History of Internet Answers to Questions

Vint Cerf

References:

1. Where Wizards Stay Up Late, Katy Hafner, Simon & Schuster l 304 pages l ISBN 9780684832678 l January 1998 - See more at: http://books.simonandschuster.com/Where-Wizards-Stay-Up-Late/Katie-Hafner/9780684832678#sthash.RVG5EZov.dpuf

2. Inventing the Internet, Janet Abbate, **Hardcover** | **$69.00 Short** | **£47.95** | ISBN: 9780262011723 | 268 pp. | 6 x 9 in | June 1999; **Paperback** | **$30.00 Short** | **£20.95** | ISBN: 9780262511155 | 268 pp. | 6 x 9 in | July 2000; **Ebook** | **$30.00 Short** | ISBN: 9780262254403 | 268 pp. | July 2000; MIT PRESS

3. "A Brief History of the Internet, Barry Leiner (Ed.), http://www.internetsociety.org/internet/what-internet/history-internet/brief-history-internet

4. Internet Timeline, http://www.zakon.org/robert/internet/timeline/

5. http://tandfonline.com/toc/rint20/current

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1. What made you want to explore the field of computer science and the development of an internetworking protocol?

I had been interested in computers after seeing the Semi-Automated Ground Environment (SAGE) system at System Development Corporation (SDC) in 1958. SDC was a spin out from the Air Force-supported RAND Corporation. SAGE was a tube based computer. See https://en.wikipedia.org/wiki/Semi-Automatic_Ground_Environment. I was also allowed to use computers at UCLA (specifically the BENDIX G-15 and later, the IBM 7090) while I was still in high school. By the time I got to Stanford, I was a mathematics undergraduate with a lot of interest in computer science – so I took every computer course I could find. I went to work for IBM in 1965 as a systems engineer and then returned to UCLA for graduate work in computer science. It was at UCLA that I was introduced to the ARPANET project. Prof. Leonard Kleinrock was awarded a Defense Advanced Research Projects Agency contract to develop a Network Measurement Center and to compare the measured results of artificial traffic on the ARPANET with the queueing theoretic models that Kleinrock and his students developed to predict network performance. Robert Kahn was one of the architects of the ARPANET packet switch ("Interface Message Processor") and I met him in 1970 when he and a colleague, David Walden, came out to UCLA to test the 4-node network.

I worked closely with my colleague, Stephen Crocker, on the host-to-host protocols for the ARPANET. Crocker created the "Network Working Group" that developed the communication and application protocols for the ARPANET, established the documentation series: "Request for Comment", and eventually served a term at DARPA as a program manager. Crocker was also instrumental in getting permission to use the computers at UCLA while we were both in high school.

After I finished my Ph.D. in computer science at UCLA, I was invited to join the Stanford faculty and it was there that I met again with Robert Kahn who outlined his "open networking" ideas in the spring of 1973. Recognizing the importance of computers in command and control led him to believe that we would need to put computers in airplanes, helicopters, ground vehicles and ships at sea. This led him to develop a mobile Packet Radio network and a mobile Packet Satellite network to complement the wireline ARPANET. Xerox PARC was working on Ethernet in the Spring of 1973 and we knew about that. Too. We worked together on the "inter-net" problem: how to interconnect an arbitrary number of dissimilar packet-switched networks in such a way that the host computers on each would be unaware of how many networks were involved, how to route traffic from any source to any destination, and how to deal with packet disordering, loss and flow control. These and other considerations led us to design the TCP (Transmission Control Protocol), develop a global, non-national address space, and to support existing applications that had been developed for the ARPANET (remote access to timeshared computers, electronic mail, file transfer, etc).

2. Did you encounter any problems with the TCP/IP protocol in either developing it and/or after its implementation? If so, what were they?

We went through four rounds of design, producing TCP, TCP2, TCP/IPv3 and TCP/IPv4[1]. The basic design is documented in [CERFKAHN1974[2]]. A complete specification of TCP was published in

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[1] https://en.wikipedia.org/wiki/Internet_protocol_suite

[2] V. G. Cerf and R. E. Kahn, "A Protocol for Packet Network Intercommunication," IEEE Transactions on Communication, Vol. COM-22, No. 5, May 1974, pp. 637-648. Reprinted in Computer Networking, edited by Blanc

December 1974 [CERFDALALSUNSHINE1974][3]. This version was implemented in 1975 at Stanford, Bolt, Beranek and Newman and University College London. Ray Tomlinson and Yogen Dalal discovered that the resynchronization mechanism resulted in the incorrect acceptance of duplicate packets and they proposed a three-way handshake and random initial sequence selection mechanism to overcome this limitation. That led to the TCP version 2 design[4] that introduced the initial sequence number selection procedure. The resynchronization procedure was still in V2 but removed in TCP version 3. The most significant change is the splitting off of the Internet Protocol (IP) from TCP which focused on host-to-host reliability and flow control while IP provided the basis for fast, potentially lossy and disordered datagram delivery. User Datagram Protocol over IP was used to support a low-latency service at the application level. We were concerned that real-time voice, video and telemetry would not be adequately supported by the original TCP design. A reconnection protocol was introduced in TCP v3 and an "end of letter" (EOL) introduced to deal with a flow control problem when the end of a CP transmission fails to consume the "window" offered by the receiver. Version 4 of TCP/IP followed version 3 in 1978 and a series of refinements to it were pursued including the removal of "rubber End of Letter" concept. RFCs[5] 791, 792 and 793 were issued in 1981 capping the final design.

In 1978, the Organization for International Standards (ISO) started an effort to define protocols for what it called Open Systems Interconnection (OSI)[6]. A fifteen year rivalry with TCP/IP lasted until 1993 when the US National Institutes of Standards and Technology (NIST) initiated a review of TCP/IP and OSI and a report was issued in 1994 confirming that all the services envisaged in the US Government Open Systems Interconnection Profile (GOSIP[7]) could be met by the TCP/IP Internet Protocol suite[8,9].

Another major battle has been the introduction of IPv6[10] to run in parallel with IPv4 so as to provide adequate IP address space for the foreseeable future. It had been hoped that IPv6 would be immediately implemented by router vendors, edge device makers (computers, servers, etc.) and by the Internet Service Providers (ISPs) but it has been a very long and slow process. ICANN ran out of IPv4 address space in February 2011 and could not longer supply it to the Regional Internet Registries

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and Cotton, IEEE Press, 1976, pp. 95-106. Reprinted in Innovations in Internetworking, Artech House, December 1988. Reprinted in Computer Communications Review, Vol. 35, No. 2, p. 71-82, 2005

[3] V. G. Cerf, Y. Dalal, C. Sunshine, "Specification of Internet Transmission Control Program," RFC 675, December 1974, [Internet Engineering Task Force documents, https://www.ietf.org/rfc.html], https://tools.ietf.org/html/rfc675.

[4] https://www.rfc-editor.org/ien/ien5.pdf [see also: https://www.rfc-editor.org/ien/ien-index.txt]

[5] http://www.rfc-editor.org/rfc-index2.html - this is the index of all RFCs

[6] https://en.wikipedia.org/wiki/Open_Systems_Interconnection

[7]https://en.wikipedia.org/wiki/Government_Open_Systems_Interconnection_Profile

[8] http://www.osti.gov/scitech/servlets/purl/106597

[9] http://doc.utwente.nl/46343/1/battle_between_-_maathuis.pdf

[10] https://www.rfc-editor.org/rfc/rfc2460.txt

(APNIC, AFRINIC, ARIN, RIPE-NCC, LACNIC). The RIRs, except for AFRINIC, have also run out of IPv4 address space as of the end of 2015 (or earlier). The coming Internet of Things is driving the demand for address space for what may be billions of devices worldwide. Google's measurements suggest that the uptake rate is increasing[11].

There are other battles having to do with security, privacy, confidentiality and integrity. The application of cryptographic methods is widespread but not uniform. Abuse of the Internet and crimes such as fraud, child porn, malware, denial of service attacks, inter alia, are the topic of discussion and debate in many forums. Recently, the use of the Internet for terrorist propaganda has raised the stakes for the open Internet even more. Maintaining an essentially open Internet where information sharing is encouraged, where users are free to run applications of their choice, where consumers have ample choice of competitive access and are free to implement new applications without having to get permission from some regulatory entity are all coming under pressure from authoritarian governments and conservative politicians.

3. How did Robert Kahn's development of packet-switching influence the development of TCP/IP?

Robert Kahn did not develop packet switching but he used it in the ARPANET design. The first papers[12,13,14] on message switching analyzed its queueing theoretic properties were published in 1961/1962 by Leonard Kleinrock at MIT and his dissertation, published in December 1962, was subsequently re-published as a book in 1964[15]. Concurrently, Paul Baran, then at the RAND corporation, carried out a study starting in 1962 on survivable command and control communications. This eleven volume study was published in 1964[16]. He invented the term "message block" to refer to a packet of digitized voice and imagined a network that was highly connected and therefore resilient to damage. His focus of attention was on maintaining voice command and control in the aftermath of a nuclear attack.

In the mid-1960s, Donald W. Davies[17] at the UK National Physical Laboratory explored similar ideas and coined the term "packet" to describe the digital blocks of information being switched in the system

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[11] https://www.google.com/intl/en/ipv6/statistics.html

[12] http://www.lk.cs.ucla.edu/data/files/Kleinrock/Information Flow in Large Communication Nets.pdf

[13] http://www.lk.cs.ucla.edu/data/files/Kleinrock/Information Flow in Large Communication Nets0.pdf

[14] http://www.lk.cs.ucla.edu/data/files/Kleinrock/Information Flow in Large Communication Nets1.pdf

[15] **L. Kleinrock**, Communication Nets; Stochastic Message Flow and Delay, New York: McGraw-Hill Book Company, 1964. (Out of Print.) Reprinted by Dover Publications, 1972 and in 2007. Published in Russian, 1971, Published in Japanese, 1975.

[16] http://www.rand.org/content/dam/rand/pubs/research_memoranda/2006/RM3420.pdf

[17] https://en.wikipedia.org/wiki/Donald_Davies

he envisaged. Davies was able to build a one-node packet-switched network (one could think of this as an early LAN). His work influenced the design of the ARPANET when Lawrence Roberts heard about the work at a 1967 ACM conference in Gatlinburg, Tennessee. There, one of Davies' colleagues, Roger Scantlebury, urged Roberts to use the highest speed dedicated telephone circuits possible to reduce transmission delay for each packet. Roberts had been thinking of lower speed 9.6 kb/s lines but subsequently decided that the ARPANET project should use 50 kb/s lines which were the highest speed then available for users.

Returning to the question of Robert Kahn's influence, it was profound. He was one of the primary architects of the packet switches of the ARPANET. These were called Interface Message Processors (IMPs) by ARPA. Kahn was responsible for much of the software architecture of the ARPANET and its internal protocols as well as the specification of the interface between the ARPANET IMPs and host computers attached to them[18]. I used these specifications and the message generators to produce artificial traffic in the original 4-node ARPANET to help Kahn analyze and demonstrate some of the weaknesses in the original IMP protocols.

Kahn originated the idea of Open Network Architecture in late 1972 before joining ARPA and brought this idea to the problem of building a multiple network system that could support command and control on the ground, in mobile operation and between ships at sea using satellite. It was this concept that he presented to me in the Spring of 1973 as we began thinking our way through the design of a network of packet switched networks using ground mobile radio, the ARPANET and Atlantic Packet Satellite network. Interestingly, Robert Metcalfe[19] at Xerox PARC, a couple of miles from my Stanford laboratory, was working on Ethernet[20] which became a major component of the Internet providing, in time, the basis for millions of local area networks (LANs) around the world.

It is worth noting that Metcalfe's Ethernet idea was stimulated by a report he read in the home of Stephen Crocker[21], another ARPANET/Internet heavy-weight, about the ALOHANET[22], which was another ARPA project! Metcalfe concluded that he could implement the ALOHANET concepts at much higher speeds on a coaxial cable such as the ones used for cable television. The Ethernet concept has evolved dramatically since its invention in 1973 and, while it still bears the name Ethernet, its detailed protocols are quite different. Ethernet is also the basis for WiFi[23].

All of these technologies (ARPANET, packet radio, packet satellite and Ethernet) are packet-switched designs although they differ in packet format, speeds, latency and length. The TCP protocol design was intended to allow networks of very diverse kinds to be interconnected in a way that made the ensemble look uniform to the hosts connected to the networks. Kahn's Open Network Architecture paved the way for the TCP and subsequently TCP/IP design.

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18 http://www.mirrorservice.org/sites/www.bitsavers.org/pdf/bbn/imp/BBN1822_Jan1976.pdf

19 https://en.wikipedia.org/wiki/Robert_Metcalfe

20 https://en.wikipedia.org/wiki/Ethernet

21 https://en.wikipedia.org/wiki/Steve_Crocker

22 https://en.wikipedia.org/wiki/ALOHAnet

23 https://en.wikipedia.org/wiki/Wi-Fi

Seetal Kaur <seekstar562@gmail.com>

Hello Mr. Vinton Cerf. My name is Seetal. I am an eighth grader and I am doing a history day project at school. For this years theme: Exploration, encounter, and exchange I have chosen Tim Berners-Lee to do my project on. To improve my project and learn more about Tim Berners-Lee, I would like to have an interview with you. I would really appreciate it if you could answer a few of my questions regarding Tim Berners-Lee and the Web.

1. Have you worked with Tim Berners-Lee for any project in the past if yes how was your experience with him?

   I know Tim, of course, for his work on the World Wide Web and its protocols (e.g. HTML and HTTP). However, we have not worked closely together on any specific projects. I am a supporter of his work in the World Wide Web Consortium and we have done panel discussions together from time to time. We received the Prince of Asturias Prize together in 2002 and the Queen Elizabeth Prize in 2013. In both cases, with others including Robert Kahn, my colleague in the design of the Internet.
2. What do you think his main goal was when he first started to create to World Wide Web?

   Tim wanted to create a method that would allow his physicist colleagues at CERN to exchange technical papers that included diagrams and formatted text.

3. Do you think that the response that he got from the public in regards to the Web was the one he had expected?

   I am not sure Tim had the public in mind during his early design work in 1989. He released his implementation in December 1991 but without much visibility. Marc Andreessen and Eric Bina at the National Center for Supercomputer Applications (NCSA) developed their graphical version of the browser, called MOSAIC, in 1992. This drew a LOT of attention because the Internet became much like a colorful magazine with a convenient point-and-click interface. Many people became "webmasters" as a consequence of the release of MOSAIC. Most of the users in that period were in the research community because the Internet was not widely available to the general public. In 1994, Netscape Communications was formed by James Clark (the former CEO and founder of Silicon Graphics) and Marc Andreessen. It went public in 1995 and its successful IPO triggered the so-called "dot-boom". Tim readily appreciated the evident desire that the general public had for sharing information simply for the satisfaction of knowing that something they shared was of value to others.

4. The Internet and World Wide Web are often mistaken for being the same thing. What do you feel about this and can you give the difference between the two in your own words?

   The Internet is the underlying substrate on which the WWW operates. The basic TCP/IP protocols and other parts of the so-called Internet Protocol Suite support the HTTP protocol that gives rise to the World Wide Web. HTTP relies on the Domain Names system of the Internet for its URL structure (e.g. http://www.google.com). Without the Internet, the WWW would not have spread as quickly or as widely and possibly not at all beyond CERN. WWW is one of the most popular applications of the Internet but it is not the only one. There are many protocols that are needed on the Internet to animate the WWW. File transfers, video streaming, voice interactions among other things are implemented using protocols that lie directly on top of UDP[24] or TCP/IP.

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[24] https://en.wikipedia.org/wiki/User_Datagram_Protocol

5. There are many controversies of the web. Which do you thing is the biggest?

   There are indeed many. I think the biggest issues have to do with freedom of expression, freedom of access to information, freedom from harm, freedom of choice of Internet sites to visit and applications to run. Authoritarian governments are often uncomfortable with the wide-ranging information available on the Internet and also fearful of the power of social media that have become especially powerful with the advent of the smart phone and the digital mobile networks that support their access to the Internet's resources.

6. What do you think of the web and how much importance does it hold for you?

   It would be fair to say that I make use of the WWW on a regular basis. It has become a vital application that permeates my daily life. I work at Google and our company is critical to the utility of the WWW. Without indexing, it would be impossible to find anything in the vast sea of information that populates the WWW of today. I consider the Internet and the WWW to be among the most important inventions of the 20 C and they certainly define what it means to live in the 21st C.

Samuel Williston <samuel_williston20@isdschoolsmail.org>

1. What was the original purpose in your opinion for the creation of the Internet?

Please see my other responses and the bibliography at the end of this collection of remarks. The creation of the Internet was initially motivated by the need for introducing computers into command and control in the US military. To achieve this objective, computers would have to be in fixed and mobile installations including ground mobile, aircraft and ships at sea. This dictated that the earlier wireline ARPANET had to be augmented to work with mobile packet radio and packet satellite. Recognizing this, Robert Kahn, then at ARPA, proposed to solve the problem by creating a network of networks and the protocols needed to make this concept work. This is what the original TCP protocol was designed to achieve and, as you can read in my responses to Peter Ciccone, the protocol evolved as we gained experience with it.

2. Where did you get the idea for making the TCP/IP?
Robert Kahn's Open Network Architecture and articulation of the "Network of Networks" problem led to the design of TCP/IP. We had experience with packet switching from the ARPANET and the ALOHA network protocols, but we also recognized the potential lossy nature of mobile radio and packet satellite communication (also on Ethernet as it happens). This led directly to the 1974 design paper published in IEEE Communications [see footnote 2]. We realized that we would need special computers, now called "routers" and once called "gateways", that could connect disparate networks and encapsulate and decapsulate Internet Protocol packets from their transport frames specialized to the underlying networks. Our idea was that each packet network, regardless of its detailed implementation and characteristics, could be used to transport Internet Protocol packets between gateways. The ensemble of networks, gateways and the hosts on each network formed the Internet. We also realized that only the hosts and the gateways needed to know anything about the Internet. The networks themselves did not need to change. So TCP and later IP showed up in the gateways and the hosts but not in the intervening networks. Later, the networks were actually constructed of routers so that the concept of underlying network often tended to disappear. There were, however, networks such as X.25 nets, Frame Relay nets, ATM networks and Ethernet of various kinds that had their own internal routing protocols but which could carry Internet Protocol packets to interconnect the gateways to form the Internet.

3. How well did you expect the internet to go with the public? did it match your expectations.

We had a lot of experience with the ARPANET that had thousands of users, mostly engineers and researchers at academic and research institutions. The invention of networked electronic mail by Ray Tomlinson[25] in 1971 and the subsequent invention of email distribution lists made it clear that there was utility in networking computers for resource and information sharing (which was the original motivation for the ARPANET project[26]. Early mailing lists included SCIFI-Lovers and Yum-Yum (a restaurant rating list) and demonstrated the social networking utility of electronic mail. The arrival of the World Wide Web (and some of its predecessors such as the Wide Area Information Sharing (WAIS) system[27], ARCHIE[28], GOPHER[29]) cemented the concept of distributed information production and sharing in a wide-area computer network (the Internet).

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[25] https://en.wikipedia.org/wiki/Ray_Tomlinson

[26] L. G. Roberts and B. D. Wessler, "Computer Network Development to Achieve Resource Sharing." Proceedings SJCC 1970, pp. 543—549.

[27] https://en.wikipedia.org/wiki/Wide_area_information_server

[28] https://en.wikipedia.org/wiki/Archie_search_engine

4. Did you ever work with Tim Berners Lee or other people seen as major pioneers of the internet/WWW (besides Robert Kahn).

   I worked with many of the pioneers of the Internet (see Internet Hall of Fame[30]). I was the founder of the Internet Configuration Control Board (ICCB) that later became the Internet Activities Board and now the Internet Architecture Board). I worked with the Internet Engineering Task Force (IETF) and the Internet Research Task Force (IRTF) on many protocols. I was the co-founder of the Internet Society[31] and its first president. I was the chairman of the Internet Corporation for Assigned Names and Numbers from 2000 to 2007 and helped to organize and support it in the early stages of its existence. It would impossible to list all the notable Internet/WWW pioneers with whom I have worked but you will find many of them in the Internet Hall of Fame.

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[29] https://en.wikipedia.org/wiki/Gopher_(protocol)

[30] http://www.internethalloffame.org/

[31] http://www.internetsociety.org/

Desteny Edwards **<desteny.edwards@gmail.com>**

Hello my name is Desteny Edwards and I am pursuing into the field of computer science. I've taken the classes for the past few years and I am currently creating a documentary for a History fair over the topic of the Internet. I would be humbled and extremely gracious if maybe we could Skype, email in order to interview with you concerning the creation of the internet. I currently live in Dallas, Tx and I understand you don't reside here therefore emailing, skyping or calling would be fine for doing this interview.

From: Eric Tran etran2018@stumail.cusd.claremont.edu
Sent: Tuesday, November 17, 2015 11:07 PM
To: National Science Board <NationalScienceBrd@nsf.gov>
Subject: A few questions for Mr. Vint Cerf

Dear Mr. Cerf,

My name is Eric Tran and I am a 10th grade student attending Claremont High School in Claremont, California. This year, I am participating in a nation wide project called History Day where we make projects on topics all throughout history. This year I chose to create the project on the Internet. As we all know, you were instrumental in the ARPANet and the development of the modern internet. With the Internet as it is now, it was not hard to find where to contact you. I would just like to ask you a few questions about your work on the ARPANet. Any of your time would be greatly appreciated. Thank you in advance.

- At the time, what did you envision for the future of the ARPANet and has it lived up to your expectations?
  - Please see my responses to similar questions above
  -
- How hard or easy was it working with Mr. Bob Kahn on the TCP/IP?
  - Bob Kahn and I worked extremely well together on the testing of the ARPANET, the development of the TCP/IP protocols, on projects at ARPA (packet radio, packet satellite, packet security and the Internet), on the founding of the Internet Society, etc. We continue to collaborate from time to time, as we have since 1970.
- Why do you think people are still using your technology some 50 years later?
  - Well, in fact, the Internet technology was solidified when the Internet went into operation formally on January 1, 1983 so it is been more like 32 years of operation. The design was robust and intended to be "future proof". It is a flexible and evolvable design. We are now working hard on getting IPv6 implemented everywhere to extend the lifetime of the network and to accommodate the coming Internet of Things. A lot more work is needed on securing the network and, especially, the computers and appliances connected to it.
- What prior concepts or ideas inspired you to create the TCP/IP.
  - Please see answers above, especially question 2 from Sam Williston.