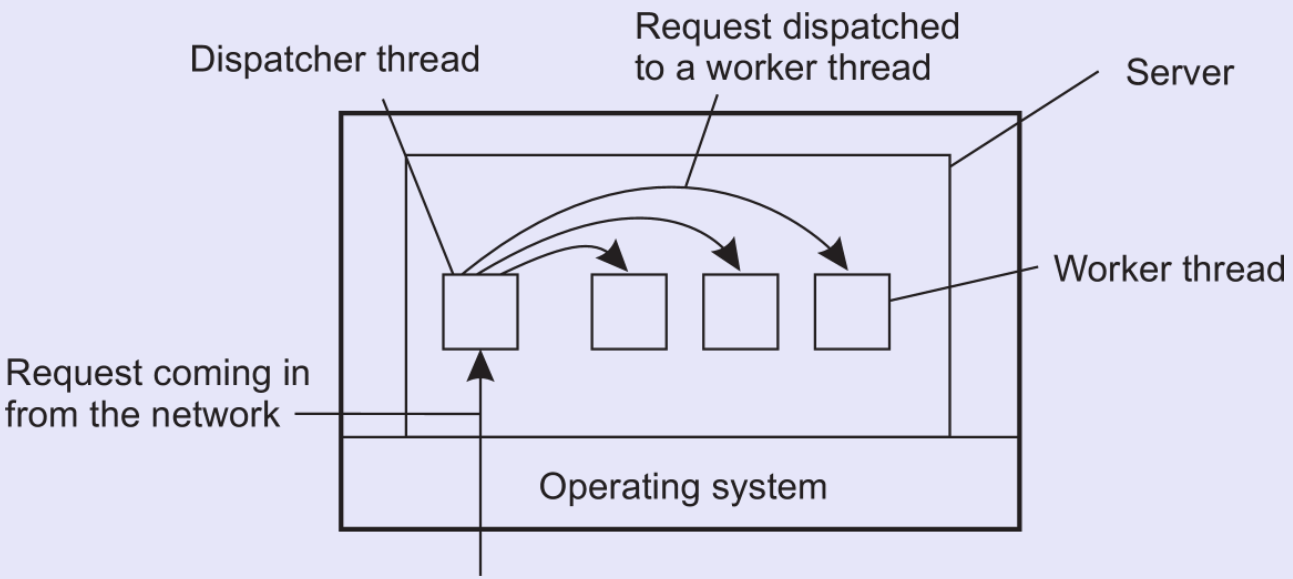
Why multithreading is popular: organization

Dispatcher/worker model



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Constructing a server

Three Ways to construct a server

Model	**Characteristics**
Multithreading	Parallelism, blocking system calls
Single-threaded process	No parallelism, blocking system calls
Finite-state machine	Parallelism, nonblocking system calls

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3.2 Virtualization

Overview

- Threads/processes allow programs to appear simultaneous.
- Single-core CPUs: illusion of parallelism via rapid switching.
- Resource virtualization extends this idea to hardware/software.
- Enables legacy software to run on new platforms.

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Virtualization: Importance and Types

Importance

- Reduces platform diversity; apps run on virtual machines.
- Provides portability, flexibility, and isolation (security).
- Supports long-lived software over changing hardware.

Types of Interfaces

- Instruction Set Architecture (ISA) – hardware-software
- System call interface – operating system
- Library/API interface – hides system calls

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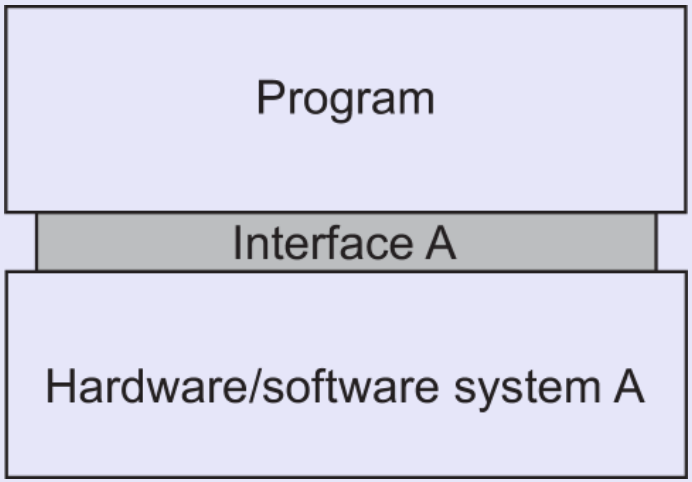
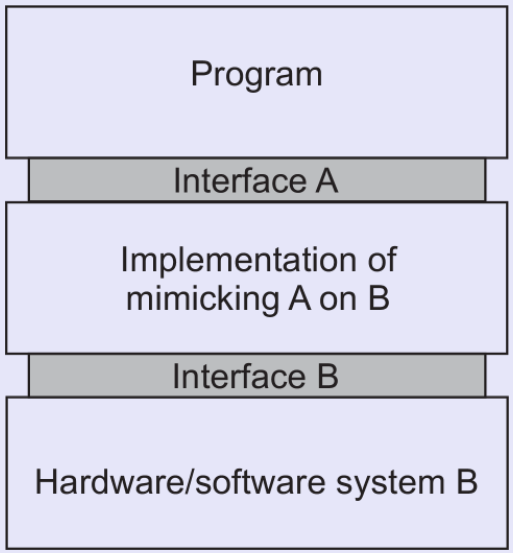
Virtualization

Principle: Mimicking Interfaces



Virtualization Example



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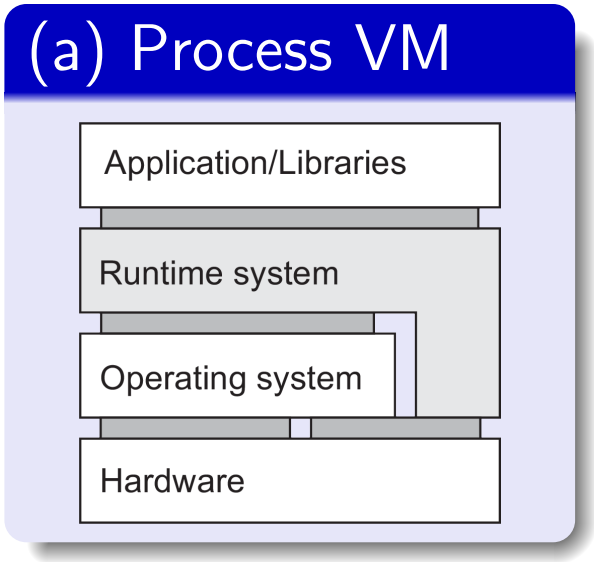
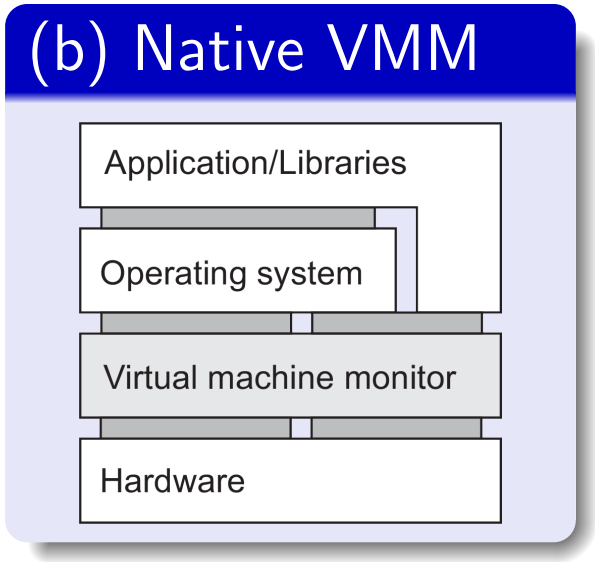
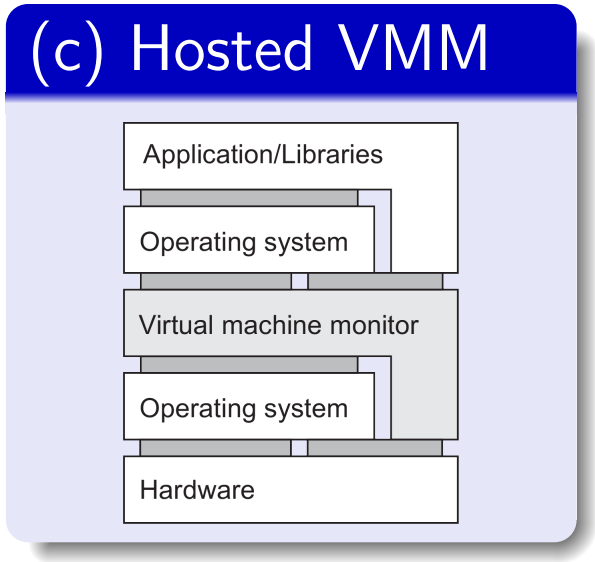
Ways of virtualization







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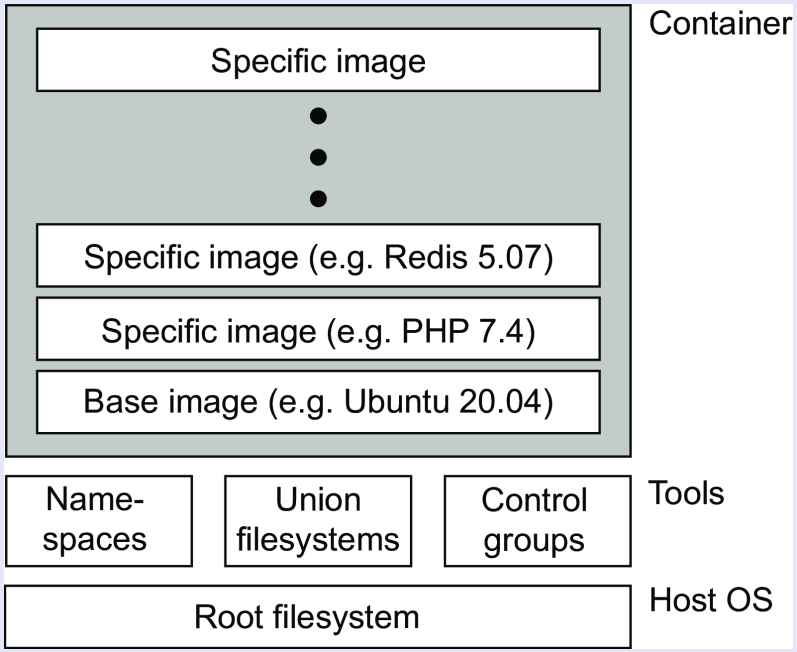
Containers

Containerization Concept



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Container Mechanisms

Core Building Blocks

- **Namespaces**: A collection of processes in a container is given their own view of identifiers.
- **Union File System**: Combine several file systems into a layered fashion with only the highest layer allowing for write operations (and the one being part of a container).
- **Control Groups (cgroups)**: Resource restrictions can be imposed upon a collection of processes.

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Code Migration

What is Code Migration?

- Traditionally, distributed systems mainly focused on passing data.
- In some cases, passing **programs** (even while executing) simplifies system design.
- We take a detailed look at **what code migration is** and why it matters.

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Reasons for Migrating Code

Why Move Code Between Machines?

- **Performance**: Move processes from heavily loaded to lightly loaded machines.
- **Resource Optimization**: Migrate VMs to minimize active nodes in data centers.
- **Data Proximity**: Execute code close to data sources (e.g., databases, mobile devices).

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Code Migration and Performance

Improving Performance

- Offload client tasks to servers to reduce network traffic.
- Run form-processing logic on clients to minimize server load.
- Mobile agents: small programs that move across sites to perform tasks in parallel.

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Code Migration for Privacy and Security

Federated Learning Example

- Sensitive data (e.g., medical records, financial transactions) stays local.
- Instead of moving data, models are trained by sending code to devices.
- Improves privacy while still leveraging distributed machine learning.

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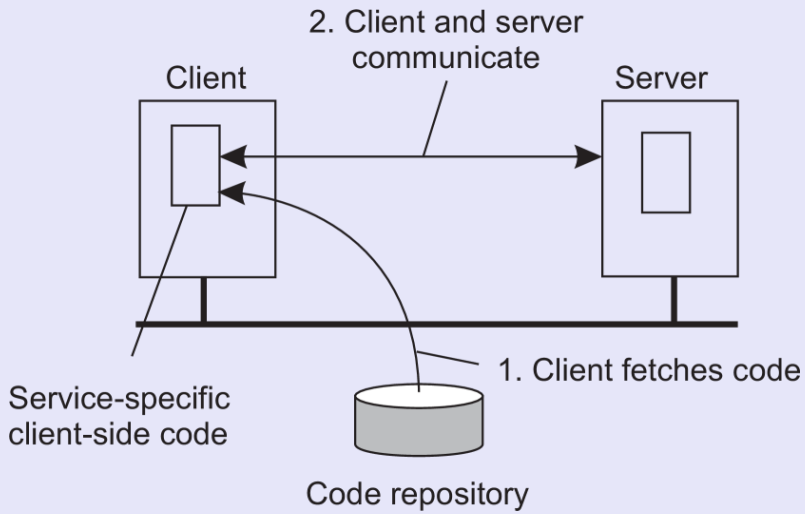
Reasons to migrate code

Load distribution



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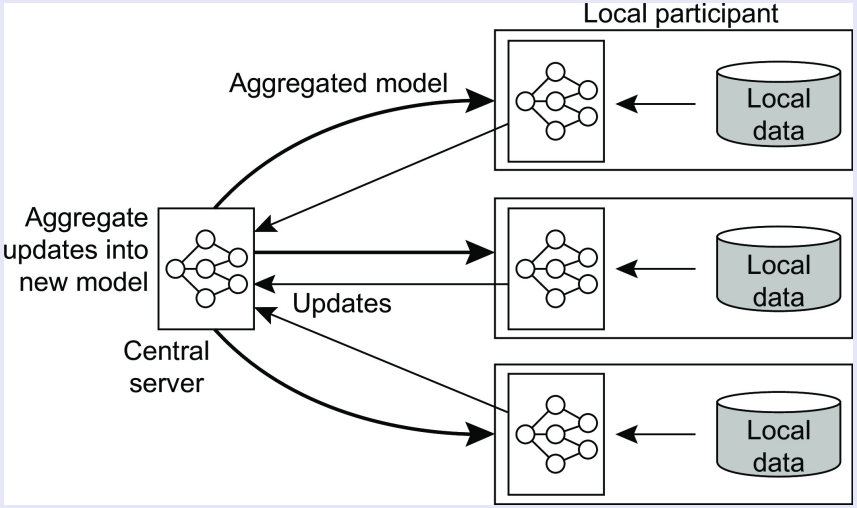
Reasons to migrate code

Privacy and security



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Questions?

Thank you for your attention!

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References

Suggested References

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