**Internet** A global system of interconnected computer networks linking billions of computing devices throughout the world; hosts: end systems running network applications, communication links: the media by which data travel (twisted pair copper wire/fiber optic cable); routers and switches: switching devices that end systems are connected to for forwarding data from one host to another; A network of networks, a communication infrastructure; **Network Protocol** defines format, order of messages sent and received between network entities & actions taken upon message transmission/receipt **Layer** a collection of conceptual similar functions that provide services to the layer above it and receives services from the layer below it; Application (supporting network applications), Transport (process-to-process data transfer), Network (data routing from source host to destination host), Link (data transfer between neighboring network devices), Physical (bit transfer on the transmission medium); At each layer, the data packet can be divided into header and data/payload; Encapsulation: the data packet from the upper layer is encapsulated in data part of a packet in this layer, and header is added over the data for control information; Decapsulation: remove header of this layer & extract data part for passing to the upper layer; **Components of the Internet** Network edge: servers & clients; Access networks: links connecting hosts to edge routers/switches; Residential access networks: digital subscriber line (use existing telephone line to central office DSL access multiplexer, a few Mbps upstream & tens of Mbps downstream), cable network (use hybrid fiber coaxial cables to connect to ISP router, tens to hundreds of Mbps upstream, tens of Mbps to a few Gbps downstream), fiber to the x (use optical fiber to provide all/ part of the last-mile telecommunication network for connecting user homes/premises to the ISP’s router, x = node, curb, building, home, …, to the home: a few Gbps upstream and downstream); Institutional access networks (school/company): Ethernet, Mobile access networks (Wi-Fi, 4G/5G); Network core: Inter-connected routers, many communication sessions share the same network, circuit-switching: frequency/time division multiplexing or packet-switching: store & forward, statistical multiplexing; **Delay** nodal processing delay = queueing delay (time waiting at output link for transmission) + transmission delay (packet length/link bandwidth) + propagation delay (length of physical link/propagation speed in medium) **Throughput** Rate at which data are transferred end-to-end from sending host to receiving host

**Web** an Internet application, an information space where documents and other web resources are identified by URLs, interlinked by hypertext links, and can be accessed via the Internet. A web page contains a base HTML file, referenced objects, each is addressable by a URL (a string of characters to identify a resource, specifying the means of locating the resource with both its primary access mechanism and network location) **HTTP** TCP, port 80; Web’s application-layer protocol, includes two types of messages: request & response, implemented in client-server mode. Uses TCP, HTTP/1.1 (using persistent connections) is the widely used HTTP version; Request Format “{method} {url} {http version}\n{header field name} {value}\n{body}” HTTP/2: highly compatible with 1.1 improving page load speed; HTTP/3 adds security, per object error- and congestion-control over UDP, and more pipelining **Email** client-server; major components: user agents (email client), mail servers (maintains mailbox & message queue), protocols: SMTP (how mail message is transferred from sender’s to recipient’s mail server), access protocols (how user agent retrieves messages from mail server)(POP3/IMAP/HTTP). SMTP: TCP, port 25; sender is client, receiver is server; Messages: must all be in 7-bit ASCII; client commands: HELO, MAIL FROM, RCPT TO, DATA, QUIT; server reply: status code & phrase; (220 - Service ready, 250 - Requested action completed, 354 - Start mail input, 221 - Service closing connection); POP3: TCP, port 110; 3 phases: authorization (client commands: user/pass; server response: +OK/-ERR), transaction(list, retr, dele, quit), update. IMAP: More features (more complex), Manipulation of stored messages on servers (allows organizing messages in folders), stateful. **DNS** UDP, port 53; hostname to IP address, map alias hostname to canonical hostname and IP address, load distribution (map one canonical name to a set of IP addresses). Recursive (default)/non-recursive.

**Transport** logical end-to-end communication between application processes; multiplexing at sender, demultiplexing at receiver; UDP: best effort, connectionless, no flow/congestion control, lower delay, easier for servers to maintain, smaller header size. Header: source port #, dest port#, length, checksum.

**TCP** Point-to-point, reliable, pipelined, full-duplex, connection-oriented, flow & congestion controlled. Header: source port #, dest port #, seq #, ack #, header length, flags, receive window, checksum, urgent ptr, options. **Flow Control** sender avoids overflowing receiver’s buffer with speed matching service (send rate = receiver drain rate); receiver sends receive window size to sender.

**Congestion control** Congestion source: long queueing delays at the routers, retransmissions due to packet loss (buffer overflow at routers), unnecessary retransmissions due to large delay. Approaches: End-to-end (no explicit feedback from network, inferred from end-system observation), Network-assisted (routers provide feedback to end systems) ­Estimation: EstimatedRTT = (1 - alpha) \* EstimatedRTT + alpha \* SampleRTT (typically alpha = 1/8); Deviation: DevRTT = (1 - beta) \* DevRTT + beta \* |SampleRTT - EstimatedRTT| (typically beta = 1/4); Accordingly, TimeoutInterval = EstimatedRTT + 4 \* DevRTT.

**Network** Deliver segments from sending to receiving host, implemented in every host & router. Functions: Forwarding (move datagrams from incoming to outgoing link within a router, data plane), Routing: (determine datagram’s path from source to destination, control plane) IPv4 datagram header: version, header length, type of service, total length, identifier, flags, fragment offset, time to live, upper layer, checksum, source IP address, destination IP address. **DHCP** UDP, steps: discovery, offer, request, acknowledgement. **NAT** reserved private IP addresses: 10.0.0.0/8, 172.16.0.0/12, 192.168.0.0/16. **IPv6** 128-bit address, fixed 40 bit header length, flow labeling and priority, no fragmentation/reassembly, no checksum; operating with mixed IPv4 & IPv6 routers: dual-stack (implement both), tunneling (use IPv6 datagram as IPv4 payload) **ICMP** used by hosts & routers to communicate network-layer information among each other (error reporting, echo request/reply). Message contains: type, code, header & first 8 bytes of IP datagram that caused the ICMP message to be generated; ICMP is above IP. Tracerouting: Source host sends series of UDP segments to destination with unlikely UDP port numbers (n-th set has TTL = n); when an IP datagram in nth set arrives at nth router, router discards datagram and sends back to source host an ICMP message (type 11, code 0, including name and IP address of router); when ICMP message arrives, source records RTTs and name/IP. address of the nth router. stopping: UDP segment eventually arrives at destination host; destination returns ICMP “port unreachable” message (type 3, code 3); source stops after receiving this ICMP message.

**Routing algorithms** centralized (link-state, Dijkstra, used by OSPF, IS-IS)/decentralized (forward-vector, Bellman-Ford, used by RIP, IGRP)

**Routing protocols: OSPF** intra-AS, each router has complete topology map of the AS, runs Dijkstra’s algorithm to decide shortest-path tree to all subnets, link cost configured by network administrator; OSPF advertisement broadcast to all routers in the AS when one neighboring link’s state changes (e.g., cost) or periodically even if no changes (at least once every 30 minutes), carried in OSPF messages over IP. **BGP** inter-AS, provides each AS a means to: (eBGP session) obtain subnet reachability information from neighboring ASs, (iBGP session) propagate reachability information to all AS-internal routers. BGP session: two BGP routers (“peers”) exchange BGP messages over TCP connection; advertises destination network prefix (x) with BGP attributes, e.g. AS-PATH: list of ASs through which the advertisement has passed & NEXT-HOP: IP address of the interface of the router leading into next-hop AS

**Link Layer** Transferring data from one node (a host or a router) to physically adjacent node over a link (communication channel that connects two adjacent nodes along a path; wired/wireless) services: framing, link access, reliable delivery, flow control, error detection & correction, duplex (half/full). Link types: point-to-point, broadcast. **Ethernet** unreliable, connectionless; header: preamble, destination address, source address, type (higher layer protocol), payload, checksum. MAC protocol: CSMA/CD for bus/hub based or switch based half duplex, none for switch based full duplex. **Switch** receive, buffer, and forward Ethernet frames, transparent. **MPLS** high-speed forwarding of selective IP datagrams based on fixed length label instead of destination IP address; header format: PPP/Ethernet header, MPLS header (label, experimental, stack end, time to live), IP header, remainder of frame