Technical Document:

1. Architecture Document

System Overview

This project demonstrates a microservices architecture implemented using two distinct containerization approaches:

1. **Lower-level Linux Primitives**: Utilizing network namespaces, veth pairs, bridges, and iptables.
2. **Docker Containerization**: Utilizing Docker Compose, multi-stage builds, and custom bridge networks.
3. **Multi-Host Overlay Networking**: Utilizing manual VXLAN tunneling and Docker Swarm for cross-host microservice communication.

The application is an e-commerce platform consisting of an API Gateway, a Service Registry, a Product Service (with caching), an Order Service (with persistence), Redis, and PostgreSQL.

Component Descriptions

- **API Gateway (Python/Flask)**: Entry point for external traffic. Performs round-robin load balancing to backend instances.
- **Service Registry (Python/Flask)**: Simplified DNS-like registry for service discovery.
- **Product Service (Python/Flask)**: Manages product data; uses Redis for caching to improve performance.
- **Order Service (Python/Flask)**: Manages customer orders; persists data in PostgreSQL.
- **Redis Cache**: High-performance key-value store used for session and response caching.
- **PostgreSQL**: Relational database for persistent storage of orders.

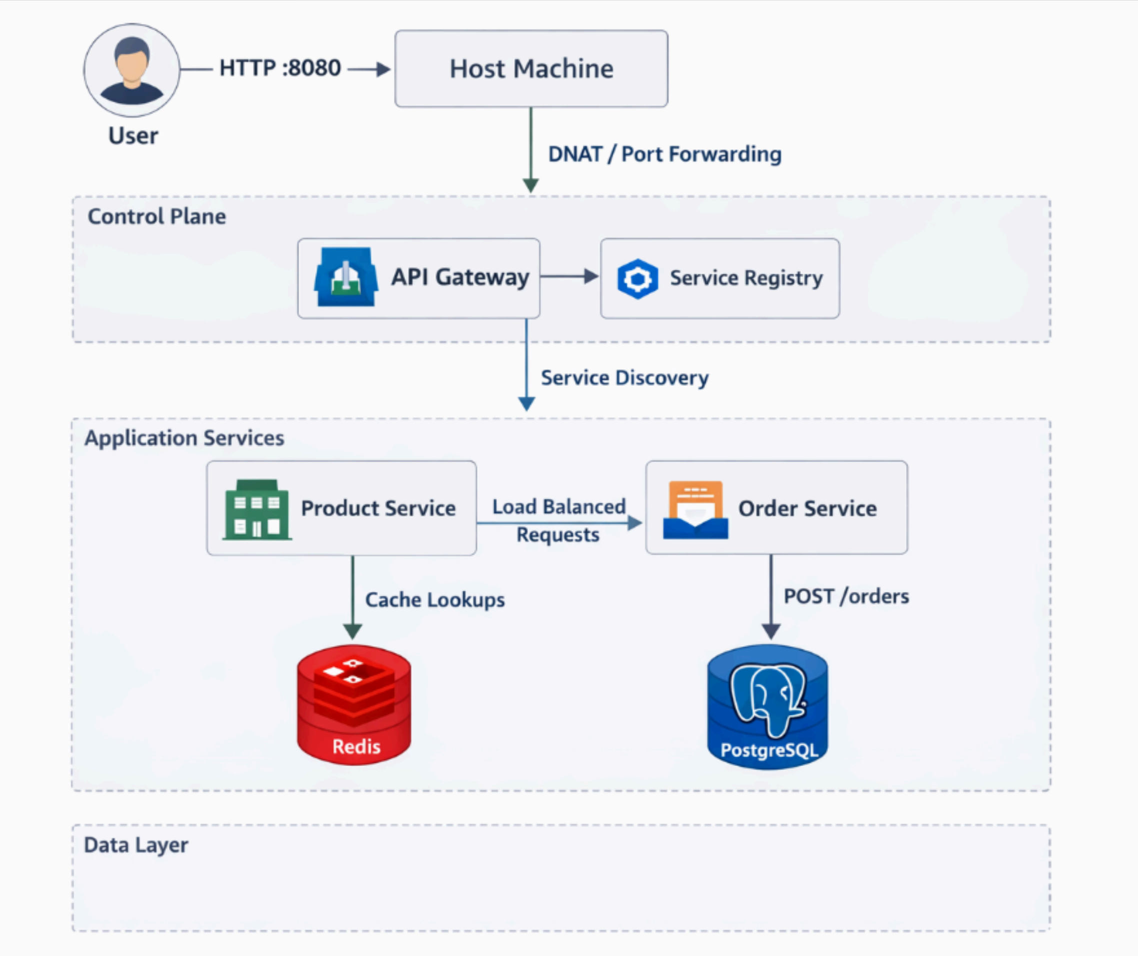
Network Topology

The system is divided into three isolated security tiers:

- **Frontend (172.20.0.0/24)**: Houses the API Gateway.
- **Backend (172.21.0.0/24)**: Houses logic services (Product, Order, Registry).
- **Database (172.22.0.0/24)**: Houses data stores (Redis, Postgres).

In the Linux implementation, each tier has a dedicated bridge (`br-frontend` , `br-backend` , `br-database`) and the host acts as the router. In the Docker implementation, all services reside on a unified `app-network` bridge with internal DNS discovery.

Data Flow Diagram



2. Implementation Guide

Step-by-Step Setup

Approach A: Linux Namespaces

1. **Configure Network**: Run `sudo ./setup_network_isolation.sh` to create bridges and namespaces.
2. **Start Services**: Run `sudo bash start_isolated_services.sh` to launch services inside namespaces.
3. **Verify**: Use `curl http://172.20.0.10:3000/api/products` from the host.

Approach B: Docker Compose

1. **Build & Launch**: Run `docker-compose up --build -d`.
2. **Verify Health**: Run `docker ps` to ensure status is "healthy".
3. **Test Endpoint**: Use `curl http://localhost:3000/api/products`.

Approach C: Multi-Host Overlay (Swarm)

1. **Prepare Tunnel**: Run `setup_vxlan_host_a.sh` on Manager and `setup_vxlan_host_b.sh` on Worker.
2. **Init Swarm**: Run `docker swarm init` on Manager and join with Worker.
3. **Deploy Stack**: Run `docker stack deploy -c docker-compose-swarm.yml myapp`.
4. **Verify Cross-Host**: `docker service ps myapp_product-service` to see tasks distributed across nodes.

Configuration Files

- **docker-compose.yml**: Defines service dependencies, resource limits, and environment variables.
- **Dockerfiles**: Use multi-stage builds (`python:3.11-slim`) to minimize image size and include built-in healthchecks.
- **setup_network_isolation.sh**: Shell script utilizing `ip netns` and `brctl` (or `ip link bridge`) for manual isolation.

Troubleshooting Guide

- **Connection Refused**: Ensure services are bound to `0.0.0.0` inside containers.
- **Registry Failures**: Check that the `SERVICE_REGISTRY` environment variable matches the internal network IP/hostname.
- **Healthcheck Unhealthy**: Verify the `/health` endpoint is reachable from within the container context.

Debugging Commands

Network namespace debugging

```
sudo ip netns exec <namespace> ip addr
sudo ip netns exec <namespace> ip route
sudo ip netns exec <namespace> ss -tulpn
```

Bridge inspection

```
bridge link show
bridge fdb show
```

iptables

```
sudo iptables -L -n -v
sudo iptables -t nat -L -n -v
```

Connection tracking

```
sudo conntrack -L
```

Docker networking `docker network inspect <network> docker exec <container> ip addr` ### Tools - tcpdump for packet capture - wireshark for analysis - ab (Apache Bench) for load testing - curl for API testing - jq for JSON processing

3. Operations Manual

How to Start/Stop Services

- **Linux Setup**:
  - Start: `sudo bash start_isolated_services.sh`
  - Stop: `pkill -f python3` and `sudo ip netns del <name>`
- **Docker Setup**:
  - Start: `docker-compose up -d`
  - Stop: `docker-compose down`

Monitoring Procedures

- **Traffic Logs**: Run `./monitor-traffic.sh` to capture live pcap/text logs from the bridge.
- **Service Status**:
  - Linux: `sudo ip netns exec <ns> ss -lntp`
  - Docker: `docker ps`
- **Resource Usage**: `docker stats` for CPU/Memory consumption.

Backup and Recovery

- **Database Backup**: Use `docker exec postgres pg_dump -U postgres orders > backup.sql`.
- **Restoration**: `cat backup.sql | docker exec -i postgres psql -U postgres orders`.

Scaling Guidelines

- **Horizontal Scaling**: Use `docker-compose up --scale product-service=3 -d` to add more instances. The API Gateway will automatically load balance via the service name alias.

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4. Comparison Analysis

Linux Primitives vs Docker

Feature	Linux Namespaces	Docker Compose
Complexity	High (Shell scripts, manual routing)	Low (YAML description)
Overhead	Minimal (Direct kernel features)	Moderate (Runtime + Proxy)
Isolation	Strong networking isolation	Standard container isolation
Ease of Deployment	Low (Environment specific)	High (Portable)

Performance Metrics

- **Throughput (RPS)**: Linux (54.07) > Docker (29.21)
- **Mean Latency**: Linux (924ms) < Docker (1711ms)
- **Observation**: Raw Linux namespaces are ~46% faster in high-concurrency scenarios due to lack of proxying overhead.

Pros and Cons

Linux Primitives:

- *Pros*: Maximum performance, educational value, deep control.
- *Cons*: Difficult to scale, brittle scripts, high maintenance.

Docker:

- *Pros*: Rapid scaling, dependency management, industry standard.
- *Cons*: Performance tax (networking hop), larger image sizes if not optimized.