Network Architecture

- General thoughts
- Ethernet architecture
- Internet architecture

What is Network Architecture?

- general concepts
- Ethernet architecture
- Internet architecture

- Services and APIs
  - » Ethernet – datagram broadcast
  - » IP – best-effort datagrams over internets
  - » socket programming interface
- Protocols
  - » IP, TCP, ARP, ICMP, DHCP, DNS, RIP, OSPF, BGP, . . .
- Algorithms/Mechanisms
  - » OSPF, BGP, DNS name resolution
  - » longest prefix matching, congestion control
  - » packet classification, policy-based packet handling
- Applications
  - » Telnet, FTP, WWW, overlay networks, . . .
  - » not strictly part of architecture, but motivate and shape it
- Usage patterns, operational procedures
  - » use of port numbers by applications
  - » administration of addresses

Architectural Assumptions

- Driving assumptions often implicit
  - »to understand architecture, need to make assumptions explicit
  - »effectiveness can depend on validity of assumptions
- Technology assumptions
  - »network bandwidth, processing capabilities of network elements
  - »maintaining state in network elements is hard/expensive
  - »wireless bandwidth is limited, wireless power is scarce
- Application assumptions
  - »internet for accessing expensive computing resources
  - »no one wants video conferencing
- Assumptions about user behavior
  - »hosts locations don't change
  - »exponential packet length distributions adequately model reality
  - »users will not abuse internet openness
- Poor assumptions can lead to poor design choices.
- Assumptions can become self-fulfilling prophecies.
- Validity of assumptions generally changes over time.

Expecting the Unexpected

- Successful networks grow and last a long time
  - » if objective is success, plan for “unreasonable” growth
  - » easy to under-estimate network usage and longevity
- Technology capabilities change
  - » can only predict with confidence for short term (say 10 years)
  - » best not to let near-term constraints limit future developments
  - » at same time, must be feasible in short term to succeed
- Networks get used in unexpected ways
  - » Murphy’s Law for Networks – if users can do it, they will
  - » unexpected uses can be positive (web) or negative (DoS)
  - » can constrain non-standard uses (e.g. telephone network) or encourage them (e.g. internet)
    - – even constrained nets get stretched (modems, fax , blue box)
- Aggregate behavior can emerge in strange ways
  - » flash crowds, fractal traffic characteristics

Understanding Motivations

- Evolution of public networks depends on many stakeholders with variety of motivations
- Internet service providers
  - » more customers and more “value-added” services
  - » reduce costs (equipment, installation, support)
- Equipment vendors (both systems and components)
  - » promote interest in new features
  - » use technology to drive down cost (production & development)
- Application and higher level service providers
  - » need network to reach users and deliver services
  - » network services constrain applications and quality of delivery
- Policy makers
  - » respond to constituents, lobbyists, technocrats
- Research community
  - » fame and (occasionally) fortune
- Users and consumer organizations
  - » avoiding growth in costs, ensuring broad access

Design Principles

- Can offer useful framework to guide design decisions
  - » help maintain consistency as network evolves
- Example: protocol layering
  - » each protocol layer should provide service through well-defined interface, while concealing implementation details
  - » to facilitate correct implementation and enable change
- Example: end-to-end argument
  - » network should provide only those services that cannot be provided effectively by endpoints
  - » to minimize network complexity, avoid limiting applications
- Design principles can become controversial
  - » admit variety of interpretations (QoS and end-to-end principle)
  - » purists and pragmatists often dispute their sanctity
- Changing conditions can challenge their validity
  - » are firewalls a blatant violation of e2e-ism, or an inevitable response to deficiencies in the internet architecture? Or both?

Elements of Effective Architectures

- Utility of provided services and supported applications
  - » must be useful and must be used
- Minimal barriers to usage
  - » easy for application developers to understand and use
- Scalability
  - » in number of endpoints – how big is big enough?
    - – *N* per person? what about tiny smart devices (smart dust)?
  - » in geographic scope – local, national, global, galactic
  - » performance of network elements (links, routers, end systems)
- Adaptability
  - » make effective use of new technology as it develops
  - » don't limit architecture to constraints of current technology
- External factors often determine success
  - » IP succeeded in spite of design flaws
    - – BSD Unix, NSF-net and web were key drivers in its success
  - » FDDI had significant technical advantages, but not enough to overcome Ethernet market dominance

Role of Geographic Distribution

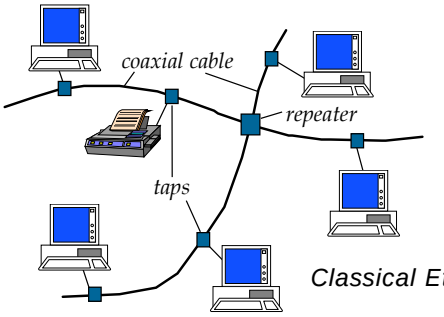
- Whole point of networks is to connect remote endpoints
- Fundamental impact of distance
  - » speed-of-light delays and impact on interactive applications
    - – for both data and control
  - » collision detection in CSMA/CD
  - » power consumption of wireless links as function of distance
- Widely distributed networks have distributed control
  - » equipment owned by individuals and organizations
  - » typically means local and variable control
  - » effective operation of the whole requires cooperation
    - – advisable to minimize aspects that require cooperation between organizations – especially if organizations are competitors
- Network connectivity
  - » constrained by technology, geography, organizational boundaries
  - » impact on how traffic flows, how failures affect communication and who makes money

Modularity in Network Architectures

- "architecture…defines how system is broken into parts & how those parts interact." – from NewArch Final Report
- Layered models used to describe network protocols
  - » useful for defining services offered by layers, and reasoning about correctness
  - » but, layer boundaries often violated for performance reasons
  - » some functions (e.g. net management) necessarily span layers
- Modules and interfaces define implementation units
  - » enable different organizations to implement different parts
  - » allow for multiple versions of given parts
- Interfaces create opportunities for new functions
  - » NAT depends on IP packet format, use of port numbers in UDP and TCP and prevalence of client-server interaction
  - » firewalls depend on application usage of port numbers
  - » usage patterns can lead to implicit interfaces

Ethernet Architecture

- general concepts
- Ethernet architecture
- Internet architecture



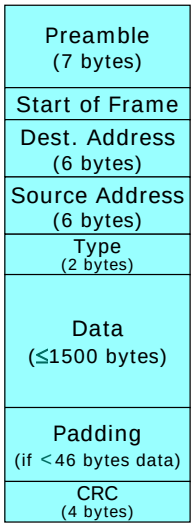
Classical Ethernet

- Designed to connect computers in building or campus
- Technology-driven architecture
  - passive coaxial cable
  - asynchronous access, synchronous transmission
  - broadcast medium
  - access using CSMA/CD
  - 10 Mb/s transmission rate with Manchester encoding

Technology and Ethernet

- Historical context in early 1970s
  - » mainframe and minicomputer era
  - » early personal workstations in research labs
- Objective to make interconnection simple
  - » manufacturer-assigned addresses, broadcast-based delivery
  - » no address administration, no routing
- Passive network cabling
  - » requires minimal planning, allowing easy expansion
  - » largely impervious to equipment failures
- Implications of technology choices
  - » need distributed arbitration method – CSMA/CD
    - – collision detection places limit on
      (data rate)(geographic reach)/(minimum packet length)
  - » asynchronous access, synchronous transmission
    - – phase-locked loops in receiving circuits had to be "trained" to lock onto sender's frequency
    - – required 7 byte *preamble* before each frame for reliable operation
    - – Manchester encoding used to help maintain frequency lock

Frame Format



- *Preamble* enables synchronization of receivers.
- *Start of Frame* marks end of preamble.
- *Address fields* identify source and destination.
  - »globally unique addresses, assigned by manufacturer of interface cards in terminals
  - »no location information provided by addresses
  - »address field of all 1's is defined as *broadcast address*
  - »*multicast addresses* specified by 1 in first address bit
    - –multicast packets distributed throughout spanning tree
    - –host Ethernet interfaces can be programmed to receive packets with specific multicast addresses
- *Type field* identifies type of data carried in frame.
- *Padding field* guarantees minimum frame length required by CSMA/CD algorithm.
  - »minimum of 72 bytes per frame of which 46 bytes can be data and 26 bytes are overhead.
  - »minimum frame duration of 57.6 μs at 10 Mb/s
- *Cyclic Redundancy Check field* (CRC) provides error detection.

Technology Evolution

- Twisted pair and passive hubs
  - » in 1980s, technology allowed Ethernet over twisted pair
  - » offices already wired in hub-spoke fashion for telephones
  - » Ethernet could use same or similar wiring
  - » for large installations, easier to manage than coax
- Bridges and switched Ethernet
  - » large Ethernets became congested
  - » first bridges were two port devices that localized traffic on different segments
    - – learned locations of hosts by observing traffic
    - – time out routing table entries to enable movement
  - » correct operation depends on absence of cycles
    - – spanning tree algorithm developed to break cycles in wiring
  - » switches evolved as multi-port generalization of bridges
  - » no change to basic protocols or packet formats
- Higher speeds (100 Mb/s, 1 Gb/s, 10 Gb/s, 100 G?)
  - » retain classical packet format
  - » more efficient transmission – 8B/6T, 4B/5B, 8B/10B, ...

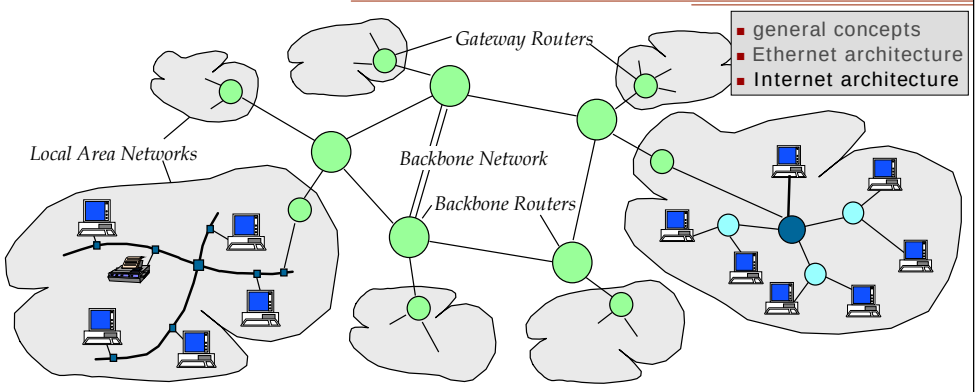
Protocol Extensions

- IEEE 802 standards developed to harmonize different LAN technologies to facilitate interoperation
  - » for Ethernet, type field replaced with *length* field and LLC-SNAP header containing type inserted after length
- Virtual LAN extension
  - » uses four byte VLAN header inserted after source address
    - – first two bytes specifies Ethertype for recognition of VLAN tag
    - – second two bytes includes 12 bit VLAN tag and 3 bit priority
  - » switches can be configured to constrain routing according to VLAN header and/or add/remove header
  - » VLAN tags define broadcast domains
  - » overlay different logical spanning trees on physical network
    - – enables expansion in overall network capacity
- Stacked VLANs and Carrier Ethernet
  - » to enable customer VLANs to be carried across carrier networks, additional VLAN header can be inserted
  - » part of industry push to extend Ethernet to WAN applications

Reflections on Ethernet

- Technical simplicity enabled inexpensive deployment while not inhibiting future extensions
  - »no real provision for extensions, but no serious obstacles
  - »evolution depended on subsequent innovations, not planning
- Open standard that displaced proprietary technologies.
  - »enabled innovation by many companies
- Dramatic improvements in network bandwidth
  - »original Ethernet took local nets from <50 Kb/s to 10 Mb/s
  - »subsequent upgrades now deliver 10 Gb/s at <$1K/switch port
- Innovation in addressing
  - »unprecedented to devote 12 bytes to addressing
  - »eliminated most system administration
- Use of broadcast foundation a mixed blessing
  - »simplicity key to initial success
  - »scaling up requires VLANs and remains awkward
  - »in switched environment multicast usage limited, since broadcast required

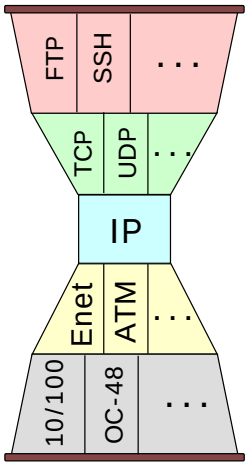
IP and the Internet



- general concepts
- Ethernet architecture
- Internet architecture

- An *internet* is a "network of networks" in which *routers* move data among a multiplicity of networks.
  - heterogenous network types, multiple admin. domains
- The Internet use the *Internet Protocol* (IP).
  - *datagram* protocol with variable length packets and structured addressing

The Internet Hourglass



- IP as the narrow waist.
- Diversity above IP
  - » transport protocols
  - » applications
- Diversity below IP
  - » LANs – Ethernet, FDDI, ATM, 802.11,
  - » physical medium – 10/100, OC-48, wireless

Design Principles (from NewArch report)

- Packets are fundamental unit of multiplexing
  - » not circuits, not virtual circuits, not cells
- Transparency – what goes in, comes out
  - » no format conversions or other processing by network
- Universal connectivity as default state
- Immediate delivery
  - » continuous connectivity, no long-term storage
- End-to-end principles
  - » generality – network knows nothing about applications
  - » robustness – if end nodes can do something, it's left to them
  - » fate-sharing – loss of state information for specific flow should coincide with loss of application
- Loose semantics
  - » best-effort delivery only – no performance guarantees
- Subnet heterogeneity
  - » assume little, so can use any subnet technology (almost)

More Design Principles

- Common bearer service
  - » best-effort, connectionless datagram service
  - » exceptions: source routing, multicast, IntServ
  - » no separate access protocol – e.g. no user-network interface
- Connectionless network mechanism
  - » no per-flow state in routers
  - » exceptions: multicast, IntServ
- Global addressing
  - » globally unique addresses, hierarchically organized for routing
  - » exception: NAT
- Protocol layering
  - » provide modularity of functions – use “header stacking”
  - » frequently violated in practice
- Distributed control
  - » no single point of failure

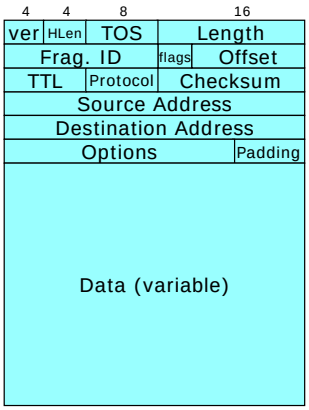
Still More Design Principles

- Global routing computation
  - » to support consistent, loop-free packet delivery using destination addresses
- Multiple administrative regions (domains)
  - » two level routing computation – inter-domain & intra-domain
  - » may add additional levels within domain using OSPF
- Mobility
  - » optimized for fixed host locations
  - » mobile hosts accommodated using compatible extensions
- Network security
  - » protection from eavesdropping is left to end-systems
  - » no protection from denial-of-service
- Resource allocation
  - » end-systems should back-off in presence of congestion
  - » network provides enough buffering for e2e congestion control
  - » Internet provides for QoS through IntServ and DiffServ
  - » no architected support for payment-for-service

Last and Perhaps Least

- Minimal dependency
  - » a minimal set of features sufficient for end-to-end packet delivery
  - » endpoints can communicate directly without intervening router

IP Packet Format (v4)



- *Version number* specifies the version of the IP protocol and determines packet format.
  - » version 6 is similar to v4 but uses longer addresses
- *Header Length* (HLen) gives number of 32 bit words in header.
- *Type of Service* (TOS) field can be used to allow application-specific treatment of packets.
- *Fragmentation Identifier, flags* and *Offset* used for fragmentation and reassembly of IP packets.
- *Time-to-live* (TTL) specifies the remaining number of hops before packet should be discarded.
  - » prevents infinite looping of packets
- *Protocol* used for demultiplexing at destination.
- *Checksum* for end-to-end error detection.
- *Address* fields specify source and destination.
  - » hierarchical address structure, CIDR
- *Options* are rarely used but must be supported in complete IP protocol implementations.
- TCP adds 40 bytes more, including port numbers.

Internet Architecture Review

- Best-effort, unicast datagram delivery service
  - » least-common denominator
    - – only service one can really count on
  - » usage of some elements discouraged (fragments, options)
  - » effective sender anonymity raises fundamental security issues
- End-to-end transport services
  - » defined by TCP, UDP and socket interface
  - » most applications use TCP's *connection-oriented* service
  - » TCP congestion control has led to unintended dependencies
    - – router buffers sized to accommodate TCP behavior
    - – de facto requirement for in-order delivery, stable routes and links with low packet loss
    - – routers preemptively signal congestion by discarding packets
    - – expectation that non-TCP protocols be TCP-friendly
  - » TCP's use of port numbers
    - – forces specific application style (servers listening on ports)
    - – requires global administration of port numbers
    - – allows network to identify application

Internet Architecture Review

- Applications
  - » email – POP, IMAP, SMTP, web-mail
    - – server-based architecture needed for storage since network does not support deferred delivery
  - » WWW – http, html, xml, CGI, javascript,...
    - – html made publication easy, browsers made it attractive to users
    - – combination triggered explosion in content creation
  - » emerging(?) applications
    - – voice – slow to develop due to poor QoS support, competing options
    - – real-time video broadcast – multicast deployment obstacles
    - – interactive video – poor QoS and limited market interest
    - – is cheap bandwidth & better queueing enough to overcome hurdles?
- Control and management – ICMP
  - » error reporting (destination unreachable, TTL expiration, ...)
    - – includes original packet's IP header + 8 bytes of payload
    - – unplanned uses – traceroute, distributed measurement efforts
  - » miscellaneous other uses
    - – echo (ping), redirect, source quench, timestamp

Internet Architecture Review

- Naming and addressing
  - » originally, IP addresses used to identify hosts – DNS added later
  - » DNS maintains (name, value) pairs of various types
  - » distributed management with extensive use of caching to speed up responses
  - » an organization's name server can use DNS to enables dynamic load balancing across servers
  - » availability of root DNS servers and correctness of DNS records is critical to Internet operation
    - – original approach statically configured records – correctness depends on trusted communication among system administrators
    - – dynamic update mechanism raises security issues – who to trust?
- Connection and address assignment – DHCP
  - » hosts discover location of DHCP server using broadcast
    - – large installations require a relay agent in each network
  - » automates address assignment in local networks
  - » enables convenient handling of mobile computers
  - » enabled by separation of names from addresses

Internet Architecture Review

- Address space conservation – NAT
  - » observation of TCP setup process, port number translation
- IP and Ethernet – ARP
  - » automates location of host with given IP address
  - » leverages broadcast feature of Ethernet
- Routing – RIP, OSPF, BGP
  - » fully distributed route computation for robustness
  - » less distributed computation may work better
  - » shortest path routing makes it difficult to distribute traffic
  - » BGP's policy-based routing leads to suboptimal decisions and is difficult to stabilize
- Management – SNMP
  - » defines management information for individual components and mechanisms to retrieve it
  - » no consistent framework for managing network as a whole

Internet Architecture Review

- Mobility – mobile IP (v4 and v6)
  - » compatibility requirement makes it inefficient, awkward to use
  - » DHCP suffices for most common cases
    - – big exception: wireless IP phones
- Multicast – IGMP, DVMRP, MOSPF, CBT, PIM, BGMP
  - » plethora of approaches, limited deployment
  - » scalability concerns for reverse path forwarding
  - » little economic motivation for ISPs
- Reservation & QoS – IntServ, RSVP, DiffServ, SIP, RTP
  - » remains incomplete, blocked by scalability concerns, association with multicast, inadequate handling of inter-domain issues,...
  - » reservation may require pay-for-service model
- Traffic Engineering – MPLS/GMPLS, RSVP-TE
  - » enable better management of carrier networks
  - » RSVP used to signal label-switched paths
  - » no provision for end-to-end signaling

Reflections on IP Architecture

- Secrets of its success
  - » the Internet idea – diversity above, diversity below
  - » Ethernet, Berkeley Unix, NSF-net, email, WWW
  - » ferocious advocacy – IP vs. the world (OSI, ATM)
- What started out simple has become complex
  - » many moving parts (some fairly complex), subtle interactions
  - » routers need large set of mechanisms to implement full IP protocol suite – many are never used (probably a good thing)
  - » open trust model problematical in large public internet
- Technical deficiencies yet to be adequately addressed
  - » address space limitations
  - » users' inability to control traffic they receive
  - » support for mobile devices
  - » quality of service, multicast
- In many cases, real issue is deployment obstacles
  - » cost to upgrade equipment
  - » need for universal agreement

General Lessons

- Beware assumptions
- Successful networks become complex
  - » diverse stakeholders, new requirements, scale, security
- Building a truly general-purpose network is hard
  - » least-common denominator approach hard to sustain
  - » unconstrained featurism leads to complex interactions, subtle dependencies and ossification
- The Internet idea is powerful, compelling, essential
  - » key question is what lies at the narrow waist
- Impact of technology profound, but uneven
  - » bandwidth becoming more plentiful
  - » extensive processing possible, even at gigabit rates
- Importance of wireless and/or mobile endpoints
  - » fixed nodes becoming a small minority of total
  - » need addressing mechanisms better suited to wireless devices
- Security a key concern for public networks
  - » should insecure nets remain an option?