



# Next Generation Internet

## IPv6 and Beyond

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# Agenda

## Motivation

- ➔ The Internet – Paradigm & Reality
- ➔ The Limits of IPv4
- ➔ Internet Service Problems
- ➔ IPv6 Highlights

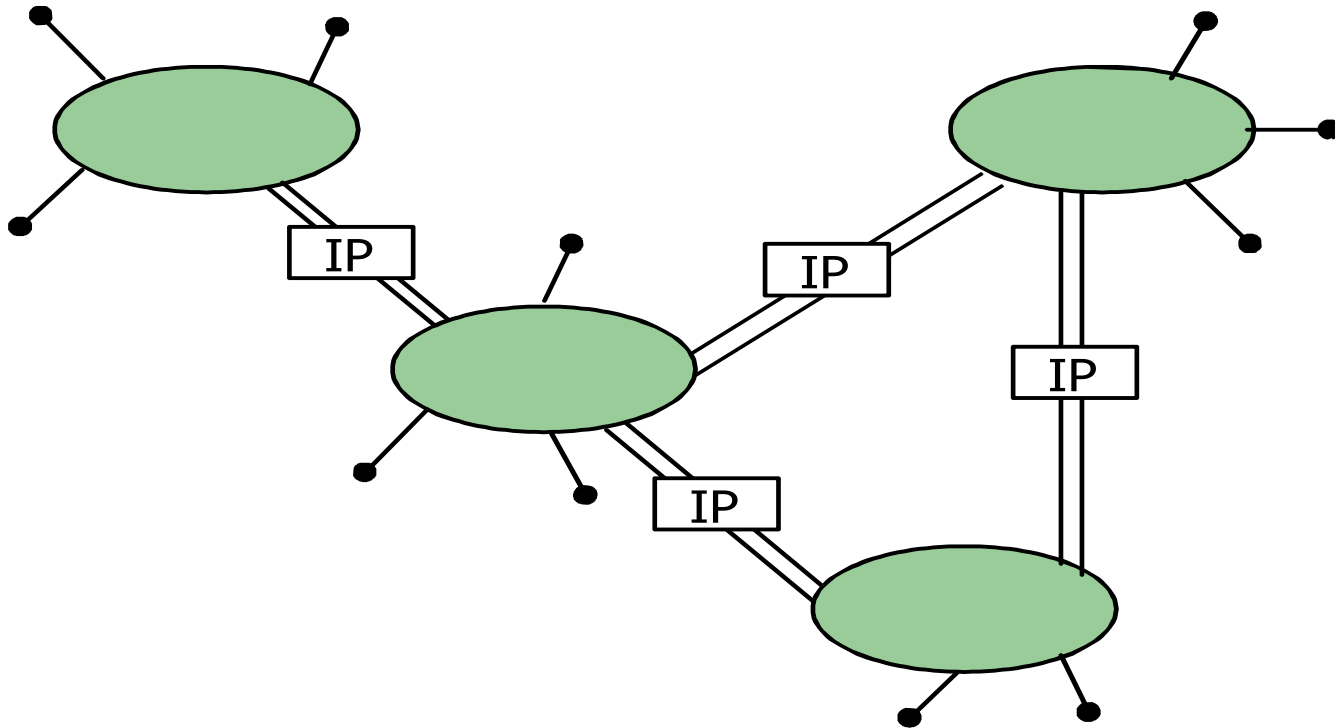
## Basic IPv6 Architecture

## IPv6 Migration: Transition and Coexistence

## Future Trends: Beyond IPv6



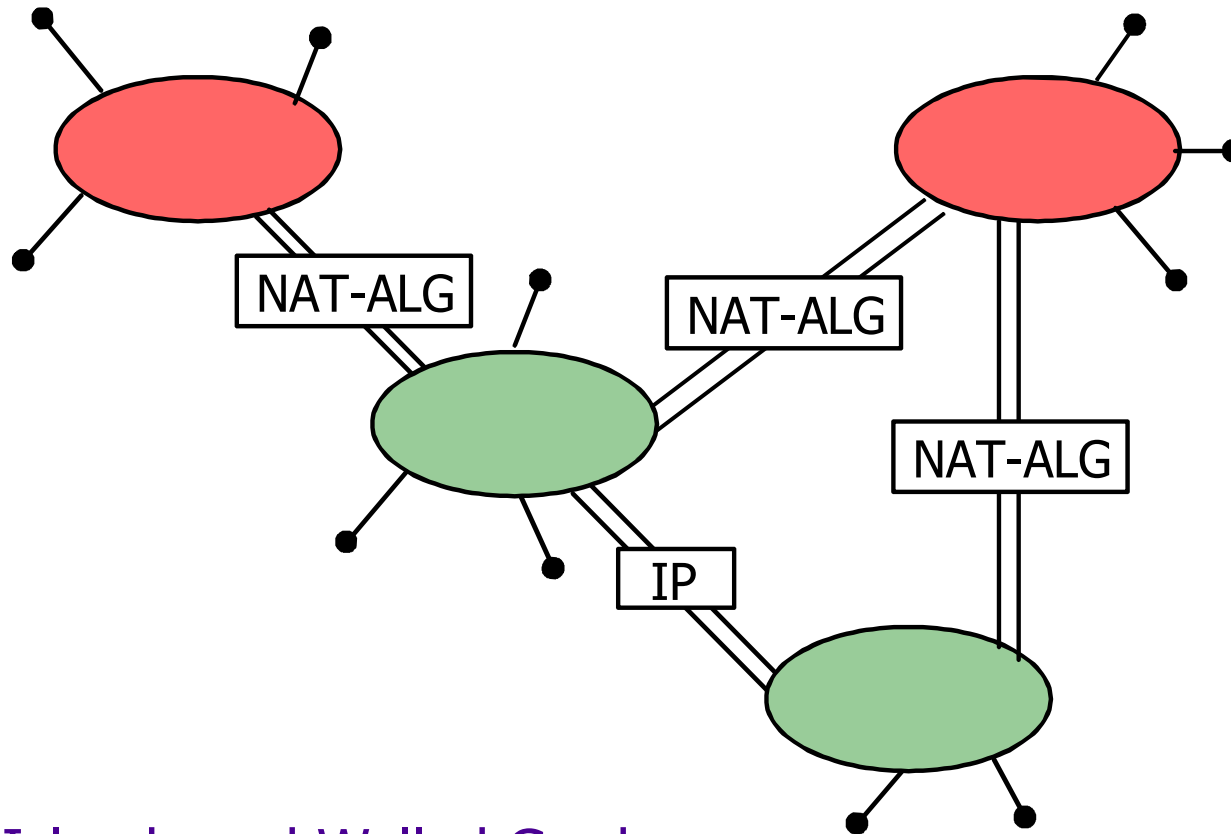
# The Internet: Original Paradigm



One **End-to-End** Internet-Layer

- Global addressing
- Simple, application independent, transparent
- Stateless, application independent gateways

# The Internet Today



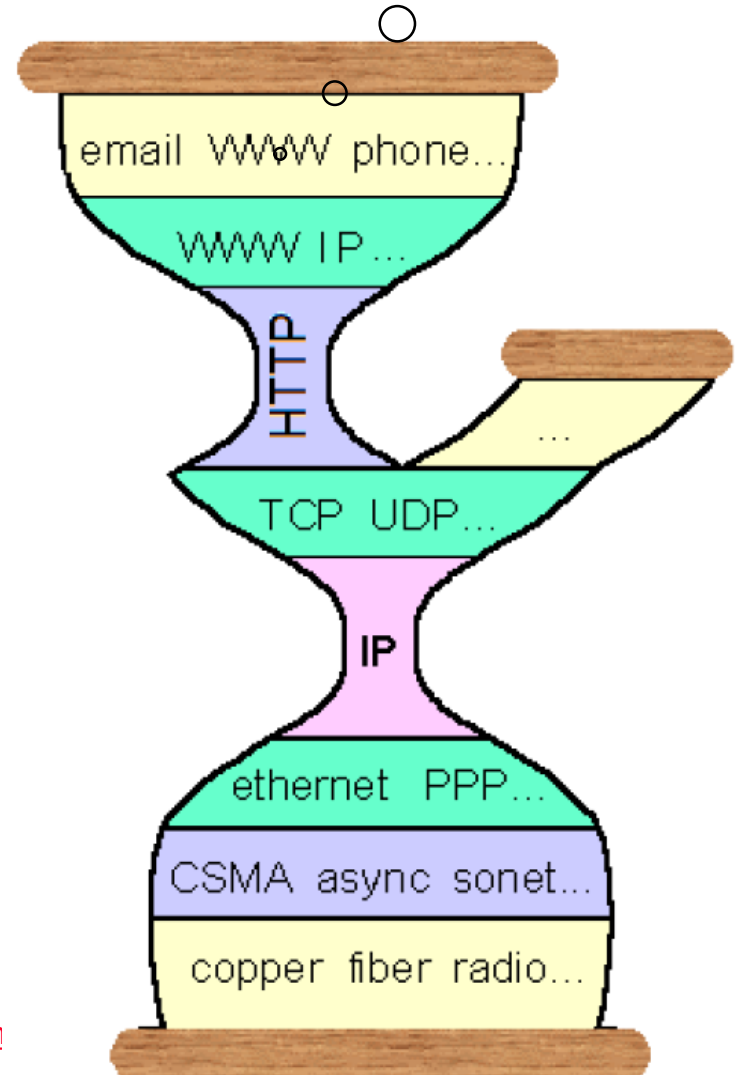
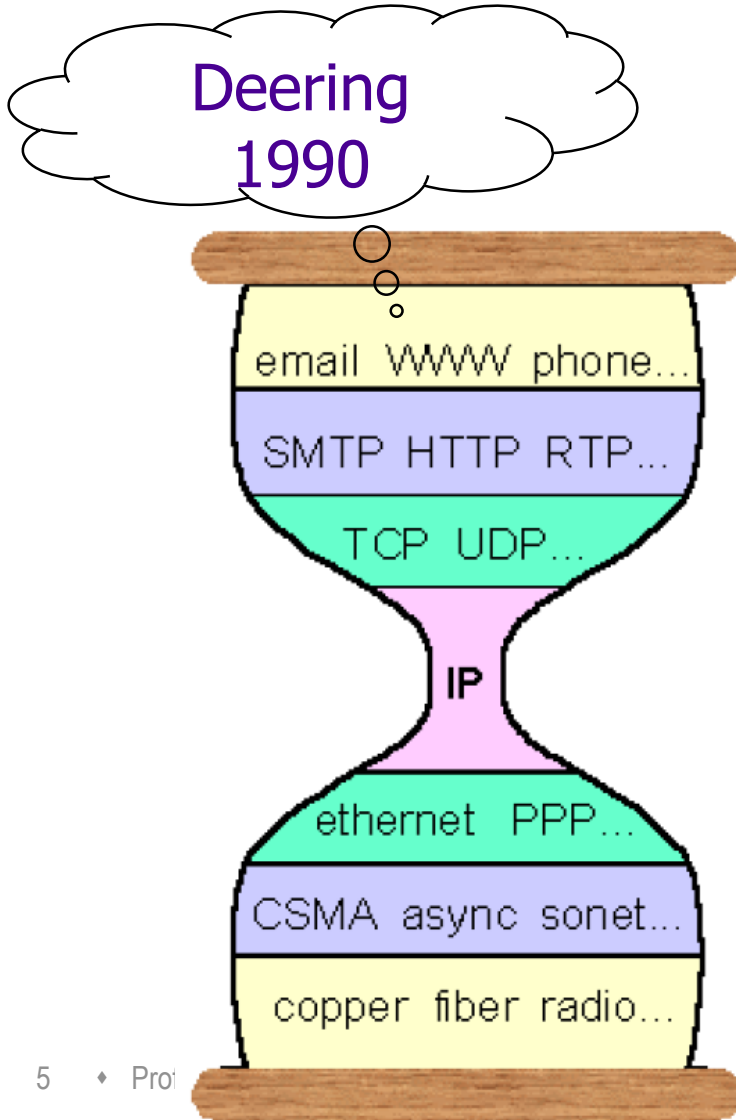
## Private Islands and Walled Gardens

- No global addressing, **NAT Application-Layer Gateways**
- Statefull gateways for selected applications



# Distortion of the IP Model (Deering/Rosenberg)

Rosenberg  
2008

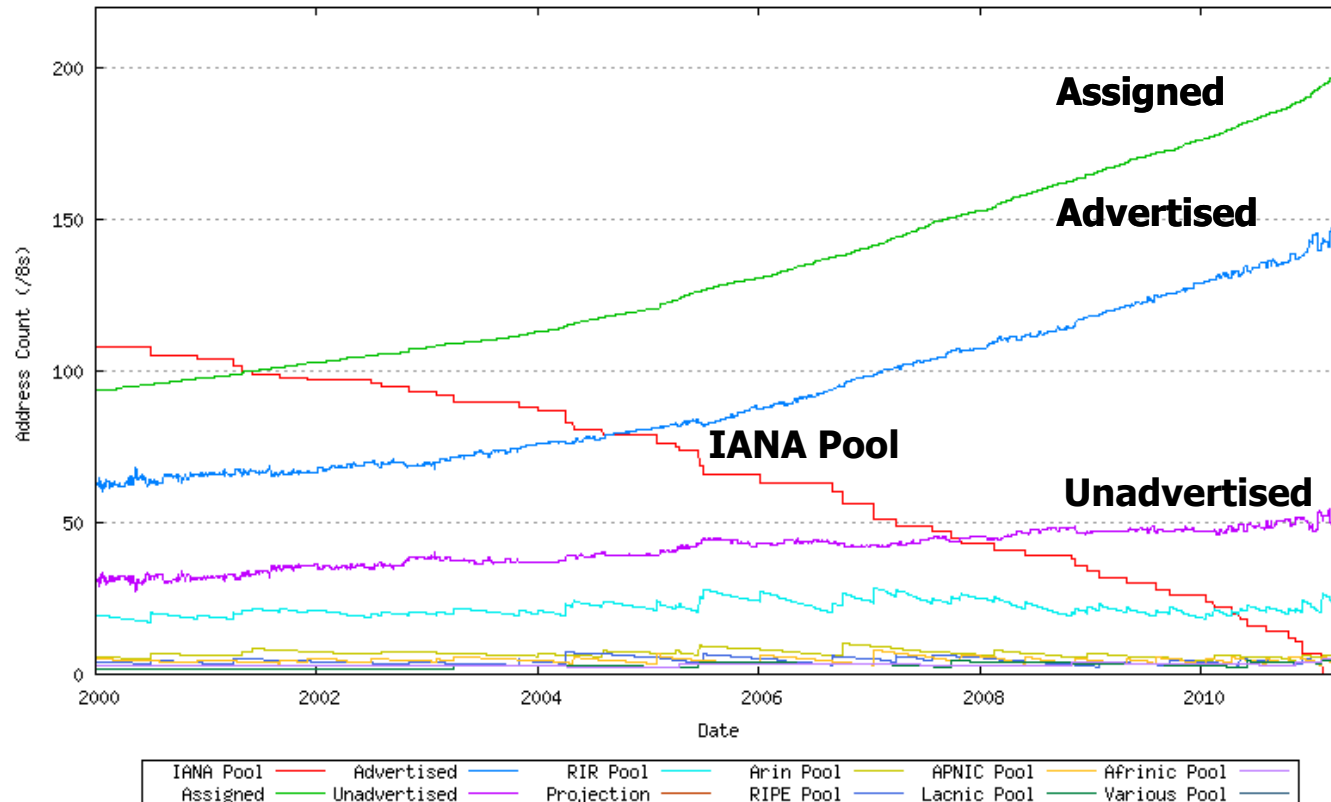


# The Limits of IPv4

- o Basic design almost 40 years old
  - Packet format ... outdated
  - Hardware development of networks overran IP algorithms
- o Address space exhausted
  - ‚Regular‘ Internet growth runs out of addresses
  - New kinds of Internet devices (mobile telephones, intelligent devices,...) need new quantities of addresses
  - Caused by address bottle-neck: NAT-ALGs
- o Support of new services tedious to implement

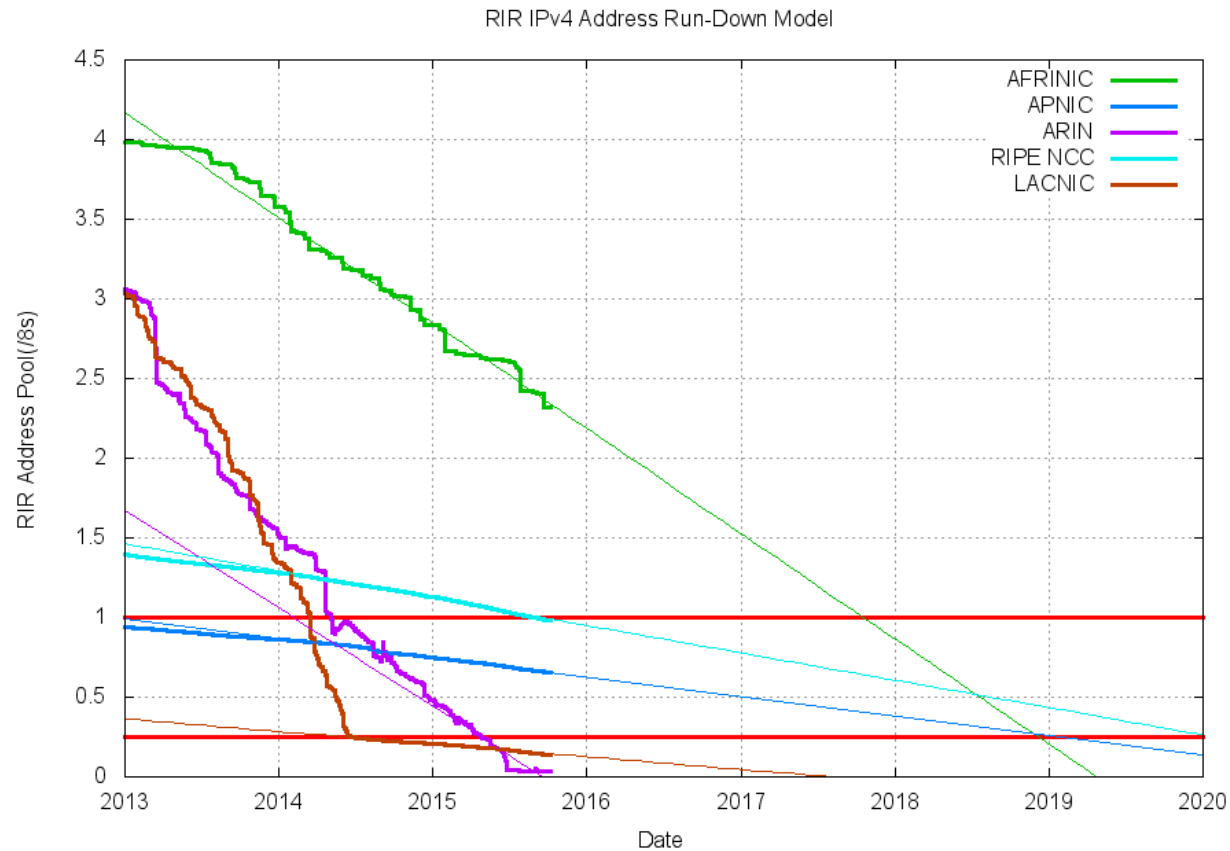


# Predicted IPv4 Address Exhaustion



- o IANA Unallocated Address Pool Exhaustion: 03-Feb-2011
  - o Projected RIR Unallocated Address Pool Exhaustion: Apr-11 – Jul-14
- Source: Geoff Huston, <http://www.potaroo.net/tools/ipv4/> as of Apr. 2011

# IPv4 Address Exhaustion



o Arin Exhaustion: 24. Sept. 2015 – remaining NULL

Source: Geoff Huston, <http://www.potaroo.net/tools/ipv4/> as of Oct. 2015



# IP Service Problems

- o **Address configuration:** Static, not stateless
- o **Backbone Routing:** Table explosion due to unstructured addresses
- o **Security:** IP over IP tunnelling
- o **Multicasting:** Routing too complex
- o **Anycasting:** Application specific solutions
- o **QoS:** No flow support
- o **Mobility:** Identifier/locator problem - inefficient triangular tunnelling
- o **Multihoming:** Provider abstraction missing



# Why IPng: IPv6 + + + ?

- o Tackle the Internet scaling problem: Addressing & Routing
- o Return to openness for new services & future development
- o Evolve the architecture of the Internet
- o Meet new requirements of a 'business-critical' network
- o Avoid tedious patchwork to keep the Internet going



# IPv6 Innovations

## o Addressing and routing

- Elimination of address bottle-neck: 128 Bit addresses
- Address hierarchy can (was intended to) simplify backbone routing
- Several addresses per interface

## o Simple administration

- Autoconfiguration of interfaces without DHCPv6
- Floating net masks, renumbering via prefix change

## o Security: IPSec

- Security header extension for authentication, integrity and encryption



# IPv6 Innovations (2)

## o Protocol architecture

- Slim, fixed header for fast processing
- Optional extension headers
- Format framework for header classes
- No header checksum
- No fragmentation in routers

## o Improved multicast, anycast, QoS and mobile services

## o Support of Jumbograms (> 64 KB)

## o Transition and coexistence concept IPv4 ↔ IPv6



# IPv6 History

- o IETF WG IPng began to work in the early 90er
- o Winter 1992: 7 proposals for development of IP
  - CNAT, IP Encaps, Nimrod, Simple CLNP, PIP, SIP, TP/IX
- o Autumn 1993: several mergers lead to
  - 'Simple Internet Protocol Plus' (SIPP) and 'Common Architecture for the Internet' CATNIP
- o July 1994: IPng Area Director recommend roadmap (RFC 1752) on basis of SIPP (Steve Deering)
- o Dec. 1995: S. Deering, R. Hinden, „Internet Protocol, Version 6 (IPv6) Specification“ (RFC 1883, now RFC 2460)
- o July 1999: End user addresses available (RIPE-NCC, APNIC, ARIN)
- o May 2007: ARIN advises Internet Community on Migration to IPv6

# IPv6 Standardisation

- o Key components in standard track:

Specification (RFC2460) Neighbour Discovery (RFC2461)

ICMPv6 (RFC2463)

IPv6 Addresses (RFC1884 ++)

RIP (RFC2080)

BGP (RFC2545)

IGMPv6 (RFC2710)

OSPF (RFC2740)

Router Alert (RFC2711)

Jumbograms (RFC2675)

Auto configuration (RFC2462)

....

- o IPv6 over: PPP (RFC2023)

Ethernet (RFC2464)

FDDI (RFC2467)

Token Ring (RFC2470)

NBMA(RFC2491)

ATM (RFC2492)

Frame Relay (RFC2590)

ARCnet (RFC2549)

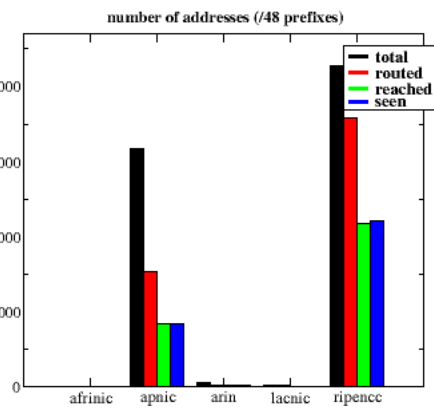
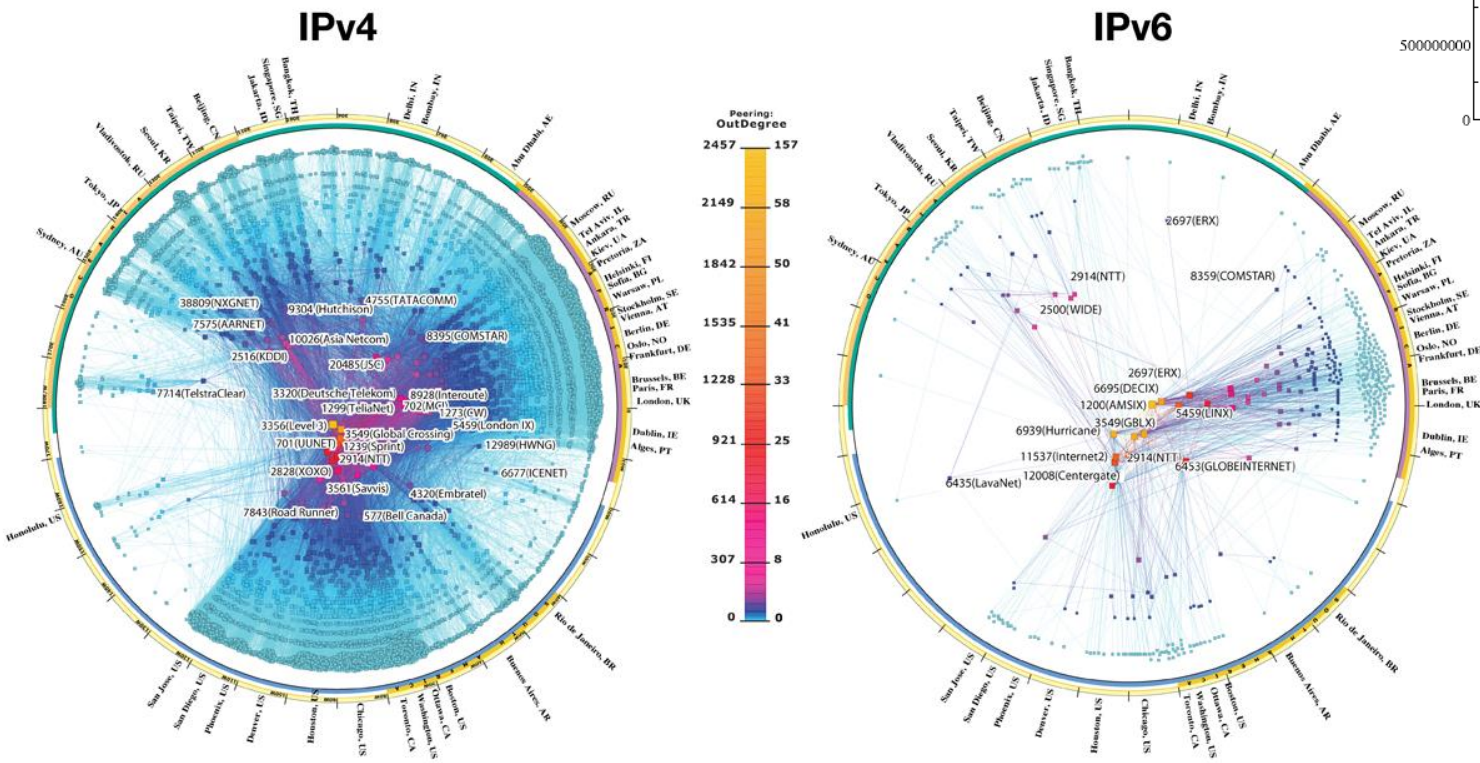
- o Since then 100++ further standards: Flow labelling, MIPv6, 3GPP, Routing advertisement, ....

- o Implemented basically in every Internetworking system platform



# IPv4 & IPv6 INTERNET TOPOLOGY MAP JANUARY 2009

## AS-level INTERNET GRAPH



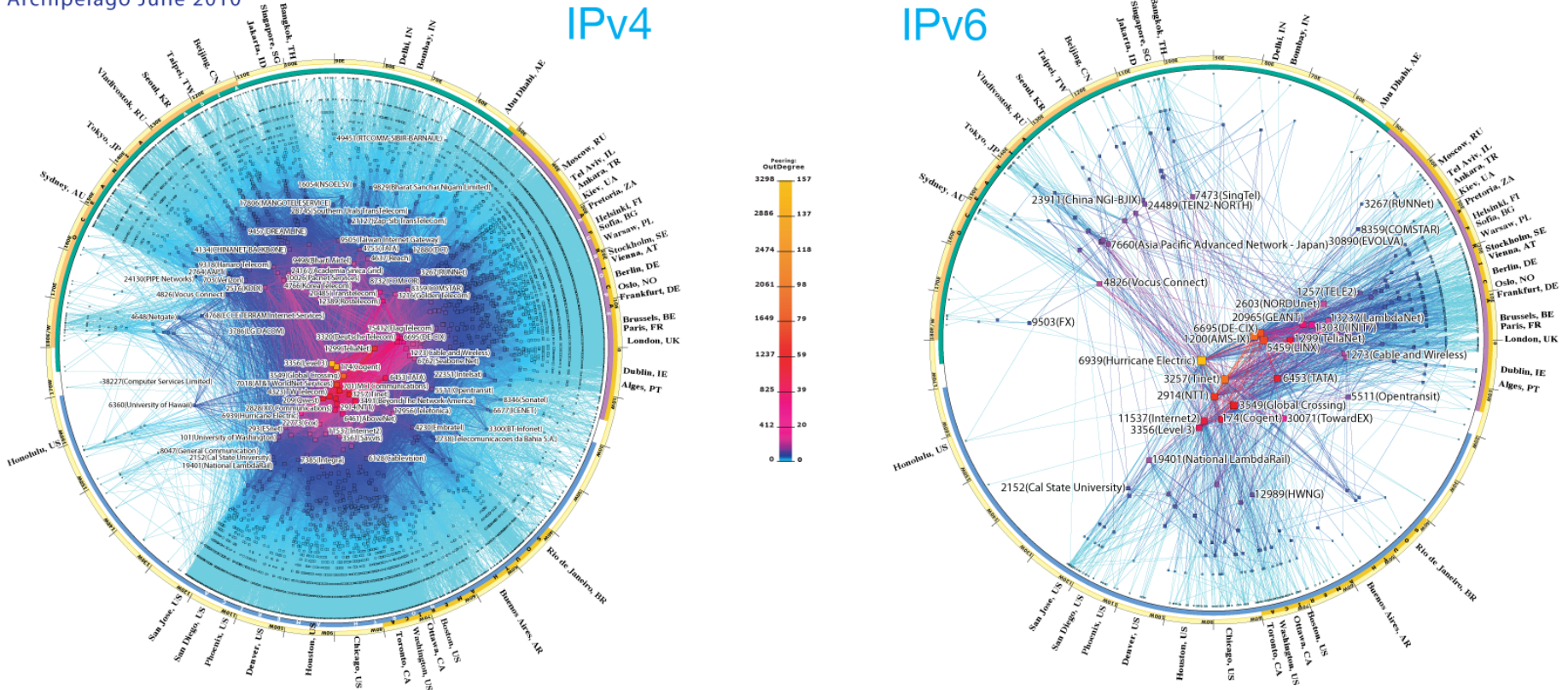
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o Source: CAIDA  
[http://www.caida.org/research/topology/as\\_core\\_network/ipv6.xml](http://www.caida.org/research/topology/as_core_network/ipv6.xml)

# IPv6 Deployment Progress June '10

## CAIDA's IPv4 & IPv6 AS Core AS-level INTERNET GRAPH

Archipelago June 2010



o Source: CAIDA

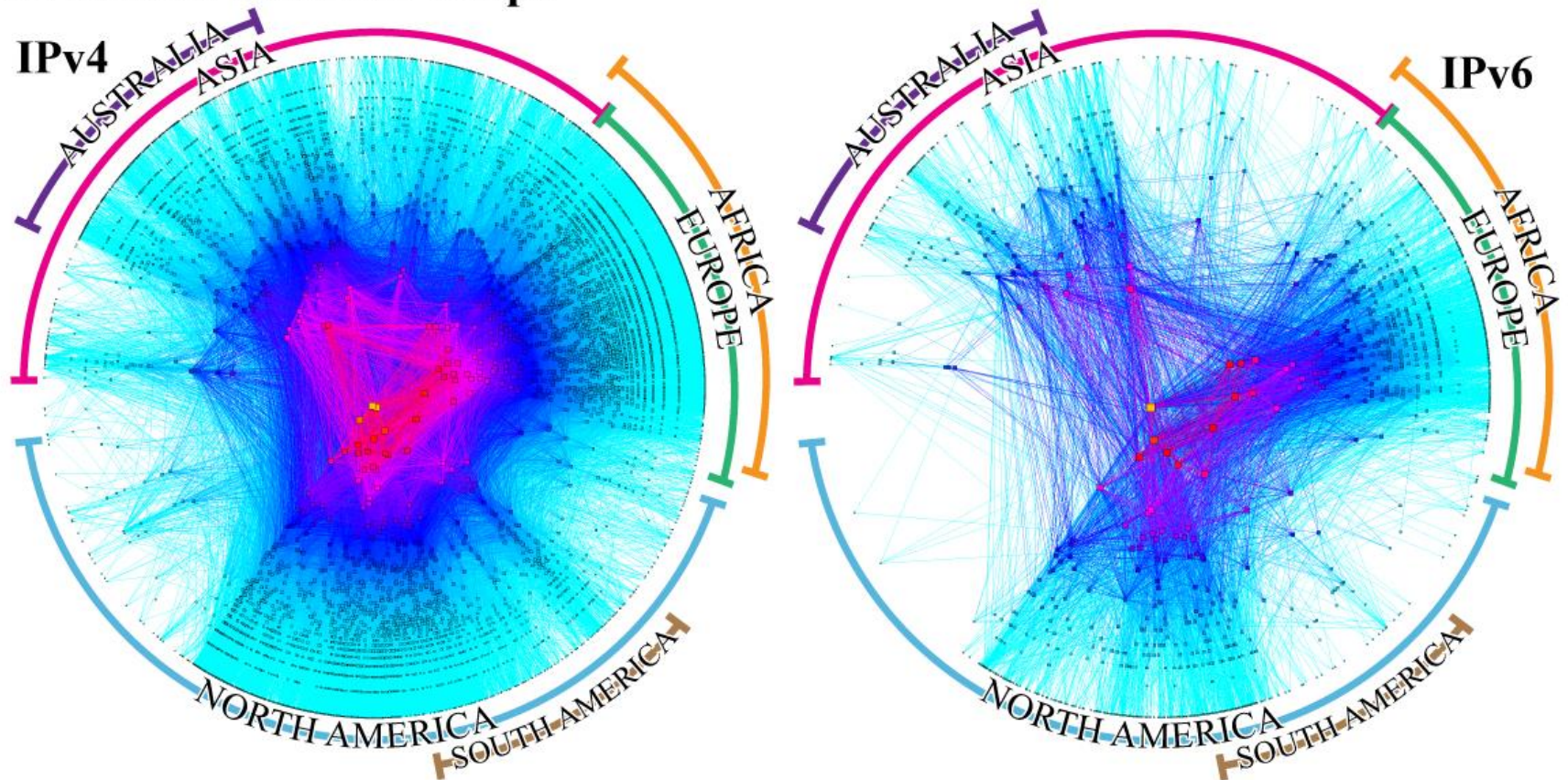
([http://www.caida.org/research/topology/as\\_core\\_network/ipv6.xml](http://www.caida.org/research/topology/as_core_network/ipv6.xml))



# IPv6 Deployment Progress Jan '13

CAIDA's IPv4 & IPv6 AS Core  
AS-level INTERNET Graph

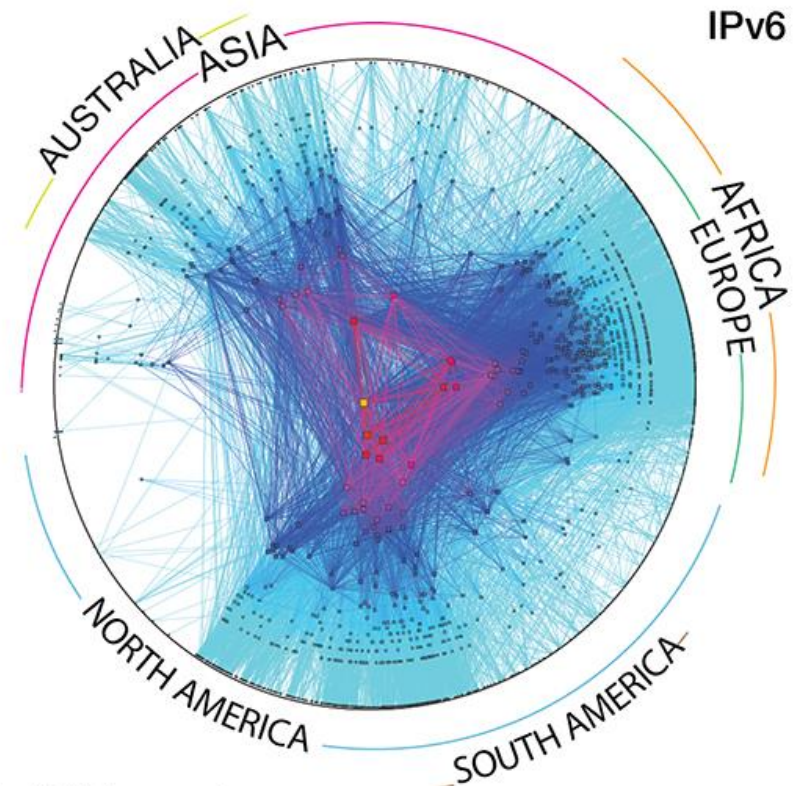
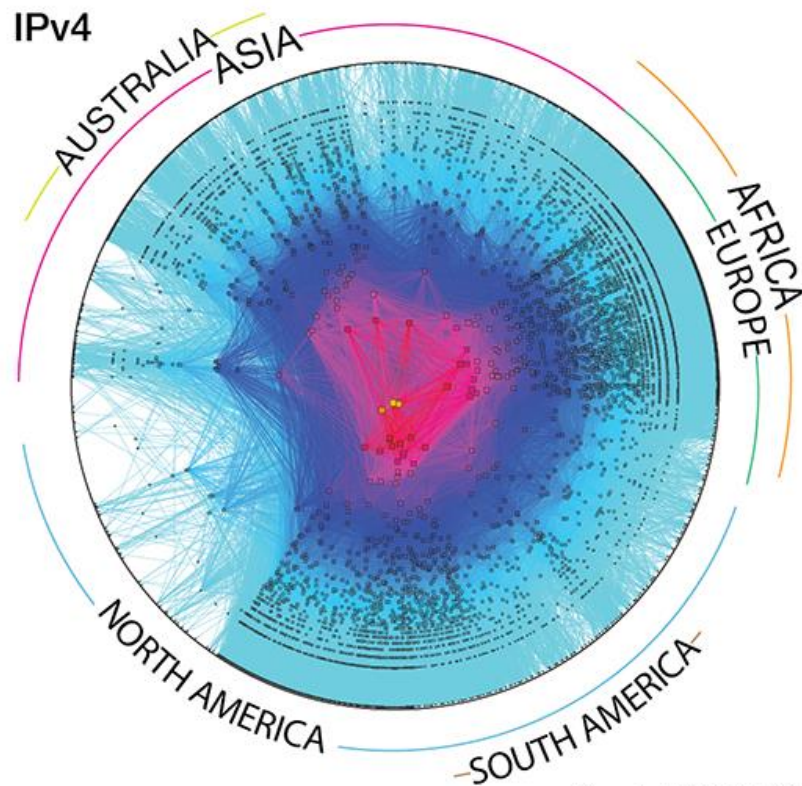
Archipelago  
Jan 2013



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# IPv6 Deployment Progress Jan '14

CAIDA's IPv4 & IPv6 AS Core  
AS-level INTERNET Graph  
*Archipelago January 2014*

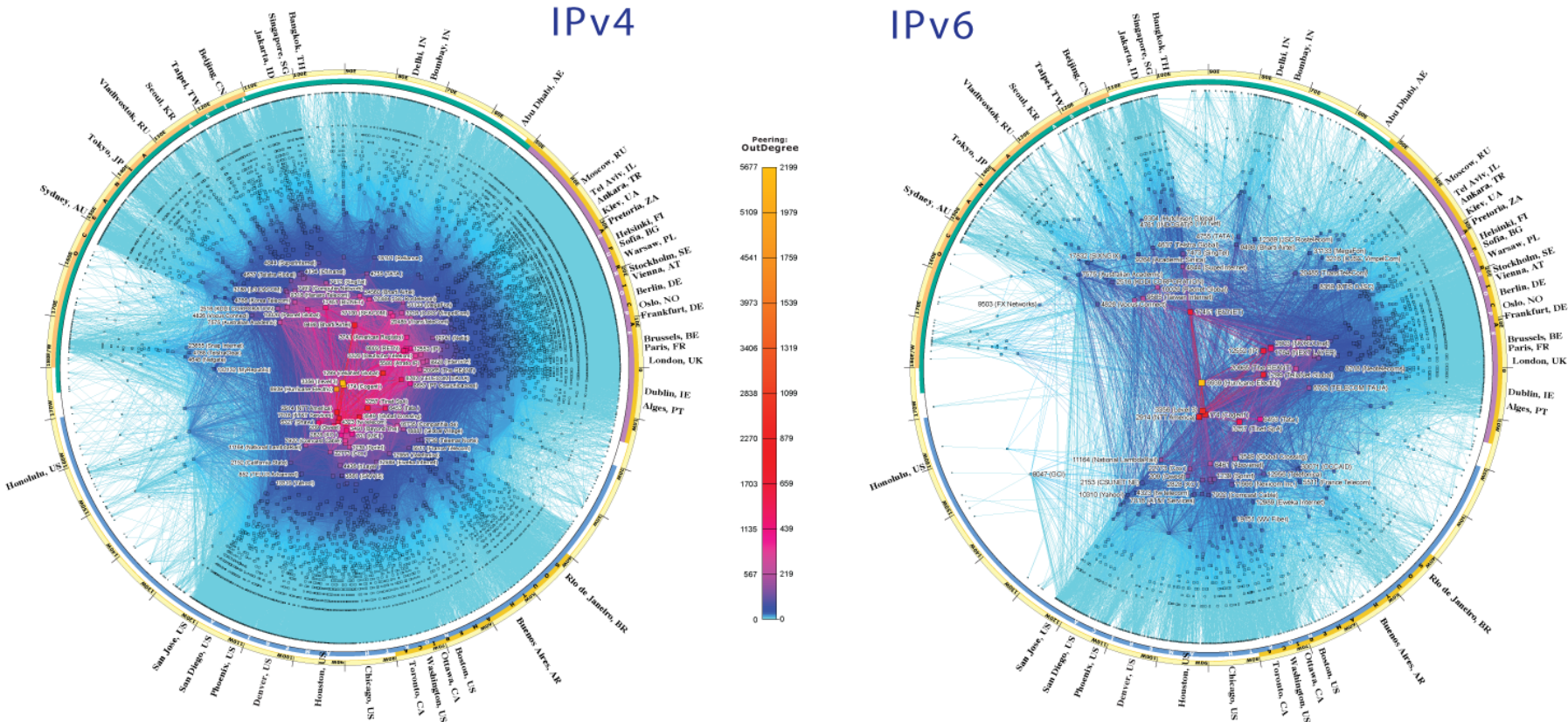


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# IPv6 Deployment Progress Jan '15

## CAIDA's IPv4 & IPv6 AS Core AS-level INTERNET GRAPH

Archipelago January 2015



# Agenda

- 🕒 Motivation
- 🕒 Basic IPv6 Architecture
  - ➔ Addressing
  - ➔ Packet Format
  - ➔ ICMP, Neighbour Discovery, Autoconfiguration
  - ➔ Routing, Anycasting, QoS, Multihoming
- 🕒 IPv6 Migration: Transition and Coexistence
- 🕒 Future Trends: Beyond IPv6



# Addressing

- o IPv6 addresses are 128-bit long and variably built
- o Address architecture: RFC 1884, now 4291 (Feb '06, Hinden & Deering)
- o Automatic address configuration
- o **Global address hierarchy** from top level allocation to the interface-ID designated
- o **Aggregation-based allocation** to simplify the global routing (target objective)
- o **Format prefix (FP)** (3 Bit initially) used for identification of address type



# Notation of IPv6 Addresses

- o **Standard form:** 8 x 16 bit hexadecimal  
Example: 1080:0:FF:0:8:800:200C:417A
- o **Short form:** sequences of nulls replaced by ::  
Example: FF01:0:0:0:0:0:0:43 → FF01::43
- o **IPv4 compatible addresses:**  
Example: 0:0:0:0:0:FFFF:13.1.68.3 → ::FFFF:13.1.68.3
- o **CIDR notation for prefixes:**  
Example: 1080:645:FF::/48

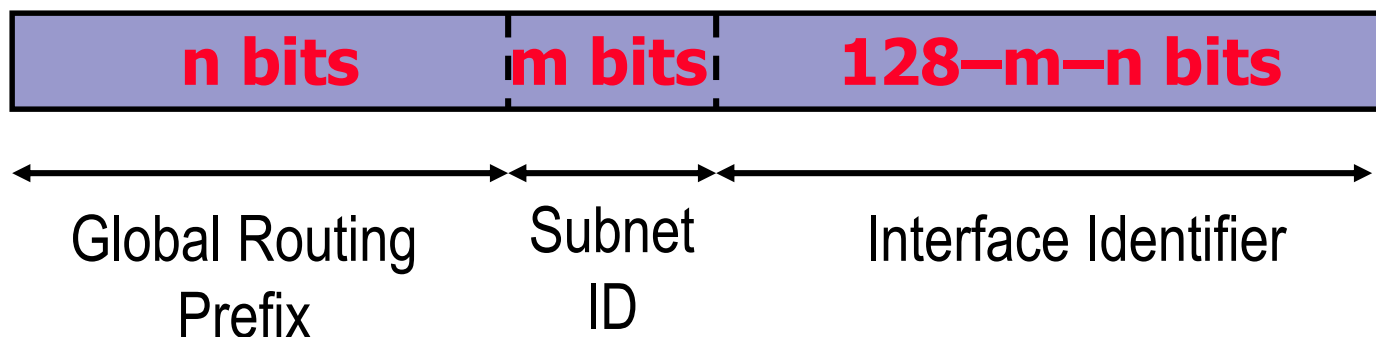


# Address Types

<u>Type</u>	<u>Binary Prefix</u>
o Unicast (one-to-one)	
- global	all not specified elsewhere
- site-local (deprecated)	1111 1110 11 (FEC0::/10)
- unique local (ULA)	1111 110 (FC00::/7)
- link-local	1111 1110 10 (FE80::/10)
- IPv4-mapped	000...0:FFFF (::FFFF:xxx.xxx.xxx.xxx)
- loopback	0000...1 (:::1/128)
- unspecified	0000...0 (:::/128)
o Multicast (one-to-many)	1111 1111 (FF00::/8)
o Anycast (one-to-nearest)	of Unicast Prefixes
o No broadcast addresses (only multicast)!	



# Global Unicast Addresses - RFC 4291

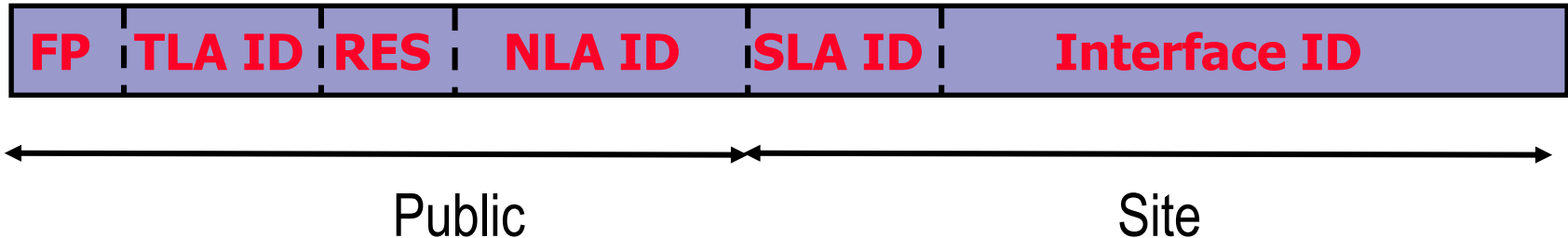


- o All fields have variable length and are not 'self-explanatory' (as of CIDR)
- o All global unicast addresses, which do not begin with 000 (binary), carry a **64 bit interface ID**, this means  $m + n = 64$
- o Mechanisms of automatic prefix exchange provided





# Historic – RFC2374: Aggregatable Global Unicast Format



- o Previous approach: Standardized prefix hierarchy as **Top/Next/Side Level Aggregator**
- o Current approach:
  - IAB/IESG Recommendations on IPv6 Address Allocations to Sites, RFC 3177
  - Left to RIR policies cf. <http://www.ripe.net/ripe/docs/ipv6policy.html>



# Local Unicast Addresses

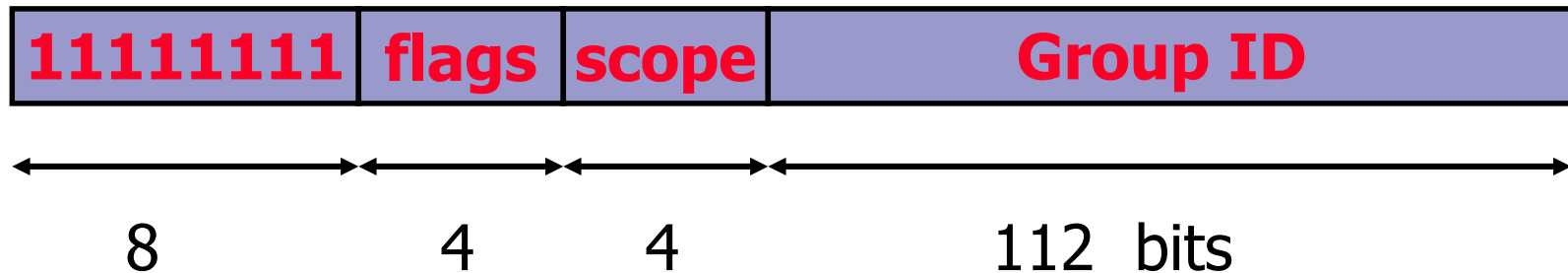
- o Link-local addresses for use during auto-configuration and in nets without routers:



- o Unique local addresses (RFC 4193), independent of TLA/NLA:
  - Globally unique for local communication, only (avoiding conflicts)
  - Not intended for global routing (but e.g., for dedicated site interconnects)



# Multicast Addresses



- o **Flag field:** lower bit indicates permanent (=0) respectively transient (=1) group, rest is reserved (==0)
- o **Scope field:**
  - 1 - node local
  - 2 - link-local
  - 5 - site-local
  - 8 - organisation local
  - B - community-local
  - E - global (other values reserved)



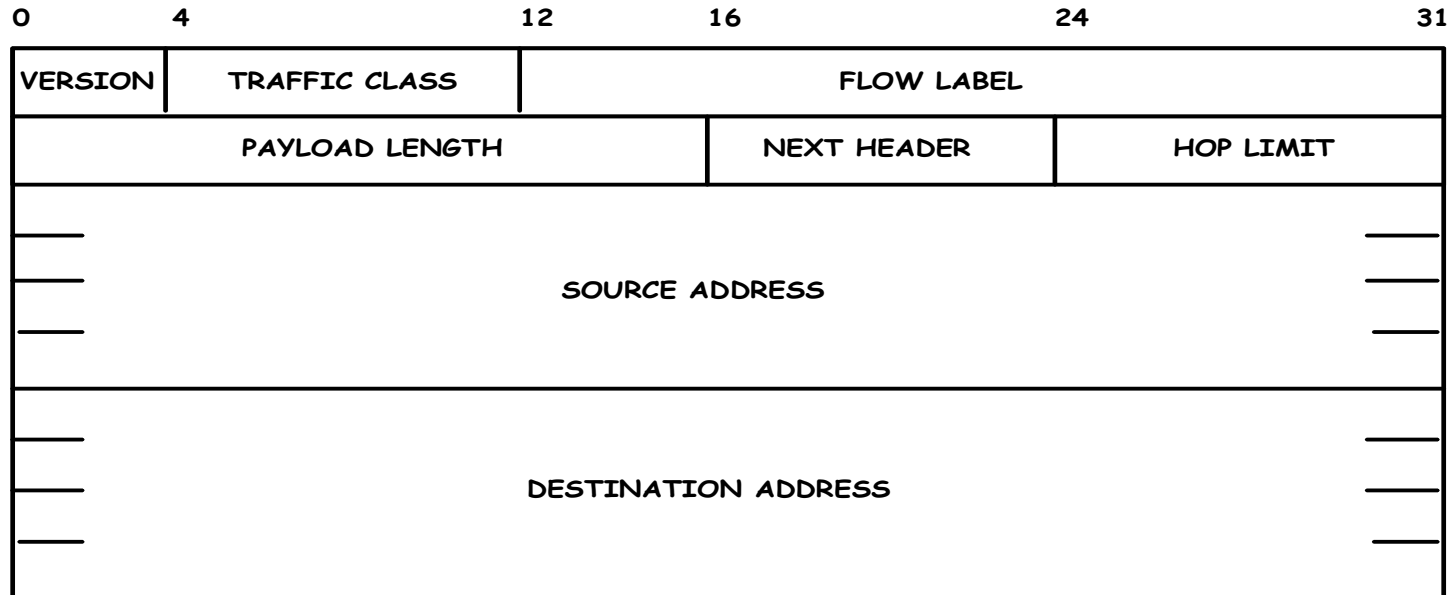
# Example: FHTW IPv6 Net

- 2001::**/16** - Pre-set prefix
- 2001:**0600**::**/24** - Regional registry Europa (RIPE)
- 2001:06**38**::**/32** - DFN prefix
- 2001:0638:**0801**::**/48** - FHTW net address
- 2001:0638:0801:**0001**::**/64** - First FHTW subnet
- 2001:0638:0801:0001:**0000:0000:0000:0001** /128
  - First IPv6 computer address at FHTW in 2001 😊

Addressing of Sub-TLAs (Ripe) according to RFC 2450



# IPv6 Packet Format: Basic Header



VERSION	4 Bit	Internet Protocol Version Number = 6
TRAFFIC CLASS	8 Bit	Type of Services (QoS DiffServ field)
FLOW LABEL	20 Bit	Flow Identification at Routers (QoS)
PAYLOAD LENGHT	16 Bit	Octetts of Payload without IPv6-Header
NEXT HEADER	8 Bit	Type of Encapsulated Protocol
HOP LIMIT	8 Bit	TTL-Counter, Decrementd per Router
SOURCE ADDRESS	128 Bit	Adress of Sender (128 Bits)
DESTINATION ADRESS	128 Bit	Adress of Receiver (128 Bits)

# Compare: IPv4 Header

## IP-Protocolkopf

1            4            8                            16    19                            24    32

Version	Länge	Servicetypen	Paketlänge			
Identifikation			D	M	Fragmenabstand	
			F	F		
Lebenszeit	Transport		Kopfprüfsumme			
Senderadresse						
Empfängeradresse						
Optionen					Füllzeichen	

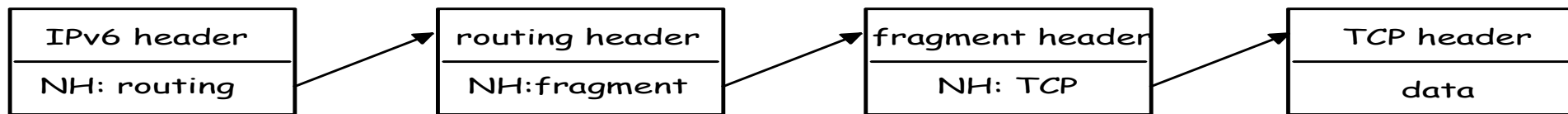
# Header Changes of IPv4

- o Addressing grows from 32 to 128 Bit
- o Fragmenting will be deleted from basis header
- o IP Options will be deleted from basis header → fixed length
- o Header Checksum drop out
- o Header length field drop out
- o Flow Label newly included
- o Time to Live → Hop Limit
- o Protocol → Next Header
- o Service types → Traffic Class
- o Length field describes data without header
- o Alignment increases from 32 to 64 Bit



# IPv6 Packet Format: Option Headers

- Extended option mechanisms: Each header references a possible successive header or data, e.g.:



- Option headers have no length limit (IPv4: 40 Octets), Padding to 8 Octets
- Option headers will be processed only at destination host, not by routers. Exception: **Hop-by-Hop** Option Header



# Basic Option Headers

- o **Routing**  
Advanced routing information (source routing)
- o **Fragmentation**  
Fragmentation / defragmentation information
- o **Authentication**  
Security information: authentication and integrity
- o **Encapsulation**  
,Tunnelling`, i.g. for confidential data
- o **Hop-by-Hop Option**  
Dedicated options to be processed by every router
- o **Destination Option**  
Information for the destination host (header extension)



# Order of Headers

The processing order of the headers will be arranged by the sender according to the following recommendation (RFC 2460):

1. IPv6
2. Hop-by-Hop Option
3. Destination Option (1)
4. Routing / Encapsulation
5. Fragmentation
6. Authentication
7. Destination Option (2)
8. Upper Layer




# Internet Control Message Protocol (ICMPv6)

- o RFC 2463 (Conta, Deering), now RFC 4443 + 4884
- o Extension header protocol class (following base IP header)
- o Defines two (expandable) message classes:

## Informational Messages

- Echo Request (128)
- Echo Reply (129)

## Error Messages

- Destination Unreachable (1)
- Packet Too Big (2)
- Time Exceeded (3)
- Parameter Problem (4) 

# IPv6 Neighbour Discovery

- o RFC 2461, now RFC 4861
- o Protocol over ICMPv6
  - Combination of IPv4 Protocols (ARP, ICMP,...)
- o Autonomous interaction between hosts and routers
  - Defines 5 ICMPv6 packet types:
    - Router Solicitation / Router Advertisement
    - Neighbour Solicitation / Neighbour Advertisement
    - Redirect



# IPv6 Neighbour Discovery (2)

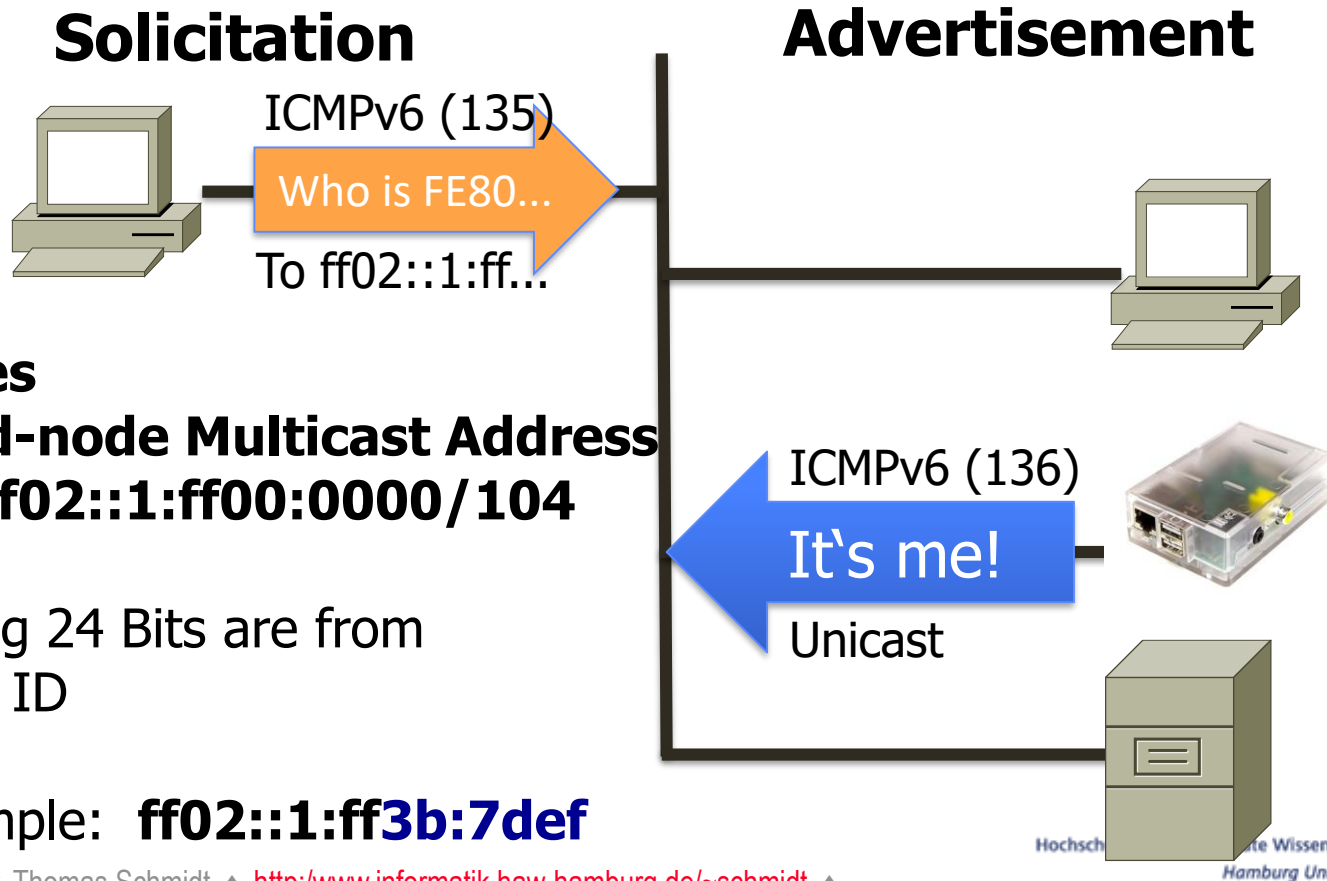
- o Defines communication mechanisms for nodes on the same link:
  - Router discovery
  - Prefix discovery
  - Parameter discovery, i.e.: link MTU, hop limit,...
  - Address auto-configuration
  - Address resolution (same function as ARP)
  - Next-hop determination
  - Neighbour unreachable detection (useful for default routers)
  - Duplicate address detection
  - Redirect
  - Network load balancing



# Neighbour Discovery Handshake

- Address of my neighbour?

Search **FE80::ba27:ebFF:FE3b:7def**64



**NDP uses  
Solicited-node Multicast Address  
Prefix: ff02::1:ff00:0000/104**

Remaining 24 Bits are from  
Interface ID

Our Example: **ff02::1:ff3b:7def**

# Stateless Auto-Configuration

1. Interface assigns a link-local address on activation (default: EUI-64 built from a hardware address).
2. Interface sends *router solicitation*, to omit waiting for router advertisements.
3. Router sends *router advertisement* (prefix, default gateway, ...).
4. The interface creates its global address from prefix and link-local address.
5. For verification of uniqueness, an ICMP *neighbour solicitation* will be issued on own address (Duplicate Address Detection).



# Secure Neighbour Discovery - SEND

- o RFC 3971 (Arkko et al.)
- o Employs Cryptographically Generated Addresses (CGAs – RFC 3972) to authenticate NDP (“prevent ARP spoofing”)
- o SEND ND messages can self-consistently authenticate its IP sender address (without PKI)
- o Router/prefix advertisements require certificates (X.509v3) from a PKI to assure routing responsibility

Details in  
MIPv6 Section





# Auto-Reconfiguration - Renumbering

- o New address-prefixes can be distributed and retreated:
  - Coexistence periods between old and new prefixes
  - Hosts learn prefix-lifecycle and priorities via router advertisements
  - Old TCP-connections survive within coexistence periods, new TCP-connections survive prefix change
- o Prefix-distribution via **router renumbering protocol**
- o DNS-Structure (AAAA) does not follow this flexibility.



# IPv6 DNS

Two approaches:

- o AAAA ("Quad A") Res. Rec. – RFC 1886, 3596

- A record type of 128 bit length
- Reverse lookup domain IP6.ARPA

- o A6 RR – RFC 2874

- Idea to support renumbering by prefix delegation
- A6 record contains a domain name pointer:

Prefix len.	Address suffix	Prefix name
-------------	----------------	-------------

- o IETF decided for AAAA – RFC 3363

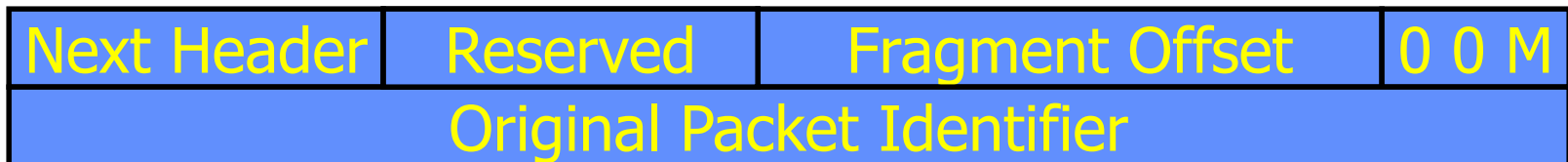


# MTU Handling

- The minimal **Link-MTU** for IPv6 is **1280 Bytes** (versus 68 Bytes for IPv4).
- **Path-MTU discovery:**
  - Repeatedly send packets with known path-MTU size until no more ICMP 'Packet-too-big' is received
  - necessary only for packets  $> 1280$  Bytes
- Minimal IP implementation can live without path-MTU discovery and without fragmentation (Packets  $\leq 1280$  Bytes).
- Upper Layer (TCP): **MSS**  $\leq$  MTU – 60.
- A Hop-by-Hop Option supports the execution of **Jumbograms** with sizes up to  $2^{32}$  Octets Payload.

# Fragmentation

- IPv6 avoids the expensive fragmentation process on routers. The sender has to fragment, if necessary.
- Sender should execute path-MTU discovery.
- Routers answer with ICMP „Packet too big“.
- IPv6 Fragmentation Header can be used to support upper layers without dynamically executing MTU-Discovery.



# Generic Packet Tunnelling of IPv6

- RFC 2473 (Conta, Deering)
- Mainly used for explicit routing path control
- Defines (statefull) end points:
  - Tunnel Entry-Point
  - Tunnel Exit-Point (at Unicast, Anycast or Multicast address)
- State variables contain MTU, Traffic Class, Flow Label
- Fragmentation may be necessary at tunnel entry point



# IPv6 Routing

- o Uses CIDR „longest prefix match“/ largest mask to go for.
- o Hierarchical addressing is a key issue for a scalable routing
  - VLSM route aggregation
  - Relies on provider-bound prefixes
- o Dynamical routing protocols from IPv4 updated:
  - Unicast: OSPF, RIP-II, BGP4+,...
  - Multicast: MLD, MOSPF, PIM, BIDIR-PIM ...
- o Can send packets through predefined regions by
  - routing headers (source routing) – type 0 deprecated (RFC 5095)
  - Anycast



# Example: BGP RIB Entry

```
TIME: 2008-7-1 02:36:49
TYPE: MSG_TABLE_DUMP/AFI_IP6
VIEW: 0 SEQUENCE: 2702
PREFIX: 2001:0638::/32
ORIGINATED: Mon Jun 30 10:29:18 2008
FROM: 2001:0418:0000:1000:0000:0000:0000:f000 AS2914
AS_PATH: 2914 3549 680
MULTI_EXIT_DISC: 1
COMMUNITIES: 2914:420 2914:2000 2914:3000
```

Inter-AS Link Metric  
Priorising redundant  
Interprovider Peerings

Routing Policy Group  
Groups type of propagation



# Anycast

- o Service to 'one out of many' , RFCs 4291, 4786
- o Addressing from unicast
  - Prefix must cover all group members (least common)
  - Reg. Global Unicast, but some reserved:
    - Subnet (RFC 2526): subnet router, MIPv6 home agent
    - RFC 3068: 6to4 relays anycast address
    - RFC 4610: anycast rendezvous point in PIM
- o Anycast Routing
  - Within IGP: Host routes (dynamic/static)
  - Globally: According to covering prefix, global Anycast ASNs



# Anycast (2)

## o There are transport issues with Anycast:

- Subsequent packets may not always reach the same peer
  - Source address may never be anycast, so a unicast address must be used in a response
- TCP and IPSec cause conflicts, UDP deployable

## o Today's deployment:

- Use for routers only
- Local / regional configuration
- DNS root servers
- 6-to-4 transition: Tunnel relay prefix 192.88.99.0/24
- Multicast: PIM rendezvous point anycast addressing + AMT

# IPv6 & QoS

Priority: Traffic Class Field (8 Bit) break down in two classes:

o Flow controlled traffic (0 - 7) – IPv4 compatible

0 Not specified

1 ‚Feeder‘ (i.g. netnews)

2 Unnoticed (i.g. email)

3 (Reserved)

4 Bulk (i.g. ftp, http)

5 (Reserved)

6 Interactive (i.g. telnet, X11)

7 Internet control (i.g. rip)

o Traffic without flow control (Realtime, Constant Bitrate, ...)

Priority from 8 to 15 (ascending)

o Remaining prioritisation according to DiffServ code points



# Flow Labels

20-bit Flow Labels can be used by senders or ingress routers to mark associated packets.

- o initial RFC 3697, now RFC 6437

- o Goal: accelerated, uniform handling of packet streams through routers

- o Flow label assignment: Random per Flow

- o Header information consistent per flow (router caching)

- o Initially defined router states, now stateless processing



# Multihoming

- o Goal: Redundant ISP connectivity for customers
  - o Problem space: Addressing & Routing
    - Using provider independent (PI) addresses prevents route aggregation
    - Using provider-bound addresses leaves administration to the end system domain
  - o Originally: No PIs in IPv6, but concept is broken
- ⇒ Threat of routing table explosion returned to IPv6

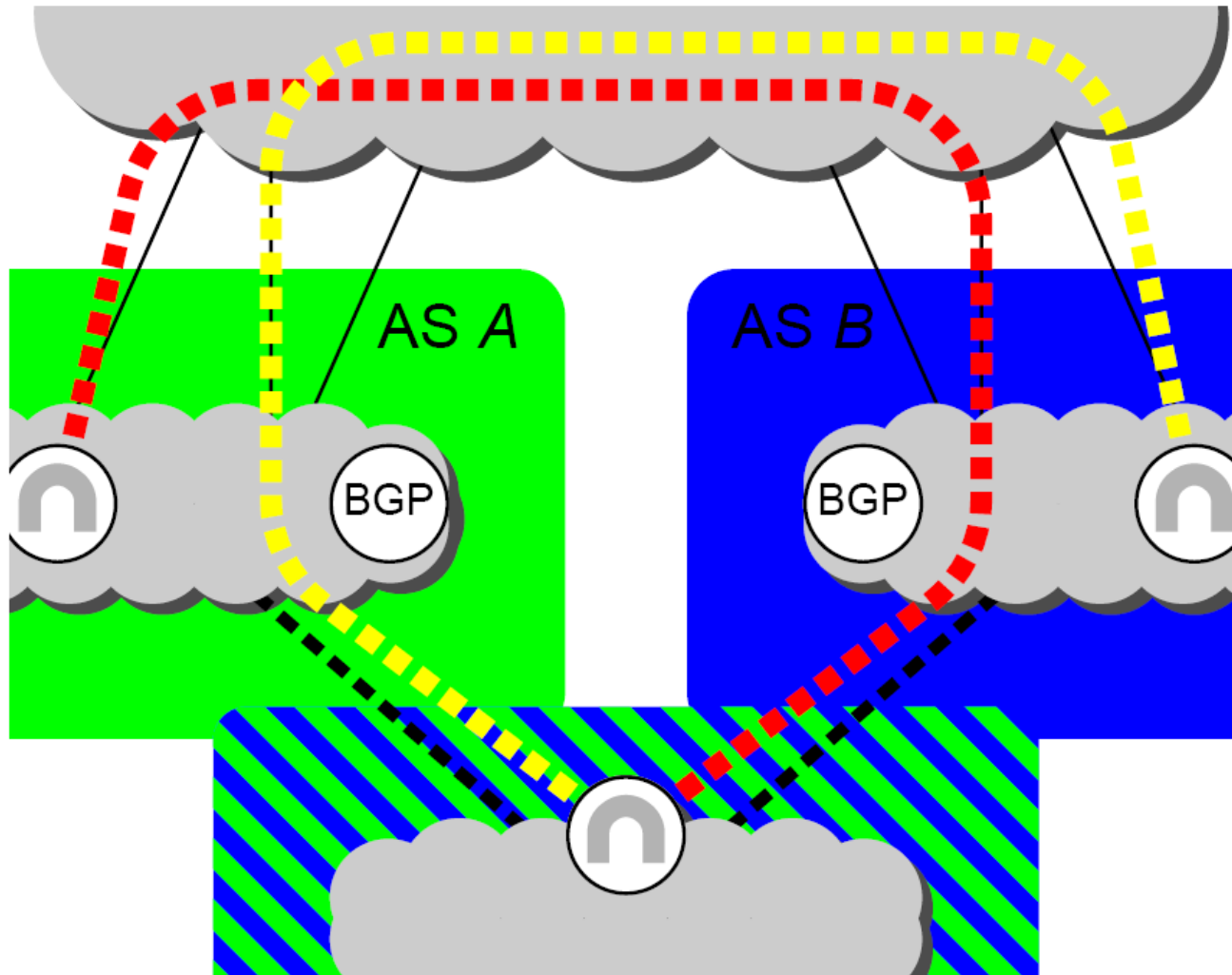


# Multihoming without PI

- o Two prefixes in end system domains
- o Solution at node level:
  - Multiple DNS entries
  - End systems must choose preferred/correct address
  - SHIM6 protocol: RFC 5533
- o Solution at network level
  - Need failover implementation in network
  - Typically: Own AS, BGP announcements
- o Continuous disturbing issue within the IETF



# Multihoming: Cooperative Redundant Connectivity



# Agenda

- 🕒 Motivation
- 🕒 Basic IPv6 Architecture
- 🕒 IPv6 Migration: Transition and Coexistence
  - ➔ Programming: IPv6 API
  - ➔ Dual Stack
  - ➔ Tunnelling
- 🕒 Future Trends: Beyond IPv6



# IPv4 → IPv6 Porting

- Source and binary code compatibility for existent application: 'all goes on', provided IPv4 is around
- Indirection for address data structure, new for IPv6:  
`addrinfo` is linked list of interface address structs
- Name-to-address translation:  
New functions to support IPv6 and IPv4
- Address conversion functions:  
New functions to support IPv6 and IPv4
- DNS resolver:  
Returns IPv6 or IPv4 address, or both
- Almost all standard (open source) applications ported



# IPv4 → IPv6 Porting: API Changes

	IPv4	IPv6	
Data structures	AF_INET	AF_INET6	
	in_addr sockaddr_in	in6_addr sockaddr_in6	
Address conversion functions	inet_aton() inet_addr()	inet_pton()	IPv4 and IPv6 functions
	inet_ntoa()	inet_ntop()	
Name-to-address functions	gethostbyname() gethostbyaddr()	getnameinfo() * getaddrinfo() *	

\* POSIX protocol independant functions

# IPv4 → IPv6 Migration

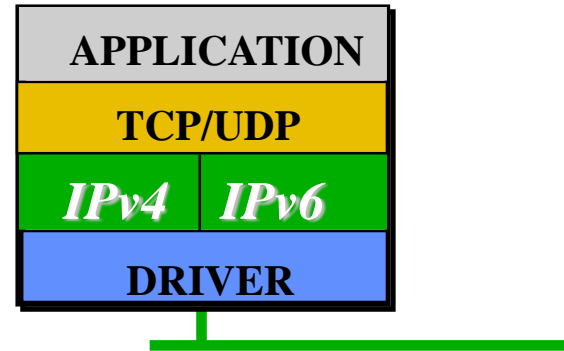
Many migration techniques have been designed and implemented according to the following approach:

- **Dual-Stack** techniques, which allow the coexistence of IPv4 and IPv6 at the same device and subnet
- **Tunnel**, which connects IPv6 regions over IPv4 regions
- **Protocol translator**, which let IPv6 devices with IPv4 devices speak

During migration, the combined use of all these methods is likely.



# Dual Stack

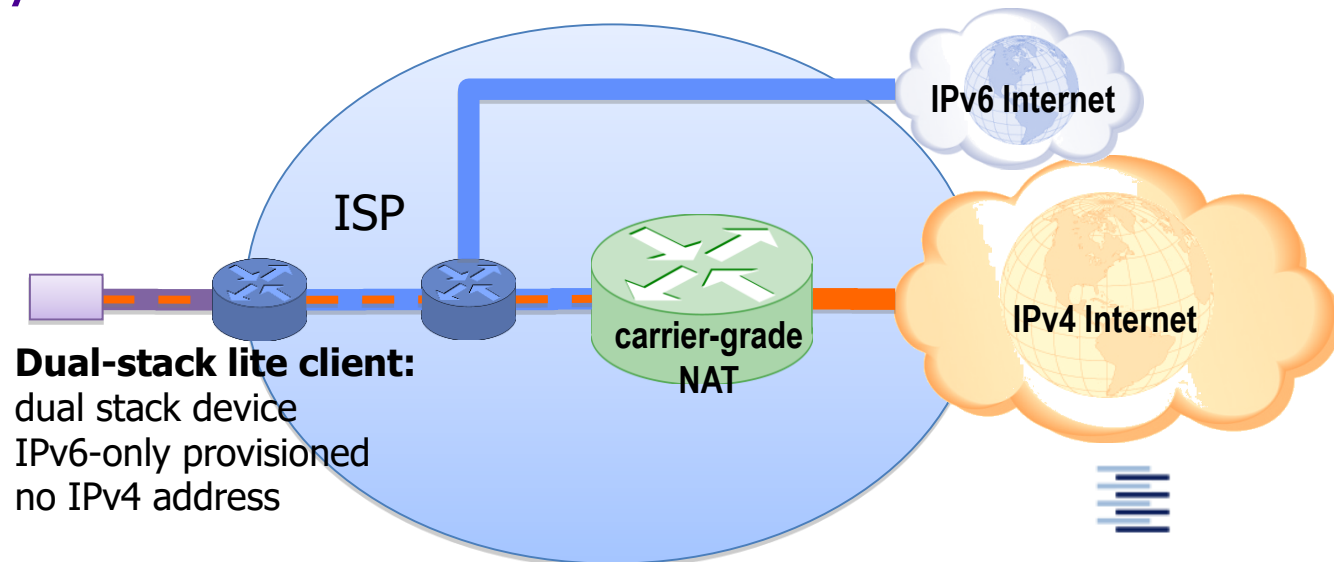


- o On activation of IPv6, the IPv4 can continuously be used (multi protocol approach)
- o Devices can keep their addresses (IPv4 in IPv6)
- o Application / libraries choose the IP version:
  - in dependence of DNS answer with IPv6 preference
  - in dependence of received packets
- o The Dual stack operation can continue without limits, allowing the step by step porting of applications
  - But requires an increasing use of IPv4-NATTING (recursive)
- o Problems result from inconsistencies of Network / DNS configurations

# Dual Stack Lite

## - RFC 6333 -

- o IPv6-only at customer – but dual stack at system
- o IPv4 over IPv6 tunnel to Carrier-grade IPv4-IPv4 NAT
- o IPv4 access via globally unique IPv4 address shared among many customers



# Transition by Tunnels

o Embedding of IPv6 packets in IPv4 packets

o Diverse methods to build a tunnel:

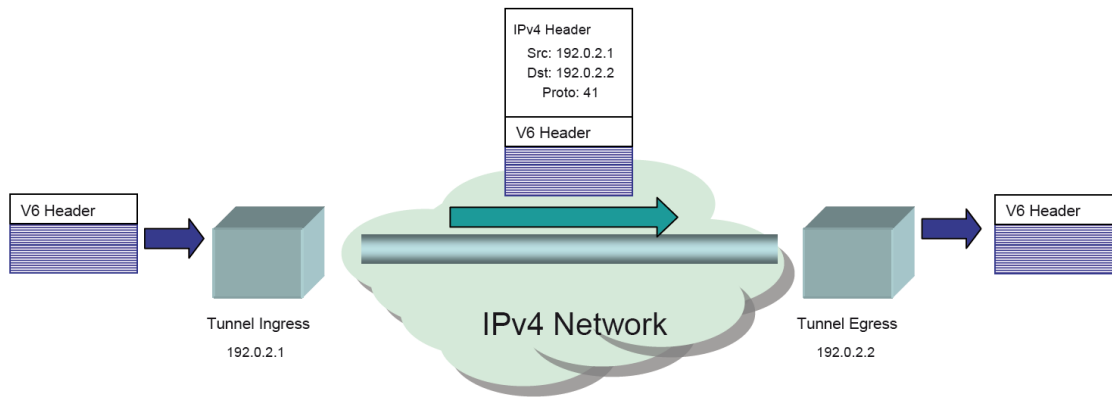
- **Manually**
- **Tunnel Broker** (web based application to build a tunnel)
- **6-over-4** (intradomain)
- **6-to-4** (interdomain, IPv4 address as IPv6 site prefix)

o Perspective:

- IPv6 use IPv4 as a virtual link layer
- IPv6 VPN over IPv4

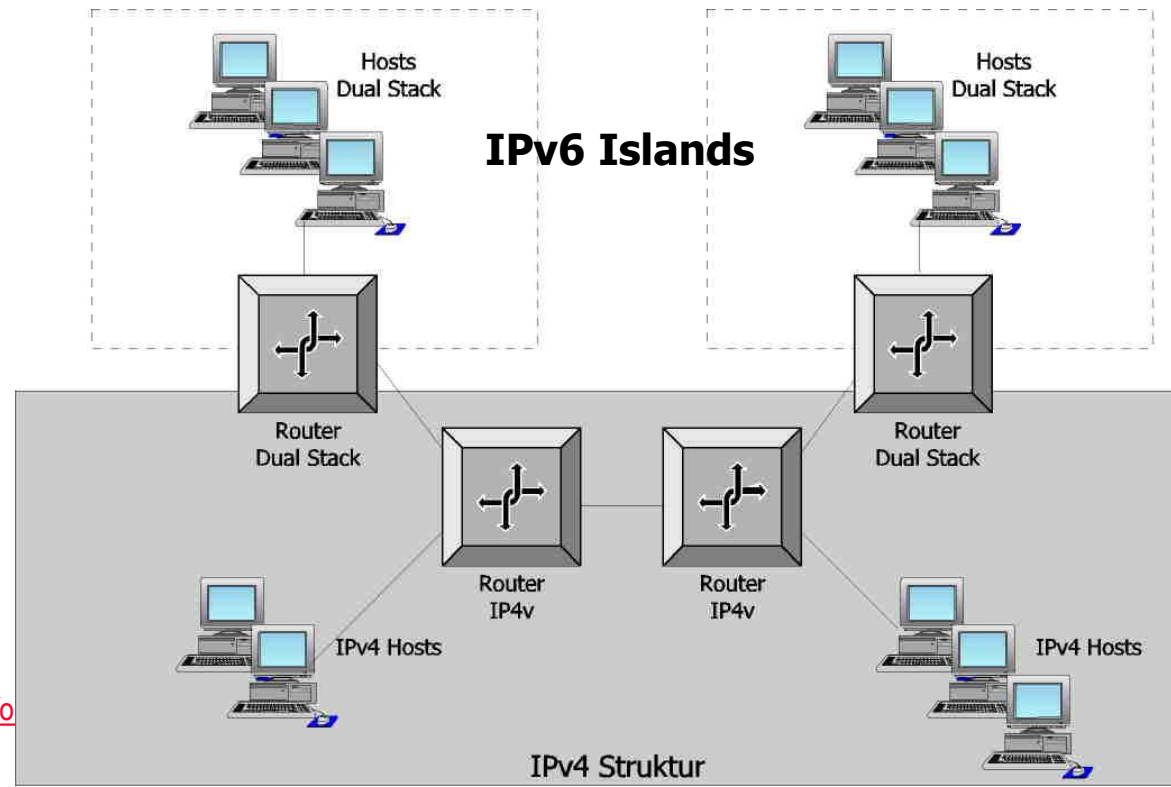


# 6-over-4 Tunnels

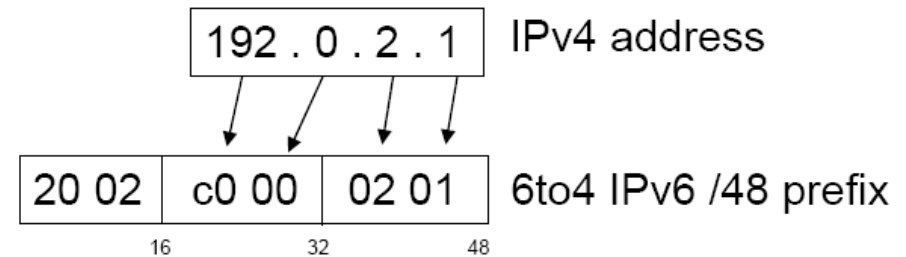


Isolated IPv6 islands in an IPv4 world

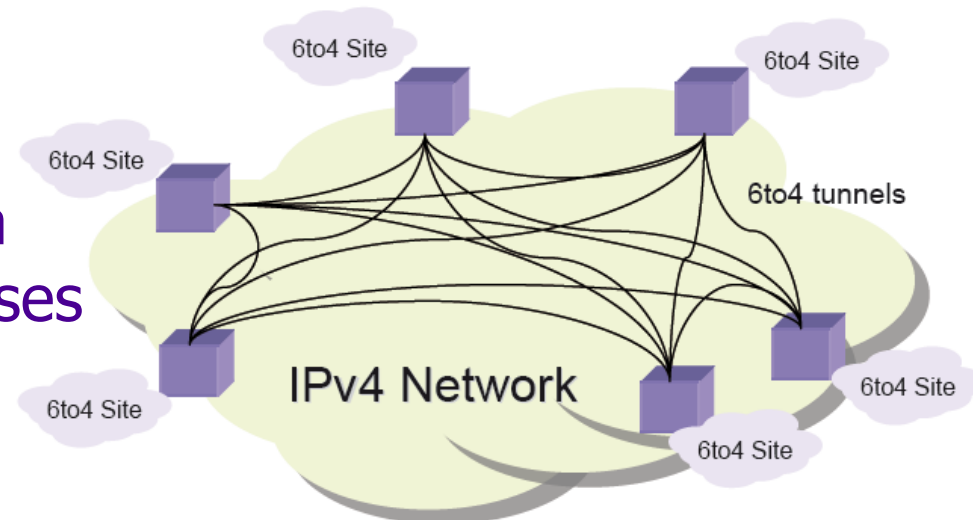
IPv6 ↔ IPv4 interconnects: Embedding  
IPv6 ↔ IPv6 interconnects: Following tunnel configurations



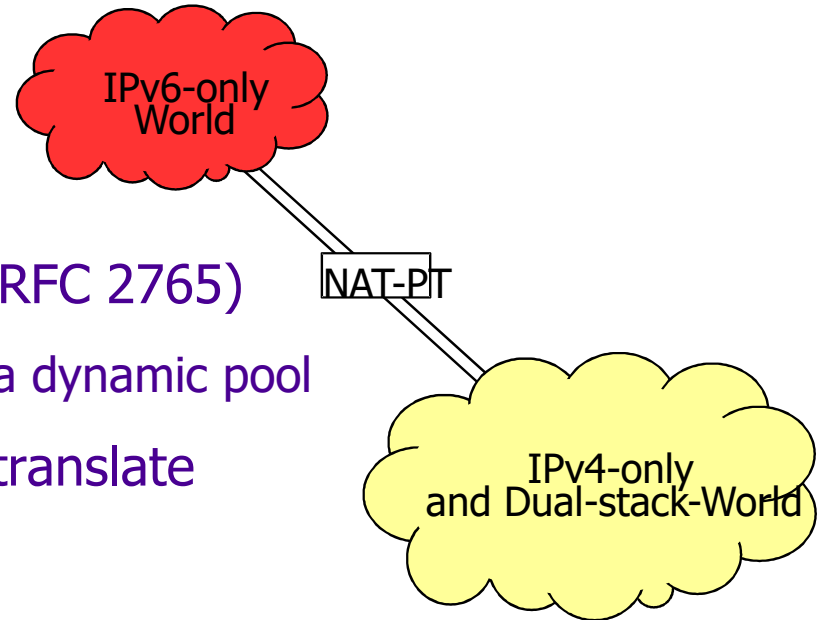
# 6-to-4



- o Defines automated point-to-multipoint tunnels, RFC 3056 ff.
- o Assigns an IPv6 network to each IPv4 address (taken as prefix)
- o Allows IPv6 islands to automatically interconnect, using IPv4 as a non-broadcast multi-access network
- o Automatic tunnel access via well-known Anycast addresses
- o TEREDO: Extension to NAT traversal



# Protocol Translation



- o Stateless protocol translation by SIIT (RFC 2765)
  - Uses temporary IPv4 addresses from a dynamic pool
- o NAT-PT: stateful extension of NAT to translate header formats and addresses
  - RFCs 3142, 2766 (deprecated by RFC 4966)
  - IPv6 nodes behind translator attain full IPv6 functionality
  - translates {TCP,UDP}/IPv6 to {TCP,UDP}/IPv4 (address + port)
- o Scenario:
  - New 'domains' from Internet devices (telephones, cars, ...)
  - When a pure IPv6 configuration should/must be used





# Agenda

- 🕒 Motivation
- 🕒 Basic IPv6 Architecture
- 🕒 IPv6 Migration: Transition and Coexistence
- 🕒 Future Trends: Beyond IPv6
  - ➡ Lessons Learned
  - ➡ IRTF/IETF Work
  - ➡ Some Visionary Proposals



# Lessons Learned

- o IPng deployment
  - Internet is inert “victim” of IPv4 success
  - Internet is “victim” of its uniqueness constraint
- o Development of innovations within the Internet
  - Clear trend: broadening of the range of applications
  - Unclear: “who steers the IP layer” – Pipe owners pushing packets versus user-driven, intelligent layer 3 services
- o Internet design – Quo Vadis?
- o Routing – *the* scaling issue
- o DNS – inflexible, updates too slow, *but scalable*



# Issue: Economic Models for Internet Operation

## o Several players:

- Infrastructure providers (pipes, routers, hosting)
- Top-level ISPs (international transit providers)
- Customer-oriented / regional ISPs
- Edge domain operators (companies, consumer-ISPs)

## o Problem: Grouping according to regions, not services

- Little room for service innovation / dedication

## o Approach: **Virtualization of infrastructure**

- Allows for slicing of cables ( $\lambda$ s), routers and servers
- Offers playground for specialized service provisioning



# Issue: Naming & Addressing

- o IP addresses carry a dual meaning of Identifier (who) and locator (where)
  - Initially ID=name, Loc=address [Cohen, D., "On Names, Addresses and Routings", IEN 23, 1978]
  - TCP used addresses as identifiers (DNS was not ready)
- o Mobility re-raises the problem
  - MIPv6 creates an ID/Locator split on network layer
- o Host Identity Protocol (HIP, RFC 5201) introduces abstraction layer between network and transport



# Issue: Route Scalability

- o Routing table size and dynamics in the core increases due to growing numbers and heterogeneity at edge domains
- o Two counter measures:
  - **Aggregation** – PA addressing as proposed by IPv6
  - **Separation** – decoupling of edges from core by a Map-Encapsulate mechanism
- o Ongoing debate
  - Map/Encap opens freedom of design at edge domains



# IRTF / IETF Work

- o IAB Workshop on Routing and Addressing  
s. [draft-iab-raws-report-00](#)
- o From 2007 on, the Routing Research Group called for and discussed proposals  
s. <http://trac.tools.ietf.org/group/irtf/trac/wiki/RoutingResearchGroup>
- o RRG made a decision March `10 and published recommendations in [RFC 6115](#) (Feb. `11)



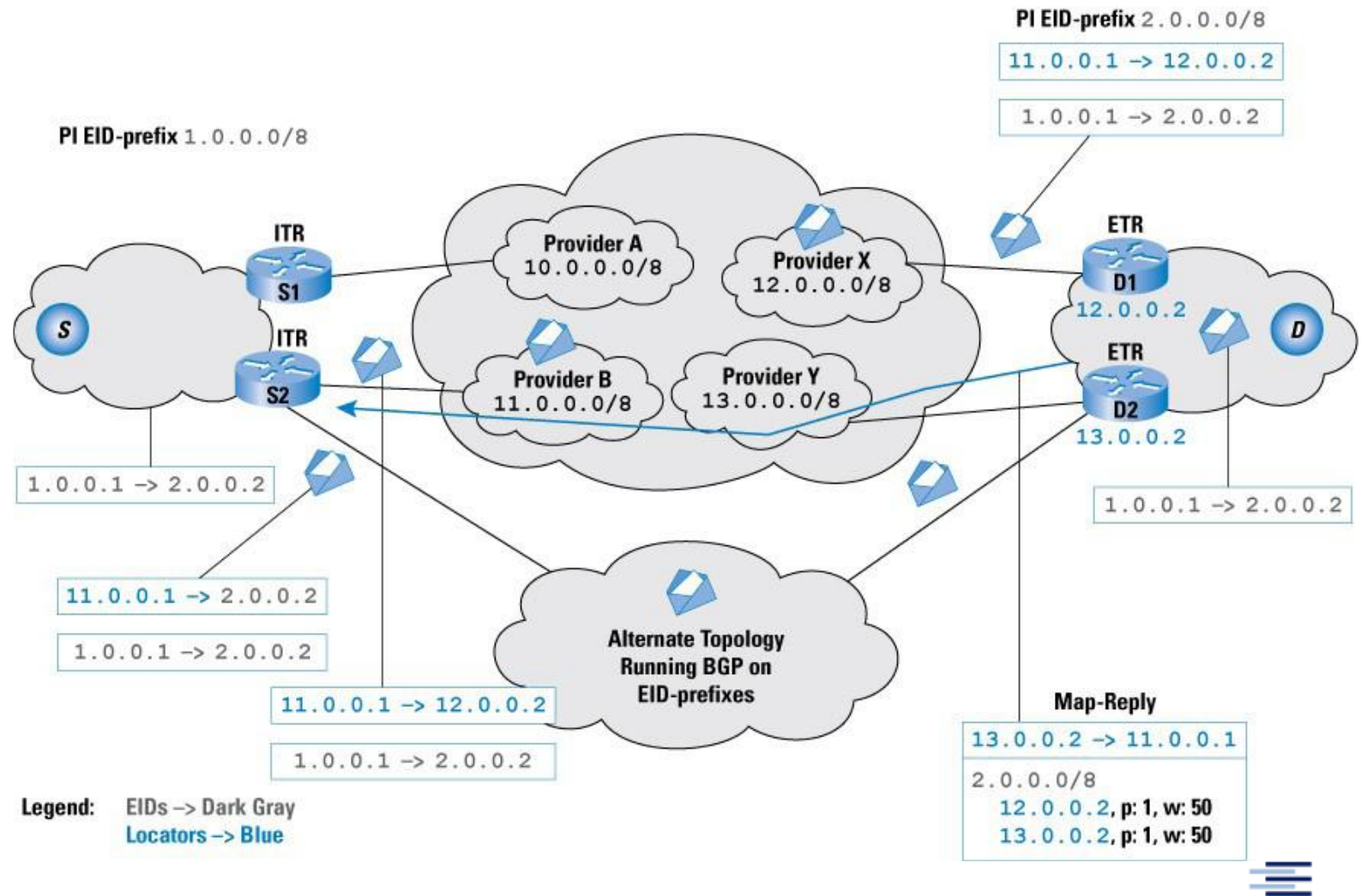
# Locator ID Separation Protocol (LISP)

## RFC 6830

- o Sites / nodes have addresses (as in DNS): provider independent IDs
- o Routers maintain a database of "Routing Locators (RLOCs)": provider-bound IP addresses of routers in a destination site
- o Packets are tunnelled from egress to ingress router using RLOCs
- o Problem: Router databases ... to be learned from ICMP advertisements in LISP
- o Result: Removes load from core routers



# LISP Scenario





# Name-based Socket

## draft-ubillos-name-based-sockets

### o Straight-forward approach

- DNS Name is Identifier
- IP Address is Locator
- Initial name exchange  
(for backward compatibility)

### o Requires change of Socket API

- New address family (AF\_NAME)

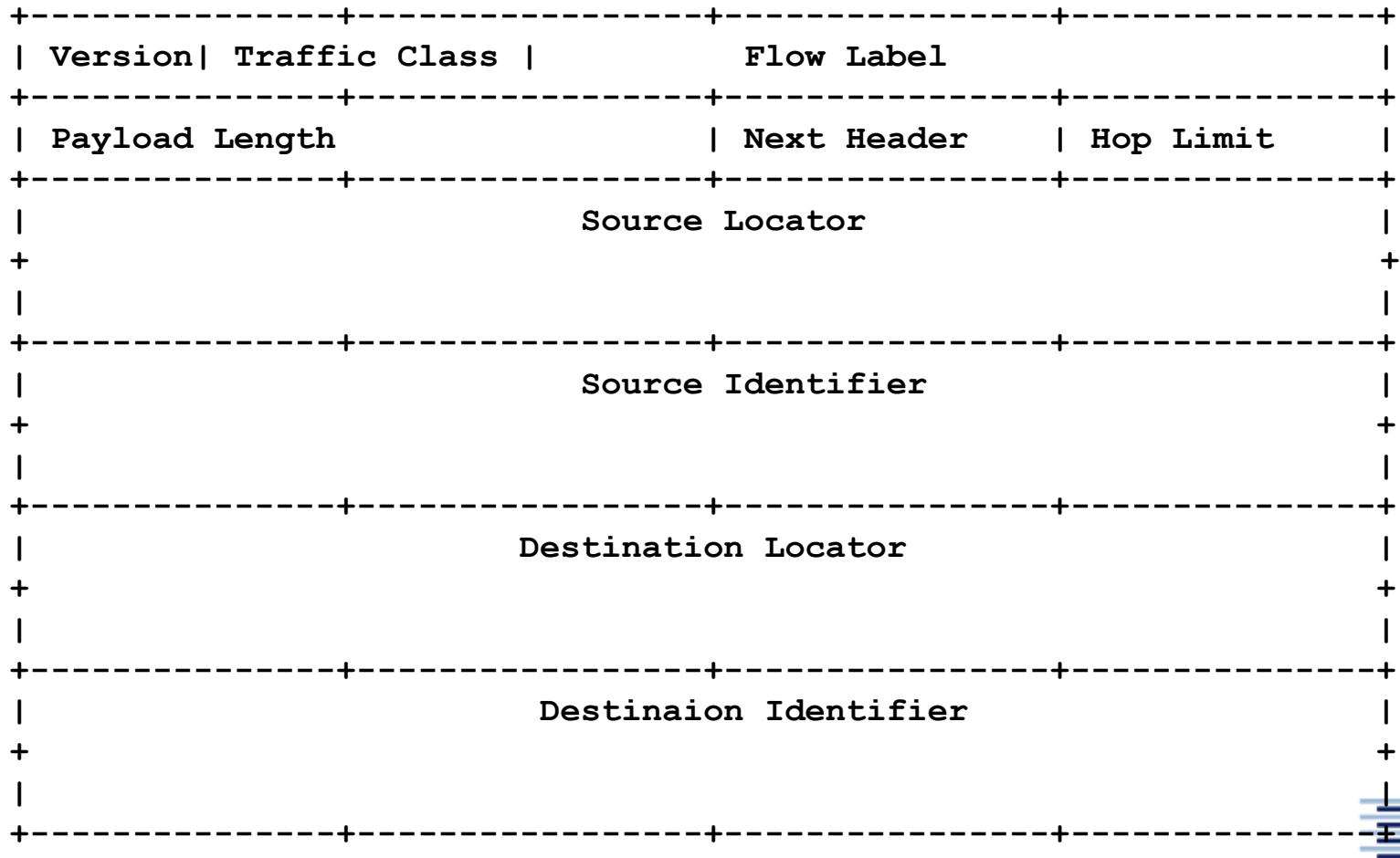


# Identifier Locator Network Protocol (ILNP) RFCs 6740–6748

- o Idea (Clark/O'Dell ~1995) to split IPv6 addresses
  - Routing Locator – in IPv6: first 64 bits
  - Unique Identifier – in IPv6: second 64 bits
- o Locator and Identifier independently stored in a (modified) DNS
  - Additional records for resolution
  - Dynamic update function for locators at DNS
- o New, high-level API



# ILNP: Re-interpretation of the IPv6 Header



# Aggregation in Increasing Scopes

draft-zhang-zhang-evolution

- o Idea: Increase aggregation on global scale on the price of possible detours
  - Reduce global prefix resolution, e.g., route to 145.01/15 to reach an Aggregation Point
  - Provide detailed knowledge (full prefix resolution) at Aggregation Point and tunnel packets over the last hops



# Recommendations of the RRG

- o Highly controversial debate lasting over more than 3-Years
- o Recommended for further development to the IETF
  1. Aggregation in Increasing Scopes
  2. ILNP
  3. Renumbering



# Software-defined Networking

## Problem:

Network components are mainly closed systems

- Vendor hardware only allows “configuration”
- Difficult to define and probe new behaviour

## Idea of Openflow:

Open network fabrics to a programming interface

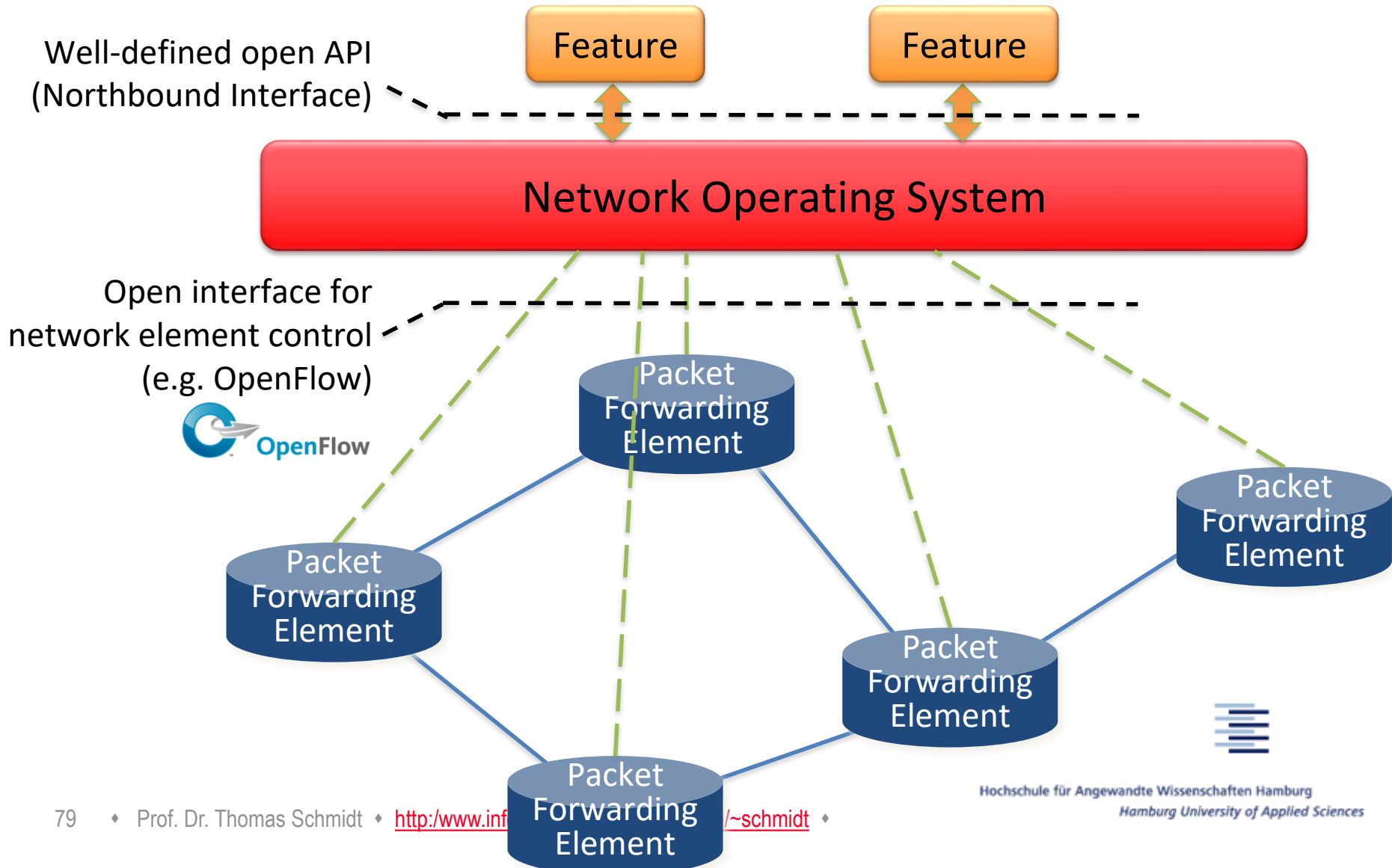
- Speed, scale, performance of vendor hardware
- Flexibility and control of software switches

## Alternative formulation

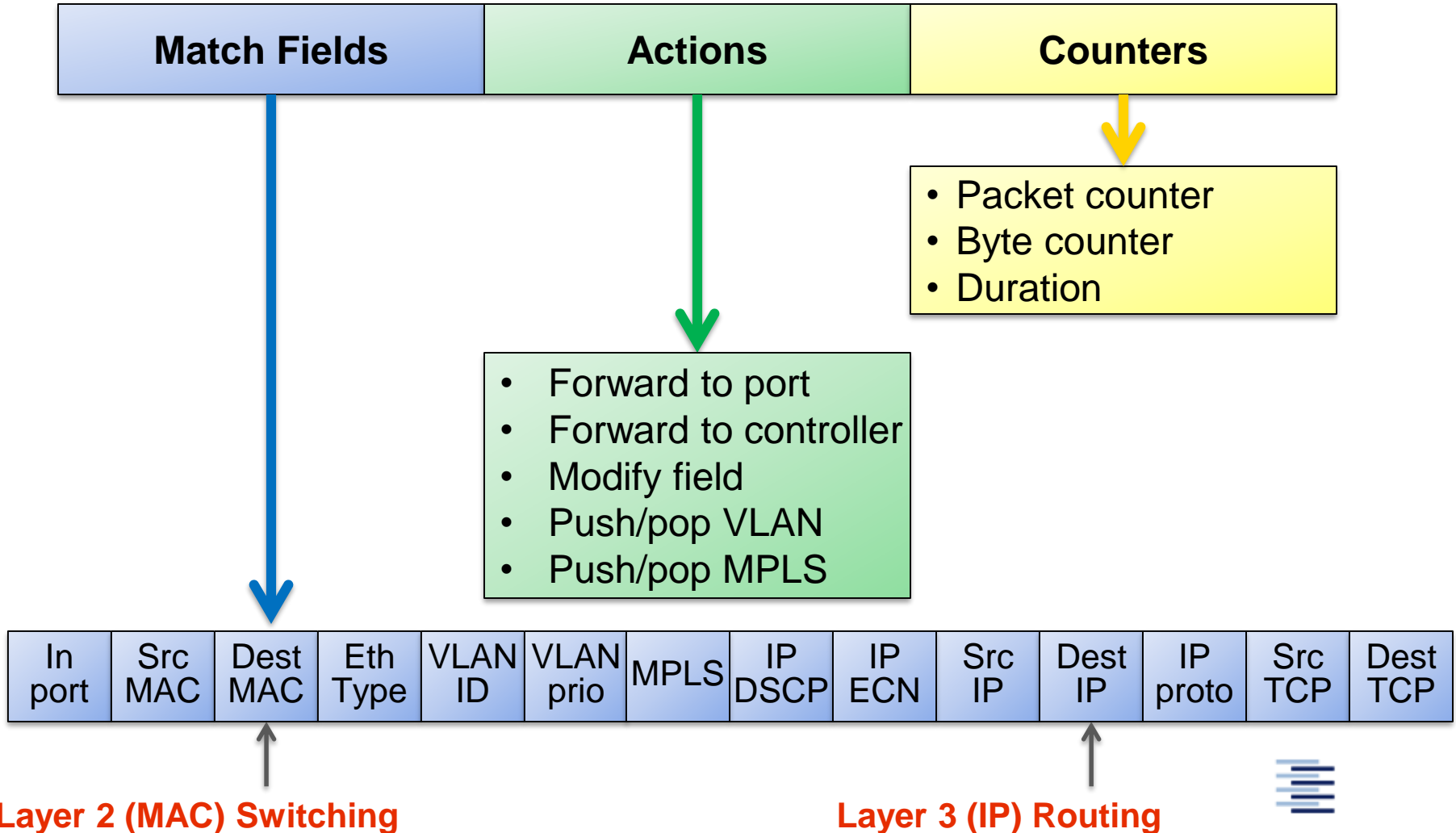
- Make switch fabrics (TCAMs) accessible to high-level intelligence
- Separate a (central) control plane



# SDN/OpenFlow Architecture



# Flow Table Entries





# Characteristic SDN Operations

- o Packet processing according to policies
  - Header match rules implemented at switches
- o Rules distributed by central controller
  - Proactively: at network configuration time
  - Reactively: in response to first unmatched packet
  - Controller provides “global” knowledge
- o Obvious scaling deficits on Internet scale
  - Common deployment: Data-centers, Enterprise Networks



# Clean Slate Internet Initiatives

- o Outside IETF/IRTF
- o Focus **scaling**: overall logarithmic ... as of DHTs ( $\beta$ )
- o Focus **virtualisation**:  
Programmable virtual infrastructures for dedicated purposes
- o Focus **pluralisation/federation**:  
Break with the paradigm of a universal network layer
- o Focus **programmability**:
  - Software-defined Networking
  - Software-defined Radios
- o Major US initiative: **GENI**
- o EU: Future Internet Research and Experimentation – **FIRE** initiative
- o Germany: German LAB (**G-LAB**)

# Bibliography

- o Pete Loshin: IPv6 – *Theory, Protocol and Practice*. Elsevier, 2004.
- o 6Net Consortium: *An IPv6 Deployment Guide*, Sept. 2005.
- o Benedikt Stockebrand: *IPv6 in Practice*, Springer, 2010.
- o Qing, Li / Jimnei, Tatuya / Shima, Keiichi: IPv6 Core / Advanced Protocols Implementation, Morgan Kaufmann, 2007.
- o Zach Shelby, Carsten Bormann: *6LoWPAN: The Wireless Embedded Internet*, 2<sup>nd</sup> Ed., Wiley & Sons, 2011.
- o Dave Thaler (IAB): *Evolution of the IP Model*, [draft-iab-ip-model-evolution](#), 2008.
- o Tony Li: *Recommendation for a Routing Architecture*, RFC 6115, 2011 .
- o Dan Jen et al.: *Towards A New Internet Routing Architecture: Arguments for Separating Edges from Transit Core*, ACM Hotnets, 2008.
- o Nick McKeown: *Software-defined Networking*, Infocom Keynote Talk, Rio de Janeiro 2009
- o Drafts, RFCs: [tools.ietf.org](http://tools.ietf.org), <http://www.rfc-editor.org>

