- The Network Layer and Routers
    - Network Layer
        - Switches vs routers
        - Packet forwarding vs routing
    - Forwarding Packets
        - Virtual circuits
        - Datagrams
    - Routers
        - Key functions
        - Input port processing
        - Switching fabrics
            - Memory
            - Bus
            - Interconnection network
        - Output port processing
        - Active queue management
        - Output port contention
        - Head-of-line blocking
- IPv4 and IPv6
    - IPv4
        - Header format
        - Subnets
        - Forwarding process
        - Fragmentation and reassembly
    - ICMP
        - Internet Control Message Protocol
    - DHCP
    - NAT
    - CIDR
        - Classful IP addressing
        - Classless interdomain routing
        - CIDR and route aggregation
        - Breaking route aggregation
    - IPv6
        - Motivation
        - Header
        - Transitioning from v4 to v6
        - Tunnels
- Routing Algorithms
    - Challenges
    - Forwarding vs routing
    - Link state algorithm
        - Dijkstra’s

    - Distance vector algorithm
        - Bellman-Ford
        - Good news travels fast, bad news travels slow
            - Solutions
                - Poisoned reverse
                - Path vector routing
    - Load-based routing
        - Bad idea, traffic oscillates back and forth
- Routing in the Internet
    - Hierarchical routing
        - Autonomous systems (AS)
        - Domain and border routers
        - Intra-domain (RIP, OSPF, IGRP)
    - RIP
        - Routing information protocol
        - Distance-vector algorithm
        - Link failure and recovery
        - Table processing
    - OSPF
        - Open shortest path first
        - Hierarchy
    - BGP
        - Basics
        - Reachability (advertise prefixes)
        - AS-PATH, NEXT-HOP
        - Route selection (policy)
    - Separation of concerns
- Broadcast and Multicast Routing
    - Broadcast
        - Spanning and Steiner trees
    - Multicast service model
        - Membership and routing
        - IGMP (Internet Group Management Protocol)
            - Messages
            - Versions
        - Problem: finding trees connection routers that have local group members
    - DVMRP
        - Distance vector multicast routing protocol
        - Reverse path forwarding
        - Pruning
        - Flood and prune
        - Soft state

        - CBT
            - Core-based trees
            - Explicit join
            - Not shortest path
        - PIM
            - Protocol-independent multicast
            - Shortest-path trees with explicit joining
        - Status
            - Multicast development
            - SSM: Source-specific multicast
                - Best solution
                - No demand for ISPs to deploy
            - Application-layer multicast
- Error Detection and Multiple Access
    - Link Layer
        - Transfers frames (e.g. Ethernet frames)
        - Reliability, flow control, error detection
        - Hardware
    - Error Detection and Correction
        - EDC bits
        - Parity checking
        - CRC (Choose r CRC bits such that D*2^r + R % 2 = 0)
    - Multiple Access Protocols
        - Sharing a single broadcast channel
        - Channel partitioning
            - TDMA: Time division multiple access
            - FDMA: Frequency division multiple access
        - Random access
            - Slotted ALOHA
            - CSMA: Carrier Sense Multiple Access
                - CSMA/CD: collision detection
        - Taking turns
            - Try to have best of channel partitioning and random access
            - Polling
            - Token passing
- MPLS, Data Centers, Retrospective
    - MPLS
        - Speed up IP forwarding
        - Traffic engineering, VPNs
    - Data Center Networking
        - Load balancing, hierarchy, innovation
    - Retrospective
        - DHCP

        - ARP
        - DNS
        - TCP and HTTP
- Switched Local Area Networks
    - Addressing
        - LAN
        - MAC addresses
    - ARP
        - Building ARP table
    - Ethernet
        - Topologies
        - Frame format
        - Historic vs modern
    - Switches
        - Hubs vs switches
        - Switches vs routers
        - Traffic isolation
        - Self-learning switches
        - VLANs
- Wireless and WiFi
    - Types of networks
        - Single vs multiple hop, infrastructure vs infrastructure-less
    - Links and Networks
        - Wireless technologies
        - Wireless signals
    - CDMA: Code Division Multiple Access
        - Multiple users transmit at same time with minimal interference
        - Encoding and decoding
    - WiFi
        - IEEE 802.11 standards
        - LAN architecture
        - Channels and association
        - Passive and active scanning
        - CSMA/CA
        - Hidden terminal problem and signal fading
        - RTS/CTS
        - Frame format
        - Address fields
        - Mobility
        - Rate adaptation
        - Power management
    - Low Power
        - BlueTooth

        - Zigbee
- Cellular Networks and Mobility
    - Cellular Networks
        - Basic architecture
        - 2G standard
            - GSM: combined FDM/TDM
            - BSC
            - MSC
        - 3G standard
            - Replace BSC with RNC (radio network controller)
        - 4G/LTE standard
            - Evolution from separate circuit-switched and packet-switched core and subdomains to one common IP core
            - EPC: Evolved packet core
                - All IP core, no circuits
                - Provides QoS to voice calls
            - LTE Radio access network
                - OFDM (FDM and TDM)
    - Mobility
        - Terminology
            - Home agent
            - Foreign agent
            - Permanent address
            - Care-of-address
        - Approaches
            - Network-layer routing
            - Application-layer routing
        - Indirect routing
        - Direct routing
            - Foreign agent chaining
    - Mobile IP
        - Indirect routing
        - Agent discovery
        - Registration with home agent
        - Mobile TCP: problems
    - Cellular Mobility
        - Call to mobile user
            - Home network, HLR (home location register), VLR (visitor location register)
        - Same MSC (mobile switching center)
        - MSC handoff steps
        - Different MSC
- Multimedia Applications and Streaming Video

- Multimedia Applications
  - Video
    - High bit rate
    - Compression
  - Audio
    - Low bandwidth
    - Analog to digital
    - Compression
  - Applications
    - Streaming stored audio/video
      - Best-effort service from application layer
      - Client buffering
      - UDP vs HTTP
      - Adaptive HTTP
        - DASH
        - Divide into 2-second chunks
      - Content distribution networks
      - Case Studies
        - Netflix
        - YouTube
        - Kankan
    - Voice and video-over-IP
    - Streaming live audio/video
- Voice-Over-IP
  - Best-Effort Service
    - Packet loss
      - Recovering
        - Forward Error Correction (FEC)
        - Interleaving
        - Error concealment
    - Packet delay
    - Packet jitter
      - Removing jitter
        - Include timestamp
        - Use buffering to delay playout
          - Fixed vs Adaptive playout delay
  - Skype
    - FEC for loss recovery
    - Codecs at various rates
    - P2P (peer to peer)
      - Super peers and ordinary peers
  - Real-Time Streaming Protocols
    - RTP: Real-Time Protocol

        - SIP: Session Initiation Protocol
            - Name translation and user location
- Network Support for Multimedia
    - Multiple classes of service
        - Motivating scenarios
        - Packet marking
        - Traffic isolation
            - Policing - enforce rate on a network flow
            - Resource reservation - allocate bandwidth to flow
    - Scheduling
        - FIFO
        - Priority Queue
        - Round Robin
        - Weighted Fair Queueing (WFQ)
        - Work-conserving vs non-work-conserving
            - Is link ever left idle if packets are ready
    - Policing
        - Limit traffic to a set of declared parameters
            - Average rate
            - Peak rate
            - Burst size
        - Leaky (Token) Bucket
        - Guaranteed Delay
            - Leaky bucket + weighted fair queueing = provable maximum delay in a queue
    - Differentiated Services
        - Architecture
        - Packet classification and traffic conditioning
        - Per-hop behaviors
            - Expedited forwarding
            - Assured forwarding
    - Integrated Services
        - Provide quality of service guarantees to individual connections
        - Components
            - Scheduling
            - Admission control
            - Resource reservation
            - QOS routing
            - Pricing and billing
        - RSVP
            - Resource ReSerVation Protocol
            - Resource reservation for multicast trees
    - Retrospective

- Most QoS benefits come from best-effort service