Next Generation Internet
IPv6 and Beyond

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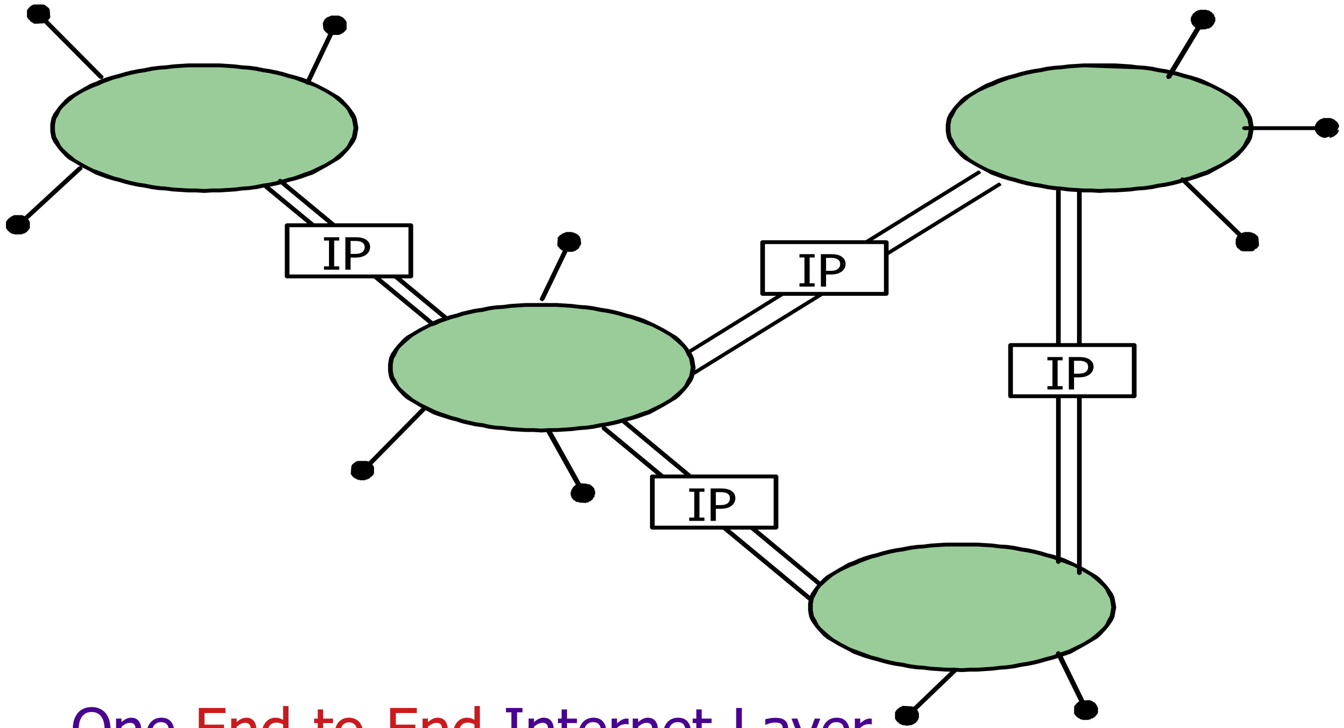
Agenda

- Motivation
- Basic IPv6 Architecture
- IPv6 Migration: Transition and Coexistence
- Future Trends: Beyond IPv6

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

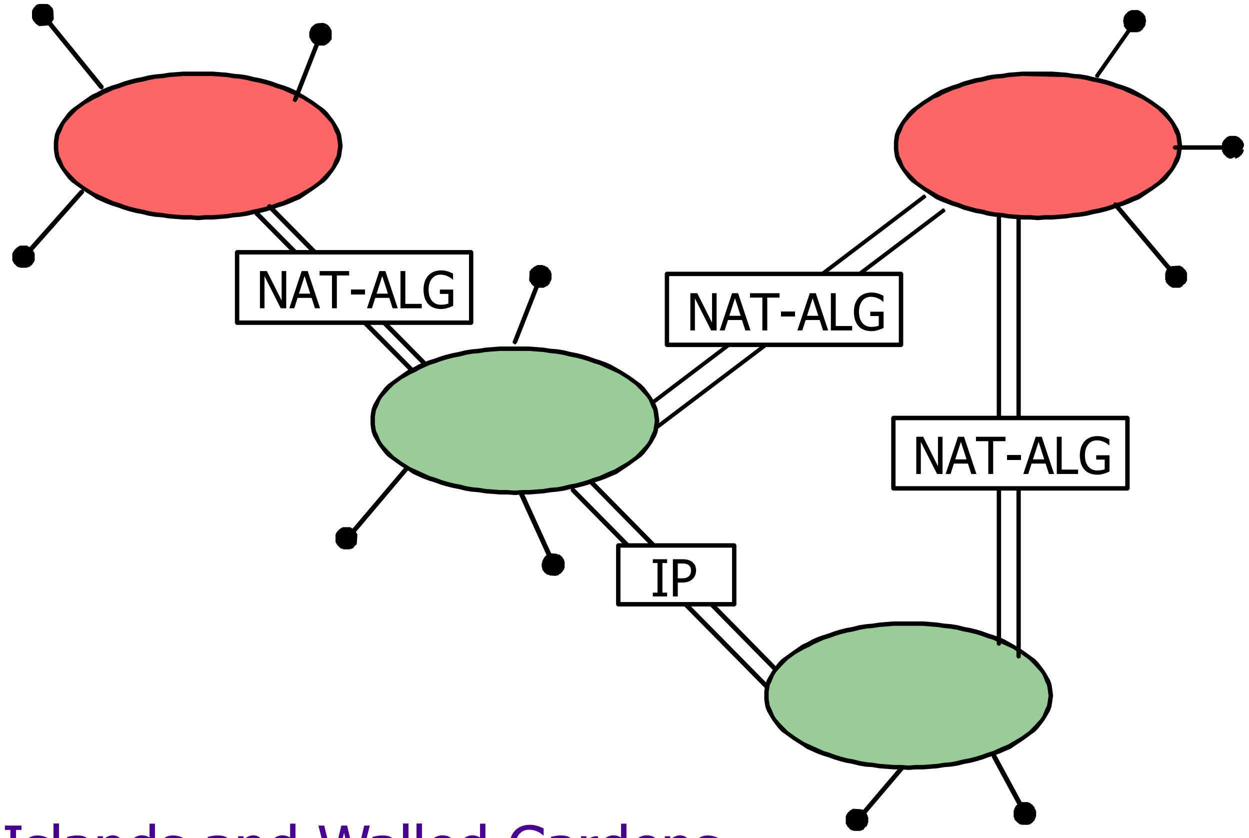
The Internet: Original Paradigm



One End-to-End Internet-Layer

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

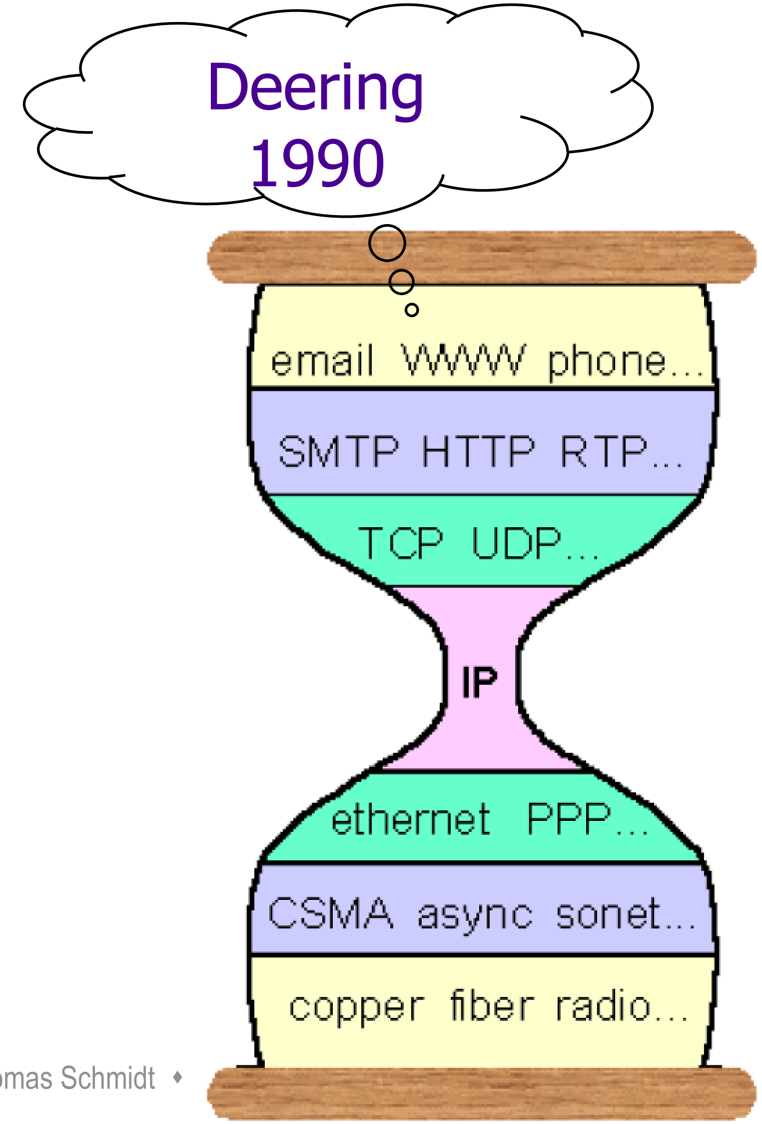
The Internet Today



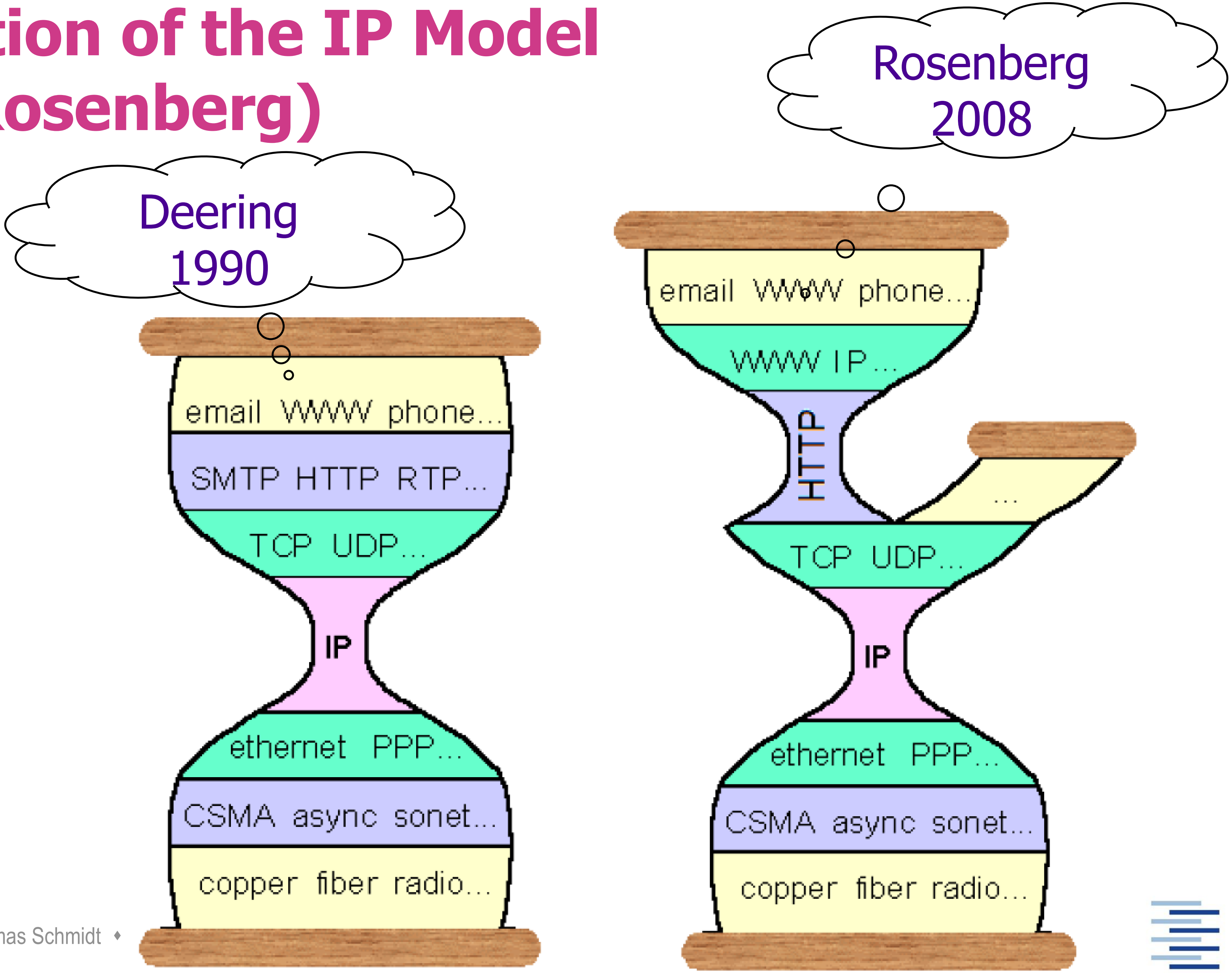
Private Islands and Walled Gardens

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

The IP Model (Deering)



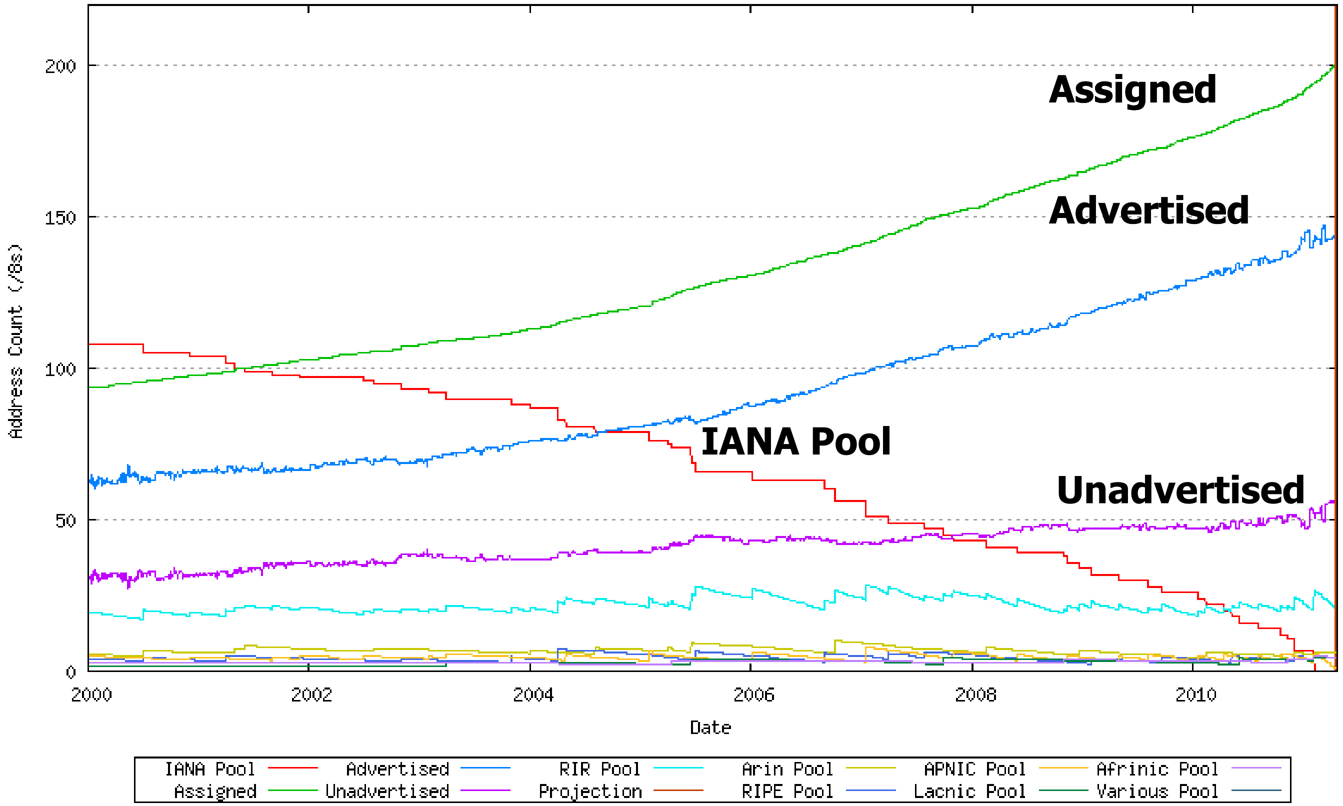
Distortion of the IP Model (Rosenberg)



The Limits of IPv4

- Basic design about 50 years old
  - Packet format ... outdated
  - Hardware development of networks overran IP algorithms
- Address space exhausted
  - ‚Regular‛ Internet growth ran out of addresses
  - New kinds of Internet devices (mobile telephones, intelligent devices,...) need new quantities of addresses
  - Caused by address bottle-neck: NAT-ALGs
- Support of new services tedious to implement

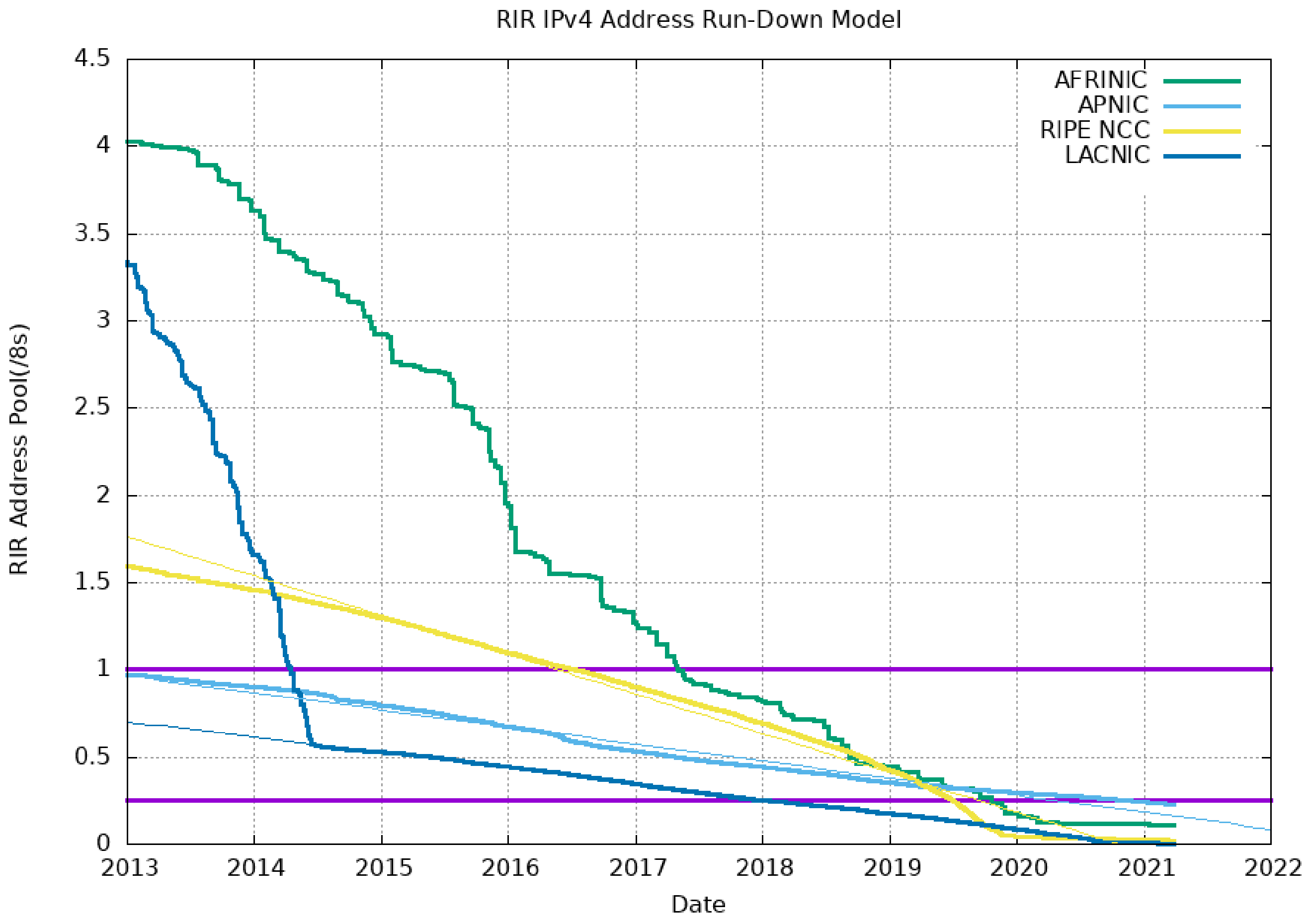
Predicted IPv4 Address Exhaustion



- IANA Unallocated Address Pool Exhaustion: 03-Feb-2011
- 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



- Arin Exhaustion: 24. Sept. 2015 – remaining NULL
- RIPE NCC: April 2021 – remaining 0.02 * /8

  Source: Geoff Huston, http://www.potaroo.net/tools/ipv4/

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IP Service Problems

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

Why IPng: IPv6 ?

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

IPv6 Innovations

- Addressing and routing
  - Elimination of address bottle-neck: 128 Bit addresses
  - Address hierarchy can (was intended to) simplify backbone routing
  - Several addresses per interface
- Simple administration
  - Autoconfiguration of interfaces without DHCPv6
  - Floating net masks, renumbering via prefix change
- Security: IPSec
  - Security header extension for authentication, integrity and encryption

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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 $\leftrightarrow$ IPv6

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IPv6 History

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

IPv6 Standardisation

- 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)	….

- IPv6 over:

PPP (RFC2023)	Ethernet (RFC2464)
FDDI (RFC2467)	Token Ring (RFC2470)
NBMA(RFC2491)	ATM (RFC2492)
Frame Relay (RFC2590)	ARCnet (RFC2549)

- Since then 100++ further standards: Flow labelling, MIPv6, 3GPP, Routing advertisement, ….
- Implemented basically in every Internetworking system platform

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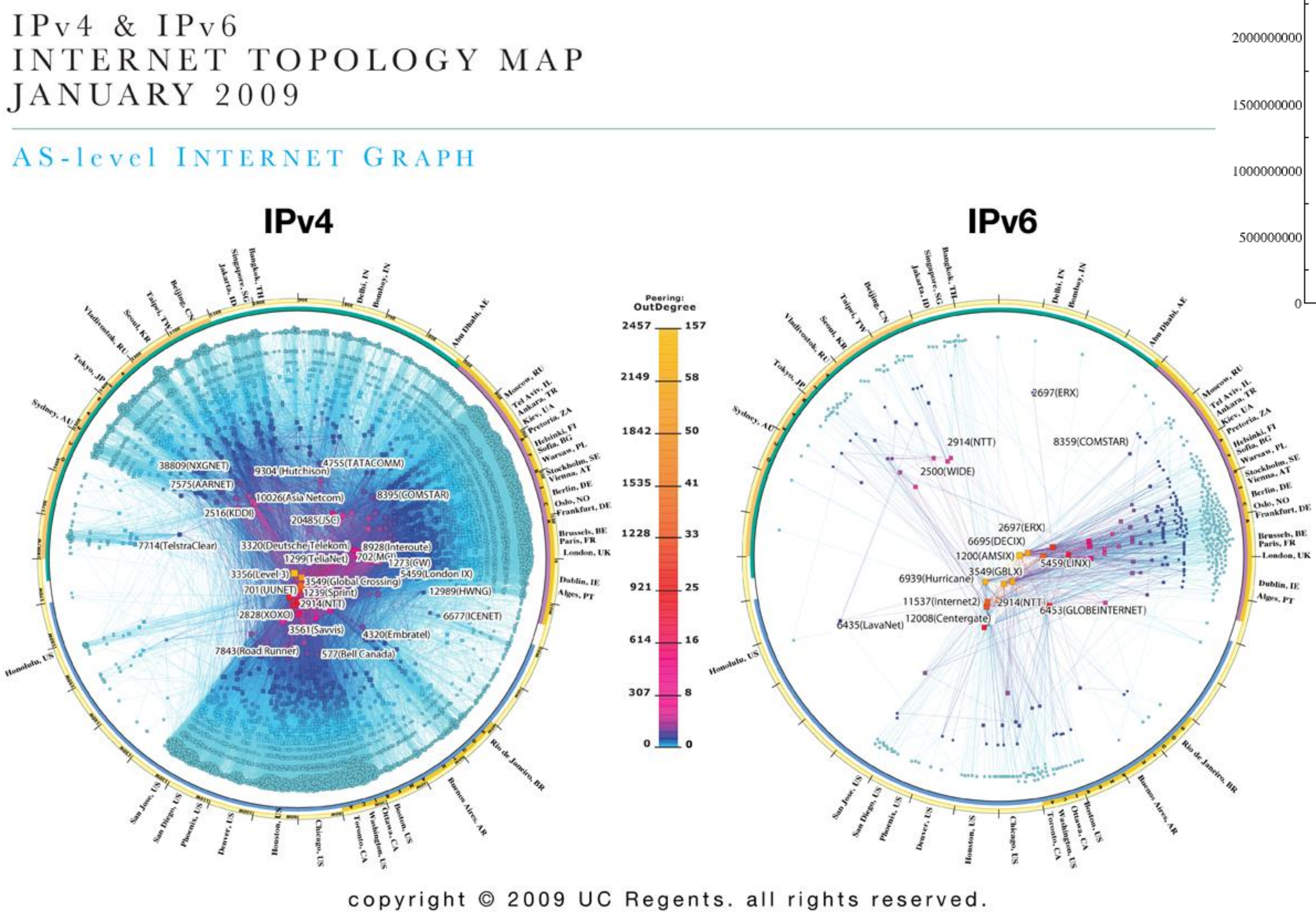

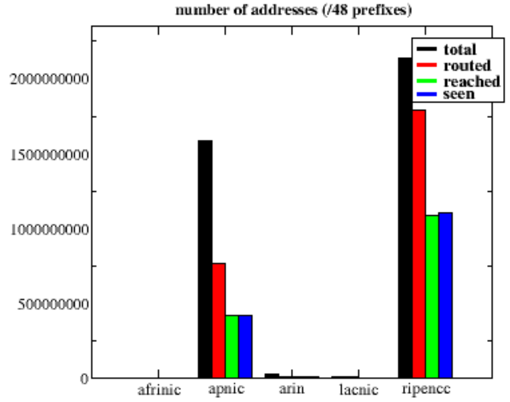

- Source: CAIDA (http://www.caida.org/research/topology/as_core_network/ipv6.xml)

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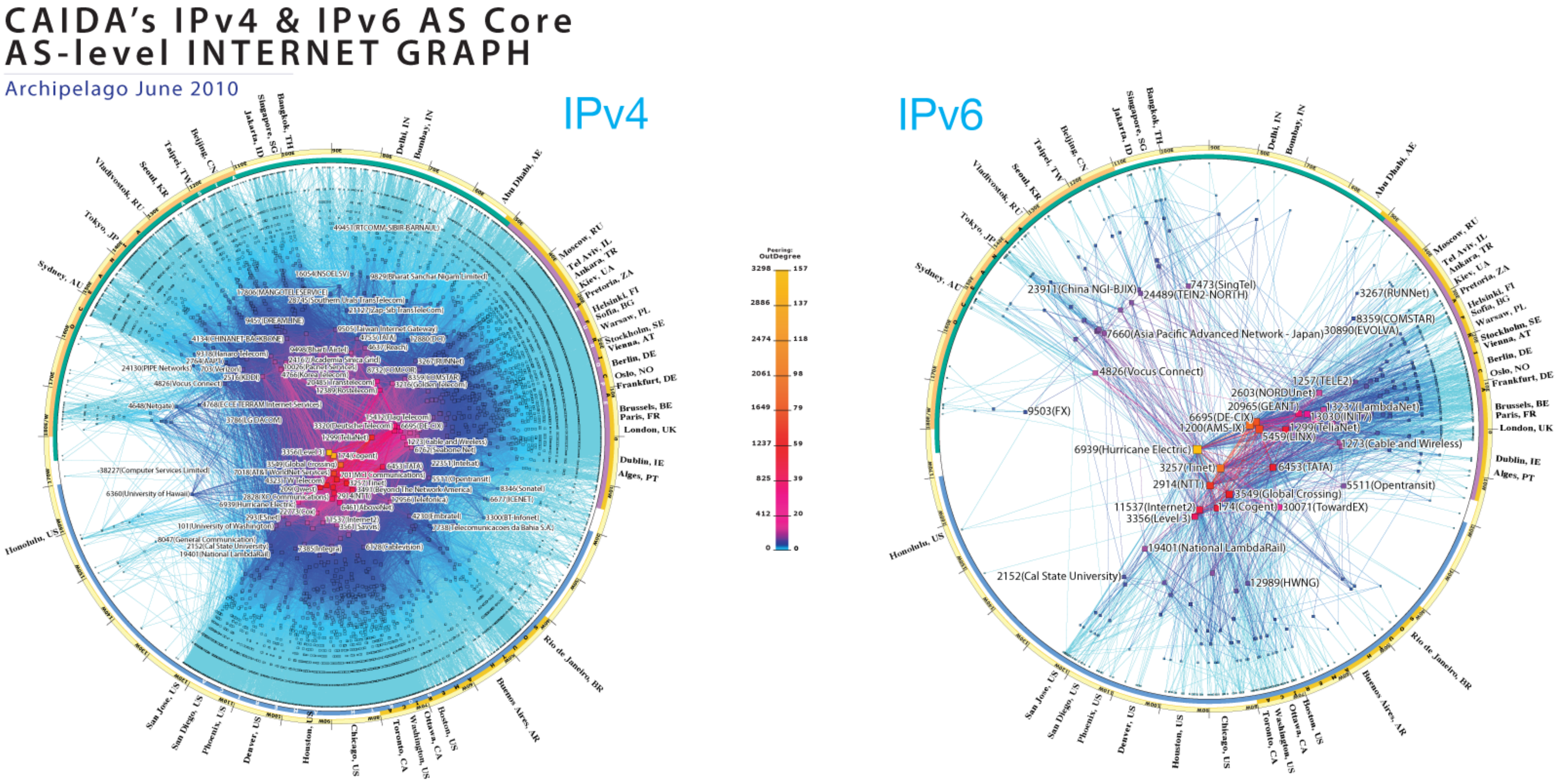
IPv6 Deployment Progress June ‘10



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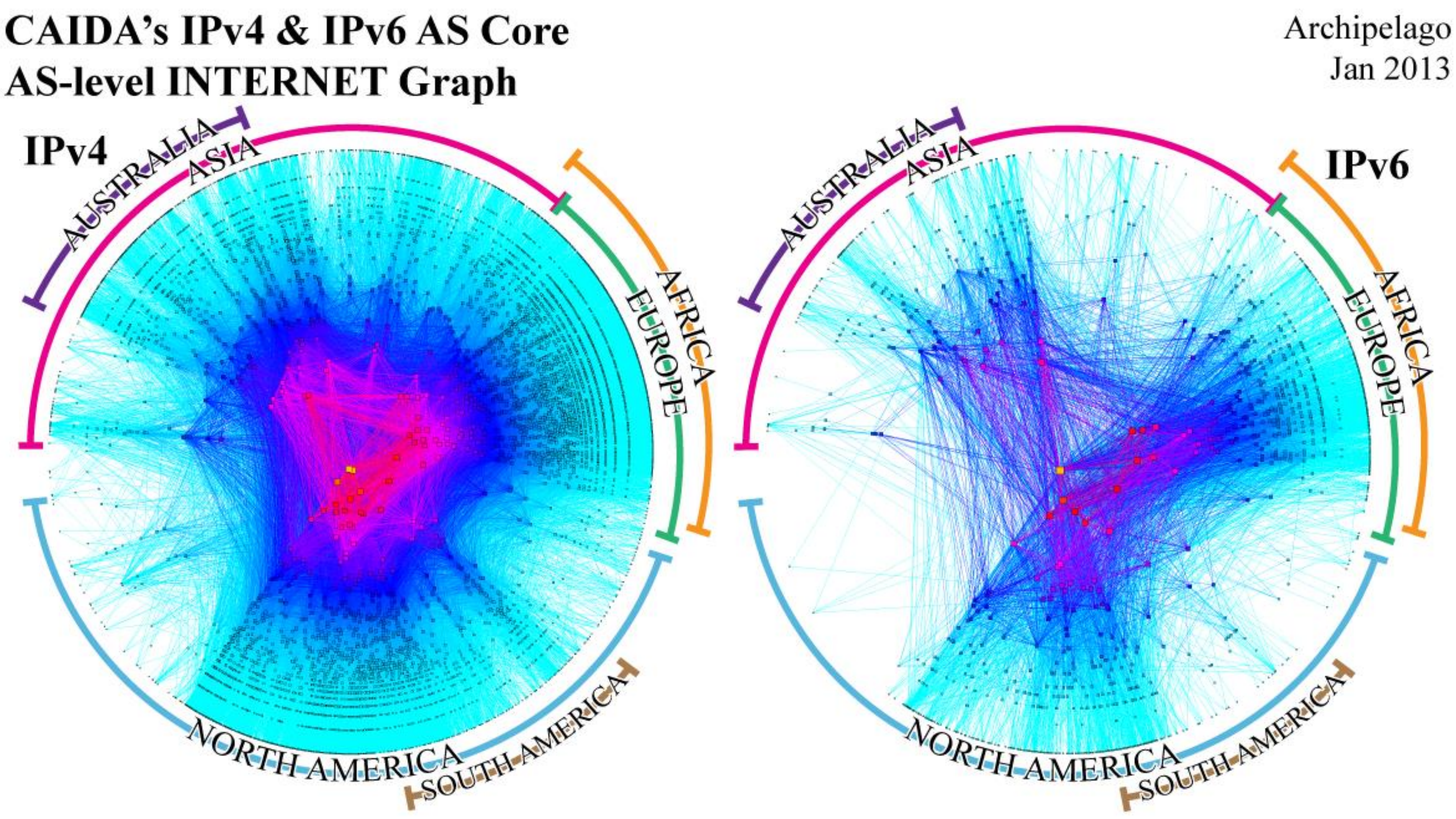
IPv6 Deployment Progress Jan ‘13



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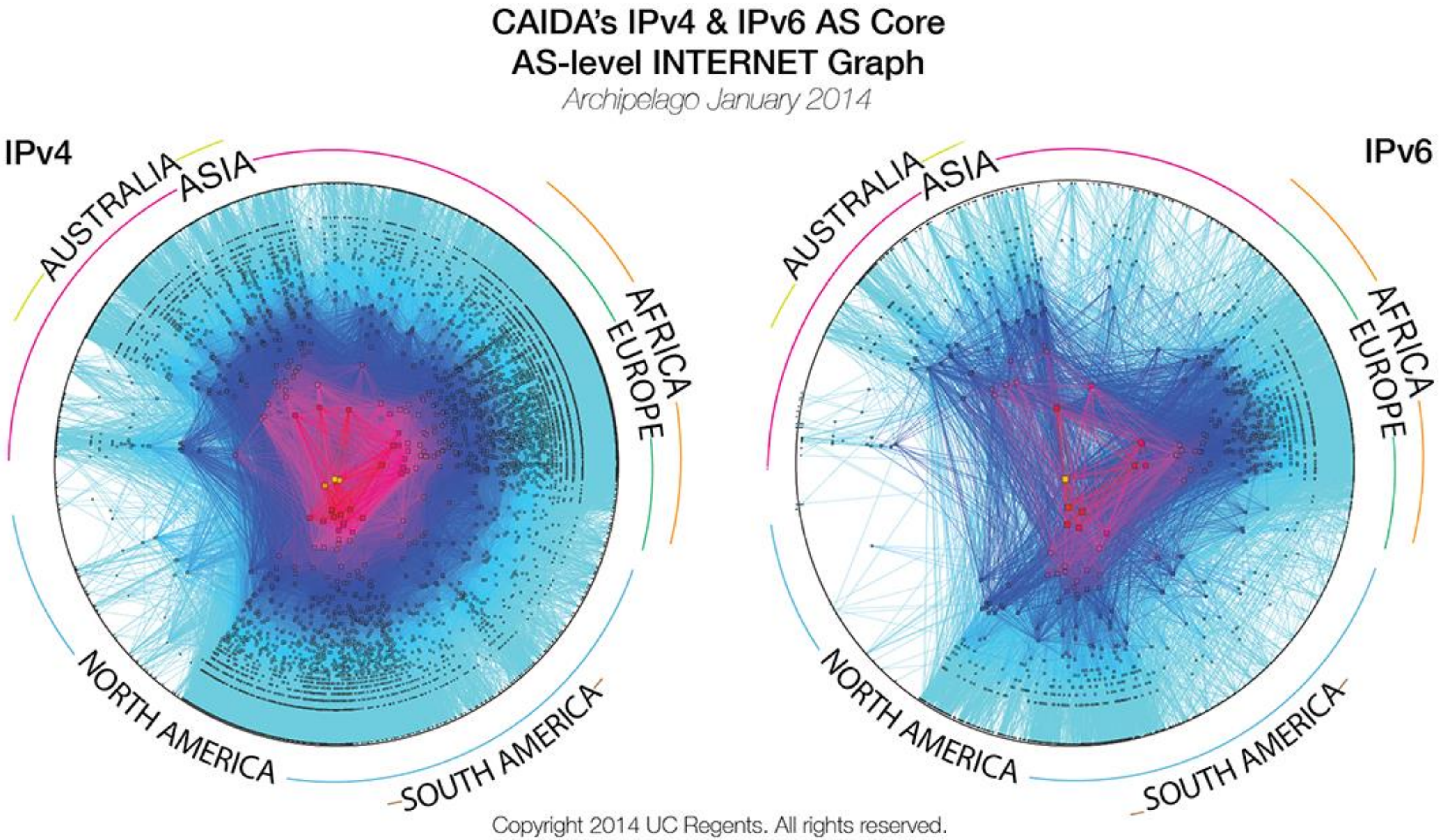
IPv6 Deployment Progress Jan ‘14



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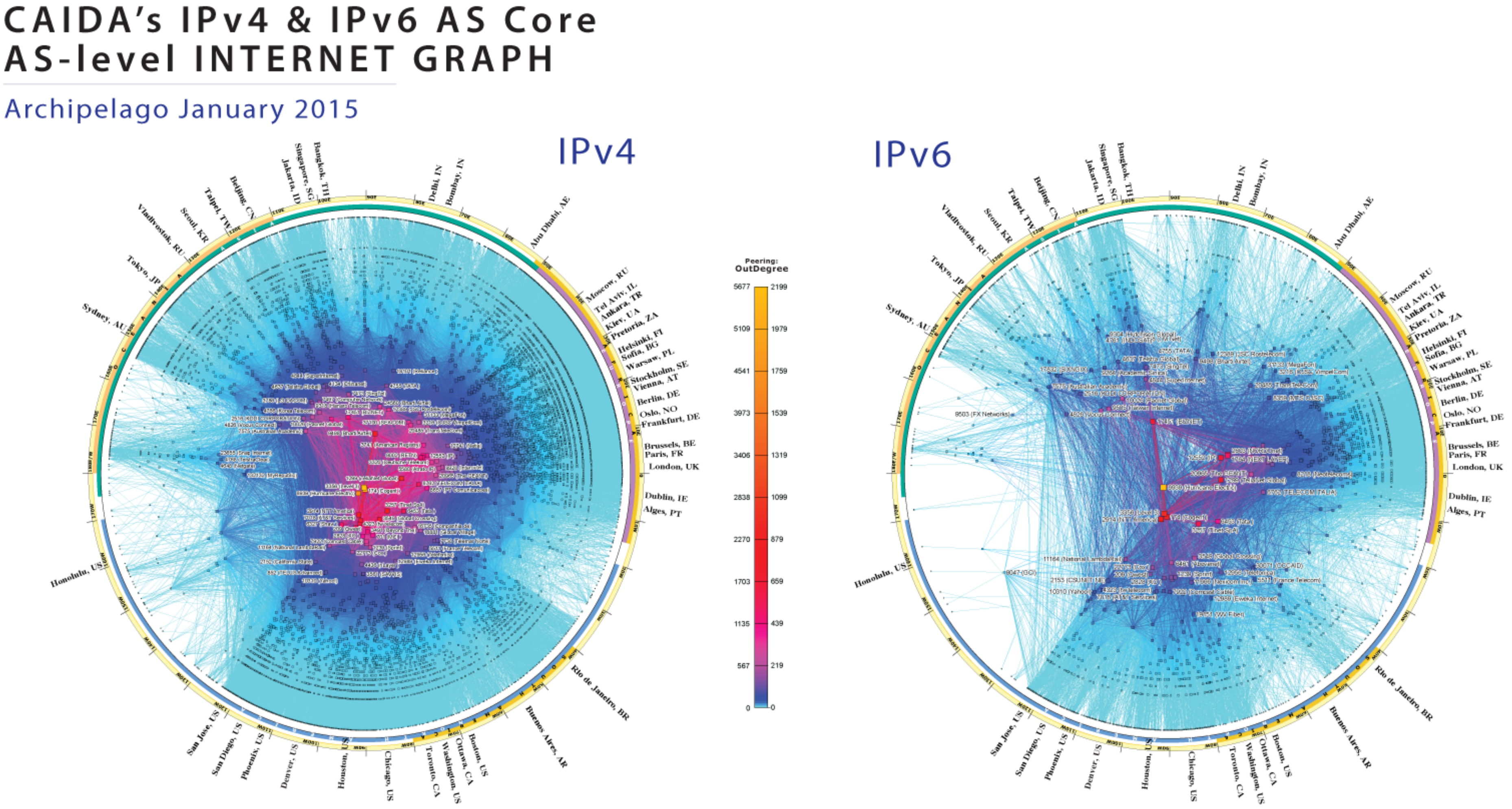
IPv6 Deployment Progress Jan ‘15



Agenda

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

Addressing

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

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Notation of IPv6 Addresses

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

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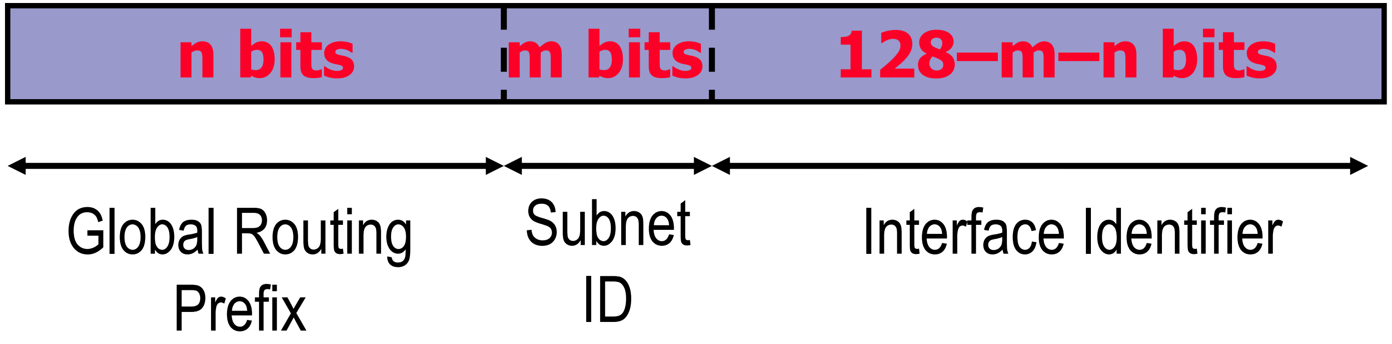
Address Types

Type	Binary Prefix	
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



- All fields have variable length and are not ‘self-explanatory’ (as of CIDR)
- All global unicast addresses, which do not begin with 000 (binary), carry a 64 bit interface ID, this means m + n = 64

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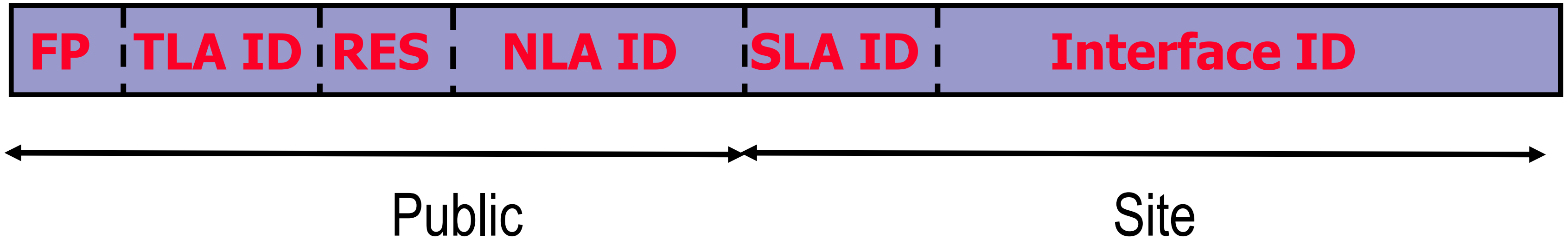
Historic – RFC2374: Aggregatable Global Unicast Format



Previous approach: Standardized prefix hierarchy as Top/Next/Side Level Aggregator

Current approach:

- IAB/IESG Recommendations on IPv6 Address Allocations to Sites
- Left to RIR policies cf. http://www.ripe.net/ripe/docs/ipv6policy.html

„Wherever possible, address space should be distributed in a hierarchical manner, according to the topology of network infrastructure."

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Local Unicast Addresses

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

1111111010	0	Interface ID

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

1111110	L	Global ID	SLA	Interface ID

Multicast Addresses

11111111	flags	scope	Group ID
8	4	4	112 bits

- Flag field: lower bit indicates permanent (=0) respectively transient (=1) group, remainder reserved for addressing schemes
- Scope field:
  - 1 - node local
  - 2 - link-local
  - 5 - site-local
  - 8 - organisation local
  - B - community-local (deprecated)
  - E - global (other values reserved)

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Example: Our First IPv6 Net in 2001

- 2001:: /16 - Pre-set prefix
- 2001:**06**00:: /24 - Regional registry Europa (RIPE)
- 2001:06**38**:: /32 - DFN prefix
- 2001:0638**:0801**:: /48 - Our network address
- 2001:0638:0801:**0001**:: /64 - Our first subnet
- 2001:0638:0801:0001**:0000:0000:0000:0001** /128

  - Our first IPv6 computer address in 2001 ☺

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

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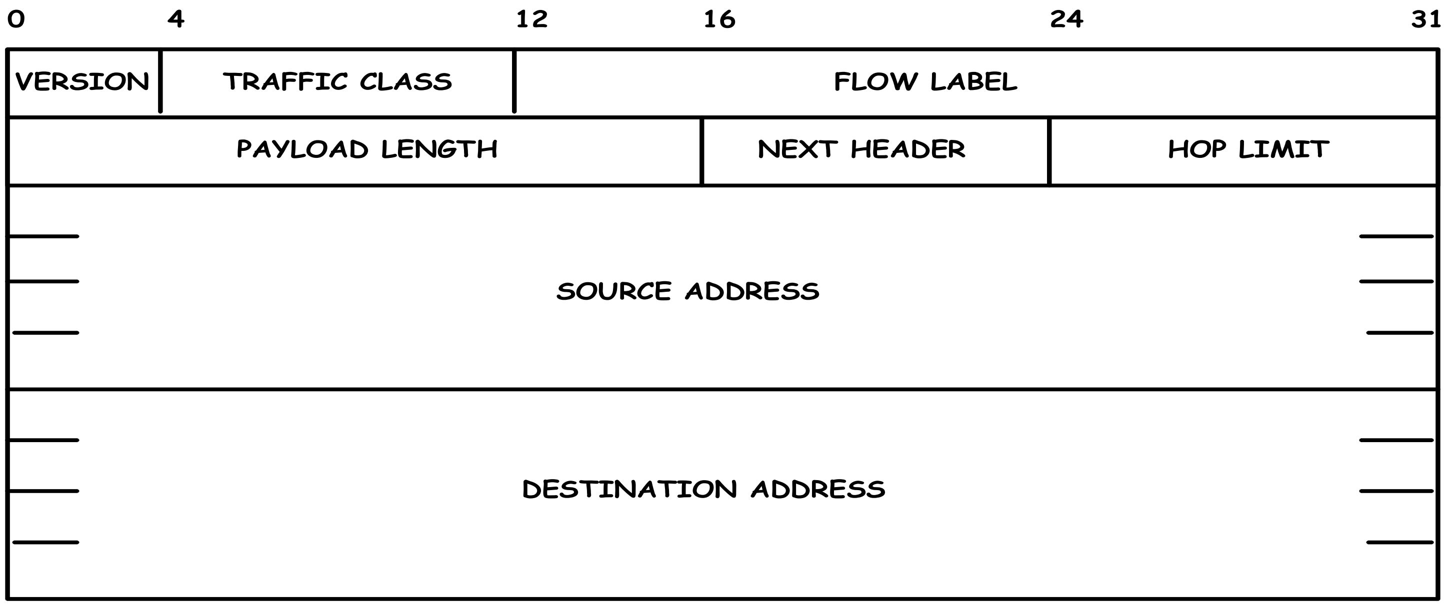
IPv6 Packet Format: Basic Header



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, Decremented 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 F	M F	Fragmenabstand	
Lebenszeit		Transport	Kopfprüfsumme			
Senderadresse						
Empfängeradresse						
Optionen					Füllzeichen	

Header Changes of IPv4

- o Addressing grows from 32 to 128 Bit
- o Fragmenting deleted from basis header
- o IP Options 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

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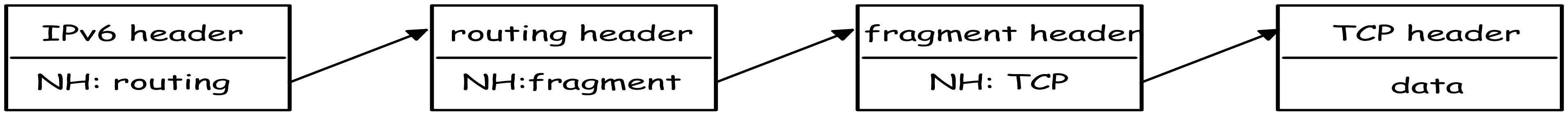
IPv6 Packet Format: Option Headers

- 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

- Routing
  Advanced routing information (source routing)
- Fragmentation
  Fragmentation / defragmentation information
- Authentication
  Security information: IPsec authentication and integrity
- Encapsulation
  Secure ‚Tunnelling': IPsec for confidential data
- Hop-by-Hop Option
  Dedicated options to be processed by every router
- Destination Option
  Information for the destination host (header extension)

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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 (for Routers with 2.)
4. Routing / Encapsulation
5. Fragmentation
6. Authentication
7. Destination Option (for Endpoints)
8. Upper Layer

Internet Control Message Protocol (ICMPv6)

- RFC 2463 (Conta, Deering), now RFC 4443 + 4884
- Extension header protocol class (following base IP header)
- 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

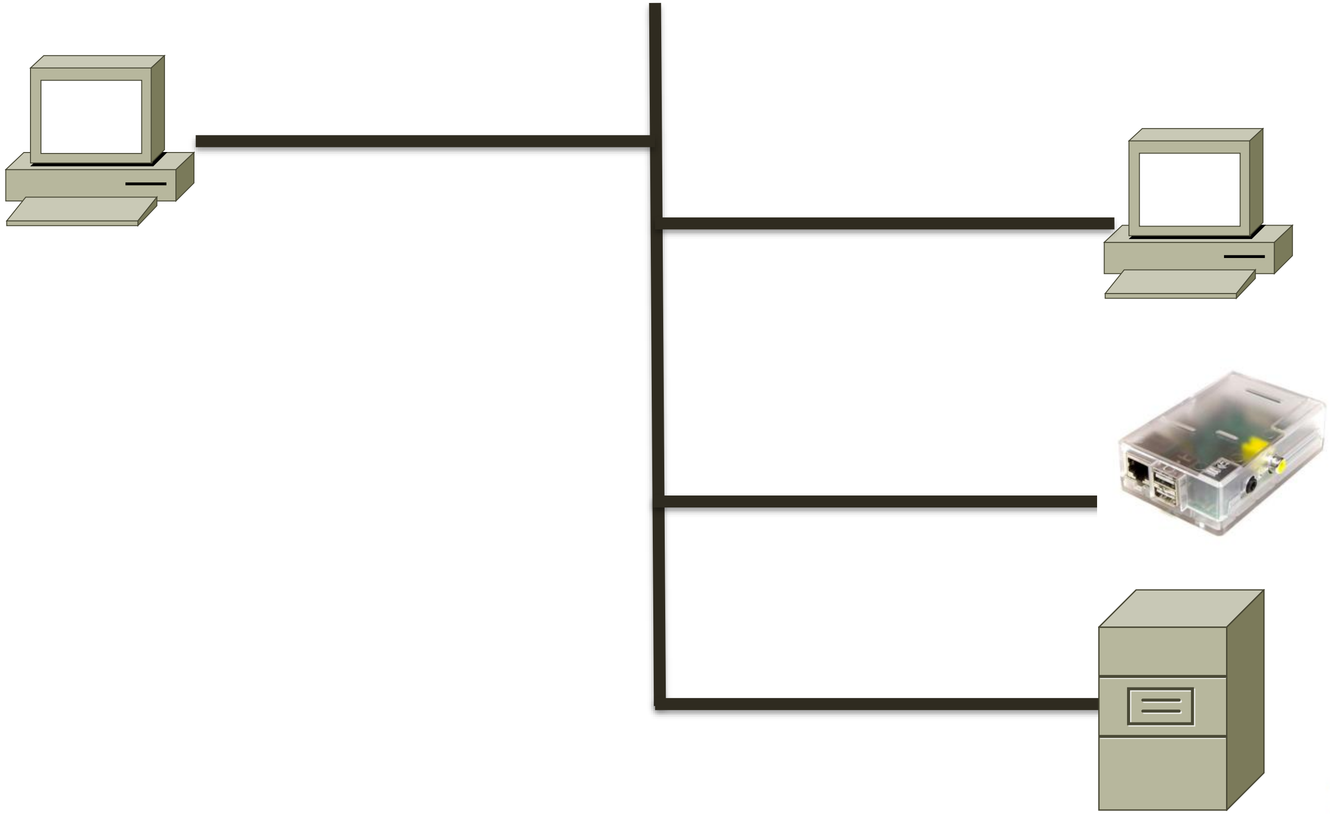
- RFC 2461, now RFC 4861
- Protocol over ICMPv6
  - Combination of IPv4 Protocols (ARP, ICMP,…)
- Autonomous interaction between hosts and routers
  - Defines 5 ICMPv6 packet types:
    - Router Solicitation / Router Advertisement
    - Neighbour Solicitation / Neighbour Advertisement
    - Redirect

IPv6 Neighbour Discovery (2)

Defines communication mechanisms for nodes on the same link:

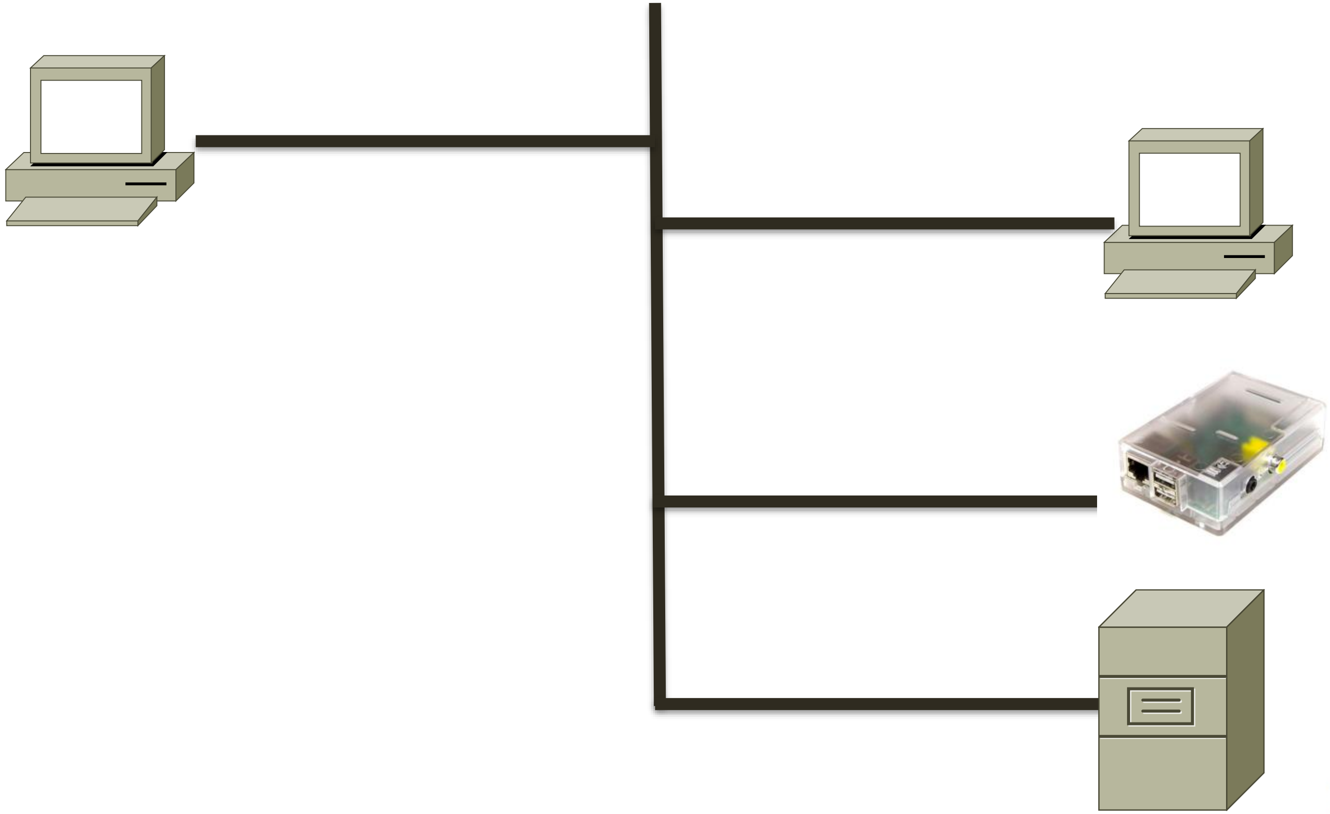
- Router discovery
- Prefix discovery
- Parameter discovery, i.e.: link MTU, hop limit,…
- Address auto-configuration
- Address resolution (same function as ARP)
- Next-hop determination
- Neighbour unreachable detection (useful for default routers)
- Duplicate address detection
- Redirect
- Network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

Neighbour Discovery Handshake



Neighbour Discovery Handshake

- Address of my neighbour?
  Search **FE80**::**ba**27:ebFF:FE3b:7def/64



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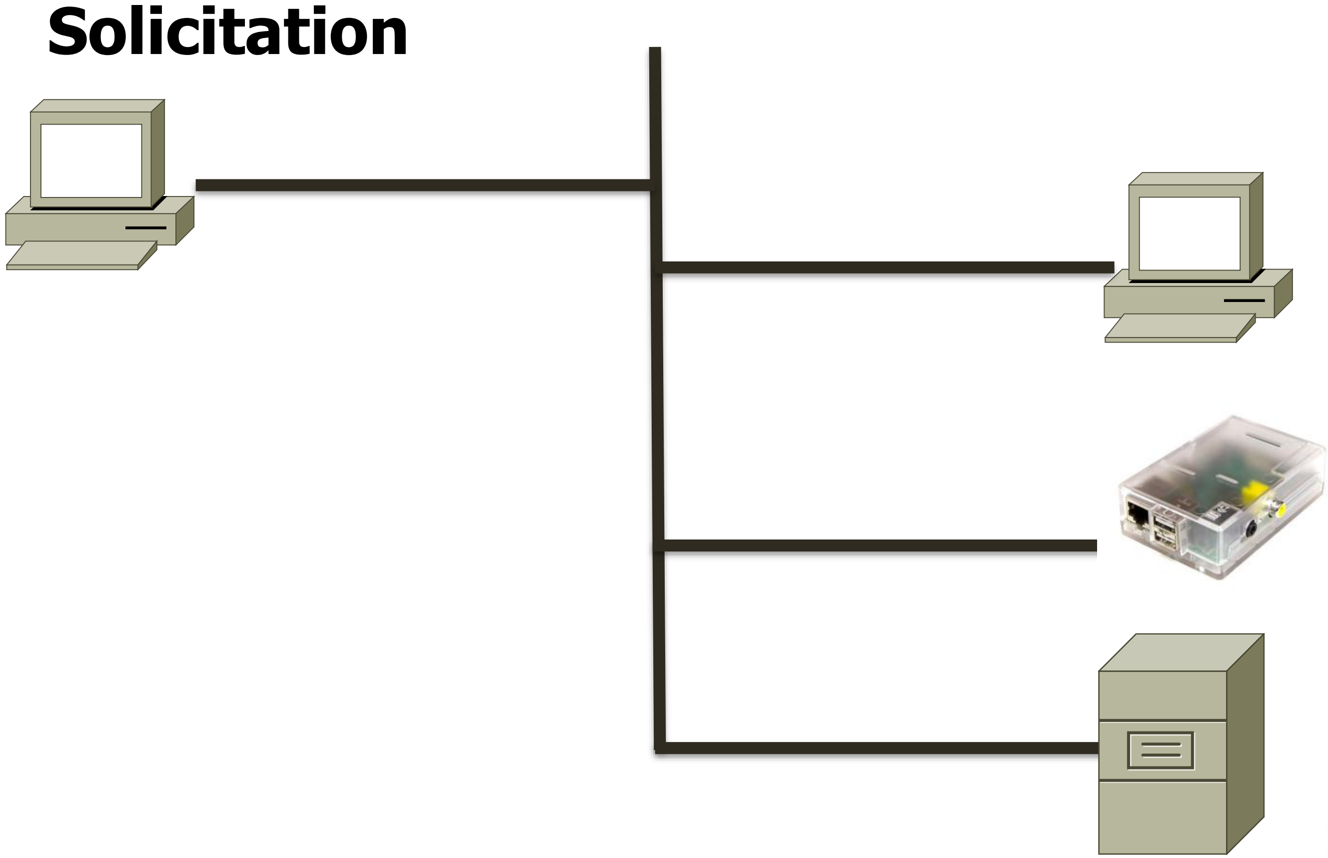

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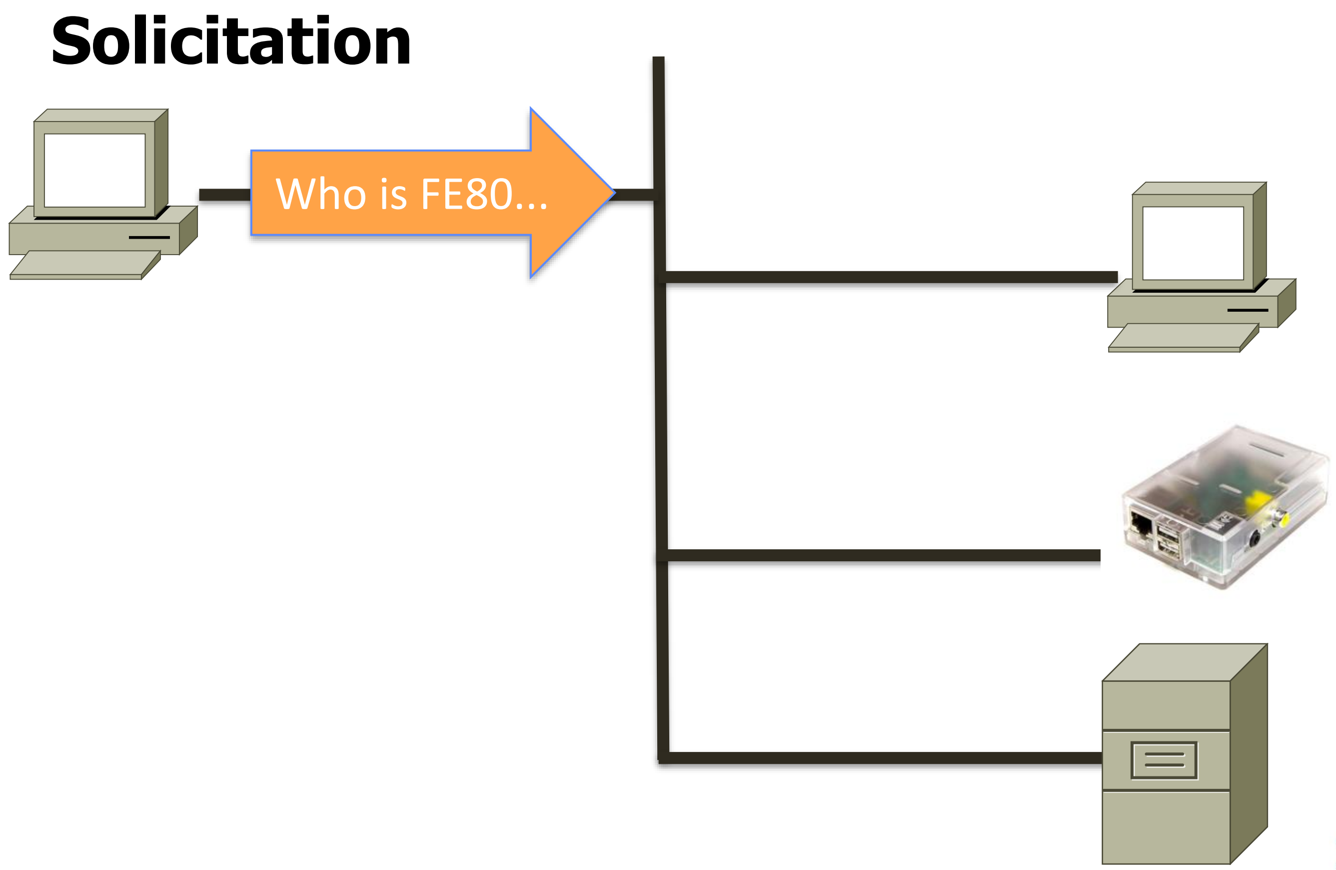

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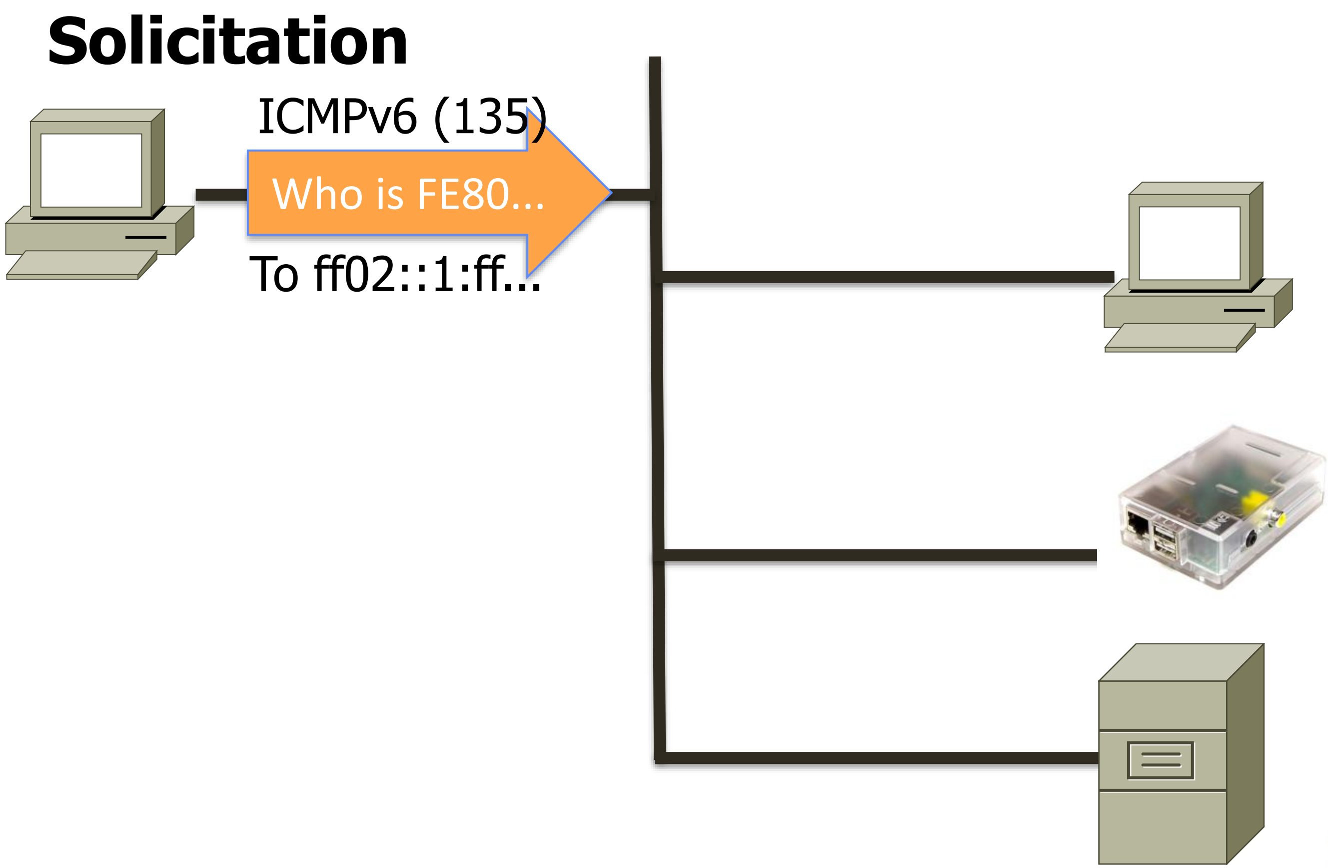

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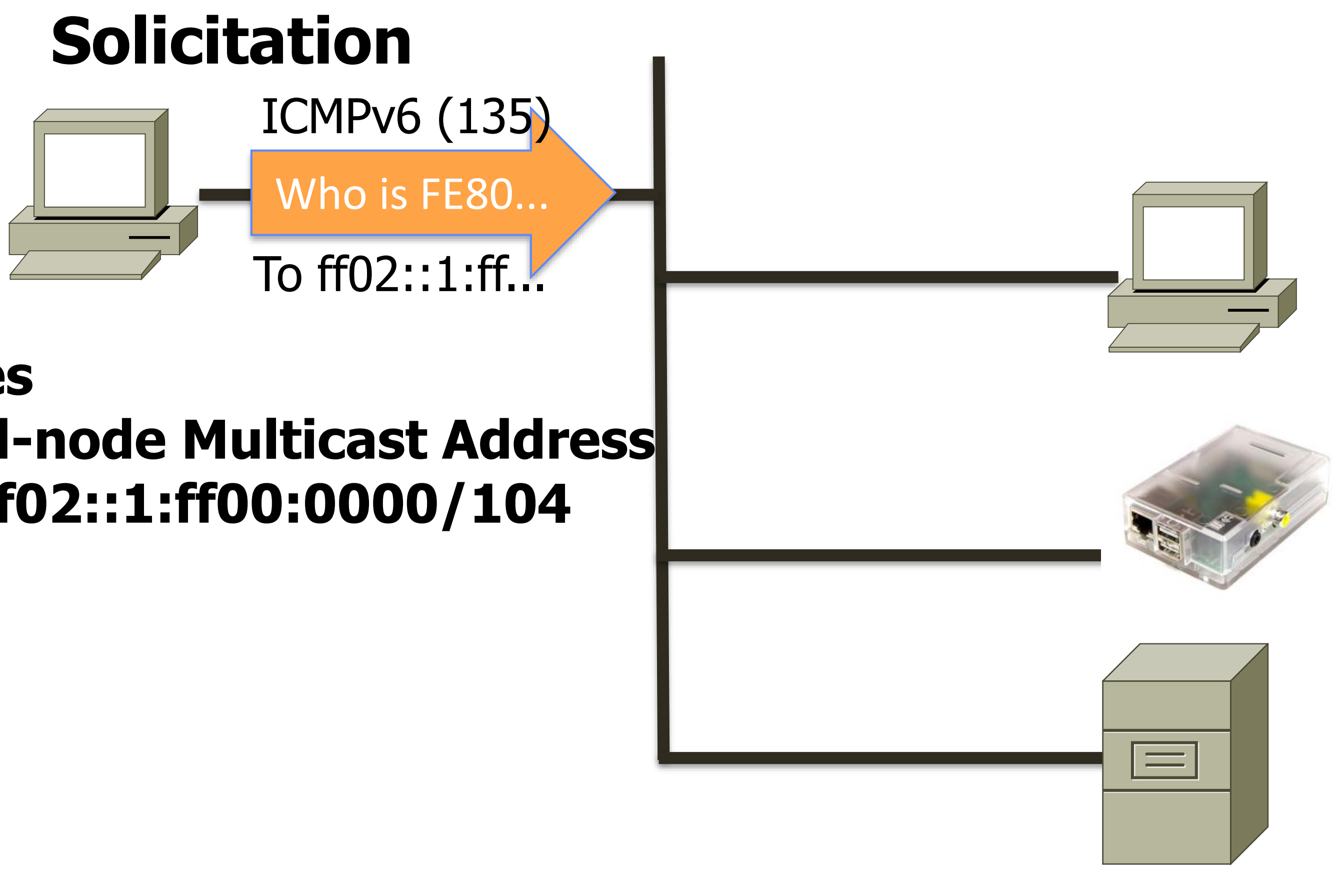

NDP uses
Solicited-node Multicast Address
Prefix: ff02::1:ff00:0000/104

Neighbour Discovery Handshake

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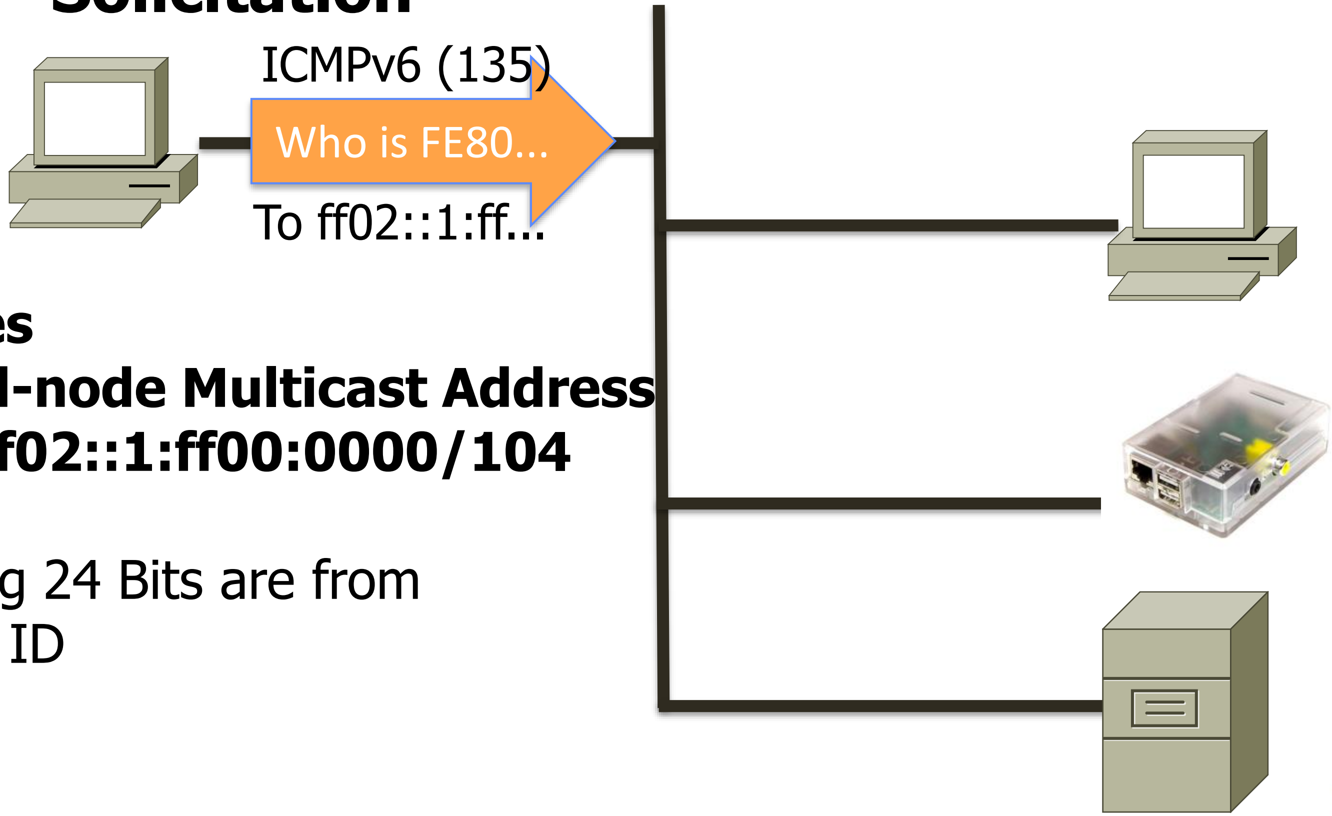
Solicitation



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Interface ID

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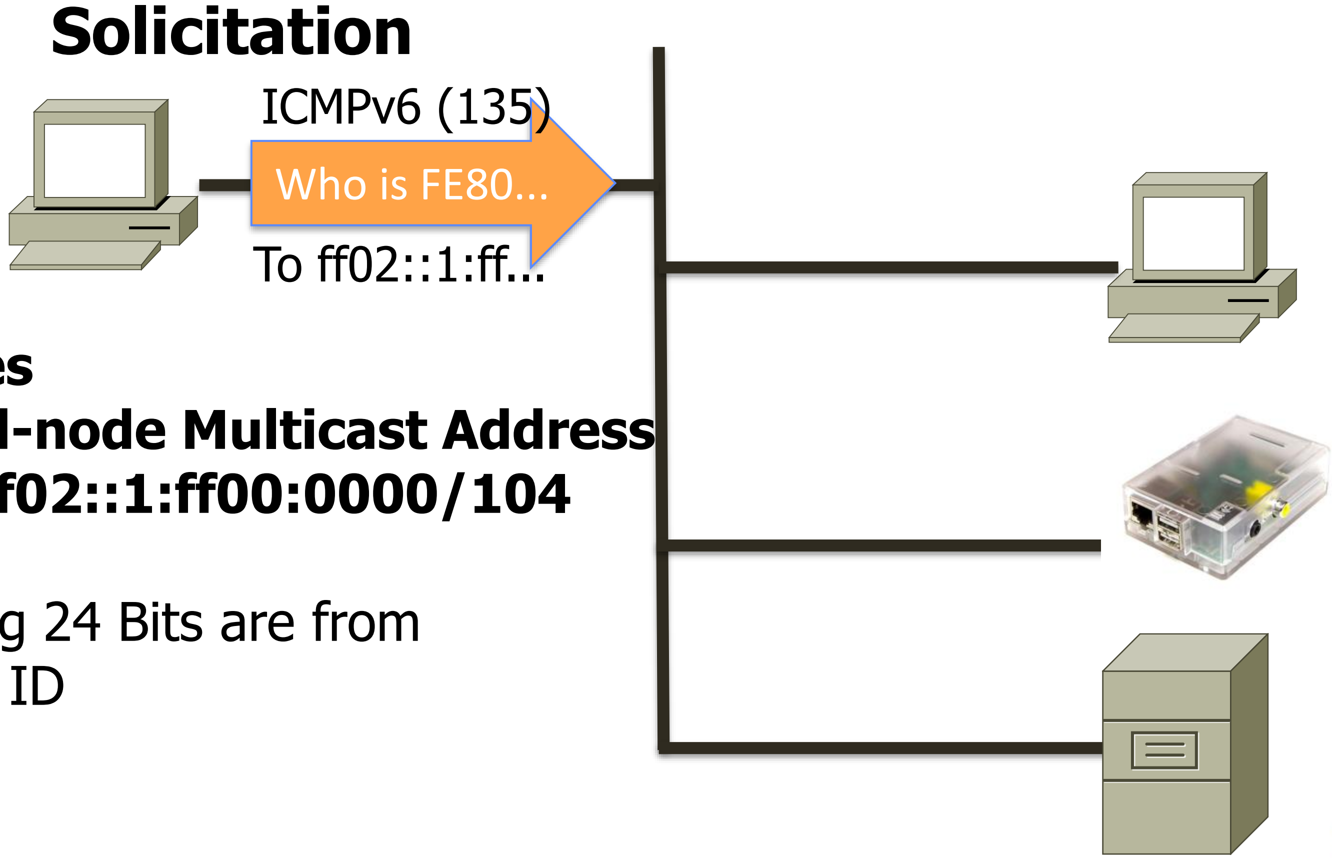

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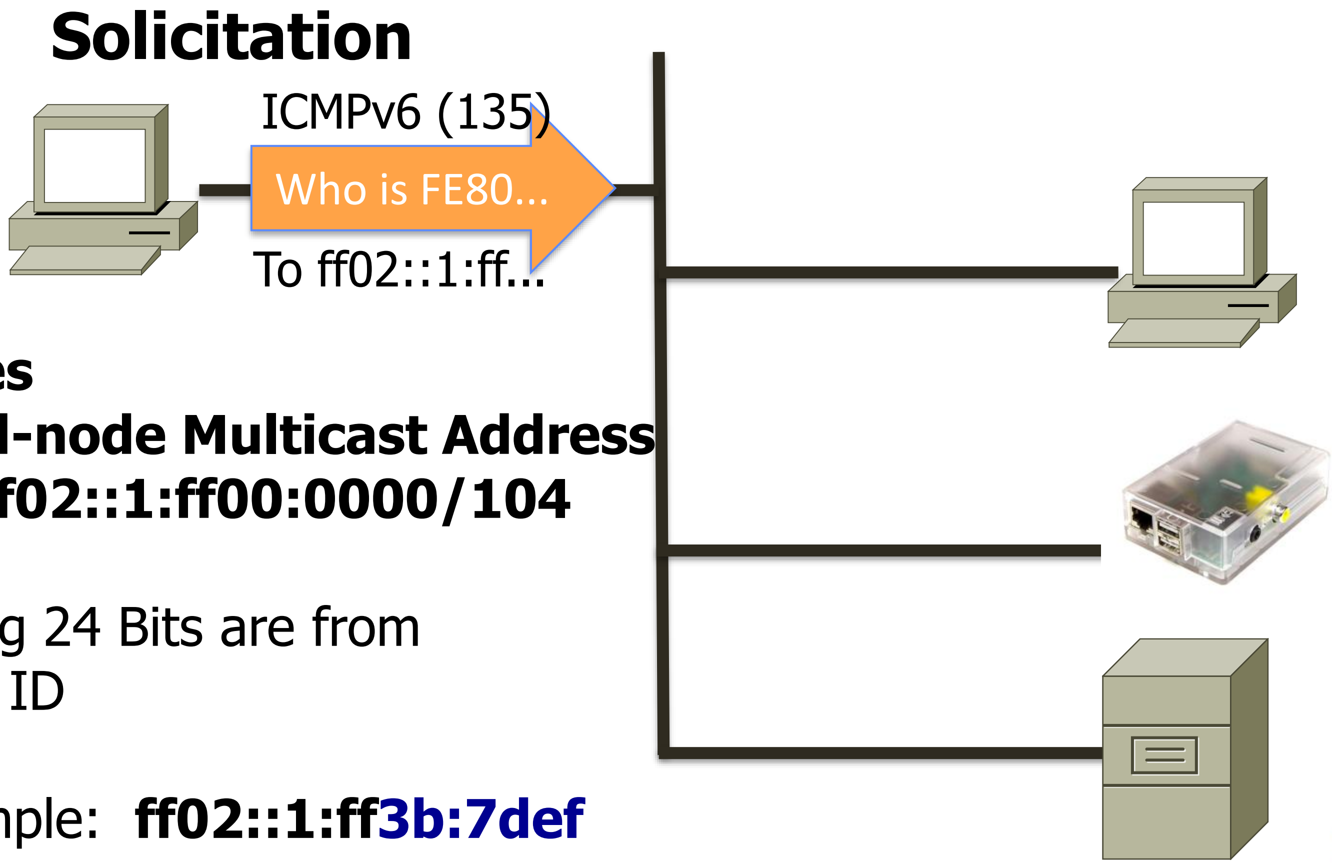

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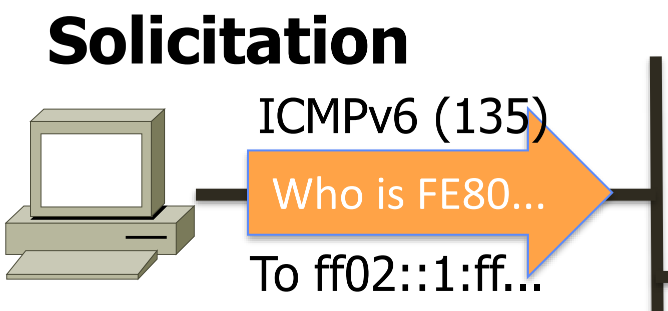

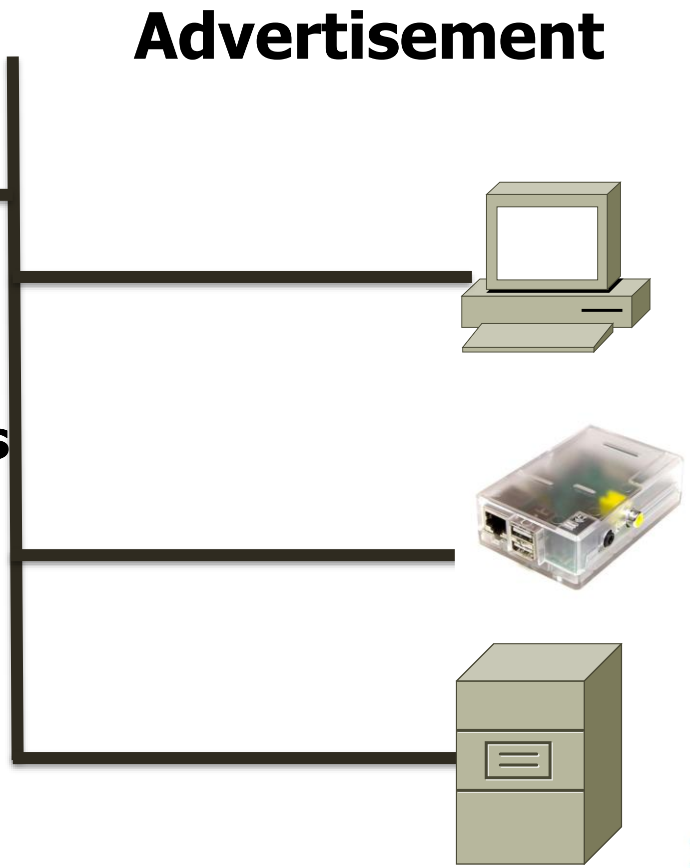

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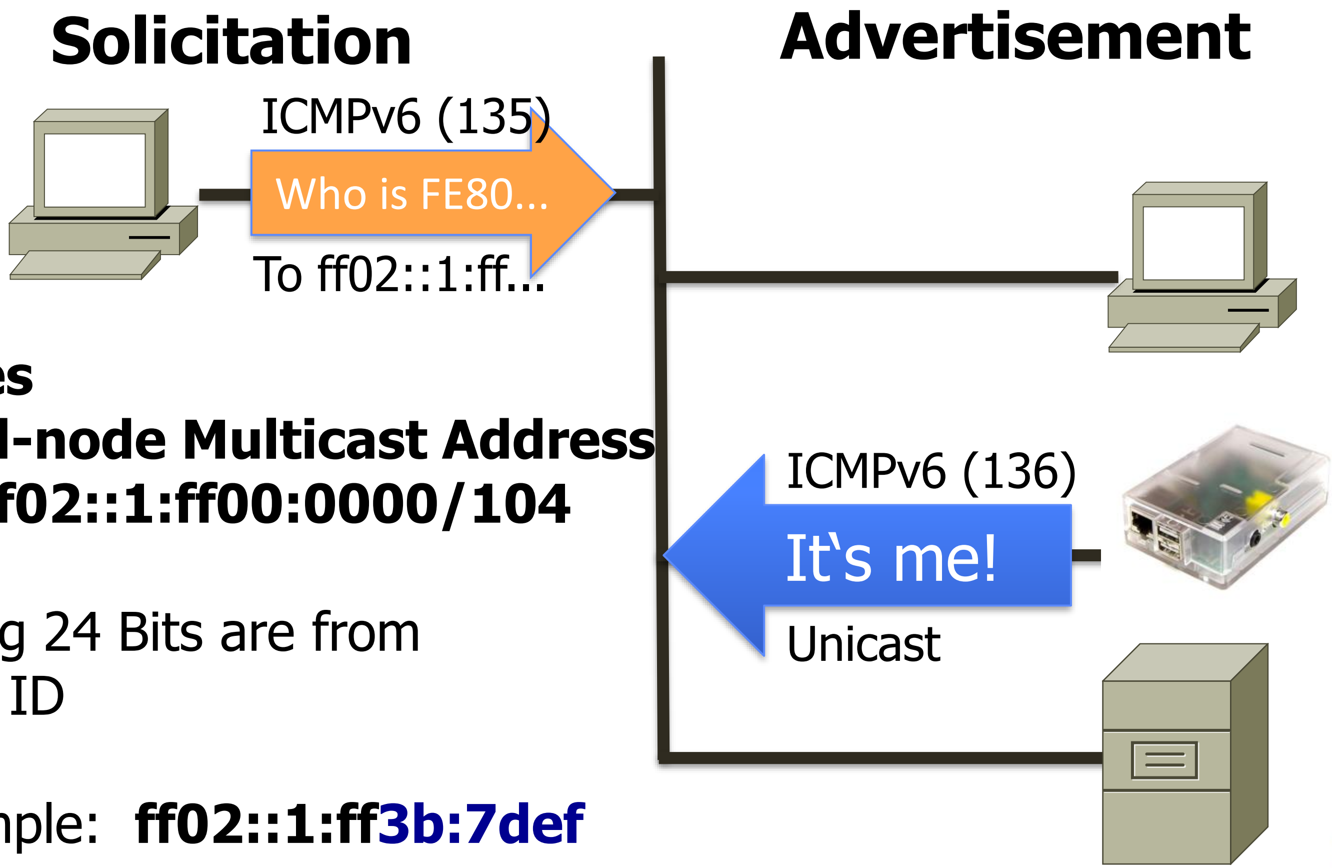

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Stateless Address Autoconfiguration - SLAAC

1. Interface assigns a link-local address on activation (default: EUI-64 built from a hardware address).
2. Interface sends *router solicitation,* to skip 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

- RFC 3971 (Arkko et al.)
- Employs Cryptographically Generated Addresses (CGAs – RFC 3972) to authenticate NDP ("prevent ARP spoofing")

  Details in MIPv6 Section
- SEND ND messages can self-consistently authenticate its IP sender address (without PKI)
- Router/prefix advertisements require certificates (X.509v3) from a PKI to assure routing responsibility

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Auto-Reconfiguration - Renumbering

- 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
- Prefix-distribution via router renumbering: RFC 4192
- DNS-Structure (AAAA) does not follow this flexibility

IPv6 DNS

Two approaches:

- AAAA (“Quad A”) Res. Rec. – RFC 1886, 3596
  - A record type of 128 bit length
  - Reverse lookup domain IP6.ARPA
- A6 RR – RFC 2874
  - Idea to support renumbering by prefix delegation
  - A6 record contains a domain name pointer:

Prefix len.	Address suffix	Prefix name

- 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 ≤ 1280 Bytes).
- Upper Layer (TCP): MSS ≤ 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 support upper layers without dynamically executing MTU-Discovery

Next Header	Reserved	Fragment Offset	0 0 M
Original Packet Identifier			

Generic Packet Tunnelling of IPv6

- RFC 2473 (Conta, Deering)
- Mainly used for explicit routing path control
- Defines (stateful) 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

New Header	Ext. Hds.	Original Packet (incl. Header)

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IPv6 Routing

- Uses CIDR „longest prefix match"/ largest mask to go for.
- Hierarchical addressing is a key issue for a scalable routing
  - VLSM route aggregation
  - Relies on provider-bound prefixes
- Dynamical routing protocols from IPv4 updated:

  Unicast: OSPF, RIP-II, BGP4+,...

  Multicast: MLD, MOSPF, PIM, BIDIR-PIM ...
- Can send packets through predefined regions by
  - routing headers (source routing) – type 0 deprecated (RFC 5095)
  - Anycast

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BGP Interdomain Routing

- BGP announces path vectors for IPv6 prefixes
  - IPv6 prefixes are treated as additional networks from the same AS
- BGP control-plane sessions bound to IP versions
  - IPv6 normally via TCP/IPv6, IPv4 via TCP/IPv4
  - This keeps next-hop in IP family
- IPv6 builds a routing topology parallel to IPv4
  - Paths and routers may differ
  - BGP routers hold two FIBs: IPv4 and IPv6

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

The Secrets of BGP

see separate BGP lecture

Anycast

- Service to 'one out of many' , RFCs 4291, 4786
- 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
- Anycast Routing
  - Within IGP: Host routes (dynamic/static)
  - Globally: Announcement of covering prefix, internally replicated instances, some global ASNs for Anycast

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Anycast (2)

- 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
- 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

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IPv6 & QoS

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

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

0	Not specified	4	Bulk (i.g. ftp, http)
1	‚Feeder' (i.g. netnews)	5	(Reserved)
2	Unnoticed (i.g. email)	6	Interactive (i.g. telnet, X11)
3	(Reserved)	7	Internet control (i.g. rip)

o Traffic without flow control (Realtime, Constant Bitrate, ...)
  Priority from 8 to 15 (ascending)

o Remaining priorisation according to DiffServ code points

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Flow Labels

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

- initial RFC 3697, now RFC 6437
- Goal: accelerated, uniform handling of packet streams through routers
- Flow label assignment: Random per Flow
- Header information consistent per flow (router caching)
- Initially defined router states, now stateless processing

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

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**

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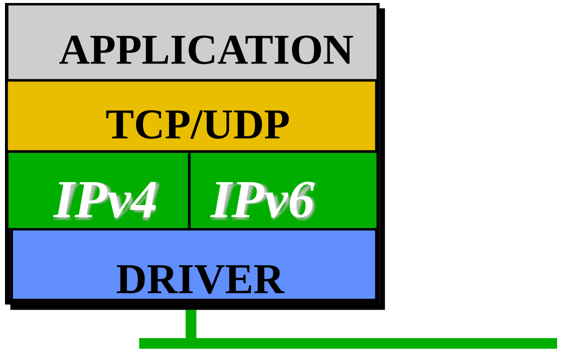
IPv4 → IPv6 Migration

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

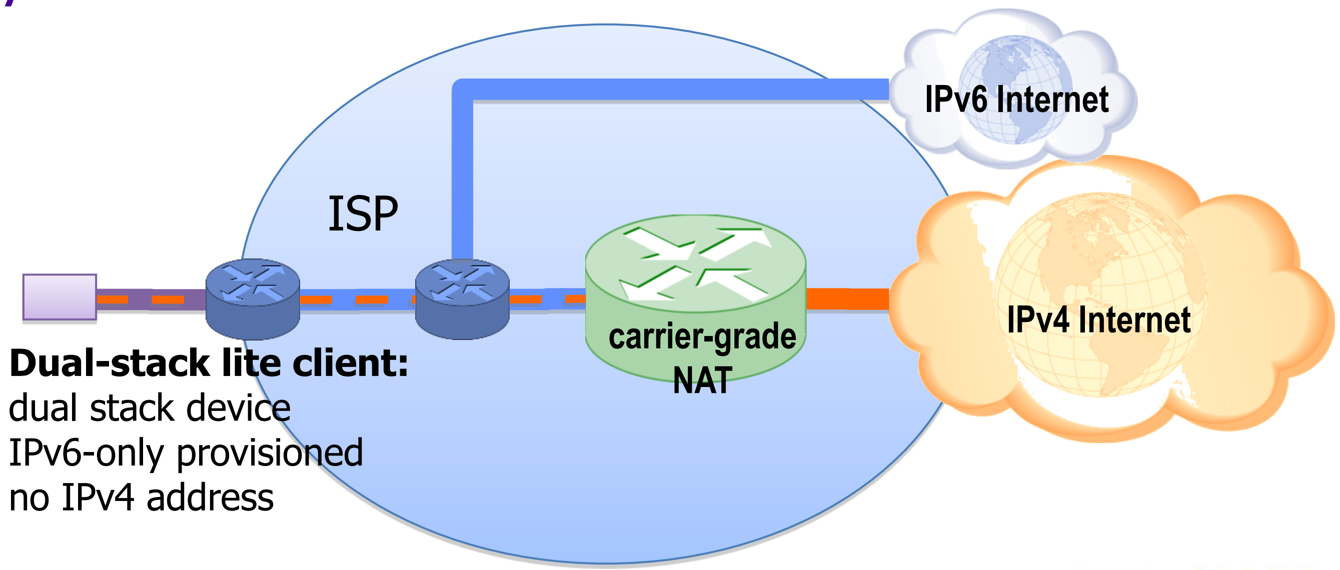


- On activation of IPv6, IPv4 can continuously be used (multi protocol approach)
- Devices can keep their addresses (IPv4 in IPv6)
- Application / libraries choose the IP version:
  - following DNS answers with a IPv6 preference
  - in response to received packets
- The Dual stack operation can continue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

Dual Stack Lite

- RFC 6333 -

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



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Transition by Tunnels

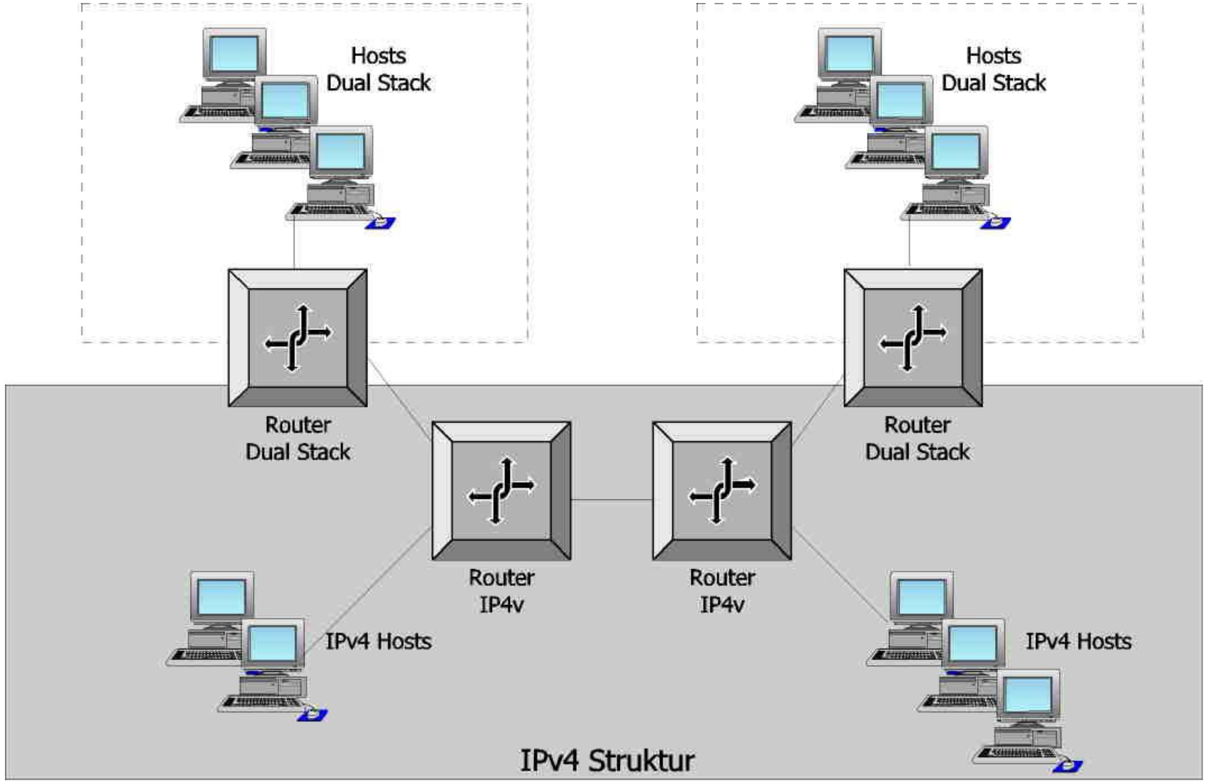
- Embedding of IPv6 packets in IPv4 packets
- Diverse methods to build a tunnel:
  - Manually
  - Tunnel Broker (web based application to build a tunnel)
  - 6-over-4 (intradomain)
  - 6-to-4 (interdomain, IPv4 address as IPv6 site prefix)
- Perspective:
  - IPv6 use IPv4 as a virtual link layer
  - IPv6 VPN over IPv4

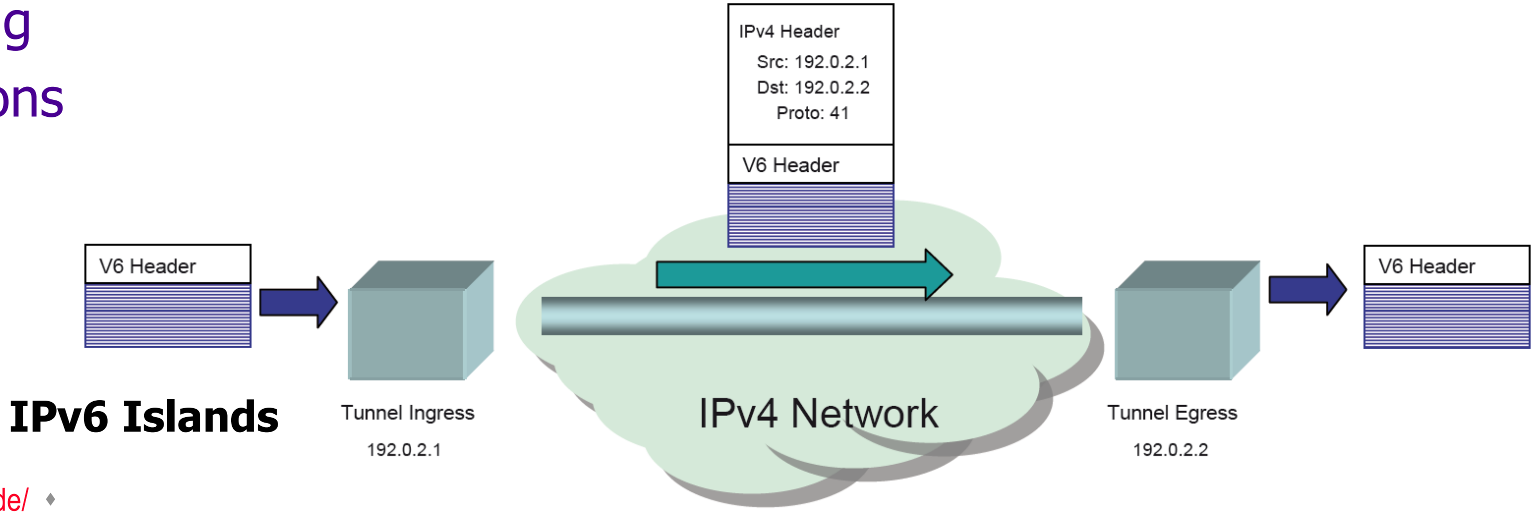
6-over-4 Tunnels

Isolated IPv6 islands in an IPv4 world

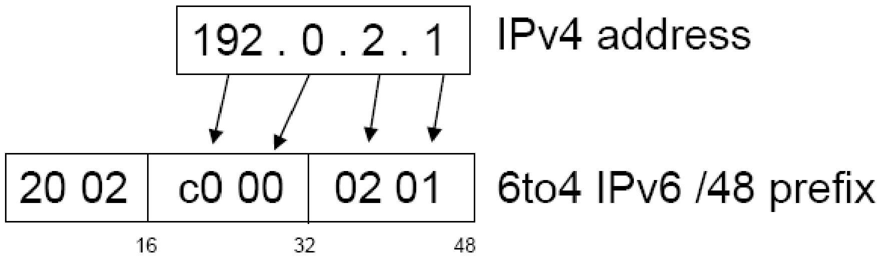
IPv6 ↔ IPv4 inter-connects: Embedding

IPv6 ↔ IPv6 inter-connects: Following tunnel configurations

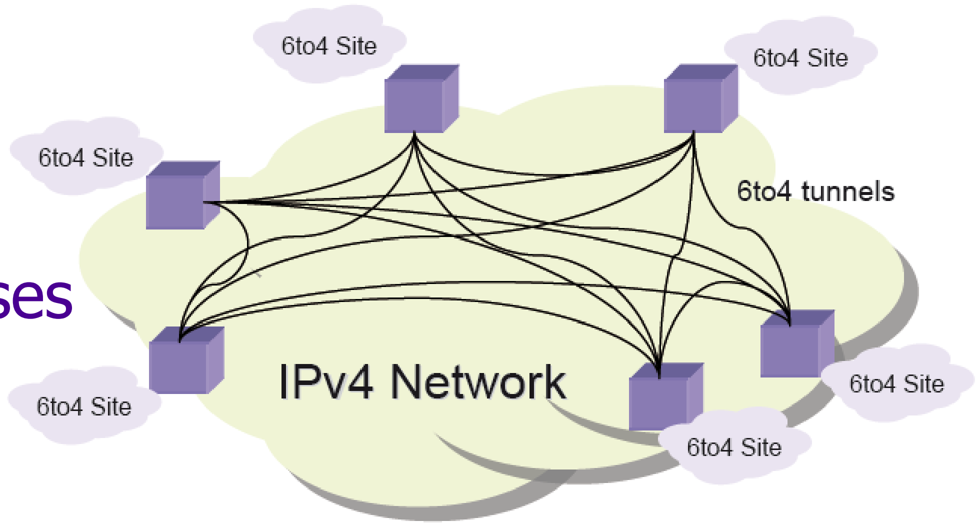




6-to-4



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



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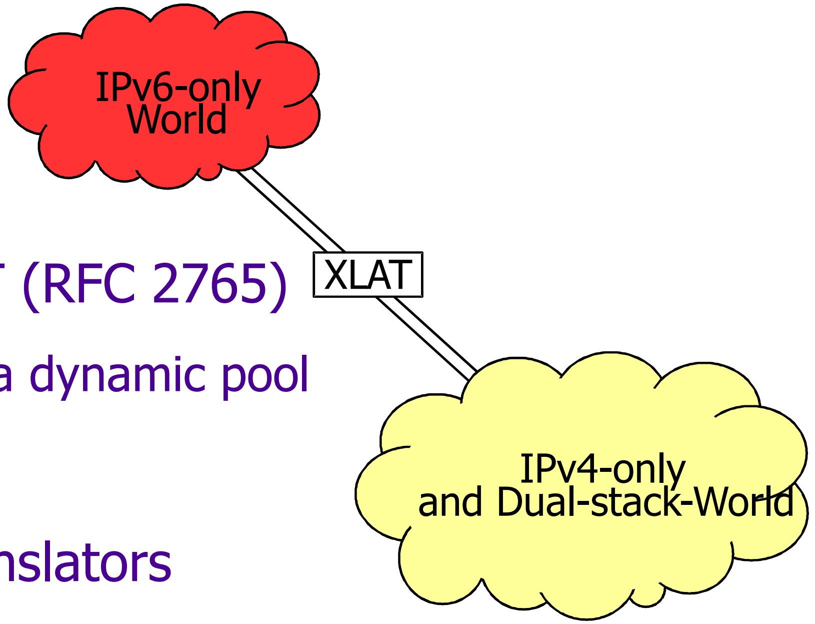
Protocol Translation



- Early stateless protocol translator: SIIT (RFC 2765)
  - Used temporary IPv4 addresse from a dynamic pool
- Current familiy of IP/ICMP protocol translators
  - XLATs: RFC 7915, addressing: RFC 6052
  - Stateful and stateless translation schemes
  - Algorithmic IPv4 embedding behind well-known prefix: 64:ff9b::/96
- Scenarios:
  - New IPv6-only domains at Internet edge
  - Old IPv4-only network islands

Agenda

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

Lessons Learned

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

Issue: Economic Models for Internet Operation

- Several players:
  - Infrastructure providers (pipes, routers, hosting)
  - Over the Top Provider (international applications & services)
  - Customer-oriented / regional ISPs
  - Edge domain operators (companies, consumer-ISPs)
- Problem: Grouping according to regions, not services
  - Little room for service innovation / dedication
- Approach: Virtualization of infrastructure
  - Allows for slicing of cables (λs), routers and servers
  - Offers playground for specialized service provisioning

Issue: Naming & Addressing

- 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)
- Mobility re-raises the problem
  - MIPv6 creates an ID/Locator split on network layer
- Host Identity Protocol (HIP, RFC 5201) introduces abstraction layer between network and transport

Issue: Route Scalability

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

IRTF / IETF Work

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

Locator ID Separation Protocol (LISP)

RFC 6830

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

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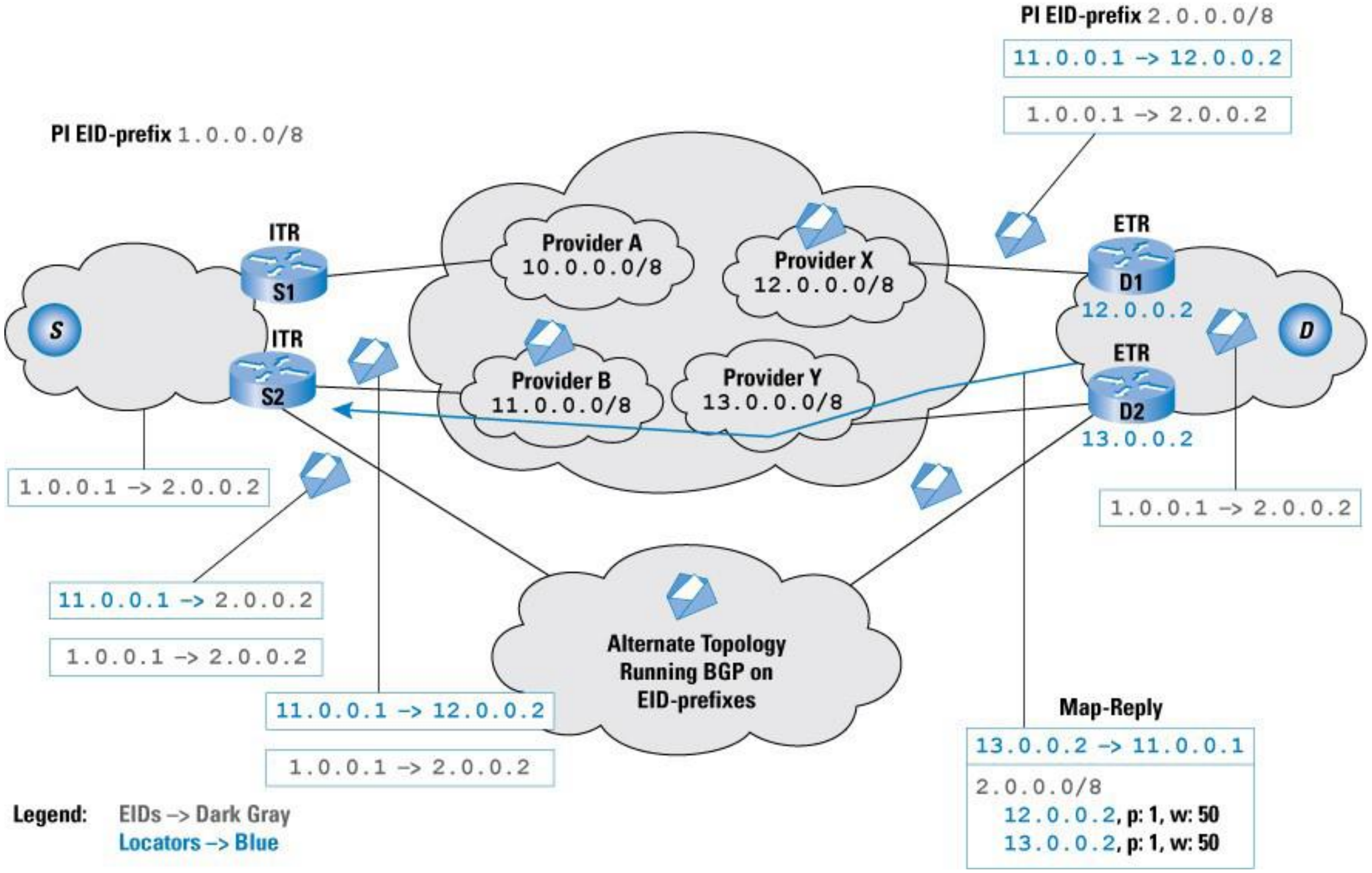
LISP Scenario



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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

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

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ILNP: Re-interpretation of the IPv6 Header

```
+---------------+----------------+----------------+---------------+
| Version| Traffic Class |          Flow Label                     |
+---------------+----------------+----------------+---------------+
| Payload Length                 | Next Header    | Hop Limit     |
+---------------+----------------+----------------+---------------+
|                          Source Locator                          |
+                                                                 +
|                                                                 |
+---------------+----------------+----------------+---------------+
|                          Source Identifier                       |
+                                                                 +
|                                                                 |
+---------------+----------------+----------------+---------------+
|                       Destination Locator                        |
+                                                                 +
|                                                                 |
+---------------+----------------+----------------+---------------+
|                        Destinaion Identifier                     |
+                                                                 +
|                                                                 |
+---------------+----------------+----------------+---------------+
```

Aggregation in Increasing Scopes
`draft-zhang-zhang-evolution`

- 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

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Recommendations of the RRG

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

Clean Slate Internet Initiatives

- Outside IETF/IRTF
- Focus scaling: overall logarithmic … as of DHTs ($/^3$)
- Focus virtualisation:

  Programmable virtual infrastructures for dedicated purposes
- Focus pluralisation/federation:

  Break with the paradigm of a universal network layer
- Focus programmability:
  - Software-defined Networking
  - Software-defined Radios
- Major US initiative: GENI
- EU: Future Internet Research and Experimentation – FIRE initiative
- Germany: German LAB (G-LAB)

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