Some Observations and Interpretations of Internet History from 1968 to 1980

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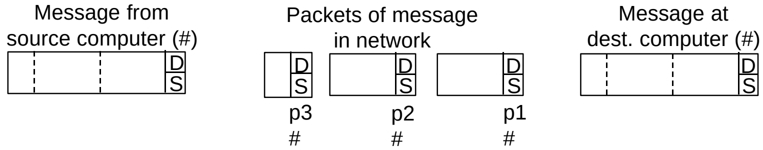
Packet-switching

- Circuit switching has no concept of a data frame--circuit is "always" available for use
- Message switching has frames that are the natural unit of data--can be indefinitely long
- Packet switching "messages" are broken into packets a (few) thousand bits in length



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Packet-switching continued

- Common user network allows many organizations and functions to share the cost of the network
- Packets are buffered in memory vs. on disk
- No blockage from long messages allows good latency
- Circuits sized to the average peak hour traffic across all users permitting decent ratio of circuit utilization to circuit cost
- Packet switching became possible because of changes in technology economics

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1968-1969

- ARPA let RFP for ARPANET (good general spec)
- Separation of packet switches (IMPs) and hosts
- BBN bid (complete design)
- BBN won and started on 1/1/69 with first system delivery required for 9/1/69
- Phone company and computer vendors argued against or ignored packet-switching

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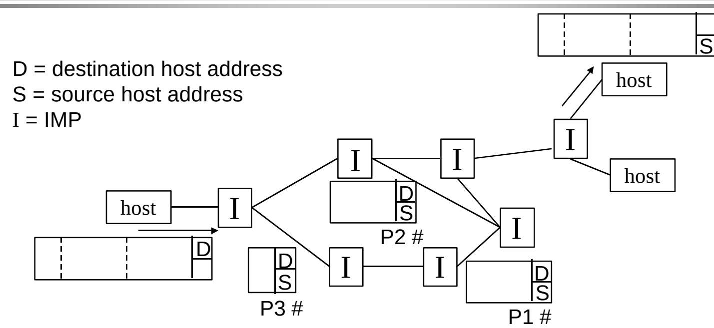
Messages and packets in the ARPANET



- Hosts send up to 8kbit messages into network of IMPs (according to "1822 protocol")
- IMPs break messages into 1Kbit or less packets that are individually routed
- IMPs to which destination hosts are connected reassemble packets into a messages

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BBN "IMP" project

- Project team: 1 part-time manager, 1 communications expert, 3 programmers, 2 electrical engineers (Frank Heart, Bob Kahn, Will Crowther, Dave Walden, Bernie Cosell, Severo Ornstein, Ben Barker*)
- Machine: .5MHz, 32K bytes (.032 Mbytes) of memory, half memory for program, and half memory for store and forward storage
- H516 computer was the size of a refrigerator; 50kbs modem rack was the same size

* Others, e.g., Alex McKenzie, joined the BBN ARPANET team slightly later

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Development environment

- Assembly language programming
- Using cross-assembler running on PDP-1
- Paper tapes of assembled coded transferred from PDP-1 to H516
- Debugger ran on H516 (breakpoints, etc.)
- No operating system in operational system

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IMP design

- Total design, including hardware/software and theory/practice trade-offs
- Defensive design
- Designed performance in
  - » Counted instructions
  - » Hardware interrupt driven with hardware support for software initiated interrupts
- Primarily concerned with getting a basic system up and working reliably
  - » Optimizing and perfecting complex network algorithms happened during following several years

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ARPANET characteristics

- Network transmitted binary data
- Significant transmission reliability provided by subnetwork of IMPs
- Dynamic routing
- Remote debugging, performance monitoring, down-line loading, etc. ("fake hosts" connected to Network Control/Operating Center)
- Immediate pressure/transition for multiple hosts per IMP and hosts remote from their IMPs
- Host/host protocol partitioned from communications subnetwork (NCP, Telnet, FTP, etc.)--protocol layers
- Pay for fixed transmission capacity--not bits sent or distance to destination (hid the cost in the organizational overheads and thus encouraged use)

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Transmission of binary data (many prior networks did not)

- IMP/IMP interface
  - » DLE STX (marking beginnings of packets) and DLE ETX (marking ends) added by transmitting IMP hardware interface
  - » Receiving IMP hardware interface detected and removed DLE STX and DLE ETX
  - » DLEs within packet contents were doubled (DLE DLE) by transmitting hardware interface, and extra DLE was removed by receiving hardware interface
  - » 24-bit CRC calculated by the transmitting hardware interface appended after DLE ETX; recalculated and checked by receiving interface
- Host/IMP and IMP/Host interface
  - » Hardware signal supported binary data transmission for local hosts
  - » Communications protocol supported binary data transmission for remote hosts

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Reliable transmission (many prior networks did not have this, or what they had did not work well)

- Checksum calculated and added in IMP hardware interface (and packet-ID added in software interface) during transmission from the source IMP and a copy of the packet is stored at the source
- Checksum calculated and checked in hardware at destination IMP
- At destination, packets with bad checksums are discarded and software ACK is sent to source for packets with good checksums
- The source copy is discarded when ACK received
- The source copy is retransmitted if ACK is not received for too long
- Host/host reliability mechanisms were still required but did not have to be exercised so often for an overall increase in network performance
- Eventually, a software packet checksum was also included to protect against IMP memory errors (such as the one that corrupted routing messages and crashed the whole network)

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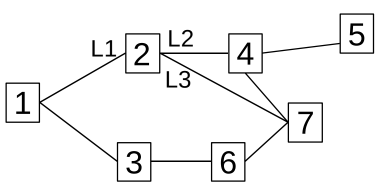
Dynamic routing (many prior networks had static routing)



Switch 2's routing tables

MD+1		Route	Min dist.	From Line L1	L2	L3	Init. MD
	0						
2	1	L1	1	1	3	3	∝
1	2		0	2	2	2	0
3	3	L1	2	2	4	3	∝
2	4	L2	1	3	1	2	∝
3	5	L2	2	4	2	3	∝
3	6	L3	2	3	3	2	∝
2	7	L3	1	3	2	1	∝

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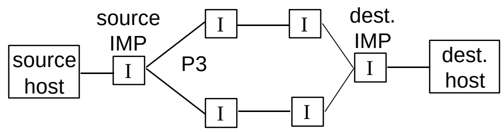
Protocol layers (many prior networks were highly “integrated”)



application protocol	Telnet, FTP, email, RPC, etc.
host OS/host OS protocol	OS compatibility
source IMP/dest. IMP protocol	messages to packets; packets to messages=>NCP *
IMP/IMP protocol	transmission between IMPs; routing across IMP network
electrical protocol on circuit	ignore this

* NCP was to ARPANET sort of what TCP is to Internet

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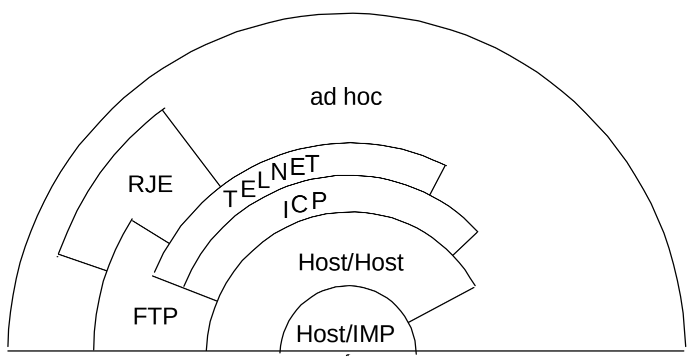
Early figure of ARPANET host protocol layers



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TIPs and TENEX

- Various sites had various host computers (Multics at MIT, Sigma 7 and IBM 360 at UCLA, IBM 360 at UCSB)
- However, many sites had TIP (shared rack or adjacent rack with IMP)
  - » Provided terminal access to network mainframe hosts for sites without mainframe hosts
  - » Provided substantial impetus for increased network use
  - » Supported by BBN and Network Control/Operations Center
- Many other sites had TENEX (OS and virtual memory version of PDP-10; became TOPs 20)
  - » Developed and supported by another BBN division
- TIPs and TENEXs enabled much early use of ARPANET
- Various Telnet issues were extensively studied between TIPs and TENEXs

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Network Working Group (NWG)

- Organization that created host protocols
- Open, free standards
- Request for Comments (RFC) series
- Participation was (largely) on a voluntary basis and decisions were made by those who were doing the work
- “Strong consensus and working code” (as described later by Dave Clark)
- Standards expected to evolve based on experience and need
- Negotiated options

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Negotiated options

- Bernie Cosell primarily conceived and worked-out Will/Won't, Do/Don't on a plane flight from Boston to a Telnet Protocol Meeting at UCLA
- Designed to:
  - » a. Address ships-passing-in-night protocol loops, i.e., either end can initiate an exchange or at same time
  - » b. Dynamically extensible protocols, i.e., supported implementation and use of protocol options without prior knowledge of other system

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Negotiated options (continued)

- Designed to be always consistent and have no loops (per 8/14/99 email from Bernie Cosell)
  - » A base minimal set of capabilities is defined, e.g., for Network Virtual Terminal
  - » Four commands
    - – Will <option>
    - – Won't <option>
    - – Do <option>
    - – Don't <option
  - » Two rules
    - – Don't send a command to confirm a state you are already in
    - – Don't ask a second time for an option that has been declined

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Some key principles (retrospectively)

- Common user network that reliably transmitted arbitrary data
- Dynamic routing from any host to any host with low delay and reasonable efficiency
- Decentralized operation with centralized monitoring and maintenance
- Billing independent of time and distance
- Layering of protocols so different levels can be changed without knowledge of applications at higher levels; separation of routing packets from application messages
- Network Working Group of individuals seeking good enough, open technical solutions that were expected to evolve

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Some other influential activities from 1968-1980 I observed from close range

- Early ideas for connectionless host/host protocols (RFC62)
- Tomlinson and networked email
- Satnet development
- Need for and specification of TCP/IP
- Internet experiments including Satnet, Packet Radio Net, ARPANET, and early “gateways”
- Early distributed operating system work of Bob Thomas et al. (early example of a worm, early instance of a distributed file system, etc.)
- Transfer of operations of ARPANET to DCA
- Early end-to-end security systems (see Steve Kent presentation)

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Some lessons I see from the early days

- Packet disassembly and reassembly in the subnetwork of IMPs had bugs early on; it also got in the way of real-time applications
- Need to pay attention to reliability and performance at every level
- 8 bits was not enough for network addresses, even for a prototype network; there is always pressure for more things to communications with other things
- It's a good idea to get something basic working that can then evolve (better dynamic routing, better network monitoring, TCP/IP, internetworking, connectionless protocols, etc. were added over time)
- In general it's good to focus on engineering solutions rather than political solutions; we go a lot farther a lot faster.

The early days of ARPANET provided important precedents

- Many of these principles have continued to be applied through several generations of internet technology over decades.