Potential Impacts on Communications From IPv4 Exhaustion & IPv6 Transition

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Federal Communications Commission
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Abstract

The Internet is in transition. The original address space, IPv4, is nearly exhausted; the Internet is in the progress of migrating to the new IPv6 address space.

The Internet Protocol version 4 (IPv4) developed in the late 1970s has the capacity for about 4 billion unique addresses. It would have been hard to imagine in the 1970s that 4 billion addresses were not going to be enough. But by the early 1990s, Internet engineers recognized that the supply of addresses was relatively limited compared to likely demand, and they set to work designing a successor to IPv4. They developed a new Internet Protocol, IPv6, with a vastly increased address space: 340 trillion trillion trillion addresses.

Broadband Internet access has become essential to the United States and the rest of the world. The exhaustion of IPv4 addresses and the transition to IPv6 could result in significant, but not insurmountable, problems for broadband Internet services. In the short term, to permit the network to continue to grow, engineers have developed a series of kludges. These kludges include more efficient use of the IPv4 address resource, conservation, and the sharing of IPv4 addresses through the use of Network Address Translation (NAT). While these provide partial mitigation for IPv4 exhaustion, they are not a long-term solution, increase network costs, and merely postpone some of the consequences of address exhaustion without solving the underlying problem. Some of these fixes break end-to-end connectivity, impairing innovation and hampering applications, degrading network performance, and resulting in an inferior version of the Internet. These kludges require capital investment and ongoing operational costs by network service providers, diverting investment from other business objectives. Network operators will be confronted with increased costs to offer potentially inferior service.

The short term solutions are necessary because there is not enough time to completely migrate the entire public Internet to "native IPv6" where end users can communicate entirely via IPv6. Network protocol transitions require significant work and investment, and with the exhaustion of IPv4 addresses looming, there is insufficient time to complete the full IPv6 transition.

But the short-term solutions are problematic. The "solution to the solution" is to complete the transition to a native IPv6 network. A native IPv6 network will restore end-to-end connectivity with a vastly expanded address space, will improve network performance, and should decrease costs. Completing the transition of the public Internet to IPv6 will take time.

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Introduction

The Internet is in transition. The original address space, IPv4, is nearly exhausted; the Internet is in the progress of migrating to the new IPv6 address space.

The Internet Protocol version 4 (IPv4) developed in the late 1970s has the capacity for about 4 billion unique addresses. It would have been hard to imagine in the 1970s that 4 billion addresses were not going to be enough. But by the early 1990s, Internet engineers recognized that the supply of addresses was relatively limited compared to likely demand, and they set to work designing a successor to IPv4. They developed a new Internet Protocol, IPv6, with a vastly increased address space: 340 trillion trillion trillion addresses.[2]

Broadband Internet access has become essential to the United States and the rest of the world.[3] The exhaustion of IPv4 addresses and the transition to IPv6 could result in significant, but not insurmountable, problems for broadband Internet services. As stated by the IEEE-USA:

> Running out of addresses does not mean the IPv4-based Internet will suddenly stop working. However, it does mean it will be difficult, if not impossible, to distribute new IP addresses to new or expanding enterprises. Such a limitation will have clear impacts on commerce and innovation.[4]

If the network were to run out of addresses, no additional computers, subscribers or services could be added to the network. In the short term, to permit the network to continue to grow, engineers have developed a series of kludges.[5] These kludges include more efficient use of the IPv4 address resource, conservation, and the sharing of IPv4 addresses through the use of Network Address Translation (NAT). While these provide partial mitigation for IPv4 exhaustion, they are not a long-term solution, increase network costs, and merely postpone some of the consequences of address exhaustion without solving the underlying problem. Some of

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[1] Senior Counsel for Internet Law, Office of Strategic Planning and Policy Analysis, FCC. The author would like to thank Susan Crawford, John Curran, Bobby Flaim, Henning Schulzrinne, Doug Sicker, Tom Wheeler, Bill Woodcock, Paul de Sa, Sherille Ismail, Walter Johnston, Chuck Needy, and Irene Wu for their comments, input and review of the paper. Special thanks go to Richard Hovey who has provided counsel to the FCC on IPv6 for many years.
[2] IPv4 Depletion and IPv6 Deployment, RIPE NCC FAQs (last visited Dec. 7, 2010) ("The Internet Engineering Task Force (IETF) developed the new protocol, IPv6, which allows for 2^{128}, or roughly 340 trillion, trillion, trillion unique IP addresses.").
[3] *See* National Broadband Plan: Connecting America, FCC (2010).
[4] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 8 (2009).
[5] A *kludge* is defined as "a software or hardware configuration that, while inelegant, inefficient, clumsy, or patched together, succeeds in solving a specific problem or performing a particular task." Kludge | Dictionary.com (accessed Nov. 30, 2010).

these fixes break end-to-end connectivity, impairing innovation and hampering applications, degrading network performance, and resulting in an inferior version of the Internet.[6] These kludges require capital investment and ongoing operational costs by network service providers, diverting investment from other business objectives.[7] Network operators will be confronted with increased costs to offer potentially inferior service.[8]

The short term solutions are necessary because there is not enough time to completely migrate the entire public Internet to "native IPv6" where end users can communicate entirely via IPv6.[9] Network protocol transitions require significant work and investment, and with the exhaustion of IPv4 addresses looming, there is insufficient time to complete the full IPv6 transition.

But the short-term solutions are problematic. The "solution to the solution" is to complete the transition to a native IPv6 network. A native IPv6 network will restore end-to-end connectivity with a vastly expanded address space, will improve network performance, and should decrease costs. Completing the transition of the public Internet to IPv6 will take time.[10]

This paper will explore the IPv6 transition and its implications for communications policy. As with other transitions, early preparation greatly facilitates transition – and like previous transitions, some companies are well on their way with transition plans, while others may not be as advanced. This paper also seeks to identify potential issues that could cause bumps along the way. These are issues that stakeholders need to be aware of to facilitate a smooth and effective transition.

Assistant Secretary of Commerce for Communications and Information, Lawrence Strickling, recently stated, "*action is needed*."

> [W]e want to impress upon everyone that this is an urgent issue, but one that can be successfully handled with good planning. And we want to encourage companies to share

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[6] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 14 (2009) ("It is one thing to offer a lesser class of service to those who do not value a full Internet experience. However, it is another to lockout a class of people by not fully explaining the importance of the full Internet experience. That is, if one subscribes to an Internet access service with a crippled NAT, and with a constantly changing IP address, one will not be able to enjoy current and future applications that rely on the end-to-end Internet model.").

[7] Lorenzo Colitti, IPv6 at Google NANOG, Slide 5 (Jun. 2010) ("network complexity creations operation / support costs").

[8] *See* Geoff Huston, Is the Transition to IPv6 a "Market Failure," CircleID (Sept. 28, 2009); Why we choose 6RD for our ADSL Access Network, Softbank, NANOG50 (Oct. 2010) ("Nobody wants to pay for IPv6 transition").

[9] Ron Broersma, Dual-Stacked Enterprise Network DREN and SPAWAR, Google IPv6 Implementors Conference Slide 3 (Jun. 10, 2010) ("If you haven't started yet, you're already behind"); Geoff Huston, Is the Transition to IPv6 a "Market Failure," The ISP Column (Sept. 2009) (The Transition Process: "The general tenor of industry comment on this transition timetable is that while it may have been feasible to complete this transition prior to IPv4 address exhaustion if the industry had commenced with this effort in the late 90's, this is no longer a feasible objective given our current situation. We are now incapable of orchestrating a comprehensive transition to IPv6 within the time available as determined by the anticipated time remaining for the unallocated pool of IPv4 addresses.").

[10] *See* OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 40 (May 2008) ("The three options available to networks that are growing after the depletion of previously unallocated IPv4 address space are *i)* denser deployment of NAT, *ii)* obtaining and deploying additional IPv4 infrastructure if actors gain access to previously allocated addresses, and: *iii)* IPv6 deployment").

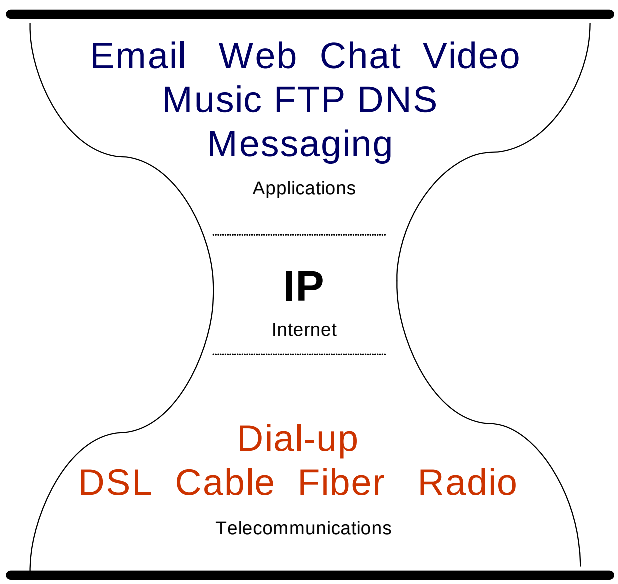
best practices on IPv6 uptake for all businesses to benefit, particularly for small- and medium-sized enterprises.[11]

Industry, governments, and consumers must prepare for the IPv6 transition, working together to minimize disruption and costs, and to maintain Internet services that have become integral and vital to our country and the world.[12]

IPv4 Addresses

The foundation of the Internet is the Internet Protocol. The Internet Protocol is a relatively simple protocol designed to interconnect networks, transmitting data back and forth. It is a general purpose protocol that facilitates networking over various physical telecommunications infrastructures (e.g., cable, DSL, fiber, wireless) and supports various applications (e.g., World Wide Web, email, video, file transfer, VoIP).

Figure 1: Internet Hourglass[13]



The Internet Protocol does not interact with or process the data that is transmitted; that is the responsibility of higher layer functionality of applications and services. The Internet Protocol does not provide lower layer infrastructure telecommunications. The responsibility of the Internet Protocol is to route packets from end-to-end across disparate networks.[14] Packets

[11] NTIA Press Release, NTIA Convenes Stakeholders to Discuss IPv6 Deployment (Sept. 28, 2010).
[12] Organizations Urged to Stop Delaying IPv6 Deployment to Safeguard Future Growth of the Internet, Numbering Resource Organization (Sept. 15, 2010) ("The biggest threat facing the Internet today is that less than 6% of the current form of IP addresses, IPv4, remains and the pool is likely to be completely depleted next year.").
[13] This is a simplified version of the Internet Hourglass. *See* J. Rosenberg, UDP and TCP as the New Waist of the Internet Hourglass, IETF Draft (Aug. 14, 2008).
[14] *See, e.g.*, Rick Whitt, MCI, A Horizontal Leap Forward: Formulating a New Communications Policy Framework Based on the Network Layers Model, 56 Fed. Comm. L.J. 587 (2004); Sicker & Mindel, "Refinements of a Layered

transmitted through the Internet have a header which includes the source and destination IP addresses; routing is based on the destination IP address.

Released in 1978, Internet Protocol version 4 (IPv4) was the first stable version of the Internet Protocol (previous versions were developmental). In 1980, The Department of Defense announced that the ARPANet would migrate to IPv4 on January 1, 1983.[15] In 1985, when the National Science Foundation initiated the NSFNET, NSF staff concluded that the use of the Internet Protocol was essential to the success of the NSFNet. In the early 1990s, NSF decided both to allow public traffic on the NSFNet and to privatize the network, establishing the foundation of the current public Internet.[16]

IPv4 has an address space containing over 4 billion unique IP addresses.[17] In the 1970s, when the ARPANet was a private network utilized by researchers and government agencies, it was thought that this would be sufficient.[18]

IP Number Allocation

The Internet Corporation for Assigned Names and Numbers (ICANN) currently manages the IP numbering resource through the Internet Assigned Number Authority (IANA) function.[19] IANA distributes large address blocks to the five Regional Internet Registries (RIRs):

- African Network Information Centre (AfriNIC),
- American Registry of Internet Numbers (ARIN),
- Asia Pacific Network Information Center (APNIC),
- Latin American and Caribbean IP Address Regional Registry (LACNIC),[20] and
- Réseaux IP Européens Network Coordination Centre (RIPE NCC).

Model For Telecommunications Policy," The Journal on Telecommunications and High Technology Law, Volume I, 2002; *A Layered Model for Internet Policy*, 1 J. TELECOMM. & HIGH TECH. L. 37 (2002).

[15] RFC 760, DOD Standard: Internet Protocol (Jan. 1980); RFC 791, Internet Protocol: DARPA Internet Program Protocol Specification, (Sept. 1981); J. Postel, RFC 801, NCP/TCP Transition Plan (Nov. 1981). ARPANet had been using the Network Control Protocol. See NCP – Network Control Protocol, Living Internet.

[16] *See* NSFNET: A Partnership for High-Speed Networking, Final Report 1987-1995, Merit Networks.

[17] Geoff Huston, IPv4 Address Report ("The IPv4 address space is a 32 bit field. There are 4,294,967,296 unique values, considered in this context as a sequence of 256 "/8s", where each "/8" corresponds to 16,777,216 unique address values."). See also Lljitsch van Beinjnum, Everything You Need to Know About IPv6, Ars Technica (Mar. 7, 2007) ("With 32 bits, it's possible to express 4,294,967,296 different values. Over half a billion of those are unusable as addresses for various reasons, giving us a total of 3.7 billion possible addresses for hosts on the Internet.").

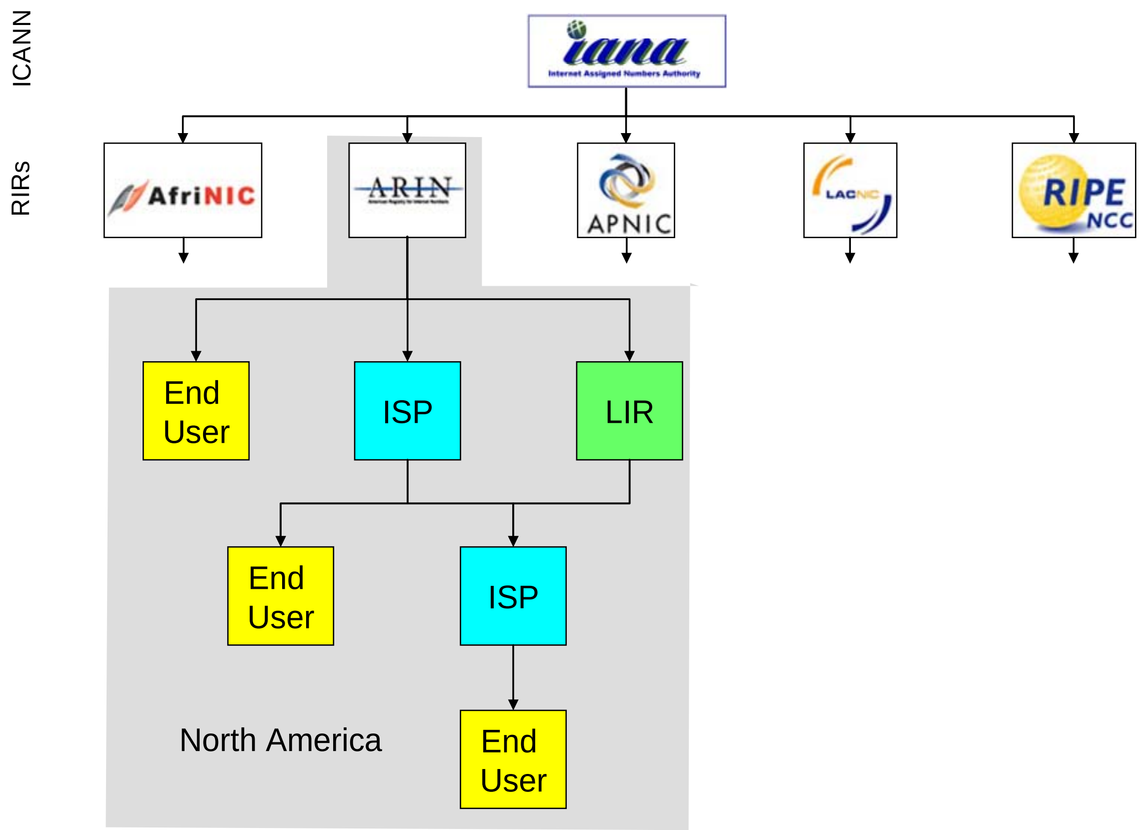
[18] See Bradner, S., A. Mankin, The Recommendation for the IP Next Generation Protocol, RFC 1752, Sec. 2 (Jan. 1995) ("Even the most farseeing of the developers of TCP/IP in the early 1980s did not imagine the dilemma of scale that the Internet faces today. 1987 estimates projected a need to address as many as 100,000 networks at some vague point in the future. We will reach that mark by 1996. There are many realistic projections of many millions of interconnected networks in the not too distant future.").

[19] IANA – About the Internet Assigned Numbers Authority (last visited Nov. 17, 2010). *See* Management of Internet Names and Numbers, Statement of Policy, US Department of Commerce, National Telecommunications and Information Administration (1998) (White Paper) (setting forth Internet governance principles of stability, competition, private, bottom-up coordination, representation).

[20] See IPv4 Allocations/Assignments, available space and forecasting, LACNIC (last visited Dec. 4, 2010).

The RIRs assign address blocks to Local Internet Registries (LIRs) or networks within their territories pursuant to each RIRs' own policies.[21] Those networks, in turn, can assign blocks of addresses to smaller networks, or individual numbers to individual subscribers.

Figure 2: IP Address Allocation



RIRs manage IP numbers as a public resource. When a registry allocates a number to an entity, it is giving that entity the ability to use that number; no property right is conferred to the recipient. IP numbers are allocated on a needs-basis pursuant to RIR policies; recipients pay fees which support the operation of the registries.[22]

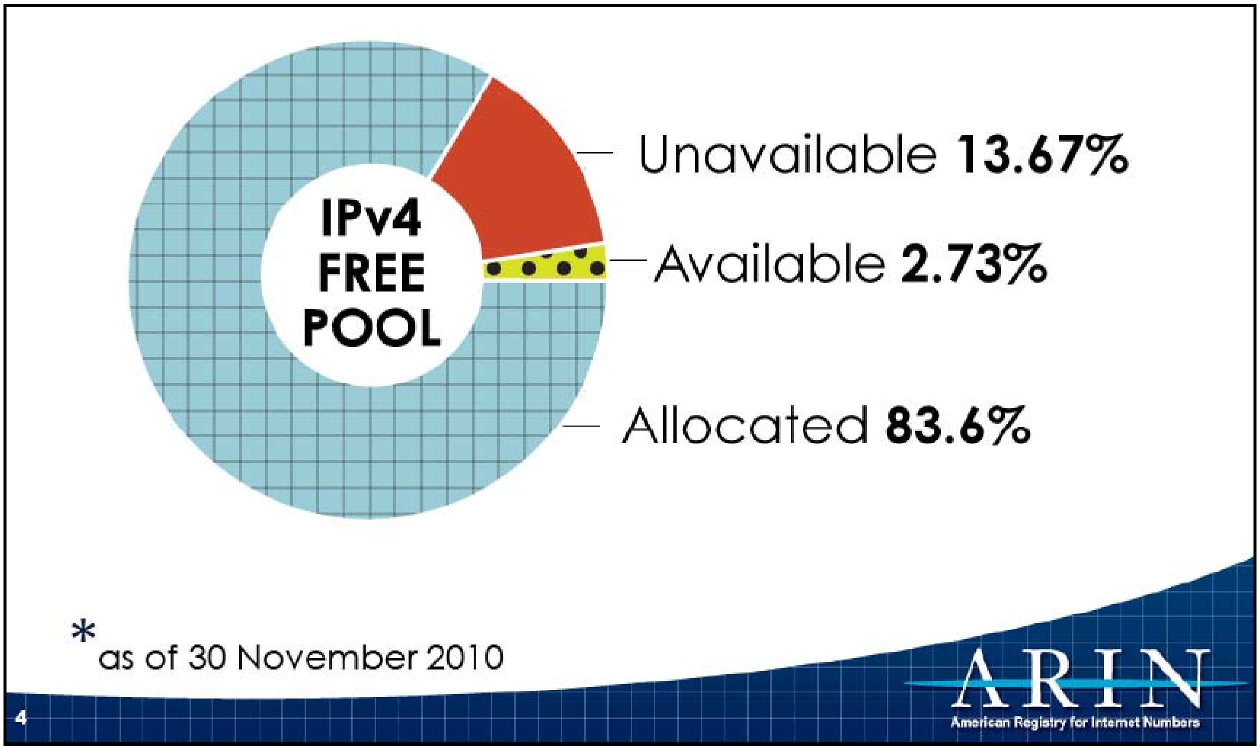
The IANA allocates IPv4 addresses to RIRs in large blocks of 16,777,216 addresses each (referred to as "/8" address blocks). Within the total IPv4 address space, there are 256 /8 address blocks. Approximately thirty-six of these address blocks are held in reserve (these addresses are used for multicasting and various other dedicated applications). Of the 220 blocks available to the IANA for distribution and allocation, 213 had been allocated as of December 2010 to the

[21] Geoff Huston, IPv4 Address Report. RIR policies are created through bottom-up policy making processes in each RIR community.

[22] *See* ARIN: Fee Schedule. See Dan Campbell, Comments on an IP Address Trading Market, CIRCLEID (Feb. 15, 2008) (discussing how IP addresses are allocated by RIRs).

RIRs, leaving 7 blocks still available in the IANA pool.[23] When the next two blocks are allocated and only 5 blocks remain at IANA, these blocks will be distributed one each to the five RIRs.[24]

Figure 3: IPv4 Address Space Utilization[25]

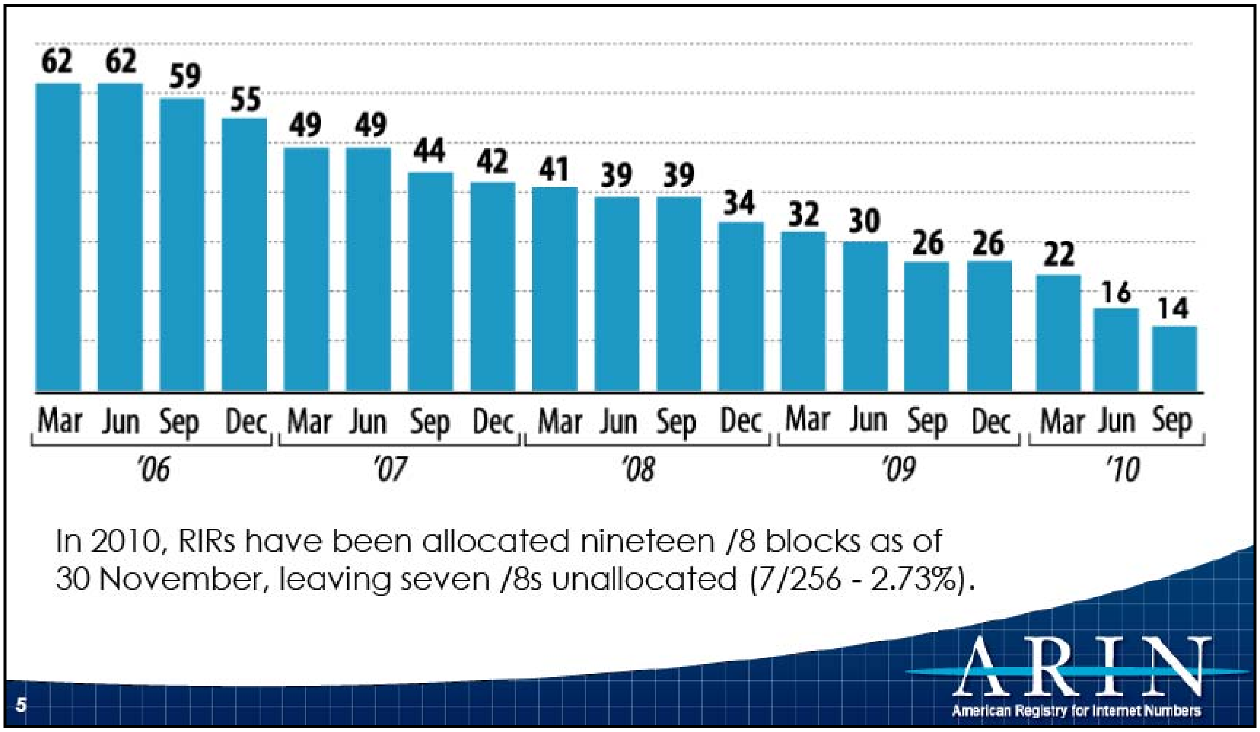


[23] *See* IANA IPv4 Address Space Registry, IANA; Four /8 Blocks Allocated to the RIRs – 2.73% Remains at IANA, ARIN (Nov. 30, 2010); Goeff Huston, IPv4 Address Report (accessed Oct. 5, 2010).
[24] Global Policy for the Allocation of the Remaining IPv4 Address Space, ICANN (Mar. 6, 2009).
[25] Slide from the ARIN IPv4 Depletion: IPv6 Adoption (Nov. 11, 2010) slide deck; slides used by permission.

IPv4 Exhaustion

With the success of the Internet has come great demand for Internet addresses, exhausting the supply of available IPv4 addresses. Experts predict that IANA's supply of IPv4 addresses will likely be exhausted by February, 2011.[26] As of November 2010, 2.73% of the total IPv4 address blocks remained available for allocation by IANA to the RIRS.[27]

Figure 4: Available IPv4 Space in /8s[28]



[26] Geoff Huston, IPv4 Address Report (last accessed Dec. 2, 2010); Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper (2009); Tony Hain, "A Pragmatic Report on IPv4 Address Space Consumption," The Internet Protocol Journal, Volume 8, Number 3. At the point where IANA's inventory of IPv4 address blocks is depleted, depletion will trickle through the system. The RIRs will still have some address blocks in inventory; projections are that their inventories will be exhausted by the Fall of 2011. Some large end users are already reporting difficulty acquiring requested IP address resources. *See* William Jackson, CIO Council Shepherds Agencies Through IPv6 Transitions, GCN (Nov. 12, 2010) (stating "shortages already are appearing. A Labor Department employee said that the department requested from Verizon, its Network vendor, three Class C IPv4 address blocks containing a little more than 500,000 addresses each, but was able to get only one block. ").

[27] Four /8 Blocks Allocated to the RIRs – 2.73% Remains at IANA, ARIN (Nov. 30, 2010); Unallocated IPv4 Internet Addresses Soon to Be Consumed, ICANN Press Release (Jan. 19, 2010). *See also* Internet Addressing – Measuring Deployment of IPv6, Working Party on Communication Infrastructures and Services Policy, Directorate for Science and Technology, OECD, p. 3 (Feb. 4, 2010).

[28] Slide from the ARIN IPv4 Depletion: IPv6 Adoption (Nov. 11, 2010) slide deck; slides used by permission.

Several factors have increased demand for IPv4 addresses. These include increased Internet deployment, and new and more advanced devices on the network.[29] As the supply of IPv4 addresses dwindles, there is concern that some networks may engage in hoarding.[30]

Relationship of IP Address to Domain Names

Most people think of domain names as "Internet addresses." Ask for someone's email address, and they will give you something with a domain name: "robert.cannon@fcc.gov". However, there is no host on the Internet with the address "fcc.gov." Instead, domain names are used as a mnemonic device to obtain IP addresses.

When a human attempts an interaction on the Internet using a domain name, a query is sent to a domain name server. That server will answer the domain name query with an IP number. For example, the domain name "fcc.gov" might resolve to "192.104.54.5." Having acquired the IP address, the human's computer now knows the address of the destination computer and will initiate interaction.

Domain names have several features. They can be easily remembered by humans. Domain names can be easily updated with a different IP address, permitting the owner of the domain name to use or move to a different host on a different service with a different IP address, even though everyone continues to communicate with the site using the same domain name. For example, when the White House was the subject of a DOS attack that focused on the IP address of one of the White House servers, the White House changed servers and changed IP addresses in the domain name record of whitehouse.gov, without changing the domain name with which people were reaching the White House.* The domain name system acts as an address book for easy look-up of IP number addresses.

* Keith A. Rhodes, Code Red, Code Red II, and SirCam Attacks Highlight Need for Proactive Measures, Testimony Before the Subcommittee on Government Efficiency, Financial Management, and Intergovernmental Relations, Committee on Government Reform, House of Representatives, GAO-01-1073T (Aug. 29, 2001).

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[29] *See* Alain Durand, IPv6 @ Comcast: Managing 100+ Million IP Addresses, Presented at RIPE 54, Slide 6 (May 2007) (Comcast Triple Play results in the need for 8 to 9 IP addresses per subscriber); GAO, Internet Protocol version 6, Federal Agencies Need to Plan for Transition and Manage Security Risks, p. 8 (May 2005); Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 8 (2009); Factsheet: IPv6 – the Internet's Vital Expansion, ICANN (Oct. 2007); Doug Montgomery, IPv6: Hope, Hype and (Red) Herrings, NIST (2006) (presentation on the promise and misunderstandings surrounding IPv6).

[30] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 9 (2009).

The IPv6 Solution

In response to IPv4 address exhaustion, the Internet Engineering Task Force (IETF) created IPv6, a new version of the Internet Protocol with a vastly expanded address space.[31] The new version also included many desired features such as enhanced security.[32] As work progressed, many IPv6 improvements have been incorporated into IPv4 networks, leaving a vastly increased address space as the one clear feature of IPv6.[33]

Figure 5: About IPv4 and IPv6[34]

IP version	IPv4	IPv6
Deployed	1981	1999
Address Size	32-bit number	128-bit number
Address Format	Dotted Decimal Notation: 192.0.2.76	Hexadecimal Notation: 2001:0DB8:0234:AB00: 0123:4567:8901:ABCD
Number of Addresses	2^{32} = 4,294,967,296	2^{128} = 340,282,366,920,938,463, 463,374,607,431,768,211,456
Examples of Prefix Notation	192.0.2.0/24 10/8 (a "/8" block = 1/256th of total IPv4 address space = 2^{24} = 16,777,216 addresses)	2001:0DB8:0234::/48 2600:0000::/12

[31] *See* Proceedings of the 18th IETF, p. 53 (August 1990) (Minutes of August 2nd Meeting, presentation by Frank Solensky on the rate of utilization of the IP space); Bradner, S. and A. Mankin, The Recommendation for the IP Next Generation Protocol, RFC 1752 (Jan. 1995).
[32] *See Planning Guide/Roadmap Toward IPv6 Adoption within the US Government*, The Federal CIO Council Architecture and Infrastructure Committee Technology Infrastructure Subcommittee Federal IPv6 Working Group, p. vii & 4 (May 2009) (discussing benefits of IPv6).
[33] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 16 (2009) ("There are a host of other features, but in the ten years since the IETF published the IPv6 specification,22 most have been back-ported to IPv4. "); OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 17 (May 2008) ("Some experts attribute additional benefits to IPv6, although many have been ported to IPv4 or are contingent on the removal of NATs, which are deeply embedded into the existing infrastructure.").
[34] Slide from the ARIN IPv4 Depletion: IPv6 Adoption (Nov. 11, 2010) slide deck; slides used by permission.

Support for the IPv6 Solution

The IPv6 solution is supported by all Internet addressing authorities: ICANN (IANA),[35] ARIN,[36] RIPE NCC,[37] APNIC,[38] LACNIC,[39] AFRINIC,[40] and Numbering Resource Organization.[41] IPv6 has also been supported by the co-designer of the original Internet Protocol Vint Cerf.[42] It is supported by the US Department of Defense, the Office of Management and Budget, and the Federal CIO Council.[43] Other supporters of IPv6 include the Internet Society,[44] the European Commission,[45] the OECD,[46] the ITU,[47] and the ICT Standards Advisory Council of Canada.[48]

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[35] On the Deployment of IPv6, ICANN Resolution (June 2007) ("the future growth of the Internet therefore increasingly depends on the availability and timely deployment of IPv6"). See also Unallocated IPv4 Internet Addresses Soon to Be Consumed, ICANN Press Release (Jan. 19, 2010) ("For the global Internet to grow and prosper without limitation, we need to encourage the rapid widespread adoption of the IPv6 protocol." Rod Beckstrom, ICANN's President and Chief Executive Officer.).

[36] IPv6 Board Resolution, ARIN (May 7, 2007) ("Be It Resolved, that this Board of Trustees hereby advises the Internet community that migration to IPv6 numbering resources is necessary for any applications which require ongoing availability from ARIN of contiguous IP numbering resources").

[37] RIPE Position Paper, IPv6 Act Now, RIPE NCC (Oct. 2007) ("Growth and innovation on the Internet depends on the continued availability of IP address space. The remaining pool of unallocated IPv4 address space is likely to be fully allocated within two to four years. IPv6 provides the necessary address space for future growth. We therefore need to facilitate the wider deployment of IPv6 addresses. While the existing IPv4 Internet will continue to function as it currently does, the deployment of IPv6 is necessary for the development of future IP networks.").

[38] APNIC – Ipv6 Program (last visited Jan. 22, 2010) ("IPv6 deployment is a very important issue in our community. It is a priority for APNIC to dedicate significant resources to help facilitate IPv6 deployment in the Asia Pacific region and provide stakeholders with the necessary information to make this important decision for their organizations.")

[39] LACNIC Portal IPv6. Why Is It Important to Implement IPv6, Portal IPv6, LACNIC (accessed January 21, 2010) ("The deployment of IPv6 is essential to avoid reaching this situation, and it is the only solution to IPv4 exhaustion that we can qualify as practically permanent.").

[40] AFRINIC – Ipv6 Resource Center (accessed January 22, 2010) ("IPv6 is the culmination of over a decade's worth of work, mainly inspired by this address exhaustion and is designed to enable the global expansion of the Internet.").

[41] Numbering Resource Organization – IPv6 ("The NRO, on behalf of the five Regional Internet Registries (RIRs), is calling on all stakeholders to make the deployment of IPv6 a priority").

[42] *See, e.g.*, Paul Krill, Internet Pioneer Cerf Urges IPv6 Migration, InfoWorld (Sept. 17, 2009). Vint Cerf is currently "Chief Internet Evangelist" at Google. Cerf's Up at Google, Google Press Center (Sept. 8, 2005).

[43] *Planning Guide/Roadmap Toward IPv6 Adoption within the US Government*, The Federal CIO Council Architecture and Infrastructure Committee Technology Infrastructure Subcommittee Federal IPv6 Working Group, p. viii (May 2009) ("The transition of the Internet to IPv6 is generally seen as the only practical and readily available long-term solution to IPv4 address exhaustion for devices connected to the public internet.").

[44] ISOC Highlights Importance of Greater IPv6 Deployment, ISOC Press Release (Nov. 12, 2007).

[45] Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Advancing the Internet: Action Plan for the Deployment of Internet Protocol version 6 (IPv6) in Europe p. 8 (May 27, 2008) ("Europe should set itself the objective to widely implement IPv6 by 2010. Concretely speaking at least 25% of users should be able to connect to the IPv6 Internet and to access their most important content and service providers without noticing a major difference compared to IPv4.").

[46] Unallocated IPv4 Internet Addresses Soon to Be Consumed, ICANN Press Release (Jan. 19, 2010). See also Internet Addressing – Measuring Deployment of IPv6, Working Party on Communication Infrastructures and Services Policy, Directorate for Science and Technology, OECD, p. 3 (Feb. 4, 2010) ("Encouraging this deployment is an explicit goal of the OECD").

[47] ITU WTSA Resolution 64. See also ITU IPv6 Study Group. ITU is requesting to be an IPv6 registry.

[48] IPv6 in Canada: Final Report and Recommendations of the ISACC IPv6 Task Group (IITG), IITG Final Report to ISACC, ISACC-10-42200 (Mar. 16, 2010). Major network equipment vendors also support IPv6. *See, e.g.*, CISCO

According to RIPE NCC,

> [U]niversal broadband will put heavy strain on the infrastructure of the Internet, as all computers connected to the global network need an IP address. To safeguard the future growth of the digital economy, a timely adoption of IPv6 is essential.[49]

The Federal Government CIO Council stated

> The emergence of IPv6, providing the world with an exponentially larger number of available IP addresses, is essential to the continued growth of the Internet and development of new applications leveraging mobile Internet connectivity. Although the information technology (IT) community has come up with workarounds for this shortage in the IPv4 environment, IPv6 is the true long-term solution to this problem.[50]

US Government

US Government activity regarding IPv6 can be divided into three areas:

- US Military Networks (Department of Defense);
- US Government non-military networks (Office of Management and Budget); and
- Private networks (Department of Commerce).

US military networks. The Department of Defense (DOD), with its network-centric operations, has high network address demands and therefore places a priority on the expanded address space. In 2003, it was the first government branch to announce an IPv6 transition policy,[51] declaring that:

> The achievement of net-centric operations and warfare, envisioned as the Global Information Grid (GIG) of inter-networked sensors, platforms and other Information Technology/National Security System (IT/NSS) capabilities (ref a), depends on effective implementation of IPv6 in concert with other aspects of the GIG architecture.[52]

> The DOD set 2008 as the deadline by which it should complete its IPv6 transition. DOD's transition to IPv6 has been described as "aggressive" and DOD has operational plans that would require a high demand on a network address space. DOD is reported to have received a substantial IPv6 address allocation.[53]

IPv6 Solutions (Last Updated Dec. 2009); Juniper IPv6 Solutions (May 1, 2002); Migrating Routed Networks and Services to IPv6 - Alcatel-Lucent.

[49] Government | IPv6 Act Now, RIPE NCC (accessed January 25, 2010).

[50] IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 3 (Feb. 2006).

[51] The DOD oversaw the network protocol transition from NCP-to-IPv4.

[52] DOD Memo for Secretaries of the Military Departments, From Dept of Defense Chief Information Officer, Subj: Internet Protocol version 6 (IPv6) (June 9, 2003).

[53] The US Department of Defense has 42 Million Billion Billion Billion IPv6 Addresses, Royal Pingdom (Mar. 26th, 2009) (DOD "has a /13 IPv6 block (the smaller the number, the larger the block). No one else in the world is even close to that. The next-largest block after that is a /19 block (which is already huge). In other words the DoD owns a block 64 times larger than anyone else's."); Captain RV Ros Dixon, IPv6 in the Department of Defense, Defense Information Systems Agency.

US government non-military networks. In 2005, the Office of Management and Budget mandated that federal agencies initiate the transition to IPv6.[54] According to the CIO Council:

> [T]he Office of Management Budget issued Memorandum M-05-22, "Transition Planning for Internet Protocol Version 6 (IPv6)", establishing the goal of enabling all Federal government agency network backbones to support the next generation of the Internet Protocol Version 6 (IPv6) by June 30, 2008. The memorandum require[d] the agency's network backbone to be ready to transmit both IPv4 and IPv6 traffic, and support IPv4 and IPv6 addresses, by June 30, 2008. . . . The requirements for June 30, 2008 [were] for the network backbone (core) only. IPv6 [did] not actually have to be operationally enabled (i.e. turned on) by June 30, 2008. However, network backbones must [have been] ready to pass IPv6 traffic and support IPv6 addresses. Applications, peripherals, and other IT assets which are not leveraged in the execution of the functions mentioned above are not required for the June 30, 2008 deadline.[55]

Moving the government's information technology from "ready" to "operational" will require additional work. On September 28, 2010, at a Department of Commerce IPv6 Workshop, OMB released a further memo *Transition to IPv6* setting forth additional deadlines for the federal IPv6 transition:

> In order to facilitate timely and effective IPv6 adoption, agencies shall:
>
> - Upgrade public/external facing servers and services (e.g. web, email, DNS, ISP services, etc) to operationally use native IPv6 by the end of FY 2012;
> - Upgrade internal client applications that communicate with public Internet servers and supporting enterprise networks to operationally use native IPv6 by the end of FY 2014.[56]

In 2005, OMB created an IPv6 Advisory Group[57] and tasked the CIO Council[58] with publishing transition planning guidance.[59] The CIO Council established an Interagency IPv6 Working Group, headed by Peter Tseronis, Senior Advisor, US Department of Energy.[60]

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[54] Karen S. Evans, Administrator, Office of E-Government and Information Technology, Transition Planning for Internet Protocol Version 6 (IPv6), M-05-22 (August 2, 2005).

[55] IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 1 & 3 (Feb. 2006) ("As of July 2008, all major agencies met the June 30, 2008 deadline for successfully demonstrating their adoption of IPv6 technology."). *See also* Carolyn Duffy Marsan, Feds: We are ready for IPv6 D-Day, Network World (Jun. 26, 2008).

[56] Vivek Kundra, Transition to IPv6, Memorandum for Chief Information Officers and Executive Departments and Agencies, Executive Office of the President, Office of Management and Budget (Sept. 28, 2010).

[57] IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 25 (Feb. 2006).

[58] "The Chief Information Officers (CIO) Council was established by Executive Order 13011, Federal Information Technology, on July 16, 1996, now revoked. The CIO Council's existence was codified into law by Congress in the E-Government Act of 2002. The CIO Council serves as the principal interagency forum for improving practices in the design, modernization, use, sharing, and performance of Federal Government agency information resources. The Council's role includes developing recommendations for information technology management policies, procedures, and standards; identifying opportunities to share information resources; and assessing and addressing the needs of the Federal Government's IT workforce. The Chair of the CIO Council is the Deputy Director for Management for

OMB also directed the National Institute of Standards and Technology (NIST) to develop standards and testing necessary to support adoption of IPv6 by US Government agencies. The NIST project is known as USGv6.[61] NIST has developed a technical standards profile for US Government acquisition of IPv6 hosts and routers, and a specification for network protection devices.[62] NIST is also actively establishing a testing program in order to test the compliance of products and vendors with the profile.[63] The Government Services Administration updated the Federal Acquisition Regulation (FAR) to reflect the IPv6 specifications,[64] and is assisting agencies with IPv6 procurement needs.[65]

Private networks. In 2004, the Department of Commerce (the National Telecommunications and Information Administration (NTIA) and the National Institute of Standards and Technology (NIST)) initiated an investigation into the US Government's policy response to IPv6. This culminated with the release of the 2006 Report *Technical and Economic Assessment of Internet Protocol, Version 6 (IPv6)*. In the Report, the Department of Commerce stated:

> Industry stakeholders and Internet experts generally agree that IPv6-based networks would be technically superior to the common installed base of IPv4-based networks. The vastly increased IP address space available under IPv6 could potentially stimulate a plethora of new innovative communications services. Deployment of IPv6 would, at a minimum, "future proof" the Internet against potential address shortages resulting from the emergence of new services or applications that require large quantities of globally routable Internet addresses.
>
> Current market trends suggest that demand for unique IP addresses could expand considerably in future years. The growing use of the Internet will likely increase pressures on existing IPv4 address resources, as more and more people around the globe seek IP addresses to enjoy the benefits of Internet access. In addition, the potential development of new classes of networked applications (e.g., widely available networked computing in the home, the office, and industrial devices for monitoring, control, and repair) could result in rapid increases in demand for global IP addresses.

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the Office of Management and Budget (OMB) and the Vice Chair is elected by the CIO Council from its membership." Federal Chief Information Officers Council, About Us (visited Jan. 25, 2010).

[59] IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 3 (Feb. 2006).

[60] IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 23 (Feb. 2006).

[61] USGv6 Technical Infrastructure, Advanced Networks Division, NIST.

[62] A Profile for IPv6 in the US Government – Version 1.0, Recommendations of NIST, NIST SP500-267 (July 2008).

[63] USGv6 Testing Program, Advanced Network Technologies Division, NIST. NIST's USGv6 documentation is a good resource for other networks embarked on the IPv6 transition.

[64] Federal Acquisition Regulation; FAR Case 2005-041, Internet Protocol Version 6 (IPv6), Final Rule, 74 Fed. Reg. 65605 (Dec. 10, 2009) ("The Civilian Agency Acquisition Council and the Defense Acquisition Regulations Council (Councils) are issuing a final rule amending the Federal Acquisition Regulation (FAR) to require Internet Protocol Version 6 (IPv6) compliant products be included in all new information technology (IT) acquisitions using Internet Protocol (IP)".).

[65] GSA – IPv6.

> Over time, IPv6 could become (as compared to IPv4) a more useful, more flexible mechanism for providing user communications on an end-to-end basis. The redesigned header structure in IPv6 and the enhanced capabilities of the new protocol could also simplify the configuration, and operation of certain networks and services. These enhancements could produce operations and management cost savings for network administrators. In addition, auto-configuration and other features of IPv6 could make it easier to connect computers to the Internet and simplify network access for mobile Internet users.[66]

Addressing the appropriate role for the government in promoting the transition, the Department of Commerce at that time concluded,

> The Task Force finds that no substantial market barriers appear to exist that would prevent industry from investing in IPv6 products and services as its needs require or as consumers demand. The Task Force, therefore, believes that aggressive government action to accelerate deployment of IPv6 by the private sector is not warranted at this time. The Task Force believes that, in the near term, private sector organizations should undertake a careful analysis of their business cases for IPv6 adoption and plan for the inevitable emergence of IPv6 traffic on both internal and external networks.[67]

In 2010, the Department of Commerce announced that grantees for the Comprehensive Community Infrastructure Awards, which are part of the NTIA Broadband Technology Opportunity Program (BTOP) stimulus grants, must report on "Internet protocol address utilization and IPv6 implementation." Recipients are required to file quarterly reports until the end of their funding.[68]

On September 28, 2010, NTIA convened an IPv6 Workshop, during which Assistant Secretary of Commerce for Communications and Information Lawrence Strickling stated,

> [F]or industry in particular – smart-phone and router manufactures, transport providers, Internet service providers, and chief information and technology officers throughout the industry – action is needed. Today we want to impress upon everyone that this is an urgent issue, but one that can be successfully handled with good planning. And we want to encourage companies to share best practices on IPv6 uptake for all businesses to benefit, particularly for small- and medium-sized enterprises.[69]

The NTIA event, which was moderated by US CTO Aneesh Chopra and US CIO Vivek Kundra, highlighted the importance of industry and government working together, sharing information

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[66] Technical and Economic Assessment of Internet Protocol, Version 6 (IPv6), IPv6 Task Force, Department of Commerce, Executive Summary (Jan. 2006).

[67] Technical and Economic Assessment of Internet Protocol, Version 6 (IPv6), IPv6 Task Force, Department of Commerce, Executive Summary (Jan. 2006).

[68] Notice of Funds Availability (NOFA) and Solicitation of Applications, Broadband Technology Opportunities Program, National Telecommunications and Information Administration, US Department of Commerce, 75 Fed. Reg. 3792 (Jan. 22, 2010). See comments of kc claffy, National Broadband Plan Proceeding, Docket 09-51 (filed Jan. 27, 2010) (commenting on the need for good data to research networks).

[69] NTIA Press Release, NTIA Convenes Stakeholders to Discuss IPv6 Deployment, Sept. 28, 2010.

and best practices that could facilitate the transition.[70] At the event, the CIO Council released its new memo with the new deadlines for the federal IPv6 transition.[71]

History: The NCP-to-TCP Transition

The Internet has seen network protocol transitions before. The precursor to the Internet was the ARPANet, initiated in 1969 as an experimental research packet-switched network by the Advanced Research Project Agency (ARPA) of DOD. ARPANet's network protocol was the Network Control Protocol (NCP).[72] By 1980, ARPANet had moved from an experiment to an operational network and was being integrated into the Defense Data Network. For this to be successful, and for the network to become a "network of networks," the network had to migrate to the new Internet Protocol (IPv4) developed by Bob Kahn and Vint Cerf.

At the time, the Defense Communications Agency (DCA) was responsible for operational management of the ARPANet. In 1980, DCA announced that ARPANet would transition to IPv4 on January 1, 1983. In hindsight, with the success of the Internet, this appears to have been an obviously good decision. But that was not evident at the time. NCP was working fine for many network operators who had little need or incentive to migrate to the new protocol.[73] To facilitate the transition and encourage the NCP-recalcitrants, ARPANet leadership engaged in awareness raising and educational campaigns, including newsletters, discussion groups, and at times more drastic measures. Twice during 1982, Jon Postel and Vint Cerf turned off NCP on the ARPANet; any non-IPv4 hosts were left offline. This subtly demonstrated to the ARPANet community the need to prepare for the transition.

In 1981, Jon Postel released the NCP/TCP (IPv4) Transition Plan.[74] The ARPANet would go through a one year transition during 1982, where Hosts would support both NCP and IPv4 (i.e., operate in dual stack mode). Postel's plan was a phased transition calling for different applications to migrate over to TCP at different times.

The NCP-to-IPv4 transition had two characteristics that distinguish it from the current transition: a flag-day transition date and a clear directive from an authority that could back it up. On January 1, 1983, NCP would be turned off. Those networks who had failed to prepare – and

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[70] Agenda, Internet Protocol Version 6 (IPv6) Workshop: The Impact of the Adoption and Deployment of IPv6 Addresses for Industry, the US Government, and the Internet Economy, US Department of Commerce, National Telecommunications and Information Administration, September 28, 2010.

[71] Vivek Kundra, Transition to IPv6, Memorandum for Chief Information Officers and Executive Departments and Agencies, Executive Office of the President, Office of Management and Budget (Sept. 28, 2010).

[72] ARPNet migrated from its original *Host-to-Host* protocol to the newer *Network Control Protocol* in 1970. See, e.g., Peter Salas, *Casting the Net: From ARPANet to Internet and Beyond*, p. 188 (Addison-Wesley Professional 1995).

[73] Janet Abbate, Inventing the Internet, p. 141 (MIT Press 2000) ("Most host system managers had no compelling interest in converting to the Internet protocols, and the transition required a number of steps that would cost the host sites time and money"); Thomas Parke Hughes, Agatha C. Hughes, Michael Thad Allen, Gabrielle Hecht, Technologies of Power; The Hidden Lives of Standards, p. 127 (MIT Press 2001).

[74] J. Postel, RFC 801, NCP/TCP Transition Plan (Nov. 1981).

there were a significant number of them – fell offline, and proceeded to spend several panicked months attempting to upgrade their computers and regain connectivity.[75]

The transition was described as "traumatic" and "disruptive." It was met with resistance and recalcitrance. Even with the superiority of IPv4 over NCP, in the end a number of those involved remarked that the transition may not have succeeded or occurred at all without the directive from the DCA and the hard deadline.[76]

Potential Issues

The IPv4-to-IPv6 transition is encountering multiple challenges. These challenges impact public policy considerations in different ways. This section surveys potential issues that would be prudent to monitor and could influence the course of the transition.

Pace of Adoption

IPv6 migration started slowly; little content was available, connectivity was limited, backbone services were not always abundant, IPv4 devices are embedded, and there was a lack of IPv6 exchange points.[77] In 2010, the OECD released a report comprehensively reviewing the state of IPv6 adoption, concluding,

> By early 2010, IPv6 was still a small proportion of the Internet. However, IPv6 use was growing faster than continued IPv4 use, albeit from a low base. And several large-scale deployments are taking place or are planned. Overall, the Internet is still in the early stages of a transition whereby end hosts, networks, services, and middleware are shifting from IPv4-only to support both IPv4 and IPv6.[78]

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[75] *See* TCP/IP Internet Protocol, Living Internet; Ronda Hauben, From the ARPANET to the Internet: A Study of the ARPANET TCP/IP Digest and of the Role of Online Communication in the Transition from the ARPANET to the Internet (recounting resistance to the transition).

[76] *See, e.g.*, Janet Abbate, Inventing the Internet, p. 141 (MIT Press 2000) ("Clearly the transition to the Internet protocols would not have occurred so quickly – perhaps not at all at many sites – without considerable pressure from the military managers."); Email from Jack Haverty to IH mailing list, NCP to TCP/IP Transition (April 27, 2009) (recounting transition). In her book, Inventing the Internet, Jane Abbate states that on the date of the cut-over to IPv4, "only about half the sites had actually implemented a working version of TCP/IP." Janet Abbate, Inventing the Internet, p. 141 (MIT Press 2000).

[77] Factsheet: IPv6 – the Internet's Vital Expansion, ICANN (Oct. 2007) (adoption of IPv6 "has been slow"); Internet Addressing – Measuring Deployment of IPv6, Working Party on Communication Infrastructures and Services Policy, Directorate for Science and Technology, OECD, p. 4 (Feb. 4, 2010) ("By the measurements explored in this report, adequate adoption of IPv6 cannot yet be demonstrated. In particular, IPv6 is not being deployed sufficiently rapidly at present to intercept the estimated IPv4 exhaustion date. Surveys show that lack of vendor support remains a barrier to IPv6 deployment, as does the lack of business models."); OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 18 (May 2008); Comcast IPv6 Monitor (showing percent of top websites that are reachable via IPv6); Geoff Huston, Is the Transition to IPv6 a "Market Failure," The ISP Column (Sept. 2009) ("The Transition Process"); Packet Clearing House Report on Distribution of IPv6-Endabled IXPs (accessed Nov. 29, 2010).

[78] Karine Perset, Internet Addressing: Measuring Deployment of IPv6, OECD (Apr. 2010).

A significant barrier to IPv6 adoption has been a negative network effect: without much on IPv6 networks, there has been little incentive to join IPv6 networks.[79] There was no one there with which to interact. With few end users joining IPv6 networks, there was little incentive to create IPv6 resources or content.[80] However, with the migration of US Government networks and other major networks and services to IPv6, network effect has been shifting, creating an incentive to join.[81]

Consumer Demand

There has not been consumer demand for IPv6. There is consumer demand for Internet access (regardless of whether IPv4 or IPv6) and for new features. Public Internet services are generally reachable today via IPv4, so there is no perceived need by consumers to run IPv6. Consumers have customer premises equipment such as cameras, TVs or game consoles that may only be IPv4 enabled. If the Internet service provider migrates to IPv6, the service provider risks upsetting consumers whose equipment may no longer work properly.

No Flag Date

Unlike the previous transition from NCP to IPv4, there is no hard date by which the transition must be achieved. There is no hard and fast deadline creating urgency, which has been key to other successful transitions.[82] Some experts predict that the transition will be protracted, potentially taking decades. However others project that there will be a network effect whereby, when sufficient amounts of online assets have migrated to IPv6, networks will tip to IPv6 and IPv4 will fade. At this point the transition could accelerate.

IPv6 Transition Methods

IPv6 is not backwards compatible.[83] IPv6 networks cannot directly interconnect with IPv4 networks. As both networks will co-exist for some time, [84] this creates an issue for how devices on IPv4 and IPv6 networks are able to interact with each other. Network engineers have

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[79] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 9 (2009); OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 37 (May 2008) ("From an end user's perspective, the key issue with transitioning to IPv6 is likely to be content rather than cost. There is currently little Internet content available via IPv6…").

[80] Briefing Paper: IPv6 Deployment: State of Play and the Way Forward, Internet Society (June 18, 2009) (describing this as the chicken or the egg problem); Harold Feld, RIPE Makes Me Vaguely Uneasy By Creating Legal Market for IP Addresses, Tales from the Sausage Factory (Jan. 7, 2009) ("Why would I spend money to build an IPv6 network when everyone else I want to talk to is on the IPv4 network? The failure of IPv6 migration to date pretty much answers that question: "no reason, so I won't do it."").

[81] *See* Carolyn Duffy Marsan, YouTube Turns On IPv6 Support, Net Traffic Spikes, PC World (Feb. 1, 2010); Carolyn Duffy Marsan, Comcast, Netflix Report Rise in IPv6 Activity, Network World (Mar. 24, 2010).

[82] *See* Planning Guide/Roadmap Toward IPv6 Adoption within the US Government, ver. 1.0, CIO Council, p. 5 (May 2009) ("Although there is an increasing sense of urgency in Federal Government to start moving toward IPv6, it is not the same situation as Y2K, which had a clear date by which transition was vital. "). As noted above, the US Government has set specific deadlines for transitioning the US Government to IPv6.

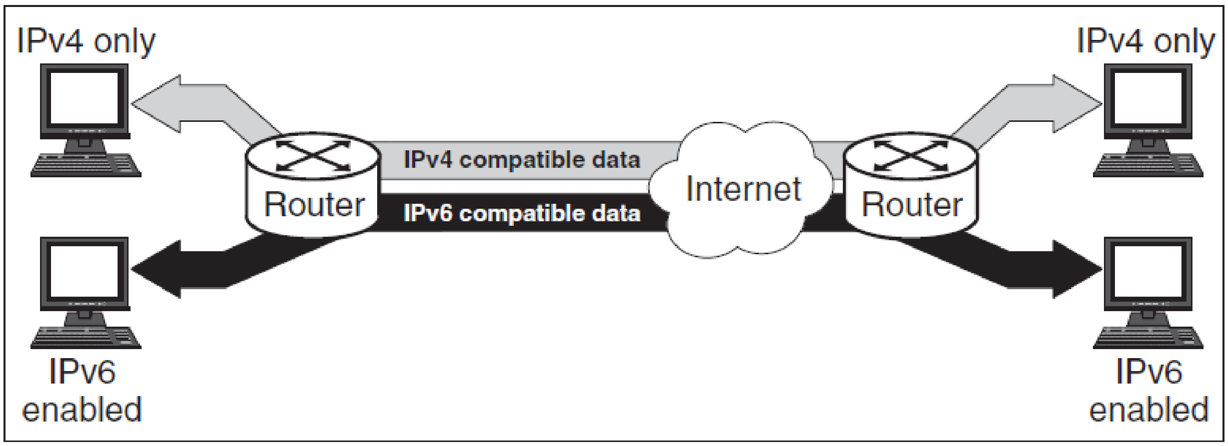
[83] IPv4 Depletion: IPv6 Adoption, ARIN, Slide 8 (Sept. 30, 2009).

[84] Internet Addressing – Measuring Deployment of IPv6, Working Party on Communication Infrastructures and Services Policy, Directorate for Science and Technology, OECD, p. 4 (Feb. 4, 2010) ("An IPv6-only network is the end-point of a potentially long transition phase where both IPv4 and IPv6 will co-exist in a "dual-stack" mode of operation on most of the Internet"); Hillary A. Elmore, L. Jean Camp, Brandon P. Stephens, *Diffusion and Adoption of IPv6 in the United States* (Mar 2008) (estimating that the transition could take between 6 and 70 years); Doug Montgomery, IPv6: Hope, Hype and (Red) Herrings, NIST (2006) (describing transition as a "marathon").

been investing significant energy in developing and deploying viable and effective transition solutions.[85] But the variety of different transition solutions also raises the concern of how well different solutions will work with each other, whether there will be conflicts, and what might get broken in the process.

Generally, the methods of solving this problem are known as Dual Stack and Tunneling.[86] With the Dual Stack solution, a host runs both an IPv4 and an IPv6 stack side by side. Traffic which reaches the host using either network protocol can interact with the host. In the GAO diagram below, the routers are dual stack and handle traffic from either IPv4 or IPv6 clients on their respective networks.

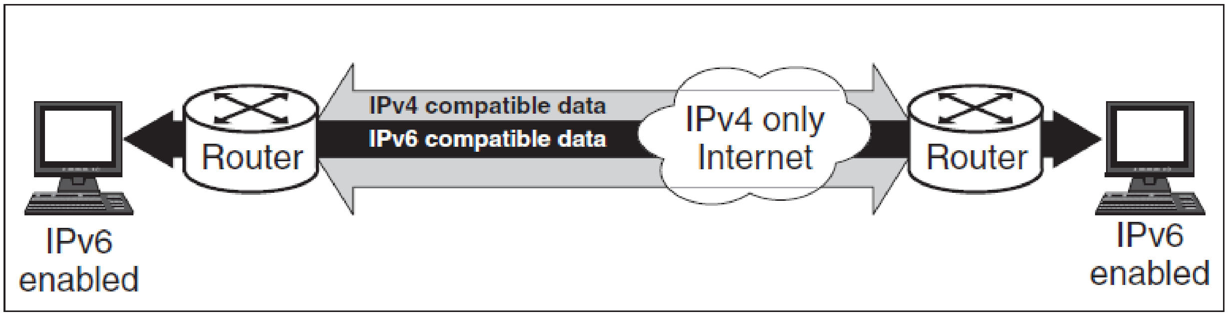
Figure 6: Example of a Dual Stack Network[87]



[85] *See, e.g.*, North American Network Operators Group (NANOG) 50 Meeting Agenda, Oct. 3 – 6, 2010, Atlanta, GA (several panels discussing IPv6 transition).
[86] *See* IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 8, Sec. 2.2.1 (Feb. 2006); IPv6 Deployment Strategies, CISCO (Dec. 23, 2002); John Curran, An Internet Transition Plan version 3, IETF Informational (May 2008). During the NCP to IPv4 transition, hosts were able to operate both NCP and IPv4 and some hosts acted as translators. See J. Postel, *NCP/TCP Transition Plan*, RFC 801 (Nov. 1981); Janet Abbate, Inventing the Internet, p. 141 (MIT Press 2000); Email from Jack Haverty to IH mailing list, NCP to TCP/IP Transition (April 27, 2009) (recounting transition).
[87] GAO, Internet Protocol version 6, Federal Agencies Need to Plan for Transition and Manage Security Risks, p. 21 (May 2005).

Tunneling is a solution utilized when there is no native IPv6 connectivity between different points on the network. IPv6 packets are encapsulated within IPv4 packets, carried across an IPv4 network to the other side where the IPv4 packet is removed and the IPv6 packets continue on their way.[88] Conversely, IPv4 packets can also be tunneled across IPv6 networks.

Figure 7: Example of Tunneling IPv6 Traffic Inside an IPv4-Only Internet[89]



Source: GAO.

Preparations for Transition

Established networks that are strongly engaged in IETF, ICANN, and RIR processes appear to be taking appropriate measures in anticipation of the IPv6 transition. However, lessons from past transitions indicate that there may be some businesses that are not as aware or prepared.[90] Unprepared businesses could begin to experience connectivity and service issues, and difficulty acquiring additional IPv4 addresses.[91] A business that delays transition could find it costly to achieved on a compressed schedule.[92]

IPv4 Allocations and Transfers

IP address blocks have historically been allocated based on need.[93] The costs involved in receiving an allocation are nominal and are not generally a factor in considering whether to apply for an allocation.[94] The principle requirement has been the ability to demonstrate need for the IP addresses, pursuant to community developed RIR address policy. If an address block was not needed, it would (in theory) be returned; it could not be traded.

IPv4 conservation has dampened the pace of IPv4 exhaustion. In the early days of the Internet when the US dominated Internet use, some US firms received large IPv4 block

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[88] Lljitsch van Beinjnum, Everything You Need to Know About IPv6, Ars Technica (Mar. 7, 2007); B. Carpenter, K. Moore, IETF RFC 3056, Connection of IPv6 Domains via IPv4 Clouds (Feb. 2001).
[89] GAO, Internet Protocol version 6, Federal Agencies Need to Plan for Transition and Manage Security Risks p. 22 (May 2005).
[90] During the NCP-to-IPv4 transition, even with a dictate from DCA to make ready for the transition, many entities put off preparations, creating "a mad rush at the end of 1982" to prepare for the switch over to TCP/IP. Janet Abbate, Inventing the Internet, p. 141 (MIT Press 2000).
[91] Lee Wei Lian, IP Scarcity Could Hit Unwary Businesses, Says Internet Body, The Malaysian Insider (Mar. 16, 2010).
[92] *See* Iljitsch van Beijnum, There is no Plan B: why the IPv4-to-IPv6 transition will be ugly, ars technical (Sept. 29, 2010).
[93] Geoff Huston, IPv4 Address Report.
[94] *See* ARIN Number Resource Policy Manual, Sec. 4.2 Allocation to ISPs (Jan. 13, 2010).

allocations; some of these entities have returned unused IPv4 address resources to Internet number registries.[95] While these conservation efforts have helped, they have merely delayed IPv4 exhaustion without solving the long-term problem.[96]

One proposal has been to allow transfers and trade of IP blocks (instead of returning unused resources to the RIRs).[97] This could create an incentive for holders of underutilized IP address blocks to sell them to parties that would put them to more productive use.[98] Transferring IPv4 number allocations would enable new entrants to acquire assignments of IP number resources that are not subordinate to a legacy stakeholder.[99] It would also take pressure off during the transition period, permitting networks to continue to expand, and allowing those engaged in the transition additional time to resolve any transition issues encountered.[100] Two RIRs have policies that permit transfers of IP address block assignments under certain conditions.[101]

The addresses transferred are just numbers. For them to be valuable, they must be routable. The routability of the numbers could be unstable if an RIR does not authenticate the transfer, if conflicting claims to the numbers arise, or if there is any other corruption in the integrity of a unique number assignment to network.[102] Unauthorized transfers could create an issue of the RIR not having a direct relationship with, and knowledge of, the transferee, and thus be unable to maintain accurate address assignment records along with associated contact

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[95] Lljitsch van Beinjnum, Everything You Need to Know About IPv6, Ars Technica (Mar. 7, 2007) ("For instance, IBM, Xerox, HP, DEC, Apple and MIT all received "class A" address blocks of nearly 17 million addresses. (So HP, which acquired DEC, has more than 33 million addresses.)"); Geoff Huston, IPv4 Address Report ("Unneeded addresses are to be passed back to the registry. "); Recovering IPv4 Address Space, ICANN Blog (Feb. 6, 2008) ("With help from the Regional Internet Registries, three /8s were returned in 2007 and last month we recovered one more.")

[96] Lljitsch van Beinjnum, Everything You Need to Know About IPv6, Ars Technica (Mar. 7, 2007) (such efforts only buys us a few more years).

[97] *See* Milton Mueller, Scarcity in IPv4 Addresses: IPv4 Address Transfer Markets and the Regional Internet Address Registries, IGP (July 20, 2008); OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 26 (May 2008); Huston, G., IPv4 address transfers, proposed to APNIC on 26 July 2007; Titley, N. and van Mook, R., Enabling methods for reallocation of IPv4 resources, (Oct. 23, 2007); Dan Campbell, Comments on an IP Address Trading Market, CIRCLEID (Feb. 15, 2008).

[98] *See* Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 11 (2009); Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Advancing the Internet: Action Plan for the Deployment of Internet Protocol version 6 (IPv6) in Europe, p. 4 (May 27, 2008). See RIPE NCC IPv4 Address Allocation and Assignment Policies for the RIPE NCC Service Region, Sec. 5.5 Feb. 2010.

[99] OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 27 (May 2008).

[100] Milton Mueller, Scarcity in IPv4 Addresses: IPv4 Address Transfer Markets and the Regional Internet Address Registries, IGP p. 17 (July 20, 2008) ("The transition could turn out to be more complicated, costly and difficult than anticipated, and we don’t know how long it will last. If we try to use an address shortage to force ISPs into making the transition before they are ready, we could develop damaging gaps in connectivity due to shortages of address resources and compatibility problems.").

[101] *See* ARIN Number Resource Policy Manual, Sec. 4.2.3 Reassigning Address Space to Customers (Sept. 2010); IPv4 Address Allocation and Assignment Policies for RIPE NCC Service Region, Sec. 5.5 Transfers of Allocations (Oct. 2010).

[102] *See* OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 27 (May 2008); Ray Plzak, IP Address Hijacking: An ARIN Perspective (Nov. 2003) (PDF).

information.[103] There is concern that the scarcity of IPv4 numbers will result in IPv4 number hijacking where addresses are utilized by someone other than the assignee of record.[104] The resulting lack of accurate address information also has significant implications for law enforcement and global anti-cybercrime efforts. Finally, there is also concern about the impact of address transfers on the routing table and fragmentation.

Cost of Transition

The cost of transitioning to IPv6 could be problematic. Costs involved in the IPv6 transition include renumbering networks, running two separate networks (IPv4 and IPv6) simultaneously, upgrading relevant software and hardware, training staff, and testing implementations.[105] The cost of IPv6 will involve capital investment and ongoing operational costs that will have to be diverted from other business goals and which can be difficult to bear in today's economic climate.[106] Some networks may be averse to expending financial resources to make the transition until absolutely required.[107] According to an IEEE White Paper,

> A report generated for the National Institute of Standards and Technology (NIST) in 2005 stated that it would take 25 years to have a total transition to IPv6 at a cost of $25B, in 2003 dollars. However, a scholarly report on the adoption of IPv6 indicates that we will run out of IPv4 addresses well before the 25 years is up. Note that the same NIST report indicates the $25B would be less than 1% on network infrastructure spending, and they estimate the benefits of migrating to IPv6 are $10B *per year*.
>
> Also take into consideration that 25 years is still relatively fast for technology adoption. The introduction of digital switching to analog switching took more than 35 years. Moreover, there are still analog switches used in the public switched network. Likewise, we are twelve years into a 25-year migration from switched voice and video services to predominantly IP-based, end-to-end, voice and video services. What is different is the old technologies coexisted fairly well with the new technology, and it was hard for the average user to notice they were communicating with older technology (except for some features or quality).

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[103] See Dan Campbell, Comments on an IP Address Trading Market, CIRCLEID (Feb. 15, 2008); IPv6 in Canada: Final Report and Recommendations of the ISACC IPv6 Task Group (IITG), IITG Final Report to ISACC, ISACC-10-42200, p. 16 (Mar. 16, 2010) ("Unclear ownership of some IPv4 addresses plus a lack of tools to block wrong addresses could lead to instability of the routing system ").

[104] Ray Plzak, IP Address Hijacking: An ARIN Perspective (Nov. 2003).

[105] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 17 (2009); Factsheet: IPv6 – The Internet's Vital Expansion, ICANN (Oct. 2007); Briefing Paper: IPv6 Deployment: State of Play and the Way Forward, Internet Society (June 18, 2009); IPv6 Economic Impact Assessment, RTI International for NIST (Oct. 2005) ; OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 36 (May 2008) ("The cost of IPv6 deployment cannot be evaluated generically, as such costs vary on a case-by-case basis according to network needs and business"); Marco Hogewoning, IPv6 at XS4ALL RIPE 59 Lisboa (Slides).

[106] Briefing Paper: IPv6 Deployment: State of Play and the Way Forward, Internet Society (June 18, 2009).

[107] The financial cost of the transition was likewise an issue during the NCP-to-IPv4 transition. See Janet Abbate, Inventing the Internet, p. 141 (MIT Press 2000) ("Most host system managers had no compelling interest in converting to the Internet protocols, and the transition required a number of steps that would cost the host sites time and money").

The NIST report also mentioned the cost to ISP's for migrating to IPv6 would be $136M (2003 dollars). Again, this cost is a fraction of annual ISP network equipment spending, and thus should not be a major impediment. However, without a clear return-on-investment to the ISP, other than being able to offer IPv6 connectivity, it is hard to get them to make the investment.[108]

Geoff Huston notes that ISPs will bear an additional cost as the result of the transition without an improvement of service to customers. Indeed, Huston notes, since many of the transition methods deteriorate end-to-end connectivity and quality-of-service, ISPs who deploy transition solutions will incur increased costs while offering inferior service – and thus will be at a potential competitive disadvantage.[109]

Conversely, officials from the Defense Research and Engineering Network (DREN) have been sharing information from their IPv6 transition experience. DREN was an early IPv6 mover and was able to incorporate IPv6 into the regular lifecycle of their networks. As a result, they indicate that they were able to migrate their networks to IPv6 with little additional money set aside for the IPv6 transition.[110] The DREN experience suggests that, with planning, anticipated expenses could be mitigated.

NAT Boxes

One of the more passionate points of discussion surrounding IPv6 involves Network Address Translation (NAT) boxes.[111] A NAT box is a host on the Internet with an IP address that has behind it a network of privately addressed computers. A specific block of addresses has been set aside for private use and is not advertised by networks to the public Internet.[112] Since these addresses only work internally and cannot be used to communicate on the public internet, they can be reused over and over again behind NATs.

An example of a NAT might be an off-the-shelf Wi-Fi access point that a residential user might use for home Internet access. The ISP assigns to that subscriber an IP address which is assigned to whatever computer the subscriber attaches at the end of the network. The subscriber attaches the Wi-Fi router. Behind the Wi-Fi router could be all of the computers in the house; the router assigns them IP addresses from the private IP address space. In this way, a subscriber

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[108] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 19-20 (2009).

[109] Geoff Huston, Is the Transition to IPv6 a "Market Failure," The ISP Column (Sept. 2009) (The Transition Process). See also J. Curran, RFC 1669, Market Viability as a IPng Criteria, IETF (Aug. 1994) ("No internetworking vendor (whether host, router, or service vendor) can afford to deploy and support products and services which are not desired in the marketplace.").

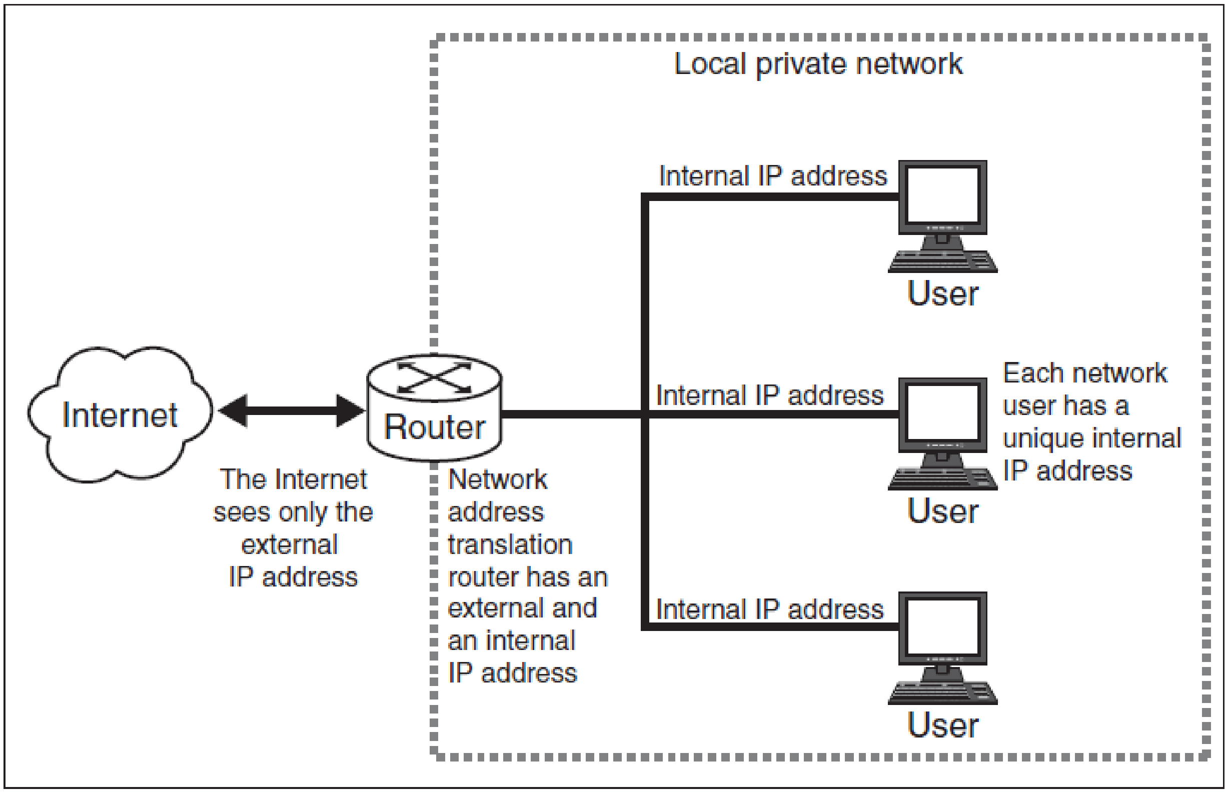
[110] DREN Helps Make the Transition to Internet Protocol 6 (IPv6), Department of Defense DREN (accessed Dec. 4, 2010); John M. Baird, Defense Research and Engineering Network (DREN) IPv6 Deployment Joint Engineering Team (Sept. 21, 2010).

[111] *See, e.g.*, IPv6 Forum, NATS: Just Say No, CIRCLEID (Oct. 24, 2003); Martin Geddes, Why NAT Isn't As Bad As You Thought, CIRCLEID (Jan. 15, 2004); Dan Campbell, As IPv6 deploys, Will We Look Back on NAT as the Ugly Step Sister or Unsung Hero, CIRCLEID (Feb. 4, 2008).

[112] Y. Rekhter, B. Moskowitz, D. Karrenberg, G. J. De Groot, E. Lear, Address Allocation for Private Internets, IETF RFC 1918 (Feb. 1996).

with one public IP number can have multiple computers attached to the Internet.[113] Commercial ISPs may utilize private IP numbers for their subscribers, and corporate LANs (such as the FCC internal network) may also utilize private IP addresses.[114]

Figure 8: An Example of a Network Address Translation[115]



Network operators utilize NATs for various objectives. First, NATs are used to conserve the scarce numbering resource; one public address maps to multiple private addresses. Second, NATs are also used for network management and security, creating single points of entry into networks.

After the transition to IPv6, with the dramatically increased address space, NATs would no longer be necessary in order to deal with the scarce numbering resource. It is expected that with IPv6 the use of NATs will likely decrease although it may not disappear.[116]

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[113] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 10 (2009).

[114] Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 10 (2009).

[115] Source: GAO, Internet Protocol version 6, Federal Agencies Need to Plan for Transition and Manage Security Risks, p. 7 (May 2005).

[116] Some argue that the use of NATs obviates the need for the IPv6 transition. Even if core networks migrate to IPv6, the argument goes, enterprise networks have no incentive to incur the burden and cost, and have sufficient addressing resource available through the use of NAT. See Johna Till Johnson, Is It Truly Necessary to Upgrade to IPv6, Network World (Oct. 3, 2007).

NAT boxes have drawbacks.[117] As stated by the CIO Council, "[w]hile NAT has to some extent delayed the exhaustion on IPv4 address space for the short term, it complicates general application bi-directional communication."[118] NAT boxes break the end-to-end nature of Internet communications, and thus interfere with some Internet applications and services, and create an impediment to innovation.[119]

NAT boxes may work well when traffic originates from within the private network and the NAT box can track which host to return traffic to (someone on the network requests a webpage, and the NAT box knows who to return the webpage to). NAT boxes do not work so well when the traffic originates outside the network trying to reach someone inside the network (for example, someone trying to set up a VoIP call with someone inside the network.[120] Since the request from the VoIP outsider came to the NAT box IP address, the NAT box has no idea which computer inside the network the outsider is actually trying to reach). [121] NAT boxes present barriers to applications which seek to take advantage of IP address transparency. They inject non-standardized intelligence into the network, requiring application developers to conform to each non-standardized implementation.[122] They require a conversion from the public address space to private address spaces, which degrade the performance of some applications.[123] NATs also result in less accurate geolocation, make identification and blocking of abuse more difficult, and frustrate IP-based authentication.[124]

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[117] *See, e.g.*, Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 12 (2009) (providing an extensive discussion of the limitation of NATs).
[118] IPv6 Transition Guidance, Federal CIO Council Architecture and Infrastructure Committee, CIO Council, p. 6 (Feb. 2006).
[119] OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6 (May 2008) (Problems often associated with NATs include increasing the complexity of networks, creating asymmetry between clients and servers, complicating the provision of public services within a local network and interfering with peer-to-peer applications.); Tom Vest, Migration or Stagflation? IPv6, Protocol Number Resource Management, and the Future of the Internet Sept 2008. See also Alain Durand, IPv6 @ Comcast: Managing 100+ Million IP Addresses, Presented at RIPE 54, Slide 4 (May 2007) (stating "In the control plane, all devices need to be remotely managed, so NAT isn't going to help us, nor is federated Net 10 islands…IPv6 is the clear solution for us.").
[120] Lljitsch van Beijnum, NAT – in Depth, Ipv6.com (2008) ("NAT breaks protocols that require incoming connections and protocols that carry IP addresses in them.").
[121] Lljitsch van Beinjnum, Everything You Need to Know About IPv6, Ars Technica (Mar. 7, 2007) ("NAT also breaks protocols that embed IP addresses. For instance, with VoIP, the client computer says to the server, "Please send incoming calls to this address." Obviously this doesn't work if the address in question is a private address."); Next Generation Internet: IPv4 Address Exhaustion, Mitigation Strategies and Implications for the US, IEEE-USA White Paper, p. 12 (2009); Factsheet: IPv6 – the Internet's Vital Expansion, ICANN (Oct. 2007).
[122] OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 14 (May 2008) ("Some have pointed out a primary reason NATs introduce complexity is the lack of standards to specify their ―behaviour in different scenarios. For example, standards to specify how NATs deal with peer-to-peer applications such as voice-over-IP, have not been devised. As a result, NAT implementations vary widely. Unable to predict how specific NATs will react, application designers have had to devise complex ―work-arounds.")
[123] Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Advancing the Internet: Action Plan for the Deployment of Internet Protocol version 6 (IPv6) in Europe, p. 4 (May 27, 2008) ("It adds a layer of complexity in that there are effectively two distinct classes of computers: those with a public address and those with a private address. This often increases costs for the design and maintenance of networks as well as for the development of applications.")
[124] Lorenzo Colitti, IPv6 at Google NANOG, Slide 6 (June 2010).

Security

IPv6 is a new network protocol which will require new training, experience, and implementations. During the transition, new vulnerabilities could be introduced, and IPv4 security devices and software may be of limited use.[125] As network operators have done when introducing anything new into networks, operators will have to work with and test IPv6 implementations in order to ensure security.[126]

Law Enforcement

The transition to IPv6 creates concerns for law enforcement. During the transition, kludges will be employed by networks in order to conserve addresses and allow networks to keep expanding. These solutions, however, break end-to-end connectively and make it difficult to map specific IP numbers to individual end users. IP numbers may map to carrier grade NAT boxes which may have behind them many households, neighborhoods, or even towns, making it difficult to know to whom an IP address belongs.[127] Law enforcement has also expressed concern that WHOIS[128] for IPv6 contain accurate and useful information. ISPs may incur additional administrative burdens of having to retain records of the dynamic mapping between addresses.[129] There may also be issues with CALEA compliance. The ARIN Government Working Group has been working on these issues.[130]

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[125] Michael Warfield, Internet Security Systems, Security Implications of IPv6 (2003) ("IPv6 is not a panacea for security, though, because few security problems derive solely from the IP layer in the network model. For example, IPv6 does not protect against misconfigured servers, poorly designed applications, or poorly protected sites. In addition, IPv6 and IPv6 transitional mechanisms introduce new, not widely understood, tools and techniques that intruders can use to secure unauthorized activity from detection. These IPv6-derived efforts are often successful even against existing IPv4 networks.").

[126] *See* *Planning Guide/Roadmap Toward IPv6 Adoption within the US Government*, The Federal CIO Council Architecture and Infrastructure Committee Technology Infrastructure Subcommittee Federal IPv6 Working Group, p. 34 (May 2009); OECD Study: Economic considerations in the management of IPv4 and in the deployment of IPv6, p. 42 (May 2008).

[127] *See* M. Ford, M. Boucadair, A. Durand, P. Levis, P. Roberts, Issues with IP Address Sharing, IETF Informational Draft (Mar. 8, 2010).

[128] *See, e.g.*, Internet Management: Prevalence of False Contact Information for Registered Domain Names , GAO-06-165 (Nov. 2005); Lennard G. Krugar, Internet Domain Names: Background and Policy Issues, Congressional Research Service (Oct. 28, 2009)

[129] *See* Jason Weil, COX, Service Provider NAT44 Overview, NANOG50, slide 5 (October 2010).

[130] *See* ARIN XXV Public Policy Meeting Day 1 Notes – 19 April 2010; ARIN XXIII Public Policy Meeting Day 2 Notes – 28 April 2009 (noting work of ARIN Government Working Group, mentioning Bobby Flaim, FBI, and Marc Moreau, Royal Canadian Mounted Police); ARIN Government Working Group (AGWG) (Apr. 2009); Supervisory Special Agent Robert Flaim, Law Enforcement and Internet Governance: "An Ounce of Prevention is Worth a Pound of Cure," AfriNIC Government Working Group Meeting Nov. 26, 2010.

Where to Go for More Information

A wealth of information is available concerning the IPv6 transition. To learn more, review the information at the following sources:

- Numbering Authorities
  - American Registry for Internet Numbers (ARIN): IPv4/IPv6: The Bottom Line
    - ARIN IPv6 Wiki
    - ARIN attends many technology conferences where it provides IPv6 information
  - Number Resource Organization: are::you:IPv6:ready?
  - IPv6 Act Now (RIPE NCC)
- United States Government
  - IPv6 Transition Guidance (CIO Council)
  - Technical Infrastructure for USGv6 Adoption (NIST)
    - USGv6 Profile
    - USGv6 Testing Program (NIST)
  - DOD Joint Interoperability Test Command IPv6
    - Defense Research and Engineering Network (DREN)
- North American Network Operators' Group (NANOG) IPv6 Tutorials
  - NANOG holds regular meetings which include IPv6 technical information; these meetings can be viewed online and are archived.
- IPv6 Forum
- Organization for Economic Cooperation and Development Resources on Internet Addressing: IPv4 and IPv6

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"Maximum Impact for Minimum Subsidy: Reverse Auctions for Universal Access in Chile and India," Irene S. Wu, FCC Staff Working Paper 2, October 2010.

"Transformative Choices: A Review of 70 Years of FCC Decisions," Sherille Ismail, FCC Staff Working Paper 1, October 2010.

"A Market-Based Approach to Establishing Licensing Rules: Licensed versus Unlicensed Use of Spectrum," Mark Bykowsky, Mark Olson, and William Sharkey, OSP Working Paper 43, February 2008.

"Modeling the Efficiency of Spectrum Designated to License Use and Unlicensed Operations," Mark Bykowsky, Mark Olson, and William Sharkey, OSP Working Paper 42, February 2008.

"Enhancing Spectrum's Value via Market-Informed Congestion Etiquettes," Mark Bykowsky, Kenneth Carter, Mark Olson, and William Sharkey, OSP Working Paper 41, February 2008.

"Competition Between Cable Television and Direct Broadcast Satellite - It's More Complicated Than You Think," Andrew S. Wise and Kiran Duwadi, Media and International Bureaus, January 2005.

"The Scarcity Rationale for Regulating Traditional Broadcasting: An Idea Whose Time Has Passed," John W. Berresford, Media Bureau, March 2005.

"A Survival Analysis of Cable Networks," Keith S. Brown, Media Bureau, December 2004.

"Traits of an Independent Communications Regulator: a Search for Indicators," by Irene Wu, International Bureau, June 2004.

"The Limits of Economic Regulation: The U.S. Experience," Peyton L. Wynns, International Bureau, June 2004.

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