Distributed Systems

Virtualization in Distributed Environments

WEEK 4: Virtualization, Virtual Machines, Containers, Resource Isolation, Cloud Infrastructure.

Online Lecture Series - 4

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Course Outline

Topics We Will Cover

- **Virtualization** — Principles, Types, Hypervisors
- **Virtual Machines (VMs)** — Components, Lifecycle, Benefits, Examples
- **Containers** — Docker, Kubernetes, Images, Runtime, Benefits
- **Resource Isolation** — CPU, Memory, Disk, Network, Security Stability
- **Cloud Infrastructure** — IaaS/PaaS/SaaS, Multi-Tier Apps, Real-World Use

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Implementation Levels of Virtualization

What is Virtualization?

- Technology allowing multiple **virtual machines (VMs)** to share one hardware system.
- Originated in the 1960s, revitalized by cloud and distributed computing.
- Purpose: **resource sharing**, improved utilization, and application flexibility.
- Hardware (CPU, memory, I/O) and software (OS, libraries) can be virtualized.
- Separates hardware from software for **better efficiency**.

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Virtualization in Distributed Systems

Why Virtualization Matters?

- Provides **large memory space** and resource abstraction (e.g., virtual memory).
- Enables efficient use of **compute engines, storage, and networks**.
- Applications and operating systems can run independently on shared hardware.
- 2009 Gartner Report: virtualization was the **top strategic technology**.

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Virtualization Architecture

Traditional vs Virtualized Systems

- **Traditional System:** Host OS directly manages hardware.
- **Virtualized System:** A virtualization layer (**hypervisor / VMM**) is added.
- Guest OS runs on virtualized CPU, memory, and I/O resources.
- Applications remain isolated inside their own VM environments.

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Levels of Virtualization Implementation

Where Can Virtualization Occur?

- Virtualization layer can be applied at different **operational levels**.
- Common levels include:
  - Instruction Set Architecture (ISA) Level
  - Hardware Level
  - Operating System Level
  - Library Support Level
  - Application Level
- Each level abstracts resources differently for VMs and applications.

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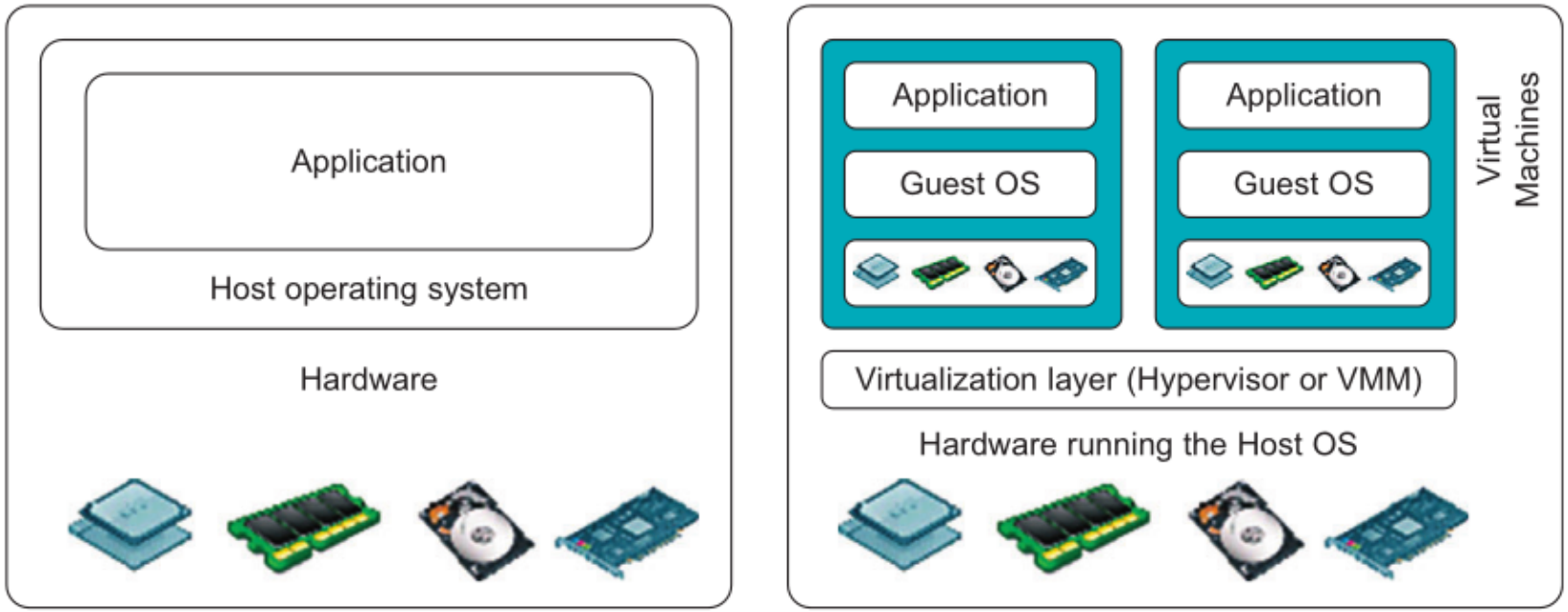
Implementation Levels of Virtualization



(a) Traditional computer

(b) After virtualization

K. Hwang, G. C. Fox, and J. J. Dongarra, *Distributed and Cloud Computing: From Parallel Processing to the Internet of Things*. Morgan Kaufmann, 2012.

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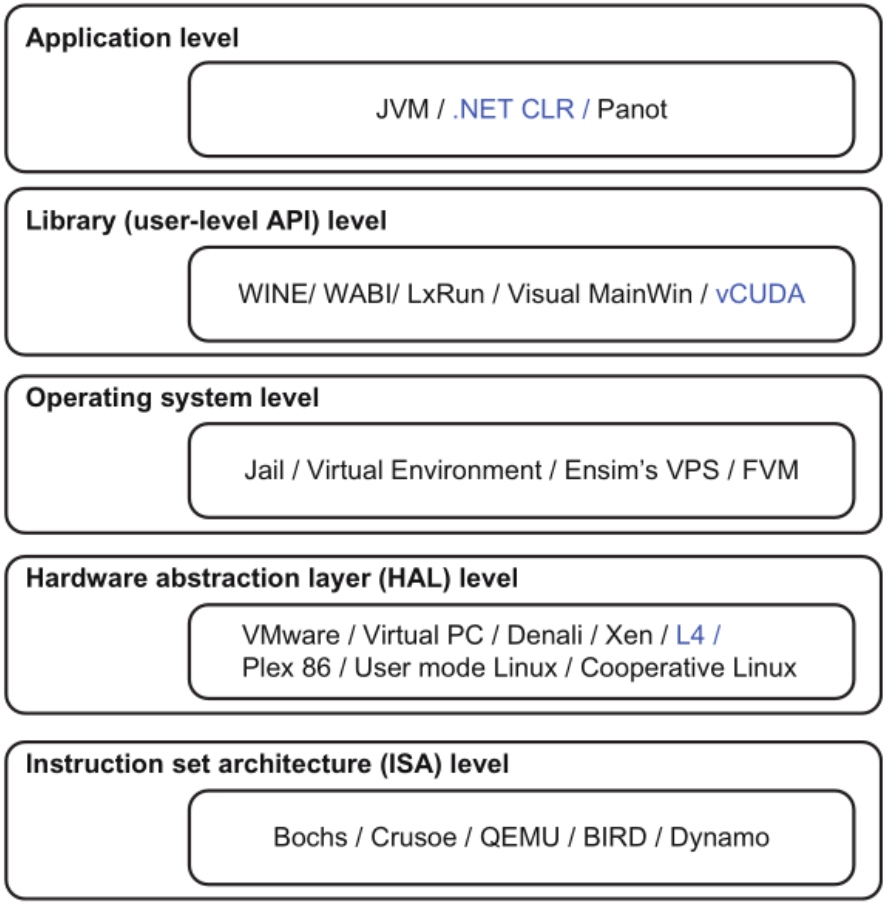
Implementation Levels of Virtualization



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Distributed and Cloud Computing:
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ISA Level Virtualization

Instruction Set Architecture (ISA) Level

- Emulates one ISA on top of another (e.g., MIPS code on x86 host).
- Supports running **legacy binaries** on new hardware.
- Implemented via:
  - Code interpretation (slow).
  - Dynamic binary translation (faster).
- Produces a **virtual ISA (V-ISA)** layer for portability.

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Hardware Level Virtualization

Directly on Hardware

- Virtualization occurs right above bare hardware.
- Provides VMs with **virtual CPUs, memory, and I/O**.
- Improves hardware utilization among multiple users.
- Early example: IBM VM/370 (1960s).
- Modern example: **Xen hypervisor** for x86 servers.

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OS Level Virtualization

Operating System Layer

- Provides an abstraction between OS and user apps.
- Creates **isolated containers** on a single server.
- Containers behave like independent servers.
- Widely used for:
  - Virtual hosting environments.
  - Server consolidation.

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Library Support Level Virtualization

Library Interface Layer

- Many applications use APIs via libraries instead of system calls.
- Virtualization intercepts API calls through **API hooks**.
- Examples:
  - WINE (Windows apps on UNIX).
  - vCUDA (GPU acceleration inside VMs).

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Application Level Virtualization

User-Application Layer

- Virtualizes applications as independent VMs.
- Often implemented via **High-Level Language (HLL) VMs**.
- Examples:
  - Java Virtual Machine (JVM).
  - Microsoft .NET CLR.
- Other approaches: application isolation, sandboxing, streaming.

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Relative Merits of Different Levels

Comparison Criteria

- Performance
- Application Flexibility
- Implementation Complexity
- Application Isolation

See Table 3.1 for detailed comparison.

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Virtual Machine Monitor (VMM)

What is a VMM?

- Hardware-level virtualization adds a layer between real hardware and OS.
- This layer is called the **Virtual Machine Monitor (VMM)**.
- Manages hardware resources of the system and intercepts program access to hardware.
- Enables multiple OS instances to run simultaneously on the same hardware.

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VMM Design Requirements

A VMM Must Provide:

1. An **identical environment** to the original machine.
2. Programs should run with only **minor performance decrease**.
3. **Complete control** of all system resources.

Note: Differences may arise from limited system resources or timing dependencies.

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Efficiency in VMMs

Key Point: Performance Matters

- Pure emulators/simulators are too slow for real machine use.
- **Efficient VMMs** execute the majority of instructions directly on hardware.
- Only exceptional cases require VMM intervention.
- Balance needed between **flexibility vs speed**.

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VMM Control of Resources

Responsibilities of a VMM

1. Allocate hardware resources (CPU, memory, I/O) to programs/VMs efficiently.
2. Prevent unauthorized access to resources not assigned to a VM.
3. Reclaim and redistribute resources when VMs terminate or underutilize them.
4. Monitor resource usage to ensure fair sharing among VMs.
5. Support performance isolation and security between VMs.

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Hypervisors and VMMs

Examples of Providers

- VMware Workstation, VMware ESX Server
- Xen Hypervisor (para-virtualization)
- KVM (Kernel-based Virtual Machine) item Microsoft Hyper-V (Windows-based hypervisor for enterprise)
- Oracle VirtualBox (desktop virtualization for testing/development)

K. Hwang, G. C. Fox, and J. J. Dongarra, *Distributed and Cloud Computing: From Parallel Processing to the Internet of Things*, Morgan Kaufmann, 2012.

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New Computing Mode: Cloud

- VM technology enables **cloud computing**.
- Cloud shifts hardware staffing costs to third parties.
- Challenges in cloud computing:
  - Variable CPU/VM requirements.
  - Slow instantiation of new VMs.

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Why OS-Level Virtualization?

Overcoming Hardware VM Limitations

- Hardware-level VMs are slow to initialize and store.
- Full hardware virtualization has:
  - Slow performance
  - Low density
  - Need for para-virtualization
- OS-level virtualization provides a faster, more resource-efficient solution.

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Virtual Execution Environments (VEs)

Containers / VPS / VE

- OS virtualization partitions physical resources for multiple isolated VMs.
- Each VE has:
  - Processes, file system, user accounts
  - Network interfaces, IPs, routing tables, firewall rules
- All VEs share the same OS kernel $\rightarrow$ called **single-OS image virtualization**.

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Advantages of OS-Level Virtualization

Benefits Compared to Hardware-Level VMs

- Minimal startup/shutdown costs and low resource requirements.
- High scalability: multiple VMs share one OS kernel.
- Host and VM states can be synchronized when needed.
- Faster initialization of VMs for cloud environments.

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Disadvantages of OS-Level Virtualization

Limitations

- All VMs must belong to the same OS family.
- Different distributions allowed, but not different OS types (e.g., Windows on Linux not allowed).
- Resource duplication can incur significant overhead if not managed carefully.
- Often considered a secondary choice compared to hardware-assisted virtualization.

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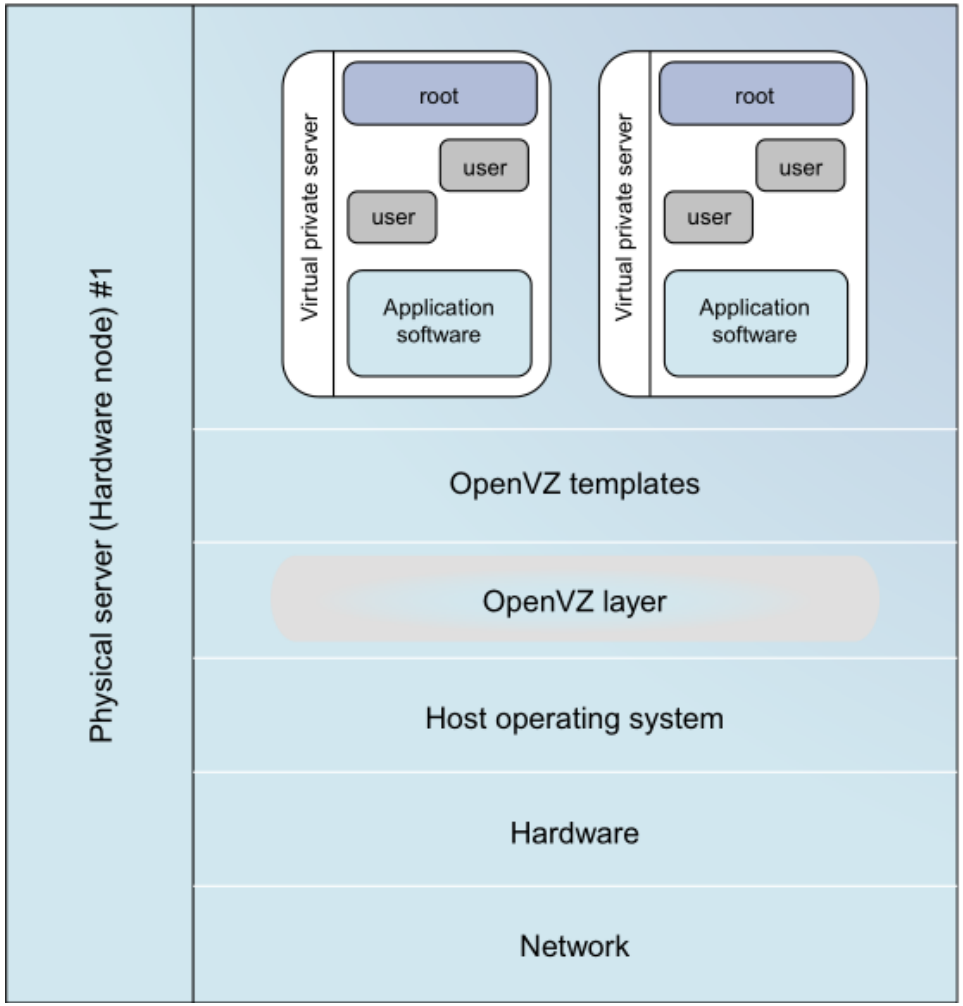
The OpenVZ virtualization layer inside the host OS



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What Are Containers?

Container Basics

- Containers bundle an application with parts of its OS environment.
- They run as a process on the host OS (e.g., Linux) rather than as a full OS.
- Each container sees itself as an independent machine:
  - Own IP address
  - Isolated filesystem
  - Isolated process tree

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Problems Containers Solve

Deployment Challenges

- **Configuration Management:** Test apps in the same environment they run in production.
- **Infrastructure Management:** Run multiple containers on a single machine.
- Containers allow scaling:
  - Move containers to larger servers when needed.
  - Run multiple containers on one physical host efficiently.

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Do Containers Use a Lot of Disk Space?

Minimal Footprint

- Containers typically include only the minimal OS required.
- Example: Alpine Linux ¡ 10 MB base image.
- Some applications can be fully packaged without an OS ("distroless" containers).
- Container runtimes manage disk usage across multiple containers efficiently.

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Docker and Containers

Container Management

- Docker is a popular tool for building, managing, and running containers.
- Docker Hub provides standardized container images.
- Containers are now largely standardized; Docker is one implementation.
- Alternatives like Podman are mostly CLI-compatible with Docker.

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History: From Emulators to VMs

Container Origins

- Early virtualization used **emulators** to simulate other computers.
- Emulation is slow but allowed running one computer inside another.
- Modern virtualization runs most instructions natively, only intercepting OS-level tasks.
- Enabled cloud computing: large physical machines can be partitioned into smaller virtual machines or containers.

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Docker Interactive Tutorial

Why Docker?

- Containers enable reliable, repeatable, and scalable deployments.
- They allow developers to manage infrastructure efficiently.
- Docker provides CLI tools to download, run, and build containers.
- Supports massive deployment with minimal effort.
- Real-world examples: AWS ECS, Kubernetes, Azure Container Instances.

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Registries, Repositories, and Tags

Docker Registry Concepts

- **Registry:** Stores container images online (e.g., Docker Hub, JFrog, AWS, Azure).
- **Repository:** Named location in a registry for a type of image.
- **Tag:** Identifies a specific version of an image (e.g., ubuntu:jammy).
- Fully qualified image name: `registry/repository:tag`.
- Tags help manage versions and updates reliably in production.

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Running Your First Container: Hello World

Command Example

- Run a simple container:

  `docker run johnnyb61820/hello-world`

- Pulls the image from Docker Hub and runs it.
- First run: downloads the image, saves locally, prints "Hello World!"
- Subsequent runs: uses local image, runs instantly.

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Understanding Containers on Your Machine

Key Commands

- List images: `docker image ls`
- List all containers: `docker container ls -a`
- Container = image + writable filesystem layer
- Each container runs as an isolated virtual machine
- Real-world example: Multiple containers running test scripts simultaneously without conflict.

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Removing Containers and Images

Cleanup Commands

- Auto-delete after run: `docker run --rm IMAGE`
- Delete non-running containers: `docker system prune`
- Add -a to remove unused images as well
- Containers share the read-only image, minimizing disk usage
- Real-world: Keep production servers clean and lightweight.

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Running a Docker Service: Web Server

Example: Simple HTTP Service

- Run a container with port mapping:

  `docker run -p 8080:8070 johnnyb61820/simple-web-server`
- Access via browser: `http://localhost:8080/`
- Run in background with `-d` flag
- Stop container: `docker container stop CONTAINER/D`

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Resource Isolation in Containers

Key Concept

- Containers provide strong isolation for resources, ensuring that each application runs independently.
- Each container can have dedicated CPU, memory, disk, and network allocation.

Real-World Example

- Containers isolated with resource limits; Kubernetes enforces this via namespaces and cgroups.

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Resource Isolation Benefits

Why It Matters

- Ensures containers do not interfere with each other.
- Improves security, stability, and predictability
- Prevents resource exhaustion by a single container
- Simplifies debugging and monitoring

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Real-World Examples of Resource Isolation

Examples in Practice

- Multiple web servers running on a single host, each with dedicated CPU and memory.
- Database containers isolated from web app containers to prevent performance interference.
- Kubernetes enforces resource quotas and limits for pods in production environments.
- CI/CD pipelines and cloud multi-tenant environments run in isolated containers.

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Cloud Infrastructure Overview

Key Concepts

- Provides on-demand computing resources over the Internet.
- Resources include virtual machines, containers, storage, and networking.
- Supports scalable, elastic, pay-as-you-go deployment.
- Enables rapid deployment of applications and services.
- Supports container orchestration and microservices architectures.
- Improves operational efficiency and reduces infrastructure costs.

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Cloud Infrastructure Examples

Popular Cloud Providers

- AWS: EC2 (VMs), ECS Fargate (containers), Lambda (serverless)
- Google Cloud: Compute Engine, GKE (Kubernetes), Cloud Run
- Azure: Virtual Machines, Container Instances, Azure Functions

Real-World Use Cases

- Netflix, Spotify, Airbnb run containerized apps on cloud.
- Startups use cloud for scalable multi-tenant applications.

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Multi-Tier Cloud Application

Application Tiers

- Web tier: Containerized web app in AWS ECS or Google Cloud Run
- Database tier: Managed RDS (AWS) or Cloud SQL (GCP)
- Cache tier: Redis or Memcached container in AWS Fargate or GKE

Supporting Components

- Load Balancer: AWS ALB or GCP Load Balancer routes traffic
- Auto-Scaling and Monitoring: Dynamically adjust containers and track performance (CloudWatch, Stackdriver)

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Questions?

Thank you for your attention!

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References

Suggested References

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3. N. Lynch, *Distributed Algorithms*, 2nd ed., Morgan Kaufmann, 1996.
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