Why We Are Here

The university is a place where a student
"apprehends the great outlines of knowledge, the principles on which it rests, the scale of its parts, its lights and its shades, its great points, and its little, as he otherwise cannot apprehend them. Hence, it is that his education is called "Liberal." A habit of mind is formed which lasts through life, of which the attributes are, freedom, equitableness, calmness, moderation, and wisdom."

– John Henry Newman
The Idea of the University, 1856

What It Is All About

The university as a place where a student "apprehends the great outlines of knowledge, the principles on which it rests, the scale of its parts, its lights and its shades, its great points, and its little, as he otherwise cannot apprehend them. Hence, it is that his education is called "Liberal." A **habit of mind** is formed which lasts through life, of which the attributes are, freedom, equitableness, calmness, moderation, and wisdom."

– John Henry Newman
The Idea of the University, 1856

A habit of mind

which lasts through life

My contribution Is Meager.

I only know how to teach it by example.

Hence, this course.

Unlike other Topics

Security is a Specialization

Analytics is a Specialization

Database is a Specialization

Operating Systems is a Specialization

Software Engineering is a Specialization

Networking is a Generalization

Our Methods

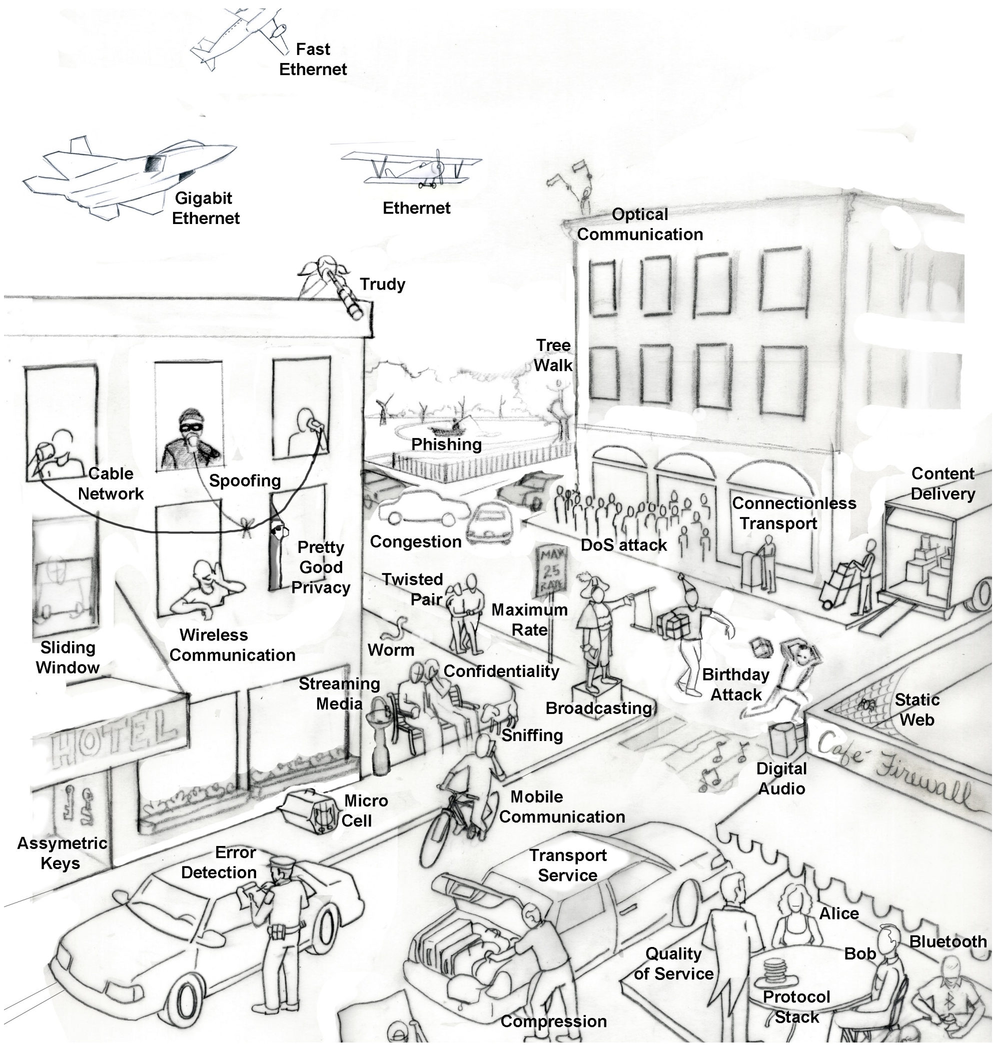
- A Well-Defined Problem is a Problem Half Solved
  - Charles Kettering
- The Problem with Reductio Ad Absurdum is Knowing When to Stop!
  - No accident that an irrational square root is a surd!
- Look at the problem from point of view of the organism, not the observer.
  - Teaching an Urn
- Theory Building – Looking for Invariances
  - What are the First Order Effectors
  - Can’t Tell a Coffee Cup from a Donut

Recognizing
First Order Effectors
Is key.

- Throwing Away The Ladder
  - Tractatus Logico Philosophicus
    - 6.54 My propositions serve as elucidations in the following way: anyone who understands me eventually recognizes them as nonsensical, when he has used them—as steps—to climb up beyond them. (He must, so to speak, throw away the ladder after he has climbed up it.)
- All Scientific Principles Only Work within a Given Set of Bounds
  - Rosencranz and Guildenstern Are Dead
- All Can Be Summed Up As: Listen to the Problem

Computer Networking

Sixth edition



Chapter 1

Introduction

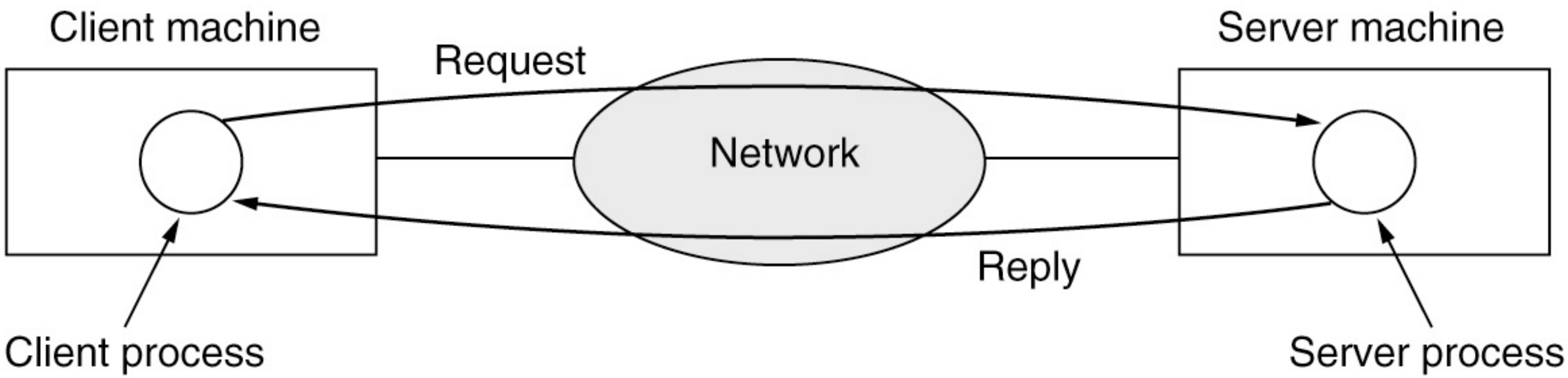
Uses of Computer Networks

- Computer network
  - Large number of separate but interconnected computers do a job
  - Collection of interconnected, autonomous computing devices
  - Interconnected computers can exchange information
- Example: the Internet
- Network uses
  - Access to information
  - Person-to-person communication
  - Electronic commerce
  - Entertainment
  - The Internet of Things

Access to Information (1 of 4)

- Web browser and smart phones retrieve information from various Web sites
- Social media platforms support targeted behavioral advertising
- Online digital libraries and retail sites host digital content
- Client-server model forms the basis of network usage
- Web applications: Server generates Web pages in response to client requests
- Peer-to-peer [sic] communication: Individuals form a loose group to communicate with others in the group

Access to Information (3 of 4)



In the client-server model, a client explicitly requests information from a server that hosts that information. Communication takes the form of the client process sending a message over the network to the server process. The client process then waits for a reply message.

Policy, Legal, and Social Issues (1 of 3)

- Online speech
  - Communications Decency Act protects some platforms from federal criminal prosecution
  - DMCA takedown notices (after the Digital Millennium Copyright Act) threaten legal action
- Net neutrality
  - ISPs should provide equal quality of service to a given type of application traffic, regardless of who is sending that content
  - No blocking, no throttling, no paid prioritization, transparency
  - Does not prevent an ISP from prioritizing any traffic
  - Zero rating: ISP might charge its subscribers according to data usage but grant an exemption for a particular service

Policy, Legal, and Social Issues (2 of 3)

- Security
  - DDoS (Distributed Denial of Service) attack
  - Botnets
  - Spam email
  - Phishing
- Privacy
  - Profiling and tracking users by collecting data about their network behavior over time
  - Storing cookies in Web browser
  - Browser fingerprinting
  - Mobile services location privacy

Policy, Legal, and Social Issues (3 of 3)

- Disinformation
  - Ill-considered, misleading, or downright wrong information
  - Fake news
  - Challenges
    - How does one define disinformation in the first place?
    - Can disinformation be reliably detected?
    - What should a network or platform operator do about it once it is detected?

What *Really* Characterizes Networks?

- The Characteristics of the Media creates bounds:
  - Point-to-point or multi-access
  - Physical limits on distance
  - Error characteristics
    - Single bit errors, bursts, affects packet size
  - Bandwidth
  - If wireless
    - Propagation characteristics
  - Cost, Cost, Cost
- Then it is a Resource Allocation Problem.

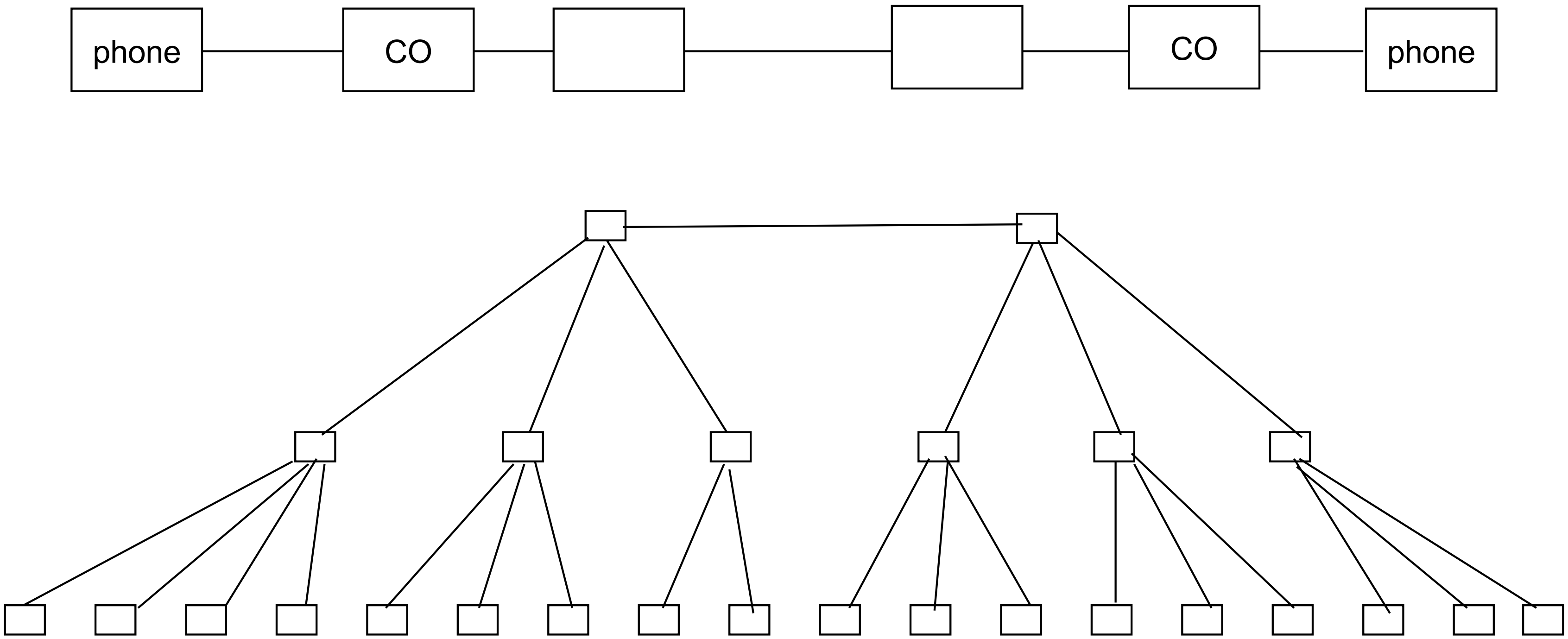
What is *Really* Important?

- Network technologies should not be built to support specific applications
- Network technologies support a specific operating range.
- Applications require a particular operating range.
  - Some applications require different ranges, some may require the same range.
- The problem in designing a network or the equipment is to match the operating range of the equipment to the operating range of a collection of applications.
  - Don’t believe what management tells you.
  - (They will change requirements 4 times before you can get it done.) ;-)

The Environment of Networking

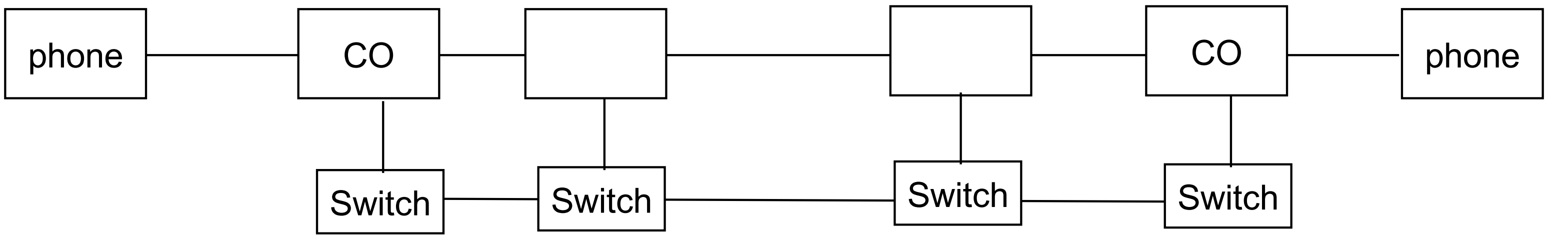
- All Endeavors are affected by economics and politics
  - But probably none more so than networking
- To understand the mindset and why we have what we have we must understand where it came from. For two reasons:
  - To make sense of the less than perfect state of the world.
  - Only by understanding the processes can we affect them,
    - i.e., those who don't know history are doomed to repeat it.
    - So far, we are doing a good job of that.
- Along the way, we will learn a few of the basic concepts.

The Phone Company I



- Beginning in the last quarter of the 19thC, telephony had always been based on a deterministic circuit model, which I call "beads-on-a-string."
- A physical circuit had to be completed from source to destination.
  - Just like turning on a light.
- The Network was fundamentally a tree.

The Phone Company II



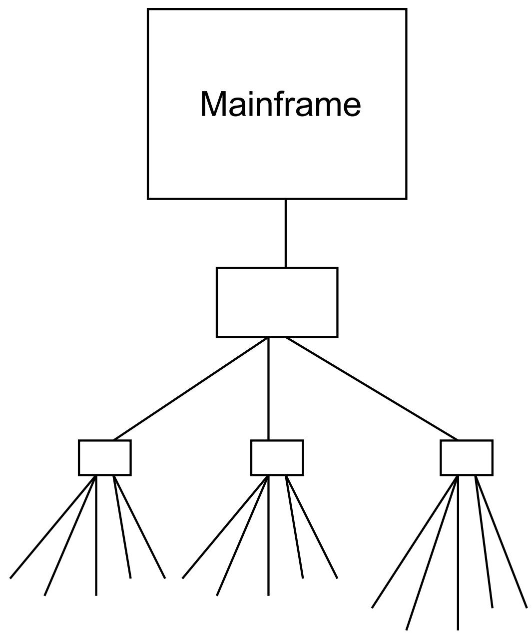
- Mechanical Switches were introduced along side the network.
  - For two reasons
- And after nearly 75 years, they became electronic.
- Even when the switches needed to communicate,
  - It is *along side* the network.
- Remember at this time, phone companies are monopolies
  - Outside the US, the phone company and the FCC were the same organization called the PTT. They had immense power.
    - Post, Telegraph, and Telephone

Change Comes

- Computers come on the scene after WWII.
- With the advent of the Transistor things get interesting.
- Making computers smaller and cheaper means they can be used in more places.
- The phone company basically begins to deploy computer controlled electronic switches.
- At first for the computer industry, communications is just a means to an end.

IBM Mainframe Model: SNA

- Asymmetric/Deterministic/Hierarchical
- Everything is the "Mainframe" (and always will be) minimal functions at the Terminal. No question: everything but the wires belongs to IBM. (just buying leased lines)
- The Mainframe and TPC co-exist nicely.
  - IBM has 85% of the computer market, very powerful.



But Big Changes are Afoot.

- In the early 1960s, Donald Davies in the UK proposes and Paul Baran at The Rand Corporation writes a series of reports investigating the networking requirements for the DoD.
- He finds that the requirements for data are very different than those for voice.
    - Data is bursty. Voice is continuous.
    - Data connections are short. Voice connections have long durations.
- There would be distinct advantages for a network built specifically for data.
    - Greater efficiency.
    - Greater survivability.
- Data would be sent in individual packets, rather than as continuous streams.
- Packet switching is born and
- By the late 1960s, the Advance Research Projects Agency (ARPA) decides to build a **Resource Sharing Network** to reduce the cost of research, . . .
    - (they didn't know it yet) but to facilitate collaboration.

A Fundamental Departure

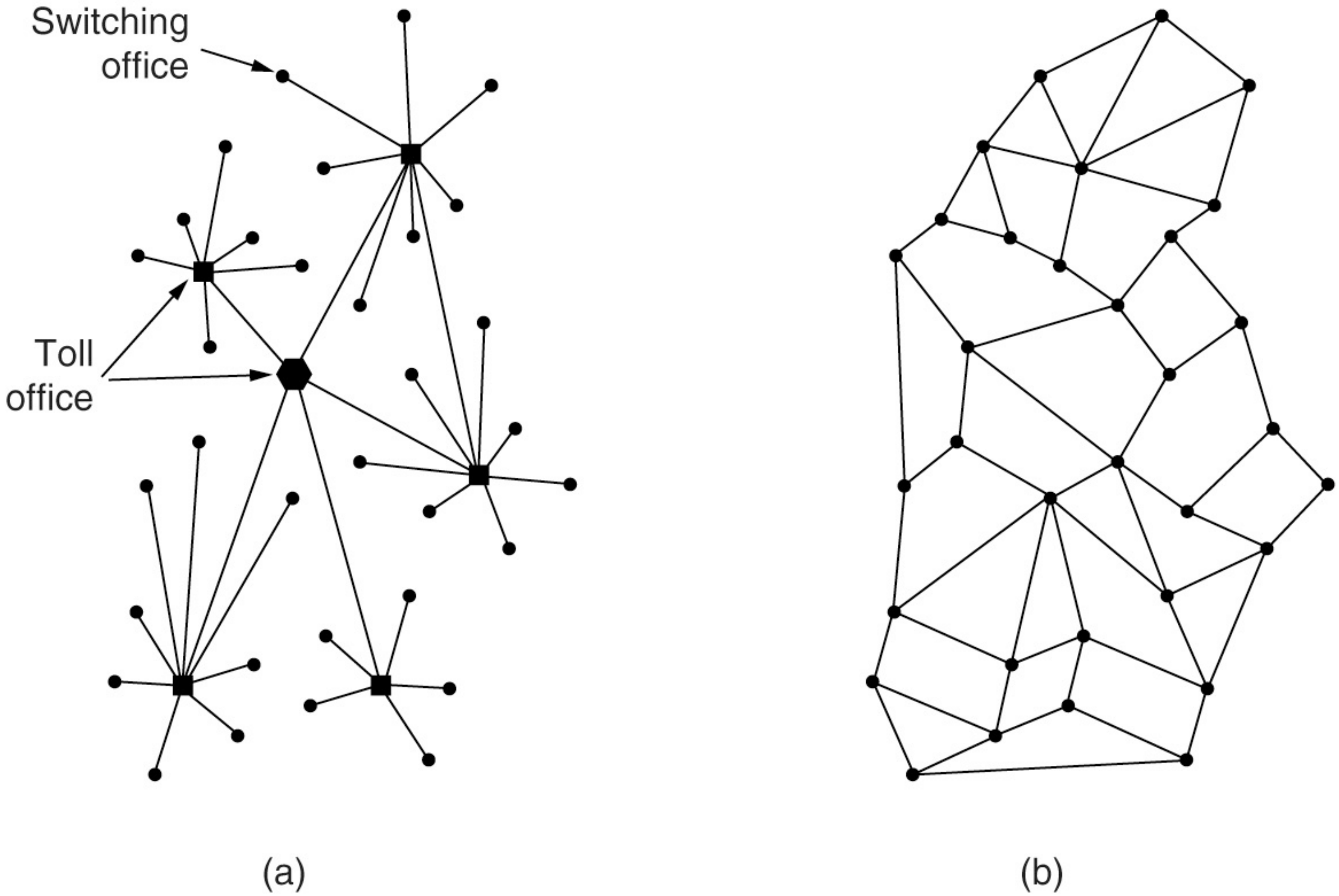
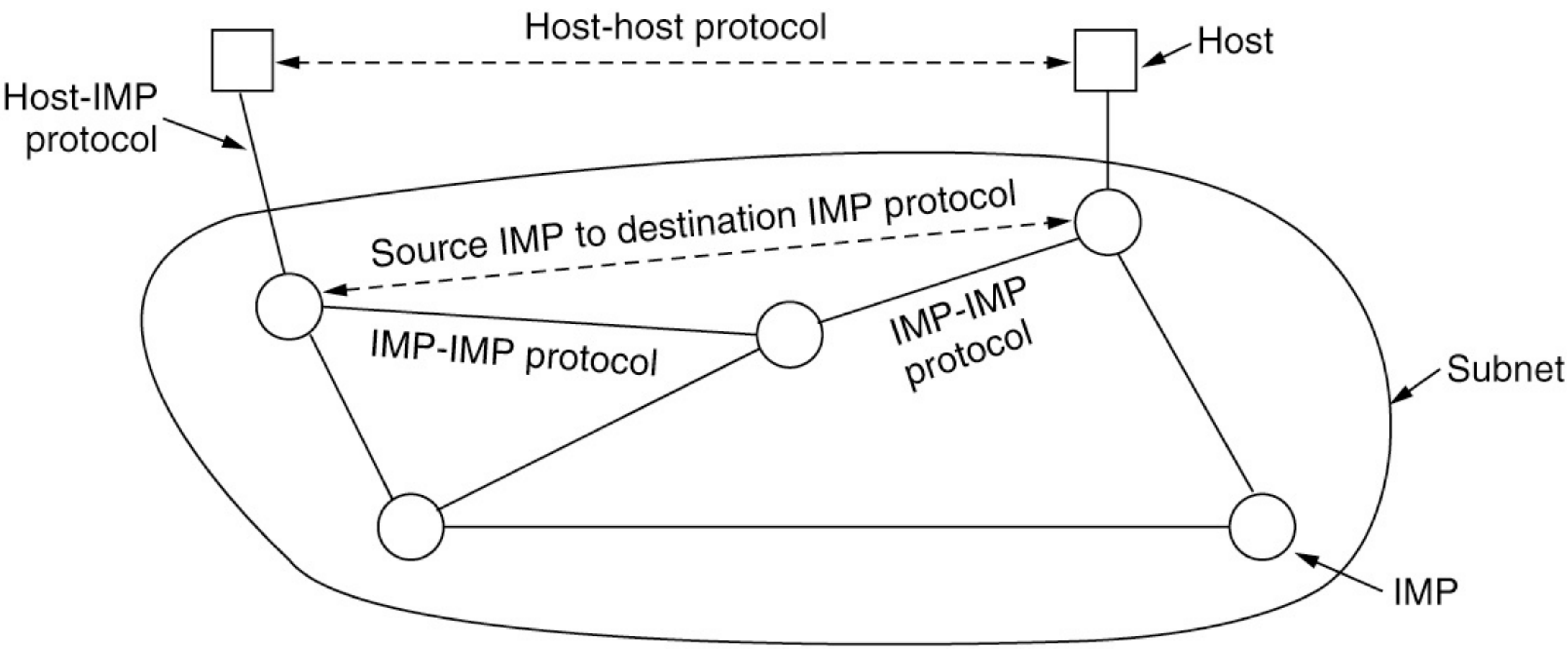


Figure (a) represents an unsecure network with little redundancy. Figure (b) illustrates a more secure packet-switched network that was initially dismissed as a solution.

The ARPANET (1 of 2)

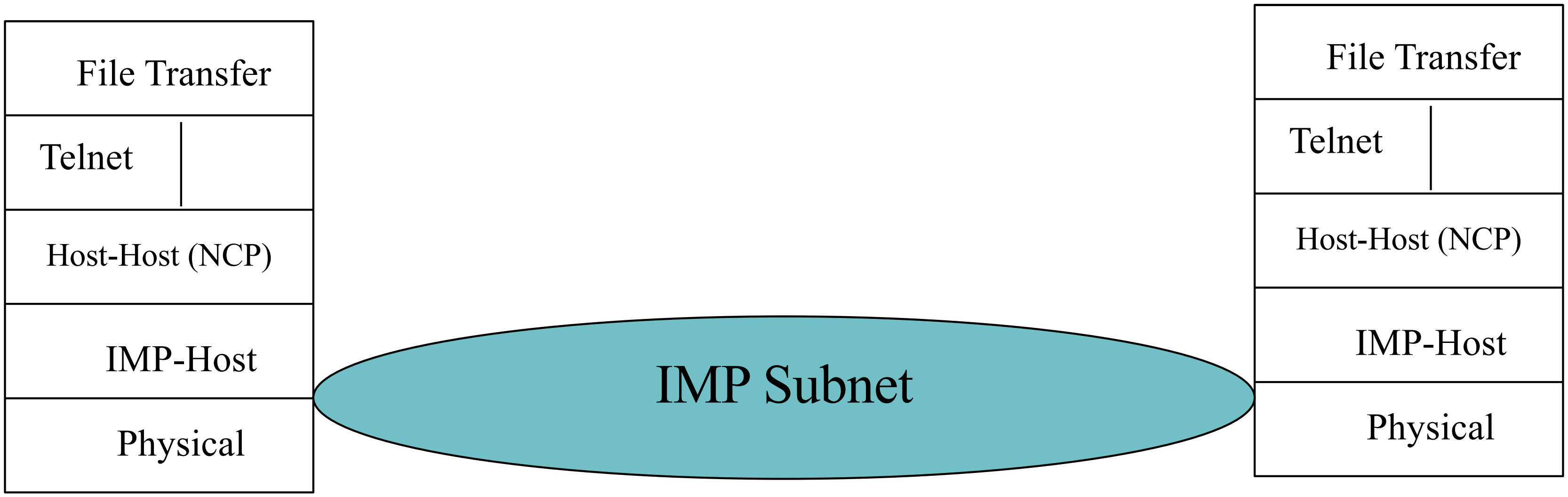


The ARPANET distinguished two parts: subnet and host. The subnet software consisted of the IMP end of the host-IMP connection, the IMP-IMP protocol, and a source IMP to destination IMP protocol designed to improve reliability.
It was assumed that the IMP was co-located with the host (< 10m).

Operating Systems Were a Big Influence

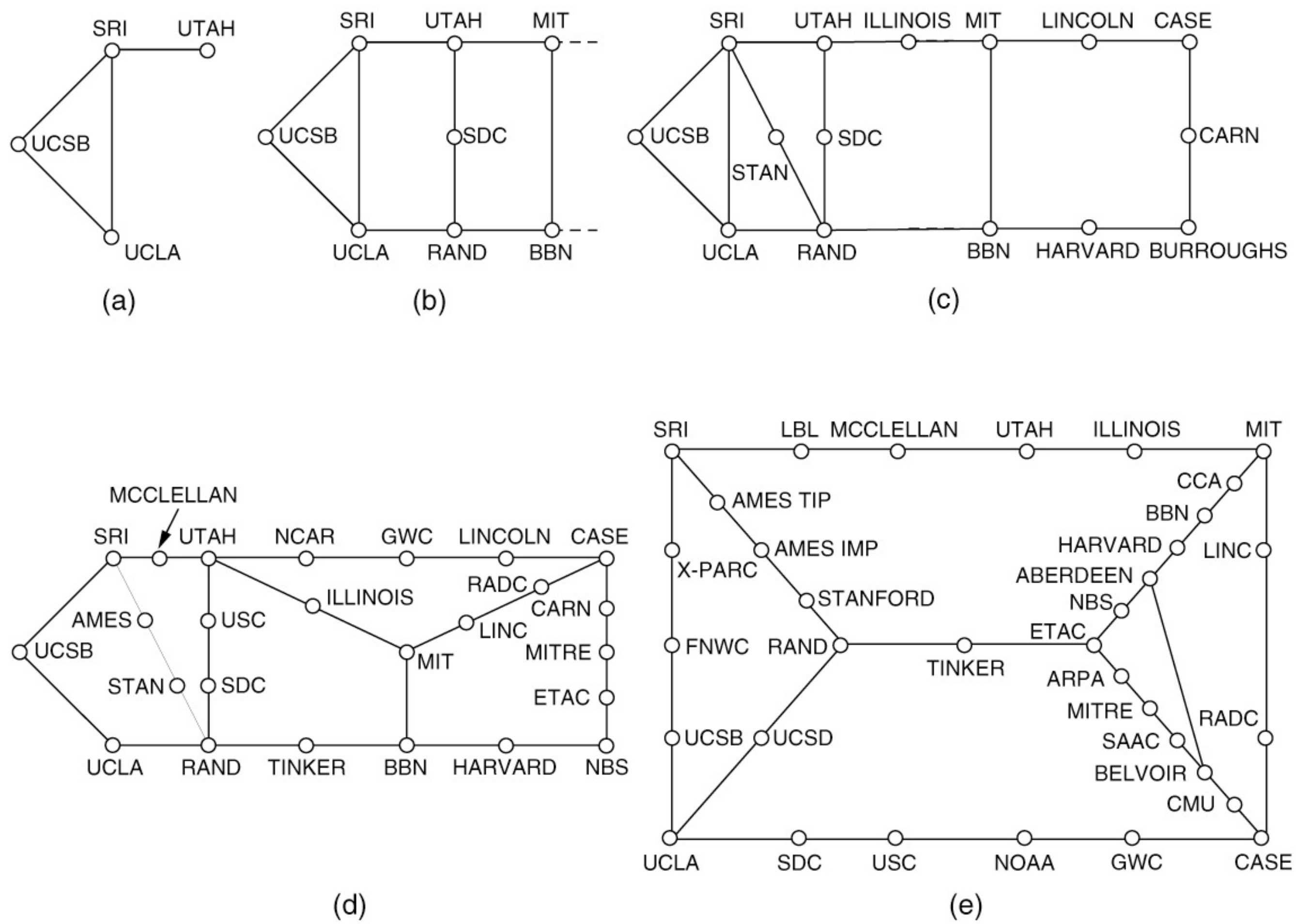
- In 1968, Dykstra publishes a very famous paper on the THE Operating System, where he proposes that the appropriate structure is
  - Layers. Layers are good for controlling complexity,
  - A Black Box that provides a service and hides its internals Furthermore,
  - Once a function is done in a layer there is no need to repeat it.
- To attach a host to a network required a new device driver. It was going to be written by the operating system team at each site.
- An OS perspective was going to be very important, because
  - Networking is a resource allocation problem, a distributed allocation problem.
  - Walden in 1970 writes an RFC on IPC in a Resource Sharing Network; in a 1972 paper for no particular reason Bob Metcalfe said "Networking is InterProcess Communication."
    - Not a big deal, it was a commonly held view.
    - As late as 1982, (RFC 871) IPC is still seen as 'axiomatic.'
- And Layers seem to be a natural occurrence in network.
    - Have always believed that the success of the ARPANET was because it was done by OS guys not telecom guys.

Getting to Layers:
ARPANET



- Remember no one had ever built one of these before and:
  - This was a production network to lower the cost of research. (deadlines!)
  - BBN was building the Network. Once they had enough completed, they involved the host organizations to develop their software.
    - (There are no diagrams of layers of the IMP subnet.)
  - This is when layers appear. They are all about Modularity.
  - Layers remain all about modularity in the Internet to this day.
- History matters.

The ARPANET (2 of 2)



Growth of the number of nodes on ARPANET. (a) December 1969. (b) July 1970. (c) March 1971. (d) April 1972. (e) September 1972.

The ARPANET is a Huge Success!

(at least within the small ARPA group)

- By 1973, the first three Applications are created:
  - Telnet, FTP, and RJE (more later)
- Almost immediately all of us are relying on the ‘Net!
  - All sorts of great things going on! A mini-boom.
  - Packet radio, packet voice, distributed database access from workstation with plasma screen and touch, network software works, NLS, IM’ing in 1972, etc.
- In mid-1973, form the User’s Interest Group (USING)
  - Make the ‘Net a true Resource Sharing Network (new protocols)
  - Advocate for the users!
- Mid-1974, ARPA shuts down USING
  - Fear they will lose control
  - We have the basics, work with them.
- But there are big things happening in the outside world!

Tensions Begin

- This is the beginnings of a paradigm shift.
- These new packet switches required fairly complex software.
  - The most complex software of the day were operating systems and this was fundamentally an OS problem.
- Telecom was unfamiliar with and suspicious of this new “software” stuff.
- These new networks were developed by people with operating system backgrounds, then the most complex software being written.

- As is common in science when a shift like this occurs, you have people who are in the old model, people with a foot in both camps, and people wholly in the new model.
  - And it may take a generation or more to settle out.
- Packet switching had been the first part of the idea but not that radical.
- The radical change was still to come.

But was Packet Switching a Major Breakthrough?

- Strange as it may seem, it depends on how old you were.
    - During this period many things are age dependent.
- If your formative years had occurred prior to the mid-60s (pre-boomer), your model of communication was defined by telephony.
    - Then this is revolutionary.
- If you are younger (boomer), your model is determined by computers.
    - Data is in buffers, How do you do communications:
        - Pick up a buffer and send it.
    - What could be more obvious!

- Even more radical changes were coming to packet switching.

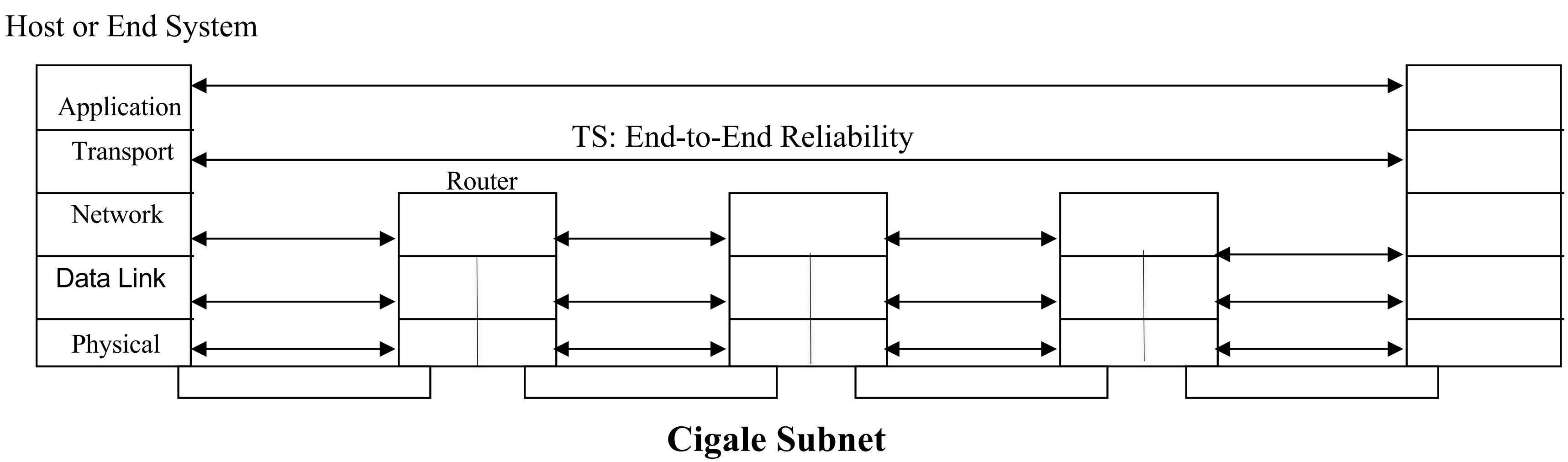
New Ideas from Europe

- Soon after the ARPANet (1971), Louis Pouzin visits and is intrigued.
  - Pouzin had been on Project MAC at MIT where he invented ‘the shell.’
  - Came to look at the ARPANET and resolved to build a network in France
- While ARPA built a network to lower the cost of research at different sites, Pouzin determined to build a network to do research on *Networks*!
  - To do that, they proceeded scientifically, methodically.
- What were the minimal assumptions that one had to make?
  - What was the least that had to be in a packet?
- Pouzin adopts Davies’ idea of the datagram and starts to reason from there.
  - Packets would be routed independently.
  - Why assume it had to be a fixed path?
  - This is now called connectionless
- And that wasn’t all, there was more.

Creating CYCLADES

- Pouzin's team (of really smart guys) reasoned that the hosts would never trust the network to be reliable, so why go to the extra work to make the network perfect!?
  - Hosts would always check to ensure data arrived and to do flow control
  - In that case, there was no need to for the network to be perfect. It could be cheaper and more resilient, if it only made a "best effort."
- They build CYCLADES and the subnet of switches was called Cigale.
  - The Cyclades are a group of Greek islands which in ancient times were loosely federated without central control.
  - Cigale means Grasshopper.
- This was truly radical! Non-deterministic, decentralized, reliable transmission with unreliable components! Outrageous.
- And that wasn't all, there was still more.

The Cyclades Architecture
(1972)



- The Layers as developed by CYCLADES were:
  - Transport Layer provides end-to-end reliability, primarily recovering from loss due to congestion.
  - The Network Layer Does Relaying and Multiplexing of datagrams with the primary loss due to congestion and rare memory errors. With datagrams, every message was independent of every other. The network only made a “best-effort” to deliver messages.
  - Building a Reliable Network from Unreliable Parts
  - The Data Link Layer detects corrupted packets and may do flow control.
    - Hence, it must keep the loss rate much less than the loss due to congestion by the Network Layer.
  - The Physical Layer is the Wire.

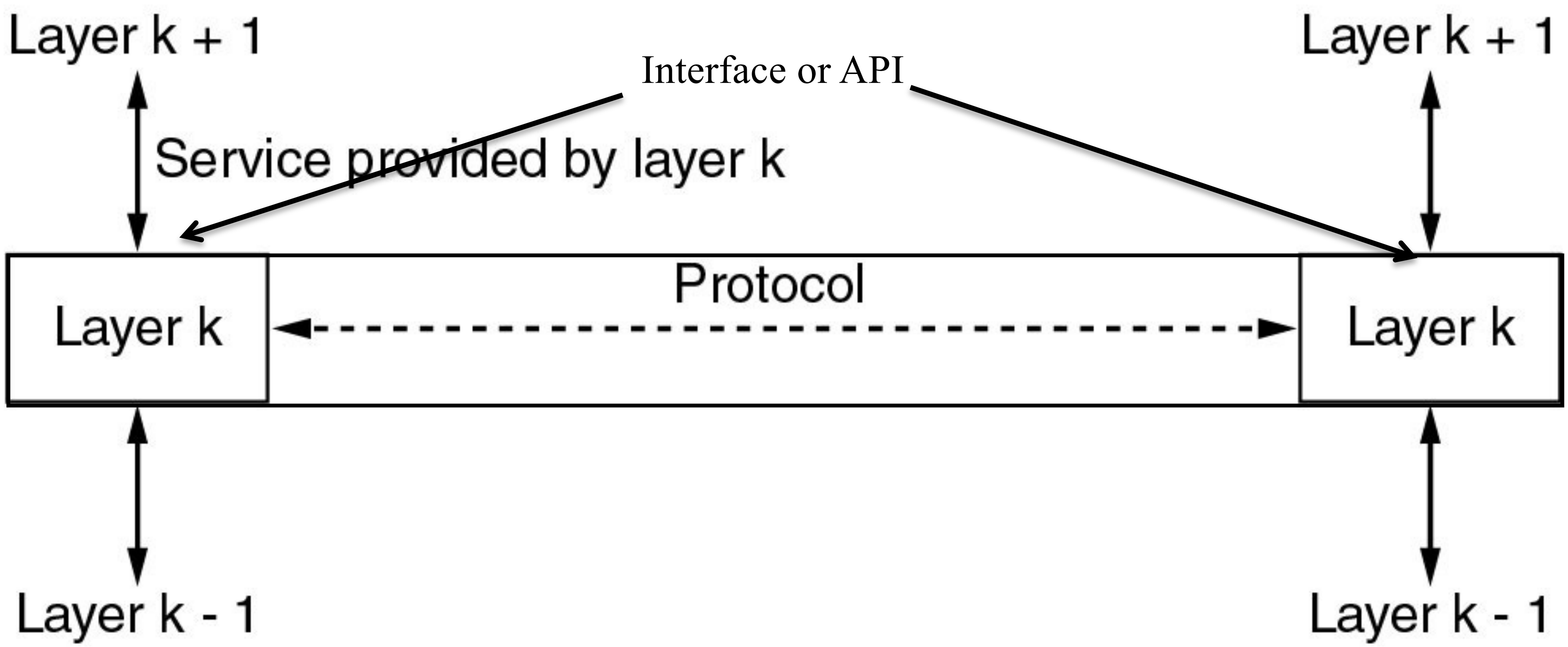
Network Software

- Layers are a Little Different in Networks
    - Not just functions in a single system.
  - A Distributed Black Box of Shared State that provides a service to the Layer above hiding the internal working of the layer.
    - A Layer is a Distribute Resource Allocator
  - Some of it is in the OS, and even that which isn't is like writing OS code.
- With Layers of Protocols.
  - Service Primitives, API: What is visible from the outside.
  - Protocols: What goes on inside the black box.
  - Let's Look at How Layers Work

Service Primitives

- Service
  - Formally specified by a set of primitives (operations) available to user processes to access the service
  - Primitives tell the service to perform some action or report on an action taken by a peer entity
- Six core primitives (the API)
  - Listen (block waiting for an incoming connection)
  - Connect (Allocate) (establish a connection with a [waiting] peer)
  - Accept (accept an incoming connection from a peer)
  - Receive (block waiting for an incoming message)
  - Send (send a message to the peer)
  - Disconnect (Deallocate) (terminate a connection)

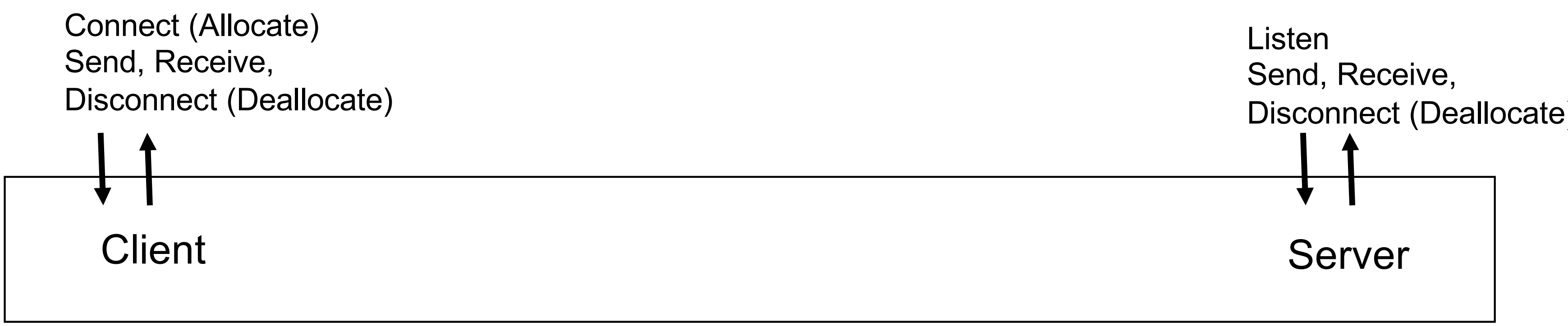
Services to Protocols Relationship



- The Service is the behavior visible above the layer
- The term Service is used as an abstraction of the interface, the API.
- In data comm, an interface is *between* boxes;
- In networking it is between layers.
- This combined with connectionless leads to a radically new paradigm for communications.

Service (Interface) Primitives

Primitive	Meaning
LISTEN	Block waiting for an incoming connection
CONNECT	Establish a connection with a waiting peer
RECEIVE	Block waiting for an incoming message
SEND	Send a message to the peer
DISCONNECT	Terminate a connection



A Layer is a (distributed black box) that provide a service.

It hides the complexity of the functions within the layer.

Service Primitives (3 of 3)

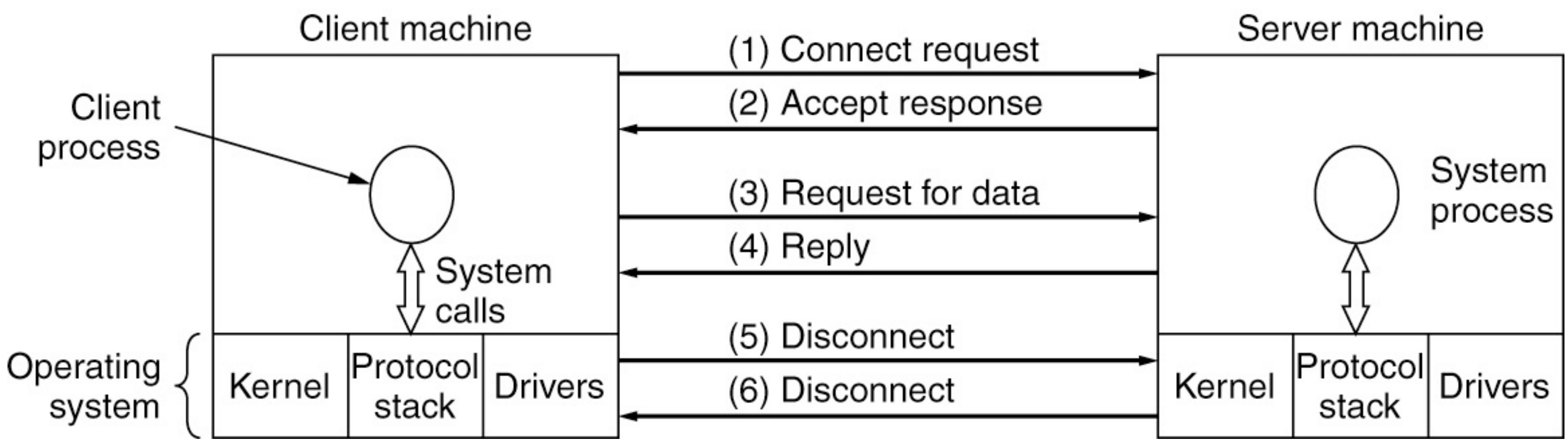
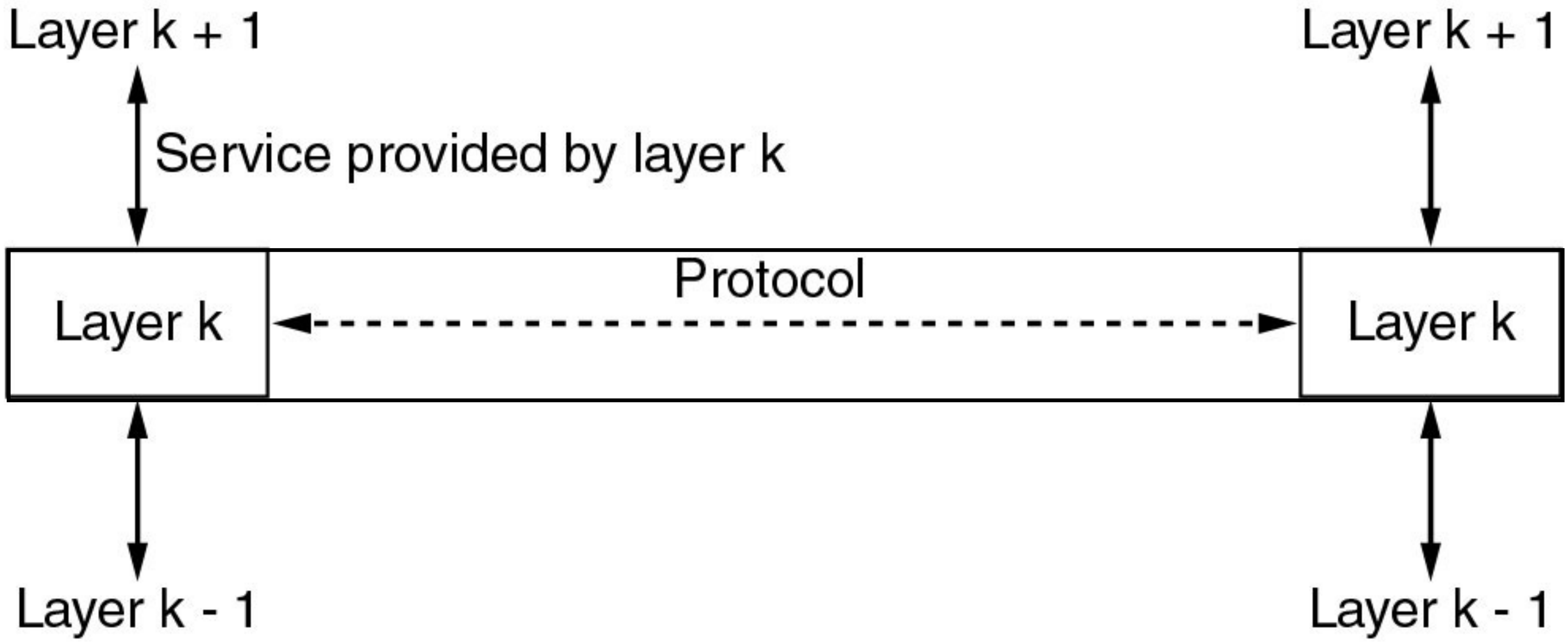


Figure 1-30 briefly summarizes how client-server communication might work with acknowledged datagrams so that we can ignore lost packets.

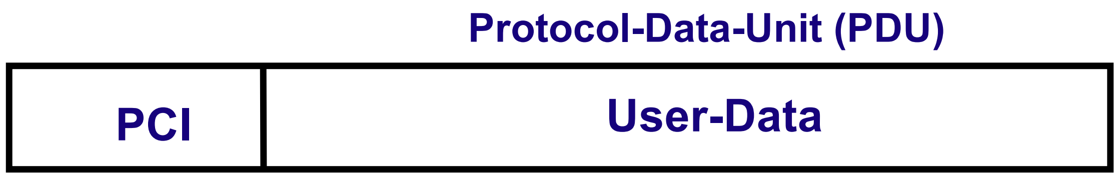
Warning: The statement above is only true if every request and response fits in one packet and nothing goes wrong.

The Important Thing about Protocols



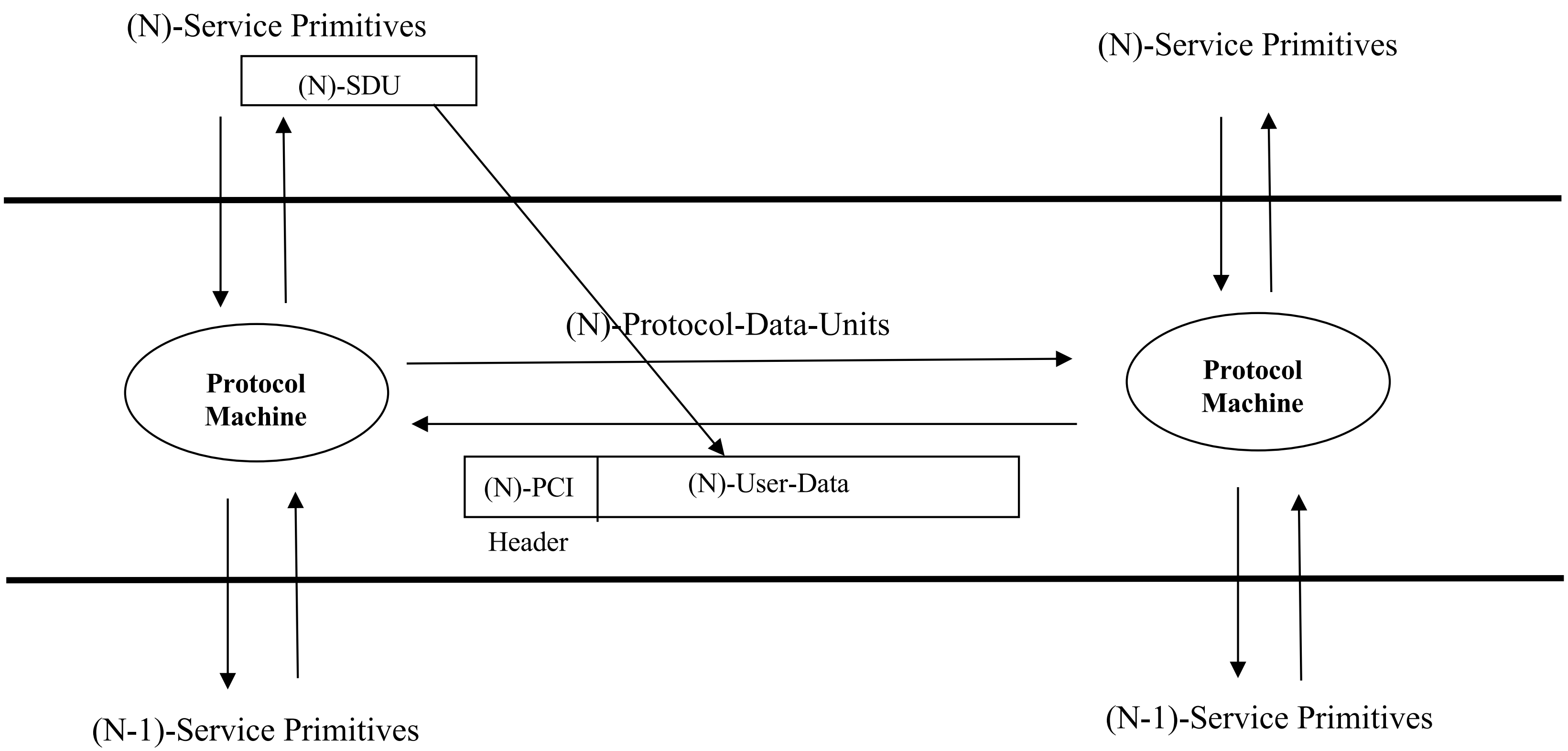
- Protocols create and maintain the shared state of the layer.
  - To do this protocols exchange messages we will call
  - PDUs (Protocol Data Units) which carry state information.
- Protocols use the service of the layer below to create the service to its user.
  - Asynchrony is inherent. The state of the protocol in members of the layer may not be the same at any point in time. However, if left alone, will converge to a consistent state.
  - Often ignored, a Layer assumes a minimal service from the layer below.

The Important Thing about PDUs



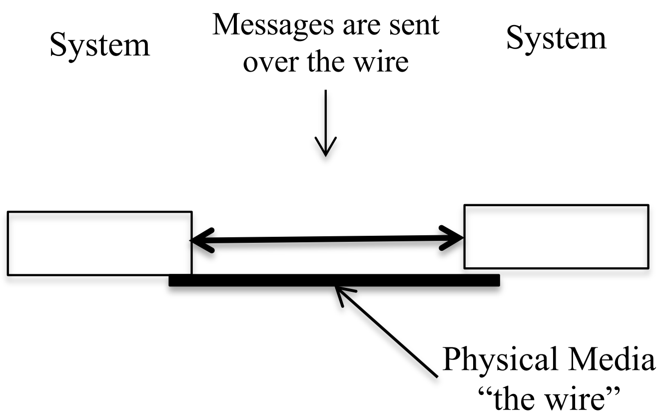
- PDUs are called packets, frames, messages, cells, segments, etc. They are all the same thing just in different places.
- If data is sent from one system to the other, have to tell it what to do with it!
- PCI or Protocol-Control-*Information* is also called the header.
  - I prefer PCI because it emphasizes that:
- *Information* is what the protocol understands, *Data* is what it doesn't understand.
  - Emphasizes the organism over the observer.
- At each layer, the protocol only processes the PCI.

Protocol Operation



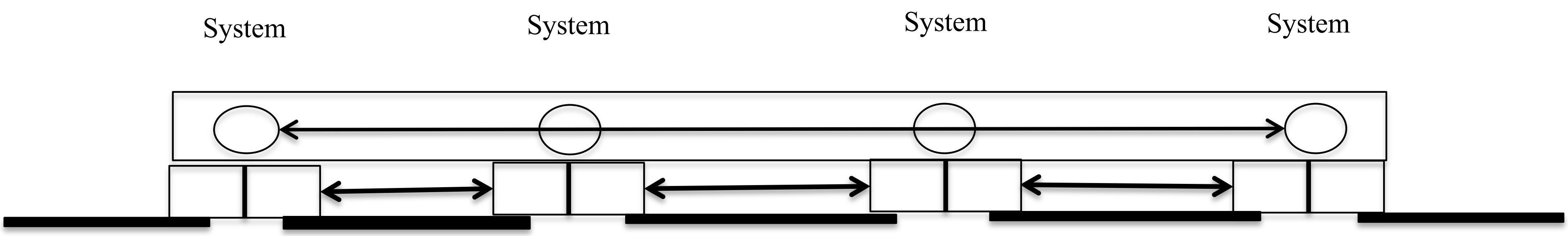
SDU (Service Data Unit), the unit of data whose identity is maintained on delivery
PDUs are also known as messages, packets, segments, frames, cells, etc.
While not rigid, the terms are generally used with specific layers.
PDU stresses that they are really all the same thing.

How Layers Come About: I



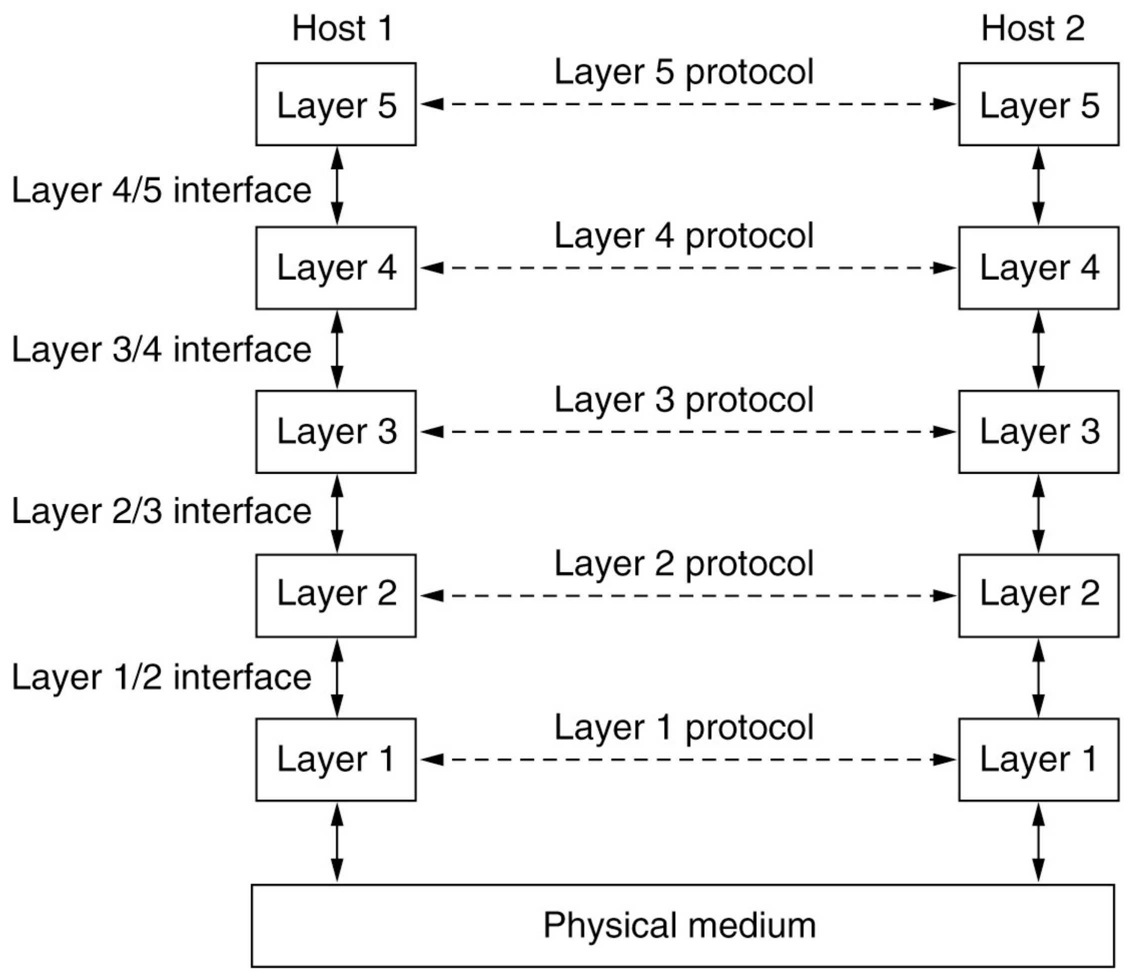
- We Have Two Systems Connected by a Wire.
- Want to send messages across the wire
  - But the other side has to know what to do with the messages
  - We need a protocol for a several reasons here:
    - To tell the other side what to do with this message
    - To provide the means to tell if it got trashed in transit
    - To keep the sender from sending too fast.
- (Other protocols may have to do other things. More on that later.)

How Layers Come About: II



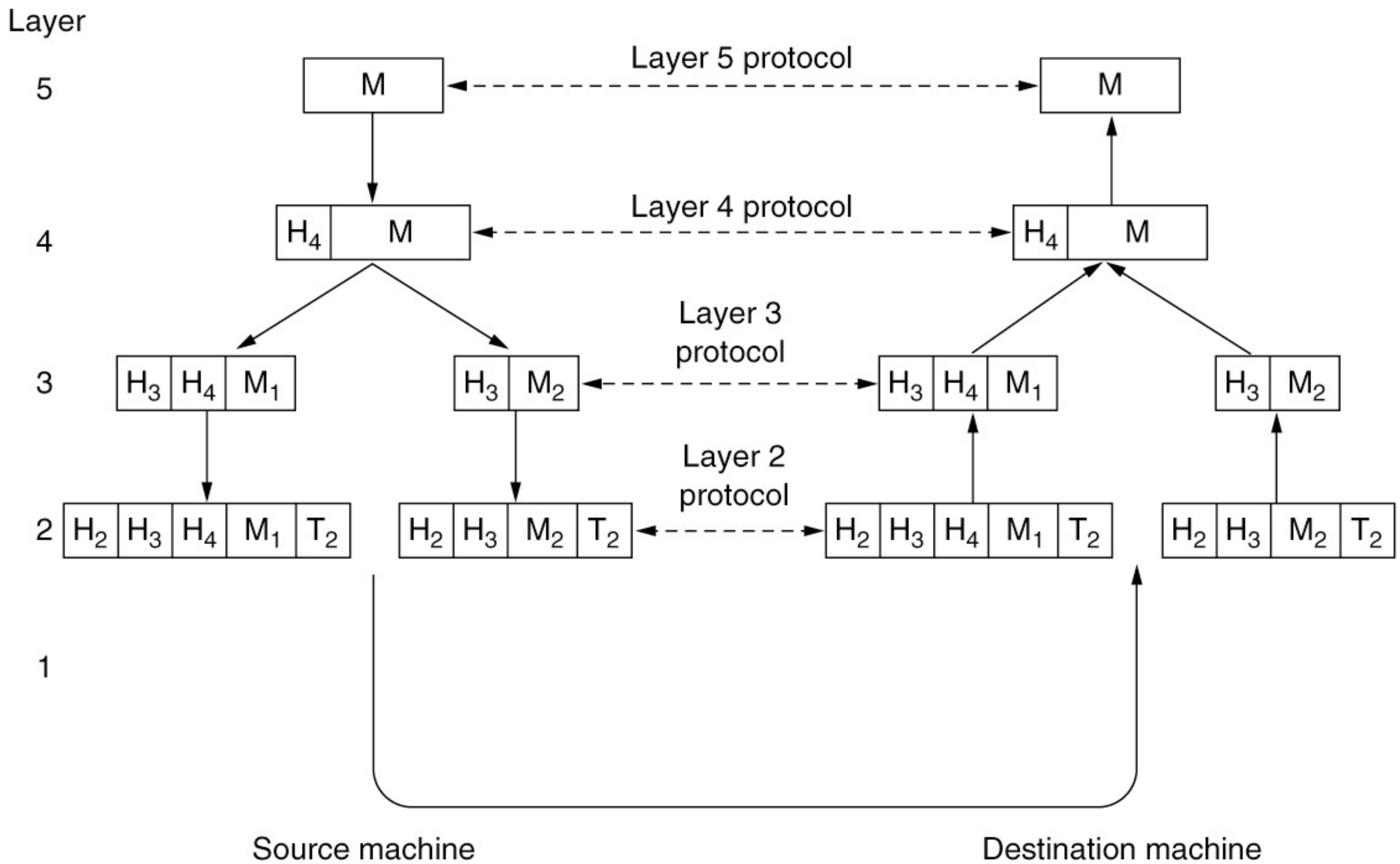
- The Media has physical constraints: distance, data rate, PDU size, cost, error rate, etc.
- Need more than one and different kinds with different protocols.
- Between each systems there could be the same or a different protocol.
  - How Do We Get Between Them?
  - Translation or Relay?
  - Translations get messy, an n^2 problem. Relaying is going to be a lot cleaner;
  - So, we need another layer.
- with a common protocol over the top to relay.
- This is why there are layers.

Protocol Layering (2 of 4)



A five-layer network where the entities comprising the corresponding layers on different machines are called peers. (Space does not permit important concept)

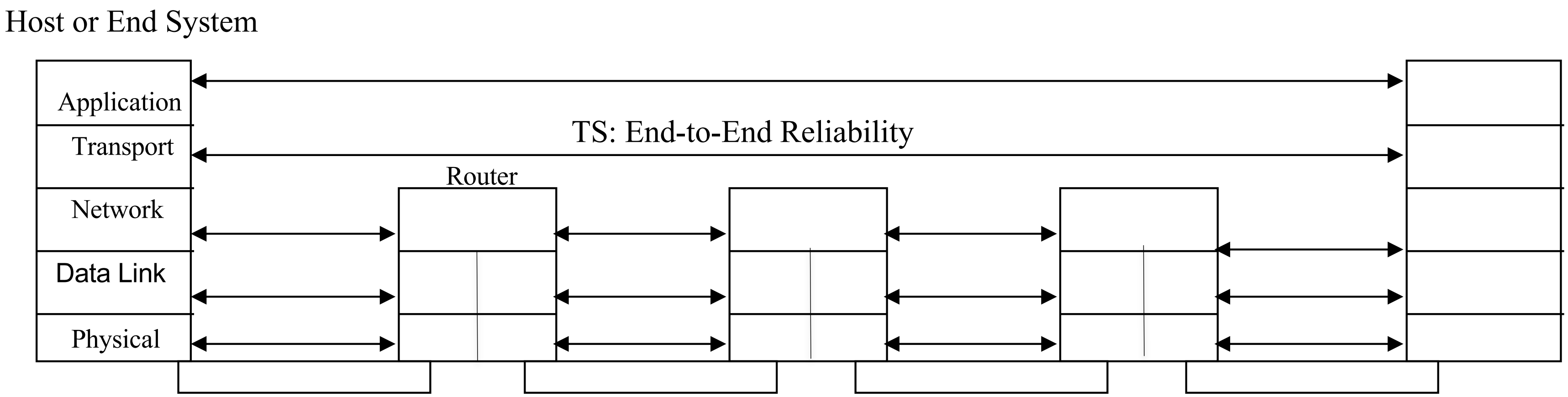
Protocol Layering (4 of 4)



An example of information flow supporting virtual communication in layer 5.

Back to Cyclades

(1972)



Cigale Subnet

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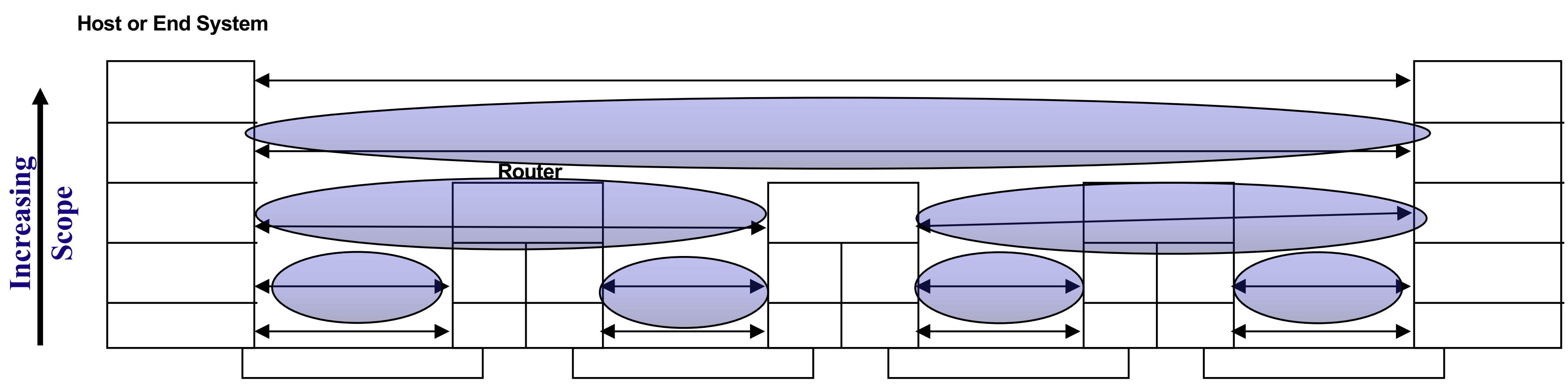
  - Building a Reliable Network from Unreliable Parts
  - The Data Link Layer detects corrupted packets and may do flow control.
    - Hence, it must keep the loss rate much less than the loss due to congestion by the Network Layer.
  - The Physical Layer is the Wire.

The (really) Important Thing about Layers

- A Layer is a locus of distributed shared state
  - In OSs, Layering was a convenience, here it is a necessity.
- Different Layers should have different scope
  - Either in terms of number of elements or range of operation
  - There are multiple layers at the same rank.
- The exchange of PDUs maintain some degree of consistency in the shared state.



Why History is Important

An Interesting Thing Happened

- This was the view that network researchers had in the mid-70s.
- However, in the late 1970s, the Internet split off and because it had much more funding than everyone else combined, eventually became dominant.
- The Internet used the CYCLADES ideas of datagrams and end-to-end transport protocol, but they built it on top of the ARPANET.
  - There was little or no direct contact between the core Internet people and the CYCLADES people.
  - The Internet saw it as just connectionless network with a reliable transport protocol with the traditional view of telecom.
  - They missed that the scope of layers was important and
  - That this was a whole new way of conceiving networks.

The New Model Had 4 Characteristics

- It was a *peer network* of communicating equals not a hierarchical network connecting a mainframe master with terminal slaves.
- The approach required coordinating *distributed shared state at different scopes*, which were treated as black boxes. This led to the concept of layers being adopted from operating systems and
- There was a shift from largely deterministic to *non-deterministic* approaches, not just with datagrams in networks, but also with interrupt driven, as opposed to polled, operating systems, and physical media like Ethernet, and last but far from least,
- This was a computing model, *a distributed computing model*, not a Telecom or Data comm model. The network was the infrastructure of a computing facility.
- Throughout the course we will see the tension between the traditional *beads-on-a-string* model and the *distributed computing* model.

For Networks, Standards Are a Must

- If boxes by multiple manufacturers are going to talk to each other, there must be agreements on how they do it.
- There had been computing standards before this, programming languages, mag tape formats, ASCII, etc.
- But computers were still entities unto themselves
  - Porting between them was very difficult and most communications was terminals, or between the same kind, and was slow, error-prone and expensive.
  - Standards were nice, but didn’t have to be followed closely
- But for networking that was going to have to change.
- Initially there were two major standards bodies. Each representing the vested interests of a particular group.

Who's Who in the Telecommunications World

- Two extremes
  - Small privately owned telephone companies
  - National government has a complete legal monopoly on all communication
- PTT (Post, Telegraph & Telephone administration)
  - Ministry of government having telecommunication authority
    - The FCC and AT&T in one organization
  - Now mostly deregulated and large private telecom companies

Who's Who in the International Standards World (1 of 2)

- ITU (International Telecommunication Union)
  - United Nations treaty agency
  - ITU-T: Telecommunications Standardization Sector, (CCITT)
  - ITU-R: Radio Sector (CCIR)
  - Publishes and produces *recommendations*
- ISO (International Organization for Standardization)
  - Publishes and produces voluntary international *standards*
- IEEE (Institute of Electrical and Electronics Engineers)
  - The largest professional organization in the world
  - IEEE's 802 committee has standardized many kinds of LANs
- NIST (National Institute of Standards and Technology)
  - Part of the U.S. Department of Commerce; does government standards

Who's Who in the International Standards World (2 of 2)

Number	Topic
802.1	Overview and architecture of LANs
802.2	Logical link control
802.3 *	Ethernet
802.4 †	Token bus (was briefly used in manufacturing plants)
802.5 †	Token ring (IBM's entry into the LAN world)
802.6 †	Dual queue dual bus (early metropolitan area network)
802.7 †	Technical advisory group on broadband technologies
802.8 †	Technical advisory group on fiber-optic technologies
802.9 †	Isochronous LANs (for real-time applications)
802.10 †	Virtual LANs and security
802.11 *	Wireless LANs (WiFi)
802.12 †	Demand priority (Hewlett-Packard's AnyLAN)
802.13	Unlucky number; nobody wanted it
802.14 †	Cable modems (defunct: an industry consortium got there first)
802.15 *	Personal area networks (Bluetooth, Zigbee)
802.16 †	Broadband wireless (WiMAX)
802.17 †	Resilient packet ring
802.18	Technical advisory group on radio regulatory issues
802.19	Technical advisory group on coexistence of all these standards
802.20	Mobile broadband wireless (similar to 802.16e)
802.21	Media independent handoff (for roaming over technologies)
802.22	Wireless regional area network

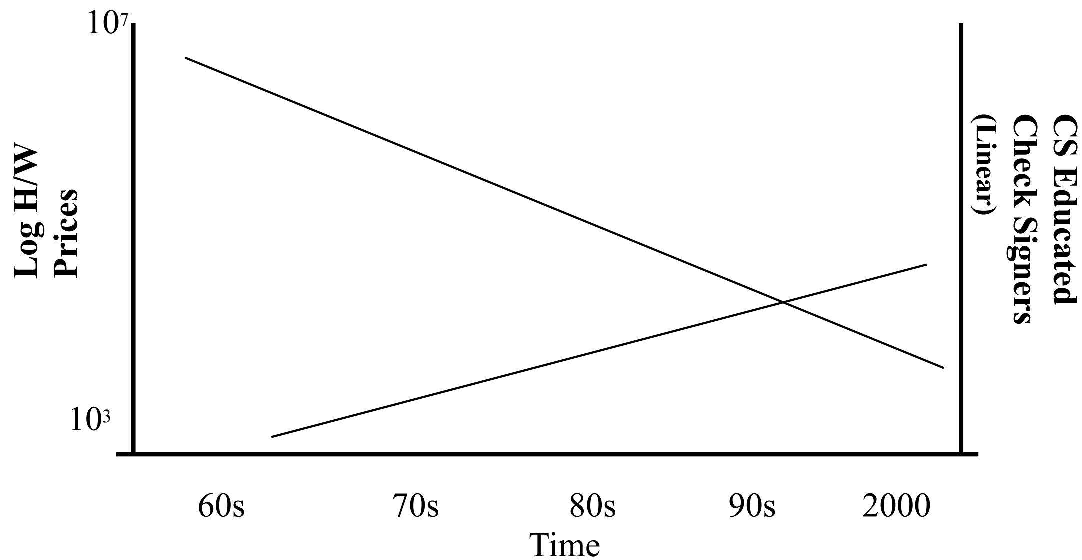
The important ones are marked with *. The ones marked with † gave up and stopped.

Everybody Has Their Own Standards Group!

- There were two big players at the time: IBM and the Phone Companies.
- The PTTs (phone companies) of the world are developing a beads-on-a-string, connection oriented, deterministic standard called X.25 in CCITT (later known as ITU-T, International Telecommunications Union-Telecommunications).
  - It looks more like the early ARPANet, not the neat new idea.
  - We know its limitations, and they don't want a transport layer!
- Researchers realize that they need to influence the process, so they create the International Network Working Group, IFIP WG6.1
- An effort is made to get datagrams in X.25 and it succeeds in name. But the PTTs don't take these researchers too seriously.
- Furthermore, the CCITT is a treaty organization and only national representatives, or phone companies can speak.
- The phone companies have this locked up.
  - Our introduction to electro-political engineering is a learning experience

IBM had Two Problems

Computing and Memory Prices were headed South . . . Fast.
Computing Power and Capacity were headed North . . . Fast.
By the late 70's, it was clear that IBM's days as the dominant computer maker were numbered

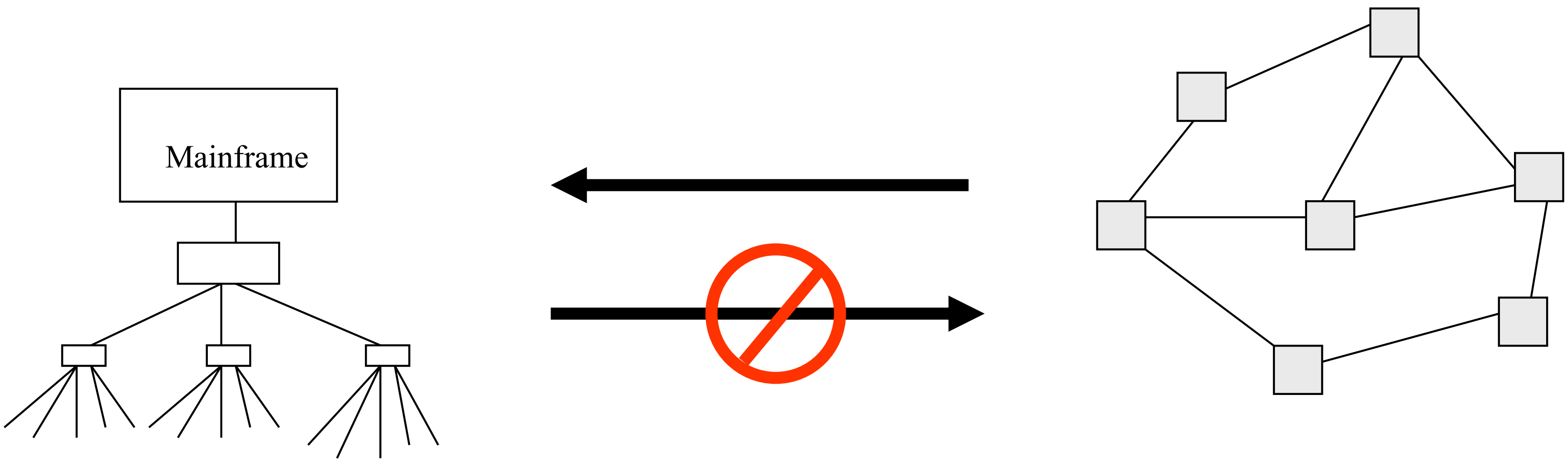


And if that weren't enough.

In Networking

IBM Found Itself at a Dead-End

You can always make a peer architecture hierarchical
But you can't go the other way.

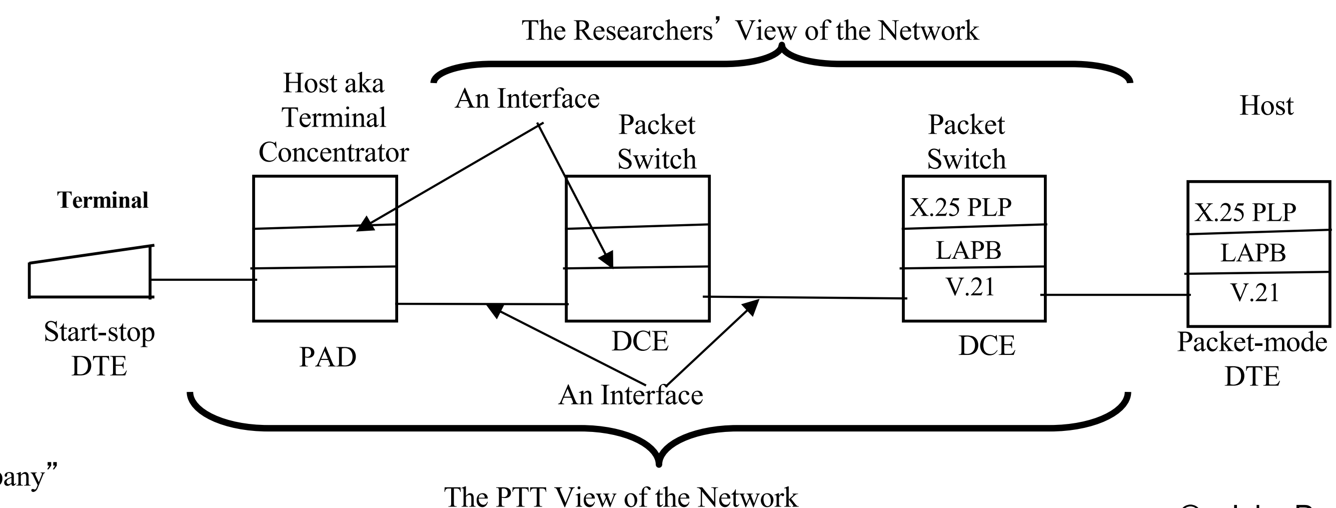


But IBM and the PTTs had carefully stayed out of each other's turf.

Had IBM made SNA a peer network and subset it for the 70s hierarchical market, the Internet would have been nothing but an interesting research project.

TPC:* The Beads-on-a-String Model

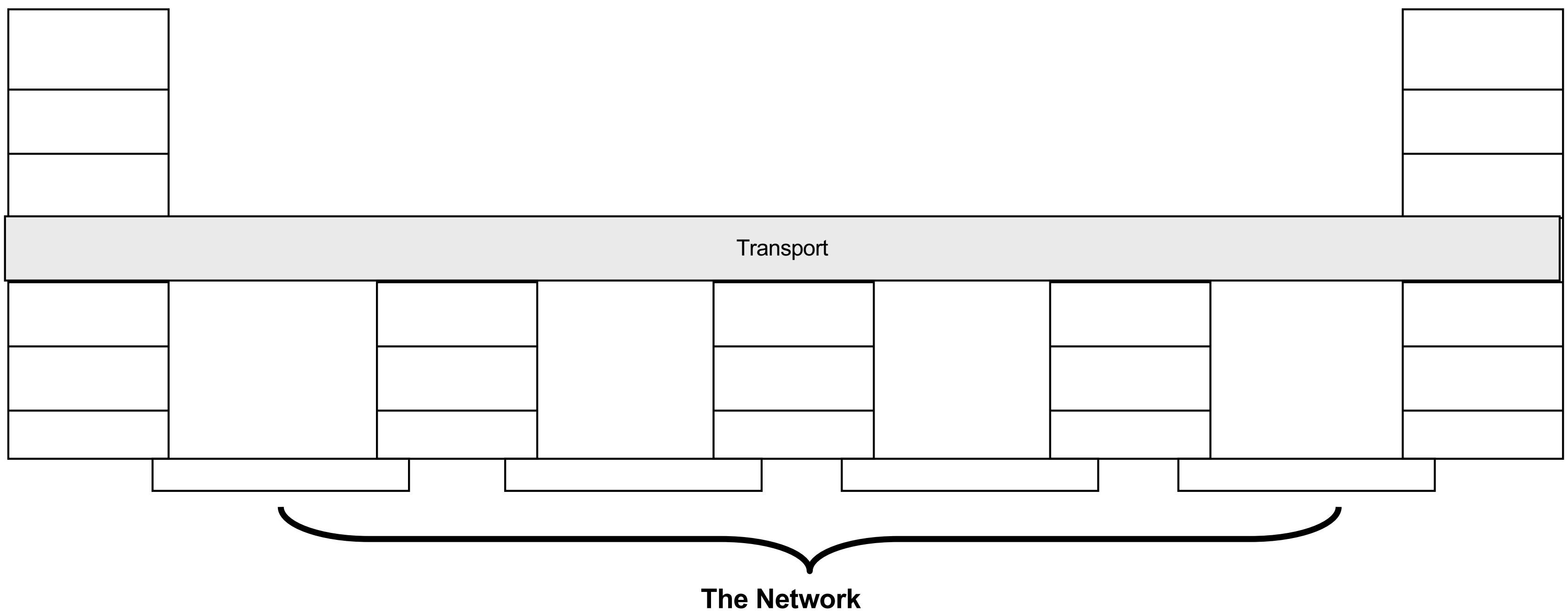
- Meanwhile TPC continues with what it is familiar with.
  - Emulating the phone system in computers
  - In this world, an interface is between *boxes*, not between layers.
  - Who cares about this academic connectionless stuff? We have *real* networks to build.
  - How do you charge for usage in a best-effort service?
- Asymmetrical/Connections/Deterministic
  - And a tendency toward hierarchy
- This Model Can not Represent Scope.
- Purpose of the architecture is to define who owns what boxes (protect a monopoly).
  - If you hear, X is *in* the network and X isn't involved with moving bits or managing moving bits, then it is beads-on-a-string.



* "The Phone Company"
with a nod to
"The President's Analyst"

TPC Relegated to a Commodity Business

- There had been an uneasy truce between TPC and IBM.
- Transport Seals Off the Lower Layers from Applications.
  - Making the Network a Commodity, with very little possibility for value-add.
- TPC counters that Transport Layers are unnecessary, *their* networks are reliable.



And they have their head in the sand, "Data will never exceed voice traffic"

The Phone Companies Weren’t Stupid ;-)

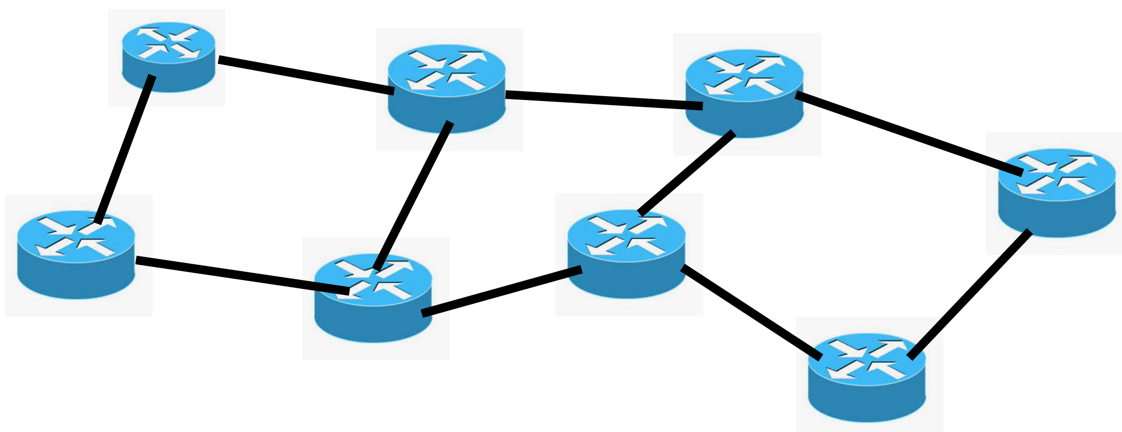
- True, this replicated in software what the phone system did physically, but
- In the 1970s, Max Packet Size was often 512 bytes or less. That isn’t much.
  - Lines were slow, error-prone and memory was expensive.
    - A minicomputer packet switch *might* have 64K bytes of memory
  - A virtual circuit X.25 header was 4 bytes vs a TCP/IP 40 bytes.
  - That is a lot of overhead!
    - But it was static allocation of buffers, although few knew that and it was somewhat counter-intuitive.
- The other case that favored Virtual Circuits was backbone routers.
  - The classic case that there isn’t a lot of traffic between Lexington MA and Lakeview, IL but there is between the Boston and Chicago regions.
  - If there is a lot of traffic all going to the same place, why look at every header!?

They Just Lacked Vision

- But the phone companies had two problems:
  - They could only see virtual circuit as being for voice
    - In the late 80s, ‘experts’ were telling me that the amount data traffic would never exceed the amount of voice traffic.
    - What were they smoking!?
  - Moore’s law and advances in modulation were working against them.
- Moore’s law relieved the memory crunch in the routers (to some degree)
  - More to allow much larger packet sizes
  - But also reduced the concern for header overhead.
    - Except when they did something stupid like ATM.
    - Incredulously, I still find people who defend ATM when it was clearly a bad idea from the start!

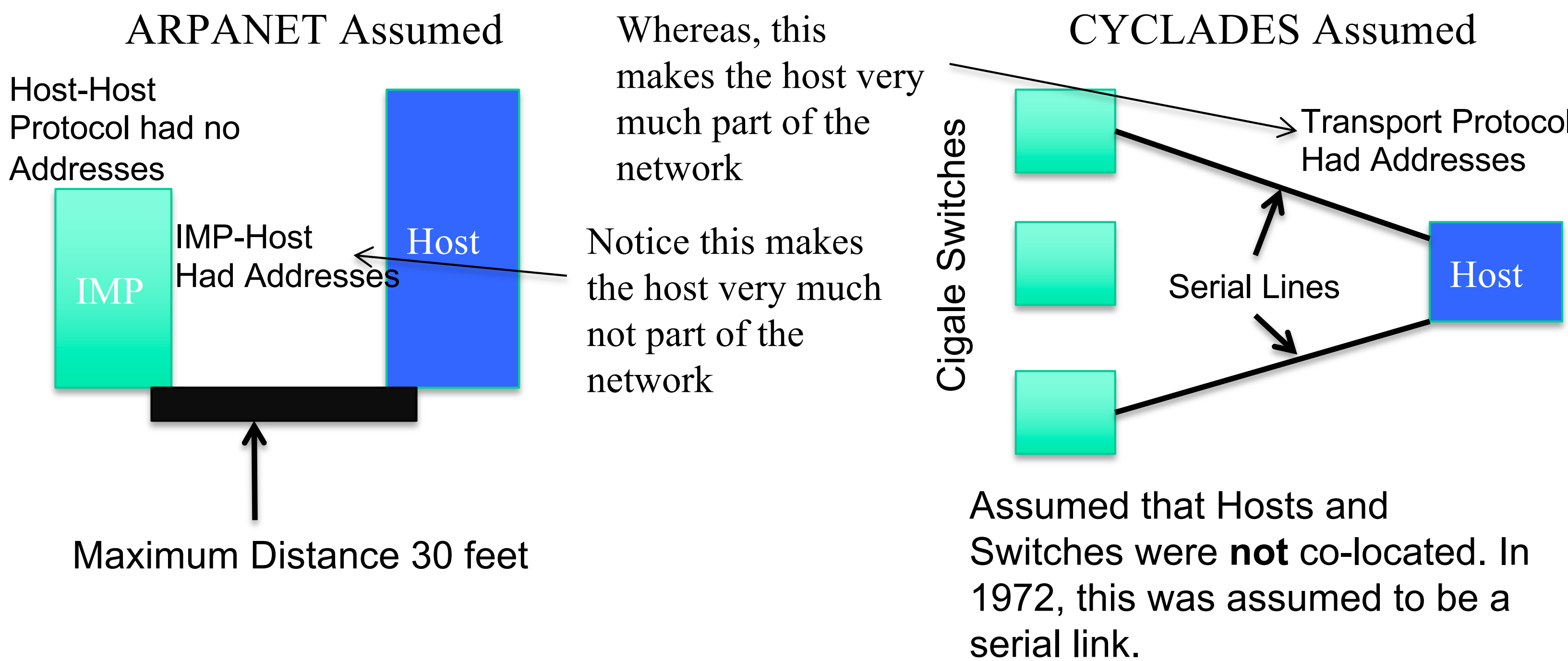
What Is the Real Difference?

- In the 'beads-on-a-string' or ITU model, boxes and wires are dominant. Layers are merely modules in a box and hosts are not part of the network.
  - If you tend to draw diagram like this, you are probably in the ITU model.



- In the CYCLADES or layered model, processes and layers are dominant. Boxes are merely containers and hosts are part of the network.

Small Differences Can Have Huge Effects



- The Difference between DoD largesse and Business Practice at the Time.
  - ARPANET: Host tells IMP to create flow, CYCLADES: Host maps to Net address.
- In CYCLADES, replace serial lines with a network, and add a relay on the Transport Addresses; otherwise, no change required
- The ARPANET was a network.
- CYCLADES was an internet architecture in 1972. (operational in mid-1973.)

Who Cares?

- The other computer companies care. They see an opportunity.
  - Even though IBM has 85% of the market there at least a dozen other computer makers, some mainframe, some minis.
- They see that IBM and the PTTs are tied down with a huge installed base and the technology trends are against them.
- With falling computer prices, and smaller minis.
  - Everyone sees computing and communications merging.
- And they want a piece of the action.
  - They create the 7-layer OSI Model standards effort.
- But this connectionless layered model has other implications that are not greeted with favor.

All Out War!

- The layered model had invalidated the business models of the two largest monopolies on the planet!
  - Rest assured they aren't going to simply fold up their tents.
  - They are going to fight it tooth and nail.
- In 1978, the computer companies initiate the OSI effort.
  - IBM and the Phone Companies are still in the data comm model;
  - The other computer companies are in the distributed computing model
  - IBM's strategy is to delay as much as possible.
  - The Europeans decide that inviting the PTTs to collaborate is better than having a competing model
    - Without deregulation, they had no choice.
    - However, it will be the death knell for the effort.
- Thus, begins a 30 years war that plagues us to this day.
  - No reconciliation of the connectionless/connection problem can be found, either technically or in terms of a business model.

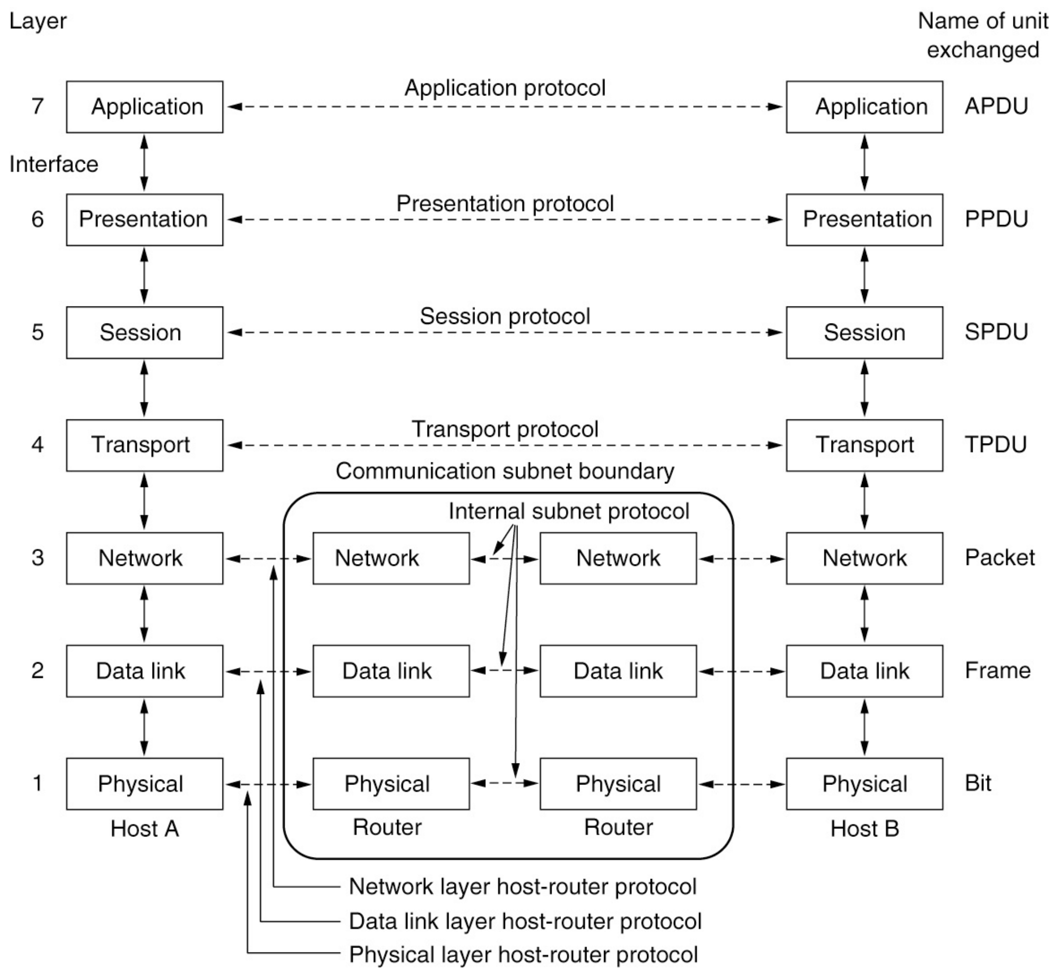
The Battlefield was Standards
(Electro-political Engineering)

- Standards are especially important in communications.
  - Without them no one can talk to anyone else.
- But no standard is purely a technical document.
  - Every one of them determines who gets to build what
  - They define markets.
  - The engineering is merely a source of arguments for markets.
- But mostly it was the connection/connectionless debate
  - that created the bunker mentality and did the most damage.
  - At first it is the old-guard against the young turks.

A Complicated War

- The US vs Europe vs Japan vs the Phone Companies
- But . . .
  - No Phone Company deregulation in the US let alone Europe
  - So European computer companies will have to co-exist with PTTs
  - US has dominate market position, primarily owing to IBM.
  - This new peer layered model is the perfect foil to IBM
    - This plays to the computer companies world-wide that aren't IBM
    - This new datagram packet switching is only 7 years old not really in the market and hence a lot of uncertainty about it.
    - The US has the most experience.
  - The deterministic mindset permeates both the computer and PTT organizations. It has religious overtones.
  - The non-deterministic view is definitely from a younger generation.

The OSI Reference Model



The OSI model has seven layers.

The 30 Years War

- The ITU developed one connection-oriented technology after another. Intent on maintaining their world view.
  - X.25,Videotex, AIN, ISDN, Frame Relay, ATM, MPLS, DSL, etc.
  - Always trying to find ways for the network not to be a commodity.
- At the same time, computer companies are trying to drive direction.
  - They are each competing with the other.
    - Each trying to get an advantage on the others.
  - IEEE 802 is formed in the early 80s by DIX.
- Interesting enough, AT&T sees this as an opportunity.
  - The break-up is a good thing.
    - Allows AT&T the flexibility to enter the computer business.
    - Rids it of the legacy twisted pair infrastructure, fiber is coming.
    - Although, some of its engineers don't see it this way.

Whoa!! Hold it!

Things are Not as They Seem!

We had Issues: I

- NCP wasn't going to scale, it needed to be replaced. But the datagram model indicated a direction.
  - CYCLADES pointed the way.
  - But the Internet had its own proposal.
- Was the basic structure correct?
  - This is all new. We haven't seen much of the problem space.
  - We knew we had a few kludges. Were these the right layers?
- What was the "upper layer" architecture?
  - 3 simple applications, but probably much more here.
  - Were more common structures to be found?
- Connectionless looks very promising but only used in the small, how would it scale?

We had Issues: II

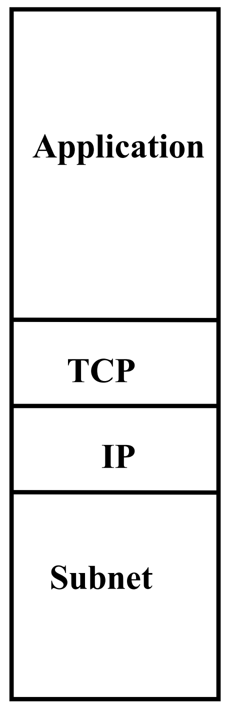
- We needed application names and a directory.
  - What did it look like?
- We needed a solution to numerous addressing problems that had turned up.
  - But being OS guys, the solution was clear. Addressing needed a hard look
- We needed better security. It was essentially non-existent.

- Quite a List! Lots of material for researchers.

So What Happened?

- USING starts in mid '73 with lots of good ideas.
- But ARPA pulls the plug in early '74, fearing they are losing control.
  - For 20 years, no new applications in the Internet.
  - This will prove to be a critical juncture. The emphasis on resource sharing is over and so is the driver to finish the architecture and the example for newcomers.
  - Newcomers just see a network think the phone system is a model.
- In 1972, INWG is formed to develop a Transport Protocol
  - In 1976, when the outcome is a synthesis of TCP and CYCLADES proposals known as INWG 96, the Internet goes its own way.
    - This will also be a critical juncture.
  - With a loss of institutional memory, there is a string of errors, but . . .
  - Moore's Law allows the problems to be papered over.
  - With major efforts going on elsewhere, they turn inward to protecting what they have and just fixing problems
    - We will come back to this in a few weeks.
  - But Nothing new is going to happen here.

In the Internet, there was no agreement about what was below the Network Layer or above the Transport Layer



Or do whatever you want

Or do whatever you want

Consequently, there is a tendency to try to see everything as issues involving one of these two.

Who's Who in the Internet Standards World

- IAB (Internet Activities Board) oversaw ARPANET
  - Renamed Internet Architecture Board
  - Communicated with RFCs (Request For Comments)
  - IRTF (Internet Research Task Force) subsidiary to IAB
  - IETF (Internet Engineering Task Force) subsidiary to IAB
  - More formal standardization process was adopted
- Internet Society
  - Created, populated by people interested in the Internet
- World Wide Web Consortium (W3C)
  - Develops protocols and guidelines to facilitate long-term growth of the Web

Standardization and Open Source

- Standards define what is needed for interoperability
  - No more, no less
- WiFi Alliance
  - Interoperability within the 802.11 standard
- ONF (Open Networking Foundation)
  - Interoperability of protocols to control programmable network switches
- Two categories of standards
  - De facto standards just happened, without any formal plan
  - De jure standards are adopted through the rules of some formal standardization body

Let’s Pause Here

- A series of problems arise over the next decade or so.
  - Congestion collapse in 1986,
  - Router table explosion, address exhaustion in 1990-92.
  - Quality of Service in the 90s
  - The Web
    - We need to understand more about networks to understand these problems, so we will hold off
- The Internet Boom is on! Confirming, that things were good. But does economic success imply solid engineering?
  - DOS was wildly successful in the market, but was it a good OS?
- Things aren’t looking good, Moore’s Law is keeping the bad problems at bay for now, but many know all is not well.
- Yes, it has been 20 years, but an incredibly fast 20 years!

Still on Pause

- Events had moved relatively fast. There was no way for researchers to stay out of the political fray.
- And there was always the old guard even among the researchers who saw this as telecom, rather than as distributed computing, and even then "researchers" were more about maintaining the 'Net than increasing understanding.
  - Science is about disproving theory, engineering is building on theory
- By 2000 Internet research has stagnated. From an NRC report on network research:

  > "A reviewer of an early draft of this report observed that this proposed framework – measure, develop theory, prototype new ideas – looks a lot like Research 101. . . . From the perspective of the outsiders, the insiders had not shown that they had managed to exercise the usual elements of a successful research program, so a back-to-basics message was fitting."

  - Must be sobering to be told you don't know how to do research.
- Something is wrong. All the signs are there. But it works! What is it?

So What Went Wrong?

- ARPA killing USING removed the only driver for change.
  - With Moore's Law, growth alone was not enough to cause it.
  - Research was pushed on the world stage too soon: bunker mentality
- By late-70s, second generation effect was in place.
- Breaking with INWG left the Internet in the ITU model.
  - The problems that would expose it did not become critical until later.
- Groupthink. So much emphasis on practice there was no theory to see where it was going and no one really trained to do it.
  - Oddly enough, every other network architecture but the Internet avoided the major problems of naming and congestion.
- Textbooks and courses are vo-tech: What is out there, not why.
  - Sells more textbooks
- The success of VC (short ROI) lead to emulation by research funding.
  - Again, an emphasis on technique (solutions) not theory (answers).

Metric Units

Exp.	Explicit	Prefix	Exp.	Explicit	Prefix
10^{-3}	0.001	milli	10^{3}	1,000	Kilo
10^{-6}	0.000001	micro	10^{6}	1,000,000	Mega
10^{-9}	0.000000001	nano	10^{9}	1,000,000,000	Giga
10^{-12}	0.000000000001	pico	10^{12}	1,000,000,000,000	Tera
10^{-15}	0.000000000000001	femto	10^{15}	1,000,000,000,000,000	Peta
10^{-18}	0.0000000000000000001	atto	10^{18}	1,000,000,000,000,000,000	Exa
10^{-21}	0.0000000000000000000001	zepto	10^{21}	1,000,000,000,000,000,000,000	Zetta
10^{-24}	0.0000000000000000000000001	yocto	10^{24}	1,000,000,000,000,000,000,000,000	Yotta

The principal metric prefixes.

Copyright

Network Protocols

(These have been pulled to the end because they were not the drivers at the time. These were developed much later to justify what was done.)

- Design goals
  - Reliability (ability to recover from errors, faults, or failures)
  - Resource allocation (sharing access to a common, limited resource)
  - Evolvability (allowing for incremental deployment of protocol improvements over time)
  - Security (defending the network against various types of attacks)
- Network protocol design: layering
  - True but the Internet doesn't follow it.
- Connection-oriented vs. connectionless service
  - Not a service but a function of the layer
- Specific service primitives
  - All layers have the same service primitives, just different values of the parameters.

Design Goals (1 of 4)

- Reliability
  - Make a network operate correctly even though it is comprised of a collection of components that are themselves unreliable
    - Error detection finds errors in received information
    - Error correction corrects a message by recovering the possibly incorrect bits
  - Find a working path through a network using routing
    - Routing allows network to automatically make the decision
    - Conditions in the network are changing too fast for a human in the loop.

Design Goals (2 of 4)

- Resource allocation
  - Scalable designs continue to work well when network gets large
  - Statistical multiplexing: sharing based on the statistics of demand
    - This is a sham. It is just ‘send data if you can.’ It just means it isn’t synchronous.
- An allocation problem that occurs at every level
  - Keeping a fast sender from swamping a slow receiver with data
  - Use flow control
- Congestion problem
  - Occurs when too many computers want to send too much traffic, and the network cannot deliver it all
  - No, occurs when too much traffic arrives at the same queue at the same time. It is subtle but the statements are very different and IMPORTANT.
- Quality of service reconciles competing demands
  - No, different kinds of traffic handled differently, which requires . . .

Design Goals (3 of 4)

- Evolvability
  - Design issue concerns the evolution of the network
  - Over time, networks grow larger and new designs emerge that need to be connected to the existing network (not really)
  - Use protocol layering structuring mechanism to support change by dividing the overall problem and hiding implementation details
    - Layers are configured to different ranges of data-rate, QoS, and scope.
  - Use addressing or naming mechanism to identify the senders and receivers involved in a particular message (not relevant)
  - Different network technologies often have different limitations
  - Overall topic is called internetworking
  - Misses the most important contributor: separation of mechanism and policy.

Design Goals (4 of 4)

- Security
  - Confidentiality mechanisms defend against eavesdropping on communications
  - Authentication mechanisms prevent someone from impersonating someone else
  - Integrity mechanisms prevent surreptitious changes to messages
  - Not really protocol design issue, but more architecture.