The Network Stack (1)

Lecture 5, Part 1: Network Stacks

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2026-2027

Introduction to Network Stacks

Rapid tour across hardware and software:

- Networking and the sockets API
- Network-stack design principles
- Memory flow across hardware + software
- Network-stack work flows
- Recent network-stack research

Lecture 5, Part 1

Lecture 5, Part 2

Lecture 5, Part 3

Networking: A key OS function (1)

- Communication between computer systems
  - **Local-Area Networks (LANs)**
  - **Wide-Area Networks (WANs)**
  - **Inter-VM communication on a single host**
- A network stack provides:
  - Sockets API and extensions
  - Interoperable, feature-rich, high-performance protocol implementations (e.g., IPv4, IPv6, ICMP, UDP, TCP, SCTP, 802.1, 802.11, …)
  - Security functions (e.g., cryptographic tunneling, firewalls...)
  - Device drivers for Network Interface Cards (NICs)
  - Monitoring and management interfaces (BPF, `ioctl`)
  - Plethora of support libraries (e.g., DNS)

Networking: A key OS function (2)

- Dramatic changes over 30 years:
  - 1980s: Early packet-switched networks, UDP+TCP/IP, Ethernet
  - 1990s: Large-scale migration to IP; Ethernet VLANs
  - 2000s: 1-Gigabit, then 10-Gigabit Ethernet; 802.11; GSM data
  - 2010s: Deployment of IPv6; 40/100-Gbps Ethernet; 3G to
  - 2020s: Billions → trillions of devices, extensive multipath
- Vanishing technologies
  - UUCP, IPX/SPX, ATM, token ring, SLIP, ...

The Berkeley Sockets API (1983)

```
close()
read()
write()
...

accept()
bind()
connect()
getsockopt()
listen()
recv()
select()
send()
setsockopt()
socket()
...
```

- **The Design and Implementation of the 4.3BSD Operating System**
  - (but APIs/code first appeared in 4.2BSD)
- Now universal TCP/IP (POSIX, Windows)
- Kernel-resident network stack serves networking applications via system calls
- Reuses file-descriptor abstraction
  - Same API for local and distributed IPC
  - Simple, synchronous, copying semantics
  - Blocking/non-blocking I/O, `select()`
- Multi-protocol (e.g., IPv4, IPv6, ISO, …)
  - TCP-focused but not TCP-specific
  - Cross-protocol abstractions and libraries
  - Protocol-specific implementations
  - “Portable” applications

BSD network-stack principles (1980s-1990s)

Multi-protocol, packet-oriented network research framework:

- **Object-oriented**: multiple protocols, socket types, but one API
  - **Protocol-independent**: streams vs. datagrams, sockets, socket buffers, socket addresses, network interfaces, routing table, packets
  - **Protocol-specific**: connection lists, address/routing specialization, routing, transport protocol itself – encapsulation, decapsulation, etc.
- **Packet-oriented**:
  - Packets and packet queueing as fundamental primitives
  - Best effort: If there is a failure (overload, corruption), drop the packet
  - Work hard to maintain packet source ordering
  - Differentiate ‘receive’ from ‘deliver’ and ‘send’ from ‘transmit’
  - Heavy focus on TCP functionality and performance
  - Middle-node (forwarding), not just edge-node (I/O), functionality
  - High-performance packet capture: Berkeley Packet Filter (BPF)

FreeBSD network-stack principles (1990s-2010s)

All of the 1980s features and also …

- **Hardware**:
  - Multi-processor scalability
  - NIC offload features (checksums, TSO/LRO, full TCP)
  - Multi-queue network cards with load balancing/flow direction
  - Performance to 10s or 100s of Gigabit/s
  - Wireless networking
- **Protocols**:
  - Dual IPv4/IPv6
  - Pluggable congestion control, delay-based congestion control (BBR)
  - Security/privacy: firewalls, IPSec, ...
- **Software model**:
  - Flexible memory model integrates with VM for zero-copy
  - Fine-grained locking and lockless algorithms (e.g., RCU)
  - Network-stack virtualisation
  - Userspace networking via Netmap