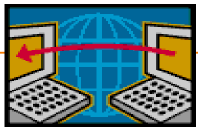

Internet Design: Goals and Principles

EE122 Fall 2012

Scott Shenker

http://inst.eecs.berkeley.edu/~ee122/

Materials with thanks to Jennifer Rexford, Ion Stoica, Vern Paxson and other colleagues at Princeton and UC Berkeley

Administrivia

- New Office Hours:
  - Thursday 12:00-1:00 in 415 **or** 420 (come find me!)
  - After class on Tuesdays: walk with me to Soda
- Class going more slowly than anticipated
  - Will pivot to real material, skipping some nonessentials
- Lecture on September 18
  - Will be returning from Moscow that day
- Homework #1 released (note submission process)
  - Due in two weeks….this should ***not*** be hard
  - Project #1 will follow shortly
  - Guesses about dates for future assignments now online

Outline

- Design Goals
- Modularity
- Layering
- End-to-End Principle
- Fate-Sharing

Internet Design Goals

David Clark

- Wrote a paper in 1988 that tried to capture why the Internet turned out as it did
- In particular, it described an ordered list of priorities that informed the design
- We have him with us here today….Eastwood-style

Internet Design Goals (Clark '88)

- **Connect existing networks**
- Robust in face of failures
- Support multiple types of delivery services
- Accommodate a variety of networks
- Allow distributed management
- Easy host attachment
- Cost effective
- Allow resource accountability

Connect Existing Networks

- Wanted single protocol that could be used to connect any pair of (existing) networks
- The Internet Protocol (IP) is that unifying protocol
  - All (existing) networks must be able to implement it
- This is where the need for best effort arose….

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Robust

- As long as network is not partitioned, two hosts should be able to communicate (eventually)
- Failures (excepting network partition) should not interfere with endpoint semantics
- *Very successful, not clear how relevant now*
  - Availability more important than recovering from disaster
- *Second notion of robustness is underappreciated*
  - Key to modularity of Internet

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Types of Delivery Services

- Use of the term "delivery services" already implied an application-neutral network
- Built lowest common denominator service
  - Allow end-based protocols to provide better service
  - For instance, turn unreliable service into reliable service
- Example: recognition that TCP wasn't needed (or wanted) by some applications
  - Separated TCP from IP, and introduced UDP

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Variety of Networks

- Incredibly successful!
  - Minimal requirements on networks
  - No need for reliability, in-order, fixed size packets, etc.
  - A result of aiming for lowest common denominator
- IP over everything
  - Then: ARPANET, X.25, DARPA satellite network..
  - Now: ATM, SONET, WDM…

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Decentralized Management

- Both a curse and a blessing
  - Important for easy deployment
  - Makes management hard today

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Host Attachment

- Clark observes that cost of host attachment may be higher because hosts have to be smart
- But the administrative cost of adding hosts is very low, which is probably more important
  - Plug-and-play kind of behavior….

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Cost Effective

- Cheaper than circuit switching at low end
- More expensive than circuit switching at high end
- Not a bad compromise:
  - Cheap where it counts (low-end)
  - More expensive for those who can pay….

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Resource Accountability

- Failure!

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Internet Motto

We reject kings, presidents, and voting. We believe in rough consensus and running code."

David Clark

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Real Goals

- **Build something that works!**
- Connect existing networks
- Robust in face of failures
- Support multiple types of delivery services
- Accommodate a variety of networks
- Allow distributed management
- Easy host attachment
- Cost effective
- Allow resource accountability

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Questions to think about….

- What priorities would a commercial design have?
- What would the resulting design look like?
- What goals are missing from this list?

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Modularity

Modularity in Computer Science

"Modularity based on abstraction is the way things get done"

--Barbara Liskov

The Role of Modularity

- We can't build big systems out of spaghetti code
  - Impossible to understand, debug
  - Hard to update
- We need to limit the scope of changes, so that we can update system without rewriting it from scratch
- Modularity is how we limit the scope of changes
  - And understand the system at a higher level

Computer System Modularity

- Partition system into modules
  - Each module has well-defined interface
- Interfaces give flexibility in implementation
  - Changes have limited scope
- Examples:
  - Libraries encapsulating set of functionality
  - Programming language abstracts away CPU
- The trick is to find the *right* modularity
  - The interfaces should be long-lasting
  - If interfaces are changing often, modularity is wrong

Finding the Right Modularity

- Decompose problem into tasks or abstractions
  - Task: *e.g.*, compute a function
  - Abstraction: *e.g.*, provide reliable storage
- Define a module for each task/abstraction
  - Involves defining a clean interface for each module
  - "Clean" means hiding unnecessary details
- Implement system a few times:
  - If interfaces seem to hold, you are on the right track…

Network System Modularity

- The need for modularity still applies
  - **And is even more important!** (why?)
- Network implementations not just distributed across many lines of code
  - Normal modularity "organizes" that code
- *Networking is distributed across many machines*
  - Hosts
  - Routers

Network Modularity Decisions

- How to break system into modules?
  - Classic decomposition into tasks
- Where are modules implemented?
  - Hosts?
  - Routers?
  - Both?
- Where is state stored?
  - Hosts?
  - Routers?
  - Both?

Leads to three design principles

- How to break system into modules?
  - **Layering**
- Where are modules implemented?
  - **End-to-End Principle**
- Where is state stored?
  - **Fate-Sharing**

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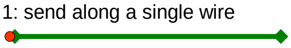
Layering

Tasks in Networking

- What does it take to send packets across country?
- Simplistic decomposition:
  - Task 1: send along a single wire



  - Task 2: stitch these together to go across country

- This gives idea of what I mean by decomposition
  - Next slide presents a much more detailed version

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Tasks in Networking (bottom up)

- Electrons on wire
- Bits on wire
- Packets on wire
- Deliver packets across local network
  - Local addresses
- Deliver packets across country
  - Global addresses
- Ensure that packets get there
- Do something with the data

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Resulting Modules (layers)

- Electrons on wire (contained in next layer)
- **Bits on wire (Physical)**
- Packets on wire (contained in next layer)
- **Deliver packets across local network (Datalink)**
  - Local addresses
- **Deliver packets across country (Network)**
  - Global addresses
- **Ensure that packets get there (Transport)**
- **Do something with the data (Application)**

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Five Layers (top-down)

- **Application**: Providing network support for apps
- **Transport (L4)**: (Reliable) end-to-end delivery
- **Network (L3)**: Global best-effort delivery
- **Datalink (L2)**: Local best-effort delivery
- **Physical**: Bits on wire
- Interactions between these components?
  - Do all components talk to each other?
  - Or are the components limited in their interactions?
- Answer: they are strictly ***layered***!

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Strictly Layered Dependencies

Applications

...built on...

Reliable (or unreliable) transport

...built on...

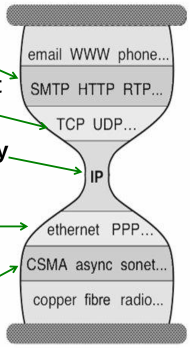
Best-effort global packet delivery

...built on...

Best-effort local packet delivery

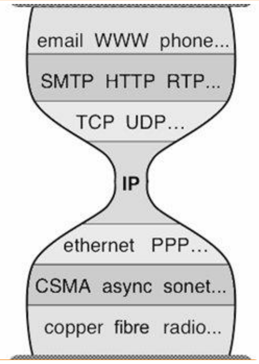
...built on...

Physical transfer of bits



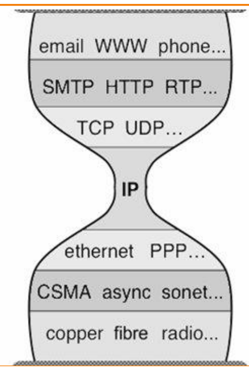
Three Observations

- Each layer:
  - Depends on layer below
  - Supports layer above
  - Independent of others
- Multiple versions in layer
  - Interfaces differ somewhat
  - Components pick which lower-level protocol to use
- But only one IP layer
  - Unifying protocol



Layering Crucial to Internet's Success

- Innovation at most levels
  - Applications (lots)
  - Transport (few)
  - Datalink (few)
  - Physical (lots)
- Innovation proceeded largely in parallel
- Pursued by very different communities
  - Like PL and chip designs



Distributing Layers Across Network

- Layers are simple if only on a single machine
  - Just stack of modules interacting with those above/below
- But we need to implement layers across machines
  - Hosts
  - Routers (switches)
- What gets implemented where?

What Gets Implemented on Host?

- Bits arrive on wire, must make it up to application
- Therefore, all layers must exist at host!

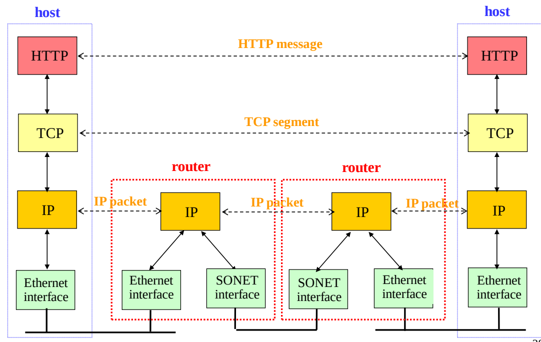
What Gets Implemented on Router?

- Bits arrive on wire
  - Physical layer necessary
- Packets must be delivered to next-hop
  - Datalink layer necessary
- Routers participate in global delivery
  - Network layer necessary
- Routers don't support reliable delivery
  - Transport layer (and above) ***not*** supported

What Gets Implemented on Switches?

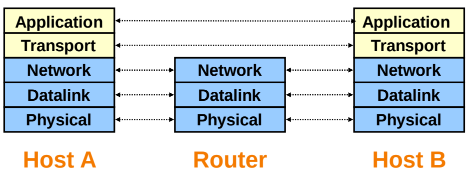
- Switches do what routers do, except they don't participate in global delivery, just local delivery
- They only need to support Physical and Datalink
  - Don't need to support Network layer
- Won't focus on the router/switch distinction
  - When I say switch, I almost always mean router
  - Almost all boxes support network layer these days

Complicated Diagram



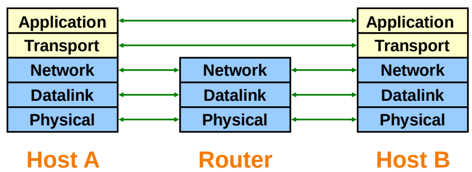
Simple Diagram

- Lower three layers implemented everywhere
- Top two layers implemented only at hosts



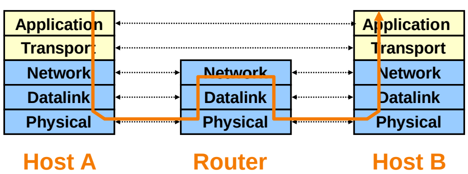
Logical Communication

- Layers interacts with peer's corresponding layer

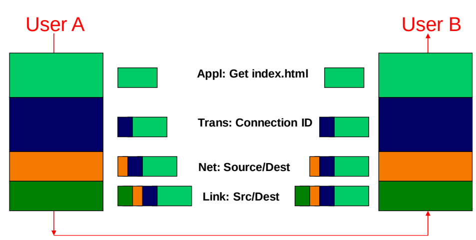


Physical Communication

- Communication goes down to physical network
- Then from network peer to peer
- Then up to relevant layer



Layer Encapsulation



Common case: 20 bytes TCP header + 20 bytes IP header + 14 bytes Ethernet header = *54 bytes overhead*

Example of Layering in the Real World

- CEO A writes letter to CEO B
  - Folds letter and hands it to administrative aide
- Aide:
  - Puts letter in envelope with CEO B's full name
  - Takes to FedEx
- FedEx Office
  - Puts letter in larger envelope
  - Puts name and street address on FedEx envelope
  - Puts package on FedEx delivery truck
- FedEx delivers to other company

Dear John,

Your days are numbered.

--Pat

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The Path of the Letter

"Peers" on each side understand the same things
No one else needs to
Lowest level has most packaging

CEO → Aide → FedEx → FedEx → Aide → CEO

Semantic Content / Letter

Identity / Envelope

Fedex Envelope (FE) / Location

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The Path Through FedEx

Higher "Stack" at Ends

Partial "Stack" During Transit

Highest Level of "Transit Stack" is Routing

Truck → FE → Sorting Office → Crate → Airport → Sorting Office (Crate, New Crate, FE) → Airport → Sorting Office → FE → Truck

Deepest Packaging (Envelope+FE+Crate) at the Lowest Level of Transport

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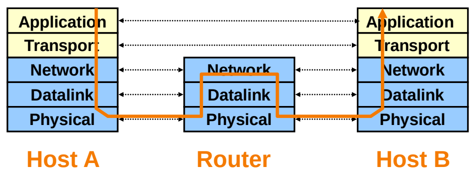
Back to Networking Picture

- Communication goes down to physical network
- Then from network peer to peer
- Then up to relevant layer



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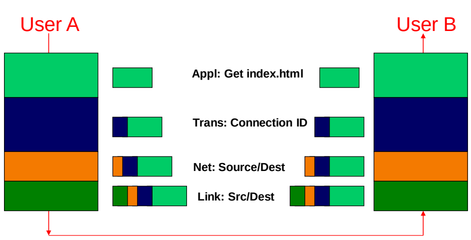
Back to Encapsulation (Headers)



Common case: 20 bytes TCP header + 20 bytes IP header + 14 bytes Ethernet header = *54 bytes overhead*

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Five Minute Break….

Three Internet Design Principles

- How to break system into modules?
  - Layering
- **Where are modules implemented?**
  - **End-to-End Principle**
- Where is state stored?
  - Fate-Sharing

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The End-to-End Principle

Everyone believes it, but no one knows what it means…..

Placing Network Functionality

- Influential paper: “End-to-End Arguments in System Design” by Saltzer, Reed, and Clark (‘84)
  - End-to-end principle
- Basic observation: some types of network functionality can only be correctly implemented ***end-to-end***
- In these cases, end hosts:
  - **Can** satisfy the requirement without network’s help
  - **Must** do so, since can’t ***rely*** on network’s help
- Thus, **don’t** need to implement them in network
  - *Debate about what the network does and doesn’t do…*

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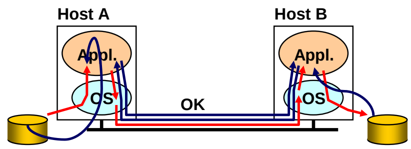
Example: Reliable File Transfer



- Solution 1: make each step reliable, and string them together to make reliable end-to-end process
- Solution 2: allow steps to be unreliable, but do end-to-end **check** and try again if necessary

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Discussion

- Solution 1 cannot be made perfectly reliable
  - What happens if a network element misbehaves?
  - Receiver has to do the check anyway!
- Solution 2 can also fail, but only if the end system itself fails (i.e., doesn’t follow its own protocol)
- Solution 2 only relies on what it can control
  - The endpoint behavior
- Solution 1 requires endpoints trust other elements
  - That’s not what reliable means!

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Robust (From Clark’s Paper)

- As long as the network is not partitioned, two endpoints should be able to communicate
- Failures (excepting network partition) should not interfere with endpoint semantics

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Question?

- Should you ever implement reliability in network?
- Perhaps, if needed for reasonable efficiency
  - Don't aim for perfect reliability, but ok to reduce error rate
- If individual links fail 10% of the time, and are traversing 10 links, then E2E error rate is 65%
- Implementing one retransmission on links
  - Link error rate reduced to 1%, E2E error rate is 9.5%

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Back to the End-to-End Principle

Implementing such functionality in the network:

- Doesn't reduce host implementation complexity
- Does increase network complexity
- Often imposes delay/overhead on all applications, **even if they don't need functionality**
- However, implementing in network can enhance performance in some cases
  - E.g., very lossy link
- Three interpretations of the end-to-end principle

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"Only-if-Sufficient" Interpretation

- Don't implement a function at the lower levels of the system unless it can be completely implemented at this level
- *Unless you can relieve the burden from hosts, don't bother*

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"Only-if-Necessary" Interpretation

- Don't implement *anything* in the network that can be implemented correctly by the hosts
  - E.g., multicast
- Make network layer absolutely minimal
  - This E2E interpretation trumps performance issues
  - Increases flexibility, since lower layers stay **simple**

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"Only-if-Useful" Interpretation

- If hosts can implement functionality correctly, implement it in a lower layer only as a performance enhancement
- But do so only if it does not impose burden on applications that do not require that functionality

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What Does E2E Principle Ignore?

- There are other stakeholders besides users
  - ISP might care about the good operation of their network
  - Various commercial entities
  - Money-chain might require insertion into the network
- The need for middlebox functionality
  - Some functions that, for management reasons, are more easily done in the network.

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Three Internet Design Principles

- How to break system into modules?
  - Layering
- Where are modules implemented?
  - End-to-End Principle
- **Where is state stored?**
  - **Fate-Sharing**

Fate-Sharing

Fate-Sharing

- Note that E2E principles relied on “fate-sharing”
  - Invariants break only when endpoints themselves break
  - Minimize dependence on other network elements
- This should dictate placement of storage

General Principle: *Fate-Sharing*

- When storing state in a distributed system, co-locate it with entities that rely on that state
- Only way failure can cause loss of the critical state is if the entity that cares about it also fails ...
  - … in which case it doesn’t matter
- Often argues for keeping *network state* at end hosts rather than inside routers
  - In keeping with End-to-End principle
  - E.g., packet-switching rather than circuit-switching
  - E.g., NFS file handles, HTTP “cookies”

A Cynical View of Distributed Systems

“A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable”

---Leslie Lamport

Decisions and Their Principles

- How to break system into modules
  - **Dictated by Layering**
- Where modules are implemented
  - **Dictated by End-to-End Principle**
- Where state is stored
  - **Dictated by Fate-Sharing**

Question

- If reliability is implemented by the ends, how is it done?
- That’s the subject of the next lecture!