Cloud Computing Fundamentals

Cloud Computing Fundamentals: Virtualization & Resource Pooling

- Introduction to Cloud Computing and its core concepts.
- Focus on Virtualization as a foundational technology.
- Hypervisors: The engine of virtualization.
- Resource Pooling: Optimizing resource utilization in the cloud.

Virtualization: Abstraction of Physical Resources

- **Definition:** Virtualization is the process of creating a virtual version of something, including hardware platforms, operating systems, storage devices, or network resources.
- **Key Benefit:** Abstraction of physical hardware, allowing multiple virtual machines (VMs) to run on a single physical server.
- **Historical Context:** Evolved from mainframe partitioning in the 1960s.
- **Current Applications:** Foundational for cloud computing, data centers, and software development.

Hypervisors: The Virtualization Engine

- **Definition:** A hypervisor, also known as a Virtual Machine Monitor (VMM), is software that creates and runs virtual machines.
- **Types of Hypervisors:**
  - **Type 1 (Bare-Metal):** Runs directly on the hardware. Examples: VMware ESXi, Microsoft Hyper-V Server, Xen.
  - **Type 2 (Hosted):** Runs on top of an existing operating system. Examples: VMware Workstation, Oracle VirtualBox.
- **Key Functions:**
  - Resource allocation (CPU, memory, storage, network).
  - VM creation and management.
  - Isolation and security.

Type 1 vs. Type 2 Hypervisors: A Comparison

Feature	Type 1 (Bare-Metal)	Type 2 (Hosted)
Performance	Generally higher due to direct hardware access	Lower due to OS overhead
Security	More secure due to smaller attack surface	Less secure due to reliance on host OS security
Resource Usage	More efficient resource utilization	Less efficient due to host OS resource consumption
Use Cases	Production environments, large-scale deployments	Development, testing, personal use

CPU Scheduling in Virtualization

- **Objective:** Efficiently allocate CPU time to VMs.
- **Techniques:**
  - **Round Robin:** Each VM gets a fixed time slice.
  - **Priority-Based:** VMs are assigned priorities, and higher-priority VMs get more CPU time.
  - **Fair Scheduling:** Attempts to provide equal CPU time to all VMs.
- **Considerations:**
  - Overhead of context switching between VMs.
  - Impact on VM performance and latency.

Memory Management: Ballooning

- **Definition:** A technique where the hypervisor reclaims unused memory from VMs.
- **Mechanism:**
  - A "balloon driver" inside the VM requests memory from the VM's OS.
  - The VM's OS then releases the memory to the hypervisor.
- **Benefits:**
  - Improved memory utilization.
  - Reduced risk of memory exhaustion.
- **Drawbacks:**
  - Performance overhead due to memory reclamation.

I/O Device Emulation

- **Definition:** The process of simulating hardware devices for VMs.
- **Purpose:** Allows VMs to access hardware resources without direct access.
- **Methods:**
  - **Full Emulation:** Simulates the entire device.
  - **Paravirtualization:** Requires modifications to the guest OS to improve performance.
- **Impact on Performance:** Emulation can introduce significant overhead.

Resource Pooling: Aggregating Resources

- **Definition:** The practice of combining compute, storage, and network resources into a shared pool.
- **Benefits:**
    - Improved resource utilization.
    - Increased flexibility and scalability.
    - Reduced costs.
- **Key Characteristics:**
    - On-demand allocation.
    - Elasticity.
    - Metering and billing.

Elastic Scaling Policies

- **Definition:** Automated rules that adjust resource allocation based on demand.
- **Types of Scaling Policies:**
  - **Target Tracking:** Adjusts resources to maintain a specific target metric (e.g., CPU utilization).
  - **Step Scaling:** Adds or removes resources based on predefined thresholds.
  - **Scheduled Scaling:** Adjusts resources based on a predefined schedule.
- **Metrics for Scaling:**
  - CPU utilization.
  - Memory utilization.
  - Network latency.
  - Queue depth.

Hypervisor Security Hardening

- **Micro-segmentation:** Isolating VMs and network segments to limit the impact of security breaches.
- **Secure Boot Chains:** Ensuring that only trusted software is loaded during the boot process.
- **Encrypted VM Images:** Protecting sensitive data by encrypting VM images at rest and in transit.
- **Runtime Integrity Checks:** Monitoring VMs for unauthorized modifications.

Side-Channel Mitigations

- **Definition:** Techniques to protect against attacks that exploit unintended information leakage from hardware.
- **Examples:**
  - Mitigations for speculative execution vulnerabilities (e.g., Spectre, Meltdown).
- **Impact on Performance:** Mitigations can reduce consolidation ratios and scheduling fairness.

Virtualization Performance Tuning

- **NUMA-Aware Placement:** Placing VMs on NUMA nodes that are close to the data they access.
- **Huge Pages:** Using large memory pages to improve TLB efficiency.
- **SR-IOV (Single Root I/O Virtualization):** Allowing VMs to directly access physical network adapters for near line-rate networking.
- **Paravirtualized Drivers (VirtIO):** Using drivers that are optimized for virtualized environments to reduce emulation overhead.
- **CPU Pinning:** Assigning VMs to specific CPU cores to stabilize latency-sensitive workloads.

Network Virtualization

- **Definition:** The process of abstracting network resources from the underlying physical infrastructure.
- **Overlay Networks (VXLAN, Geneve):** Creating virtual networks on top of the physical network.
- **Virtual Switches (OVS):** Software-based switches that provide network connectivity for VMs.
- **Service Mesh:** An infrastructure layer that manages service-to-service communication.

Overlay Networks: VXLAN and Geneve

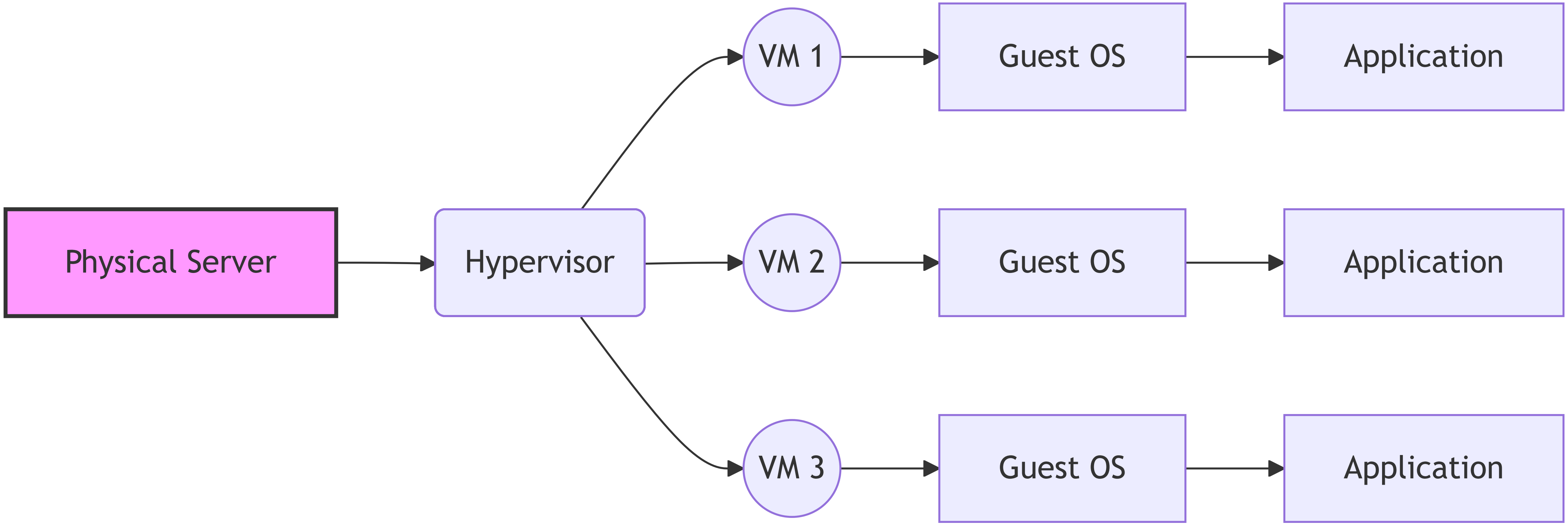
- **VXLAN (Virtual Extensible LAN):** A tunneling protocol that encapsulates Layer 2 Ethernet frames within UDP packets.
- **Geneve (Generic Network Virtualization Encapsulation):** A more flexible tunneling protocol that supports a wider range of header options.
- **Benefits:**
  - Increased scalability.
  - Multi-tenant isolation.
  - Improved network mobility.

Virtual Switches (OVS)

- **Definition:** A software-based switch that runs on a hypervisor.
- **Key Functions:**
  - Forwarding traffic between VMs.
  - Enforcing ACLs (Access Control Lists).
  - Implementing QoS (Quality of Service).
- **Benefits:**
  - Flexibility.
  - Programmability.
  - Cost-effectiveness.

Service Mesh: L7 Traffic Management

- **Definition:** An infrastructure layer that manages service-to-service communication.
- **Key Features:**
  - Traffic routing.
  - Load balancing.
  - Service discovery.
  - Security.
  - Observability.
- **Examples:** Istio, Linkerd, Consul Connect.


Physical Server
Hypervisor
VM 1
VM 2
VM 3
Guest OS
Guest OS
Guest OS
Application
Application
Application

Consolidation Ratios

- **Definition:** The number of virtual machines that can be run on a single physical server.
- **Factors Affecting Consolidation Ratios:**
  - Workload characteristics.
  - Hardware resources.
  - Hypervisor efficiency.
  - Security mitigations.
- **Importance:** Higher consolidation ratios reduce hardware costs and improve resource utilization.

Virtualization: Key Takeaways

- Virtualization is a foundational technology for cloud computing.
- Hypervisors are the engines of virtualization.
- Resource pooling optimizes resource utilization.
- Security and performance are critical considerations.
- Network virtualization enables multi-tenant isolation and scalability.

Future Trends in Virtualization

- **Containerization:** Lightweight virtualization using containers (e.g., Docker, Kubernetes).
- **Serverless Computing:** Abstracting away the underlying infrastructure.
- **Edge Computing:** Bringing compute resources closer to the edge of the network.
- **Confidential Computing:** Protecting data in use by encrypting it within VMs.

References

- Popek, G. J., & Goldberg, R. P. (1974). Formal requirements for virtualizable third generation architectures. *Communications of the ACM, 17*(7), 412-421.
- Barham, P., Dragovic, B., Fraser, K., Hand, S., Harris, T., Ho, A., ... & Warfield, A. (2003). Xen and the art of virtualization. *ACM SIGOPS Operating Systems Review, 37*(5), 164-177.
- Rosenberg, D., Matei, Y., & Foster, I. (2009). Resource pooling for data centers. *IEEE Internet Computing, 13*(4), 62-69.
- Burns, B., Grant, B., Oppenheimer, D., Brewer, E., & Wilkes, J. (2016). Borg, omega, and kubernetes: Lessons from three container-management systems. *Communications of the ACM, 59*(5), 50-59.
- National Institute of Standards and Technology (NIST). (2011). *The NIST Definition of Cloud Computing*. (Special Publication 800-145). Gaithersburg, MD.