ESnet
ENERGY SCIENCES NETWORK

BERKELEY LAB

U.S. DEPARTMENT of ENERGY

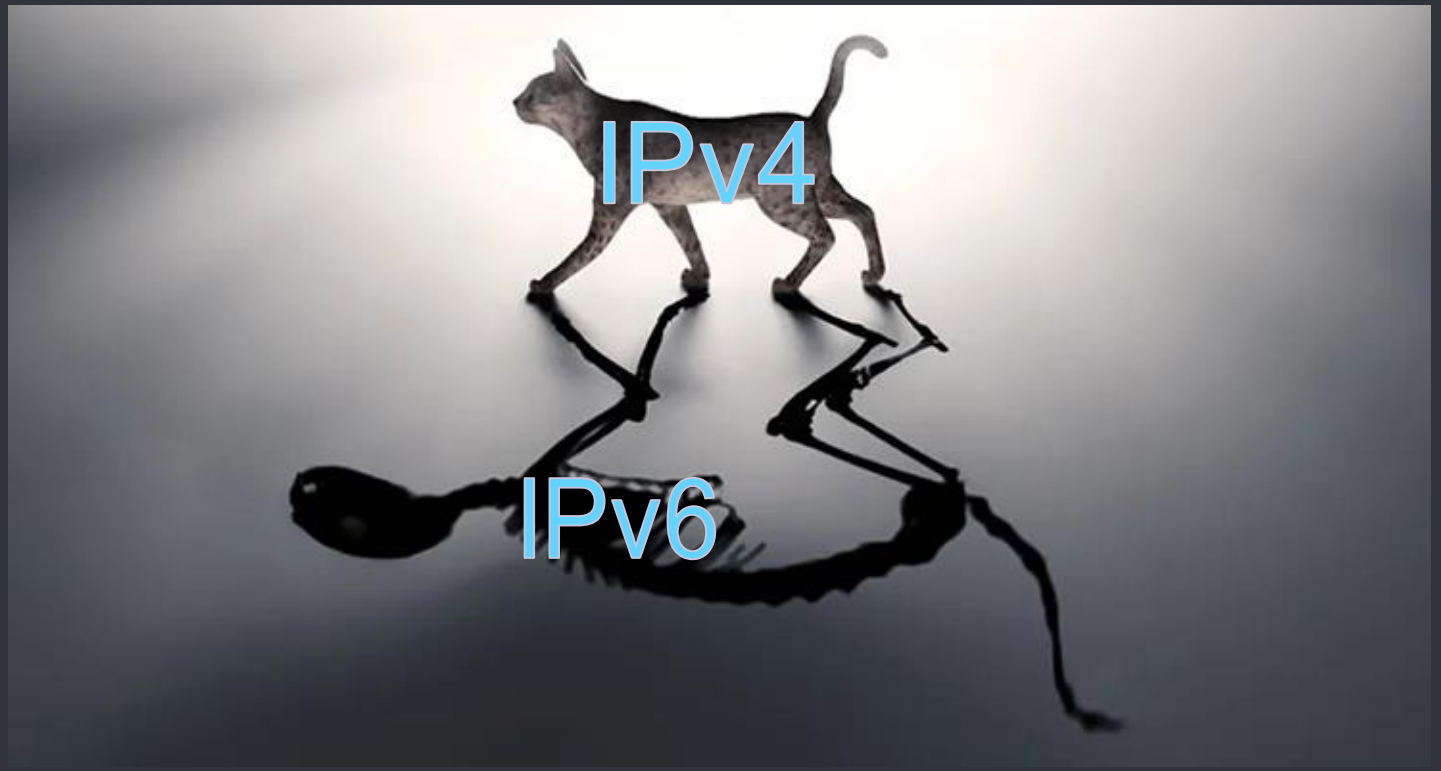
The Nine Lives of an Early Adopter:
Leading Cats to Water in the IPv6 Era

Inder Monga
Executive Director
ESnet

Nick Buraglio
Planning and Architecture
ESnet

ARIN 57
20-April-2026

The State We Are In



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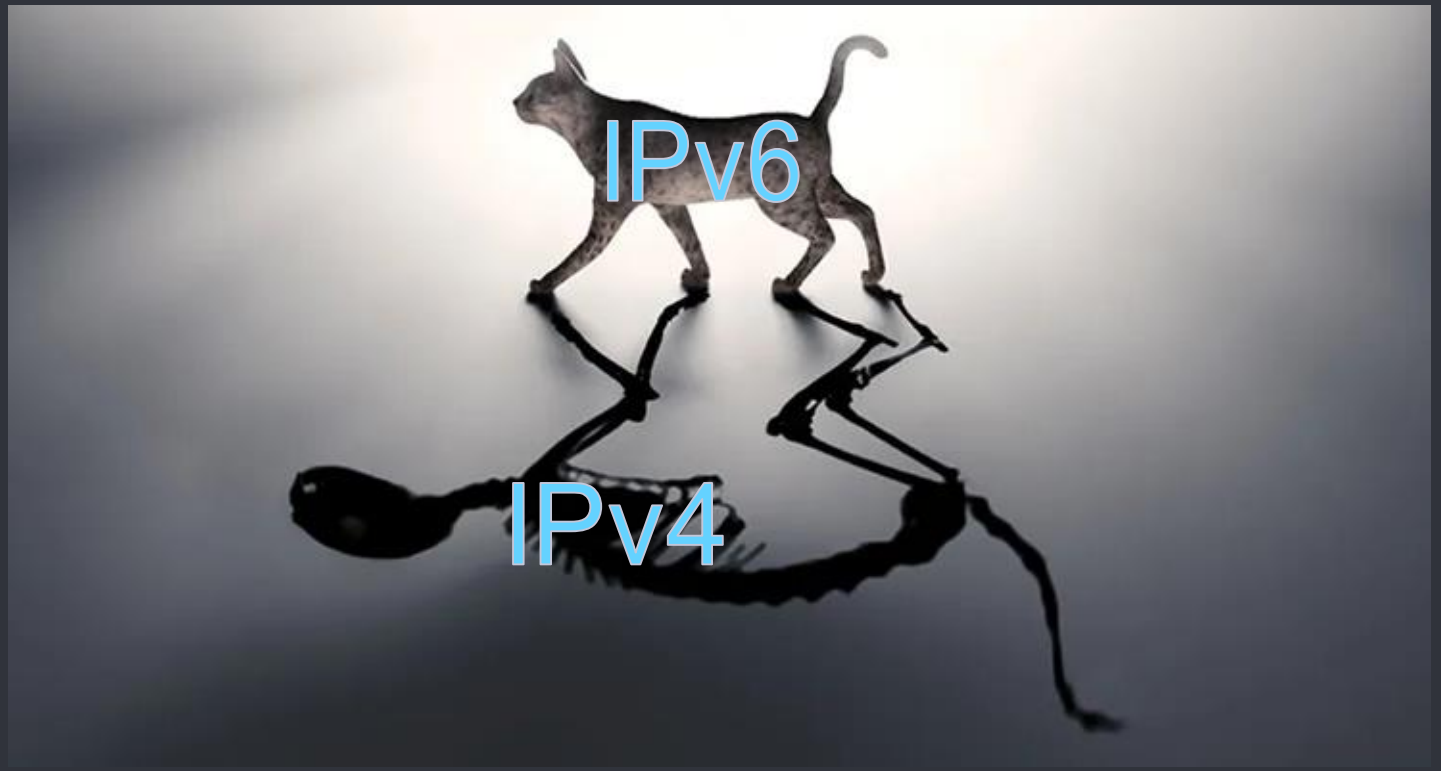
The State We Want to be In



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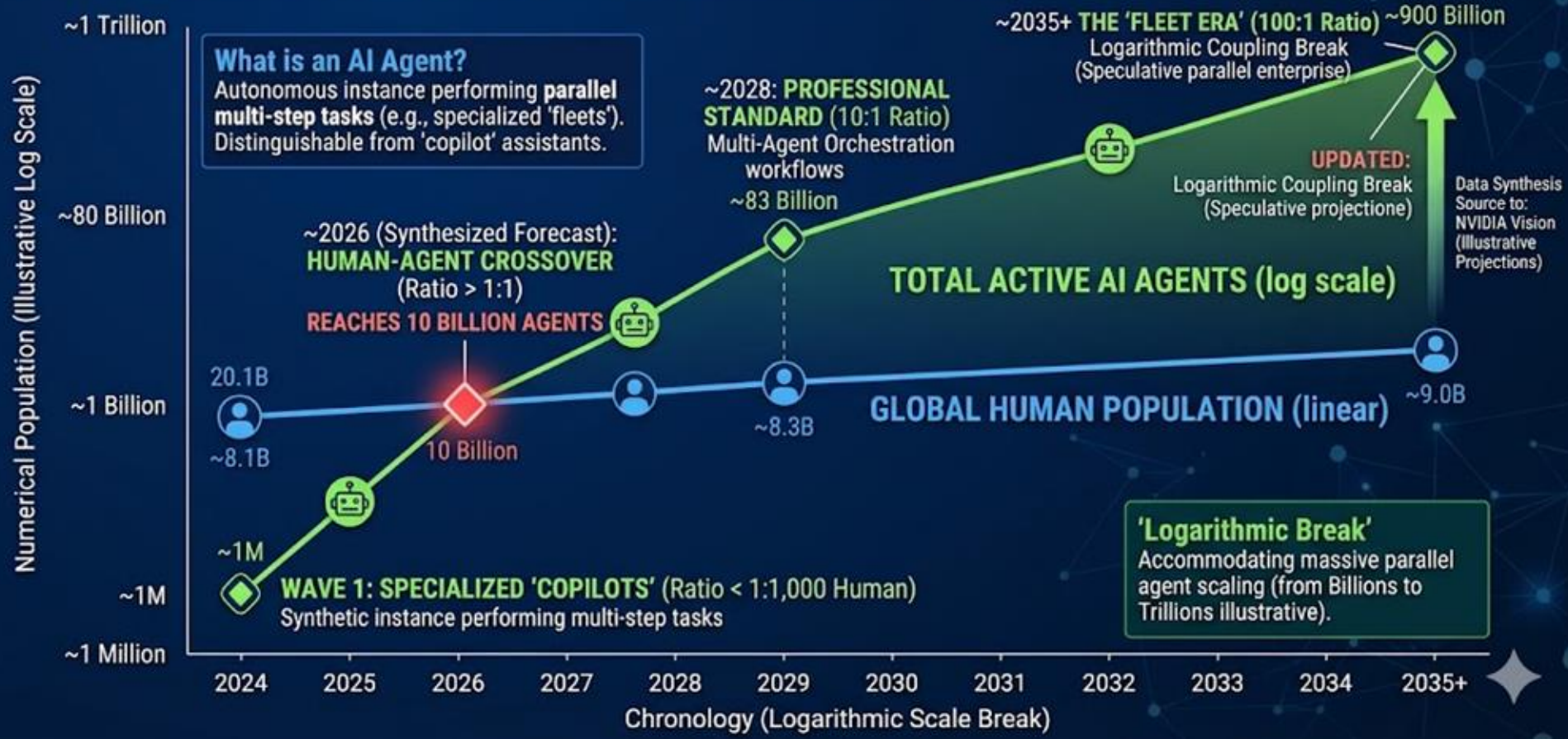
THE AGE OF THE AI AGENT: POPULATION CROSSOVER (2026) & MASSIVE PARALLEL SCALING (2035+)

Forecasted Growth: Active AI Agents vs. Global Human Population (Synthesis)



Only IPv6 can handle the AI onslaught

- With so many agents on the network, can you imagine running it on private IPv4 addressing and NAT?
- For AI to succeed without friction, we would need:
  - Simplicity (elimination of middleboxes)
  - Consistency for end-to-end automation (one addressing scheme)
  - Hyper-connectivity (any-to-any)

ESnet’s Journey navigating the nine lives of both IPv4 and IPv6

ESnet is the DOE's data circulatory system…

17 Department of Energy National Labs

28 User Facilities and Science Instruments worldwide

Global Research and Education Network

The Cloud

The Public Internet

ESnet

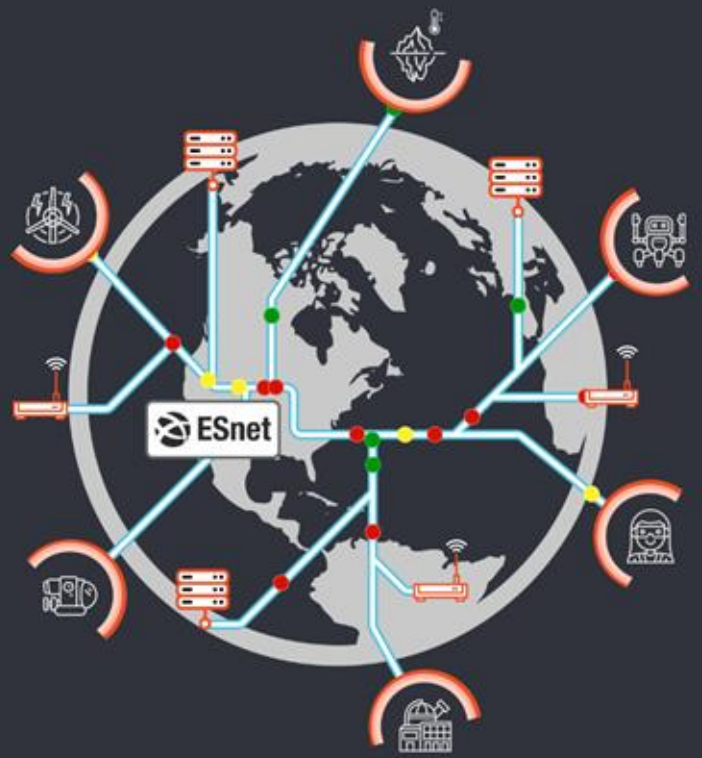
…and the stage for a global science laboratory.

ESnet's Vision

Scientific progress will be completely unconstrained by the physical location of instruments, people, computational resources, or data.

ESnet's Mission

Networking that accelerates science.



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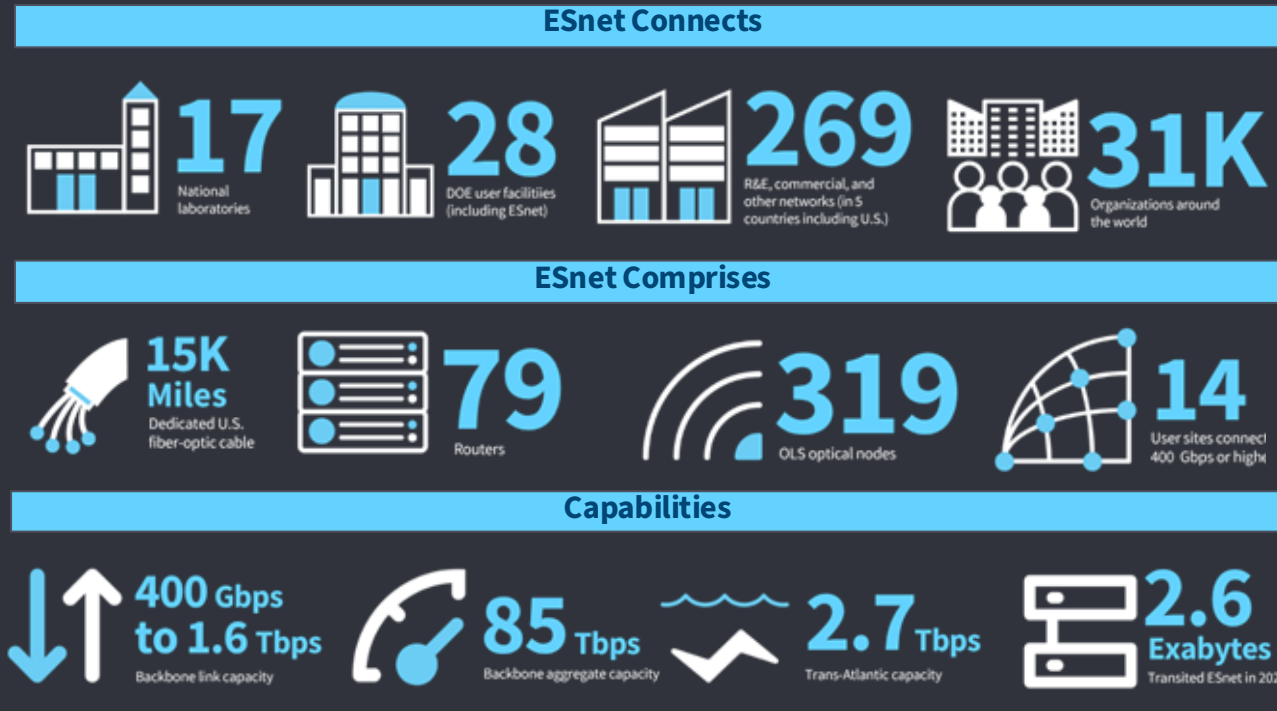
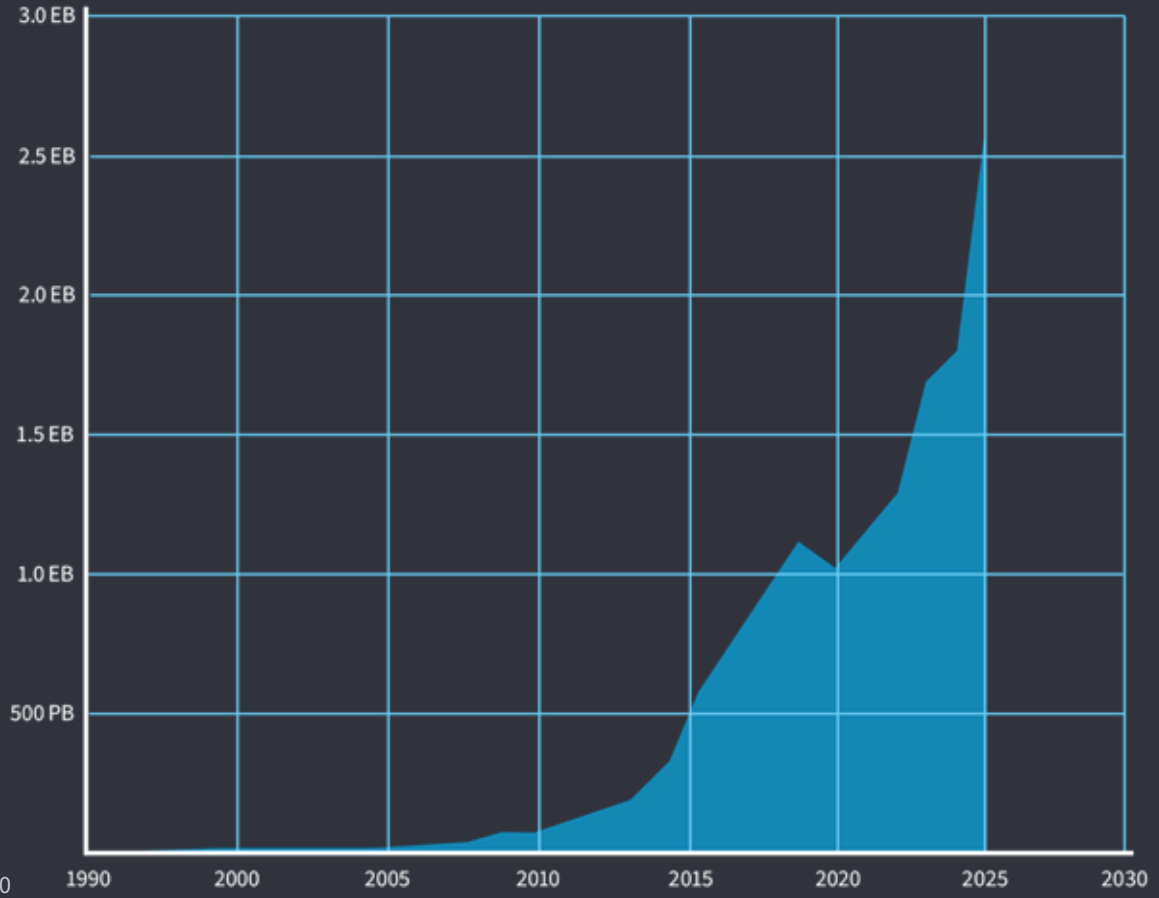
ESnet by the Numbers



ESnet is measured and expected to provide 99.9% site uptime. The network regularly exceeds that standard, providing near 100% uptime to almost all connected sites.

***From the 2024 ESnet Site Coordinators Committee survey*

ESnet's Traffic Growth



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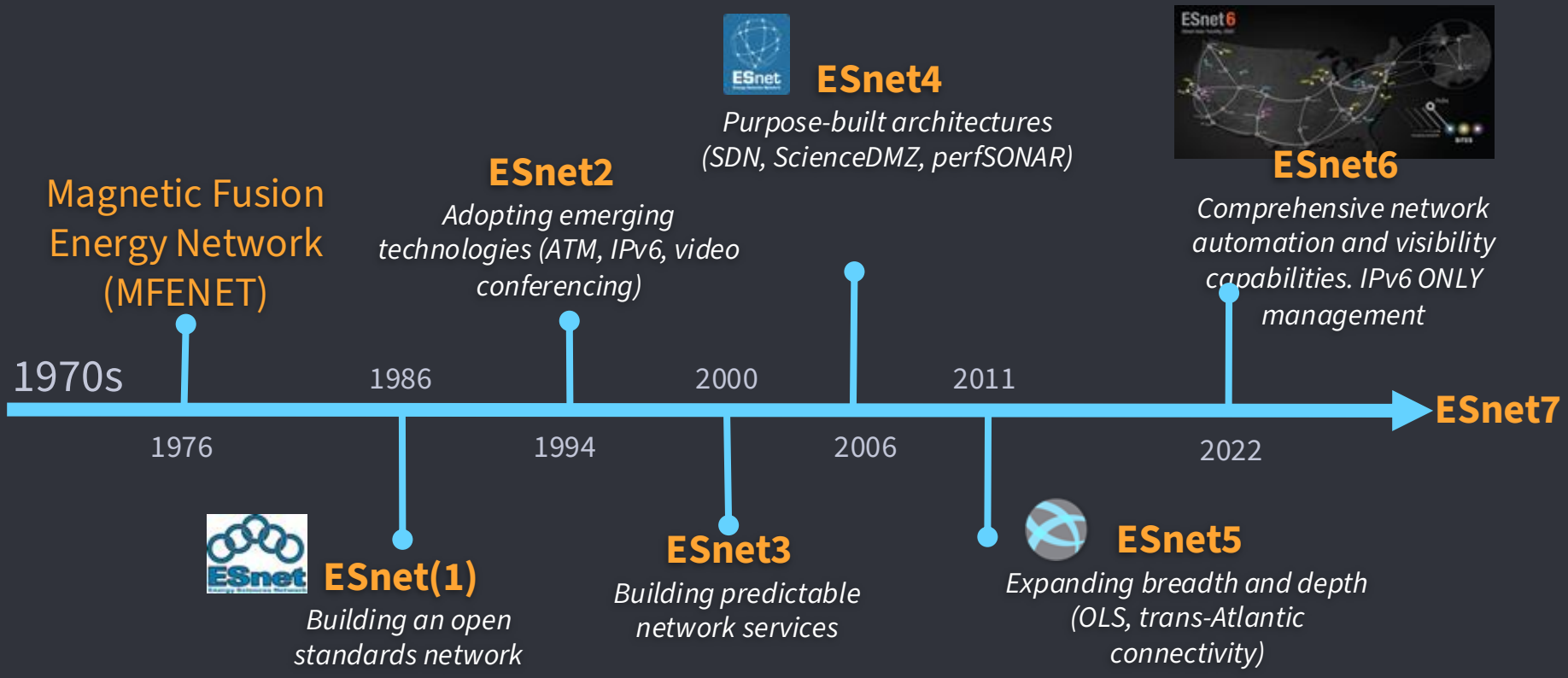
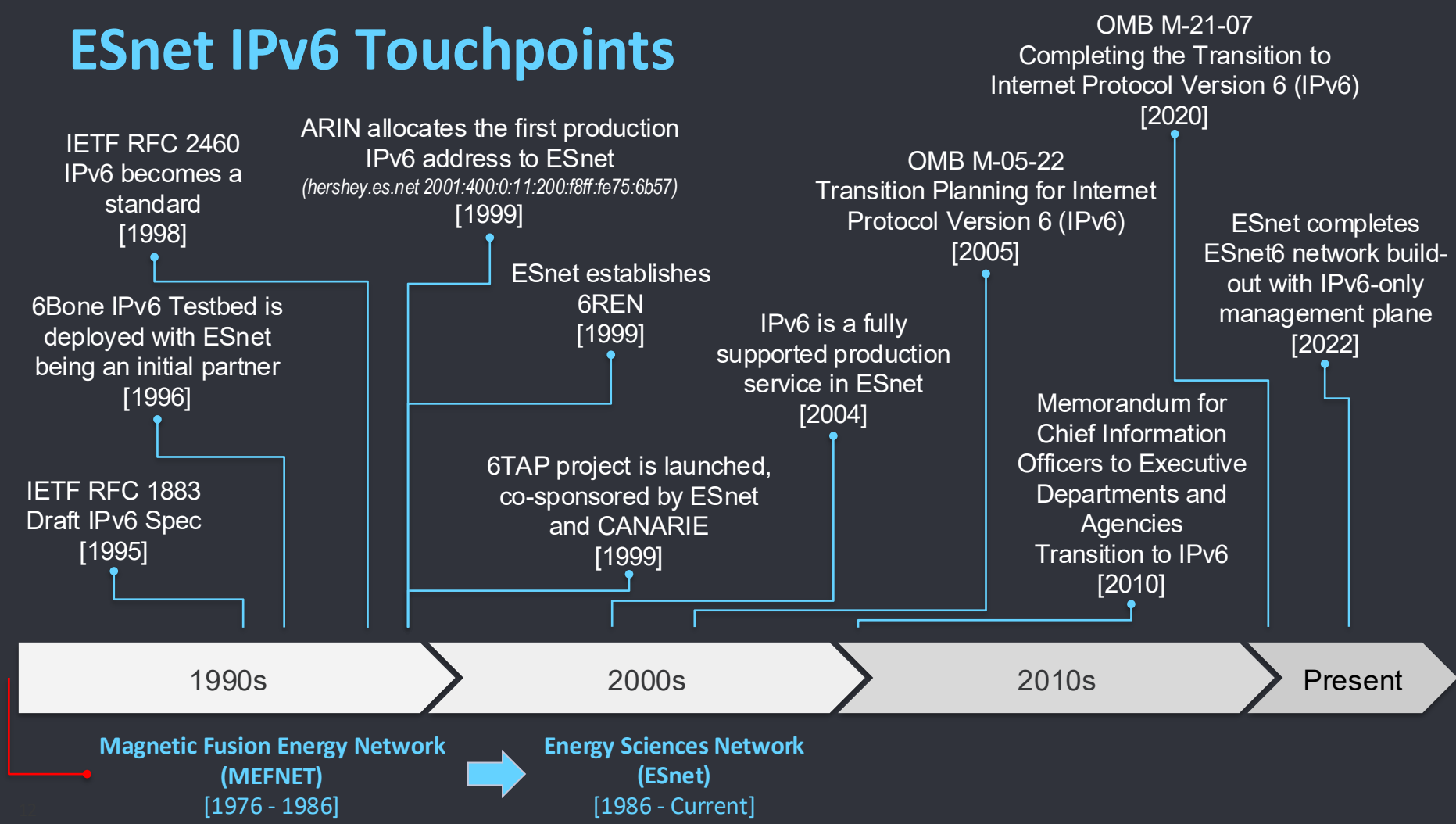
The Evolution of ESnet's Innovative Infrastructure



ESnet IPv6 Touchpoints



ESnet IPv6 Touchpoints

OMB M-21-07
Completing the Transition to
Internet Protocol Version 6 (IPv6)

ARIN allocates the first

ESnet started actively working with Sun, Digital, Kame, and Cisco in the development and testing of IPv6 developmental code

[1999]

6Bon
depl
being an initial partner
[1996]

IETF RFC 1883
Draft IPv6 Spec
[1995]

Network Working Group
Request for Comments: 1883
Category: Standards Track

S. Deering, Xerox PARC
R. Hinden, Ipsilon Networks
December 1995

Internet Protocol, Version 6 (IPv6)
Specification

Status of this Memo

This document specifies an Internet standards track protocol for the Internet community, and requests discussion and suggestions for improvements. Please refer to the current edition of the "Internet Official Protocol Standards" (STD 1) for the standardization state and status of this protocol. Distribution of this memo is unlimited.

Abstract

This document specifies version 6 of the Internet Protocol (IPv6), also sometimes referred to as IP Next Generation or IPng.

1990s | 2000s | 2010s | Present

Magnetic Fusion Energy Network (MEFNET)
[1976 - 1986]

Energy Sciences Network (ESnet)
[1986 - Current]

ESnet IPv6 Touchpoints

OMB M-21-07
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Internet Protocol Version 6 (IPv6)

IETF RFC 2460
IPv6 becomes a
standard
[1998]

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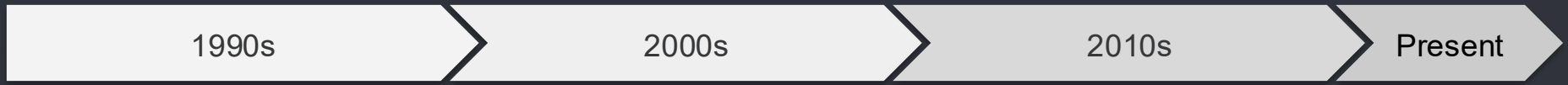
6Bone IPv6 Testbed is deployed with ESnet being an initial partner [1996]

IETF RFC 1883
Draft IPv6 Spec
[1995]

- Worldwide informal collaborative testbed for IPv6
- Started in March 1996 outside the official IETF process, but oversight from IETF NGtrans (IPv6 Transition) Working Group.
- Initially implemented as a virtual network, using IPv6 over IPv4 tunneling/encapsulation, but slowly grow to include native IPv6 links.
- ESnet provided overall management and coordination for 6bone.
- 6bone phaseout plan introduced in March 2004:

Network Working Group — R. Fink
Request for Comments: 3701 — R. Hinden
Obsoletes: 2471 — March 2004
Category: Informational

6bone (IPv6 Testing Address Allocation) Phaseout



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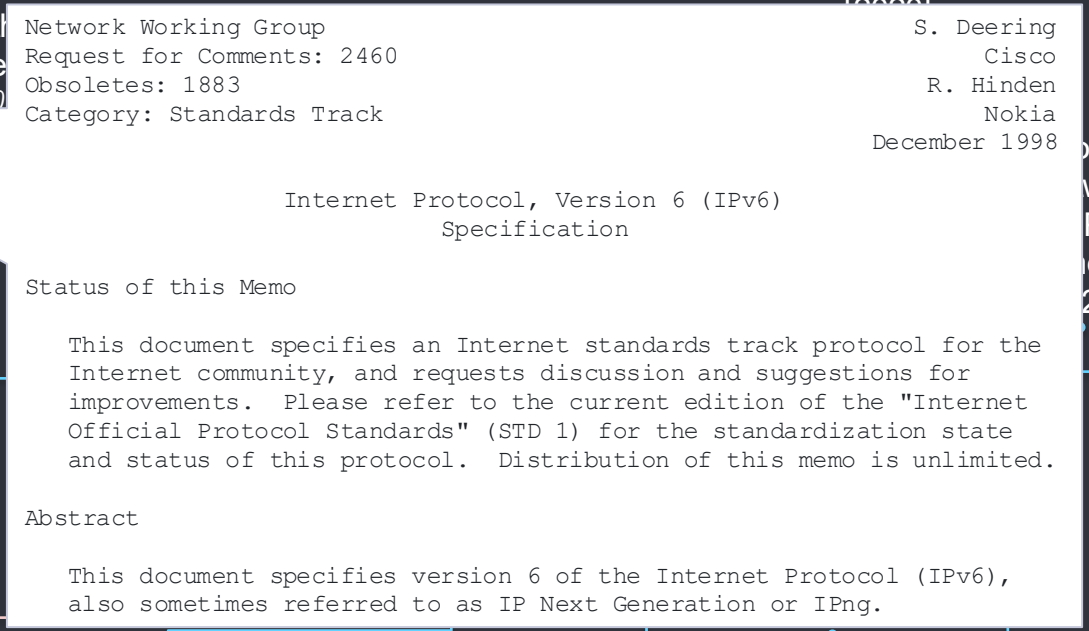

Network Working Group — S. Deering
Request for Comments: 2460 — Cisco
Obsoletes: 1883 — R. Hinden
Category: Standards Track — Nokia
December 1998

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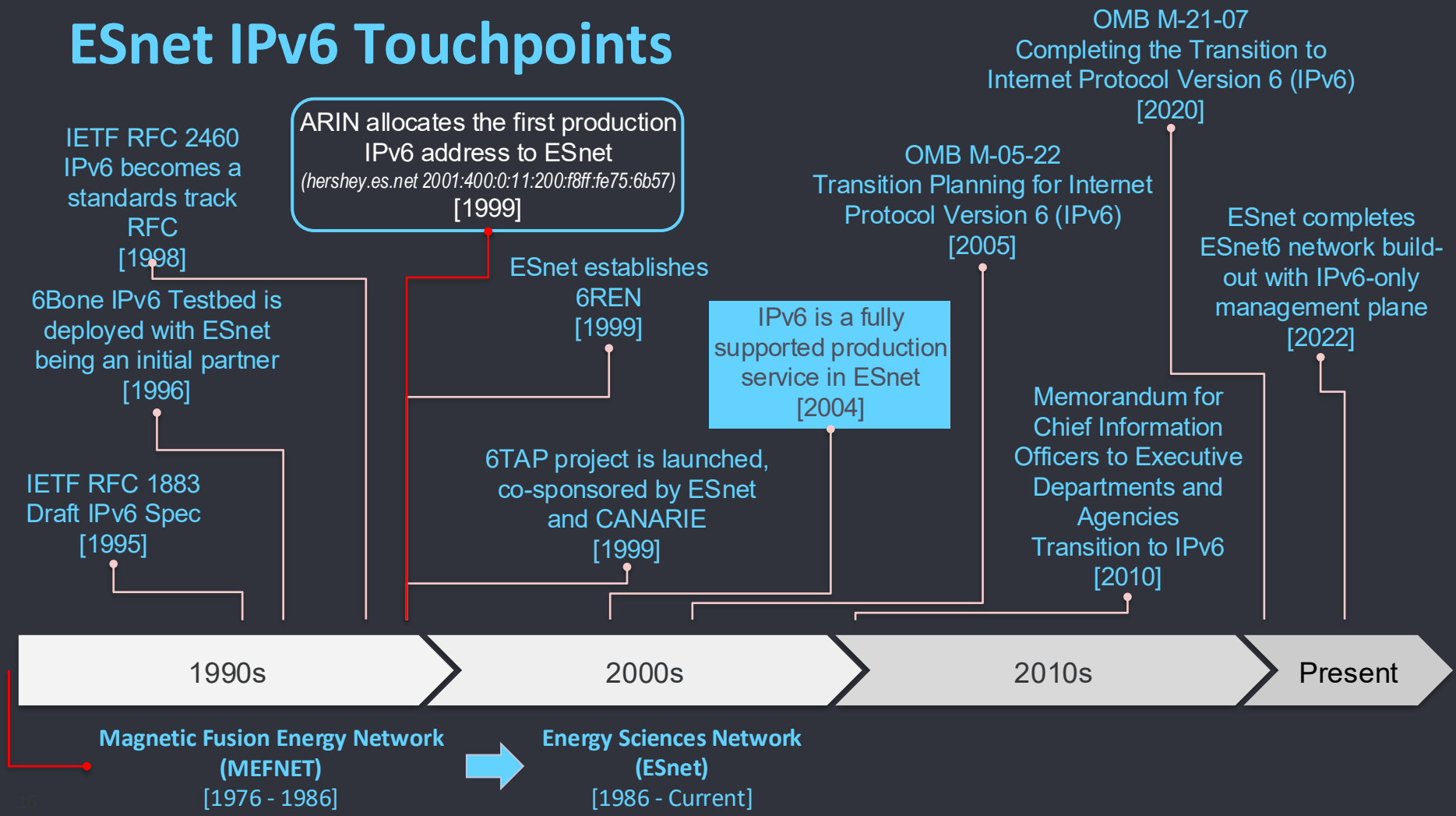

ESnet IPv6 Touchpoints

IETF RFC 2460
IPv6 becomes a standards track RFC
[1998]

ARIN allocates the first production IPv6 address to ESnet
(hershey.es.net 2001:400:0:11:200:f8ff:fe75:6b57)
[1999]

ESnet establishes 6REN
[1999]

IPv
suppor
servi

6REN Participants
circa July 1999

CAIRN (US)
Canarie (CA)
CERNET (CN)
Chungwa (TW)
ESnet (US)
Internet2 (US)
Renater/G6 (FR)
MCI/vBNS (US)
NTT (JP)
IPFnet (DE)
Sprint (US)
SURFnet (NL)
WIDE (JP)

6TAP project is launched,
sponsored by ESnet
[1999]

6REN – IPv6 Research & Education Networks

Overview and Introduction

In October of 1998, the Energy Sciences Network (ESnet) established a "6REN" initiative for promoting the introduction of IPv6 services into the production Internet. As ESnet is a US national-level "Research & Education Network", the focus was set on encouraging and helping Research & Education Networks worldwide to start providing IPv6 services.

Thus the 6ren is a voluntary coordination initiative of Research and Education Networks that provide production IPv6 transit service to facilitiate high quality, high performance, and operationally robust IPv6 networks.

Participation is free and open to all Research and Education Networks that provide IPv6 service. Other for-profit and not-for-profit IPv6 networks are also encouraged to participate.

Email from Bob Fink <fink@es.net>
Fri, 29 Jan 1999

1990s | 2000s | 2010s | Present

Magnetic Fusion Energy Network (MEFNET)
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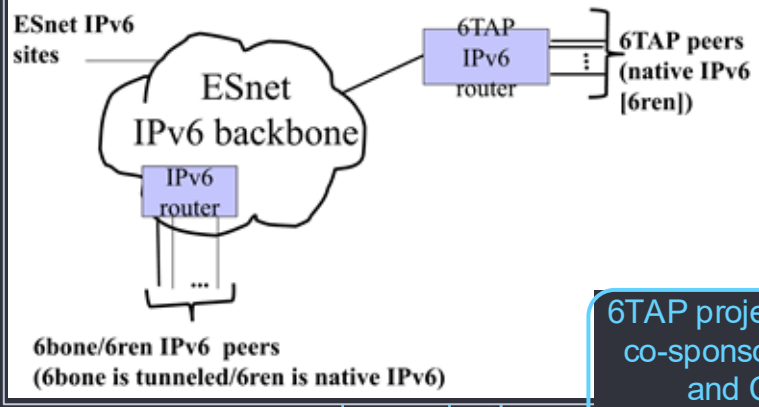
ESnet IPv6 Touchpoints

ESnet will provide IPv6 routing and transit between 6TAP peers and non 6TAP 6bone/6ren peers (as well as to ESnet sites).



[1995]

6TAP project is launched, co-sponsored by ESnet and CANARIE [1999]

IPv6 is a fully supported productic service in ESnet [2004]

6TAP

The 6TAP project, co-sponsored by ESnet and CANARIE, provides native and tunneled IPv6 interconnections at STAR TAP, to provide early IPv6 production networks the ability to build and demonstrate IPv6-based applications. 6TAP will develop: IPv6 route server technology, network tools for network measurement, analysis and display, and experience in supporting, provisioning and operating IPv6 Internet exchange points.

The 6TAP routers, route servers and net measurement / management systems are co-located with the STAR TAP switching systems to allow native router IPv6 interconnections to STAR TAP attached networks. The 6TAP became operational in July 1999, and is supported on a 24x7 operational basis by ESnet network operations staff at Lawrence Berkeley National Laboratory, USA.

Contact:
Bob Fink
ESnet / Lawrence Berkeley National Laboratory
fink @ es.net

Marc Blanchet
Viagenie / CANARIE
Marc.Blanchet @ viagenie.qc.ca

http://www.startap.net/startap/ENGINEERING/6tapInfo.html

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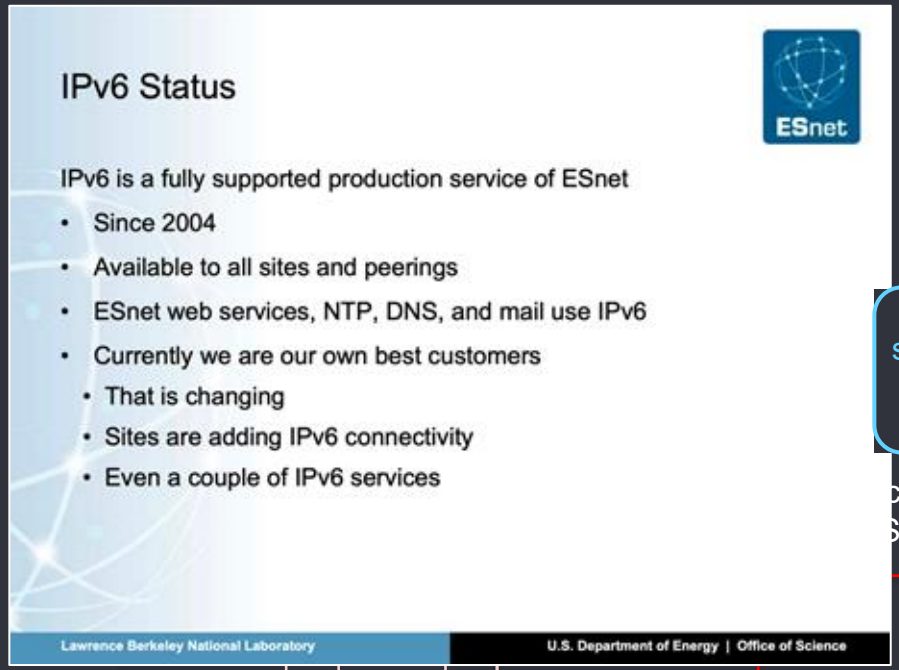

Slide from "IPv6 Implementation at a Service Provider Internet" presentation, 2010 Inter Agency IPv6 Information Exchange, August 2010

OMB M-21-07
Completing the Transition to Internet Protocol Version 6 (IPv6)
[2020]

OMB M-05-22
Transition Planning for Internet Protocol Version 6 (IPv6)
[2005]

ESnet completes ESnet6 network build-out with IPv6-only management plane
[2022]

IPv6 is a fully supported production service in ESnet
[2004]

Memorandum for Chief Information Officers to Executive Departments and Agencies
Transition to IPv6
[2010]

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Where are we now?

Dual Stack: A Transitional State

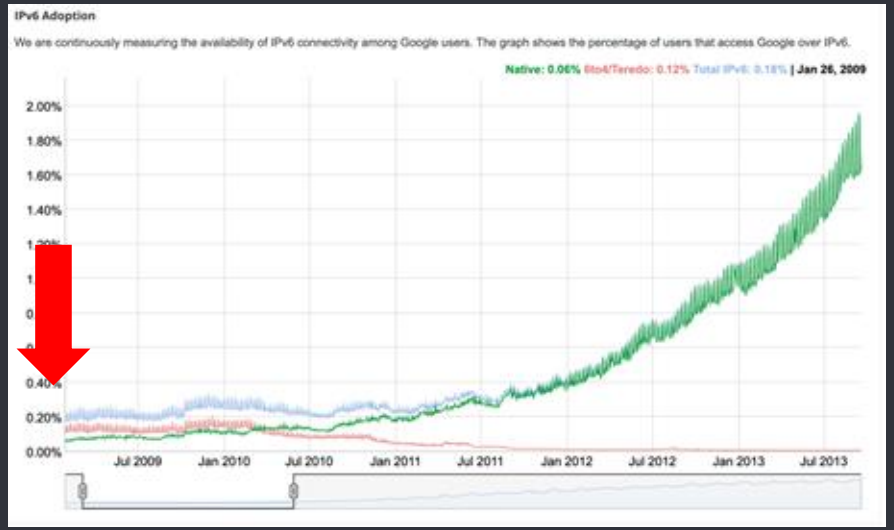
- RFC 3484 defines original source address selection algorithm
- Published in 2003(!)
- Defines IPv6 as preferred when available in a dual-stacked environment
- Replaced by RFC 6724 (soon to be replaced by RFC 6724-update)
- Augmented by Happy eyeballs
- Not intended to be a permanent solution

Dual Stack: A Transitional State

~2006 - 2020

Dual-stack operates as the de facto standard deployment model

Notable attention starting shortly before World IPv6 day (June 6, 2012)



Dual Stack: A Transitional State

So what does this really mean?

- IPv6 was being staged for success (albeit a long tail)
- “If you have both, use IPv6”

Unintended side effect:

- Dual stack may obfuscate significant issues
- It fails to IPv4 when IPv6 is broken
- Makes troubleshooting more complex (or hides need for it)
- Happy eyeballs do the same

Protocols Moving at the Speed of Science

- High energy physics research has long been moving to disable IPv4

Protocols Moving at the Speed of Science

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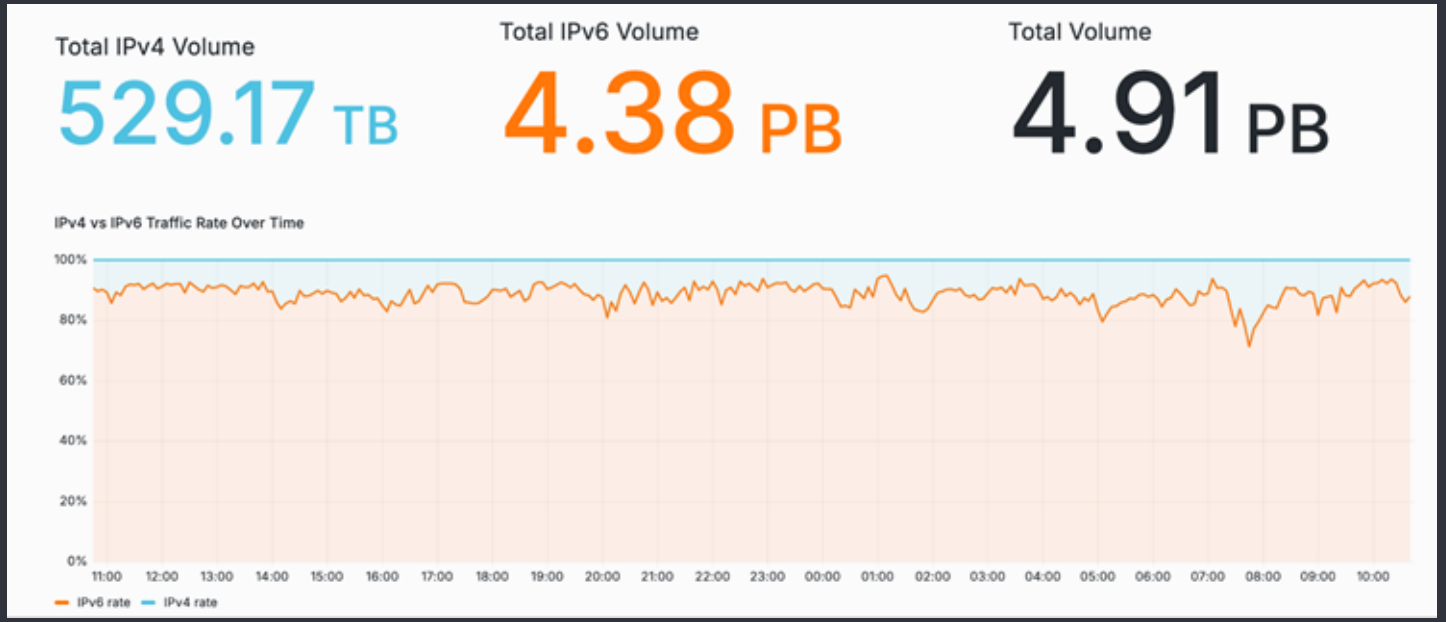


Protocols Moving at the Speed of Science

ALGT2 sites over last 24 months

IP Version	Rate	Total Volume
IPv6	31.5 Gb/s	124.2 PB
IPv4	1.3 Gb/s	5.1 PB

To boldly go….

November 19, 2020
OMB M-21-07 - “Completing the Transition to Internet Protocol Version 6 (IPv6)”
ESnet / DoE completes first IPv6-only pilot

But before that……

Leading the Way

IPv6-only management network

- As part of our current network deployment, we opted for an IPv6-only management network
- Predated the OMB Mandate
- Includes everything from the optical network to the management protocols
- Years long project
- Forced significant vendor engagement

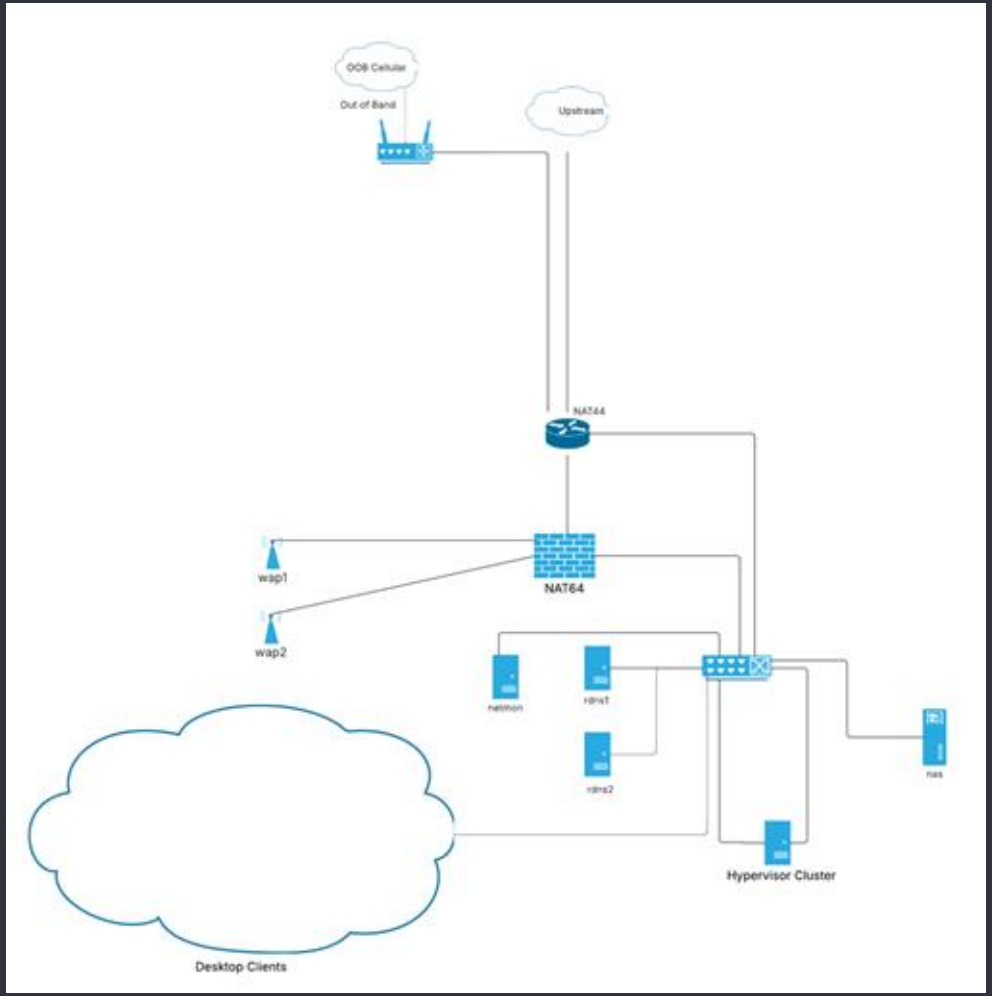
Ahead of the Curve

- When the OMB mandate was published we already had processes and tests for determining IPv6-only viability
- Positioned ESnet as a leader in the transition projects
- Left us well prepared to build the DoE IPv6-only pilot network
- More importantly - it showed us how to interact with both vendors and constituents / users

Ahead of the Curve

DoE IPv6-only Pilot 1

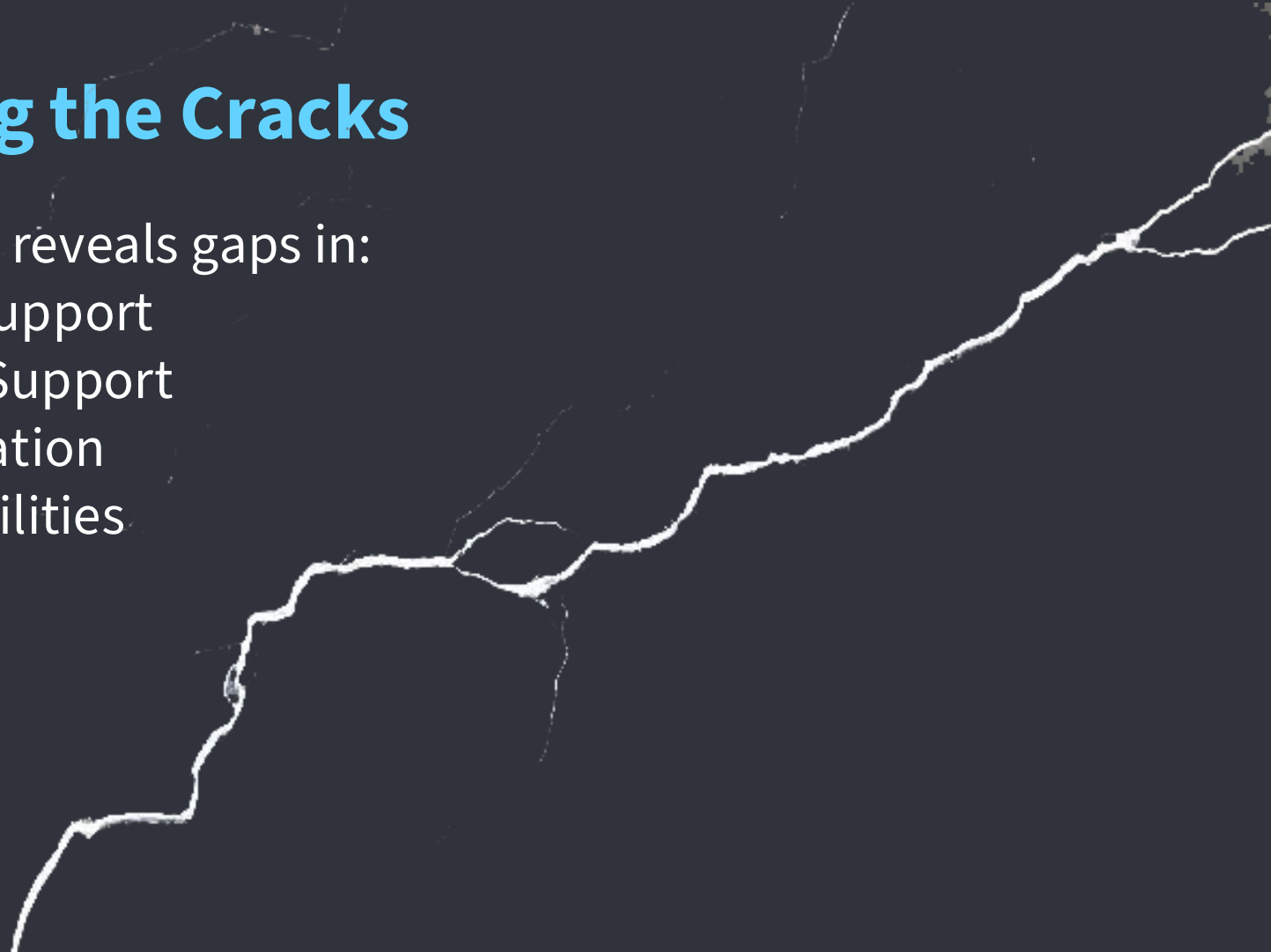
- Daily use office
- No dual stacked hosts
- NAT64/DNS64
- Predated CLAT on Non-mobile devices



Uncovering the Cracks

Removing IPv4 reveals gaps in:

- Software Support
- Hardware Support
- Documentation
- Tool capabilities
- Etc…



IPv6-only Data Centers

- Operationally lower overhead
  - Perfect for containerization / AI
  - Easy to provision “single use addresses” - IPv6 lends itself well to Zero Trust Architectures (ZTA)
  - Freedom from RFC1918 space
- Significantly less complexity
  - No compromises for address space
  - One set of policies
  - Little to no translation overhead when everything is IPv6

Gaps in Standards

- Work uncovered some necessary updates to standards
- RFC 6724 was in need of some eyes and some updates
- Need for operational guides for
  - IPv6-mostly
  - Neighbor Discovery Security
  - SRv6 Security
  - Translation Prefix Discovery
  - Definition of “IPv6-only”

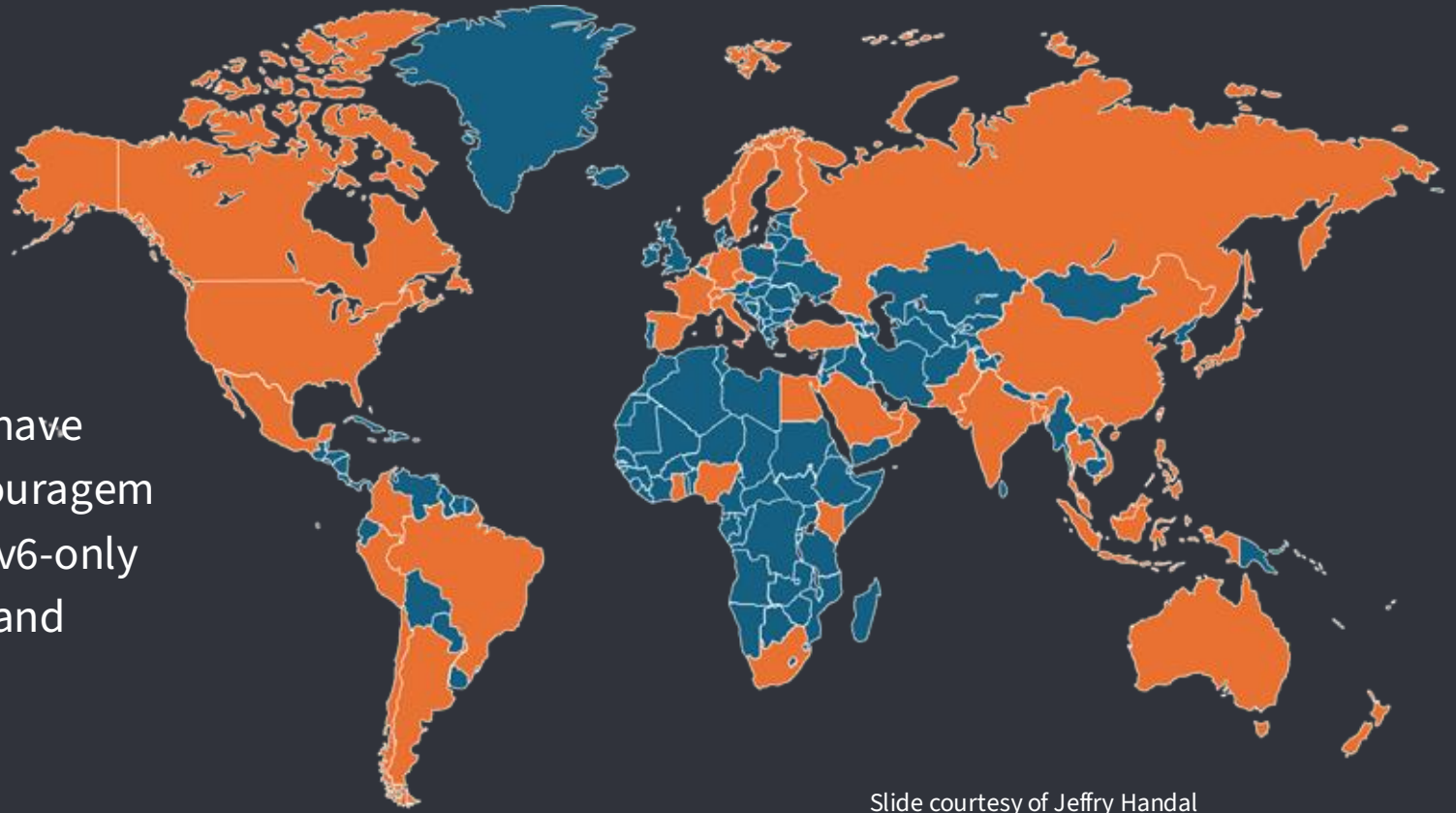
Where are we now?

- We still have work to do
  - Work with application developers to either defer to system preferences or explicitly support IPv6
  - Engage with vendors to reiterate the importance of IPv6 as a preferred protocol
  - Still a significant need for outreach and engagement with enterprises, users, service providers
  - Research and publish advantages of IPv6 as the preferred protocol

Where are *we* now?

- ~50% of global internet traffic overall is IPv6
- ~52% U.S. is traffic IPv6
- ~45% of internet traffic in Canada is IPv6
- ~80% of internet traffic in France is IPv6
- Mobile traffic is 50% more likely to be IPv6
- Enterprises remain the last frontier of IPv6 deployment

Where are *we* now?



50+ countries have mandate/encouragement for IPv6/IPv6-only between now and 2030+.

Slide courtesy of Jeffry Handal

Landing on All Fours

- **AI Agents are coming—and they will suffocate in a RFC1918 world**
  - The world needs a borderless, end-to-end v6-only architecture
  - The alternative is a 'Shadow Network' of overlays, that makes the network irrelevant (or dumb pipes).
- **Dual-stack is a *Schrödinger* trap, not a destination**
  - It doubles your complexity and masks broken connectivity
- **Complacency is the biggest bottleneck**
  - Software and vendors gaps get fixed when we force transition
- **Don't just support v6 quietly—prioritize it**
  - Share the lessons, plant your flag, lead the community
- **Next Step:** Start your first IPv6-only pilot this year!

..and stop herding v4 cats and start turning it OFF

What’s next?

- More evangelism
- More communication
- More education
- More uncovering of “cracks”
- More fixes
- Rince, repeat.

Thank you

And many thanks to ESnet contributors across decades
Thanks to Michael Sinatra and Dale Carder for content help with these slides