The First 31 Years of the Internet --
An Insider's View.

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Outline

A. Historical Overview

- **1961 - 1968: Pre-history**
- **1969 - 1973: ARPAnet research period**
- **1974 - 1983: Internet Research Period**
- **1984 - 1990: Academic Internet**
- **1990 - ??: Commercial (and Popular) Internet**

B. **The Internet Architecture**

C. **Conclusions and Challenges**

1961 - 1968: Pre-History

MIT: Len Kleinrock, J. C. R. Licklider, Larry Roberts

- **Kleinrock: Paper on theory of packet switching, 1961**
- **Licklider: Memos on "Galactic Network", 1962**
- **Roberts: Plan for the "ARPANET", 1967**

Rand: Paul Baran

Report on packet switching for secure voice, 1964

NPL (UK): Donald Davies & Roger Scantlebury:

Paper on a packet-switching network, 1967

IRIA (France): Louis Pouzin -- Cyclades

1969 - 1973: ARPAnet Research Period

o **ARPAnet: a prototype packet-switching network.**

-- The unit of multiplexing is a *packet* of data,

bearing a *destination address*.

-- Packet switches ("IMPs") : Minicomputers -- DDP 316, 516

-- High-speed leased lines (56Kbps)

-- Distributed adaptive routing algorithm

ARPA selected Bolt, Beranek, and Newman (BBN) to design, build, and operate the IMPs and the ARPAnet infrastructure.

ARPAnet Protocols

o IMP-Host Interface: defined by BBN Report 1822

>> Bit-serial

o Communication Service:

Reliable delivery to a specified host system of a message of arbitrary bit length.

-- I.E., a "reliable datagram" service

-- The 8-bit byte not universal yet; computers used 8, 12, 16, 18, 24, 32, 36, 48, ... bit words.

-- ARPAnet host addresses were 24 bits (IMP#, host#)

ARPAnet Protocols

How can host software use this communication service?

Need rules , i.e., *protocols*.
Quickly invented: Protocol Layering.

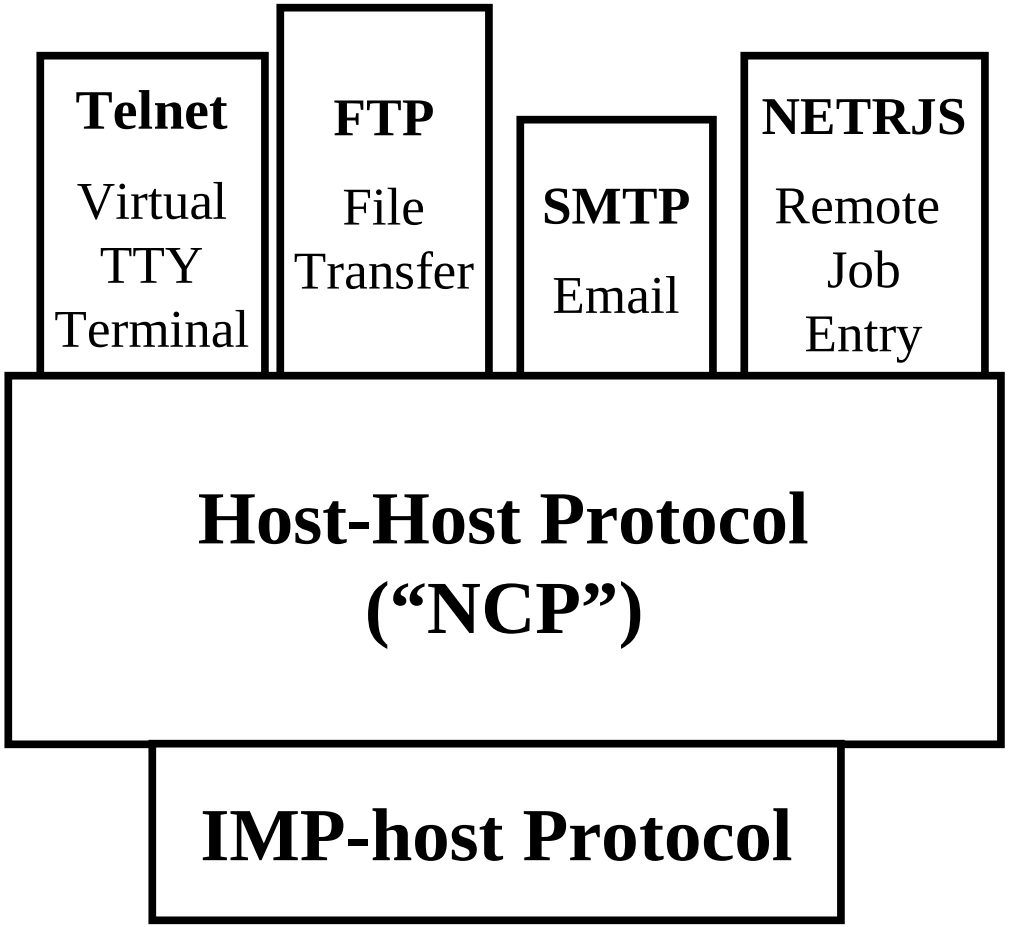
> "Second-level" Host-to-host protocol ("NCP")

Simplex logical byte streams *(connections)* with specified *byte size*.

> "Third-layer" Application protocols:

- **File Transfer: FTP [RFC542 8/73; included email]**
- **Remote login: Telnet [RFC495 5/73]**
- **Network Voice Protocol: NVP [RFC 741 11/77]**
- **Remote Job Entry Protocols: RJE [RFC 407 10/72]**
  and NETRJS [RFC 189 7/71].

ARPAnet Protocol Stack



Reliable full-duplex H-to-H connections

IBM "Big Iron" on the ARPAnet

Original ARPAnet purpose was "Resource Sharing"

- **Era of the bi...iig mainframe computers**
  Performance ~ (cost)2: Grosch's Law**
- **ARPA wanted the IBM 360/91 at UCLA as a computing resource to be accessed via the ARPAnet.**
  (1970: I got the software job...)
- **1971: 360/91 became host 2, imp 1 on the ARPAnet;**
  aka CCN aka UCLA-CCN.ARPA.
- **We were in it for the money... Very large climate dynamics simulations for Rand, using the ARPAnet.**

UCLA-CCN ...

- **Had to design & implement:**
  - **> An interprocess communication system for IBM OS/MVT.**
  - **> An NCP implementation for IBM OS/MVT.**
  - **> An ARPAnet remote job entry protocol, NETRJS [RFC 189 7/71].**

- **We later added ARPAnet access to:**
  - **> FTP server**
  - **> Telnet server for IBM's TSO timesharing system (3270s!)**
  - **> SMTP-based Email**

- **Hurdles:**
  - **-- The IBM Culture: batch processing, a *baroque* file system, and the EBCDIC character set.**
  - **-- Uncooperativeness of IBM Corp.**
  - **-- A bit of arrogance of our friends at BBN, MIT, and the UCLA Computer Science department…**

Overview of ARPAnet Period

- **The ARPAnet grew from 10 hosts to ~ 200.**

  Mixture of research and DoD production nodes

- **Many new ideas...**

  -- Protocol Layering

  -- Link state routing protocols

  -- Connections ("virtual circuits")

  - **Reliable, flow-controlled; requires state setup.**

  -- Datagrams [Pouzin, <1974]

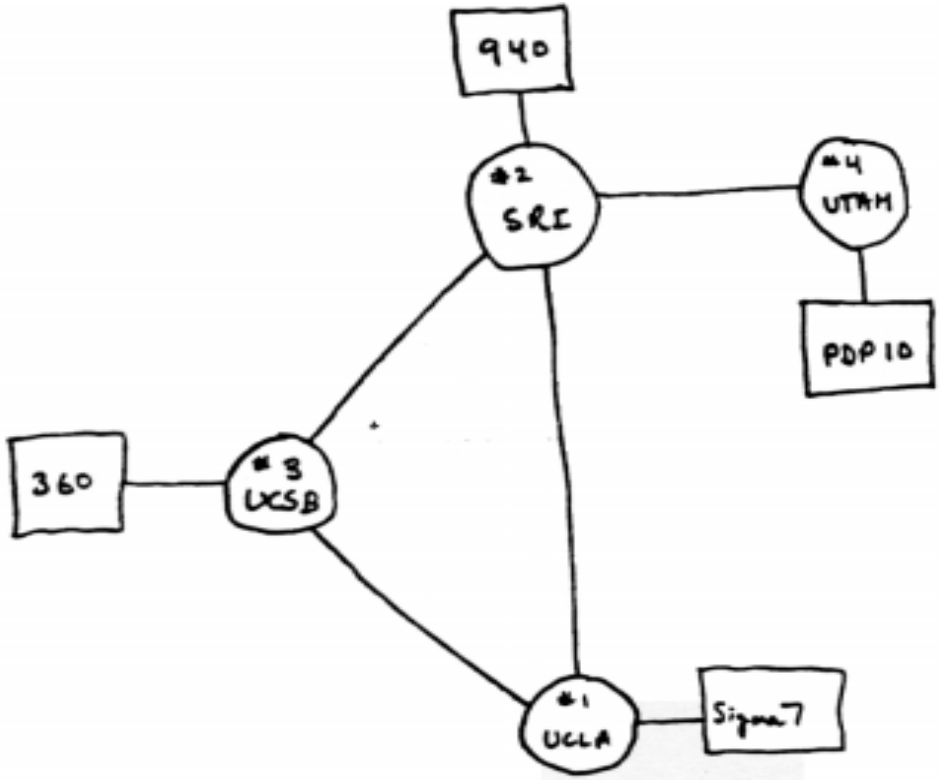
  - **Single packet sent with minimum overhead**
  - **Unreliable**

  -- Packet voice [Cohen@isi] -- multimedia

  -- Email

  -- Presentation Layer [Postel & White @ SRI]

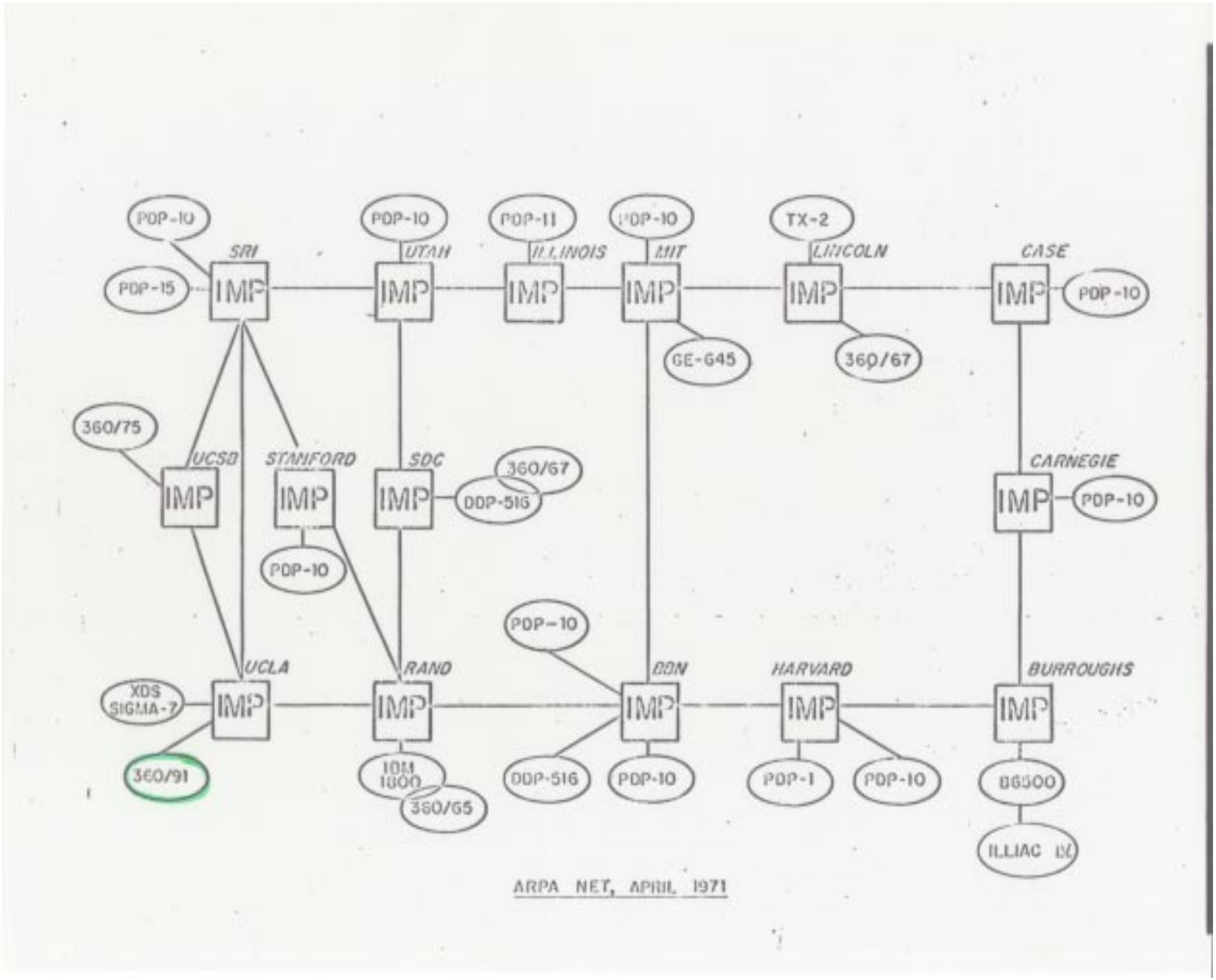
  -- RPC (Remote Procedure Call)



THE ARPA NETWORK

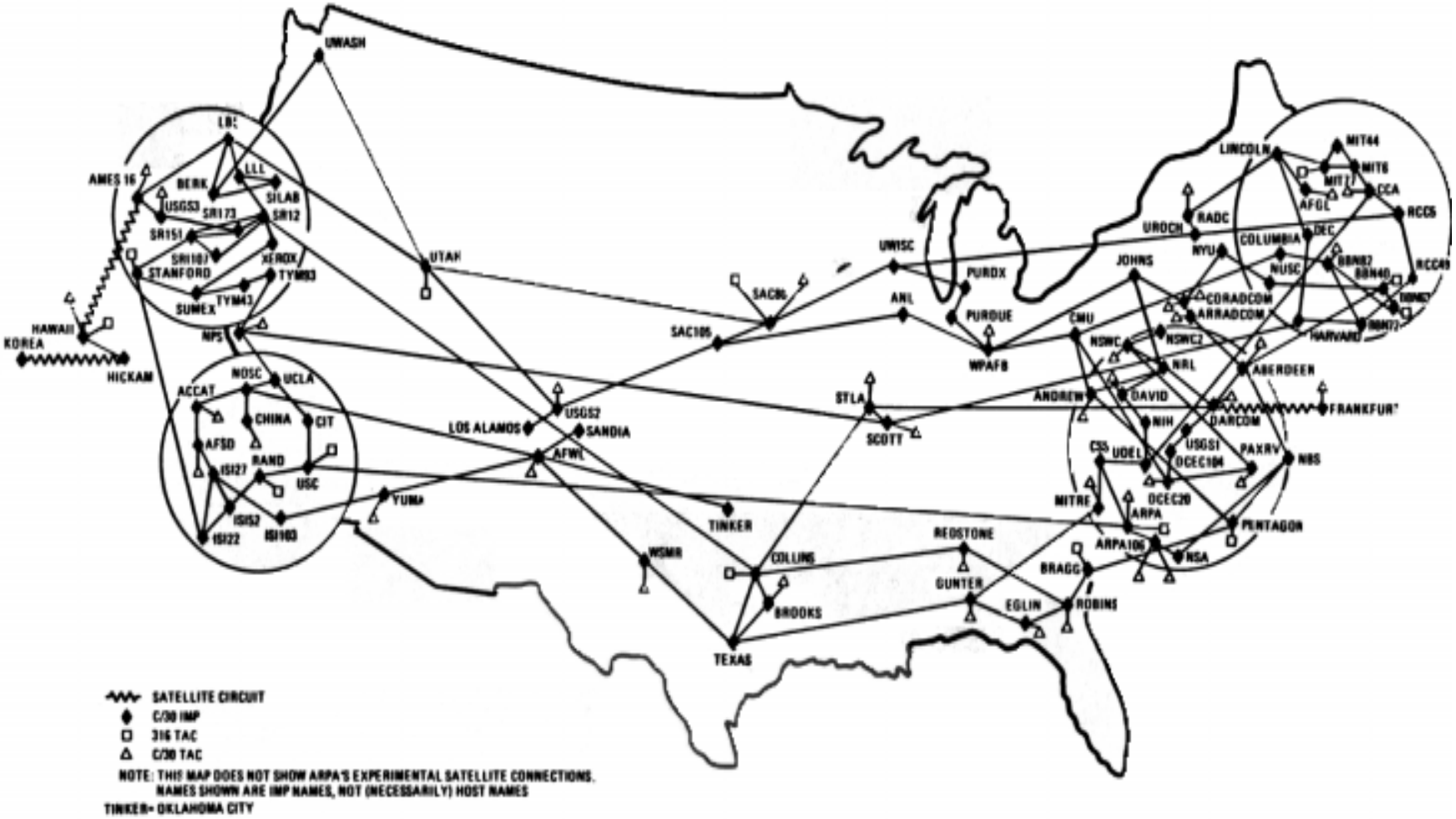
DEC 1969

4 NODES



ARPA NET, APRIL 1971

ARPANET/MILNET GEOGRAPHIC MAP, FEBRUARY 1984



Internet Research Period: 1974-1983

- **By 1974, other packet-switching technologies had been developed or were planned:**
  - **-- Packet Radio network (“ad hoc wireless”)**
  - **-- LAN: Ethernet**
  - **-- Packet-satellite network (SATNET)**

DoD's problem: how to hook them together??

Solution: a network of networks -- an INTERNETWORK.

Internet Research Period: 1974-1983

Beginning: "*A Protocol for Packet Network Interconnection*", Vinton G. Cerf and Robert E. Kahn,

IEEE Trans Comm., com-22, no. 5, May 1974.

End: ARPAnet cutover from NCP to TCP/IP:

January 1, 1983 (Orchestrated by Jon Postel, ISI)

Protocol Developments by Internetwork Working Group :

- **NCP replaced by Network and Transport Protocols: IP, TCP, UDP, ICMP.**
- **Application layer: TCP/IP versions of application protocols Telnet, FTP, SMTP (and NETRJS!)**
- **Routing protocol: GGP (distance vector, ancestor to RIP)**

The Foundation Documents

o Protocol evolution detailed in the IEN documents

See http://www.rfc-editor.org/history.hmtl

o RFC 801: "NCP/TCP Transition Plan", Jon Postel, Nov 81.

IP	RFC 791
ICMP	RFC 792
TCP	RFC 793
Telnet	RFC 764
FTP	RFC 765
SMTP	RFC 788
Name Server	IEN 116
Assigned Numbers	RFC 790

Although many contributed, these all bear Jon Postel's name.

Network Table: RFC 790, Nov 1981

000.rrr.rrr.rrr		Reserved	[JBP]
001.rrr.rrr.rrr	BBN-PR	BBN Packet Radio Network	[DCA2]
002.rrr.rrr.rrr	SF-PR-1	SF Packet Radio Network (1)	[JEM]
003.rrr.rrr.rrr	BBN-RCC	BBN RCC Network	[SGC]
004.rrr.rrr.rrr	SATNET	Atlantic Satellite Network	[DM11]
005.rrr.rrr.rrr	SILL-PR	Ft. Sill Packet Radio Network	[JEM]
006.rrr.rrr.rrr	SF-PR-2	SF Packet Radio Network (2)	[JEM]
007.rrr.rrr.rrr	CHAOS	MIT CHAOS Network	[MOON]
008.rrr.rrr.rrr	CLARKNET	SATNET subnet for Clarksburg	[DM11]
009.rrr.rrr.rrr	BRAGG-PR	Ft. Bragg Packet Radio Net	[JEM]
010.rrr.rrr.rrr	ARPANET	ARPANET	[17,1,VGC]
011.rrr.rrr.rrr	UCLNET	University College London	[PK]
012.rrr.rrr.rrr	CYCLADES	CYCLADES	[VGC]
013.rrr.rrr.rrr		Unassigned	[JBP]
014.rrr.rrr.rrr	TELENET	TELENET	[VGC]
015.rrr.rrr.rrr	EPSS	British Post Office EPSS	[PK]
016.rrr.rrr.rrr	DATAPAC	DATAPAC	[VGC]
017.rrr.rrr.rrr	TRANSPAC	TRANSPAC	[VGC]
018.rrr.rrr.rrr	LCSNET	MIT LCS Network	[43,10,DDC2]
019.rrr.rrr.rrr	TYMNET	TYMNET	[VGC]
020.rrr.rrr.rrr	DC-PR	D.C. Packet Radio Network	[VGC]
021.rrr.rrr.rrr	EDN	DCEC EDN	[EC5]
022.rrr.rrr.rrr	DIALNET	DIALNET	[26,16,MRC]
023.rrr.rrr.rrr	MITRE	MITRE Cablenet	[44,APS]
024.rrr.rrr.rrr	BBN-LOCAL	BBN Local Network	[SGC]
025.rrr.rrr.rrr	RSRE-PPSN	RSRE / PPSN	[BD2]
026.rrr.rrr.rrr	AUTODIN-II	AUTODIN II	[EC5]
027.rrr.rrr.rrr	NOSC-LCCN	NOSC / LCCN	[KTP]
028.rrr.rrr.rrr	WIDEBAND	Wide Band Satellite Network	[CJW2]
029.rrr.rrr.rrr	DCN-COMSAT	COMSAT Dist. Comp. Network	[DLM1]
030.rrr.rrr.rrr	DCN-UCL	UCL Dist. Comp. Network	[PK]
031.rrr.rrr.rrr	BBN-SAT-TEST	BBN SATNET Test Network	[DM11]
032.rrr.rrr.rrr	UCL-CR1	UCL Cambridge Ring 1	[PK]
033.rrr.rrr.rrr	UCL-CR2	UCL Cambridge Ring 2	[PK]
034.rrr.rrr.rrr	MATNET	Mobile Access Terminal Net	[DM11]
035.rrr.rrr.rrr	NULL	UCL/RSRE Null Network	[BD2]

NCP ->Two Protocol Layers

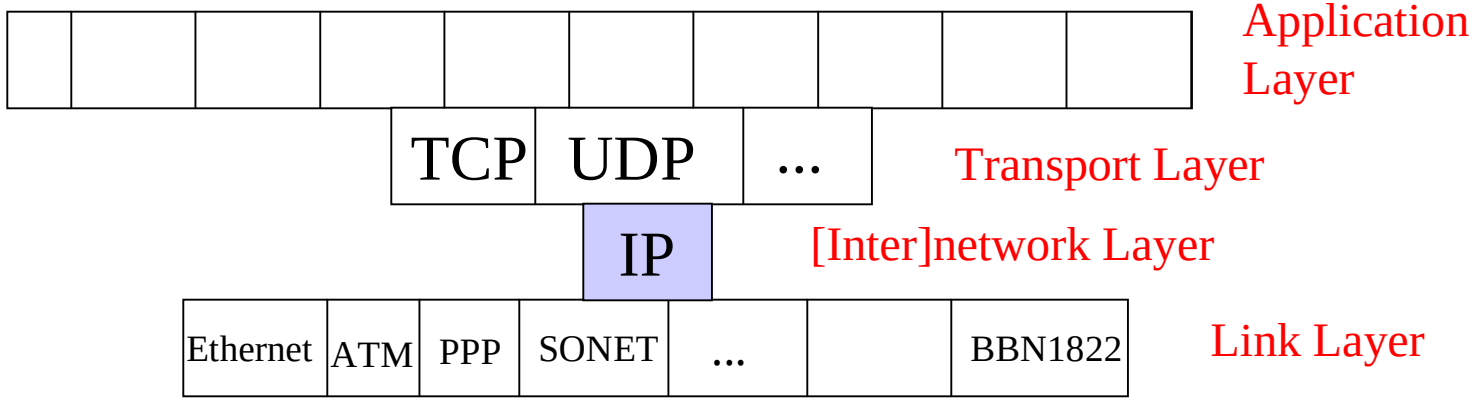
Internetwork Layer: IP (Internet Protocol)

-- IP header carries global destination address E2E.

-- Each router examines IP header and forwards packet towards destination.

Transport Layer: only host-to-host.

> TCP: Reliable full-duplex byte stream
> UDP: Datagram service



Research Prototypes 1978-1983

TCP/IP Implementations:

> LSI/11:	Jim Mathis, SRI
> UNIX (C)	Mike Wingfield, BBN
> UNIX (Macro11)	Jack Haverty, BBN
> Tenex/TOPS20	Bill Plummer, BBN
> Multics	Dave Clark, MIT
> IBM 360/370	Bob Braden, UCLA

Prototype IP router on LSI/11, running GGP

Ginny Strasizar, BBN

1984 - 1990: Academic Internet

- **NSF began to fund Internet growth through NSFnet and CSNET, bringing the Internet to US higher education.**
- **Higher line speeds: 56 Kbps -> T1 (1.5Mbps) lines**
- **Exponential growth => repeated growth crises**
- **ISO OSI threatened to replace TCP/IP**

Academic Internet (cont'd)

Important new Internet protocol technology was introduced

(a) Domain Name System

Mappng host names => IP addresses

(b)Two-level routing hierarchy: [scalability, evolvability]

IGPs (Interior Gateway Protocols) route within domains (think of area codes), plus:

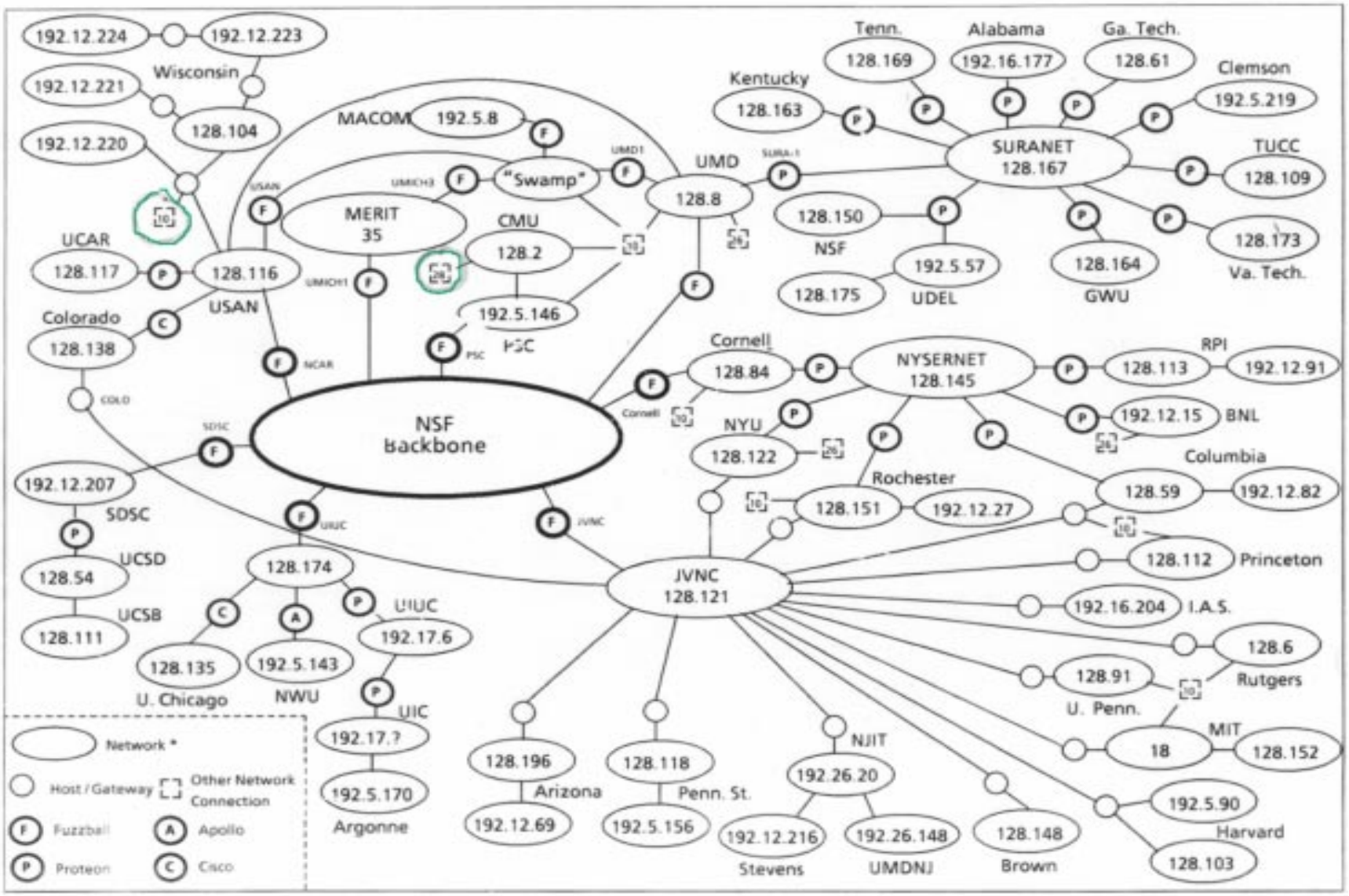
BGP (Border Gateway Protocol) to route among domains

(c) Solution to congestion collapse: Van Jacobson

(d) Network management: SNMP

(e) IP Multicast

NSFNet Logical Connectivity -- April 87



* Internal structure of networks (e.g. subnets) is suppressed.

1984-1990: Who was Running the Internet?

- **US government agencies: NSF, ARPA, DOE, NASA, ... had important influence. (Paying the bills!)**

- **Technical Control: a junta of Internet researchers, the Internet Activities Board (IAB).**

  -- Set up by ARPA (Vint Cerf) ~1980 to advise on research program
  -- Increasingly independent; self-selecting; passionate supporters of the Internet architecture

  -- Created Task Forces, led by IAB members (1983)

  -- ONE of these task forces grew into the Internet Engineering Task Force (IETF)

  -- IAB retained control over Internet protocol standards until the IETF membership deposed it in 1993.

1990 - Present: Commercial Internet

- **Government funding & operation replaced by ISPs**
- **HTTP and the WWW were invented (~1993) and rapidly became the dominant application.**
- **PCs became dominant hosts**
- **Exponential growth accelerated!**
- **32 bit IP addresses ran low => developed IPv6**
- **New protocols and algorithms for:**
  -- Mobile IP
  -- Security
  -- QoS
  -- Traffic Engineering

Internet "Architecture"

o Network architecture: fundamental design principles

-- Inform technical decisions, e.g., protocol design

-- Simple and general => elegant

o Deep philosphical gap between Computer Scientists who developed Internet architecture, and telecommunication engineers:

> Engineers: The Internet is under-engineered -- it does not solve all current problems in the most optimal and controllable manner.

Besides, we LOVE virtual circuits and complexity.

> Internet Researchers: Optimal is NOT the point.

The future adaptability of the Internet to new technologies and to provide new services depends on NOT over-engineering the Internet! Uncertainty: live with it.

Besides, we LOVE datagrams and simplicity.

Internet Architecture: Deep Assumptions

o Packet switching

-- Unit of data is a packet

-- Packets are statistically muxed (not deterministic: TDM)

Because computers don't hum to each other, they CHATTER!

I.E., Computer communication is fundamentally bursty.

o Strict protocol layering

-- Successive layers of functional abstraction

-- formalized in OSI model

o Strict header encapsulation

-- Headers added/removed in strict LOFO order

-- "Stack"model.

Architectural Requirements

o **Generality**
  -- Support ANY set of diverse applications,
  -- Either datagrams (think video) or VCs (think web).

o **Heterogeneity**
  -- Interconnect ANY set of network technologies

o **Robustness**
  -- More important than efficiency

o **Extensibility**
  -- More important than efficiency

o **Scalability**
  (A later discovery. How many ARPAnets could the world support? A few hundred, maybe… ?)

The End-to-End Principle

Foundation of the Internet architecture:

Dumb network, smart end systems

(Exact opposite of telephone network!)

o Dumb networks: require only least common service

-- Datagram service: no connection state in routers

-- Best effort: all packets treated equally.

-- Can lose, duplicate, reorder packets.

o Smart hosts:

-- Maintain state to enhance service for applications.

-- "Fate-sharing"-- If a host crashes and loses comm state, applications that are communicating share this fate.

Internet Architecture

o Hop-by-hop forwarding

-- We believed this would be more robust than source routes or connection-oriented subnetworks.

=> Asymmetric routes are normal

=> Require global consistency of routing tables

End-to-End Principle

An Ongoing Architectural Battlefront…

- **o "Middle boxes" -- perform useful functions but apparently violate the E2E Princ.**

  Web caches, application-level firewalls, NAT boxes, performance-enhancing proxies, …

- **o "Right" answer not always clear.**

  E.g., fixing "impairments" in network: good and bad .

  -- Reliable delivery can enhance TCP performance.

  -- But adds to latency

Internet Architecture: Serious Problems

- Multihoming does not work well
- No Quality of Service (QoS)
- Serious feature interactions among security, QoS, mobility, ...
- IPv6 transition painful, uncertain
- NAT boxes destroy general E2E connectivity
- Accounting is very hard
- Mobility is complex and limited
- Multicast is a disaster

Internet Architecture Melting...

- o Orgy of tunnel-vision engineering taking place in IETF to meet these problems, and others.
- o A shortage of wisdom; continual need for damage control.
- o Easily forget the cost of [over-] engineering; remember: generality, heterogeneity, robustness, extensibility?
- o Maybe we need to pay people NOT to develop new protocols.
- o But perhaps, it is also time to rethink the architecture.

We Survived ...

o We, and our architure, survived a series of real (and imaginary) threats over the years.

-- X.25

-- FAX (opposing email)

-- Many minor competitors --
e.g., XNS, DECNET, BITNET, MFENET, …

-- ISO Open Systems Interconnect (OSI)
CLNP, TP4, FTAM, …

-- ATM

and I predict that it will survive the latest hype, optical networking.

Why did the Internet Succeed?

1. Leadership from a handful of visionaries who emerged from US government bureaucracy

   Larry Roberts (ARPA)
   Vint Cerf (ARPA)
   Bob Kahn (ARPA)
   Steve Wolff (NSF)

2. ARPA-funded BSD Unix development used TCP/IP

   Publicly funded OS --> many vendor products

3. Triumph of the startups -- small networking companies were agile and creative

   BBN, Cisco, Sun, Proteon, ...

4. Military (ARPA) funding insulated early research from commercial pressures

Why ... (cont'd)

Alternative example: Europe

-- PTTs (government monopoly phone companies) did not believe.
-- PTTs put their money on the X.25 model: the phone companies do all the switching; limited service model.
-- AT&T did not believe either, but they thought TCP/IP was wrong-headed and irrelevant.

5. Military obsession with "robustness" led to easily-deployed connectionless IP protocol.

- Plug-and-play => populist model fueled growth at critical stage

6. Silicon- and Fiber-revolutions were perfectly timed.

Why ... (cont'd)

7. **The IAB accidentally killed OSI by embracing it (1992).**
8. **The WWW popularized the Internet.**
9. **The Internet architecture provided the generality and extensibility to survive the past and the present.**
10. **Exponential growth is a mighty engine, and vendors and ISPs have been running to keep up.**

Phone Company Thinking Evolved

(a) "X.25 will satisfy all needs for data traffic"

(b) "OSI will (ditto)"

(c) "Anyway, voice traffic >> data traffic"

(d) "We will interconnect Internet and phone network"

(e) "The phone network will be replaced by Internet technology"

The Future… is fuzzy.

- Economic, business, and political forces are now central
- The Internet ~ railroads in 1875.
- Large companies rule
- Mergers leading to monopolies?
- Can we believe the mega companies won't screw it up?
- Internet could fragment into pieces
- Technical underpinnings will have to evolve further.