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Mathematical Reasoning Y10.1105.01

2 December 2003

A Perspective on IPv4's Address Schema Limitation

Internet Protocol Version 4 (IPv4) enables digital information exchange between networked computer devices and is a result of a 1970's government-funded research project. Through its work with academia researchers and commercial technology pioneers, the Advanced Research Projects Agency (ARPA, a division of the U.S. Department of Defense) established protocols and standards, which represent the contemporary Internet's foundation.

Comparable to the postal service, IPv4 acts as the Internet's information carrier. It transmits data between entities (Internet devices) and facilitates logical addressing to ensure the data reach their intended recipient. Market demand and additional research led to the protocol's maturing and the creation of supplementary standards, enabling the use of Internet technology in ways previously not envisioned. For example, Storage Area Networks (SAN) communicate through the protocol 'SCSI[1] over IP', which encapsulates SCSI data into IPv4 transmissions (it literally wraps SCSI into IP).

In the 1990's, IPv4 conquered businesses and homes. Organizations and individuals connected to the Internet to communicate or generate profits. IPv4 also replaced standards such as IPX[2] in many corporate networks. Consequently, managing heterogeneous environments became less complex, and protocol translation between corporate and Internet networks was no hurdle any more. IPv4's widespread adoption resulted in a remarkable increase of Internet

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[1] Small Computer System Interface, commonly used to connect storage and optical devices to processing units

[2] Internetwork Packet Exchange, a protocol from Novell, Inc. fulfilling the same purpose as IPv4

users. A problem emerged, which Christian Huitema portrayed in 1996 as the "Internet's crisis" (2): rapid address-space consumption. Imagine a world in which the postal service allotted all ZIP code, street, and apartment numbers. No additional addresses are available, and mail carriers cannot deliver correspondence to entities without an address. A similar scenario concerns the Internet.

Internet devices are addressable by their unique decimal-notated address. Each address comprises four dot-separated, non-negative integers. For example: 192.168.139.1. The demand for Internet connectivity (and therefore for addresses) led to a 1994 projection that all IPv4 addresses will be assigned as early as 2005 (Hagen 1). The prognosis bases on the rising number of earth's inhabitants, technology evolution leading to more Internet-enabled services, and a mathematical limitation in IPv4's address-schema. Three impractical approaches to solving this dilemma by preventing further address-assignments would be: curtailing population growth (too drastic), avoiding technology innovation (unrealistic), or restricting the Internet to privileged users only (unjust). An Internet Engineering Taskforce (IETF) formed in 1994 to develop IPv4's successor. One of the objectives became eliminating the mathematical limitation in the protocol's address-schema.

In a computer network, protocols ensure that information transmissions between devices with different purpose and from a variety of manufacturers succeed. To illustrate: the Internet standards Simple Mail Transfer Protocol (SMTP) and Post Office Protocol (POP) detail how electronic mail (Email) transmits. Since sender and receiver may use Email-software and Personal Computers (PC) from diverse vendors, protocols make certain that the receiver understands information transmitted by the sender. Protocols have two functions: describing rules that organize the exchange of information, or translating the information when no common protocol exists. Conceptually, this compares to human language and interpreters. We agree to communicate in the same language, or use a translator. In digital and human worlds, information does not reach the recipient without a protocol.

The mathematical limitation in IPv4's address-schema resulted in a finite number of 32-bit addresses: 4,294,967,296. The term '32-bit address' derives from the 32 positions (bits) an IPv4 address comprises when written in binary notation. Decimal 192.168.139.1, for example, appears binary in four dot-separated octets: 11000000.10101000.10001011.00000001. Binary (or Base-2) numbering uses only two values: zero and one. Base-10 numbering, in contrast, comprises the numbers zero to nine and is customary to count points in basketball or verify an invoice. Given that the 32 IPv4 address-bits use only two values in each position, we now understand IPv4's mathematically caused address-schema-limitation: 2^{32} equals 4,294,967,296.

Computer users send Emails and access online-databases without realizing they use IPv4, since its functions are contained in operating systems and application software. Computers process binary instructions only and the software converts binary IPv4 addresses for users to the less-obscure decimal notation. This conversion involves addition and subtraction operations and employs the table shown in Exhibit 1.

128	64	32	16	8	4	2	1
1	1	0	0	0	0	0	0

Exhibit 1: Binary Converted to Decimal[3]

Row two in the table represents eight logical switches, allowing 'on' and 'off' settings for each column. The eight columns represent all bits of one 32-bit address-octet. A binary one in a column in row two represents status on, a binary zero represents off. The decimal results from adding all numbers in row one that are 'switched on' through a binary one on row two.

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[3] All octets convert individually, and to convert from decimal to binary, the same table is used

Solutions surfaced over the years, attempting to prolong IPv4's life by bypassing the mathematical limitation in the address-schema. They do not enlarge the schema, but increase the efficiency of its use. Four of them are: address reclaiming, Network Address Translation (NAT), dynamic addressing (DHCP)[4], and subnetting.

The American Registry for Internet Numbers (ARIN) and its associations administer all IPv4 addresses and allot subsets of the address-schema to institutional entities[5]. For example, AT&T uses addresses ranging from 12.0.0.0 to 12.255.255.255[6]. AT&T's technology-related business objectives and its multinational reach justified allocating a large range. However, other entities received a larger scope than they require. Address reclaiming recovers uneconomically assigned (and thus likely unused) addresses. Yet, it also requires redesigning networks, which is as unpopular as it is complex (DeMaria 83). James Klein agrees that reclaiming "has yet to gain much momentum."

Incidentally, the division into ranges was no arbitrary decision. Exhibit 2 exemplifies how (similar to the mathematically caused limitation) classes and ranges are determined:

Class	Decimal Range: from - to	Binary Range: from … to
A	0.0.0.0 - 127.255.255.255	**00**000000.00000000.00000000.00000000 01111111.11111111.11111111.11111111
B	128.0.0.0.0 - 191.255.255.255	**10**000000.00000000.00000000.00000000 10111111.11111111.11111111.11111111
C	192.0.0.0.0 - 223.255.255.255	**11**000000.00000000.00000000.00000000 11011111.11111111.11111111.11111111

Exhibit 2: IPv4 Address Classes

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[4] Dynamic Host Configuration Protocol

[5] Addresses for personal use are obtained through Internet Service Providers (ISP), which are institutional entities

[6] Source: ARIN WHOIS. Updated 29 November 2003. Accessed 30 November 2003. http://www.arin.net

The first two address-bits in the first octet determine the address-classes A, B, and C (see conversion table). Class D and E addresses are not available to the public. Furthermore, ARIN restricted selected ranges within classes by policy. For example, the Class A 10.0.0.0 and Class C 192.168.0.0 networks can be used in private installations. Usable decimals in each octet range from 1 to 254 since 2^8 permits 256 combinations (0 and 255 are reserved by design). The address 944.896.712.699 (for example) therefore can never exist.

NAT has greater prevalence than address reclaiming and can be installed without considerable network-redesign. It artificially inflates the address-schema by disguising IPv4 addresses (recall that each address must be unique). Between two networks, both may use identical addresses internally, as long as NAT translates them into legitimate addresses when communicating externally with Internet networks. DHCP, on the other side, manufactures an address-schema increase by exploiting user mobility. This protocol temporarily 'leases' addresses to devices. Upon disconnect from the network, a device releases its address, which becomes available to other systems. Lastly, subnetting (which can be implemented along with NAT and DHCP) minimizes the uneconomical use of address-schema-segments through a logical division of already assigned ranges into sub-networks.

Address reclaiming, NAT, DHCP, and subnetting have only short-term potential to extend IPv4's life. They are insufficient to meet additional future growth since they result only in a modest (and artificial) expansion of the address-schema. Exhibit 3 illustrates the probability of continuously increasing demand for Internet addresses:

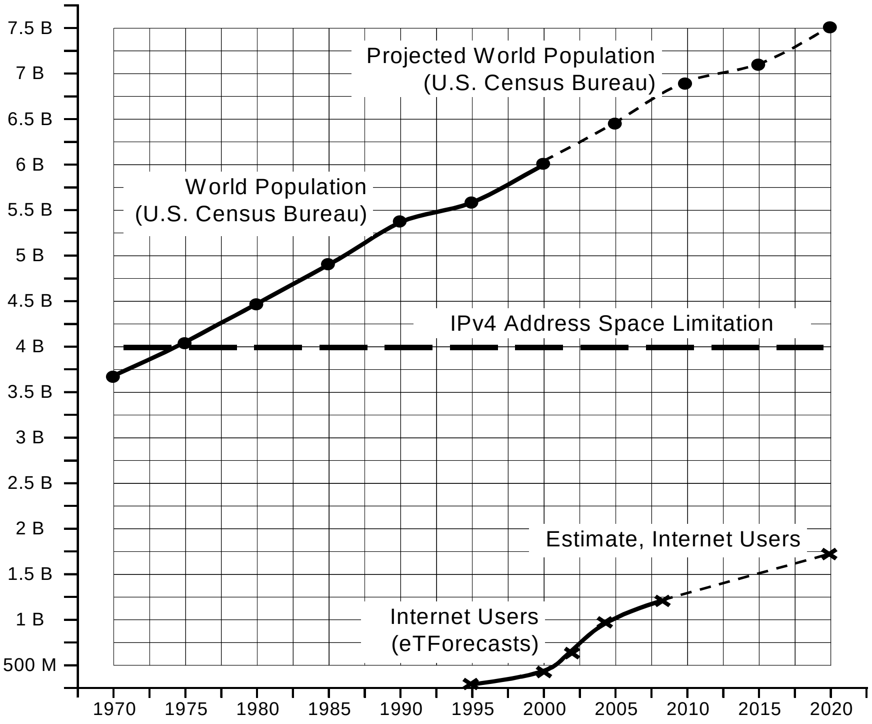

Exhibit 3: Growth (Population, Internet)[7]

Unlike the chart implies it is erroneous to conclude that IPv4's address-schema will suffice for 1.75 billion Internet users in the year 2020[8]. Since users commonly own numerous devices (PDA[9], multiple PC's) and connect each to other networks through shared intermediate systems, a perceived need of 'one IP address per user' is imprecise. Moreover, future "Internet-appliances" such as refrigerators (Singer) and new "always-on devices" such as cars and phones ("Introduction to IPv6") require permanent simultaneous network access. Estimating '1.5 addresses per user, per device owned' therefore seems more accurate[10]. IPv4 and its bypassing solutions (better management of the IPv4 address-schema and address-sharing) will not accommodate another intensification of the demand for addresses (Hagen 4). Thus, the elimination of the mathematical limitation in the address-schema is vital.

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[7] Sources of population figures: U.S. Bureau of the Census, eTForecasts (chart is self-created)

[8] 1.75 billion users in the year 2020 is a linear estimate based on the eTForecasts prognosis for the years 2004-7

[9] Personal Digital Assistant

[10] The 'half address' represents shared links to other networks

IPv4's successor therefore should address known problems while retaining familiar features to simplify its implementation. According to Douglas Comer, the design specifications of Internet Protocol Version 6 (IPv6) achieve these objectives (602)[11]. Its foundation is a 128-bit address-schema using hexadecimal (hex) address-notation[12], providing 340,282,366,920, 938,463,463,374,607,431,768,211,456 addresses. That is 'three hundred forty undecillion, two hundred eighty-two decillion, three hundred sixty-six nonillion, nine hundred twenty octillion, nine hundred thirty-eight septillion, four hundred sixty-three sextillion, four hundred sixty-three quintillion, three hundred seventy-four quadrillion, six hundred-seven trillion, four hundred thirty-one billion, seven hundred sixty-eight million, two hundred eleven-thousand, and four hundred fifty-six' addresses. Alternatively: "[…] 665,570,793,348,866,943,898,599 addresses per square meter of […] planet Earth […]" (Hinden). It appears impossible to imagine –currently– that the IPv6 address-schema will ever exhaust.

Although, the design-flaw that caused IPv4's address-schema-limitation might prevail in IPv6. According to Comer, IPv4 designers "failed" to foresee "growth" (148). They assumed that 32 bits provide a sufficiently scaled address-schema for the Internet. Huitema writes that IPv6 designers based their work on a prognosis, too. They envisioned "[…] hundred computers per human […] in 2020" (3). IPv6 is expected to accommodate more than this estimate. However, the decision for 128 bits provokes the question whether another redesign may be required in the future, for similar reasons that led to IPv6's creation.

The IPv6 designers did what is in their power to avoid this scenario. They abandoned an early recommendation to use 64 bits (Huitema 5) in favor of 128. In addition, they invited review of their work to ensure its appropriateness. Internet design propositions circulate online

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[11] IPv5 specifications were drafted for a different experimental protocol (Huitema 6)

[12] These are two noteworthy changes; IPv6 comprises other features that are beyond this paper's scope

through numbered 'Request for Comments' (RFC), which solicit reactions to proposed concepts and technologies from Internet, academic, and industry communities. Douglas Comer writes:

> Unlike scholarly scientific journals, […] RFCs provide a record of ongoing conversations among the principals involved in designing, building, measuring, and using the global Internet. […] RFCs include the thoughts of researchers on the leading edge of technological innovation, not the studied opinions of scholars who have completely mastered a subject. The authors […] clearly realize the issues are too complex to understand without community discussion. (624)

This practice resembles the United Nations: members draft resolutions, discuss them in a forum, agree to the content, and subsequently implement a decided course of action. The process is time-consuming (Comer 601), but makes certain that sufficiently reviewed proposals incorporate required functional specifications. As an RFC circulates, responses influence successive versions of the document, and it receives an incremented 'RFC number'. In the case of Internet standards, software and hardware manufacturers enable the implementation of an endorsed RFC-based proposal by incorporating the new technology into their products. Two IPv6 RFC's, 3513 and 2185, describe addressing and routing aspects.

Hex-notated IPv6 addresses are written in eight colon-separated blocks. For example: C0A8:C12:C0A8:C12:C0A8:C12:C0A8:C12. Hex is a Base-16 numbering system comprising the values 0 to 15. The letters A, B, C, D, E, and F represent the integers 10 to 15. To convert from binary to hex, groups of four bits are converted. For example, hex C (decimal twelve) equals to adding the third and fourth bit in the binary conversion table. Exhibit 4 illustrates:

Binary	Decimal	Hex
00001100	12	C

Exhibit 4: Binary, Decimal, Hex Number

The length of an IPv6 address seems to make its comprehension difficult. However, hex-notation permits compression. Comer states: "[the] address [is] slightly more compact and easier to enter [when] using colon hexadecimal notation" (611). Robert Hinden explains why: "Hex is more dense (i.e., more bits can be represented in a single character)."[13] In addition to higher density, IPv6 also uses zero-suppression. For example: binary 00000010.00001010 appears in hex as 02A. Zero-suppression compresses it to 2A (Hagen 29-30)[14]. Hence, IPv6 addresses are less complex than they appear initially. Exhibit 5 illustrates the three notations:

IPv6 Binary Notation (Base-2)[15]:

11000000.10101000.00001100.00010010.11000000.10101000.00001100.00010010.
11000000.10101000.00001100.00010010.11000000.10101000.00001100.00010010

IPv6 Hexadecimal Notation (Base-16):

C0A8:C12:C0A8:C12:C0A8:C12:C0A8:C12

Decimal Notation (Base-10; comparison only, not used in reality):

192.168.12.18.192.168.12.18.192.168.12.18.192.168.12.18

Exhibit 5: IPv6 Address in Binary, Hex, Decimal Notation

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[13] Cited from an Email received on 29 October 2003

[14] Only 16 of 128 bits used in this example

[15] 128 bits shown in two rows due to space limitations

The address-schema provided through IPv4 will eventually exhaust, just as telephone-numbers in Manhattan's 212-area code ran out in the 1990's. Over the past three decades, IPv4 showed its reliability and emerged as the digital language of choice. Its designers laid the foundation for the Internet by creating rules for electronic information transmissions and device addressing. Bypassing solutions attempted extending IPv4's life, but a departure from it is unavoidable. The solution to IPv4's mathematical address-schema-limitation is IPv6 and its two notable features: a substantially larger address-schema and hex-notation for addresses.

A transition to IPv6 will progress over years due to the technological complexity and size of the Internet. IPv6 characteristics, such as the hierarchical organization of the address-schema, compare conceptually to IPv4 and result in a moderate learning curve for network administrators. Both protocols co-exist and allow a gradual implementation of IPv6, but they are mutually incompatible. Implementation strategies include protocol translation (recall the translator), tunneling (a synonym for data encapsulation), and equipment upgrades. Although, infrastructure upgrades are expensive to procure and implement. Given the Internet's status in the contemporary society we should hope that potentially delayed infrastructure investments in regions that lack financial resources resulting from economical downturn will not result in adverse effects. The Internet's designers achieved what no one envisioned: connecting people of all origins, ages, and social statuses. A potentially slow IPv6 migration in parts of this world should not disconnect some of them.

Works Cited

Comer, Douglas E. Internetworking with TCP/IP Vol.1: Principles, Protocols, and Architecture, Fourth Edition. Upper Saddle River, NJ: Prentice-Hall, 2000.

DeMaria, Michael J. "Slow Road to IPv6." Network Computing [Manhasset, NY] 2.4.2002 (2002 February): 83-85. Accessed 19 October 2003. http://networkcomputing.com.

Hagen, Silvia. IPv6 Essentials. Sebastopol, CA: O'Reilly, 2002.

Hinden, Robert M. "IP Next Generation Overview." 14 May 1995. Accessed 25 October 2003. http://playground.sun.com/pub/ipng/html/INET-IPng-Paper.html#CH99

Huitema, Christian. IPv6-The New Internet Protocol. Upper Saddle River: Prentice-Hall 1996.

"Internet User Forecast by Country." eTForecasts. 304 W. White Oak, Arlington Heights, IL 60005. Updated December 2002. Accessed 19 October 2003. http://etforecasts.com.

"Introduction to IPv6." Cisco Networkers 2003 Conference. Cisco Systems, Inc. 170 West Tasman Drive, San Jose, CA 95134. Accessed 25 October 2003. http://www.cisco.com

Klein, James. "IPv6: The Quiet Revolution." LA VOX. Larta, 714 West Olympic Boulevard, Suite 750, Los Angeles, CA 90015. Accessed 2 October 2003. http://www.larta.org.

Singer, Alan. "Viewpoint: Back to the Future with Internet Devices." iApplicanceWeb. CMP Media LLC, 600 Community Drive, Manhasset, New York 11030. 6 January 2003. Accessed 16 November 2003. http://www.iapplianceweb.com

"World Population Information: Total Midyear Population for the World: 1950-2050." U.S. Bureau of the Census. Data updated 17 July 2003. U.S. Census Bureau. 4700 Silver Hill Road. Washington, DC 20233. Accessed 10 October 2003. http://www.census.gov

Works Consulted

"A Brief History of the Internet. Version 3.31." Internet Society International Secretariat. 1775 Wiehle Ave., Suite 102, Reston, VA 20190. Last revised 4 August 2000. Accessed 25 October 2003. http://www.isoc.org.

Hinden, R., with S. Deering. "Request for Comments: 3513. Internet Protocol Version 6 (IPv6) Addressing Architecture." IETF The Internet Engineering Task Force. 1895 Preston White Drive, Suite 100 Reston, VA 20191-5434. Published April 2003. Accessed 27 October 2003. ftp://ftp.rfc-editor.org/in-notes/rfc3513.txt

"Introduction to IP Version 6. Microsoft Windows Server ™ 2003 White Paper." Microsoft Corporation. Published September 2003. Accessed 2 October 2003 http://microsoft.com

"Novell Internet Access Server 4.1 Routing Concepts. The IPX Protocol." NetWare Online Documentation. Novell Inc. 1800 South Novell Place, Provo, Utah 84606. Accessed 27 October 2003. http://www.novell.com/documentation/lg/nw5/docui/index.html

The Pocket Oxford American Dictionary of Current English. New York: Oxford, 2002.

Rengifo, Andres. Internetworking Fundamentals. Boston: Pearson, 2002.

Thomasson, Joanne, with Bob Pesuit. Experiencing Introductory and Intermediate Algebra, Second Edition. Upper Saddle River, NJ: Pearson, 2002.

"Whatis.com Look it up." whatis.com, 117 Kendrick Street, Suite 800, Needham, MA 02494. http://www.whatis.com