Chair for Network Architectures and Services – Prof. Carle
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Master Course Computer Networks IN2097

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Architecture: the big picture

Architecture: the big picture

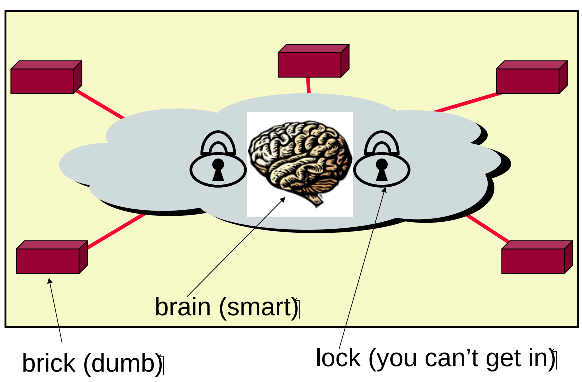
Goals:
- identify, study principles that can guide network architecture
- "bigger" issues than specific protocols or implementation wisdom,
- *synthesis:* the *really* big picture

Overview:
- Internet design principles
- rethinking the Internet design principles
- packet switching versus circuit switching revisited

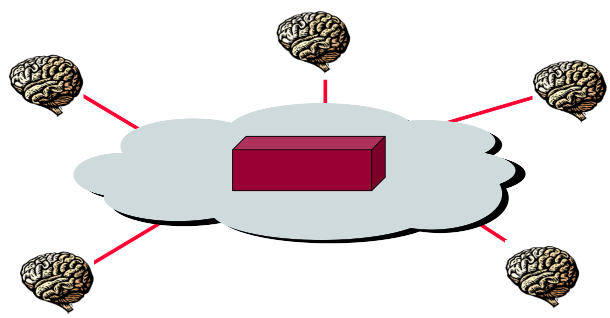
Key questions

- How to decompose the complex system functionality into protocol layers?
- Which functions placed *where* in network, at which layers?
- Can a function be placed at multiple levels?
- Answer these questions in context of
  - Internet
  - Telephone network
    (Nickname 1: Telco — telecommunications provider)
    (Nickname 2: POTS — "plain old telephone system")

Common View of the Telco Network: Smart network, dumb endpoints



Common View of the IP Network: Dumb network, smart end hosts

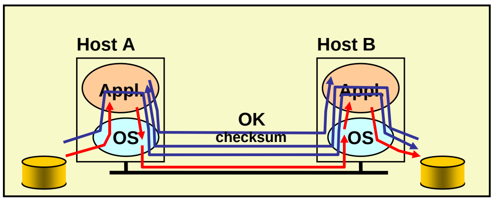


The Internet End-to-End principle

Internet End-to-End Principle

- "…functions placed at the lower levels may be *redundant* or of *little value* when compared to the cost of providing them at the higher level…"
- "…sometimes an *incomplete* version of the function provided by the communication system (lower levels) may be useful as a *performance enhancement*…"
- This leads to a philosophy diametrically opposite to the telephone world of dumb end-systems (the telephone) and intelligent networks.

Example: Reliable File Transfer



- Solution 1: make each step reliable, and then concatenate them
- Solution 2: each step unreliable: end-to-end check and retry (…the Internet way)

Discussion

- Is solution 1 good enough?
  - No — what happens if components on path fail or misbehave (bugs)?
- Is reliable communication sufficient:
  - No — what happens if disk errors?
- So need application to make final correctness check anyway!
- Thus, full functionality can be entirely implemented at application layer; *no* need for reliability from lower layers

Discussion

Q: Is there any reason to implement reliability at lower layers?

A: YES: "easier" (and more efficient) to check and recovery from errors at each intermediate hop

- e.g.: faster response to errors, localized retransmissions
- Concrete example: Error correction on wireless links (in spite of TCP packet loss detection)

Trade-offs

- application has more information about the data and semantics of required service (e.g., can check only at the end of each data unit)
- lower layer has more information about constraints in data transmission (e.g., packet size, error rate)
- *Note:* these trade-offs are a direct result of layering!

Internet & End-to-End Argument

- Network layer provides one simple service: best effort datagram (packet) delivery
- Transport layer at network edge (TCP) provides end-end error control
  - Performance enhancement used by many applications (which could provide their own error control)
- All other functionality …
  - *All* application layer functionality
  - Network services: DNS
  - ⇨ Implemented at application level

Internet & End-to-End Argument

- Discussion: congestion control, flow control: why at transport, rather than link or application layers?
- congestion control needed for many applications (assumes reliable application-to-TCP data passing)
- many applications "don't care" about congestion control – it's the network's concern
- consistency across applications — you ***have*** to use it if you use TCP (social contract — everybody does)
- why do it at the application level
  - Flow control — application knows how/when it wants to consume data
  - Congestion control — application can do TCP-friedly congestion control

Internet & End-to-End Argument

- Discussion: congestion control, flow control: Why not at the link layer?
  1. Not every application needs it/wants it
  2. Lots of state at each router (each connection needs to buffer, need back pressure) — it's hard
  3. Congestion control in the entire network, e.g., load-adaptive dynamic IP routing? — multiple reasons against it:
     - hard to do
     - prone to oscillations
     - didn't work out in ARPANET → "never again" attitude

E2E Argument: Interpretations

- One interpretation:
  - A function can only be completely and correctly implemented with the knowledge and help of the applications *standing at the communication endpoints*
- Another: (more precise…)
  - A system (or subsystem level) should consider only functions that can be *completely and correctly* implemented within it.
- Alternative interpretation: (also correct …)
  - Think twice before implementing a functionality that you believe that is useful to an application at a lower layer
  - If the application can implement a functionality correctly, implement it a lower layer *only* as a performance enhancement

End-to-End Argument: Critical Issues

- End-to-end principle emphasizes:
  - *function placement*
  - *correctness, completeness*
  - *overall system costs*
- Philosophy: if application can do it, don't do it at a lower layer — application best knows what it needs
  - add functionality in lower layers iff (1) used by and improves performances of many applications, (2) does not hurt other applications
- allows *cost-performance* tradeoff

End-to-End Argument: Discussion

- End-end argument emphasizes correctness & completeness, but does not emphasize…:
  - *complexity:* Does complexity at edges result in a "simpler" architecture?
  - *evolvability:* Ease of introduction of new functionality; ability to evolve because easier/cheaper to add new edge applications than to change routers?
  - *technology penetration:* Simple network layer makes it "easier" for IP to spread everywhere

Internet Design Philosophy (Clark' 88)

In order of importance:

Different ordering of priorities would make a different architecture!

0. Connect existing networks
   - initially ARPANET, ARPA packet radio, packet satellite network
1. Survivability
   - ensure communication service even with network and router failures
2. Support multiple types of services
3. Must accommodate a variety of networks
4. Allow distributed management
5. Allow host attachment with a low level of effort
6. Be cost effective
7. **Allow resource accountability**

1. Survivability

- Continue to operate even in the presence of network failures (e.g., link and router failures)
  - as long as network is not partitioned, two endpoints should be able to communicate
  - any other failure (excepting network partition) should be transparent to endpoints
- Decision: maintain end-to-end transport state only at end-points
  - eliminate the problem of handling state inconsistency and performing state restoration when router fails
- Internet: stateless network-layer architecture
  - No notion of a session/call at network layer
  - Example: Your TCP connection shouldn't break when a router along the path fails
- Assessment: ??

2. Types of Services

- Add UDP to TCP to better support other apps
  - e.g., "real-time" applications
- arguably main reason for separating TCP, IP
- datagram abstraction: lower common denominator on which other services can be built
  - service differentiation was considered (remember ToS field in IP header?), but this has never happened on the large scale (Why?)
- Assessment: ?

3. Variety of Networks

- Very successful (why?)
  - because the minimalist service; it requires from underlying network only to deliver a packet with a "reasonable" probability of success
- …does not require:
  - reliability
  - in-order delivery
- The mantra: IP over everything
  - Then: ARPANET, X.25, DARPA satellite network..
  - Subsequently: ATM, SONET, WDM…
- Assessment: ?

Other Goals

- Allow distributed management
  - Administrative autonomy: IP interconnects networks
    - each network can be managed by a different organization
    - different organizations need to interact only at the boundaries
    - … but this model complicates routing
  - Assessment: ?
- Cost effective
  - sources of inefficiency
    - header overhead
    - retransmissions
    - routing
  - …but "optimal" performance never been top priority
  - Assessment: ?

Other Goals (Cont)

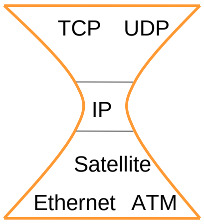
- Low cost of attaching a new host
  - not a strong point → higher than other architecture because the intelligence is in hosts (e.g., telephone vs. computer)
  - bad implementations or malicious users can produce considerably harm (remember fate-sharing?)
  - Assessment: ?
- Accountability
  - Assessment: ?

What About the Future?

- Datagram not the best abstraction for:
  - resource management, accountability, QoS
- new abstraction: flow (see IPv6)
  - Typically: (src, dst, #bytes) tuple
  - But: "flow" not precisely defined
    - when does it end? Explicit connection teardown? Timeout?
    - *src* and *dst* =...? ASes? Prefixes? Hosts? Hosts&Protocol?
  - IPv6: difficulties to make use of flow IDs
- routers require to maintain per-flow state
- state management: recovering lost state is hard
- in context of Internet (1988) we see the first proposal of "soft state"!
  - soft-state: end-hosts responsible to maintain the state

Summary: Internet Architecture

- packet-switched datagram network
- IP is the glue (network layer overlay)
- IP hourglass architecture
  - all hosts and routers run IP
- stateless architecture
  - no per flow state inside network



IP hourglass

Summary: Minimalist Approach

- Dumb network
  - IP provide minimal functionalities to support connectivity
  - addressing, forwarding, routing
- Smart end systems
  - transport layer or application performs more sophisticated functionalities
  - flow control, error control, congestion control
- Advantages
  - accommodate heterogeneous technologies (Ethernet, modem, satellite, wireless, ...)
  - support diverse applications (telnet, ftp, Web, X windows)
  - decentralized network administration

But that was yesterday

……. what about tomorrow?

Rethinking Internet Design

What's changed?

- operation in untrustworthy world
  - endpoints can be malicious: Spam, Worms, (D)DoS, ...
  - If endpoint not trustworthy, but want trustworthy network ⇨ more mechanisms in network core
- more demanding applications
  - end-to-end best effort service not enough
  - new service models in network (IntServ, DiffServ)?
  - new application-level service architecture built on top of network core (e.g., CDN, P2P)?

Rethinking Internet Design

What's changed (cont.)?

- ISP service differentiation
  - ISP doing more (than other ISPs) in core is competitive advantage
- Rise of third party involvement
  - interposed between endpoints (even against will)
  - e.g., Chinese government, recording industry, Vorratsdatenspeicherung
- less sophisticated users

All five changes motivate shift away from end-to-end!

What's at stake?

"At issue is the conventional understanding of the "Internet philosophy"

- freedom of action
- user empowerment
- end-user responsibility for actions taken
- lack of control *"in"* the net that limit or regulate what users can do

The end-end argument fostered that philosophy because they enable the freedom to innovate, install new software at will, and run applications of the users choice."

[Blumenthal and Clark, 2001]

Technical response to changes

- Trust: emerging distinction between what is "in" network (*us*, trusted) and what is not (*them*, untrusted).
  - ingress filtering
  - emergence of Internet UNI (user network interface, as in ATM)?
- Modify endpoints
  - harden endpoints against attack
  - endpoints/routers do content filtering: Net-nanny
  - CDN, ASPs: rise of structured, distributed applications in response to inability to send content (e.g., multimedia, high bw) at high quality

Technical response to changes

- Add functions to the network core:
  - filtering firewalls
  - application-level firewalls
  - NAT boxes
  - active networking

… All operate within network, making use of application-level information
  - which addresses can do what at application level?
  - If addresses have meaning to applications, NAT must "understand" that meaning

Epilogue: will IP take over the world?

- Reasons for success of IP:
  - *reachability:* reach every host; adapts topology when links fail.
  - *heterogeneity:* single service abstraction (best effort) regardless of physical link topology
- many other claimed (or commonly accepted) reasons for IP's success may not be true

  …. let's take a closer look

1. IP already dominates global communications?

- business revenues (in US$, 2007):
  - ISPs: 13B
  - Broadcast TV: 29B
  - Cable TV: 29.8B
  - Radio broadcast: 10.6B
  - Phone industry: 268B
- Router/telco switch markets:
  - Core router: 1.7B; edge routers: 2.4B
  - SONET/SDH/WDM: 28B, Telecom MSS: 4.5B

Q: IP equipment cheaper? Economies of scale? (lots of routers?)

Q: per-device, IP is cheaper (one line into house, multiple devices)

Q: # bits carried in each network?

Q: Internet, more traffic and congestion is spread among all users (bad?)

2. IP is more efficient?

- Statistical multiplexing versus circuit switching
- Link utilization:
  - Avg. link utilization in Internet core: 3% to 30% (ISPs: never run above 50%!)
  - Avg. utilization of Ethernet is currently 1%
  - Avg. link utilization of long distance phone lines: 33%
- low IP link utilization: purposeful!
  - predictability, stability, low delay, resilience to failure
  - at higher utilization: traffic spikes induce short congestion periods → deterioration of QoS
- At low utilization, we loose benefits of statistical multiplexing!

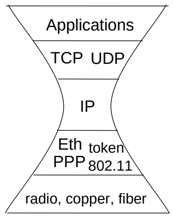
3. IP is more robust?

- "Internet was built to sustain a nuclear war" — marketing vapor!
  - Remember large-scale network outages, e.g. on Sep 11th 2001?
- Median IP network availability: downtime: 471 min/yr
- Avg. phone network downtime: 5 min/yr
- Convergence time with link failures:
  - BGP: ≈ 3–15 min, intra-domain: ≈ 0.1–1 s (e.g., OSPF)
  - SONET: 50 ms
- Inconsistent routing state
  - human misconfigurations
  - in-band signaling (signaling and data share same network)
  - routing computation "complex"

4. IP is simpler?

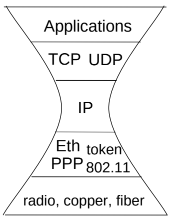
- Intelligence at edge, simplicity in core
  - Cisco IOS: 8M lines of code
  - Telephone switch: 3M lines of code
- Linecard complexity:
  - Router: 30M gates in ASICs, 1 CPU, 300M packet buffers
  - Switch: 25% of gates, no CPU, no packet buffers

Big picture: Original idea, the IP hour glass figure

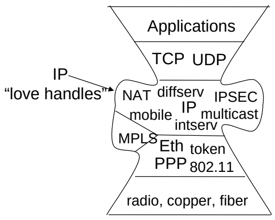


IP “hourglass”

Big picture: supporting new applications – losing the IP hour glass figure? (1)

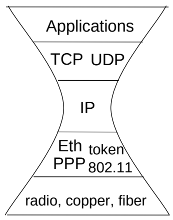


IP “hourglass”

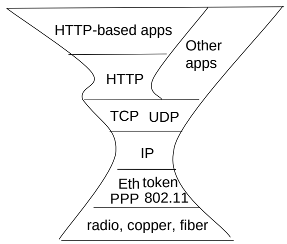


Middle-age IP = “hourglass” ?

Big picture: supporting new applications – losing the IP hour glass figure? (2)

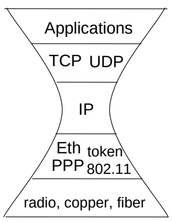


Original idea:
IP is greatest common denominator

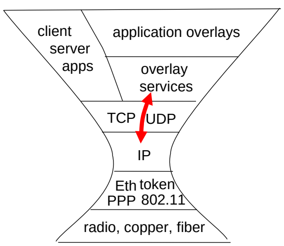


Today:
HTTP is greatest common denominator

Big picture: supporting new applications – losing the IP hour glass figure? (3)



IP “hourglass”



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Some advice on protocol design

- A loose collection of important thoughts related to protocol design
- ... actually, not only protocol design, but also
  - Programming in general
  - Systems in general (e.g., workflows in companies)
  - Life :)

Thought-triggering questions (1)

What problem am I trying to solve?

- Have at least one ***well-defined*** problem in mind
- Solve other problems without complicating the solution?

Will my solution scale?

- Think about what happens if you're successful: your protocol will be used by millions!
- Does the protocol make sense in small situations as well?

Thought-triggering questions (2)

How "robust" is my solution?

- adapt to failure/change
  - self-stabilization: eventually adapt to failure/change
  - Byzantine robustness: will work in spite of malicious users
- What are the underlying assumptions?
  - What if they are not true? catastrophe?
- maybe better to crash than degrade when problems occur: signal problem exists
- techniques for limited spread of failures
- protocol should degrade gracefully in overload, at least detect overload and complain

Further thoughts

Forward compatibility

- think about future changes, evolution
- make fields large enough
- reserve some spare bits
- specify an options field that can be used/augmented later

Parameters...

- Protocol parameters can be useful
  - designers can't determine reasonable values
  - tradeoffs exist: leave parameter choice to users
- Parameters can be bad
  - users (often not well informed) will need to choose values
  - try to make values plug-and-play

Simplicity vs Flexibility versus optimality

- Is a more complex protocol reasonable?
- Is "optimal" important?
- KISS: "The simpler the protocol, the more likely it is to be successfully implemented and deployed."
- 80:20 rule:
  80% of gains achievable with 20% of effort

Why are protocols overly complex?

- design by committee
- backward compatibility
- flexibility: heavyweight swiss army knife
- unreasonble stiving for optimality
- underspecification
- exotic/unneeded features

Trading accuracy for time

- If computing the exact result is too slow, maybe an approximate solution will do
  - optimal solutions may be hard: heuristics will do (e.g., optimal multicast routing is a Steiner tree problem)
  - faster compression using "lossy" compression
    - lossy compression: decompression at receiver will not exactly recreate original signal
- Real-world examples?
  - games like chess: can't compute an exact solution

Don't confuse specification with implementation

- A general problem of computer scientists!
- Specifications indicate external effects/interaction of protocol.
- How protocol is implemented is up to designer
- Programming language specifications: in addition to specifying *what*, tend to suggest *how*.

- real-world example: recipe
  1. Cut onions
  2. Cut potatoes
  3. Put onion and potatoes into pot and boil

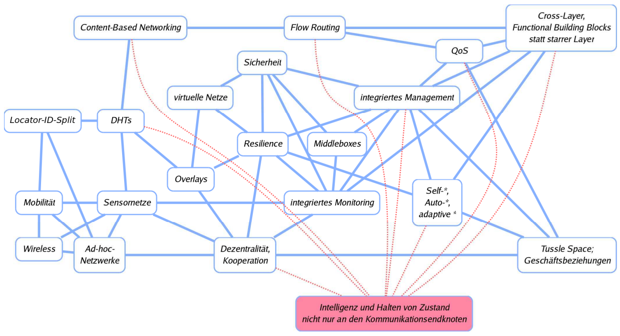
  steps 1 and 2 can obviously be interchanged……

Where are we headed: Current/upcoming research topics

- Network management: Measurement, automation (“managemt. plane”)
- Service management:
  - Application-level networks, overlays, distributed hash tables (DHT)
  - QoS: Not a solved problem end-end
- Wireless networking, mobility
- New types of networks:
  - Sensor nets, body nets, home nets
- Security:
  - Lack of cryptographic signatures in many protocols
  - Most traffic unencrypted (…which is good for measurement…)
- Resilience: more robust networks (reacting faster / to more failures)
- “Future Internet”
  - Evolutionary approach: step-by-step introduction of new protocols
  - Revolutionary / clean-slate approach: Radical architecture change
- Ease of use, deployment (but what are the research problems here?)

Future Internet

(sorry for the German labels, but most notions are in English anyway…)



The *really* big picture

- Importance of user requirements

“It’s the end-user, stupid”

“It’s the application, stupid”

“It’s the network, stupid”

of course, not everyone agrees ….

Verizon product, purchased 2007

The end!